Modeling and Analysis for Hardness and Structure of Nonferrous Alloy castings produced using Zcast Metal casting Process through Response Surface Methodology

Rajesh Kumar [a,*], Inderpreet Singh Ahuja [a], Rupinder Singh [b]
[a] Department of Mechanical, Punjabi University, Patiala, India
[b] Department of Production Engineering, Guru Nanak Dev Engineering College, Ludhiana, India

Article Info
Article history:
Received 20 February 2015
Received in revised form
25 February 2015
Accepted 28 February 2015
Available online 15 March 2015

Keywords
Hardness,
Structure,
Mathematical Modeling,
Three Dimensional Printing,
Response Surface Method

Abstract

The purpose of this investigation is to develop a mathematical model for predicting the influence of casting parameters on hardness of non ferrous alloy (NFA) castings produces using Zcast process by employing response surface methodology (RSM). An association has been proposed between hardness of castings and shell wall thickness (SWT), weight density (WD) and pouring temperature (PT) of the shell mould fabricated using three dimensional printer (3DP). The experiments were conducted using NFA materials like; aluminium, zinc, lead, copper, brass and bronze. An effective procedure of RSM has been utilized for the optimal values of casting parameters. Mechanical Micro-Vickers hardness was measured in which the indent is produced by applying a known load to the specimen and then measuring the size of the appropriate diagonals optically. Based on experimental data the investigation has led to conclusion as Quadratic model have been established for predicting the response in the form of hardness of castings.Further, the model developed was validated by analysis of variance (ANOVA) which indicated the significance of model. The Model F-value of 2477.66 implies that the model is significant. There is only a 0.01% chance that a Model F-Value could occur due to noise. Values of "Prob > F" less than 0.05 indicate model terms are significant. The statistical analysis of second order quadratic equation results showed that the most significant parameters, favoring the hardness are B, C and A^2. The superiority of the quadratic mathematical models were developed in confidence intervals of 99.75% with prediction error sum of squares of 3.6%for the prediction of the harness. Microstructure analysis was also performed for justification of hardness data.

1. Introduction

Present research is to develop a mathematical model for NFA castings. As foundry practice is the oldest streams known to mankind. The designing and making of cast-tooling such as pattern, core, gating system and mould is the most time consuming segment of casting process particularly in low volume production and for generating prototype casting. This is the today's need in foundry industry. Additive manufacturing (AM) technology has emerged as a solution to shorten the product development cycle, achieve flexibility for manufacturing small batch sizes and to carry out manufacturing of functional components having complex design at a low cost. AM is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [1]. After nearly 20 years of research, the AM industry continues to grow with the addition of new technologies, methods and its applications [2]. Rapid casting (RC) is one of the latest potential applications of AM technology which allows foundries to cast parts of any geometry without the application of traditional casting tools. Many researchers proved successful studies related to the application of different AM processes in casting techniques. There are many combinations gives satisfactory approach [3]. Creation of ready to pour moulds (pattern-less casting) using AM techniques has further created a uprising in the casting techniques. Using rapid sand casting solutions for fabrication of direct pattern-less moulds, highly complex and difficult designed component can be cast in very less time and at low cost, which was earlier impossible for the traditional foundry practice [4]. Direct fabrication of moulds from CAD files for metal casting can be achieved by using two prominent techniques of AM, either selective laser sintering (SLS) or three dimensional printing [5]. Three dimensional printing (3DP) plays an important role in manufacturing and this technology has been used as rapid shell casting to make the shell moulds. The process of 3DP was patented in 1994 under U.S. patent number 005340656 [6]. Based on three dimensional printing, ZCorporation developed a innovative RCsolution which enables to create shell moulds directly from the digital data for casting of non-ferrous alloy materials at relatively high speed and lowcost [7]. The process is recognized as ZCast direct metal casting. It eradicates the pattern-creation phase of the traditional sand casting process in a innovative way, resulting in drastic reduction of the casting lead time from weeks to days [8]. Eradicating the constraints of designing and making of patterns and cores, ZCast process provides foundry practice with ability to generate cost effective lots

Corresponding Author,
E-mail address: rajeshseptus@yahoo.com

of one-off complex cast components that were previously impossible to cast. In addition, multiple product design repetition can be possible without increasing much production lead time as well as without sustaining any additional cost of reshaping and re-producing the patterns. ZCast process uses ZCast501 powder, which is a proprietary mixture of powdered metal, plaster and ceramic composite designed for casting non-ferrous alloy metals [9]. Using 3D printer of ZCorporation, ZCast process allows the user to print the shell mould layer by layer using ZCast501 powder and by depositing Zb56 binder on the powdered layer where considered necessary with respect to the CAD data.After printing, the excess powder is removed during depowdering machine followed by the post processing of the shells in an oven with curing time 4-8 h and recommended curing temperature range is 180–230^{o}C [10].

Bassoli et al. [11] experimentally verified the feasibility of ZCast process for the production of aluminium alloy and also evaluated the dimensional accuracy of the process. The shell moulds were modeled with wall thickness between 12 mm and 25 mm in order to minimize the ZCast material to limit production time and cost. The technological prototype obtained using ZCast process was completely acceptable in terms of dimensional tolerances. Dimitrov et al. [8] investigated the capabilities of sand casting of rapid tooling process chains using 3D printing as core technology. Mckenna et al. [12] carried out an experimental investigation (based on statistical design of experiments) to find the effect of factors such as curing time and temperature, on compressive strength and permeability of moulds produced using ZCast 501 process. Mathematical model was also developed using linear regression. Bassoli and Atzeni [13] experimentally evaluated the mechanical and dimensional performances of the ZCast process by changing the thermal treatment parameters. Result showed temperature as the major influencing parameter for compressive strength whereas time has a negligible effect on the compressive strength.

Many researchers [14–17] experimentally get into the feasibility of decreasing the shell mould wall thickness of moulds produced by ZCast process from the recommended thickness (12 mm) by supporting the shell moulds with the loose sand from outside to save the cost and time for the production of castings in low brass, lead, zinc and aluminium respectively. For better functioning of cast components with strength, hardness is one of the important quality characteristics of any cast component. The primary objective of current research is to analyses the hardness of castings obtained using a ZCast process for non-ferrous alloys (NFA) such as aluminium, zinc, lead, copper, brass and bronze. The hardness of a casting is an indicator of the quality of the cast surface produced from the 3D printed moulds using ZCast process. In previous study, authors of this paper have experimentally investigated (using RSM) the effect of casting parameters such as materials SWT, WD and PT (having different pouring temperature) on dimensional accuracy of rapid castings obtained using ZCast process and accepted to publish in the year 2014 [18].

The review of basic experimental designs for a description of methods todeterminthe optimum operating conditions includes discussions concerning response surface models with random effects, generalized linear models, and graphical techniques for comparing response surface designs. The mathematical model found after giving a description to the data can sometimes not satisfactorily describe the experimental domain studied.

The main objectives of the present study are:

1. To develop a mathematical model for obtaining hardness of castings with shell moulds of different shell wall thicknesses fabricated using ZCast process by employing RSM.
2. To investigate the fitness of mathematical models for hardness and to develop predicting equation of measured hardness based on data collected by design of experiment.
3. To investigate experimentally for the optimized values of hardness for selected NFA materials with respect to the input casting parameters.
4. To investigate the significance of mathematical model and model terms on material property.
5. To perform the microstructure analysis for the justification of hardness data.

2. Response Surface Methodology

The RSM is useful for the modeling and analysis of problems, in which a response of interest is influenced by several variables and the objective is to optimize the response [19]. The fundamental impression of ANOVA is to compare the variation due to the treatment (change in the combination of variable levels) to the variation due to random errors inherent in the measurements of the generated responses [20]. As [21] and [22] reported that RSM is a collection of mathematical and statistical techniques. These are useful for modelling and analysis of problems in which response is influenced by several input variables. These serve the purpose to find the correlation between the response and the variables. In order to develop the RSM, firstly the function must be assumed as a mathematical polynomial form having coefficients that should be determined. These coefficients are determined by applying the set of the experimental results as reported by [23].The Sequential model sum of the square values suggests the quadratic model with the help of mean square value and Fisher's (F) value. The most reliable way to evaluate the quality of the model fitted is by the application of analysis of variance (ANOVA). Analysis of variance (ANOVA) is used to check the competency of the model for the responses in the experimentation. ANOVA calculates the Fisher's (F) value F-ratio, which is the ratio between the mean square regression and the mean square error. The model is adequate at desired significance level α, If the calculated value of F-ratio is higher than the tabulated value of F-ratio for hardness. For testing the significance of individual model coefficients, the model is optimized by adding or deleting coefficients through backward elimination, forward addition or stepwise elimination or addition. It involves the determination of P-value or probability of significance that relates the risk of falsely rejecting a given hypothesis. If the P-value is less or equal to the selected α-level, then the effect of the variable is significant.

3. Materials and Methods

A spigot joint cap used in tandem truck suspension system of CHALMERS 800 series truck was selected as benchmark. The geometrical drawing of the spigot joint cap is shown in Fig. 1. The components like spigot joint present a good degree of complexity, and for casting in low volume production, the application of ZCast process will be more cost effective than the traditional sand casting process. The first step of this research was the drawing and model creation of shell moulds using CAD software. Based on the component drawing, the CAD model of shells was prepared using the UNIGRAPHICS (Ver. NX 5) CAD software, shown in Fig. 2. For casting of selected component, split type of shells were designed. The CAD models of upper and lower shells were made for different values of the shell wall thickness. The wall thickness values selected for shells were 12 mm down to 2 mm. For producing castings of six non-ferrous alloys (viz. Al, Zn, Pb, Cu, Brass and Bronze) and due to the small shape and small volume of the castings, the feeder of molten metal was considered as the riser. The minimum height of the riser was calculated from the condition that the riser should solidify after the solidification of the main casting. The upper and lower shell models were then converted into STL (Stereolithography) file format. To establish the consistency, the STL format has been chosen as the standard for the AM industry. For experimentation, ZCorp 3D printer Z510 has been used to print the shell mould of different wall thicknesses (12, 11, 10, 9, 8, 7, 6, 5, 4, 3, and 2 mm) for the selected component using ZCast RC solution. Shell moulds were fabricated as per the technical data and procedure recommended by ZCorp. Fig. 3. Shows the 3D Zprinter Z510 (spectrum) with inside view of shell printing. Final printed shells were cured in an electric oven at a temperature of 180°C for 4 h. Shells (upper and lower) of all thicknesses were assembled using core paste. Fig.4 shows the shell moulds of different shell wall thickness ready for pouring and the melted NFA materials were poured to obtain the final castings. Experiments were conducted for the same set of parameters.

3.1 Process Parameters

Important parameters selected for present research related to shell moulds production are Layer thickness, orientation and post curing time. The input parameters for casting are materials having different shell wall thickness, pouring temperature and weight density) for generating castings using ZCast process were selected for the hardness analysis in order to develop a mathematical relation for predicting the hardness of rapid castings as response parameter. It is assumed that recommended parameters related to 3D printer are optimum for printing the shell moulds using ZCast process. Four parameters like three inputs and one response as output parameter were selected for developing the mathematical model. Presently three parameters have been investigated. On the bases of preliminary investigation and review of literature, the range of input parameters which were finally selected with their low and high levels are shown is given in table 1. These values of process parameters of shell casting were utilized for conducting the experimentation. The responding variable in terms of Vicker hardness was investigated.

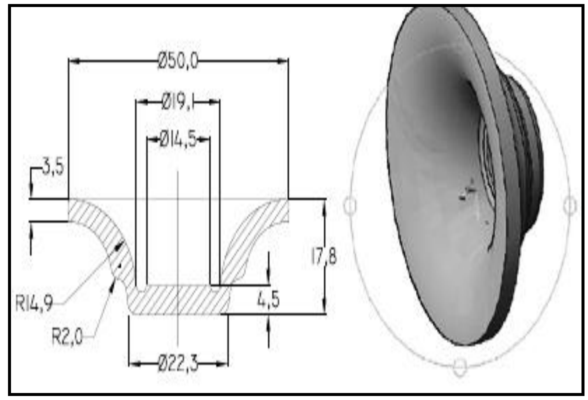


Fig: 1. Selected Component with Dimensions

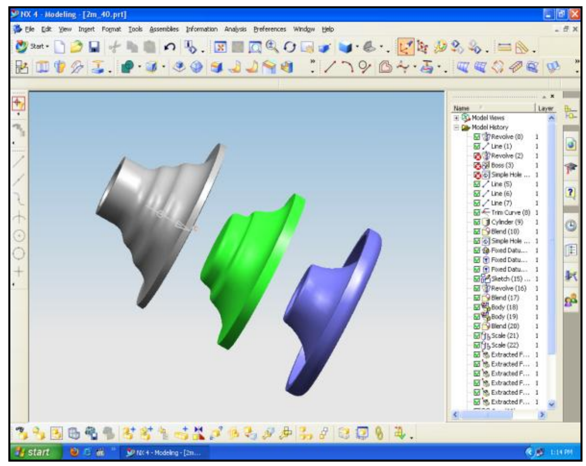


Fig: 2. CAD Model of Upper Shell, Component and Lower Shell

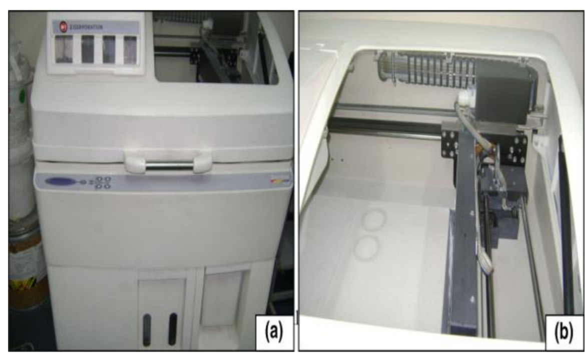


Fig: 3 (a). 3D Zprinter Z510 (Spectrum)
(b). inside view of printing of Shell

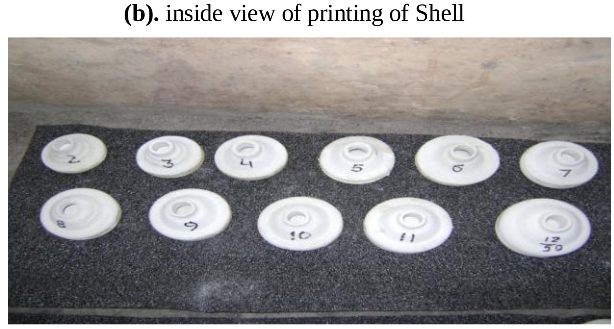


Fig: 4. Ready Shells for Pouring

3.2 Measurement of Hardness

In order to measure hardness, mechanical Micro-Vickers hardness testers (Model No.MBK-H2) manufactured by Mitutoyo (Akashi) Japan was used. The tester equipped with micrometer of travel 0 to 25 mm and eye piece with magnification range of 100X to 400X. The indent is produced by applying a known load on the specimen for measuring the size of the appropriate diagonals optically. Micro hardness is primarily determined by the Vickers indenture under test loads in the range of 1 to 2000 gram-force. It is used to measure the hardness of specific phases, small particles. The Vickers test is easy in that case where the calculations are independent of the size of indenter. It is useful for a variety of applications: testing very thin materials like foils or measuring the surface of a part, small parts or small areas, measuring individual microstructures, or measuring the depth of case hardening by sectioning a part and making a series of indentations to describe a profile of the change in hardness [24]. The Vickers method is more commonly used. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV). The VHN is obtained by dividing the applied load in kilogram-force by the surface area of the indentation. The area of the indentation produced from the Vickers square-based pyramidal diamond is determined by the mean distance between the two diagonals of the indentation. The load selected for measurement was 500 grams. The VHN as computed from the average length of the diagonals. Three consecutive readings were taken by orienting the machined surface. An average of these three readings was taken as shown in table 2. To justify the research work, microscopy using metallographic microscopes was used for understanding the relationship between hardness and microstructure. The observations for the process parameters and average response values are shown in table 2. The value of response factor in the form of Vickers hardness obtained was analyzed through RSM to develop their respective models in terms of input shell casting parameters. As very useful methodology, RSM has been used to study the relationships between hardness and selected parameters.

Table: 1. Process Parameters with their Values at Different Levels

Code	Process parameters	Units	Low	High	Low coded	High coded
A	Shell wall thickness (SWT)	[mm]	2	12	-1	1
B	Pouring temperature (PT)	[deg.C]	330	1084	-1	1
C	Weight Density (WD)	[gm/cm3]	2.77	10.20	-1	1

Table: 2. The observed values of process parameters and response in terms of Vickers Hardness (VHN) values

Std.	Run	SWT (mm)	PT (Deg. C)	WD (gm/cm3)	VHN (Vickers hardness)
1	30	5.00	330.00	10.20	8.00
2	1	12.00	790.00	2.77	94.00
3	46	11.00	978.00	8.67	90.00
4	51	6.00	978.00	8.67	94.60
5	60	8.00	1037.00	8.80	102.00
6	59	9.00	1037.00	8.80	98.00
7	35	11.00	1084.00	8.94	98.00
8	40	6.00	1084.00	8.94	110.00
9	42	4.00	1084.00	8.94	96.00
10	54	3.00	978.00	8.67	94.00
11	6	7.00	790.00	2.77	93.00
12	48	9.00	978.00	8.67	96.50
13	12	12.00	432.00	7.10	47.00
14	17	7.00	432.00	7.10	50.00
15	25	10.00	330.00	10.20	7.00
16	2	11.00	790.00	2.77	93.00
17	16	8.00	432.00	7.10	47.00
18	4	9.00	790.00	2.77	89.00
19	64	4.00	1037.00	8.80	98.00
20	57	11.00	1037.00	8.80	95.00
21	33	2.00	330.00	10.20	7.00
22	41	5.00	1084.00	8.94	103.00
23	8	5.00	790.00	2.77	98.00
24	45	12.00	978.00	8.67	91.00
25	28	7.00	330.00	10.20	7.00
26	52	5.00	978.00	8.67	92.70
27	7	6.00	790.00	2.77	96.00
28	26	9.00	330.00	10.20	8.00
29	18	6.00	432.00	7.10	50.00

30	22	2.00	432.00	7.10	47.00
31	44	2.00	1084.00	8.94	94.00
32	32	3.00	330.00	10.20	7.00
33	62	6.00	1037.00	8.80	115.00
34	5	8.00	790.00	2.77	94.00
35	34	12.00	1084.00	8.94	97.00
36	3	10.00	790.00	2.77	94.00
37	11	2.00	790.00	2.77	89.00
38	19	5.00	432.00	7.10	58.00
39	66	2.00	1037.00	8.80	99.00
40	14	10.00	432.00	7.10	45.00
41	29	6.00	330.00	10.20	8.00
42	47	10.00	978.00	8.67	102.00
43	63	5.00	1037.00	8.80	103.00
44	65	3.00	1037.00	8.80	92.00
45	49	8.00	978.00	8.67	104.00
46	27	8.00	330.00	10.20	7.00
47	58	10.00	1037.00	8.80	96.00
48	55	2.00	978.00	8.67	90.00
49	38	8.00	1084.00	8.94	101.00
50	43	3.00	1084.00	8.94	95.00
51	20	4.00	432.00	7.10	50.00
52	36	10.00	1084.00	8.94	96.00
53	61	7.00	1037.00	8.80	105.00
54	56	12.00	1037.00	8.80	98.00
55	24	11.00	330.00	10.20	8.00
56	37	9.00	1084.00	8.94	99.00
57	21	3.00	432.00	7.10	47.00
58	10	3.00	790.00	2.77	92.00
59	31	4.00	330.00	10.20	7.00
60	53	4.00	978.00	8.67	92.00
61	23	12.00	330.00	10.20	7.00
62	13	11.00	432.00	7.10	53.00
63	39	7.00	1084.00	8.94	108.00
64	15	9.00	432.00	7.10	48.00
65	9	4.00	790.00	2.77	92.00
66	50	7.00	978.00	8.67	98.00

4. Result and Discussion

On the basis of observations for each experiment as mentioned in complete design table 2.,Further analysis of results were performed by using software design expert.For the response factor, the best fit was described by the quadratic model as the Fisher's (F) value for the model is 53.08, suggested the significant model. In case of parameters and their interactions, with "Prob> F" lesser than 0.05 indicates that theterms are also forhardness as shown in table 3. The R^2 value for the suggested quadratic model was the 0.9975 highest, predicted R-Squared value is also 0.9967 and the corresponding PRESS values were lower, indicating the superiority of the quadratic model over the other models as shown in table 4.

Table: 3. Sequential model Sum of Squares

Source	Sum of Squares	Degree of freedom (df)	Mean Square	F Value	Probability > F	
Mean	198.38	1	198.38			
Linear	9.39	3	3.13	112.94	< 0.0001	
2FI	1.58	3	0.53	288.42	< 0.0001	
Quadratic	**0.079**	**3**	**0.026**	**53.08**	**< 0.0001**	**Suggested**
Cubic	3.327E-003	6	5.546E-004	1.14	0.3560	Aliased
Quartic	1.076E-003	6	1.794E-004	0.34	0.9132	Aliased
Fifth	6.836E-003	6	1.139E-003	2.63	0.0316	Aliased
Sixth	2.790E-003	6	4.651E-004	1.09	0.3901	Aliased
Residual	0.013	31	4.266E-004			
Total	209.45	65	3.22			

Table: 4. Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.17	0.8474	0.8399	0.8252	1.94	
2FI	0.043	0.9904	0.9894	0.9886	0.13	
Quadratic	**0.022**	**0.9975**	**0.9971**	**0.9967**	**0.036**	**Suggested**

4.1 Analysis of variance (ANOVA)

ANOVA table has been used to summarize the test for significance of the model, test for significance for the individual model coefficient and test for lack of fit. Summary output revealed that quadratic model is statistically significant for the responses as shown in table 3 and table 4. Significant model terms were identified at 95% significance level goodness of fit was evaluated from R^2 (coefficient of correlation) and CV (coefficient of variation) in order to check the reliability and precision of the model. Degree of Freedom (DF) means the number of values that can vary independently. By selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for hardness at casting condition is shown in table 5.

Table: 5. Anova for second order model for hardness in shell casting of NFA

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Significant
Model	11.05	9	1.23	2477.66	< 0.0001	Significant
A	1.924E-005	1	1.924E-005	0.039	0.8445	
B	1.389E-003	1	1.389E-003	2.80	0.0498	Significant
C	4.157E-003	1	4.157E-003	8.39	0.0054	Significant
A2	7.214E-003	1	7.214E-003	14.56	0.0003	Significant
B2	2.136E-004	1	2.136E-004	0.43	0.5142	
C2	1.346E-003	1	1.346E-003	2.72	0.1050	
AB	3.177E-005	1	3.177E-005	0.064	0.8011	
AC	3.422E-006	1	3.422E-006	6.905E-003	0.9341	
BC	3.619E-004	1	3.619E-004	0.73	0.3965	
Residual	0.027	55	4.955E-004			
Cor Total	11.08	64				

Final Equation in Terms of Coded Factors

$$Log10\ (VHN) = -3.21985 + 0.017176 * A + 3.61376E\text{-}003 * B + 1.14340 * C - 1.18862E\text{-}003 * A^2 + 1.16016E\text{-}006 * B^2 - 0.070239 * C^2 - 7.53159E\text{-}007 * A * B + 3.00906E\text{-}005 * A * C - 4.86736E\text{-}004 * B * C \quad (1)$$

Final Equation in Terms of Actual Factors

$$Log10\ (VHN) = -3.21985 + 0.017176 * SWT + 3.61376E\text{-}003 * PT + 1.14340 * WD - 1.18862E\text{-}003 * SWT^2 + 1.16016E\text{-}006 * PT^2 - 0.070239 * WD^2 - 7.53159E\text{-}007 * SWT * PT + 3.00906E\text{-}005 * SWT * WD - 4.86736E\text{-}004 * PT * WD \quad (2)$$

In this case Eq. 1 shows model B, C and A^2, are significant model coded terms. Eq. 2 shows the actual significant model terms like PT, WD and SWT^2. The values greater than 0.1 indicate the model terms are not significant. The main effect is of second order of SWT was the most significant factor associated with hardness as shown in equation 1 and 2, which was in accordance with the work on mould wall thickness [25]. Model fitting with the help of Design-Expert software suggested that a quadratic model provided the best fit, and the model was found to have insignificant lack of fit. This was desirable as we wanted a model that fit.The Model F-value of 2477.66 implies the model is significant.

As shown in table 5, there is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicates model terms are significant. In this case B, C, A2 are the significant model terms means the results identified that the SWT is the most important parameters, favoring the hardness. Where as PT and WD arealsosignificant terms to improve the hardness. The ANOVA table for reduced quadratic model indicated that the model was significant at $p < 0.0001$. Degree of freedom (DF) means the number of(1) values that can vary independently of one another. By selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for hardness at casting condition is shown in table 5.

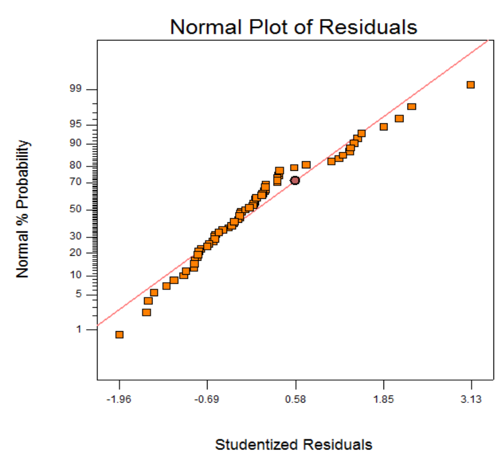


Fig: 5. Normal probability plot of the residuals for hardness

For diagnose the statistical properties of the model by using the design expert can be analyzed by inspection of various plots. The most important diagnostic will be the normal probability plot of the studentized residuals. Fig. 5 shows the straight line formed in the graph. Model values for response in the form of hardness and dotted points show the observed values found best distribution.

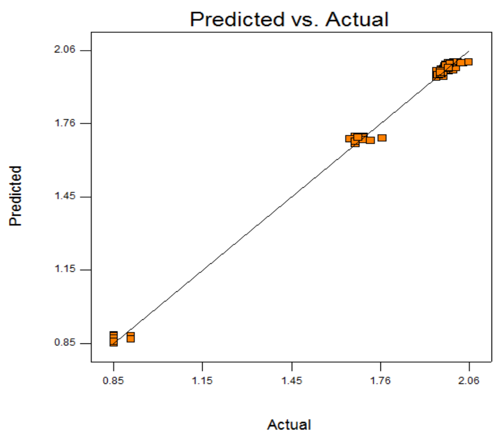


Fig: 6. Predicted verses actual value

The Fig.6 shows the relation between predicted and actual value with respect to the experiments performed for the hardness value as a response. The dot shows the relation between predicted and actual value for all experiments performed.

Fig. 7 shows the response surface of Vickers hardness number with the interaction of SWT and PT. The value of hardness also increases with the increase of pouring temperature with respect to shell wall thickness. Fig.8 shows the response surface of Vickers hardness number with the interaction of SWT and WD. The value of hardness also increases with the increase of WD with respect to shell wall thickness. Fig. 9 shows the response surface of Vickers hardness number with the interaction of SWT and WD. The value of hardness also increases with the increase of PT with respect to WD.

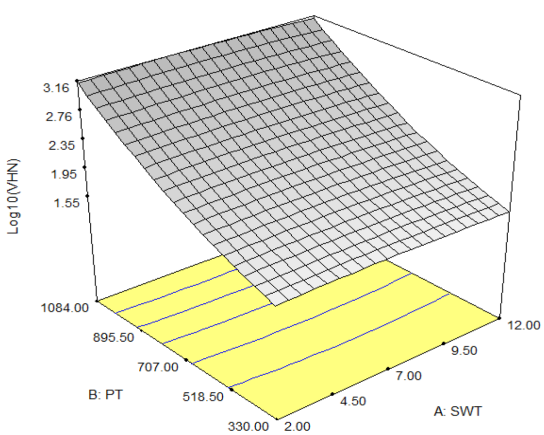


Fig: 7. Effects of SWT and PT on Vickers Hardness Number

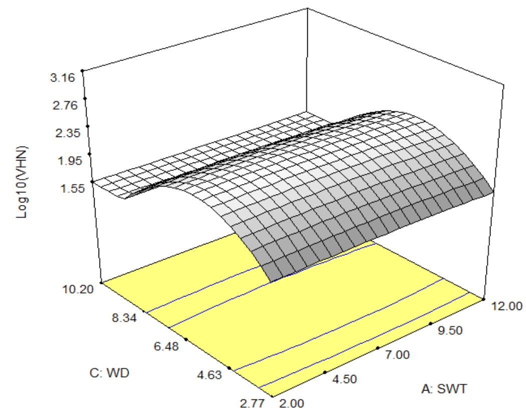


Fig: 8. Effects of SWT and WD on Vickers Hardness Number

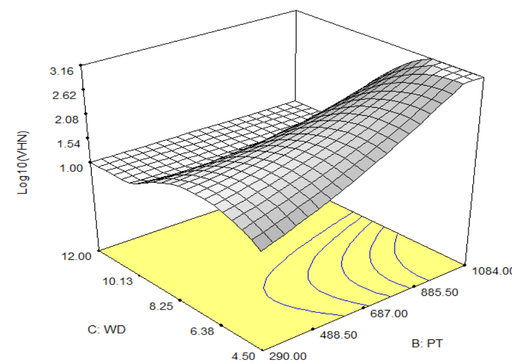


Fig: 9. Effects of PT and WD on Vickers Hardness Number

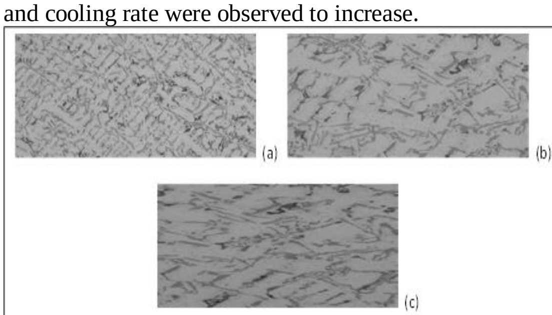
Table: 6. Responses with Respect to Model

Std. Dev.	0.022
Mean	1.75
C.V.	1.27
PRESS	0.036
R-Squared	0.9975
Adj R-Squared	0.9971
Pred R-Squared	0.9967
Adeq Precision	133.889

The R-Squared value was high, close to one, which was desirable. The predicted R-Squared measure the amount of variation in new data explained by the model. PRESS measures how well the model fits each point in the design. The "Pred R-Squared" is of 99.67%, which is in reasonable agreement with the "Adj R-Squared" value of 99.71%. As shown in Table 6, "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The analysis is saying that the model indicates adequate signal as the adequate precision value is greater than 4. This model can be used to navigate the design space. Prediction Error Sum of Squares (PRESS) is a measure of how well the model for the experiment is likely to predict the responses in new experiments. Smaller values of PRESS are desirable. For calculation of PRESS, the model is used to estimate each point using all of the design points except the one being estimated. PRESS is the sum of the squared differences between the estimated values and the actual values over all the points. A good model will have a large predicted R-Squared, and a low PRESS as shown in Table 6. Adequate precision measures signal to noise ratio was computed by dividing the difference between the maximum predicted response and the minimum predicted response by the average standard deviation of all predicted responses. In this present case the value of PRESS is 0.036 which indicates the good quality of Model.

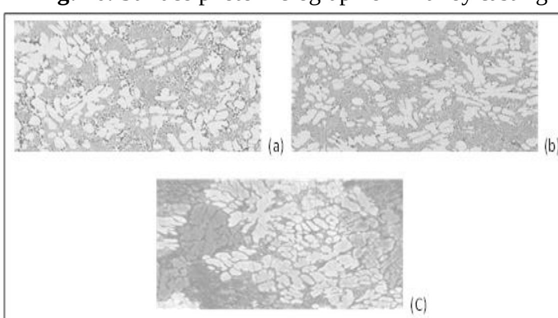
In this present research, an understanding of the relationship between hardness and microstructure provide useful information in the favour of manufacturing industry. Fig. 10-15 shows the microstructure of samples with higher hardness and lower hardness with respect to SWT, PT and WD for the selected NFA alloys. Microstructure and hardness analysis justify that SWT can be reduced from 12 mm to 2 mm and good results was found for selected NFA as Al, Zn, Pb, Cu, Brass, and Bronze were 5 mm, 5 mm, 6 mm, 6 mm, 7 mm & 6 mm respectively.

Micrographs show the phenomena lead to an increased number of nuclei that affect the dendrite arm space. The variation of the dendrite arm space with a decrease in shell wall thickness was observed. The variation of the space of dendrite arm affects the strength and hardness of castings. The grain structure of aluminium alloy in Fig. 10, showing dendrites formed during solidification. The microstructure of the Zn alloy revealed primary α dendrites as shown in Fig. 11. Dendritic structures of directionally solidified Pb alloy for different growth rates and temperature gradients were observed. Primary dendrite arm spacing and secondary dendrite arm spacing were observed to decrease while the temperature gradient in the liquid, the growth rate and cooling rate were observed to increase.



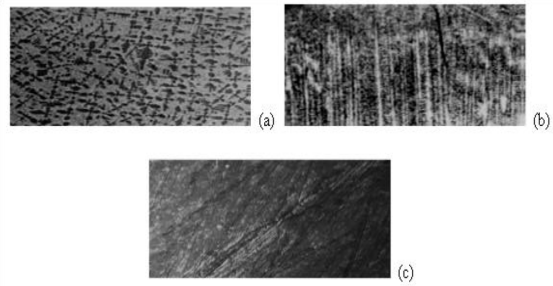
(at 790 °C (PT), 2.8 gm /cm^3 (WD),
(a) 12 mm (SWT), 94 VHN, (b) 5 mm (SWT), 98 VHN, (c) 2 mm (SWT), 89 VHN)

Fig: 10. Surface photomicrograph of Al alloy casting



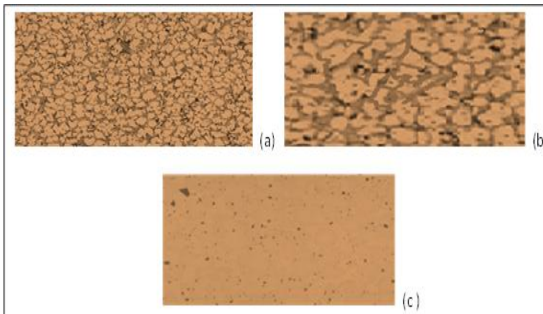
(at 432 °C (PT), 7.1 gm /cm^3 (WD),
(a) 12 mm (SWT), 55 VHN, (b) 5 mm (SWT), 56 VHN, (c) 2 mm (SWT), 47 VHN)

Fig: 11. Surface photomicrograph of Zn alloy casting



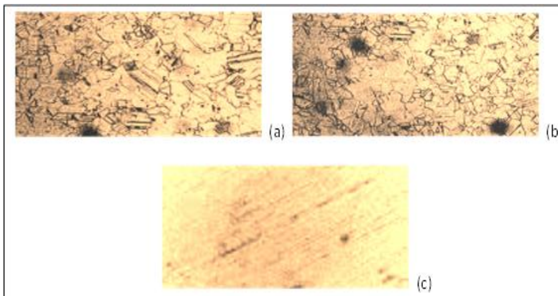
(at 330 °C (PT), 10.20 gm /cm^3 (WD),
(a) 12 mm (SWT), 7 VHN, (b) 6 mm (SWT), 8 VHN, (c) 2 mm (SWT), 7 VHN)

Fig: 12. Surface photomicrograph of Pb alloy casting



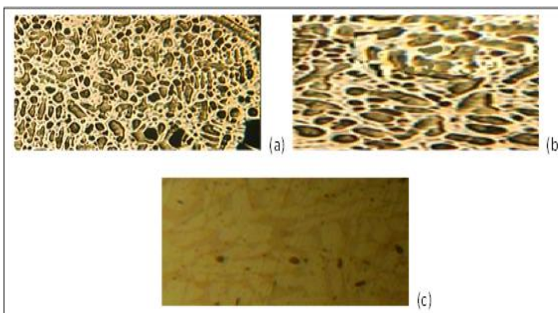
(at 1084 °C (PT), 8.94 gm /cm^3 (WD),
(a) 12 mm (SWT), 94 VHN, (b) 6 mm (SWT), 98 VHN, (c) 2 mm (SWT), 89 VHN)

Fig: 13. Surface photomicrograph of Cu alloy casting



(at 978 °C (PT), 8.67 gm /cm^3 (WD),
(a) 12 mm (SWT), 94 VHN, (b) 7 mm (SWT), 98 VHN, (c) 2 mm (SWT), 90 VHN)

Fig: 14. Surface photomicrograph of brass alloy casting



(at 1037 °C (PT), 8.80 gm /cm^3 (WD),
(a) 12 mm (SWT), 98 VHN, (b) 6 mm (SWT), 115 VHN, (c) 2 mm (SWT), 89 VHN)

Fig: 15. Surface photomicrograph of bronze alloy casting

[26] suggested in their research that the formation of dendritic structures containing only axes of the first and second order. In Fig. 12, Dendrite arm spacing was found to be moredependent on the temperature gradient, growth rate and cooling rate rather than primary dendrite arm spacing. Longitudinal section and Transverse section were observed. The microstructure shows copper dendrites interspersed with globules of lead which are darker in colour. Fig. 13 shows dendrite structure is an almost universal feature of copper alloy ingots. Increasing the cooling rate decreases the solidification time lead to increase dendrite arm spacing. The increase of the dendrites leads to grain growth. Dendrites of one color as shown in Fig. 14 form uniform grains. The dependence of the grain grown in the cooling rate is similar to the dependence of the distance between the axis of second-order dendrites. The increase in primary dendrite arm spacing improved the wear resistance. This microstructure is shown in Fig. 15 is typical of the general distribution of constituents produced by hot working the duplex aluminium bronzes. The α is surrounded by a matrix of darker etching β, both constituents having been elongated in the direction of working. Twins are present there and could be revealed by heavy etching. The solidification rate affects the microstructure forms such as grain size and dendrite arm spacing[27], [28], [29] and [30].The microstructure that results from solidification directly affects on the mechanical properties of alloys. The VHN increases as the rate of solidification increases.

5. Conclusion

In this research paper the study was carried out to develop mathematical model for predicting hardness of NFA castings and to investigate the influence of casting parameters like SWT, PT and WD on the response as hardness for six NFA material castings has led to following conclusions:

I. The model has been data fitted based on the experimental results generated by producing NFA material castings with 3D printed shell moulds having different shell wall thickness using ZCast process by successfully employing RSM based on appropriate parameters. Quadratic model was found to authenticate the significance of desired modelling. The ANOVA table for the quadratic model specified that at $p < 0.0001$. the model was significant The experimental results were closely correlated with data obtained by the regression equation.

II. The resulted hardness values of NFA castings produced by reducingthe shell mould wall thickness from 12 mm down to 2 mm, both in case of experimentation as well as in predictions, are acceptable with the standard sand cast hardness values range (8–115 VHN). The developed model may be used to predict the hardness of castings for different non-ferrous alloy materials as well as for moulds having different shell mould wall thicknesses fabricated using ZCast process.

III. The optimal values for hardness obtained for non-ferrous alloys as selected Al, Zn, Pb, Cu, Brass and bronze was 98VHN for 5 mm SWT at 790°C PT and 2.8 gm/cm^3 WD, 56VHN for 5 mm SWT at 432°C PT, 7.1 gm/cm^3 WD, 8 VHN for 6mm SWT at 330°C PT and 10.20 gm/cm^3 WD, 98 VHN for 6mm SWT at 1084°C PT and 8.94 gm/cm^3 WD, 98 VHN for 7 mm SWT at 978°C PT and 8.67 gm/cm^3 WD, 115 VHN for 6mm SWT at 1037°C PT and 8.8 gm/cm^3 WD respectively.

IV. As a result of the RSM experimental trials, it was found that the Shell wall thickness and weight density were the most significant factors affecting the hardness. The quadratic mathematical models were developed in confidence intervals of 99.75% for the prediction of the harness with prediction Error Sum of Squares of 3.6%.

The feasibility of reduced SWT was justified by hardness and microstructure analysis.The microstructure that results from solidification directly affects on the mechanical properties of alloys. The hardness increases as the rate of solidification increases. The results of this investigation contributes to develop a data base for obtaining hardness of different NFA castings produced using shell moulds having different wall thickness using ZCast process in order to make this RC solution economically feasible for small scale foundries.

Reference

[1] ASTM F2792-10e1, Standard terminology for additive manufacturing technologies, http://www.astm.org/Standards/F2792.html, 2010

[2] T. T. Wohlers, Wohlers report, executive sSummary. Annual Worldwide Progress Report, Wohlers Associates Inc., Fort Collins, CO. http://www.wohlersassociates.com/2001-ExecutiveSummary.pdf, 2007

[3] Z. Shan, Y. Yan, Zhang, Q. Lu, L. Guan, Rapid manufacture of metal tooling by rapid prototyping. Int. J. Adv. Manuf. Technol. 21, 2003, 469–475

[4] M. Chhabra, R. Singh, Rapid casting solutions: a review. Rapid Prototyp. J. 17(5), 2011, 328–350

[5] N. McKenna, Gravity and centrifugal casting of light metal alloys using rapidly produced sand moulds. Thesis (M.E.), Auckland University of Technology, 2010

[6] E. M. Sachs, J. S. Haggerty, M. J. Cima, A. P. Wiliams, Three dimensional printing techniques, United States Patent No. US 005340656, 1994

[7] D. Bak, Rapid prototyping or rapid production? 3D printing processes move industry towards the latter. Assembly Autom.23(4), 2003, 340–345

[8] [8]. D. Dimitrov, W.V. Wijck, N.D. Beer, J. Dietrich, Development, evaluation, and selection of rapid tooling process chains for sand casting of functional prototypes. Proc. IMechE B 221, 2007, 1441–1450

[9] P. Waurzyniak, Rapid metal-rapid manufacturing and rapid tooling for metal parts gain support. Manuf. Eng. 131(3), 2003, 49–57

[10] ZCorporation. ZCast501 Direct metal casting, design guide.http://www.zcorp.com, 2004

[11] E. Bassoli, A. Gatto, L. Luliano, M.G. Violentte, 3D printing technique applied to rapid casting. Rapid Prototyp. J. 13(3), 2007, 148–155

[12] N. McKenna, S. Singamneni, O. Diegel, D. Singh, T. Neitzert, J. George, A.R. Choudhury, P. Yarlagadda, Direct Metal casting through 3D printing, in A critical analysis of the mould characteristics. in 9th Global Congress on Manufacturing and Management (GCMM2008) in Surfurs Paradise, Australia, 2008
[13] E. Bassoli, E. Atzeni, Direct metal rapid casting: mechanical optimization and tolerance calculation. Rapid Prototyp. J. 15(4), 2009, 238–243
[14] J. P. Singh, R. Singh, Investigations for statistically controlled rapid casting solution of brass alloys using three dimensional printing.Int. J. Rapid Manuf. 1(2), 2009, 208–221
[15] J. P. Singh, R. Singh, Investigations for statistically controlled rapid casting solution of lead alloys using three dimensional printing.J. Mech. Eng. Sci. 223, 2009, 2125–2134
[16] R. Singh, Effect of moulding sand on statistically hybrid rapid casting solution for zinc alloys. J. Mech. Sci. Technol. 24(8), 2010, 1–7
[17] R. Singh, M. Verma, Investigation for reducing wall thickness of aluminium shell casting using three dimensional printing. J. Achiev. Mater.Manuf. Eng. 31, 2008, 565–569
[18] R. Kumar, R. Singh, I. P. Singh, Modeling of dimensional accuracy in three dimensional for light alloy casting" Material science forum, Vol. 808, (Accepted) pp. 65-78.Doi.10.4028/www.scientific.net/MSF.808.65., 2014
[19] D. I. Lalwani, N. K. Mehta, P. K. Jain, Experimental investigation of cutting parameters influence on cutting forces and surface roughness in finish hard turning of MDN250 steel, Journal of Materials Processing and Technology, 206, 2008, 167–179
[20] S. E. Vieira, R. Hoffmann, Estatística Experimental. Editora Atlas, São Paulo, 1989
[21] D. C. Montgomery, Design and analysis of experiments, New York, John Wiley & Sons, 1997
[22] R. H. Myers, D. C. Montgomery, Response surface methodology: process and product optimization using design of experiments", John Wiley Sons, New York, 1995
[23] G. E. P. Box, K. B. Wilson, The exploration and exploitation of response surfaces: some general considerations and examples, Biometrics, 10, 1954, 16 – 60
[24] C. K. Chauhan, K. C. Joseph, B. B. Parekh, M. J. Joshi, Growth and characterization of Struvite crystals, National Journal of Pure & Applied Physics, 46, 2008, 507-512
[25] Madhusudhan, S. Narendranaath, G. C. Mohankumar P. G. Mukunda, Effect of Mould Wall Thickness on Rate of Solidification of Centrifugal Casting, International Journal of Engineering Science and Technology, 2(11), 2010, 6092-6096
[26] N. Martyushev, Parameters of the dendritic structure of copper alloys, Ivan Franko National University of Lviv Chem. Met. Alloys 3, 2010, 197-200
[27] J. Campbell, The New Metallurgy of Cast Metals, Second Edition, Butterworth Heinemann, 2003
[28] D. M. Stefanescu, Science and Engineering of Casting Solidification, Kluwer Academic/Plenum Publisher, 2002
[29] J. Hemanth, Effect of cooling rate on dendrite arm spacing (DAS), eutectic cell count (ECC) and ultimate tensile strength (UTS) of austempered chilled ductile iron, Materials and Design 21, 2000, 1-8
[30] M. A. Talamantes-Silva, G Rodri, A. Talamantes- J. S. Silva, S. Valtierra, L. Cola, Effect of Solidification Rate and Heat Treating on the Microstructure and Tensile Behavior of an Aluminum-Copper Alloy, The Minerals, Metals & Materials Society and ASM International 2008