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Full Length Research Paper

Experimental investigation on centrifugal casting of 5500 alloy: A Taguchi approach

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Design of experiments has been used, to study the influence of process parameters on the mechanical properties during centrifugal casting of aluminum alloy (5500). Taguchi method of design of experiments was employed to optimize the process parameters and to increase the mechanical properties such as UTS, elongation, BHN. 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 and were analyzed with process parameters by correlating with the mechanical properties of the aluminum alloy.

Key words: Centrifugal casting, 5500 alloy, Taguchi technique, ANOVA.

INTRODUCTION

Al-Mg Alloys are extensively used in defence, aerospace and automobile industries. As it exhibits excellent castability and good corrosion resistance with excellent mechanical properties, they are widely used in various industries (Daniel et al., 1968; Striter and Maenner, 1946). The use of Al-mg casting alloys structural materials are determined by their physical properties and their mechanical properties. These alloys are strongly influenced by their poly-phase microstructure, that is, features such as morphologies of dendritic α-Al, mg-particles and intermetalics that are present in microstructure (Chirita et al., 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 (ASM International, 1988).

Traditionally, the centrifugal casting process has been 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 et al., 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 (Nathan, 1988), but the quality of tubular parts obtained during centrifugal casting is strongly influenced by various process parameters like pouring temperature, die-speed, pre-heat temperature of the mould. The present investigation is focused on the optimization of process parameter during centrifugal casting of 5500 Al-Mg alloy of IS 617:1975 by Taguchi method using analysis of variance (ANOVA) which is a

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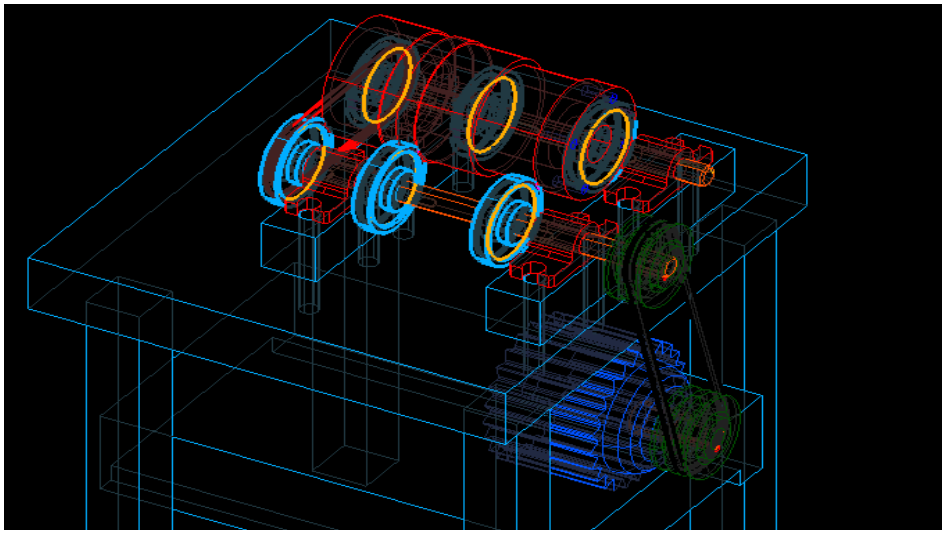

Figure 1. Horizontal centrifugal casting machine.

Figure 2. Horizontal centrifugal casting machine.

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.

EXPERIMENTAL PROCEDURE

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. The working Pro-E 3D model of the horizontal casting machine is shown in Figure 1. 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.

Two different speeds of rotation at 900 and 1440 rpm were 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. Figure 2 shows the horizontal centrifugal casting machine used for producing cast rings.

The alloy was prepared in a pit type furnace from commercially pure Al, Si, Mg and Mn. The nominal composition of the alloy is shown in Table 1. The melt composition was checked by an Atomic

Figure 3. Cross section of tubular parts.

Table 1. The nominal chemical compositions of aluminum alloys.

Alloy	Cu	Si	Mg	Fe	Mn	Ni	Zn
5500	0.1	0.25	9.5-11.0	0.3	1.1	0.1	0.1

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 is poured into mould as fast as possible with the pouring temperatures of the melt during the process were considered at 720 and 780°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 which were tubular in shape as shown in Figure 3.

Material

The material used was an Al-mg alloy (5500) of IS:617:1975 with following composition: Mg-9.5-11.0%, Fe-0.3%, Mn-1.1%, Cu-0.1%, Si-0.25%, N-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 (Jones and Pearson, 1976).

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 (that is, mechanical properties).
7. Analysis of the results and selecting the optimum process parameters through ANOVA.
8. Confirmation test.

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.

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 Equation 1:

$$\frac{S}{N} = -\mathbf{10}\log\left(\frac{i}{n}\sum_{i=i}^{N} Y^2\right) \quad (1)$$

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) is considered significant if its influence is large compared to the

Table 2. Variables and their levels.

Factor	Level 1	Level 2
Pouring temperature (°C) (A)	720	780
Die speed (rpm) (b)	900	1440
Pre heat temperature of the mould (°C) (c)	100	200
K of coating (W/mk) (D)	0.7 (Zirconia)	1.3 (Graphite)

Table 3. Main effects and suspected interactions.

Experimental No.	Pouring temperature (°C)	Die speed (RPM)	PT X DS	Pre heat temperature 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

experimental error as estimated by the analysis of variance (ANOVA) statistical method given by Equations 3 and 4. Shown below if this is the case, the design parameter is a critical factor in determining the optimal solution to the design problem:

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

$$SS_A = [\sum^{N}_{i=1}(S/N)i^2] - T^2/N^2 \quad (3)$$

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 and Ramazan, 2007; Joseph et al., 2009).

Selection of orthogonal array

By applying Taguchi method of approach four two-level process parameters that is, 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. The interaction effects between the casting process parameters have also been considered (that is, 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. 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. Eight sets of experiments were conducted with two repetitions as per the experimental layout, whereby 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 to 10. F-Test was carried out to determine the factors, which significantly affect the properties. The comparison on the Graph with S/N ratio with process parameters on the mechanical properties is shown in Figure 4.

Confirmation test

In order to predict and verify the mechanical properties, conformation experiment was performed. The test condition for the conformation test was so chosen that they are within the range of the levels defined previously. The

Table 4. Experimental lay out (L8 (2^7)) Orthogonal array.

Experimental 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

Table 5. Experimental results of 5500 alloy for the ultimate tensile strength (UTS).

Experimental No.	Response 1	Response 2	S/N ratio
1	345	345.65	50.76
2	344	343.75	50.72
3	347.8	348	50.82
4	347.65	346.45	50.80
5	345.25	345.15	50.76
6	343.78	342.75	50.71
7	344	346.246	50.75
8	343.5	342	50.69

Table 6. Results of the ANOVA for the ultimate tensile strength (UTS) of 5500 alloy.

Symbol	Degree of freedom	Sum of square	Mean square	F - ratio	% of contribution
A	1	0.00483366	0.00483366	955394121.6	33.29
B	1	0.00208596	0.00208596	389044932.8	13.55
A*B	1	0.003179232	0.003179232	612447172.8	21.34
C	1	0.003466594	0.003466594	858678307.2	29.92
A*C	1	0.000323642	0.000323642	45467952	1.58
B*C	1	2.26222E-06	2.26222E-06	975948.8	0.03
D	1	8.61457E-05		7071422.4	0.24
Error	9	3.63798E-12	4.54747E-13		2.79E-07
Total	15				100

predicted value and the associated experimental value were compared and the percentage error was calculated. The error percentage is within permissible limits.

RESULTS AND DISCUSSION

Statistical treatments were applied to the results. Results of ANOVA tests indicated 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 the 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 and 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.

Table 7. Experimental results of 5500 Alloy for the percentage elongation.

Experimental No.	Response1	Response 2	S/N ratio
1	16	16.65	24.25
2	15	15.75	23.72
3	18.8	18.85	25.49
4	17.56	17.7	24.92
5	15.25	15.15	23.63
6	14.8	13.8	23.09
7	15	17.5	24.13
8	14.5	14	23.07

Table 8. Results of the ANOVA for the percentage elongation.

Symbol	Degree of freedom	Sum of square	Mean square	F - ratio	% of contribution
A	1	2.48674533	2.48674533	3.64561E+12	49.23
B	1	1.0685251	1.0685251	1.56647E+12	21.15
A*B	1	0.477461367	0.477461367	6.99966E+11	9.45
C	1	0.915802428	0.915802428	1.34258E+12	18.13
A*C	1	0.033847719	0.033847719	49621281013	0.67
B*C	1	0.040350044	0.040350044	5915379072	0.79
D	1	0.02822459	0.02822459	41377687048	0.55
Error	9	5.45697E-12	6.82121E-13		1.08E-10
Total	15				100

Table 9. Experimental results of 5500 Alloy for the Hardness (BHN).

Experimental No.	Response 1	Response 2	S/N ratio
1	91	92.75	39.26
2	90	91.5	39.15
3	92.75	93.7	39.39
4	92.5	93.25	39.35
5	89.2	89.45	39.01
6	89	88.5	38.96
7	90.5	92	39.20
8	89.5	91	39.10

Table 10. Results of the ANOVA for the BHN.

Symbol	Degree of freedom	Sum of square	Mean square	F - ratio	% of contribution
A	1	0.09512676	0.09512676	1.39457E+11	58.83
B	1	0.05418444	0.05418444	79435224563	33.51
A*B	1	2.54659E-09	2.54659E-09	3733.333333	1.57493E-06
C	1	0.010597639	0.010597639	15536302707	6.55
A*C	1	1.99587E-05	1.99587E-05	29259712	0.01
B*C	1	0.000149777	0.000149777	219575837	0.092
D	1	0.001617063	0.001617063	2370639533	1.00
Error	9	5.45697E-12	6.82121E-13		3.37E-09
Total	15				100

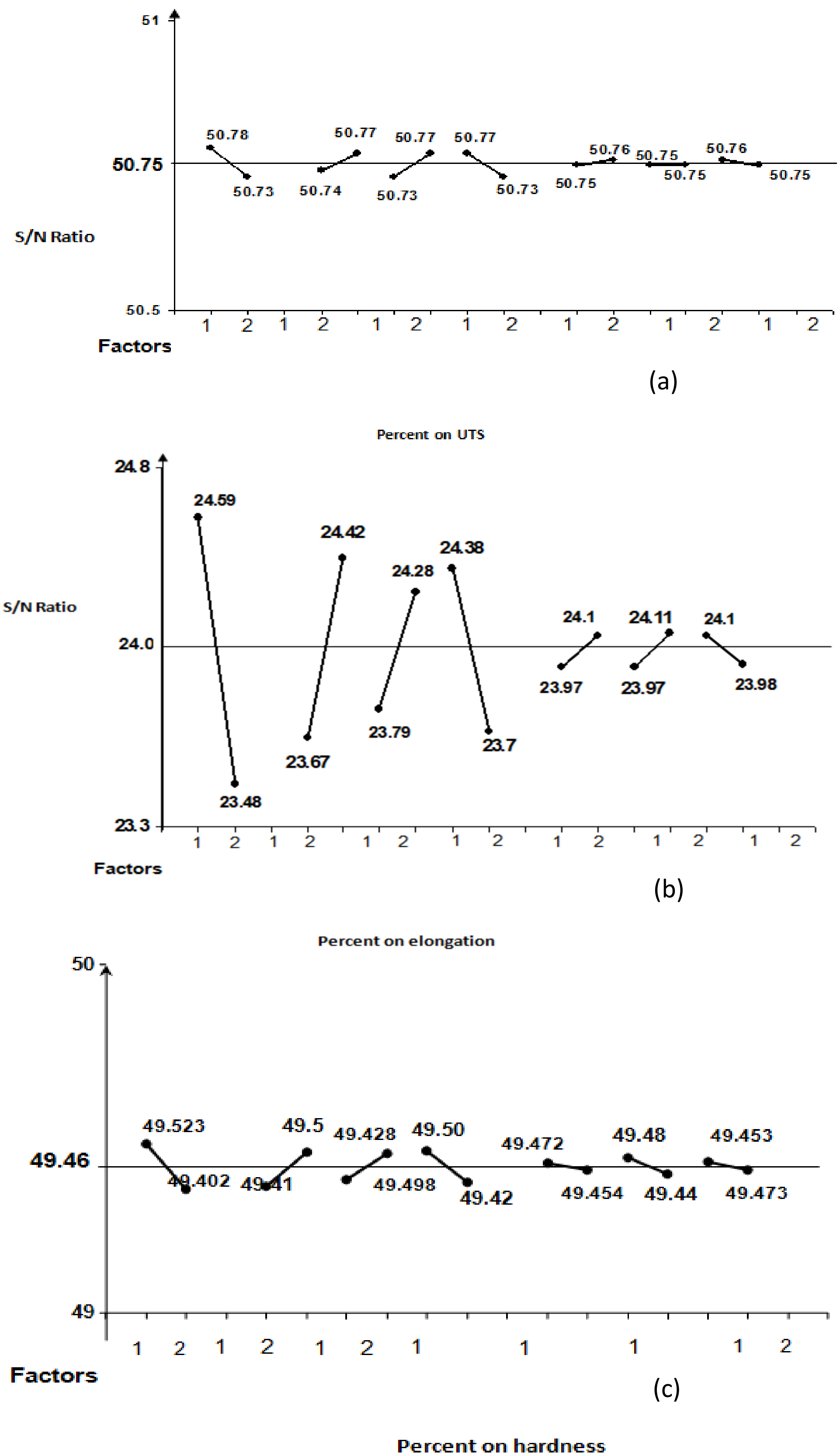

Figure 4. Graphical representation of S/N ratio and percent contribution of parameters and their interactions of responses of centrifugally casting of 5500 aluminum alloy per cent on (a) UTS (b) elongation (c) hardness.

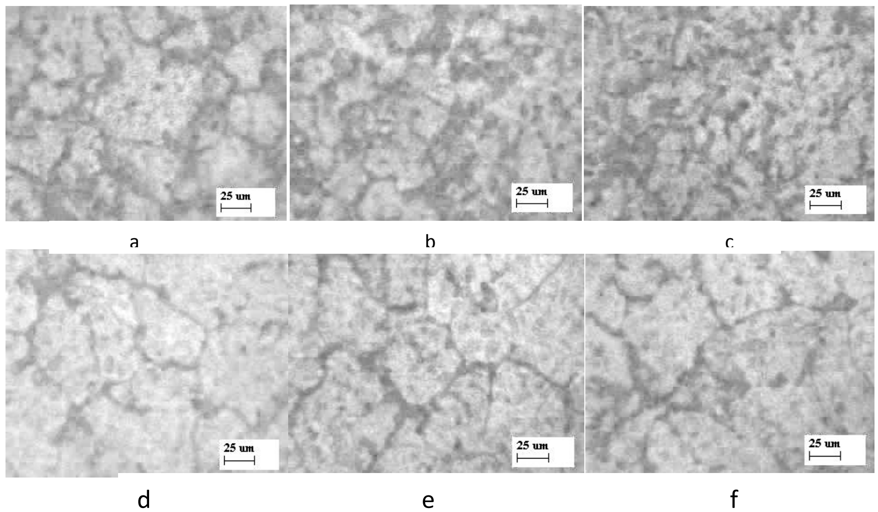

Figure 5. Microstructures of inner, middle and outer periphery at 900 rpm (a, b and c), and at 1440 rpm (d, e and f). The microstructure shows α Al dendrites and Mg particles are of different size.

Influence of process parameters on mechanical properties and microstructures

The mechanical properties such as UTS, elongation, BHN of the aluminum alloys drastically varies depending upon the each process parameters such as pouring temperature, die speed, pre heat temperature and thermal conductivity of coatings.

Influence of pouring temperature

During experimentation, it was founded that pouring temperature has significant effect on all the mechanical properties and lower pouring temperature of 720°C was recommended for higher mechanical properties. By Increasing the pouring temperature, results in increasing the fluidity.

At 780°C as there is rise in the pouring temperature there is increase in the time of solidification which results in columnar structure that is, there is a grain-coarsening effect, which reduces the ultimate tensile strength. The microstructure is shown in Figure 6d, e and f. This grain coarsening effect was also seen during SEM analysis as shown in Figure 9. At 720°C the microstructure at the inner layer subcutaneous and outer layer was observed as shown in Figure 6a, b and c, and it was observed that the structure at the inner layer has dense grey particles of Mg when compared to α-Al dendrites. At subcutaneous layer and outer layer α-Al dendrites are more and are coarser when compared to inner layer. During SEM analysis, as shown in Figures 7 and 8, it was found that the structure consists of an interdendritic network of Mg_2Al_3 phase (grey) with α-Al and Mg precipitates in the matrix. These precipitates observed were maybe due to the addition of grain refiner Al-5Ti-1B which led to fine grain structure.

Influence of die speed and position

A higher rotation of 1440 rpm is recommended for higher ultimate tensile strength. The increase would be due to a higher centrifugal force acting on the solidifying metal and resulting in equiaxed structure. Similarly, the hardness and density are also improved due to high speed. At 1440 rpm, the results showed that the addition of Al-5Ti-1B refines the coarser columnar α-Al dendrites to fine equiaxed α-Al dendrites and the eutectic Mg is also refined. Addition of grain refiners has affected the morphology of α-Al dendrites and eutectic Mg in addition to their individual effects.

Mg particles were observed to be modified into a rounded shape as shown in Figure 5d, e and f, and it was future quantified by SEM as shown in Figure 8. Higher rotation of 1440 rpm is recommended for higher ultimate tensile strength. The increase would be due to a higher centrifugal force acting on the solidifying metal and resulting in fine grain structure. Similarly, the hardness and density are also improved due to high speed.

It was observed that the structure at 900 rpm consists of an interdendritic network of Mg_2Al_3 phase (grey). From the figure, it is noted that the structure consists of α-Al, Al_3Fe, Al_8Mg_5 and Mg_2Si phases. It was observed that the α-Al dendrites at the inner periphery have equiaxed grains. At the subcutaneous and at the outer layer, the microstructures are similar to inner layer, but there is not that much variation in the percentages of Al solid solution and Mg particles as shown in Figure 5a, b and c. It was also seen during SEM analysis as shown in Figure 10

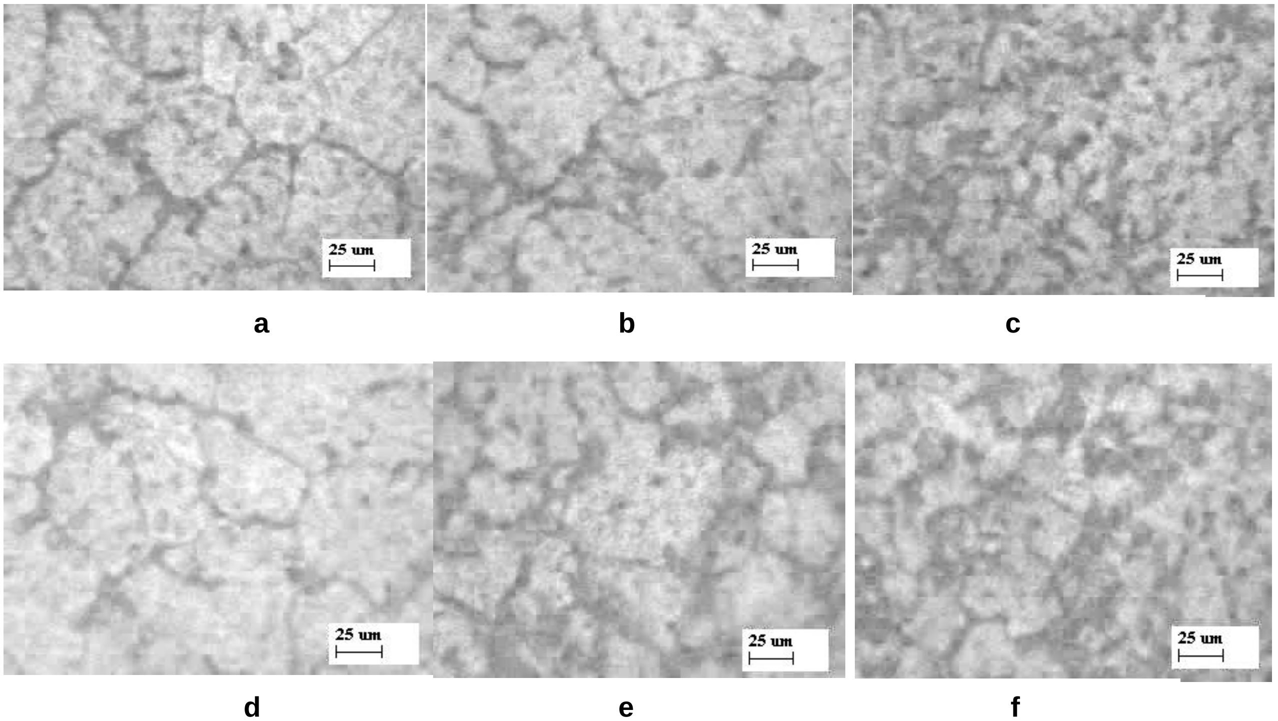

Figure 6. Microstructures of inner, middle and outer periphery at 720 (a, b and c), and 780°C (d, e and f). The microstructure shows α Al dendrites and Mg particles are of different size.

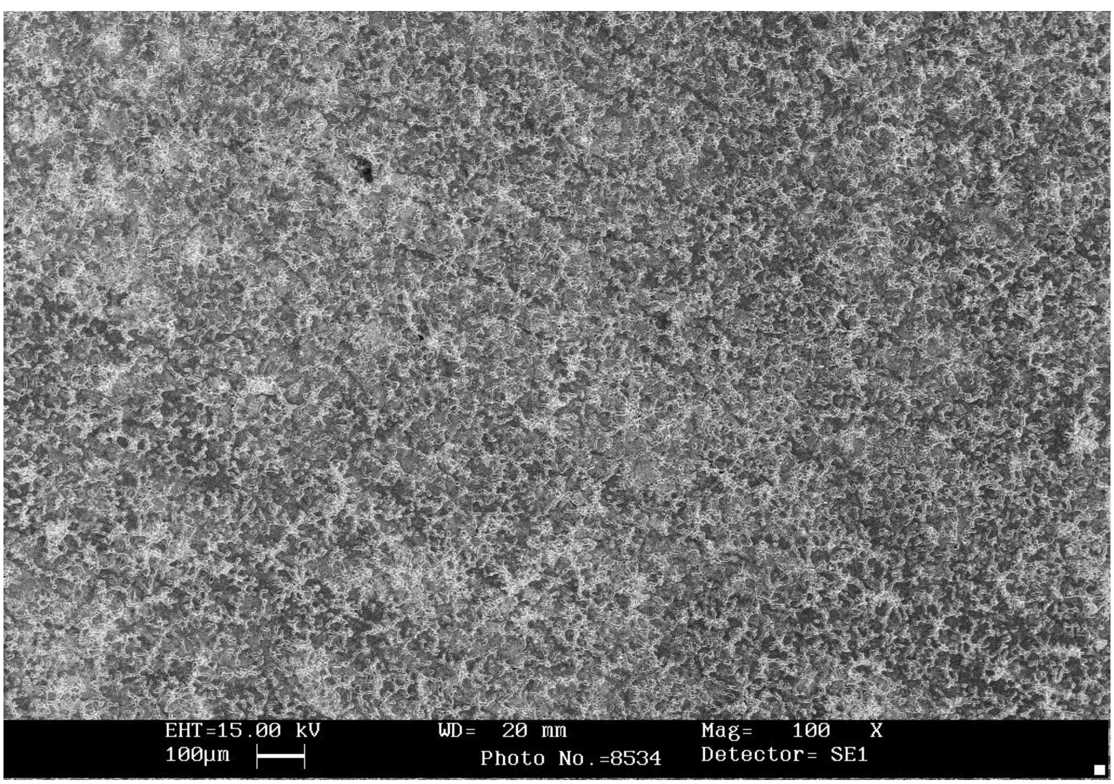

Figure 7. Scanning Electron Micro (SEM) graph reveals the structures at 1440 rpm and at 720°C at 100 X. It shows α Al dendrites and magnesium particles. It shows 3-D nature of lamellar plates and faceted morphology of modified structure.

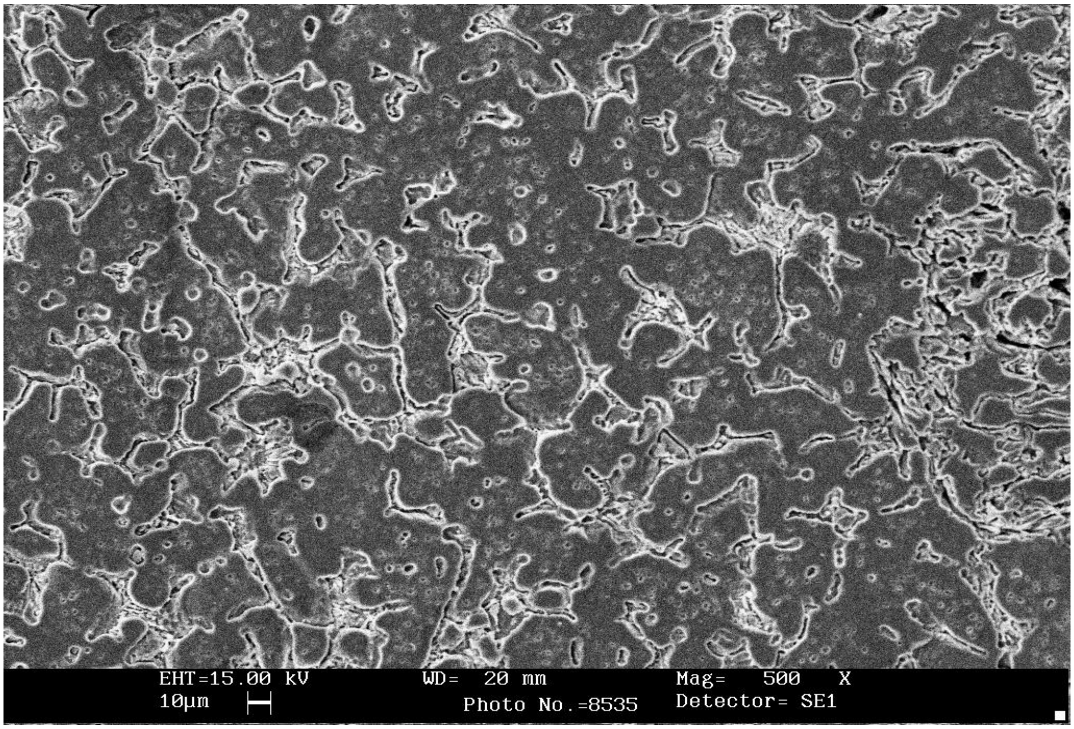

Figure 8. Scanning Electron Micro (SEM) graph reveals the structures at 1440 rpm and at 720°C at 500 X. It shows α Al dendrites and magnesium particles. It shows 3-D nature of lamellar plates and faceted morphology of modified structure.

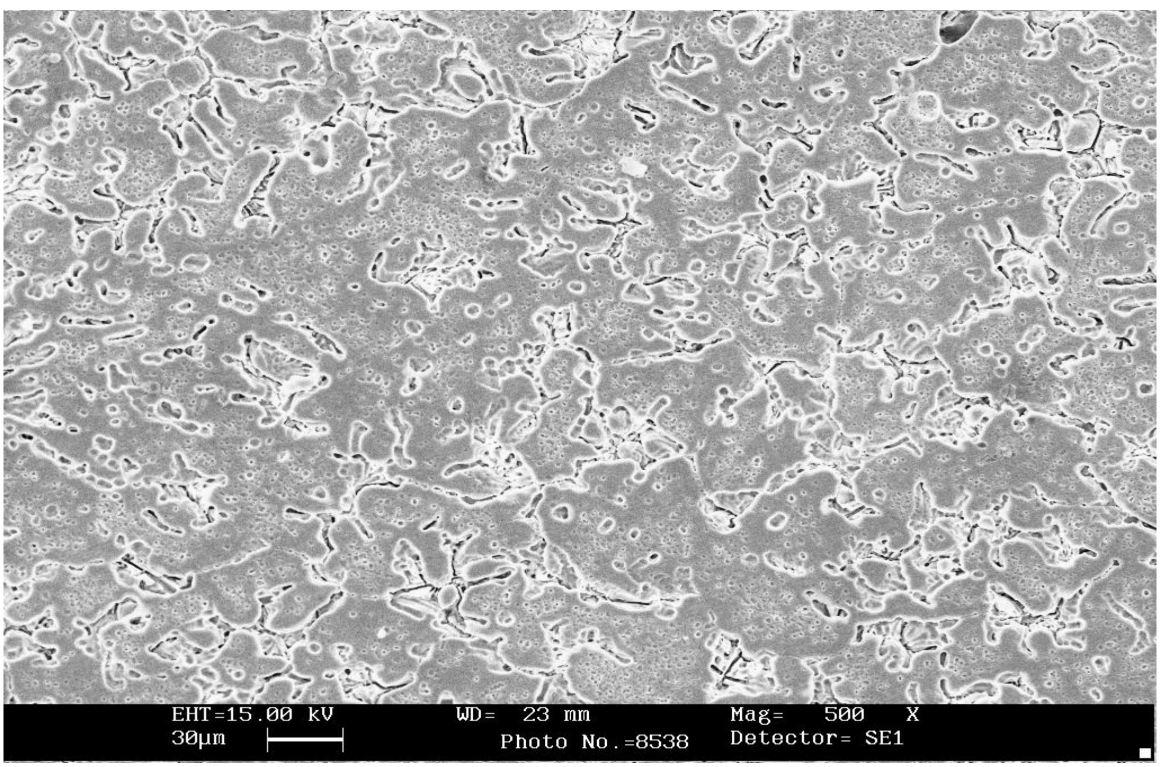

Figure 9. Scanning Electron Micro (SEM) graph reveals the structures at 900 rpm and at 780°C at 500 X. It shows α Al dendrites and magnesium particles. It shows 3-D nature of lamellar plates and faceted morphology of modified structure.

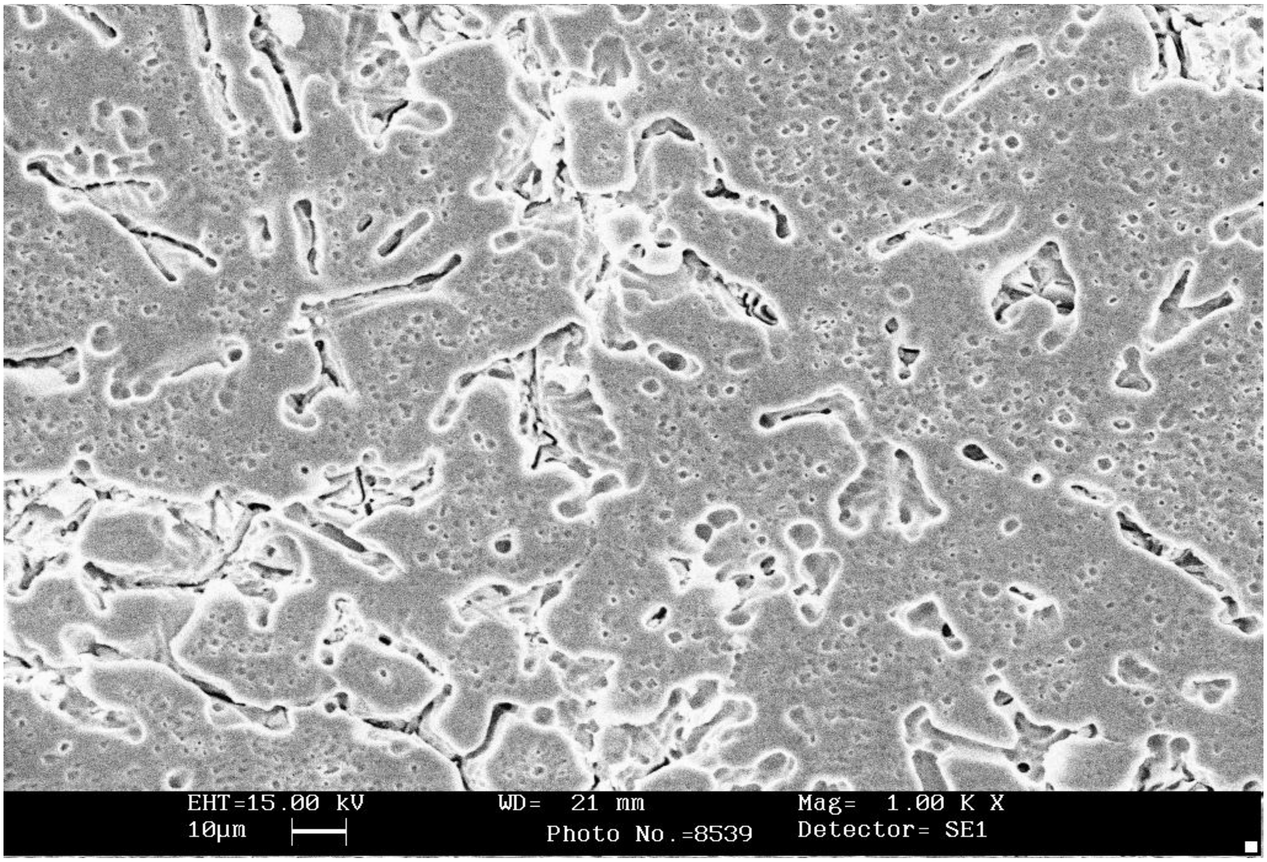

Figure 10. Scanning Electron Micro (SEM) graph reveals the structures at 900 rpm and at 780°C at 100 X. It shows α Al dendrites and magnesium particles. It shows 3-D nature of lamellar plates and faceted morphology of modified structure.

that there is 3-D nature of lamellar plates and faceted morphology of α-Al dendrites and Mg Particles.

Influence of preheat temperature of the mould

Pre heat temperature of the mould is not significant. This alloy acts as an aid for increasing the fluidity for all the properties considered.

Influence of thermal conductivity of coating

The thermal conductivity of various coatings considered did not have any significant effect. Similarly, percentage elongation was not affected by the factors considered.

Influence of interaction effects

The interaction effect between pouring temperature and die speed is not very significant on ultimate tensile strength and hardness of the material. Similarly, the interactions between pouring temperature and thermal conductivity of coating and die speed and thermal conductivity of coating have no significant effect.

Conclusions

A detailed investigation carried out on the selection of optimizing mechanical properties of 5500 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 and it was found as:

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.

The microstructural analysis of the tubular parts made with the above process parameters indicates finer grains at the inner periphery and the particles of magnesium are smaller and less angular for 5500 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 5500 alloy the structure shows α-Al dendrites and magnesium particles. The eutectic has found a lacy network and rosettes of Mg_2Al_3 grey phase.
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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