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PISTON DEVELOPMENT AND OPTIMIZATION OF SANDCASTING PROCESS PARAMETERS FOR THE MANUFACTURE OF 0.67HP GASOLINE GENERATOR PISTON

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Abstract

The piston is an important engine component which withstands severe thermal stresses. The critical working condition of the piston makes it very paramount for its material to be meticulously chosen putting into perspective various mechanical properties. Petrol generator piston scraps were collected and subjected to melting. A sand casting method was used to cast the piston while paying attention to four important process parameters which are pouring temperature, vibration frequency, vibration time and runner size. The varying vibration frequency occasioned by an attached Variable Frequency Machine was considered as one of the process parameters. A Taguchi L_9 Orthogonal array Design of Experiment was used to conduct the sand casting experiment. A number of 9 experiments were conducted at 3 levels each using Taguchi orthogonal array. The cast parameter investigated in this study is hardness. Signal-to- noise ratio and Genetic algorithm tools were employed to find optimal levels for the process parameters and their results were subjected to comparison. Also, Multiple linear regression technique was used to develop mathematical model for the response variable. A statistical ANOVA test that was conducted predicted that three of the four process parameters were found to be significant in the hardness model. A spectrographic test was carried out to determine the chemical composition of the local cast piston and an imported piston showed that local piston is LM 20. An efficiency of 80% and indicated power of 417 Watts was developed during a performance test carried out on the piston in the generator.

Keywords: *Design of Experiment, Genetic algorithm, and Signal-to-noise ratio,*

1.0 Introduction

Presently, automobile engine pistons are mostly manufactured from aluminium silicon alloys [1]. The aluminium silicon alloy (Al-Si) is light in weight and the alloying silicon element controls the rate of expansion of the piston as well as improves the castability of the piston during production [2]. The relevance of silicon and copper elements in eutectic aluminium alloys have been adjudged to be satisfactory in improving mechanical properties [3]. Yamaha piston using a Silumin aluminium alloy material chosen on the basis of high fatigue strength, high wear resistance and hardness had been used most recently.

The study on mechanical properties of engine cylinder block and piston was carried out by [4] in determining a suitable material for engine component that can withstand severe thermal stress and cyclic gas pressure. The study showed that high wear resistance and high tensile strength are important mechanical properties necessary for selection suitable material for the manufacture of cylinder block and engine pistons

Basically, in the development of pistons it will be important to develop experimental layout for the various parametric conditions necessary to carry out effective casting and attainment of great mechanical properties of the alloy [5]. Aluminium alloys are the most preferred materials for the manufacture of pistons both in gasoline and diesel engines due to the these specific characteristics: thermal conductivity, low density, simple net shape fabrication techniques, easy machinability, high reliability and quality recycling characteristics [6].

The importance of recycling aluminium scrap component in the emerging global technology was studied by [7]. The study analysed the environmental benefits for recycling of aluminium alloy scraps to include energy saving; which reveals that the recycling of aluminum scraps save almost 95% of the energy needed to produce pure aluminium from bauxite. The study also showed that direct energy needed to produce aluminium from scrap components is 13.6 CJ per tonne as against 113GJ per tonne required to produced aluminium from bauxite during electrolysis [8]. Other benefits of recycling of aluminium scraps as given in the study are reduction of solid waste disposal and reduction of Greenhouse gases which are emitted at various points in the production of aluminium during electrolysis. The major finding of the study is that the use of recycled aluminium in place of primary aluminium is a major environmental and economic revolution.

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The Importance of obtaining aluminium alloys components from the recycling of industrial aluminium alloy casting waste was investigated by [9]. The recycled aluminium alloy was heat treated with titanium to modify the microstructure. The result showed that the thermal homogenizing of the industrial waste microstructure altered the needle shaped eutectic silicon into spherical shape.

A design change to achieve a piston with less volume and improved efficiency was carried out by [10]. The study investigated the design and material optimization of Aluminium and Silumin pistons. The FEA optimization result showed a reduction of weight and volume of an original piston before optimization. Furthermore, the comparison between Aluminium and Silumin during optimization concluded that the best material for piston is Silumin for its low deformation values

A study on the hardness of AA6061 cast alloy was carried out by [11] using genetic algorithm method to optimize the process parameters during squeeze casting process. The process parameters examined in the study are die pre-heat temperature, pressure time and squeeze pressure. The study showed that the squeeze pressure was the most significant parameter.

This study is focused on the development of 0.67Hp generator piston and the optimization of the sand casting process parameters in the manufacture of the gasoline pistons.

2.0 Materials and Methods

The materials used in this study are Mechanical mould vibrating machine, stopwatch, frequency meter, aluminium alloy pistons scraps, graphite crucible furnace, digital thermocouple, Rockwell hardness machine and CNC lathe machine [12]. The process parameters and the various levels employed in this study are presented in Table 1. The data were used to carry out sand casting of the Aluminium alloy pistons in the foundry workshop [13]. Table 1 shows the process parameters and the various levels used in the experiment.

Table 1: Process parameters and their various levels

Process parameters	LEVELS		
	LEVEL 1	LEVEL 2	LEVEL 3
Pouring temperature,A (^{0}C)	700	725	750
Vibration Frequency,B(Hz)	10	30	50
Vibration time,C (seconds)	30	45	60
Runner size,D (mm^2)	180	335	490

The Taguchi method was used to create a layout for the parameters and their various levels shown in Table 1. Scrap aluminium alloy pistons were collected and melted in a crucible furnace to a temperature of about 755^{0}C as measured with a digital thermocouple. The molten metal was scooped with a ladle and introduced into the prepared sand mould cavity on the mould vibrating machine. The mechanical mould vibrating machine which was connected to a variable frequency machine was used to vibrate the solidifying molten metal. A total of 9 experiments were carried out. Hardness test Specimens measured 10mm in diameter and 16mm in length were prepared from the casting using lathe machine [14]. The Rockwell hardness testing machine shown in Figure 1 was used to determine the values of hardness of the aluminiun alloy piston. The prepared specimen was obtained by cutting out a dimensioned 10mm diameter and a length of 16mm from an ingot of each experiment.

The Rockwell hardness number is determined using equation (1) by applying the sustained increase in penetration depth as a result of introducing and removing of the major load.

$$HR = E - e \qquad (1)$$

Where HR=Rockwell hardness number
E = Indenter constant: diamond indenter maintains 100 units and steel ball has 130 units
e = Permanent penetration depth increase caused by the major load

Figure 1: Rockwell hardness machine

Fig. 2: Hardness test specimens

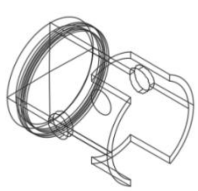

Figure 3: Isometric Drawing of piston

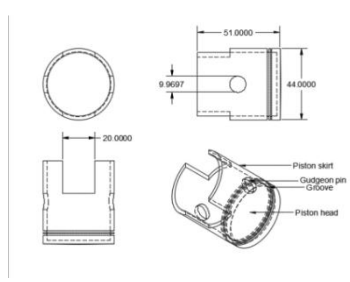

Figure 4: Third Angle Orthographic Projection

3.0 Result and discussion

A Zwick Roell Rockwell hardness testing machine was used to conduct the hardness test. The hardness test values are shown in Table 2.

Table 2: Taguchi L9 orthogonal array for hardness test values

Experiment No.	Random order of exp.	Pouring temp(^{0}C)	Frequency(Hz)	Vibration time(seconds)	Runner size(mm^2)	Hardness	
						Trial 1	Trial2
1	3	700	10	30	180	50.00	51.00
2	4	700	30	45	335	53.00	51.00
3	1	700	50	60	490	53.20	56.40
4	5	725	10	45	490	51.90	54.50
5	2	725	30	60	180	57.60	55.60
6	8	725	50	30	335	55.80	58.40
7	9	750	10	60	335	57.50	59.50
8	6	750	30	30	490	55.80	57.40
9	7	750	50	45	180	60.10	58.90

Minitab 17 was used to obtain the signal to noise(S/N) ratio for hardness. Table 3 shows the S/N ratio values for hardness.

Table 3: Experimental values of hardness and their corresponding S/N ratio

Experiment No.	Average hardness	S/N ratio
1	50.50	34.07
2	52.00	34.19
3	54.80	34.38
4	53.20	34.41
5	56.60	34.53
6	57.10	34.62
7	58.50	34.72
8	56.60	34.77
9	59.50	34.84

3.1 Taguchi Orthogonal Array and S/N ratio analysis for Hardness

The signal to noise ratio values for hardness is displayed in Table 4. The optimal values for the process parameters are shown in the signal to noise ratio main effect plots represented by Figures 5. The optimal values for pouring temperature, vibration frequency, vibration time and runner size are depicted in Figure 5 are 750^{0}C, 50Hz, 60secs and 335mm^2 respectively.

Table 4: S/N ratios for hardness with respect to factor levels

Level	Pouring temp(A)	Vibration Frequency(B)	Vibration time (C)	Runner size(D)
1	34.39	34.64	34.75	34.87
2	34.90	34.81	34.78	34.93
3	35.30	35.13	35.06	34.78
Delta	0.91	0.49	0.31	0.15
Rank	1	2	3	4

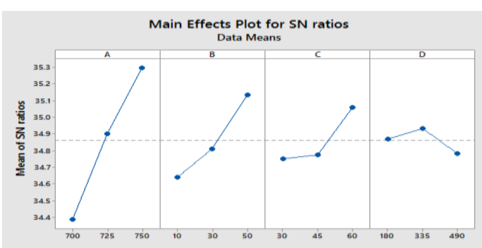

Figure 5: Signal to noise ratio plot for the parameters in hardness model

The relationship between hardness and the various process parameters was derived using the multiple linear regression technique [15]. The Minitab 17 software was employed to get the mathematical model as given in equation (2)

$$H = -32.60 + 0.1153A + 0.0767B + 0.0633C - 0.00215D \quad (2)$$

Where A= pouring temperature (^{o}C)

B= vibration frequency (Hz)

C= vibration time (s)

D= runner size (mm^2)

3.2 Significance Test for the Hardness Mathematical Model

A significance test was carried out on the developed regression model to determine if there is an existing relationship between the response variable H and the regressor variables A, B, C and D. The test for significance is shown in Table 5.

Table 5: Result for test for significance

Term	Coef	SE Coef	T-value	P-value
Constant	-32.57	9.90	-3.29	0.030
A	0.1153	0.0135	8.53	0.001
B	0.0767	0.0169	4.54	0.011
C	0.0633	0.0225	2.81	0.048
D	-0.00215	0.00217	-1.09	0.338

Using a confidence level of 95%, the p-values of regressors A, B and C were found to be less than 0.05.This connotes that pouring temperature, vibration frequency and vibration time are very significant to the response variable (hardness).

Also, Analysis for Variance (ANOVA) was applied to test the adequacy of the regression model. Table 6 depicts the ANOVA result from Minitab software.

Table 6: ANOVA result for adequacy

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	4	70.214	17.554	25.61	0.004
A	1	49.802	49.802	72.78	0.001
B	1	14.107	14.107	20.58	0.011
C	1	5.415	5.415	7.90	0.048
D	1	0.811	0.811	1.18	0.338
Error	4	2.742	0.686		
Total	8	72.956			

R^2 =96.34% R^2(adj) =92.48%

The result from the ANOVA shows that the R square is 96.34% and the adjusted R^2 is 92.48%.This value of R^2 indicates that the mathematical model developed through the use of Taguchi orthogonal array is statistically adequate. In testing for significance of regression the following hypotheses were made

H_0: $\beta_1=\beta_2=\beta_3=\beta_4=0$

H_1: $\beta_x\neq 0$ for at least one x

Where $\beta_1,\beta_2,\beta_3,\beta_4$ are the regression coefficients of pouring temperature, vibration frequency, vibration time and runner size respectively. Also, β_x represents the individual regression coefficients

From Table 6.0, $F_0 = \frac{MSR}{MSE} = \frac{17.54}{0.686} = 25.6$ (3)

Where f_0 =test statistic calculated to be 25.61

F_{cv}= critical value from the Fishers distribution table. It is written as $f_{0.05,4,4}$. In this case we have the degree of freedom for numerator (MSR) and denominator (MSE) to be 4.While the level of significance is taken to be 0.05.

From the Fishers distribution table, $f_{,0.05,4,4}$ =6.39

The null hypothesis is rejected since $f_0>f_{cv}$ .It is safe to say that there exist a linear relationship between the hardness and the process parameters. Furthermore, model adequacy for hardness response was probed for using Normal probability plot shown in Figure 6.

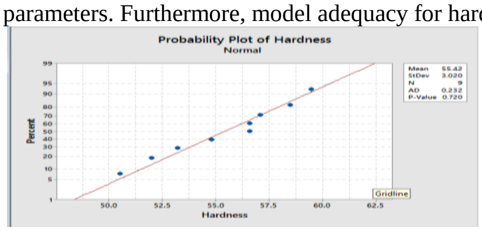

Figure 6: Normal probability plots for hardness test data

The normal probability plot for hardness data shown in Figure 6 indicates that the residuals lie close to the diagonal line which represents the ideal normal distribution. Also, the Anderson-Daling value and p-value which are 0.232 and 0.720 respectively show that there is not enough evidence to reveal any deviation and as such the conditions of normality are satisfied.

3.3 Genetic Algorithm Analysis on Hardness

The mathematical model obtained through multiple linear regression was used as the objective function in the MATLAB genetic algorithm tool. Population size used was 50 while the number of variables is 4. A crossover probability and mutation probability adopted was 85% and 0.01 respectively. A time limit of 100 seconds and100 generations was used for the optimization.

Lower bound of parameters={ 700, 10, 30, 180 }

Upper bound of parameters={750, 50, 60, 490 }

Table 7: Tested levels and best optimal levels from Genetic algorithm on hardness.

Factor	Parameter	Level range	Optimal level
A	Pouring temp(^{0}C)	700-750	749.98
B	Frequency(Hz)	10-50	49.98
C	Vibration time(s)	30-60	59.99
D	Runner size(mm^2)	180-490	275.04

The optimal fitness value for the response value, hardness is 60.953.

3.4 Comparison of Taguchi and Genetic Algorithm results

Tables 8 and 9 show the various optimized values for the process parameters and the response value. The optimized process parameters from both methods showed high level of similarity. The only noticeable difference between the two methods in the area of optimized process parameter result is in the runner size values. The fitness value of hardness is shown in Figure 7.

Table 8: Comparison of results of optimized process parameters

Serial number	Process parameters	Taguchi method	Genetic Algorithm method
1	Pouring temp.(A) ^oC	750	749.98
2	Frequency(B)Hz	50	49.98
3	Vibration time(C)s	60	59.99
4	Runner size(D) mm^2	335	275.04

Table 9: Comparison of hardness result

Serial number	Response parameters	Taguchi method	Genetic Algorithm method
1	Hardness	61.56	60.95

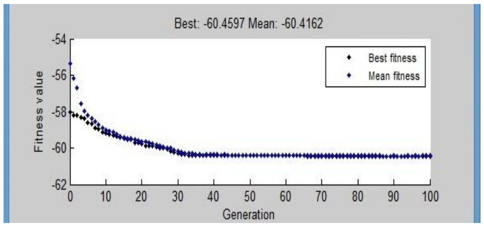

Figure 7: Genetic algorithm plot for the hardness fitness value and its variables

3.5 Validation of the developed linear model

In addition to the model validation carried out by ANOVA and R^2 statistic further model validation was carried out for the linear model by performing actual experiment using the determined optimal values. The optimal values obtained from the optimization of the linear models were substituted into the developed hardness linear model to produce predicted values utilized for the validation process. The result of comparison between the predicted and experimental values of the linear models is shown in Table 10. The prediction percentage error determined showed that slight difference exists between the predicted and experimental values.

Table 10: Comparison of predicted and experimental values of the linear models

	Pouring temp.(^0C)	Vibration frequency, Hz	Vibration time,(sec)	Runner size(mm^2)	Hardness(HRC)
Predicted value	749.98	49.99	59.98	273.50	60.92
Experimental value	749.98	49.99	59.98	273.50	61.50
Prediction error (%)					0.943

3.6 Performance test

A performance test was carried out on the machined piston with the fitted gudgeon pin and rings well positioned in the generator engine block. In carrying out the test the pistons were subjected to about 8 hours running on maximum load. The generator used for the performance test was Tiger 950 with specifications: fuel tank capacity 4 litres; dry weight 35kg; engine type single cylinder; 2 stroke ;stroke length of 92mm; piston bore 40mm;fuel consumption rate 0.41 litres/hours; fuel spark ignition; and power rating 0.60KVA. Some basic engine parameters applied in the performance test for the local piston and the imported piston are shown in table 5.43. The indicated power developed in the combustion chambers was determined to be 417 Watts from an indicated mean effective pressure of 2.55bar and gasoline calorific value of 45800kj/kg. The thermal efficiency of the engine which can be defined as the ratio of developed thermal energy successfully converted into mechanical energy to the input fuel energy was determined to be 80.00% and 80.90% for the local piston and the imported piston respectively. The developed pistons are shown in Figure 8.

Figure 8: Developed pistons

Table 11: Performance test for developed piston

Engine parameters	Local piston	Imported pistons
Voltage output(volts)	220	220
Engine speed(rpm)	850	850
Run time for full fuel tank(hours)	8.0	8.2
Efficiency(%)	80.00	80.90

3.7 Conclusion

Pistons were developed using sand casting by applying conditions inherent in the Taguchi L_9 orthogonal array. Mathematical model was developed by the application of Multiple Linear Regression technique and used to determine the cast piston responses. Optimal levels of the process parameters were determined using Signal-to-noise ratio and Genetic algorithm. The optimal values obtained from the Signal-to noise and Genetic algorithms were approximately similar. The ANOVA test result showed that the developed model is adequate with an adjusted coefficient of determination value of 92.48%. The models were validated by carrying out a performance test using the determined optimal conditions for the linear model as input values. The outcome of the response value measured is similar to the predicted value obtained when the model is applied. The cast piston introduced into the generator performed well with a thermal efficiency of 80.00%.

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