Full Paper

# A DESIGN FOR LOCAL PRODUCTION OF ALUMINIUM ALLOY (AL 6063) BASED ON THE OPTIMIZATION OF THE ELASTOPLASTIC RESPONSE OF CASTINGS

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## ABSTRACT

A high quality product at a relatively minimal cost is the goal of modern manufacturing. To achieve this, the foremost strategy is to consider at the product design stage, the optimal levels of production process parameters. This paper provides an insight into the robust manufacture of die-cast aluminium alloy Al 6063 based on the production process parameters of pouring temperature ($T$), die-preheat temperature ($T_m$) and the amplitude of vibration during casting ($V$). An experimental design based on the Taguchi's orthogonal array of L8 (25) was formulated and carried out at two levels of $T$ (660$^0$C, 720$^0$C), $T_m$ (130$^0$C, 250$^0$C) and $V$ (200µm, 600µm). The data obtained from mechanical tests of each cast was analysed by the signal to noise (S/N) ratio and ANOVA statistics to determine the optimal combination of process parameters most consistent with product performance. Numerical validation of the experimental approach was subsequently carried out using the Finite Element (FEM) code of COMSOL Multiphysics. Test results show that the most significant values for optimisation is set at the process parameters combination of (660$^0$C, 250$^0$C and 200µm) for $T$, $T_m$ and $V$ from which the predicted values of the hardness, percentage elongation to fracture, yield strength, and ultimate tensile strength were given as 43.75, 1.39%, 29.80MN/m$^2$, 88.34MN/m$^2$ respectively. The details of numerical investigations in terms of the elastic properties of cast products were also found to be in close agreement with the statistical estimates.

**Keywords**: *Die-cast, Taguchi, process parameters, Al 6063.*

## 1. INTRODUCTION

There is currently a rising demand for the use of aluminium die-cast components in various applications in the automotive, aeroplane, ship, electronics and precision machinery industries globally. The reason for this is not far-fetched, since the carefully-engineered lighter aluminium can now replace steel parts in energy-saving, weight-critical applications and in relation to the cost-effectiveness and ease of manufacture; the die-casting process is now considered to be most efficient in the mass production of aluminium products with tight tolerances [1].

Die casting is a precision casting method of injecting molten metal into a die cavity by applying light pressure. It is a process considered for making parts that otherwise cannot be produced by any other manufacturing process [2]. To this date, a significant amount of research and development work has been done in order to optimize the die-casting process and improve the quality of the castings [3-6]. The optimization methods have been encouraged by the technical characteristics of the casting process in conjunction with its capability to produce complex engineering components. To optimize any manufacturing process, it is well known that the trial and error method can be used to identify the best parameters to manufacture a quality product. However, this method demands extensive experimental work and results in a great waste of time and money [2]. To circumvent this, the state-of-the-art is now to optimize the characteristics of a product based on the knowledge of influencing parameters operated at different adjustment levels. Usually, the objective is to specify the nominal values for these parameters, resulting in minimizing variability transmitted from uncontrollable variables [3].

The die casting process is controlled by several parameters that when properly determined and adjusted, result in the improvement of the quality of the die casting parts. The authors [2, 5] have considered the die casting machine related parameters such as the mould temperature, plunger velocity, hydraulic pressure and cast metal related parameters of metal temperature, filling time, composition of cast metal etc., as most essential. According to Taguchi [2] processing parameters can be adjusted to varying levels of intensity so that some settings can result in the robustness of the manufacturing process. Against this backdrop, extensive literature is available on the quality of cast products. The influence of casting defects on the mechanical properties has been studied [7, 8], the application of the die-casting process to the manufacture of composites has also been investigated [9-12] and new approaches towards maximize die performance have been proposed [13-16].

At any rate, there is hardly anything that goes unnoticed in the die casting industry with respect to the enhancement of casting quality. There is now a tremendous competition among stakeholders in regard to improving the overall performance of products. In line with this philosophy, the objective of this current paper is to present a framework for the robust manufacture of Al 6063 castings locally, since currently available techniques are not fully standardized. It is hoped that the outcome of this work would facilitate the mechanization of existing systems towards achieving a better resource utilization of cast products locally.

## 2. MATERIALS AND METHODS

### 2.1. The Base Material and Experimental Set Up

The material considered in this study is Aluminium alloy, Al6063. The chemical composition is as shown in Table 1. The die casting process was carried out using a set-up which incorporates the principle of vibration for casting. The mechanism allows the positioning of a specially-designed die made from heat-treated high-temperature chromium steel on top of a vibrating machine as shown in Fig 1(a). The molten metal from the furnace (Fig. 1b) is transferred to the die and the vibrating machine is operated at a predetermined level of frequency for a specified period of time after which the melt is allowed to solidify followed by part ejection. Prior to this operation, the pre-heat temperature of the die and the pouring temperature of the melt were measured at specified levels using a pyrometer (Fig.1c). Two cast elements in their finished forms as shown in Fig 1(d) are produced in one operation.

### 2.2. Experimental design

In order to obtain statistically reliable results based on the elastic-plastic properties of the castings, an experimental procedure was formulated according to the Taguchi's off-line concept of quality performance [2].

*Table 1. Chemical components of Al 6063 alloy*

| Element | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| Weight % | 0.30 | 0.35 | 0.10 | 0.10 | 0.45 | 0.10 | 0.10 | 0.01 | Balance |

*(a)*

*(b)*

*(c)*

*(d)*

*Fig.1: The die casting process showing (a) Vibrating machine for measuring amplitude of vibration (b) furnace preheating the die, (c) pyrometer for measuring temperatures, (d) finished cast products.*

#### 2.2.1. *Important die parameters and their working levels*

The process parameters for the die-casting process that were selected in consideration of the quality of the castings that would be produced, were the pouring temperature, pre-heat temperature and amplitude of vibration. These parameters along with their working levels as shown in Table 2 had been chosen in accordance with the recommendations of previous researchers [2, 3, and 18]. The temperature levels were calibrated using the pyrometer. Other parameters such as thermal conductivity, density of material, dimension of the die cavity, were considered as fixed variables.

*Table 2: Process parameters with their working levels*

| Symbol | Process Parameter | Units | Lower level (1) | Higher level (2) |
|---|---|---|---|---|
| $T$ | Pouring Temperature | °C | 660 | 720 |
| $T_m$ | Pre-heat Temperature | °C | 130 | 250 |
| $V$ | Amplitude of Vibration | μm | 200 | 600 |

*Source: [2, 3 and 18]*

#### 2.2.2. *Selection of orthogonal array*

The orthogonal array had been selected in accordance with the recommendations of Taguchi [2] which explicitly presents the relationship between control factors and associated response variables. The process parameters have been considered with respect to interactions levels of operation. Each two level parameter has one degree of freedom (DOF) and on this basis, an L8 $(2^5)$ orthogonal array for conducting the experiments was selected as shown in Table 3.

*Table 3 Orthogonal array of experiment*

| Exp. no. | $T$ | $T_m$ | $V$ | $T \times T_m$ | $T \times V$ | $T_m \times V$ |
|---|---|---|---|---|---|---|
| Pm1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Pm2 | 1 | 1 | 2 | 1 | 2 | 2 |
| Pm3 | 1 | 2 | 1 | 2 | 1 | 2 |
| Pm4 | 1 | 2 | 2 | 2 | 2 | 1 |
| Pm5 | 2 | 1 | 1 | 2 | 2 | 1 |
| Pm6 | 2 | 1 | 2 | 2 | 1 | 2 |
| Pm7 | 2 | 2 | 1 | 1 | 2 | 2 |
| Pm8 | 2 | 2 | 2 | 1 | 1 | 1 |

### 2.2.3. *Mechanical testing*

The tensile and Brinell hardness tests were conducted according to the ASTM standard B557 [18], using Universal Testing Machine at the Materials Testing Laboratory, Covenant University, Canaan Land, Ota, Ogun state, Nigeria. The specimen geometry and the test apparatus are shown in Figs 2 and 3, respectively. The jaw grips accessories and compression plates were used to position the specimen in-between a stationary base plate and a vertically moving cross-head. The tests were monitored in real time while in-built algorithms carried out numerous calculations. The ultimate tensile strength, yield strength, percentage elongation to fracture and hardness of the cast specimen were determined for all experimental conditions.

*Fig. 2 Test specimen showing dimensions in mm*

*Fig.3 Universal Materials Testing Machine*

### 2.2.4. *Analysis of data*

Data from experiments was used to analyse the mean response. The Taguchi method however stresses the importance of studying the variation of the response using the signal to noise (S/N) ratio. The reason for this is to minimize the variation in quality characteristics due to uncontrollable parameters. The S/N ratio is given by,

$$n_j = -10\log\left[\frac{1}{n}\sum\frac{1}{Y_{ijk}^{2}}\right] \tag{1}$$

where, n is the number of tests and $Y_{ijk}$ is the experimental value of the $i^{th}$ quality characteristics in the $j^{th}$ experiment at the $k^{th}$ test.

In order to study the significance of process parameters, a variance analysis (ANOVA) based on the values of experimental data was performed, based on the following equations:

The sample variation for each number of experiments performed is expressed as,

$$S_i^{2} = \frac{(x_{ij} - \bar{x}_{ij})}{n_i - 1} \tag{2}$$

Where $n_i$ = total number of repetitions

The Pooled estimate of population variance for k trial conditions is given by

$$S_p^{2} = \sum_{i=1}^{k} \frac{(n_i - 1)S_i^{2}}{N - k} \tag{3}$$

Where $N = \sum_{i=1}^{k}$ , $n_i$ = total observations

$N - k$ = Total degrees of freedom

Total number of replications in this case is 2, i.e. $R_1$ and $R_2$

(Number of positive signs in a column) × (Number of replications) = 4 × 2 = 8

The standard deviation is given by;

$$\text{S.D. (Standard Error/Deviation)} = \sqrt{V(effect)} \tag{4}$$

Where

$$V(effect) = V(\bar{Y}_{+}) + V(\bar{Y}_{-}) - 2CoV(\bar{Y}_{+}\bar{Y}_{-}) \tag{5}$$

When the covariance, $2CoV(Y_{+}Y_{-})$ tends to zero there is no interaction between $Y_{+}$ and $Y_{-}$.

The main effect for each parameter is given by $S_p^{2}$ ± S.D.

The magnitude of the values obtained from the main effect determines which parameter is significant.

### 2.2.5. *Finite element modeling*

The incremental solution for elastoplastic behaviour was implemented in the COMSOL multiphysics environment based the von Mises criterion. The material structure is modelled as aluminium alloy with linear and isotropic properties.

The initial response of the material conditions is obtained from cyclic stress-strain data fitted with the Ramberg-Osgood relationship given as:

$$\varepsilon_{eq} = \frac{\sigma_{eq}}{E^{*}} + \left(\frac{\sigma_{eq}}{H}\right)^{\frac{1}{m}} \tag{6}$$

where $E^{*} = 3E/2(1 + v)$, $v$ is the Poisson's ratio, n is the cyclic strain hardening exponent and H is the cyclic strain hardening coefficient. The elastic strain and plastic strain were obtained from the relations $\varepsilon^{e} = \sigma/E$ and $\varepsilon^{e} = \varepsilon - \varepsilon^{e}$. The geometry of the test specimen was modelled by refined finite element mesh as shown in Fig.4. The structure is represented by 1722 finite elements and 8222 nodes. The standard tetrahedral 8-noded element with 8 Gauss points was adopted in the finite element analysis.

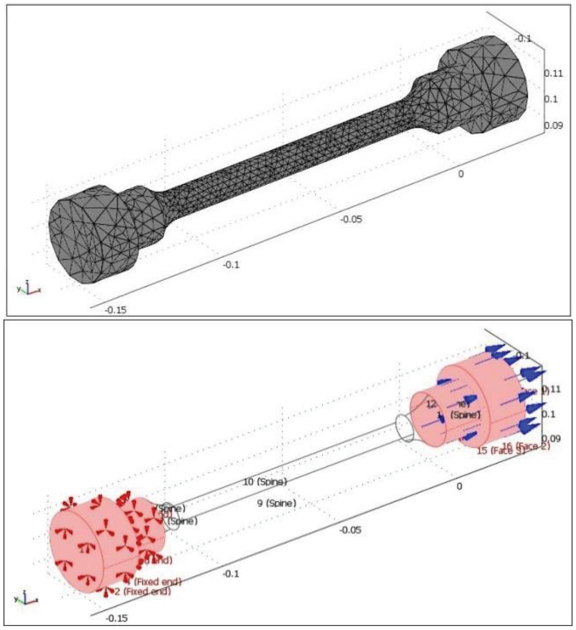

*Fig. 5 (a) FEA model showing interactive mesh elements and refinements (b) Positions of applied loads and constraints*

## 3. RESULTS AND DISCUSSION

### 3.1. Signal to noise (S/N) ratio analysis

The means and Signal-to-Noise ratios (S/N) for each control factor has been calculated in order to assess the influence of factors on the response. The mechanical properties (BHN, percentage elongation to fracture, yield strength and UTS) were analysed to determine the effect of die casting process parameters. The experimental results were then transformed into averages and S/N ratio. The details are given in Tables 4-7. The analysis of mean for each of the experiments gives the better combination of parameters levels that ensures a high level of tensile strength according to the experimental set of data.

The mean response refers to the average value of performance characteristics for each parameter at different levels. The mean for one level was calculated as the average of all responses that were obtained at that level. The mean response and S/N ratio of performance characteristics for each parameter at levels 1 and 2 were calculated and are given in Appendix A. The means and S/N ratio of the various process parameters when they changed from the lower to higher levels were also given in these tables. The optimal level of process parameter is considered the level of highest S/N ratios for Yield strength, UTS, BHN and percentage elongation to fracture. The comparison of mean effect and S/N ratio are presented in Figs. 6-8. These indicate that the mechanical properties were at maximum values when the pouring temperature, pre-heat temperature and amplitude of vibration were at levels 1 (660 °C), 2 (250 °C) and 1 (200 μm) respectively.

### 3.2. Analysis of variance (ANOVA)

The ANOVA details for all the mechanical properties of means and S/N ratio are given in Table 8.

The results of the ANOVA indicate that the pouring temperature and die pre-heat temperature were highly significant factors affecting the BHN, percentage elongation to fracture and Yield strength, while all the three parameters were significant for UTS. The interaction effects of the parameters were neglected. This indicates that in practice, the pouring and the die pre-heat temperature levels should be closely-controlled in order to maximize the quality characteristics of the castings.

### 3.3. Estimation of Optimum Performance Characteristics

The optimum values of performance characteristics were predicted at the selected levels of significant parameters. On this basis, the highest values of the S/N ratios and mean levels (Figs 6-9) for the significant factors T, $T_m$, and V, indicates the overall optimum condition for reducing variabilities in the die-casting process in order to maximise the quality performance of the castings

*Table 4 Orthogonal array for L8 with BHN response (raw data and S/N ratio)*

| | Input parameter | | | Response | | Mean value | S/N ratio |
|---|---|---|---|---|---|---|---|
| No | $T$ | $T_m$ | $V$ | R1 | R2 | | |
| 1 | 1 | 1 | 1 | 35 | 36 | 35.50 | 31.01 |
| 2 | 1 | 1 | 2 | 36 | 39 | 37.50 | 31.49 |
| 3 | 1 | 2 | 1 | 44 | 45 | 44.50 | 32.97 |
| 4 | 1 | 2 | 2 | 42 | 47 | 44.50 | 32.98 |
| 5 | 2 | 1 | 1 | 33 | 33 | 33.00 | 30.37 |
| 6 | 2 | 1 | 2 | 35 | 37 | 36.00 | 31.13 |
| 7 | 2 | 2 | 1 | 41 | 43 | 42.00 | 32.47 |
| 8 | 2 | 2 | 2 | 38 | 35 | 36.50 | 31.25 |

*Table 5 Orthogonal array for L8 with Elongation to Fracture response (raw data and S/N ratio)*

| | Input parameter | | | Response | | Mean value | S/N ratio |
|---|---|---|---|---|---|---|---|
| No | $T$ | $T_m$ | $V$ | R1 | R2 | | |
| 1 | 1 | 1 | 1 | 0.47 | 0.49 | 0.48 | -6.37 |
| 2 | 1 | 1 | 2 | 1.49 | 1.30 | 1.40 | -2.91 |
| 3 | 1 | 2 | 1 | 1.24 | 1.45 | 1.35 | -2.60 |
| 4 | 1 | 2 | 2 | 1.14 | 1.47 | 1.31 | -2.38 |
| 5 | 2 | 1 | 1 | 0.37 | 0.32 | 0.35 | -9.22 |
| 6 | 2 | 1 | 2 | 0.42 | 0.39 | 0.41 | -7.85 |
| 7 | 2 | 2 | 1 | 1.40 | 1.30 | 1.45 | -3.23 |
| 8 | 2 | 2 | 2 | 0.29 | 0.26 | 0.28 | -11.20 |

*Table 6 Orthogonal array for L8 with Yield Strength response (raw data and S/N ratio)*

| | Input parameter | | | Response | | Mean value | S/N ratio |
|---|---|---|---|---|---|---|---|
| No | $T$ | $T_m$ | $V$ | R1 | R2 | | |
| 1 | 1 | 1 | 1 | 20.57 | 21.20 | 20.89 | 26.40 |
| 2 | 1 | 1 | 2 | 21.49 | 21.12 | 21.31 | 26.57 |
| 3 | 1 | 2 | 1 | 27.20 | 29.60 | 28.40 | 29.07 |
| 4 | 1 | 2 | 2 | 30.20 | 31.42 | 30.81 | 29.78 |
| 5 | 2 | 1 | 1 | 20.27 | 19.89 | 20.08 | 26.06 |
| 6 | 2 | 1 | 2 | 20.60 | 20.23 | 20.42 | 26.20 |
| 7 | 2 | 2 | 1 | 30.94 | 31.30 | 31.12 | 29.86 |
| 8 | 2 | 2 | 2 | 19.53 | 19.22 | 19.38 | 25.75 |

*Table 7 Orthogonal array for L8 with UTS response (raw data and S/N ratio)*

| | Input parameter | | | Response | | Mean value | S/N ratio |
|---|---|---|---|---|---|---|---|
| No | $T$ | $T_m$ | $V$ | R1 | R2 | | |
| 1 | 1 | 1 | 1 | 78.38 | 79.40 | 78.89 | 37.92 |
| 2 | 1 | 1 | 2 | 73.07 | 71.69 | 72.38 | 37.92 |
| 3 | 1 | 2 | 1 | 80.68 | 82.52 | 81.60 | 38.23 |
| 4 | 1 | 2 | 2 | 81.82 | 84.74 | 83.28 | 38.41 |
| 5 | 2 | 1 | 1 | 71.38 | 70.50 | 70.94 | 37.02 |
| 6 | 2 | 1 | 2 | 67.67 | 64.51 | 66.09 | 36.41 |
| 7 | 2 | 2 | 1 | 93.73 | 94.34 | 94.04 | 39.47 |
| 8 | 2 | 2 | 2 | 64.18 | 61.76 | 62.97 | 35.98 |

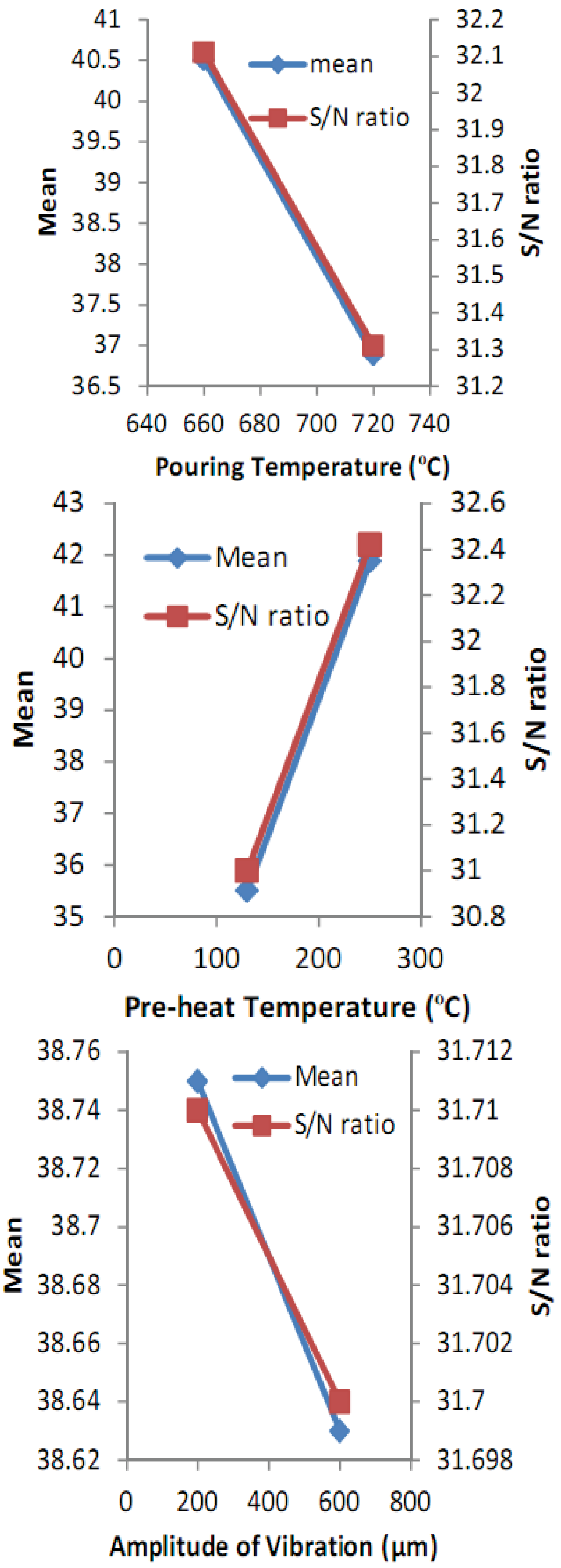

*Fig. 6 Comparison of mean effect and S/N ratio of BHN*

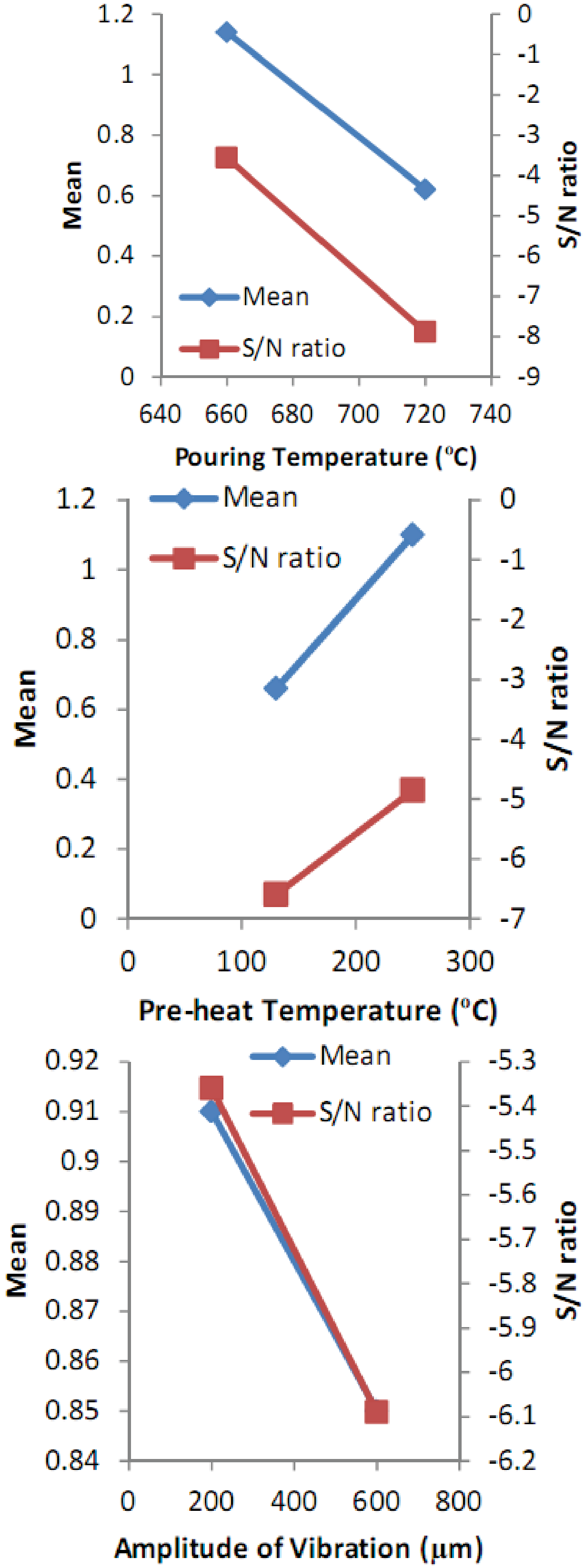

*Fig 7 Comparison of mean effect and S/N ratio of Percentage Elongation to Fracture*

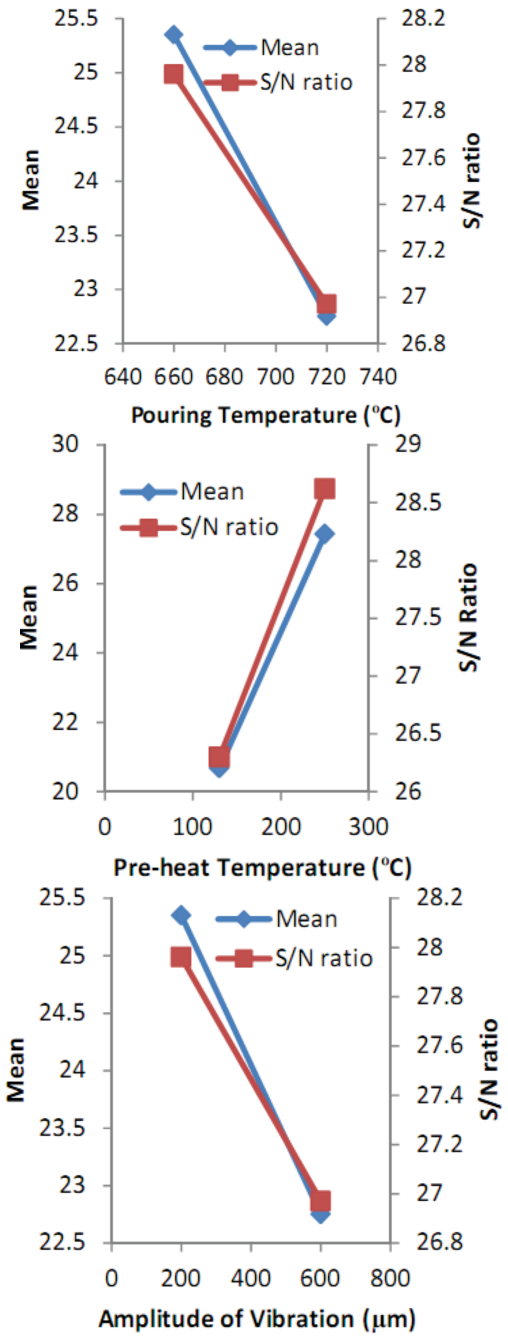

*Fig 8 Comparison of mean effect and S/N ratio of Yield Strength*

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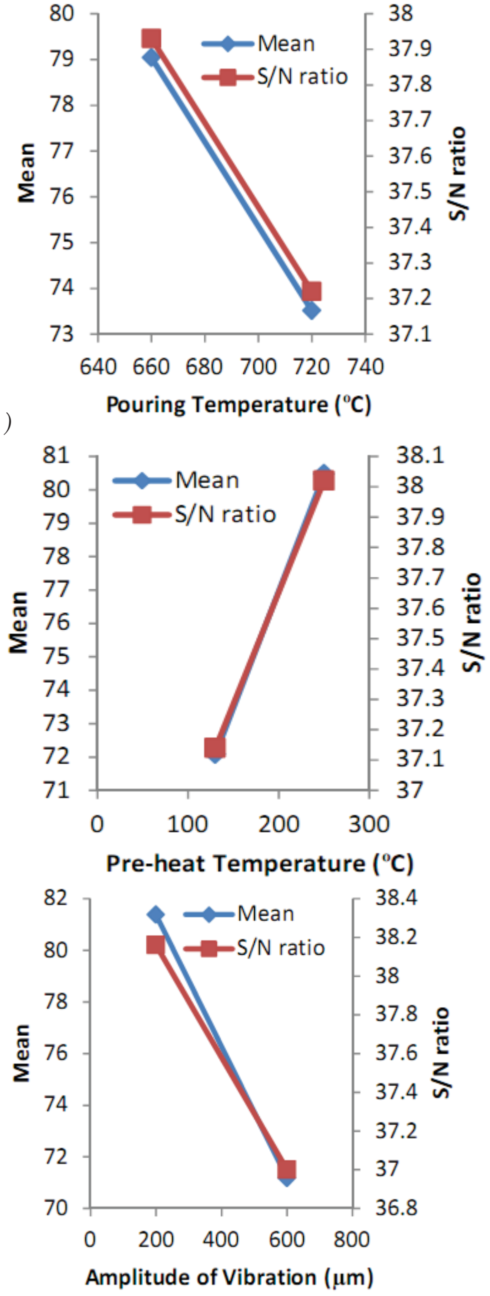

*Fig 9 Comparison of mean effect and S/N ratio of UTS*

*Table 8 Summary of ANOVA for investigated Mechanical Properties (S – Significant, NS – Not Significant*

| Estimates | | BHN | Elongation | Yield Strength | UTS |
|---|---|---|---|---|---|
| Average | | 38.69 ± 0.47 (S) | 0.88 ± 0.03(S) | 24.05 ± 0.18(S) | 76.27 ± 0.36 (S) |
| Main effects | $T$ | -3.63 ± 0.94 (S) | -0.51 ± 0.06 (S) | -10.41 ± 0.36 (S) | -5.53 ± 0.71 (S) |
| | $T_m$ | 6.38 ± 0.94 (S) | 0.44 ± 0.06 (S) | 6.75 ± 0.36 (S) | 8.40 ± 0.71 (S) |
| | $V$ | 0.13 ± 0.94 (NS) | -0.06 ± 0.06 (NS) | -2.14 ± 0.36 (NS) | -10.19 ± 0.71 (S) |
| Interaction effects | $T \times T_m$ | -1.63 ± 0.94 (NS) | 0.05 ± 0.06 (NS) | -1.75 ± 0.36 (NS) | -1.59 ± 0.71 (NS) |
| | $T \times V$ | -1.13 ± 0.94 (NS) | -0.50 ± 0.06 (S) | -3.56 ± 0.36 (NS) | -7.77 ± 0.71 (S) |
| | $T_m \times V$ | -2.63 ± 0.94 (NS) | -0.55 ± 0.06 (S) | -2.52 ± 0.36 (NS) | -4.51 ± 0.71 (NS) |
| | $T \times T_m \times V$ | -1.63 ± 0.94 (NS) | -0.07 ± 0.06 (NS) | -3.52 ± 0.36 (NS) | -8.60 ± 0.71 (S) |

This condition was attained at a combination of process parameters of $T_1$, $T_{m2}$, and $V_1$ respectively. The amplitude of vibration of casting $V_1$ is however of little significance when the outcome of this analysis was compared with the results of the authors [2, 18].

The estimated means of the response characteristics (performance characteristics) are given in Table 9.

*Table 9 Optimum values of performance characteristics*

| Response Characteristics | Estimated Mean |
|---|---|
| BHN ($H$) | 43.75 |
| Percentage elongation($e$) | 1.39 % |
| Yield strength(Y) | 29.80 MNm$^{-2}$ |
| UTS($U$) | 88.34 MNm$^{-2}$ |

### 3.4. Finite element analysis

The results from Newton-Raphson Iteration method results were obtained for each specimen model based on the FEA solid-state variables of displacement, stress and strain.

In this analysis, the load acts axially causing the model to experience displacement in the positive x-direction under applied stresses and strains. Under the application of tensile load at one end of the model, the magnitude of the displacement of the model elements increased linearly in the direction of the applied load and decreased linearly towards the constraint end. The elongation to fracture also occurred at the same critical point that shows larger total displacement.

A typical von Mises stress distribution profile on a representative tensile specimen is shown in Fig.10. In all cases considered i.e (Pm1- pm8), the dynamic analysis shows that high stress concentrations were found on the extremities of the model, which compares well with the failure points in all the experimental runs during tensile testing.

In a similar context, the normal strain contour plot which describes the deformation profile as tensile load was applied is shown in Fig. 11. It was observed that a one-one constitutive correspondence exists between the strain and displacement since the effect of strain distribution is at maximum over extremities of the model as the displacement increases towards the boundaries over which the tensile load was applied. The details for the stresses and strains profiles corresponding to the process parameters combinations Pm1-Pm8 are presented in Table 10. From this, it is evident that Pm3, has the highest yield resistance, that is; the highest stress state before the onset of plastic flow with better hardening rate than the other process parameters combinations. The difference in quality performance from this standpoint is however marginal when compared with the properties of Pm4 and Pm7 respectively. Nonetheless, this trend is in close agreement with the results from statistical analysis.

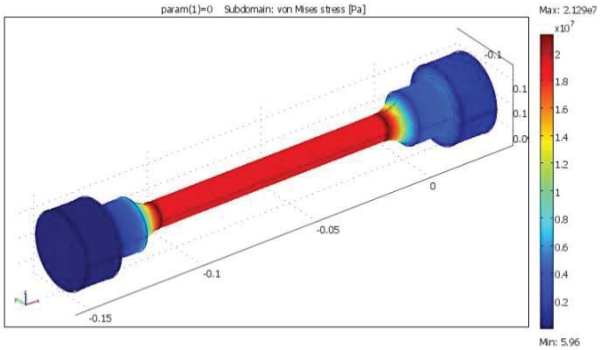

Fig 10 von Mises stress contour plot

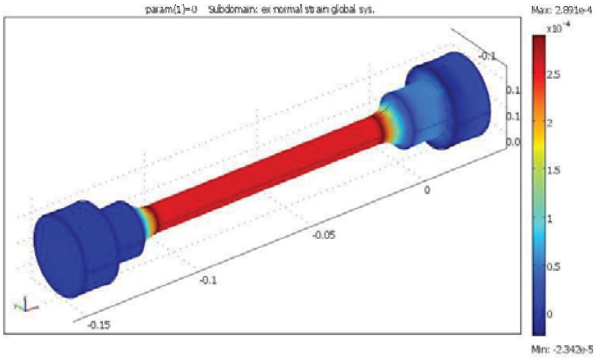

Fig 11 Normal strain contour plot

*Table 10 Deformation profile for the experimental investigations by the finite element method*

| Specimen | Minimum von Mises stress (Pa) | Maximum von Mises stress (Pa) | Maximum normal Strain | Minimum normal Strain |
|---|---|---|---|---|
| Pm1 | 5.96 | 2.129 × 10$^7$ | 2.891 × 10$^{-4}$ | -2.342 × 10$^{-5}$ |
| Pm2 | 5.96 | 2.271 × 10$^7$ | 3.697 × 10$^{-4}$ | -2.995 × 10$^{-5}$ |
| Pm3 | 5.96 | 3.139 × 10$^7$ | 3.791 × 10$^{-4}$ | -3.072 × 10$^{-5}$ |
| Pm4 | 5.96 | 3.123 × 10$^7$ | 4.626 × 10$^{-4}$ | -3.748 × 10$^{-5}$ |
| Pm5 | 5.96 | 2.129 × 10$^7$ | 2.951 × 10$^{-4}$ | -2.391 × 10$^{-5}$ |
| Pm6 | 5.96 | 2.129 × 10$^7$ | 3.150 × 10$^{-4}$ | -2.552 × 10$^{-5}$ |
| Pm7 | 5.96 | 3.123 × 10$^7$ | 3.802 × 10$^{-4}$ | -3.080 × 10$^{-5}$ |
| Pm8 | 5.96 | 1.987 × 10$^7$ | 2.797 × 10$^{-4}$ | -2.266 × 10$^{-5}$ |

## 4. CONCLUSIONS

1. A framework has been presented in this study towards maximising the cost of producing aluminium alloy by the die-casting process locally.
2. Experimental investigations based on the Taguchi's parametric design has shown that the most significant values for optimisation of Al6063 aluminium alloy by die-cast is achieved at the process parameters combination of (660$^0$C, 250$^0$C and 200µm) for the pouring temperature, die-preheat temperature and amplitude of vibration of casting, respectively.
3. The results from numerical investigations based on the elastic-plastic deformation profile of the castings were found to be consistent with representative data from mechanical tests and these, have also been related to the quality performance of the castings.

## APPENDIX A

*Table A1 Main effects on BHN (means and S/N ratio)*

| Process parameter | Level | Mean | | | S/N ratio | | |
|---|---|---|---|---|---|---|---|
| | | $T$ | $T_m$ | $V$ | $T$ | $T_m$ | $V$ |
| Average | L$_1$ | 40.50 | 35.50 | 38.75 | 32.11 | 31.00 | 31.71 |
| Value | L$_2$ | 36.88 | 41.88 | 38.63 | 31.31 | 32.42 | 31.70 |
| Main effect | L$_2$-L$_1$ | -3.62 | 6.38 | -0.12 | -0.80 | 1.42 | -0.01 |

*Table A2 Main effects on Percentage Elongation to Fracture (means and S/N ratio)*

| Process parameter | Level | Mean | | | S/N ratio | | |
|---|---|---|---|---|---|---|---|
| | | $T$ | $T_m$ | $V$ | $T$ | $T_m$ | $V$ |
| Average | L$_1$ | 1.14 | 0.66 | 0.91 | -3.57 | -6.59 | -5.36 |
| Value | L$_2$ | 0.62 | 1.10 | 0.85 | -7.88 | -4.85 | -6.09 |
| Main effect | L$_2$-L$_1$ | -0.52 | 0.44 | -0.06 | -4.31 | 1.74 | -0.73 |

*Table A3 Main effects on Yield Strength (means and S/N ratio)*

| Process parameter | Level | Mean | | | S/N ratio | | |
|---|---|---|---|---|---|---|---|
| | | $T$ | $T_m$ | $V$ | $T$ | $T_m$ | $V$ |
| Average | $L_1$ | 25.35 | 20.68 | 25.12 | 27.96 | 26.30 | 27.85 |
| Value | $L_2$ | 22.75 | 27.43 | 22.98 | 26.97 | 28.62 | 27.08 |
| Main effect | $L_2$-$L_1$ | -2.60 | 6.75 | -2.14 | -0.99 | 2.32 | -0.77 |

*Table A4 Main effects on UTS (means and S/N ratio)*

| Process parameter | Level | Mean | | | S/N ratio | | |
|---|---|---|---|---|---|---|---|
| | | $T$ | $T_m$ | $V$ | $T$ | $T_m$ | $V$ |
| Average | $L_1$ | 79.04 | 72.08 | 81.37 | 37.93 | 37.14 | 38.16 |
| Value | $L_2$ | 73.51 | 80.47 | 71.18 | 37.22 | 38.02 | 37.00 |
| Main effect | $L_2$-$L_1$ | -5.53 | 8.39 | -10.19 | -0.71 | 0.88 | -1.16 |

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