Effect of external parameters like mold material, mechanical mold vibration and pouring temperature on wear and hardness properties of Al - Si alloy casting.

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Abstract

This study summarises the research work on the effect of external parameters like mold material,pouring temperature and presence of mechanical mold vibration during solidification on some mechanical properties like wear and hardness of Al-12.6%Si (LM6) alloy castings. Cylindrical castings of size Ø 30mm x 200mm length were produced in cast iron and graphite mold subjected to vibration during the solidification process. Also the pouring temperature was varied. Factorial design of experiments technique was used to conduct the experiments wherein the above mentioned three factors mold material, pouring temperature and vibration were considered at two levels (2^3 factorial design). ANOVA has been conducted to predict the statistical significance of the factors. The results indicate that the two input parameters i.e pouring temperature and presence of vibration have a major contribution in affecting the responses measured ie wear and hardness

Key words: Factorial Design of Experiments, Artificial neural network, Mechanical Mold vibration, Al-Si alloy, Grain refinement and wear test.

1. Introduction

Aluminium-Silicon alloys are one of the most commonly used foundry alloys because they offer many advantages such as good thermal conductivity,excellent castability,high strength to weight ratio,wear and corrosion resistance,etc. Therefore they are well suited to automotive cylinder heads,engine blocks,aircraft components etc. The mechanical properties of Auminium-Silicon alloys are related to the grain size and shape.

Imposition of vibration on liquid metal during solidification has shown several advantages like grain refinement, increased density, degassing,shrinkage and improvement of mechanical properties.Grain structure of casting changes from columnar dendritic to equiaxed dendrites or globular. It has been observed that in order to get pronounced grain refinement, the solidifying melt should be kept under the influence of vibration energy for reasonably long time ranging from 1-5 minutes [1]. This can be done by choosing alloys with long freezing range or preheating the mold.

Different methods have been used to apply vibrations during solidification. Electromagnetic vibration is one of the non contact methods used to induce vibration in the solidifying metal [2-8]. Several other researchers have investigated the effect of vibration on the microstructure of castings [9-12]. The effects include grain refinement, fragmentation of the dendrite structure and degassing resulting in reduced porosity.

Pandel et al [13] have reported reduction in average size of silicon needles with increase in amplitude of vibration from 1- 3 mm, for hypoeutectic and hyper eutectoid Al-Si alloys. Burbure et al [14] have reported grain refinement in aluminum casting solidified under the influence of low frequency vibration of 50 Hz. The refinement was more pronounced with increase in casting size and at lower initial mold temperature. Abu-Dheir et al [15] have reported increase in percent elongation in the castings subjected to vibration of 100 Hz and varying amplitude of 18-199 micron. Also increase in amplitude has been reported to reduce interlamellar spacing between silicon needles.In another study, Kadir Kocatepe [16] reported that the amount and size of pores were increased in LM25 and LM6 alloys with increasing frequencies between 15 and 41.7 Hz and amplitudes between 0.125 and 0.5 mm.

Thus, it is clear that vibration promotes changes in microstructure and consequently in mechanical properties.

The present work has been carried out to study the effect of vibration during solidification and other factors like mold material and pouring temperature on Al- 12.6% Si (LM6) alloy properties.

Also an attempt has been made to develop soft computing based models such as artificial neural network. Artificial neural networks are parallel computational models comprised of densely interconnected adaptive processing units and have gained prominence among researchers [17-19]. ANN's are capable of learning patterns by training with a number of known pattern. The learning process automatically adjusts the weights and threshold of the processing elements once adjusted with minimal difference between ANN output and targeted output, the neural network is said to be trained

2. Methodology

Statistical design of experiments [20] refers to the process of planning the experiment, so that an appropriate set of data can be collected and then analyzed using the regression analysis for drawing inferences on the input- output relationship of a system.

In this work, full factorial design of experiments with the factors set at their respective two levels (2^3 factorial) has been used to develop linear relationship between the input-output parameters. The number of experiments required is less and the analysis provides complete information on the main and interaction effects of the input parameter on the response.

2.1 Selecting Process parameters and their levels

The following parameters which may affect the solidification process were considered for study.

Mold material

The thermal characteristics of mold material affect the solidification process. A mold material having good thermal conductivity dissipitates heat faster. The two levels of mold material considered were Cast Iron having lower thermal conductivity (Low level 0) and Graphite having higher thermal conductivity (High level 1).

Vibration

The effects of vibration (High level 1) and without vibration (Low level 0) were studied.

Pouring temperature

The two levels considered for pouring temperature were 700℃ (Low level 0) and 800℃ (High level 1).

Table 1 shows the factors selected and their levels.

Table 2 shows the design matrix and the possible treatment conditions.

2.2 Conducting experiments

Experiments were conducted as per the design matrix of full factorial design as shown in Table 2. For each combination of input factors two replicates were considered.

Alloy

Commercial Al-12.6%Si (LM6) alloy was melted in a graphite crucible using 3 phase,12 KW electrical resistance furnace and the temperature was raised up to 870˚C. After proper degassing with hexachloroethane and removing the slag, the melt was poured into the vibrating mold. Temperature of the charge was measured using chromel-alumel thermocouple just before pouring.The vibration was maintained until the melt was completely solidified. After solidification the castings were removed and specimens were prepared for mechanical testing.

Mold

Molds preheated to 200℃ were used to produce the castings. Cylindrical castings of diameter 30 mm x 200mm length were produced.

Vibration Arrangement

A simple mechanical vibrator set up was used for subjecting the mold to vibration. The set up consists of a power oscillator on which the mold is mounted as shown in Fig 1. The frequency of vibration can be changed in the range of 1Hz - 10 KHz with a maximum displacement of 12mm peak to peak. In the present study frequency and amplitude of vibration was kept constant at 25 Hz and 0.05 mm.

2.3 Responses measured

Wear

The wear test specimen was prepared with the dimension of diameter 5mm x 20 mm length. Specimens from each casting were prepared for the test. Computerized pin on disc wear testing machine shown in Fig 2 having integrated software for data collection was used to conduct the wear test. The test was conducted for duration of 1 hour at speed of 300 rpm under a normal load of 1 kg.

Hardness

The hardness of the specimen was obtained with a 10mm ball indenter and applying 500kg load.

2.4 Statistical Analysis

Analysis of variance (ANOVA) was conducted for each of the responses to check the adequacy of the models. The detailed analysis of the effects of parameters and their interaction on the responses was also done through the main effect plots. MINITAB software was used for this purpose.

2.5 Training and Testing of neural network

The statistical model developed through DOE might be able to predict the responses accurately. However the developed models are independent in the sense that each response is determined separately as a function of input variable. But in actual practice, all the responses are measured for a particular set of input parameters. It is here that the artificial neural network can be used to solve the problem. ANN can be trained in such a way that all the responses will be the function of input variables simutaneously. ANN have many structures and architecture. Multilayered Preceptron (MLP) is the simplest and therefore commonly used NN architecture. Fig 3 shows a MLP with three layers: an input layer, an hidden layer and an output layer.

The training for the neural network requires a huge amount of data. The training data related to the response wear and hardness were artificially generated using the statistical model developed by the factorial design of experiments.The data was generated by selecting the values of input variable lying within their respective ranges and determining the responses.

Test data was the actual experimental data collected. Neurosolution for excel software was used to train and test the data.

Multilayered perceptronwith back propagation having five neurons in the one hidden layer using hyperbolic tan function was the default architecture in the software used for training the network.

3. Results

The experimental data collected is shown in Table 3.This data is used to develop linear regression model based on full factorial design using minitab software.

The statistical analysis of the developed model was performed through the ANOVA tests. The input-output relations were studied with the help of main effect and interaction effect plots for the responses, wear and hardness.

3.1 Wear

The linear model based on full factorial design is shown in the following equation:

$$\text{Wear} = 572.81 - 29.06X_1 - 45.31X_2 + 37.81X_3 - 45.94X_1X_2$$

$$- 4.06X_1X_3 - 95.31X_2X_3 + 4.06X_1X_2X_3 \qquad \text{(Eq 1)}$$

Significance test was carried out to study the effects, contributions and significance of the input parameters and their interaction terms on the response – wear. The significance test results are shown in Table 4.

The different terms used in Table 4 have been explained as follows: The term 'Coef' indicates the coefficients used in equation 1 for representing the relationship between the said response and the factors. The term 'SE Coef' represents the standard error for the estimated coefficient, which measures the precision of the estimate.The *T*-values are calculated as the ratio of corresponding value under coefficient and standard error. The *p*- value is the minimum value for the pre-set level of significance, at which the hypothesis of equal means for a given factor can be rejected.

As the *p* values of the terms X_1 X_3 and X_1 X_2 X_3 (Table 4) were found to be more than 0.05, those terms were considered to have no significance contributions on the response wear at 95% confidence level, whereas all other main and interactions terms were found to have significant contribution.

Analysis of variance (ANOVA) was performed to test the significance of the factors for the response – wear. The results of ANOVA are shown in Table 5.

The different terms used in this table have been explained as follows:the term 'DF' represents the degree of freedom. The degree of freedom indicates the number of terms that will contribute to the error in prediction. The term 'Seq SS' indicates the sum of squares for each term, which measures the variability in the data contributed by that term.The adjusted sum of errors i.e 'Adj SS' is the sum of squares obtained after removing insignificant terms from the model. The sum of squares is divided by the degrees of freedom to determine the mean square. The adjusted mean square i.e 'Adj MS' is the mean square obtained after removing the insignificant terms from the response equation. The 'F' value for regression is used to test the hypothesis, which is calculated as the ratio of adjusted mean square value to the residual error.

From the table ,it is to be noted that the 2- way interaction term X_1 X_3 and the 3- way interaction term X_1 X_2 X_3 are found to be insignificant for this response. The coefficient of correlation for this model was found to be equal to 0.998. The results of ANOVA and the coefficient of correlation indicate that the developed regression model based on full – factorial design is statistically adequate.

The contributions of the input variables and their interactions are shown in the form of Pareto chart in Figure 4. From the figure it can be seen the the interaction of vibration and pouring temperature contribute significantly to the measured response followed by the interaction of mold material and vibration, vibration,pouring temperature,and finally mold material.The interaction of all three variables and the interaction effect of mold material and pouring temperature are insignificant.

The contributions of the input variables and their interactions on the measured response are shown in Figure 5 and Figure 6 respectively.From the main effects plot in Figure 5, it can be seen that graphite as the mold material, with vibration and pouring temperature of 700℃ gives lower mean value of wear.

From the interaction plot in Figure 6, it can be seen that the vibrated graphite mold gives lower mean value of wear as compared to unvibrated graphite mold. Also it can be seen that the effect of vibration is inconsequential for cast iron mold.

Similiarly it can be seen that alloy poured at 700℃ in both cast iron as well as graphite mold gives lower mean value of wear as compared to alloy poured at 800℃.

Alloy poured at 800℃ in a vibrated mold gives better result than an alloy poured in an unvibrated mold. Similiarly it can be seen that an alloy poured at 700℃ in an unvibrated mold gives better result as compared to a vibrated mold.

3.2 Hardness

The linear model based on full factorial design is shown in the following equation:

$$\text{Hardness} = 62.6956 + 0.5156X_1 + 0.8694 X_2 - 0.9956 X_3 + 1.4244 X_1 X_2 + 0.0469 X_1 X_3 + 1.6381 X_2 X_3 - 0.0494 X_1 X_2 X_3 \quad \text{(Eq 2)}$$

Significance test was carried out to study the effects, contributions and significance of the input parameters and their interaction terms on the response – hardness. The significance test results are shown in Table 6.

As the *p* values of the terms X_1 X_3 and X_1 X_2 X_3 (Table 6) were found to be more than 0.05, those terms were considered to have no significance contributions on the response hardness at 95% confidence level, whereas all other main and interactions terms were found to have significant contribution.

Analysis of variance (ANOVA) was performed to test the significance of the factors for the response – hardness. The results of ANOVA are shown in Table 7.

From the table ,it is to be noted that the 2- way interaction term X_1 X_3 and the 3- way interaction term X_1 X_2 X_3 are found to be insignificant for this response. The coefficient of correlation for this model was found to be equal to 0.997. The results of ANOVA and the coefficient of correlation indicate that the developed regression model based on full – factorial design is statistically adequate.

The contributions of the input variables and their interactions are shown in the form of Pareto chart in Figure 7. From the figure it can be seen the the interaction of vibration and pouring temperature contribute significantly to the measured response followed by the interaction of mold material and vibration, pouring temperature, vibration, and finally mold material.The interaction of all three variables and the interaction effect of mold material and pouring temperature is insignificant.

The contributions of the input variables and their interactions on the measured response are shown in Figure 8 and Figure 9 respectively.From the main effects plot in Figure 8, it can be seen that graphite as the mold material, with vibration and pouring temperature of 700℃ gives higher mean value of hardness.

From the interaction plot in Figure 9 , it can be seen that the vibrated graphite mold gives higher mean value of hardness as compared to unvibrated graphite mold whereas an unvibrated cast iron mold gives higher mean value of hardness as compared to vibrated cast iron mold.

Similiarly it can be seen that alloy poured at 700℃ in both cast iron as well as graphite mold gives higher mean value of hardness as compared to alloy poured at 800℃.

Alloy poured at 800℃ in a vibrated mold gives better result than an alloy poured in an unvibrated mold. Similiarly it can be seen that an alloy poured at 700℃ in an unvibrated mold gives better result as compared to a vibrated mold.

3.3 Results of ANN

The neural network was trained with the artificially generated data as explained above. The training was carried for 1000 epochs and the lowest mean squared error is 0.000165. Fig 10 shows the graph of MSE v/s epoch.

After training the network was tested on the experimental data.The correleration coefficient between the tested value and the predicted value is 0.98 for wear and 0.99 for hardness. The mean absolute error is 22.70,minimum absolute error 0.54, maximum absolute error 53.63 and the mean squared is 745.57 for the response wear. The corresponding values for the response hardness are 0.45,0.0098,1.16 and 0.318.

3.4 Comparision

Table 8 and Table 9 compares the outputs of factorial design of experiment and neural network with the experimental data for the responses wear and hardness respectively. For the response wear the deviation for DOE was found to vary from -10 to10 whereas for NN it was found to vary from -41.57 to 59.38. For the response hardness the deviation for DOE was found to vary from -0.47 to 0.48 whereas for NN it was found to vary from -0.65 to 1.17.

Fig 11 and Fig 12 shows the comparision between the three results for the responses wear and hardness respectively.The pattern are similiar for the results. However the predictions of DOE seems to outperfom the predictions of NN.

4. Discussion

From the literature review, it is well documented that vibration during solidification results in grain refinement. From the results,it is seen that the presence of vibration along with the pouring temperature has a significant role in improving the properties of the alloy.

Effect of vibration is prolonged if the melt is superheated to higher temperature which results in fragmentation of dendrites resulting in fine grains.In the absence of vibration, however lower pouring temperature results in better properties due to faster heat dissipitation again resulting in fine grains.

Mold material by itself is the least significant factor but when combined with vibration, it plays a significant role. Vibrated graphite mold results in better properties. Graphite mold being good conductor of heat along with the influence of vibration, which aids in heat dissipitation results in finer grains.The effect of cast iron mold material seems to be negligible.

It was seen that the prediction of DOE outperformed the prediction of NN. It may be due to the inherent disadvantage of the NN of getting trapped in the local minima.

5. Conclusion

The following conclusions are drawn out of the experiments conducted.

i) Presence of vibration during the solidification process of Al-12.6% Si alloy castings has a positive impact on the mechanical properties. Higher pouring temperature of the melt further enhances the significance of vibration.

ii) Statistics model using DOE technique was developed and tested using ANOVA and could be used for making predictions.

iii) Artificial neural network was trained and tested and can also be used for prediction for the given range of input parameters.

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TABLES

Table 1 Factors and their levels

	Notation		Levels	
Factors considered	Uncoded	Coded	Low level (-1)	High level (+1)
Mold material	A	X_1	Cast Iron	Graphite
Vibration	B	X_2	Without vibration	With vibration (Freq 25 Hz Ampl 0.05mm)
Pouring temperature	C	X_3	700℃	800℃

Table 2 Design Matrix

		Factors		
Experiment Number	Label	A	B	C
1	(1)	-1	-1	-1
2	a	1	-1	-1
3	b	-1	1	-1
4	c	-1	-1	1
5	ab	1	1	-1
6	bc	-1	1	1
7	ac	1	-1	1
8	abc	1	1	1

Table 3 Experimental data

Trial Number	Input Parameters			Responses	
	A	B	C	Wear (µm)	Hardness BHN
1	-1	- 1	-1	460	65.38
2	1	- 1	- 1	500	63.25
3	-1	1	-1	670	60.95
4	-1	- 1	1	735	60.06
5	1	1	- 1	500	64.91
6	-1	1	1	540	62.27
7	1	- 1	1	770	58.38
8	1	1	1	390	65.67
9	-1	- 1	-1	460	65.55
10	1	- 1	- 1	520	63.66
11	-1	1	-1	650	61.01
12	-1	- 1	1	750	59.95
13	1	1	- 1	520	64.82
14	-1	1	1	550	62.27
15	1	- 1	1	750	58.38
16	1	1	1	400	66.62

Table 4 Results of significance test on the model, coefficients, *T*- statistics and *p* values for response - wear

Term	Effect	Coef	SE Coef	T	P
Constant		572.81	2.813	203.67	0.000
X_1	-58.12	-29.06	2.812	-16.11	0.000
X_2	-90.63	-45.31	2.812	13.44	0.000
X_3	75.63	37.81	2.813	-16.33	0.000
X_1X_2	-91.88	-45.94	2.813	-16.33	0.000
X_1X_3	-8.12	-4.06	2.812	-1.44	**0.187**
X_2X_3	-190.62	-95.31	2.812	-33.89	0.000
$X_1X_2X_3$	8.13	4.06	2.812	1.44	**0.187**

Table 5 Results of ANOVA for the response – wear

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Main Effects	3	69242	69242	23081	182.37	0
X_1	1	13514	13514	13514	106.78	0
X_2	1	32852	32852	32852	259.57	0
X_3	1	22877	22877	22877	180.75	0
2-way interactions	3	179380	179380	59793	472.44	0
$X_1 X_2$	1	33764	33764	33764	266.78	0
$X_1 X_3$	1	264	264	264	2.09	**0.187**
$X_2 X_3$	1	145352	145352	145352	1148.46	0
3-way interactions	1	264	264	264	2.09	0.187
$X_1 X_2 X_3$	1	264	264	264	2.09	**0.187**
Residual Error	8	1012	1012	127		
Pure Error	8	1013	1013	127		
Total	15	249898				

Table 6 Results of significance test on the model, coefficients, *T*- statistics and *p* values for response – hardness

Term	Effect	Coef	SE Coef	T	P
Constant		62.6956	0.06624	946.48	0.000
X_1	1.0312	0.5156	0.06624	7.78	0.000
X_2	1.7387	0.8694	0.06624	13.12	0.000
X_3	-1.9912	-0.9956	0.06624	-15.03	0.000
X_1X_2	2.8487	1.4244	0.06624	21.50	0.000
X_1 X_3	0.0938	0.0469	0.06624	0.71	**0.499**
X_2 X_3	3.2762	1.6381	0.06624	24.73	0.000
X_1 X_2 X_3	-0.0987	-0.0494	0.06624	-0.75	**0.477**

Table 7 Results of ANOVA for the response – hardness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	32.207	32.2072	10.7357	152.92	0.000
X_1	1	4.254	4.2539	4.2539	60.59	0.000
X_2	1	12.093	12.0930	12.0930	172.25	0.000
X_3	1	15.860	15.8603	15.8603	225.91	0.000
2-Way Interactions	3	75.432	75.4319	25.1440	358.14	0.000
X_1X_2	1	32.462	32.4615	32.4615	462.37	0.000
X_1X_3	1	0.035	0.0352	0.0352	0.50	**0.499**
X_2X_3	1	42.935	42.9353	42.9353	611.56	0.000
3-Way Interactions	1	0.039	0.0390	0.0390	0.56	0.477
X_1 X_2 X_3	1	0.039	0.0390	0.0390	0.56	**0.477**
Residual Error	8	0.562	0.5617	0.0702		
Pure Error	8	0.562	0.5617	0.0702		
Total	15	108.240				

Table 8 Comparison of experimental, DOE and ANN results for the response - wear

Trial No.	Experimental	DOE		NN	
		Predicted Value	Deviation	Predicted Value	Deviation
1	460	460	0	491.55	-31.55
2	500	510	-10	510.15	-10.15
3	670	660	10	616.36	53.64
4	735	742	-7	723.18	11.82
5	500	510	-10	520.54	-20.54
6	540	545	-5	542.84	-2.84
7	770	760	10	710.62	59.38
8	390	395	-5	431.57	-41.57
9	460	460	0	491.55	-31.55
10	520	510	10	510.15	9.85
11	650	660	-10	616.36	33.64
12	750	742	8	723.18	26.82
13	520	510	10	520.54	-0.54
14	550	545	5	542.84	-2.84
15	750	760	10	710.62	59.38
16	400	395	5	431.57	-31.57

Table 9 Comparison of experimental, DOE and ANN results for the response - hardness

Trial No.	Experimental	DOE		NN	
		Predicted Value	Deviation	Predicted Value	Deviation
1	65.38	65.46	-0.08	64.81	0.57
2	63.25	63.45	-0.2	63.53	-0.28
3	60.95	60.98	-0.03	61.6	-0.65
4	60.06	60	0.06	60.32	-0.26
5	64.91	64.86	0.05	64.81	0.1
6	62.27	62.27	0	62.06	0.21
7	58.38	58.38	0	59.28	-0.9
8	65.67	66.14	-0.47	65.45	0.22
9	65.55	65.46	0.09	64.81	0.74
10	63.66	63.45	0.21	63.53	0.13
11	61.01	60.98	0.03	61.6	-0.59
12	59.95	60	-0.05	60.32	-0.37
13	64.82	64.86	-0.04	64.81	0.01
14	62.27	62.27	0	62.06	0.21
15	58.38	58.38	0	59.28	-0.9
16	66.62	66.14	0.48	65.45	1.17

Figures

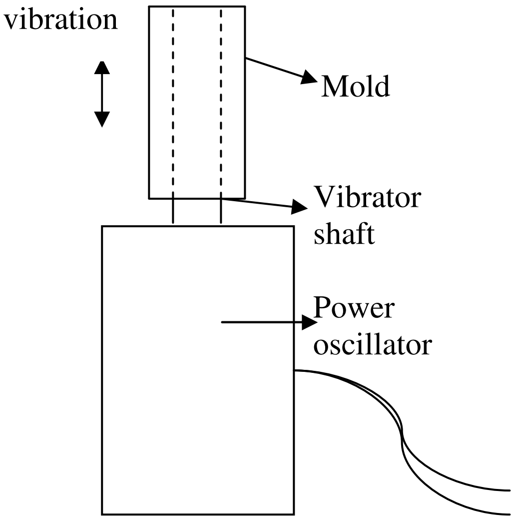

Fig 1. Vibration set up arrangement

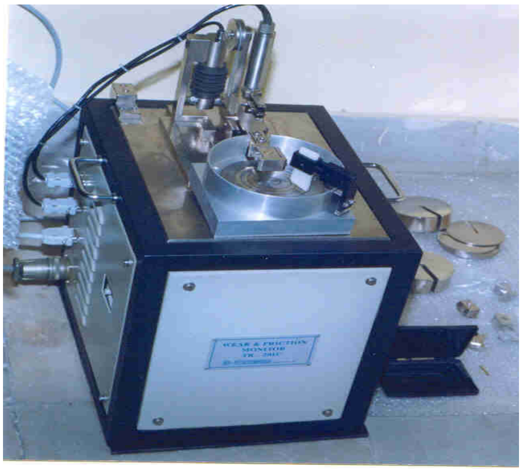

Fig 2. Computerised Pin on disc wear testing

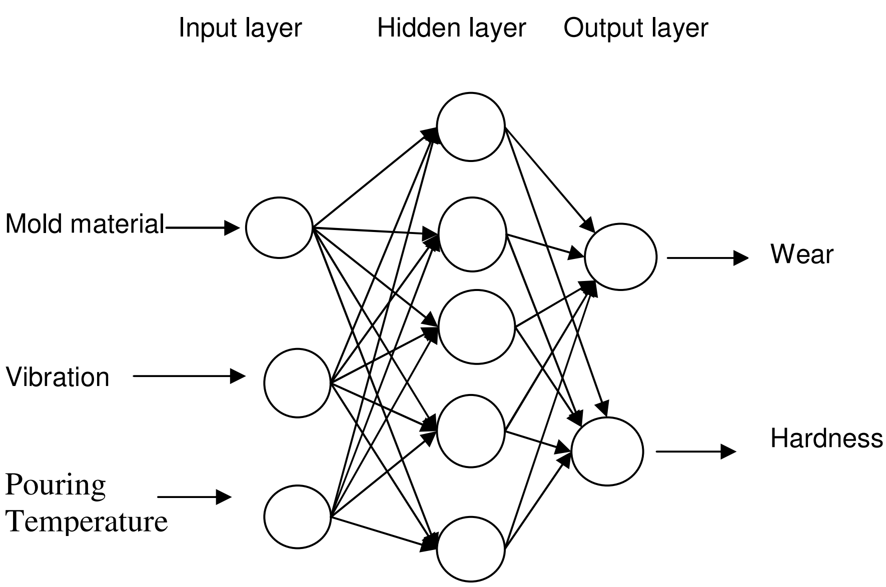

Fig 3 Structure of neural network for the data

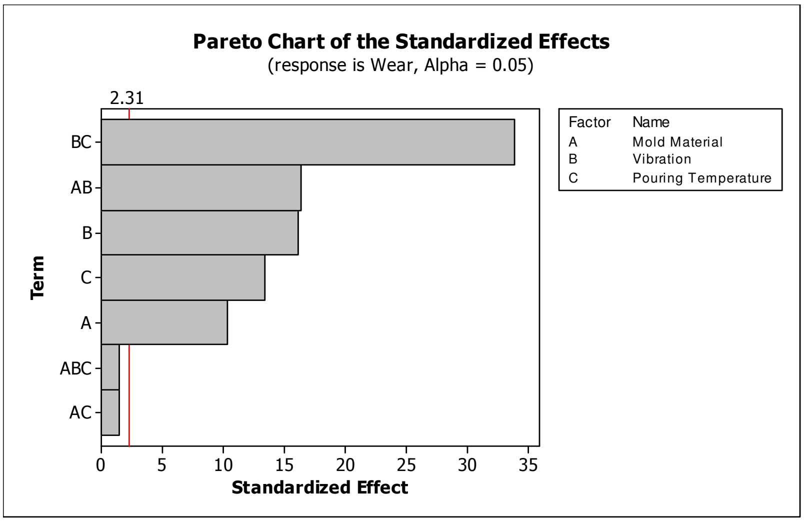

Fig 4 Pareto chart for the response -wear

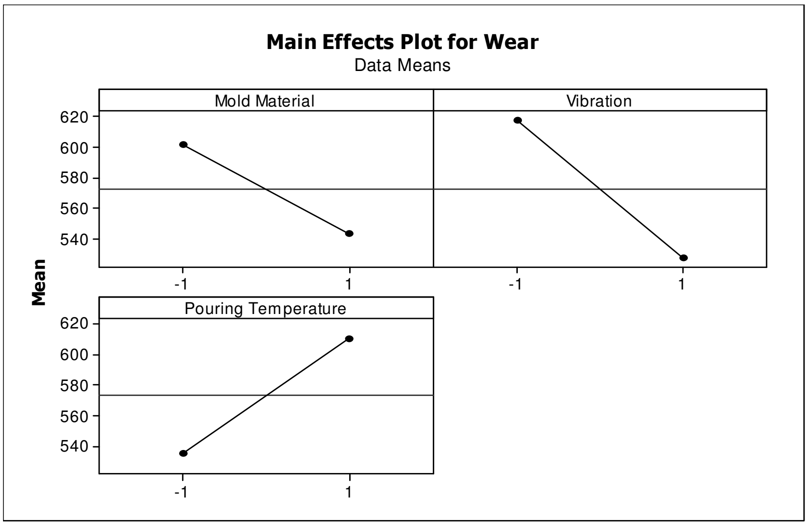

Fig 5 Main effects plot for the response –wear

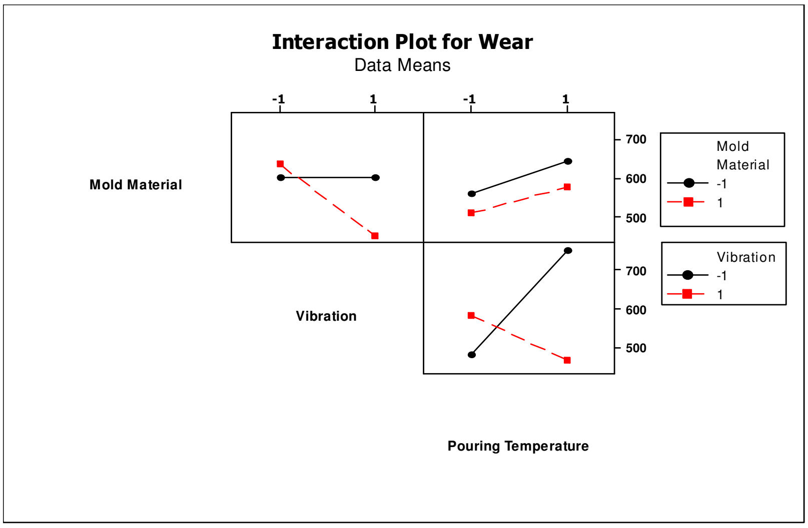

Fig 6 Interaction Plot for the identified factors. Response – wear

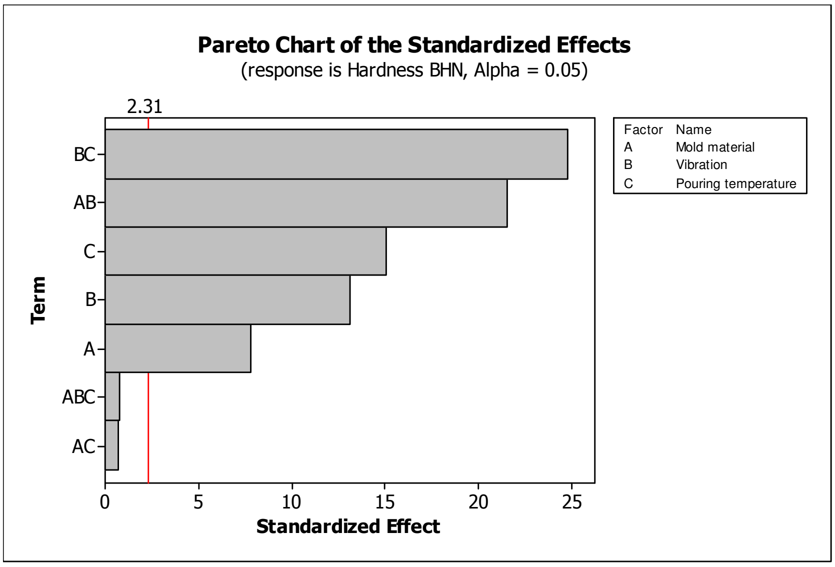

Fig 7 Pareto chart for the response –hardness

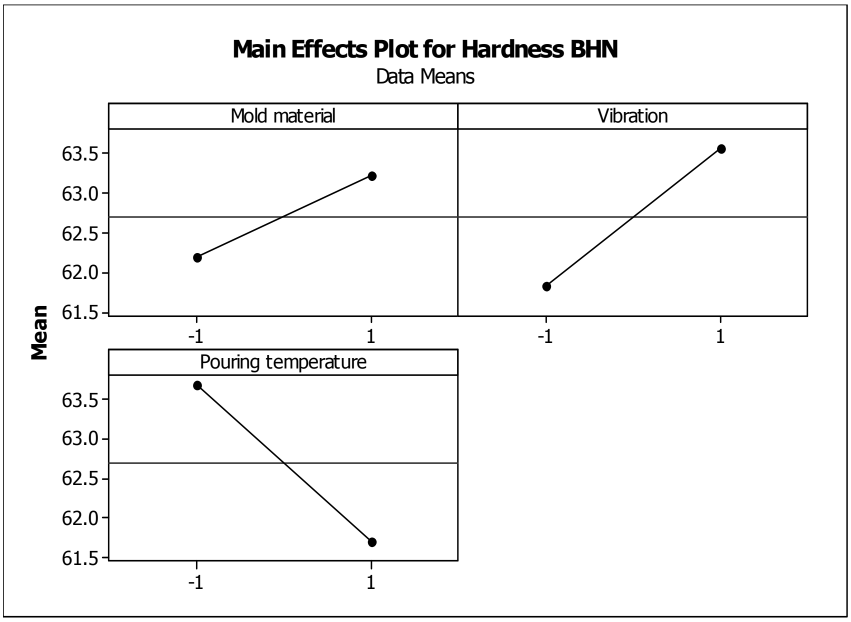

Fig 8 Main effects plot for the response - hardness

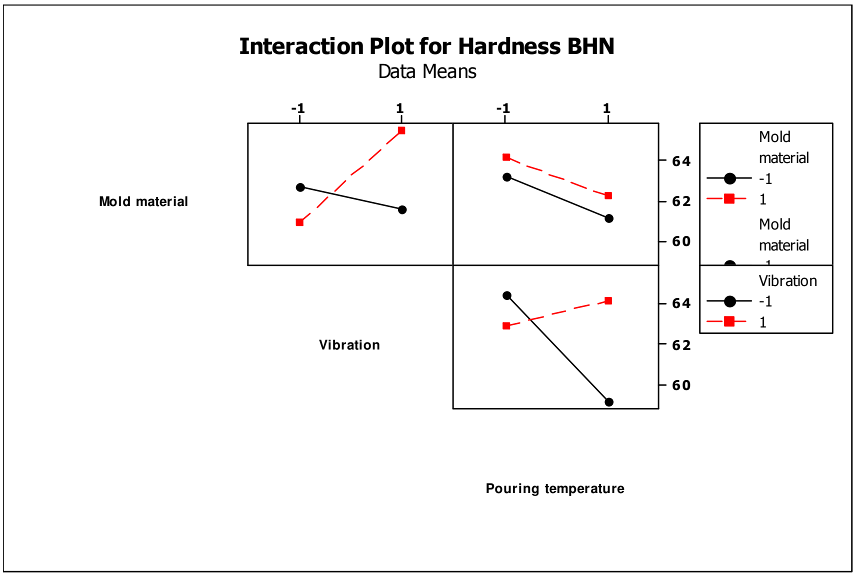

Fig 9 Interaction Plot for the identified factors, response - hardness

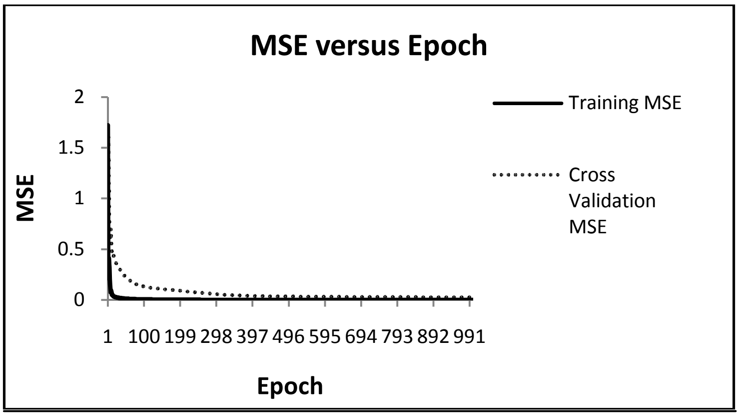

Fig 10 Mean squared error vs. epoch

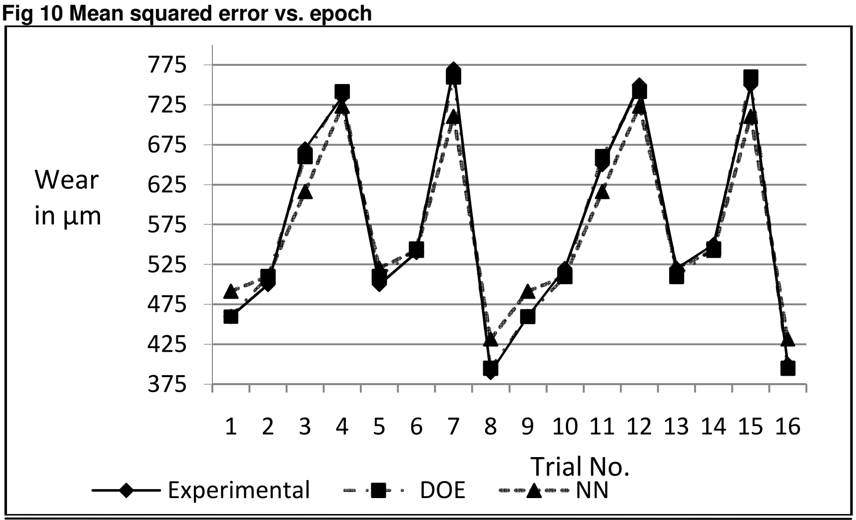

Fig 11 Comparison of experimental values of wear with model generated values of wear for different trials.

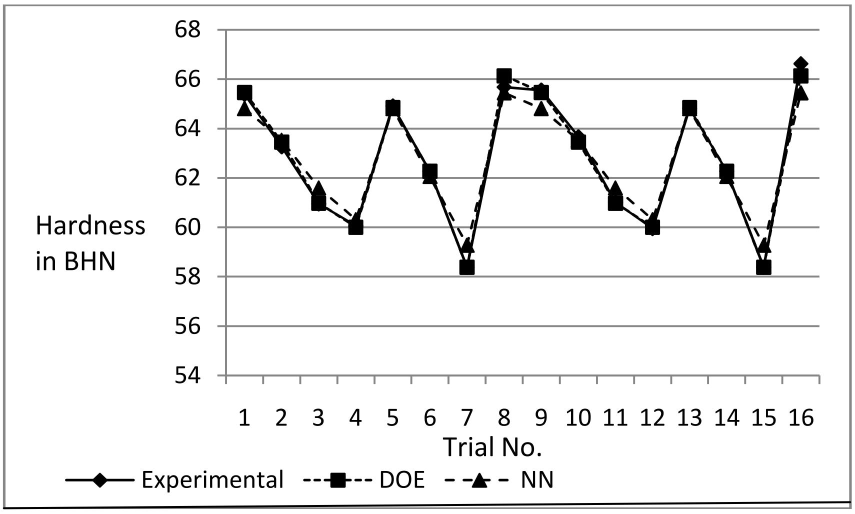

Fig 12 Comparison of experimental values of hardness with model generated values of hardness for different trials.