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Optimization of Process Parameters for Aluminum Alloy Sand Cast: An ANOVA Approach

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Abstract: ANOVA is an organized and systematic method for the strategic investigation of process parameters and their effect on the mechanical properties of Aluminum alloy cast. The two process parameters considered as permeability of sand and pouring temperature of aluminum alloy. ANOVA has been proposed to determine the effect of these selected parameters on the impact strength of alloy. The result shows that the formulation and use of this technique is an effective tool for analyzing sand casting process and helps to find the treatment mean square, response mean square and mean square of error as 8.54, 8.255 and 0.435 respectively. The research concluded that at the 5% level of significance, permeability of sand is the more significant parameter influencing the impact strength of cast alloy.

Keywords: ANOVA, Aluminum Alloy; Impact Strength; Pouring Temperature; Permeability of Sand.

I. Introduction

Aluminum is one of the most common elements in earth crust. It has the many desirable properties such as high resistance to corrosion, high thermal and electrical conductivity, low weight and bright color which give it an edge over the other materials in aerospace, electrical, constructive and automotive industries [1]. The important aluminum alloy used in industries is Al-Si in which the percentage change of silicon (4.0-13%) contributes to good casting. On the other hand, sand casting is the oldest and most widely used casting process due to its property of collapsibility and recycling. Casting is the metal object obtained by allowing molten metal to solidify in the prepared mould [2]. The casting product is then machined to remove surface imperfections. Over the decades, the application of different statistical tools has increased in the design and analysis of casting process [3-5]. Analysis of variance (ANOVA) is an extremely useful technique in the industrial experiments. In this considered multiple factors are altering with respect to different given conditions for the summarization of a classical linear model associated along with a test (the F-test) of the hypothesis [6].

As there are many casting parameters such as permeability of sand, mould conditions(temperature, moisture, types of sand and binders used) melting temperature of charge, pouring temperature, pouring speed, gate design, size of casting and the type of cast alloy. It has been observed that the variation in most of these parameters affects on the mechanical properties of the cast material such as impact strength, tensile strength, hardness, percentage elongation and so on [7-8]. This assertion leads to the differences in microscopic structure of casting. Because of these differences which cannot be eliminated completely, there is the need to investigate the varying effect of these parameters on the mechanical properties. In this work, the only two parameters such as permeability of sand (is the amount of air can trapped through the sand and it depends upon the size of sand grains) and pouring temperature (ranging 700 ^{0}C to 900 ^{0}C) are considered. The purpose of the ANOVA is to investigate the effect of these process parameters on the impact strength of the casting under the similar conditions.

II. Material And Method

2.1 Composition of the Charge

The chemical composition of the aluminum alloy used for the casting is shown in the table 1.

Table 1: Chemical composition of Al alloy

Element	Al	Si	Fe
Concentration (Wt %)	93.9	4.0	1.5

2.2 Preparation of the mould and casting of specimen

Foundry sand of the known specification was prepared for the moulding having low(30 Darcy) and high(60 Darcy) permeability of sand respectively. The pattern of square slab was placed in the mould box (drag). Then the moulding sand was added to the pattern and rammed properly. After ramming, the other mould box (cope) was kept over the drag by applying the parting sand between them. At the end when sand was properly rammed, the cope and pattern were removed. Now the molten metal was poured into each mould. This process was repeated three times each at low permeability and high permeability with the different pouring temperature of 700 ^{0}C, 800 ^{0}C & 900 ^{0}C respectively. A total 18 samples were produced.

2.3 Determination of Impact Test

The castings were machined to the required shape (shown in figure 1) using the shaper machine. The impact testing machine has the capacity of 150 joule. The pendulum was raised to the maximum height and the test piece was then placed horizontally at the specimen holder. After noting the reading of the pointer, the pendulum was released which strikes the specimen at the notch. The pointer's reading was noted again. The difference between the readings is the energy that was used to fail the specimen. This process was repeated for other specimens also.

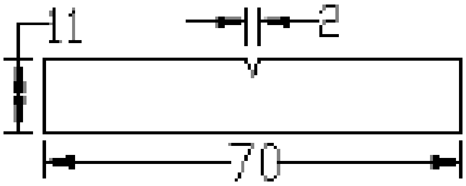

Fig. 1: Specimen for Impact Strength

III. Formulation For Two – Factor Experiments

Two way ANOVA techniques are used when the data is classified on the basis of two factors. The formulation adopted for this work is as developed by [8]. Here we have presented '**a**' for permeability of sand and '**b**' for pouring temperature. For row j and column k, we denote this value by X_{jk} . The mean of the entities in the jth row is denoted by $\bar{X}_j$, where j =1,..., a, while the mean of the entries in the kth column is denoted by $\bar{X}_k$,where k=1,...,b. The overall or grand mean is denoted by$\bar{X}$.

In symbols:

$$\bar{X}_j = \frac{1}{b}\sum_{k=1}^{b} X_{kj}$$

$$\bar{X}_k = \frac{1}{a}\sum_{k=1}^{a} X_{jk}$$

$$\bar{X} = \frac{1}{ab}\sum_{j,k} X_{jk}$$

3.1 Variation for Two Factor Experiments:

We define the variation to be:

$$V = \sum_{j,k}(X_{jk} - \bar{X})^2$$

Therefore,

$$V = \frac{1}{b}\sum_{jk} X_{jk}^2 - \frac{T^2}{ab}$$

$$V_R = \frac{1}{b}\sum_{k=1}^{b} T_J^2 - \frac{T^2}{ab}$$

$$V_C = \frac{1}{a}\sum_{k=1}^{b} T_k^2 - \frac{T^2}{ab}$$

$$V_E = V - V_R - V_C$$

Where, V is total variation, V_E is variation due to error, V_R is variation between rows (permeability of sand) and V_C is variation between columns (pouring temperature).

Also, T_j is the total of entry in the jth row, T_k is the total of entries in the kth column and T is the total of all entries.

3.2 Analysis of Variance for Two Factor Experiment

The generalized mathematical model for one factor experiment is given by

$X_{jk} = \mu + \alpha_j + \beta_k + \varepsilon_{jk}$

Where $\Sigma\ \alpha_j = 0$ and $\Sigma\ \beta_k = 0$. Here μ is the population grand mean, α_j is that part of X_{jk} due to the different permeabilities of sand, β_k is that part of X_{jk} due to the different pouring temperatures and ε_{jk} is that part of X_{jk} due to chance or error.

To calculate the more effective variable for the impact strength of sand casting product, the authors considered the permeability of sand as the null hypothesis and also the more effective variable. So here,

$H_0 =$ Permeability of Sand (Row wise) influences impact strength: that is $\alpha_j = 0$ and j = 1,…..a.

$H_a =$ Pouring Temperature (Column wise) influences impact strength: that is $\beta_k = 0$ and k= 1,……b.

At the first, the correction factor:

Correction Factor= $(T)^2 / n$

Where T is total value of individual items and n is the total number of experiments.

Now square all the items one by one and make a total of all. Then subtract the correction factor from this total added squared values to obtain the total variance:

Total variance $V = \sum T_{jk}^2 - (T)^2/n$

Similarly, calculate the value of variations between the rows (V_R) and variations of columns (V_C) respectively. Also the value of error of deviations for variance by subtracting the results of variations of rows and columns as shown below:

V for residual or error variance (V_E) = Total $V - (V_R + V_C)$

By defining the degree of freedom for rows and columns respectively, calculate the value of mean squares (MS) as shown below:

MS = Variation / Degree of freedom

Therefore;

Mean square of rows (MS_R) = $V_R / (a-1)$ [a=2, number of rows]

Mean square of columns (MS_C) = $V_C / (b-1)$ [b=3, number of columns]

Mean square of residual error (MS_E) = $V_E / (a-1)(b-1)$

To test the hypothesis, consider the statistics MS_R / MS_E and MS_C / MS_E between the rows and columns respectively. Under the hypothesis H_0, the statistics of mean square between rows and mean square of residual error has the F ratios with $a-1$ and $(a-1)(b-1)$ as degree of freedom. And under the hypothesis H_a, the statics of mean square between columns and mean square of residual error has the F ratios with $b-1$ and $(a-1)(b-1)$ as degree of freedom. Both F- ratios are compared with the table values for the given degree of freedom at specified level of significance. If the calculated value of F-ratio is more than the tabled value then the hypothesis H_0 is rejected and variable is significant.

IV. Results And Discussion

The experiment was performed by taking different pouring temperature and permeability of sand as shown in the Table 2. This shows that the impact strength of aluminum alloy is decreased with the increase of permeability of sand and pouring temperature.

Table: 2 Impact Strength at different levels of process parameters.

Permeability of Sand(Darcy)	Pouring Temperature(^{0}C)								
	700			800			900		
30	6	6.1	5.8	5	5.1	5.2	3.2	3.3	3.1
60	4.3	4.1	4.2	3.6	3.4	3.7	2.3	2.4	2.4

The Table 3 represent the mean value of different samples at the one level of permeability of sand and pouring temperature and their total effect on the impact strength of the aluminum alloy.

Table: 3 Mean Impact Strength.

Permeability of Sand(Darcy	Pouring Temperature(^{0}C)			Mean Impact Strength (Joule/mm^2)
	700	800	900	
30	$(6^2+6.1^2+5.8^2)/3=$ 17.9	$(5^2+5.1^2+5.2^2)/3=$ 15.3	$(3.2^2+3.3^2+3.1^2)/3=$ 9.6	42.8
60	$(4.3^2+4.1^2+4.2^2)/3=$ 12.6	$(3.6^2+3.4^2+3.7^2)/3=$ 10.7	$(2.3^2+2.4^2+2.4^2)/3=$ 7.1	30.4
Mean Impact Strength (Joule/mm^2)	30.5	26	16.7	73.2

By using the table given above, the values of correction factor, variations are calculated.

Correction Factor = $(73.2)^2/ 18 = 5358.24/18 = 297.68$

Total Variation (V) = $(6)^2+(6.1)^2+(5.8)^2+(5)^2+(5.1)^2+(5.2)^2+(3.2)^2+(3.3)^2+(3.1)^2+(4.3)^2+(4.1)^2+(4.2)^2+(3.6)^2+(3.4)^2+(3.7)^2+(2.4)^2+(2.4)^2+(2.3)^2-297.68 = 323.6-297.68 = 25.92$

$V_R = (42.8)^2+(30.4)^2/ 9-297.68 = 306.22-297.68 = 8.542$

$V_C = (30.5)^2+(26)^2+(16.7)^2 / 6 - 297.68 = 930.25+678 = 16.51$

$V_E = 25.92-8.542-16.51 = 0.87$

Table 4 shows an analysis of variance (ANOVA) obtained by numerical computations. The values of mean squares are obtained by dividing the sum of squares of each of the source by the respective degree of freedom. The F- ratio provides the information that how well the factors describe the statistical variance and it is calculated by dividing the mean square of the factor to the mean square of the error.

Table: 4 ANOVA table

Source of variation	Variation	Degrees of Freedom	Mean Square	F- Ratio
Between the rows	8.542	1	8.54	19.63
Between columns	16.51	2	8.255	18.97
Residual Error	0.87	2	0.435	
Total	25.92	5		

At the 5% level, the F- distribution table (statistical table) values are:

$F_{0.05}$ at V (1,2) = 18.513 which is less than calculated F-ratio (19.63).

$F_{0.05}$ at V (2,2) = 19.00 which is more than the calculated F- ratio (18.97).

The table above shows that at 5% level of significance, the calculated value of F-ratio exceeds 18.513; therefore the null hypothesis is rejected and concludes that the permeability of sand has the significant effect on the impact strength of the aluminum cast alloy. This is in tandem with previous work by [9] who adopted the simplex method developed by Dantzig [10] to optimize the effect of sand casting process parameters on the mechanical properties of an aluminum alloy.

V. Conclusions

The research indicates that the selected process parameters have different affects on the impact strength of the aluminum alloy. At the 5% level of significance, the permeability of sand is the more significant factor which influences the impact strength of Al-Si alloy. This result can be applied in foundry shop if the numbers of casting defects are on the high side. In future, ANOVA can be applied to other casting parameters (mould temperature, runner size, pouring speed, etc.) to analyze the effect on other mechanical properties such as hardness, tensile strength.

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