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Original Research Article

Optimization of Process Parameters of Fatigue Strength of Aluminium Alloy

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ABSTRACT

The optimization of process parameters of fatigue strength of aluminium alloy (AA 6061) has been successfully carried out. This involves refining the manufacturing variables to minimize internal defects and provide a fine homogeneous structure. Materials in any form depend on the influence of mechanical properties. If the strength of materials is compromised it could invariably jeopardize the structural ability of the facility. Fatigue strength of materials accounts for the maximum stress level attained when materials undergo repeated stresses. In determining the fatigue strength of aluminium alloy, Design of Experiment (DOE) platform was used to project the parametric conditions of the study. Optimal levels of the parameters were determined using Taguchi Design and Analysis of Variance (ANOVA). The optimal levels of sand casting parameters such as pouring temperature, pouring time and runner size were determined to be 760 °C, 15 s and 200 mm^2 respectively. Statistical analysis by ANOVA showed that the pouring temperature and pouring time were significant with a p-value of 0.001 and 0.002 respectively. The multiple linear regression technique yielded the mathematical model which was determined to be significant with a p-value of 0.001. The Signal-to-noise ratio revealed that the pouring temperature was the most influential parameter among the process parameters studied.

1. INTRODUCTION

Aluminum alloy has enjoyed patronage in virtually every facet of the product manufacturing sectors. It has numerous industrial advantages, one of which is its light density that makes it highly valuable in aircraft manufacturing (Adke and Karanjkar, 2014). Other well applied physical and mechanical properties include: corrosion resistance, strength-to-weight ratio, casting ability, recycling ability, good thermal, and high electrical conductivity. These properties have presented the alloy as a very dependable metal alloy for various sectors (Agarwal *et al.* 2013).

Automobile industries have leveraged on the light weightiness and corrosion resistance in the production of many of their components. Its ability for good machinability has also been a great advantage for component manufacturing (Jayaram, 2015). This metallic alloy has been very effective in the construction industry as it is deployed for various reasons in structural and building engineering. In the building of structures, it is applied for windows and doors construction. Furthermore, aluminium alloy has gained wide expression in the electrical wiring segment of the engineering field as its good thermal and high electrical conductivity property has been a major reason for its adoption in the domestic and industrial wiring of building structures and electrical outfit such as transformers, substations, distribution and transmission lines. Aluminium alloy conductors and cables are light nature and it is known to conductor electricity favourably as good as its silver and copper counterparts (Agarwal and Saharan, 2014).

The recycling ability of aluminium alloy has really helped in the field of metallic component manufacturing as alloys turned into scraps are recycled with the application of less energy without any loss of material quality and texture (Carvelheira and Goncalves, 2016). This is a technique that has been used to add value to discarded metallic alloys. Engine components production using recycling of scraps was done in by Al-Mosawi *et al.* (2015). The engine components produced had similar strength as the commercially available. Some other researchers have produced pistons from aluminium alloy scraps. Engine cylinder block from scraps was developed by Ebhojiaye and Sadjere, (2017).

Casting is a major engineering technique for developing metallic components. It is foundry practice for developing new components with application of temperature and pressure to the metallic ingots or materials scraps (Cui and Roven, 2015). To come up with an efficient casting yield it is pertinent to apply optimal casting parameters. There are various types of casting mainly deployed in foundry. Sandcasting is an important casting practice. It involves various process parameters such as pouring temperature, pouring time, runner size, riser size, green strength, and mould temperature. Some of the process parameters have been applied in developing high-quality yield aluminium alloy. Despite these great and excellent qualities of aluminium alloy, it has been discovered that the alloy is highly susceptible to fatigue failure resulting from cyclic loading conditions.

Many component failures have been known to occur as a result of fatigue failure, making it a key factor in the development of structures and mechanical components (Atzori, *et al*., 2020). Fatigue failure is said to occur when a structure or component is subjected to repeated stress cycles paving way for crack initiation and propagation that finally leads to fracture of the material below the stress levels of ultimate tensile strength. It has been reported that many mechanical failures have been traced to fatigue failures.

Fatigue strength is the determinant stress level at which materials withstand repeated stress that they are subjected to (Martin, *et al*., 2016). The fatigue strength of the aluminium alloy is dependent on several factors such as heat treatment, material composition, surface finish, casting parameters, surface roughness and machine parameters (Mohammed, *et al.,* 2020). The casting parameters mainly observed are pouring temperature, pouring time, pouring rate, mould temperature and green strength (Karunakar and Yadav, 2011). While the machining parameters are depth of cut, feed rate, and cutting speed. Surface roughness portrayed by a metallic alloy is a major determinant of fatigue failure as rough surfaces are known to act as stress concentrators thereby promoting crack initiation and fast propagation (Bedkowski, 2014).

In a bid to improve on material or structural fatigue it is imperative to adjust the process parameters to attain a greater yield (Azhagan, *et al.,* 2014). Optimizing process parameters becomes a major option so as to bring about the requisite values that may promote better response. Determination of optimal values is important so that the deployment of trial by error method, which is costly, indecisive and time-consuming will be completely eliminated. It becomes very difficult to apply this crude trial method when multiple variables are brought to play. To avoid this logjam, it will be wise to deploy statistical and experimental design methods as applied in modern engineering in determining optimal values of the process parameters.

One of the evolving experimental design methods deployed in solving optimization problems is Taguchi Design. It was invented and introduced by Ginichi Taguchi in 1951. This technique produces a systematic form of solving optimization problems by using orthogonal arrays to study as many variables as possible at reduced number of experiments. It is a technique that is adjudged to be very efficient.

This study is targeted at applying Taguchi design in carrying out the fatigue strength optimization of the process parameters of the aluminium alloy. The technique will enable us determine the significant parameters affecting the response and their optimal levels. The technique will improve fatigue strength, determine optimal values of the parameters and equally reduce cost while promoting efficiency.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in this study are aluminium alloy scraps, charcoal, bentonite, and green sand. The equipment used include a crucible, a thermocouple, and a fatigue strength testing machine.

2.2. Method

The aluminium alloy scraps were heated in the crucible furnace to temperatures above 600 ºC when they became molten. The pouring temperatures were maintained at 700 ºC, 730 ºC and 760 ºC as prescribed by the design matrix. The charcoal acted as fuel for the crucible to melt the aluminium scraps. The thermocouple was to used read off the temperature. The molten metal was poured into the developed mould box through the gating system.

2.3. Process Parameters and their Levels

The process parameters used in this study are pouring temperature, pouring time and runner size. The levels were obtained from related literature (Kidu and Asmamaw, 2016). The process parameters and their levels are shown in Table 1. The design of experiment (DOE) displaying all the levels and number of experiments is shown in Table 2.

Table 1: Process parameters and their levels

Process parameters	Levels		
	L1	L2	L3
Pouring temperature, A (ºC)	700	730	760
Pouring time, B (s)	5	10	15
Runner size, C (mm^2)	180	200	285

Table 2: L9 Taguchi orthogonal experimental design

Experiment No.	Pouring temperature, A (ºC)	Pouring time B, (s)	Runner size, C (mm^2)
1	700	5	180
2	700	10	200
3	700	15	285
4	730	5	200
5	730	10	285
6	730	15	180
7	760	5	285
8	760	10	180
9	760	15	200

The obtained castings were machined to the specimen size according to the ASME code of ASTM-E466-82 standard (Eugene and Marks, 2007). The fatigue strength specimen is shown in Figure 1. The fatigue machine shown in Figure 2 comprises a counter, shaft, load cell, and a bearing housing (Shoukat *et al*., 2019). The applied stress was determined by Equation (1) obtained from Sharma and Aggarwal (2013).

$$\sigma_f = \frac{125.7 \times P \times 32}{\pi \times D^3} \tag{1}$$

Where σ_f=Applied stress (N/mm^2), P=load (N), and D=diameter (mm)

The fatigue strength specimen is shown in Figure 1.

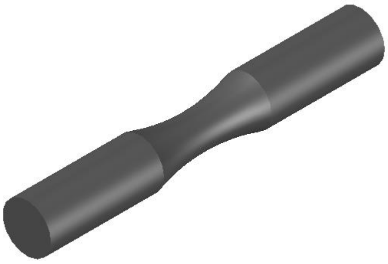

Figure 1: The fatigue strength specimen

Figure 2: Fatigue strength testing machine

3. RESULTS AND DISCUSSION

3.1. Experimental Results

The results obtained from the fatigue strength experiment are shown in Table 3. Table 3 contains the experimental values including fatigue strength response and the number of cycles to failures obtained in the course of this study. The fatigue strength values were noticed to be greatly influenced by pouring temperature of the aluminium alloy as evident in Shashidhar, *et al*, (2018). The fatigue strength testing machine used for this study and the plot of fatigue strength against number of cycles to failure are shown in Figure 2 and 3 respectively. It was noticed that an increase of the pouring temperature leads to an increase in fatigue strength of the alloy (Nukman, *et al,* 2014). The number of cycles to failure increases with decrease of fatigue strength as shown in Figure 3.

Table 3: Fatigue strength experimental data

Experiment No.	Input parameters			Output parameters	
	Pouring temperature, A(°C)	Pouring time, B (s)	Runner size, C (mm^3)	Fatigue strength (MPa)	No. of cycles × 10^3
1	700	5	180	132	20.7
2	700	10	200	141	16.7
3	700	15	285	152	13.1
4	725	5	200	158	10.4
5	725	10	285	165	6.0
6	725	15	180	172	4.0
7	750	5	285	184	2.2
8	750	10	180	202	0.83
9	750	15	200	220	0.44

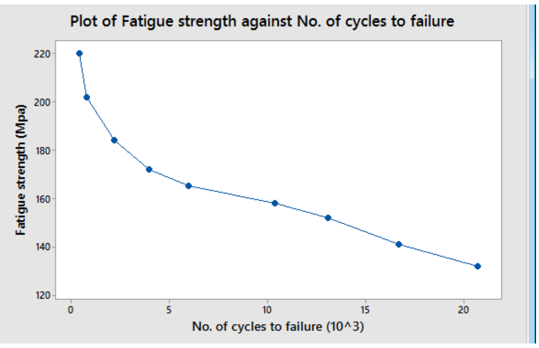

Figure 3: Plot of fatigue strength against cycles of failures

3.2. Analysis for variance (ANOVA) Results

The analysis for variance results is shown in Table 4. The p-values for pouring temperature, pouring time and runner size were determined to be 0.001, 0.002 and 0.523 respectively. This is an indication that all the parameters but runner size are significant using a significance level of 0.05. Also, the regression model is adequate with a p-value of 0.001 as shown in Table 4.

Table 4: Analysis of variance test for the fatigue strength

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	3	6296.03	2098.68	51.39	0.001
A	1	5460.17	5460.17	133.70	0.001
B	1	816.67	816.67	20.00	0.002
C	1	19.20	19.20	0.47	0.523
Error	5	204.19	40.84		
Total	8	6500.22			

The R^2 value is 96.86 %, and R^2 adjusted 94.97 % and the R^2 predicted is 89.24 %. The high values of the R^2 is an evidence that the developed model is adequate. The developed mathematical model using multiple linear regression is as given in Equation (2).

$$Fatigue\ strength = -580.7 + 1.0056A + 2.333B - 0.0321C \tag{2}$$

Where A=pouring temperature (°C), B=pouring time (s), and C=runner size (mm^2)

The normal probability plot shown in Figure 4 portrays that the obtained data lie very close to the diagonal line. This further buttress the fact that the model is really adequate.

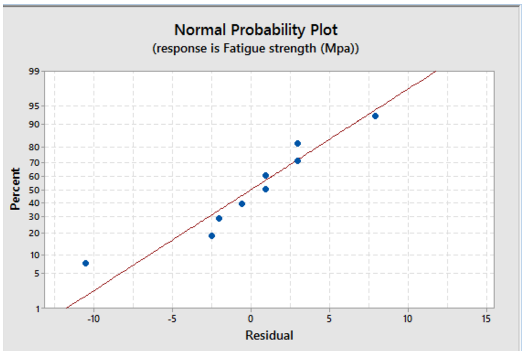

Figure 4: Normal probability plot

3.3. Signal-to-Noise Ratio Analysis

The Signal to Noise ratio results is shown in Figure 5. It reveals that the pouring temperature, pouring time and runner size have optimal levels of 760 °C, 15 s and 200 mm^2 respectively. It is worthy of note that the pouring temperature is the most influential parameter in the developed model.

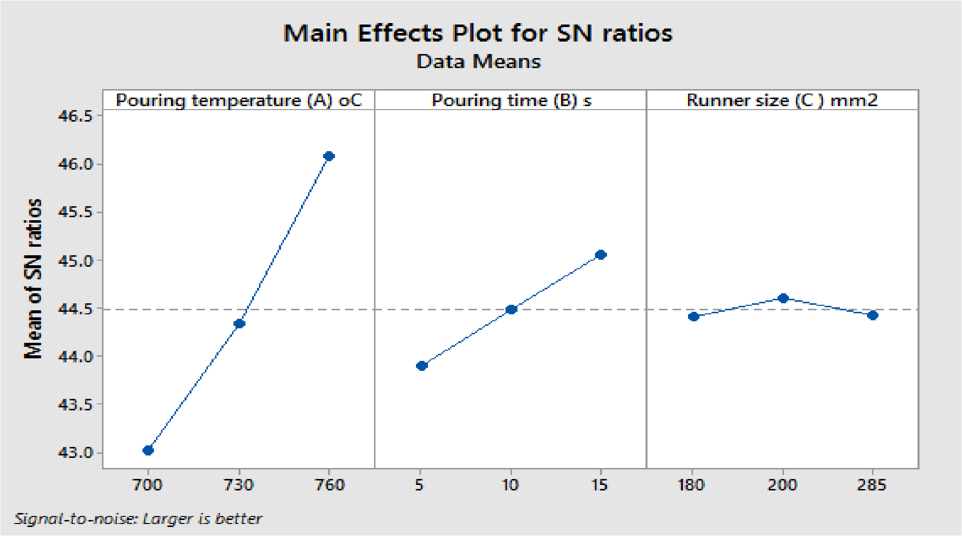

Figure 5: Signal-to-noise ratio results

4. CONCLUSION

The optimization of process parameters of the fatigue strength of aluminium alloy (AA 6061) has been carried out using design of experiment to project the parametric conditions of the study. Optimal levels of the parameters were determined by the application of Taguchi Design and signal-to-noise ratio. The optimal levels of pouring temperature, pouring time and runner size were determined to be 760 ^{o}C, 15 s and 200 mm^2 respectively. The ANOVA presented the pouring temperature and pouring time to be significant with a p-value of 0.001 and 0.002 respectively. The developed mathematical model was determined to significant with a p-value of 0.001. The Signal to noise ratio showed that the pouring temperature is the most influential parameter.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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