Statistical Model for Predicting the Ultimate Tensile Strength of Aluminium Alloy Sand Castings under Different Process Parameters

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Abstract: This study presents a statistical multiple regression model for predicting the ultimate tensile strength of aluminium alloy castings under different sand casting process parameters. Three sand casting process parameters namely mould temperature; pouring temperature and runner size were selected for the work. While other casting parameters were kept constant, the selected parameters were varied to produce cast specimens which where tested to obtain their ultimate tensile strengths. The model results obtained shows a unity multiple correlation coefficient (R-value) of 1 for the test data, and a low mean square error (MSE) of 0.01. The statistical regression model equation using mould temperature, pouring temperature and runner size as predictors was obtained as $\mathrm{UTS} = 193 - 0.180\ \mathrm{mould\ temp} - 0.178\ \mathrm{pouring\ temp} + 0.112\ \mathrm{runner\ size}$. Validation of the derived statistical model gave rise to correction factors not greater the 0.7% indicating the reliability of the model. The result of this work can be employed for research purposes and in sand casting production processes where it is obvious that the percentage of defective castings is still high.

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1. Introduction

One of the main concerns in physical metallurgy is how the size and orientation of the grains of metals and their alloys are related to their properties (Ward, 1993). The wide ranges of application of aluminium alloys are very obvious. Their desirable characteristics of light weight, excellent resistance to corrosion in the atmosphere and water, strength (Allen, 1979) and high thermal conductivity gives them an edge over other metals in the electrical, aviation, marine, aerospace, construction and automotive industries just to mention but a few (KarL, 2005). This increased usage creates the need for a deeper understanding of their mechanical behaviour and the influences of processing parameters, (Mrwka–Nowotnik et al., 2007; Kauffman and Rooy,2005). This knowledge enables the designer to ensure that the casting will achieve the desired properties for its intended application (Li ,2004; Shabestari and Moemeni, 2004).

Casting is one production process that is efficient and has minimal losses in terms of materials utilization (Taylor et al., 1959). Abu et al.(2010), Mohammed and Akpan (2007), Lee (2007), and Boileau (1997) just to mention but a few have successfully carried out studies on the varying effects of casting process parameters on the mechanical properties of casted metals and their alloys. Also, studies on the applications of statistical tools and concepts that depend heavily on the statistical theory of experimental design in the design and analysis of casting processes have increased over the years (Johnston, 1989; Kumar and Gaindhar, 1995; Barua et al., 1997). In literature, several approaches based on through-process modelling for prediction of the structural behaviour of high pressure die casting (HPDC) magnesium and aluminium alloy components subjected to static and dynamic loads have been suggested (Avalle, 2002; Dorum, 2007; Dorum, 2009a; Dorum, 2009b).

Generally, two different routes based on constitutive models (Lee, 2007; Cáceres, 1996), or statistical and stochastic approaches (Dorum, 2007) are used. The Ghosh constitutive model (Ghosh, 1977) can accurately predict the experimental tensile properties of aluminium alloys, even though they used a simple constitutive model. In the model, based upon the tensile instability, the tensile strength and deformation of material with internal discontinuities significantly depend upon the fraction of internal discontinuity, the strain rate sensitivity and strain-hardening ability. On the other side, the effects of structural defects on mechanical properties have been characterized by Weibull statistics, more specifically, by the two-parameter Weibull modulus (Green and Campbell, 1993). In these early studies, the Weibull modulus appeared to be a useful measure of the reliability of the casting process. Since then, the two-parameter Weibull modulus has been extensively used to characterize the tensile properties, especially the tensile strength.

The objective of this work is to develop a mathematical model for predicting the ultimate tensile strength of aluminium alloy castings under different mould temperature, pouring temperature and runner size based on the multiple regression technique since it can accommodate more than two independent parameters.

2. Material and Methods

Keeping the percentage of the iron and silicon constant, high purity aluminium electrical wires obtained from Northern Cable Company (NOCACO) Kaduna, Nigeria (free from dust and contamination) was charged in a graphite crucible kept in electric resistance furnace. 0.01% sodium chloride-potassium chloride (Nacl-Kcl) powder was used as a cover for melting the alloy to minimize oxidation of aluminium by excluding oxygen and creating a protective atmosphere inside the furnace.

Upon initiation of melting of pure aluminium, the temperature of the furnace was raised to 720°C. The required quantity of silicon (4.6%) and iron (1.5%) was added using Ferro-silicon, and resulting melt thoroughly stirred with progressive melting, the furnace temperature was raised to 780°C and the melt was held at this temperature for ten minutes. It was then skimmed to remove the oxides and impurities. The molten metal was continuously stirred in order to ensure a near-uniform distribution of alloying elements from settling at the bottom on account of their higher density. For each melting 1.6kg of charge materials were used to produce the alloy. The result of the chemical analysis and the composition of aluminium alloy used is shown in Table 1.

Table 1. Chemical composition of aluminium alloy

Element	Al	Fe	Si
Weight Percentage (W %)	93.9	1.5	4.6
Concentration(mgl)	939	15	46

2.1 Preparations of the mould and casting of specimen

Azare foundry sand (Adelemoni, 2001) of known specification was prepared for moulding by adding some quantity of water. The mould boxes (i.e. drag and cope) were produced using wood. One of the boxes was on a board and then a cylindrical pattern was placed on the board. The cylindrical pattern was used because the specimens to be produced are of cylindrical shapes (figure 1).

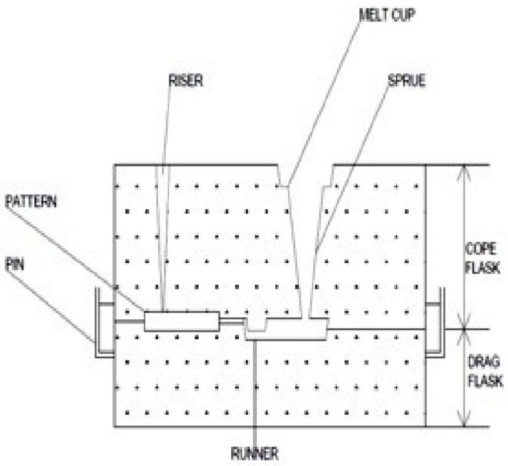

Figure 1: Mould assembly for sand casting

The prepared moulding sand was then added to the pattern and rammed, properly. When it was properly rammed, the mould box containing the pattern was turned upside down and the parting sand was applied before placing the other box (i.e. cope). The moulding sand was then added, but before the moulding sand was added, pipes were placed to locate the position of the gate and the riser. The sand was then rammed. When it was properly rammed, the cope was removed and then the pattern was removed. At the sprue the cross-sectional area of the pouring cup was 380mm^2, and at the cavity the cross-sectional area was100mm^2. After this, the assembled mould was placed in a furnace and preheated to temperature of 37°C, 100°C, 150°C, 170°C, and 230°C for holding time of 35 minutes. Again the molten metal was then poured into each mould. After this, the process was repeated with the molten metal poured at pouring temperatures of 690°C, 700°C, 730°C, 770°C and 790°C and the runner size varied in the range of 100mm^2 to 315mm^2 as shown in table 2, for the same holding time of 20 minutes respectively. Four samples were prepared for each case as shown in table 2 (bringing the total number of casted samples to twenty) and the average recorded. The effect of the selected parameters is as shown in Table 3 (which is an extension of table 2).

Table 2. Experimental trial table

CASE	ULTIMATE TENSILE STRENGTH, UTS (N/mm^2)				AVERAGE UTS (N/mm^2)
	Trial I	Trial II	Trial III	Trial IV	
A	71.3	82.3	74.2	69.4	74.3
B	61.3	73.5	75.4	70.6	70.2
C	61.7	69.0	54.2	54.3	59.8
D	51.9	53.4	70.9	65.4	60.4
E	45.1	52.9	51.2	48.8	49.5

Table 3. Effect of process parameters on ultimate tensile strength

Case	PROCESS PARAMETERS			Ultimate tensile Strength (N/mm^2)
	Mould temperature (^{o}C)	Pouring temperature (^{o}C)	Runner size (mm^2)	
A	37	690	100	74.3
B	100	700	180	70.2
C	150	730	200	59.8
D	170	770	285	60.4
E	230	790	315	49.5

2.1 Tensile test

The castings were machined to the required shape using the lathe machine. The equipment used for the ultimate tensile test is a universal material testing machine, model SSR25 14, digital indicating system. The machine is hydraulically operated. The test specimen having been machined to the required specification was then fed into a locking socket which provided the grip of specimen at the base and at the top, with the press loosened to release the extensive to allow for easy monitoring on the tensile test piece alongside the socket in which it is fitted, the test piece was held at both end as made to be tensioned slightly and the meter was set to zero with the pump handle in the down position and locked. The pump handle was raised and pressed down so as to apply the load. The load was increased uniformly and the corresponding extension was noted. This process was repeated for other specimens.

To obtain the ultimate tensile strength the following formula was used (Donald, 1989):

$$UTS = \frac{P_{max}}{A_o} \qquad (1)$$

Where P_{max} is the maximum load reading on the machine.

A_o is the original cross sectional area

3. Regression Model

Minitab software package was used to carry out the regression analysis and modeling of the ultimate tensile strength using mould temperature, pouring temperature and runner size as predictors.

From the analysis the model equation obtained was;

$$UTS = 193 - 0.180 \text{ mould temp} - 0.178 \text{ pouring temp} + 0.112 \text{ runner size} \qquad (2)$$

The value of R is compared with the value from tables (Lipson and Sheth, 1973) to test its significance. From the tables, with 3 degrees of freedom and 99 percent confidence, the value of R is 0.983. Since the calculated value of R (1) is greater than the tabulated value 0.983, it can be concluded with 99 percent confidence that the variations in the three process parameters are interdependent; and under the stated conditions 100% percent of the total variation in one parameter can be accounted for by the variation in the others (Lipson and Sheth, 1973; Murray and Larry, 2007).

Table 4: Minitab output for the effect of process parameters on ultimate tensile strength

Predictor	Predictor Coef	St Dev	T	P
Constant	192.876	3.705	52.05	0.012
Mould te	-0.179824	0.00242	-74.2	0.009
pouring	-0.178496	0.00570	-31.3	0.020
runner s	0.112317	0.00252	44.57	0.014
S = 0.08835 R-Sq = 100.0% R-Sq(adj) = 100.0%				
Analysis of Variance				
Source	DF	SS	MS	F P
Regression	3	378.64	126.2	16170.63 0.006
Error	1	0.01	0.01	
Total	4	378.65		
Source	DF	Seq SS		
Mould te	1	362.99		
pouring	1	0.14		
runner s	1	15.51		

4. Model Validation

Since validation is an important aspect of modeling (Dyn, 2004; Anu, 1997), the derived model was validated by evaluating the model-predicted values of UTS of the aluminium alloy casting with those derived from experiment.

Analysis and comparison between the model-predicted values and the respective corresponding experimental values shows deviations of model data from the experimental data. Consequent upon these deviations there is the need for the introduction of a correction factor to bring the model-predicted values as close as possible to their corresponding experimental values.

Thus, the Deviation (D_v) of the model-predicted UTS values from the corresponding experimental values is given by

$$D_V = \left[\frac{U_M - U_E}{U_E}\right] \times 100 \qquad (3)$$

Also, the Correction factor (C_f) is the negative of the deviation i.e.

$$C_f = -D_v \qquad (4)$$

Where

(D_v) = Deviation of the model-predicted UTS values from the corresponding experimental values

C_f = Correction factor

U_M = Model-predicted UTS values

U_E = UTS values obtained from the experiment

Therefore

$$C_f = -\left[\frac{U_M - U_E}{U_E}\right] \times 100 \qquad (5)$$

Introduction of the value of C_f from equation (3) into the models give exactly the corresponding experimental values.

The introduction of the correction factor is also indicative of the reliability and validity of derived generalized model. The results shown in table 5 indicates that the deviation in each case did not exceed 0.7% indicating the model's reliability.

Table 5: Comparison of the UTS as obtained from experiment and as predicted by derived model (each as a function of the three predictors).

Derived Model	Case	U_M	U_E	D_V(%)	C_f(%)
$UTS = 193 - 0.180\ MT - 0.178\ PT + 0.112\ RS$	A	74.7	74.3	0.54	-0.54
	B	70.6	70.2	0.57	-0.57
	C	60.2	59.8	0.67	-0.67
	D	60.8	60.4	0.66	-0.66
	E	49.8	49.5	0.60	-0.60

5. Conclusion

The results of this study indicated that the developed multiple regression model can be effectively adopted for predicting the ultimate tensile strength of aluminium alloy sand castings under the same conditions. Work is in progress to adopt the taguchi method to investigate the percentage contributions of each of these parameters to the test results obtained. The results of this work can be applied in foundry shops where it is evident that the number of defective castings produced is still significant. It can also be used as input data for research purposes.

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