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Optimization of process parameters of Al-Si alloy by centrifugal casting technique using Taguchi design of experiments

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Abstract

In this paper, the influence of process parameters on the mechanical properties during centrifugal casting of aluminum alloy (4600) is studied. Taguchi method of design of experiments was employed to optimize the process parameters and to increase the mechanical properties. The investigation has indicated that increase in pouring temperature reduces mechanical properties while increase in die speed increases mechanical properties and density. Results were analyzed using ANOVA technique to know the percentage of contribution of each casting process parameters. Microstructures were studied under optical microscope and SEM were analyzed with process parameters by correlating with the mechanical properties of as cast structures.

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Keywords: *Centrifugal casting, Mechanical properties, microstructure.*

1. Introduction

Al-Si Alloys are extensively used for Marine 'on deck' castings, water-cooled manifolds and jackets, and intricate castings. The general use of these alloys is the corrosion resistance of marine atmospheres or service conditions, which are especially suitable for castings that are to be casted in defence, aerospace and automobile industries. As it exhibits excellent castability, good corrosion resistance with good mechanical properties these alloys are widely used (Daniel, 1968, Striter 1946).The use of Al casting alloys structural materials are determined by their physical properties and their mechanical properties.

These alloys are strongly influenced by their poly-phase microstructure. i.e., features such as morphologies of dendritic α-Al, Si-particles and either intermetalics that are present in microstructure (Chirita 2008).

To improve the mechanical properties of these alloys either grain refining is to be done by adding grain-refining elements or by using cast technology depending upon particular alloys. Each technology has particular aspects that interface a microstructure and consequently on mechanical properties.

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Traditionally, the centrifugal casting process was mainly used for obtaining cylindrical parts with axisymmetry. There are essentially two basic types of centrifugal casting machines: the horizontal types, which rotate about horizontal axis, and vertical types, which rotate about vertical axis. These are the casting process, which makes use of centrifugal force generated by rotating cylindrical mould to force the molten metal against the mould wall to form the desired shape (Cook, 1980).

However, the problems associated with these castings are unknown to the type of machine, the size of the tube and the type of alloy (Janco, 1988), but the quality of tubular parts obtained during centrifugal casting is strongly influenced by various process parameters like pouring temperature, Die-speed and pre-heat temperature of the mould.

The present investigation is focused on the optimization of process parameter during centrifugal casting of 4600 Al-Si alloy of IS 617:1975 by Taguchi method using Analysis of Variance(ANOVA) which is a statistical tool applied on the results. Taguchi approach is a standardized version of design of experiments (DOE), where systematic approach of design and analysis of the experiments for the improving the quality characteristics is done (Ller, 1988, Ross, 1996). ANOVA was used for analyzing the results of designed experiments.

2. Experimental procedure

2.1 Casting Process

In horizontal centrifugal casting machine, the centrifugal force is generated by a rotating cylindrical mould to throw the metal against the mould wall and form the tubular shape. Here the casting mould is a heat resisting cast iron drum with an inner diameter of 100 mm and a length of 235 mm with mould wall thickness of 28 mm whose cast tubular part. Pro-E 3D model of the horizontal casting machine is shown in Fig 1.

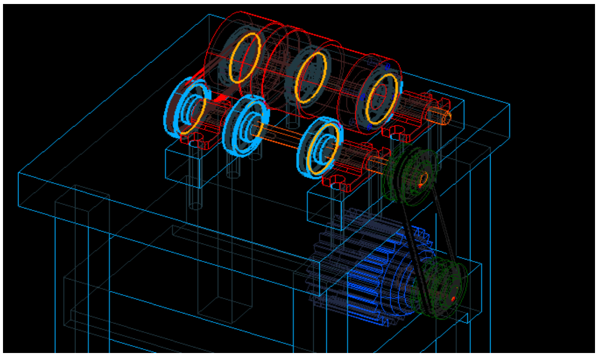

Fig 1: Pro-E 3D Model of Centrifugal Casting Machine

The opening end of the mould was exposed to receive the pouring melt and the closed end was coaxially connected to the shaft of a speed variable motor outside the box. The different types of coatings, which are applied inside the mould, are spirit based graphite coating and water based zirconium silicate coating for good surface finish and easy withdrawal of the casting.

Two different speeds of rotation at 900 and 1440 rpm are been used and recorded with the help of a tachometer placed in front of the drum. The front end of the machine is fixed with a ring cover so that the molten metal is being prevented from splashing. The alloy was prepared in a pit type furnace from commercially pure Al, Si, Mg and Mn. The nominal composition of the alloy is tabulated in table 1.

Table 1 the nominal chemical compositions of aluminium alloys

Alloy	**Cu**	**Si**	**Mg**	**Fe**	**Mn**	**Ni**	**Zn**
4600	0.1 Max	10.0 -13.0	0.1 Max	0.6 Max	0.5 Max	0.1 Max	0.1 Max

The melt composition was checked by an Atomic Emission Spectrometer to ensure that it would fall within the nominal composition range of these alloys. After degassing and slag cleaning, the melt was taken from the crucible and it is poured in the laddle. During process Al-Ti-B grain refiners were added in the crucible to yield the finest grain structure, now the melt was poured into mould as fast as possible with the pouring temperatures of the melt during the process were considered at 720^{o}C and 780^{o}C. Meanwhile the rotational speed of the machine was increased to attain the required rpm and approximately, after three minutes, the motor was switched off and the cylindrical cast ring was pulled out with the help of tongs. The thickness of the cast rings was controlled to be approximately 28 mm by taking a suitable volume of the melt.

3. Material

The material used was an Al-Si alloy (4600) of IS:617:1975 with following composition: Si-10.0-13.0%, Mg-0.1%, Fe-0.6%, Mn-0.5%, Cu-0.1%, Ni-0.1%, Zn-0.1% which is resistance to both hot cracking and solidification shrinkage. Successful production of high-quality castings requires close control of alloy composition, grain refining, and melt temperature, fluxing, and heat-treating practices [9].

4. Scheme of investigation

Taguchi technique derived for process optimization and identification of optimal combination for maximizing the quality following steps have been involved.

1. Identification of the response functions and their quality characteristics
2. Identification of process parameters
3. Fixing the corresponding level of upper and lower limits for parameters and possible Interactions between them.
4. Selecting the appropriate orthogonal array
5. Conduct the experiments as per the selected orthogonal array.
6. Record the quality characteristics (i.e., mechanical properties)
7. Analysis of the results and selecting the optimum process parameters through ANOVA
8. Confirmation test.

4.1 Identification of process parameters

Process parameter identified for experimental investigations are pouring temperature (A), die-speed (B), pre heat temperature of the mould (C) and thermal conductivity of coating (D) with two levels of experimentation are been considered.

4.2 Design of experiments

The present experiments were designed to apply the Taguchi's methods to establish the effects of four casting parameters on the mechanical properties of aluminum alloy during casting. The common principle of the Taguchi method is to develop an understanding of the individual and combined effects of a variety of design parameters from a minimum number of experiments. Taguchi method uses a generic signal-to-noise (S/N) ratio to quantify the present variation. There are several S/N ratios available depending on the type of characteristics, including "lower is better " (LB), "nominal is best" (NB), and "higher is better" (HB). The **S**/N ratio for the HB characteristics is related to the present study, which is given by

$$\frac{S}{N} = -10\log\left(\frac{i}{n}\sum_{i=i}^{N} Y^2\right)$$

Where n is the number of repetition in a trial under the same design conditions, y_i represents the measured value and subscript i indicates the number of design parameters in the orthogonal array (OA). In the Taguchi method, design parameters (factor) considered significant if its influence is large compared to the experimental error as estimated by the analysis of variance (ANOVA) statistical method given by Eqs. Shown below if this is the case, the design parameter is a critical factor in determining the optimal solution to the design problem.

$SS_r = [\sum^{N}_{i=1}(S/N)i^2] - T^2/N^2$

$SS_A = [\sum^{N}_{i=1}(S/N)i^2] - T^2/N^2$

Where, ss_t is the sum of squares due to total variation, N is the total number of experiments, ss_a represents the sum of squares due to factor A, K_a is number of levels for factor A. A_i stands for the sum of the total i_{th} level of factor A . T is the sum of total (S/N) ratio of the experiments, v_{total} is the degrees of freedom, V_{factor} is the variance of the factor, SS_{factor} represents the sum of squares of the factor and F_{factor} is the F ratio of the factor (Omer, 2007).

4.3 Selection of Orthogonal array

By applying Taguchi method of approach four two-level process parameters i.e., pouring temperature (A), die-speed (B), pre heat temperature of the mould (C) and thermal conductivity of coating (D) are being considered and the values of the casting process parameters at different levels are shown in Table 2.

Table 2 Variables and their Levels

Factor	**LEVEL1**	**LEVEL2**
POURING TEMPERATURE (ºC) (A)	720°C	780°C
DIE SPEED (RPM) (B)	900 RPM	1440 RPM
PRE HEAT TEMP. OF THE MOULD (ºC) (C)	100°C	200°C
K of COATING (W/mK) (D)	0.7 (ZIRCONIA)	1.3 (GRAPHITE)

The interaction effects between the casting process parameters have also been considered [i.e., pouring temperature x die-speed (AxB), pouring temperature x thermal conductivity (AxC) of coating and die-speed x thermal conductivity of coating (BxD)]. The main effects and suspected interactions are shown in Table 3.

Table 3 Main Effects and Suspected Interactions

Exp. No.	Pouring Tempe-rature (°C)	Die Speed (RPM)	PT X DS	Pre Heat Temp of Mould (°C)	PT X K of Coating	DS X K of coating	Thermal conductivity of coating (W/mK)
1	720	900	1	100	1	1	0.7
2	720	900	1	200	2	2	1.3
3	720	1440	2	100	1	2	1.3
4	720	1440	2	200	2	1	0.7
5	780	900	2	100	2	1	1.3
	780	900	2	200	1	2	0.7
7	780	1440	1	100	2	2	0.7
8	780	1440	1	200	1	1	1.3

The total degrees of freedom for all process parameters and their interactions were found to be seven. Hence, an orthogonal array with seven degrees of freedom was chosen. The experimental lay out for casting process parameters using the L_8 (2^7) orthogonal array is shown in Table 4.

Table 4 Experimental Lay Out (L8 (2^7)) Orthogonal array

Exp.No.	A	B	A*B	C	A*C	B*C	D
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Eight sets of experiments were conducted with two repetitions as per the experimental layout where, by changing the process parameters for four characteristics namely ultimate tensile strength, percentage of elongation and hardness are evaluated. The experimental results of the mechanical properties and results of ANOVA with their respective mechanical properties are tabulated from Table 5-10.

Table 5 Experimental Results of 4600 Alloy for the Ultimate Tensile Strength (UTS)

Exp. No.	Response 1	Response 2	S/N ratio
1	187	190	45.50
2	183	185	45.29
3	191	191	45.64
4	188	190	45.52
5	182	185	45.27
6	180	181	45.14
7	183	183	45.26
8	182	181	45.19

Table 6 Results of the ANOVA for the Ultimate tensile strength of 4600 Alloy

Symbol	Degree of freedom	Sum of Square	Mean Square	F – ratio	% of contribution
A	1	0.34803	0.34803	8.74666E+11	69.06
B	1	0.057581	0.057581	1.44712E+11	11.42
A*B	1	0.006028	0.006028	15151298942	1.19
C	1	0.088062	0.088062	2.21316E+11	17.47
A*C	1	0.0001103	0.0001103	277342282.3	0.021
B*C	1	0.0013410	0.0013410	3370350	0.26
D	1	0.0027337	0.0027337	6870316	0.54
Error	9	0.00510694	1.13687E-13		6.32E-10
Total	**15**				**100**

Table 7 Experimental Results of 4600 Alloy for the Hardness (BHN)

Exp. No.	Response 1	Response 2	S/N ratio
1	57	57	35.11
2	57	56	35.10
3	58	59	35.34
4	58	58	35.31
5	55	55	34.84
6	55	55	34.84
7	56	57	35.03
8	55	55	34.90

Table 8 : Anova for BHN

Symbol	Degree of freedom	Sum of Square	Mean Square	F - ratio	% of contribution
A	1	0.1926	0.1926	4.23726E+11	72.52
B	1	0.0583	0.0583	1.28338E+11	21.96
A*B	1	0.00440	0.00440	96827758	1.65
C	1	0.00422	0.00422	92826758	1.58
A*C	1	0.00112	0.00112	24757469	0.42
B*C	1	0.00293	0.00293	6449983	1.10
D	1	0.00196	0.00196	4328551	0.74
Error	9	3.63798E-12	4.54747E-13		1.37E-09
Total	**15**				**100**

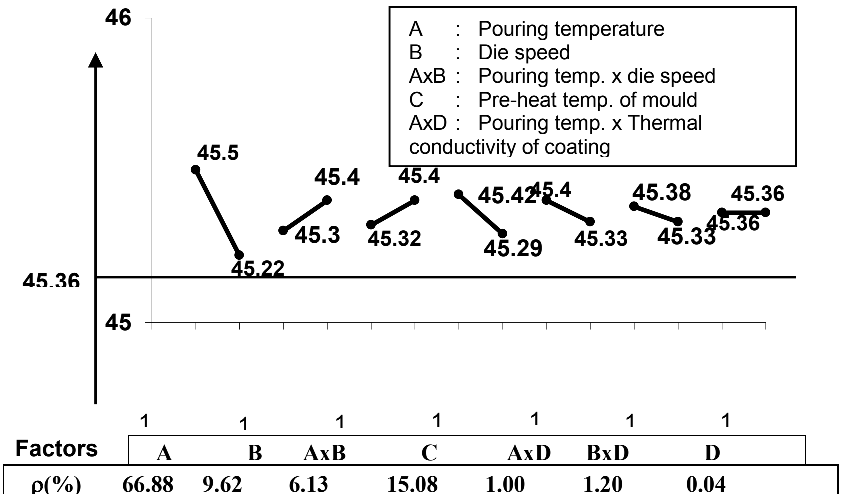

Fig 2: Percent contribution on UTS

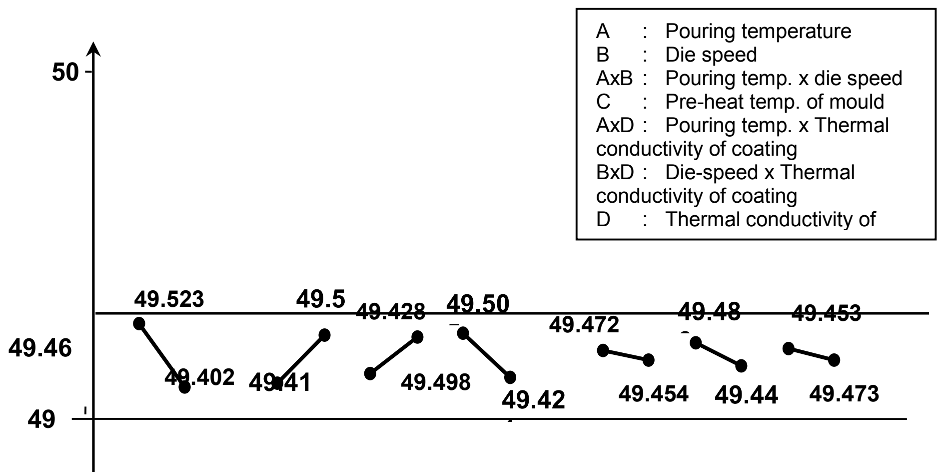

Fig 3: Percent contribution on hardness

Graphical representation of S/N ratio and percent contribution of parameters and their interactions of responses of centrifugally casting of 4600 aluminium alloy (a) UTS, (b) hardness

4.4 ANOVA (Analysis of Variance)

- To determine those process parameters which significantly affect the mechanical properties.
- F-Test is carried out to determine the factors, which significantly affect the properties.
- Signal to noise ratio (S/N ratio) analysis.
- The larger S/N ratio is better.
- Confirmation test was carried out to verify the optimum process parameters arrived throughout the experiments.

4.5 Confirmation Test

The final stage is to predict and verify the mechanical properties. The predicted S/N ratio using the optimal level of the process parameters was calculated shows the comparison of the experimental results using the initial and optimal casting process parameters, from which it can be seen that the mechanical properties was improved from this study.

5. Results and Discussions

The statistical treatments were applied to the results. Results of ANOVA tests indicate that the pouring temperature, die-speed and pre- heat temperature of the mould were significant. The percentage contribution for these casting process parameters are based on the S/N ratio results where larger the S/N ratio it was found as better and the casting process parameters with pouring temperature at level 1, Die speed at level 2, preheat temperature of mould at level 1 were found to be significant.

All the cast samples obtained during Centrifugal Casting were cut to the required dimensions. In addition, the pieces were polished form rough to fine finish with the help of Swiss emery papers of grades 1/0, 2/0, 3/0 & 4/0. Diamond paste was applied on the specimen for mirror image during disc polishing. All the specimens were etched using Keller's etchant and rinsed with water. All specimens were examined under optical microscope (Leica), UK and the structures were taken through image analyzer from inner layer to outer layer and scanning electron microscope (SEM), Leica 440i UK.

5.1 Influence of process parameters on mechanical properties and microstructures

5.1.1 Influence of pouring temperature:

During experimentation, it was founded that pouring temperature has significant affect on all the mechanical properties and lower pouring temperature of 720^{o}C was recommended for higher mechanical properties.

By Increasing the pouring temperature, results in increasing the fluidity, as rising the pouring temperature it elongates the time of solidification and results in columnar structure i.e., there is a grain-coarsening effect, which reduces the ultimate tensile strength.

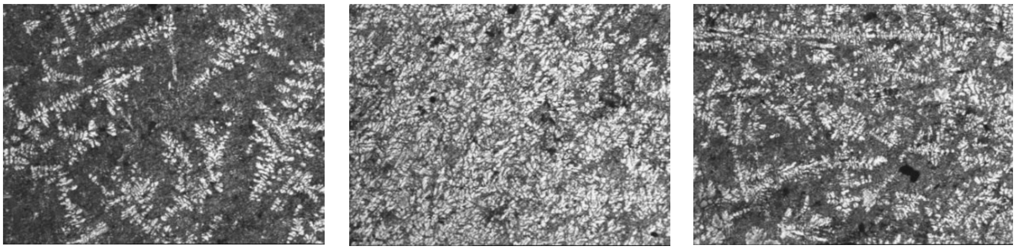

Fig: 4 a, b & c reveals the microstructures of inner, middle and outer layer at 1440 rpm and at 720ºC at 100 ºC

0 X. It shows α Al dendrites and silicon particles without adding grain refiner

At 720^{o}C the microstructure at the inner layer subcutaneous and outer layer was observed as shown in the figure, and it was observed that the structure at the inner layer has dense grey particles of Si when compared to @-Al dendrites. At subcutaneous layer and outer layer @-Al dendrites are more and are coarser when compared to inner layer as shown in Fig 4 During SEM analysis, as shown in Fig 5 it was found that the structure consists of an interdendritic network of Si phase (grey) with @-Al and Si precipitates in the matrix. These precipitates observed were may be due to the addition of grain refiner Al-5Ti-1B which led to fine grain structure. Because of low pouring temperature and less rpm the grain size was found to be somewhat coarser.

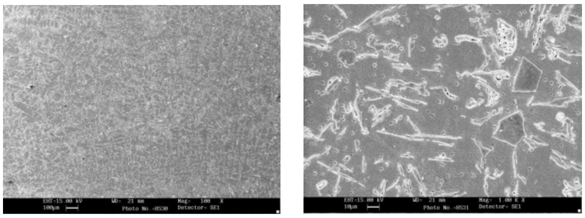

Fig: 5, Scanning Electron Micro (SEM) graph reveals the structures at 1440 rpm and at 720ºC at 100 X, and 1000 X. It shows α Al dendrites and silicon particles. It shows 3-D nature of lamellar plates and faceted morphology of modified structure.

6. Conclusions

A detailed investigation carried out on the selection of optimizing mechanical properties of 4600 alloy by centrifugal casting using Taguchi method has resulted in the combination of process parameters yielding highest mechanical properties. The effects of various process parameters and their interactions on mechanical properties have been determined. The theoretical explanation on the behavior of this alloy and the various processing conditions has been done.

The conclusions arrived at are:

1) Decrease in pouring temperature leads to increases in all the mechanical properties due to fine grains in matrix formed during the process.
2) Increase in Die-speed increases ultimate tensile strength due to the effect of centrifugal force acting on the metal.
3) Thermal conductivity of coating does not have any significant effect on the mechanical properties.
4) The interaction effect of pouring temperature and die-speed has less significant effect.
5) The microstructural analysis of the tubular parts made with the above process parameters indicates finer grains at the inner periphery and the particles of silicon are smaller and less angular for 4600 alloy. The grains are finer at the inner layer because, the aluminum density is higher than the density of silicon, aluminum moves towards the mould external wall due to a higher centrifugal force. For 4600 alloy the structure shows Al dendrites and silicon particles. The eutectic has found a lacy network and rosettes of si phase grey.

Analysis of microstructure indicates that aluminum concentration is more at outer periphery location for all the aluminum alloys considered. This could be due to the combined effect of density variations of aluminum and magnesium along with the centrifugal force being applied on the liquid metal.

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