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Research Article

Optimization of Process Parameters for the Ultimate Tensile Strength of Aluminium Alloy Sand Castings using Taguchi Method

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Abstract: An optimization technique for sand casting process parameters based on the Taguchi method is reported in this paper. While keeping some casting parameters constant, aluminium alloy castings were prepared by sand casting technique varying three different parameters, namely; the mould temperature, pouring temperature and runner size. Tensile tests were done for the resulted castings. The settings of parameters were determined by using the Taguchi experimental design method. The level of importance of the parameters on the ultimate tensile strength was determined using the analysis of variance (ANOVA). The optimum parameter combination was obtained by using the analysis of signal-to-noise (S/N) ratio. Analysis of the results show that 100oC mould temperature, 700oC pouring temperature, and 285mm2 runner size are the optimal values of the factors and offer the highest ultimate tensile strength of 87.92N/mm2. The pouring temperature was the most influential parameter on the ultimate tensile strength of the castings. 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.
Keywords: Taguchi method, optimization, sand casting, process parameters, ANOVA, signal-to-nose ratio.

INTRODUCTION

The wide range of the application of aluminium alloys is very obvious. Their desirable characteristics of light weight, excellent resistance to corrosion in the atmosphere and water, high-strength-weight ratio [1] and high thermal conductivity gives them an edge over other metals in the electrical, aviation, marine, aerospace, construction and automotive industries just to mention a few [2]. This increased usage creates the need for a deeper understanding of their mechanical behaviour and the influences of processing parameters, [3, 4]. This knowledge enables the designer to ensure that the casting will achieve the desired properties for its intended applications [5, 6].

There is no doubt that casting as a process involves so many parameters [7, 8, 9] such as melting temperature of the charge, temperature of the mould, pouring speed, pouring temperature, composition, microstructure, size of casting, runner size, composition of the alloy and solidification time etc. Some researchers have successfully carried out studies on the varying effects of casting process parameters on the mechanical properties of casted metals and their alloys [7-12].

One of the recent most important optimization processes is the Taguchi method [13] conceived and developed by Japanese scholar Engr. Dr. Genichi Taguchi in 1950. Taguchi technique is a powerful tool for the design of high quality systems [14, 15]. It provides a simple efficient and systematic approach to optimize design for performance, quality and cost. The methodology is valuable when design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristic through the setting of design parameters and reduce the sensitivity of the system performance to source of variation [16, 17]. The Taguchi approach enables a comprehensive understanding of the individual and combines parameters from a minimum number of simulation trials. This technique is multi - step process which follow a certain sequence for the experiments to yield an improved understanding of product or process performance [18].

The objective of this study is to determine the optimal settings of sand casting process parameters using Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal levels and to analyze the effect of the casting process parameters on ultimate tensile strength values.

EXPERIMENTAL DESIGN

A standard Taguchi L_9 Orthogonal Array (OA) is chosen for this study as it can operate three parameters, each at three levels as presented in table 2. This format is chosen from a preliminary works [10, 19, 20] by the authors which identified three parameters, namely; the mould temperature, pouring temperature and runner size as important casting process variables which affect the ultimate tensile strength. Sufficient details of the effect of different parameter values on experimental results can be obtained by choosing three levels for each parameter to investigate. The criteria used for choosing the three parameter levels are to explore a maximum range of experimental variables. In addition, it is unnecessary to have uniformly spaced levels because of the counterbalance property of the Orthogonal Array [21]. Previous work by [11] has shown that the optimum pouring temperature range is 700 - 750 ^oC, so for this study the speed level range is 700 - 750^oC. The three levels for mould temperature parameter and runner size parameter are selected also according to literature reviews and previous casting experiences.

Taguchi methods which combine the experiment design theory and the quality loss function concept have been used in developing robust designs of products and processes and in solving some taxing problems of manufacturing [22]. The degrees of freedom for three parameters in each of three levels were calculated as follows [14].

In this study, nine experiments were conducted at different parameters. Taguchi L_9 orthogonal array was used, which has nine rows corresponding to the number of tests, with three columns at three levels. L_9 OA has eight DOF, in which 6 were assigned to three factors (each one 2 DOF) and 2 DOF was assigned to the error. For the purpose of observing the degree of influence of the process parameters, three factors, each at three levels, are taken into account, as shown in Tables 3. The ultimate tensile strength (UTS) values corresponding to each experiment were shown in Table 4. The casting setup is shown as figure 1.

REGRESSION ANALYSIS

The mould temperature, pouring temperature and runner size were considered in the development of mathematical models for the ultimate tensile strength. The correlation between the three factors and ultimate tensile strength on the aluminium alloy castings were obtained by multiple linear regressions (using mould temperature, pouring temperature and runner size as predictors). The standard commercial statistical software package MINITAB was used to derive the model of the form:

$$\mathrm{UTS} = 193 - 0.180\mathrm{MT} - 0.178\mathrm{PT} + 0.112\mathrm{RS} \quad (1)$$

ANALYSIS OF THE S/N RATIO

Taguchi method uses the (signal – to – noise (S/N) ratio, because it minimizes quality characteristic variation due to uncontrollable parameter. The ultimate tensile strength is the objective function so that "the larger-the-better" S/N ratio is chosen. The S/N ratio used for this type of response is given by [14]. The S/N ratio for the larger-the-better is:

$$\mathrm{S/N_{LTB}} = -10\log[\mathrm{MSD}] \quad (2)$$

$$\mathrm{MSD} = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i^2}\right)\right] \quad (3)$$

Where n is the number of measurements in a trial/row, in this case, n = 1 and y is the measured value in a run/row. The S/N ratio values are calculated by taking into consideration Eqn. 2.

The UTS values measured from the experiments and their corresponding S/N ratio values are listed in Table 5. The UTS response table for the mould temperature, pouring temperature and runner size was created in the integrated manner and the results are given in Table 6. Regardless of the category of the performance characteristics, a greater S/N value corresponds to a better performance. Therefore, the optimal level of the casting process parameters is the level with the greatest S/N value. Based on the analysis of the S/N ratio, the optimal UTS was obtained at 100^oC mould temperature (level 1), 700^oC pouring temperature (level 1) and 285mm^2 runner size (level 3). The varying effects of process parameters on the UTS values are shown in Figure 2. The UTS decreases with increase in mould temperature (above 100^oC) and pouring temperature (above 700^oC). An increase in runner size however produced increase in the UTS.

ANALYSIS OF VARIANCE (ANOVA)

Analysis of Variance (ANOVA) is a computational technique to quantitatively estimate the relative contribution, which each controlled parameter makes to the overall measured response and expressing it as a percentage. ANOVA uses the S/N ratio responses for calculations. The basic idea of ANOVA is that the total sum of squares of the standard deviation is equal to the sum of squares of the standard deviation caused by each parameter. The total sum of squared deviations SS_T from the total mean S/N ratio η_m can be calculated as [23]:

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \quad (4)$$

Where n is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the *i*th experiment. Other parameters employed are defined below:

$$P = \frac{SS_d}{SS_T} \quad (5)$$

$$DOF = L - 1 \quad (6)$$

$$V_{factor} = \frac{SS_{factor}}{DOF} \quad (7)$$

$$F_{factor} = \frac{V_{factor}}{V_{error}} \quad (8)$$

An F test, named after Fisher [16] is used to determine design parameters which have a significant effect on the quality characteristic. In the analysis, the F-ratio is a ratio of the mean square error to the residual error, and is traditionally used to determine the significance of a factor. Percent (%) is defined as the significance rate of the process parameters on the UTS. The percent numbers depict that the mould temperature, pouring temperature and runner size have significant effects on the UTS. It can also be observed from Table 7 that the pouring temperature, mould temperature, and runner size affect the UTS by 40.40%, 27% and 22.73% respectively.

Table 1: Chemical composition of aluminium alloy

Element	Al	Fe	Si
Weight Percentage (W %)	97.2	0.7	2.1
Concentration(mgl)	972	7	21

Table 2: Taguchi L_9 Orthogonal Array for Ultimate Tensile Strength

Expt No	Mould Tempt (^oC)	Pouring Tempt (^oC)	Runner Size (mm^2)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3: Process Parameters and Their Values at 3 Levels

Process Parameters	LEVELS		
	L1	L2	L3
Mould Tempt (^oC)	100	150	170
Pouring Tempt (^oC)	700	720	750
Runner Size (mm^2)	180	200	285

Table 4: Standard L_9 Array for Ultimate Tensile Strength

Expt No	Mould Tempt (^oC)	Pouring Tempt (^oC)	Runner Size (mm^2)	UTS (N/mm^2)
1	100	700	180	70.20
2	100	720	200	69.40
3	100	750	285	73.42
4	150	700	200	63.80
5	150	720	285	69.76
6	150	750	180	52.66
7	170	700	285	69.72
8	170	720	180	54.40
9	170	750	200	51.30

Table 5: UTS Values and S/N Ratio Values for Experiments

Expt No	UTS (N/mm^2)	S/N Ratio (dB)
1	70.20	36.93
2	69.40	36.83
3	73.42	37.32
4	63.80	39.09
5	69.76	36.87
6	52.66	34.43
7	69.72	36.88
8	54.40	34.71
9	51.30	34.20

Table 6: S/N Ratio Values for UTS by Factor Level

LEVEL	Mould Tempt (^oC)	Pouring Tempt (^oC)	Runner Size (mm^2)
1	37.03*	37.63*	35.36
2	36.80	36.14	36.71
3	35.26	35.32	37.02*
Delta	1.77	2.31	1.66
Rank	2	1	3

*Optimum Level

Table 7: ANOVA Results for Ultimate Tensile Strength of Aluminium Alloy Castings

Source of Variation	Degree of freedom (DOF)	Sum of squares (SS)	Variance (V)	F-ratio (F)	Percentage Contribution (P)
Mould Tempt (^oC)	2	5.56	2.78	2.82	27%
Pouring Tempt (^oC)	2	8.32	4.16	4.22	40.40%
Runner Size (mm^2)	2	4.68	2.34	2.38	22.73%
Error	2	1.97	0.99		9.87%
Total	8	20.59			100%

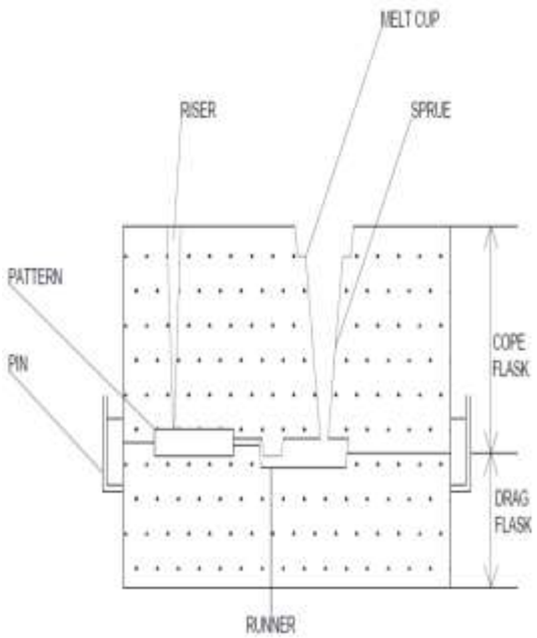

Fig.1: Experimental setup

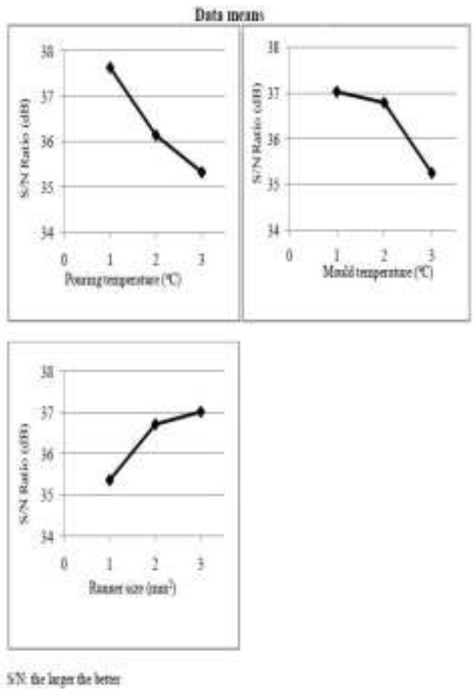

Fig. 2: Effect of process parameters on UTS

CONCLUSION

This study has discussed an application of the Taguchi method for investigating the effects of sand casting process parameters on the UTS value of aluminium alloy castings. From the analysis of the results using the conceptual signal-to-noise (S/N) ratio approach, regression analysis, analysis of variance (ANOVA), and Taguchi's optimization method, the following can be concluded from the present study:

i. Statistically designed experiments based on Taguchi method was performed using L_9 orthogonal array to analyze the ultimate tensile strength as response variable.
ii. From the results obtained, a Regression Model has been developed for ultimate tensile strength. From this equation we can predict the value of ultimate tensile strength if the values of mould temperature, pouring temperature and runner size are known.
iii. Within the experimental level ranges, the most significant influencing parameter is the pouring temperature, which accounts for 40.40% of the total effect, followed by the mould temperature (27%), and runner size (22.73%) respectively.
iv. The maximum ultimate tensile strength is calculated as 87.92N/mm^2 by Taguchi's optimization method.
v. The UTS decreases with increase in the mould temperature and pouring temperature. An increase in runner size however produced increased in UTS.

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