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Parametric Optimization for Improving Hardness of Squeeze Cast LM24 Casting Through Experimental Studies

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Keywords：LM24 aluminium alloy, squeeze casting, hollow castings, stirring speed, genetic algorithm

ABSTRACT

This experimental study focuses on processing of LM24 aluminium alloy for making castings through squeeze casting process. The primary objective was to analyse the influence of the process parameters namely stirring speed, melt temperature, squeeze load and die temperature on hardness of castings. Samples were cast for each experimental condition based on L9 orthogonal array. From ANOVA, it was observed that stirring speed and squeeze load were the process parameters making a noticeable improvement in hardness. A mathematical model representing the process was developed using nonlinear regression analysis with the help of MINITAB software. The optimum casting conditions were obtained through Taguchi method and MATLAB genetic algorithm and checked through the confirmation experiments. In this study, it was confirmed that the castings obtained for the optimum squeeze casting conditions exhibited nearly 25% improvement in hardness compared to the gravity die casting condition.

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INTRODUCTION

Alloys of light weight metals such as aluminium and magnesium are widely used in automobile, marine and aerospace fields due to their desirable properties such high strength, good fluidity and excellent corrosive resistance. These alloys would lead to low fuel consumption and better environmental benefits due to a decrease in pollution [1]. Particularly in automotive vehicles, utilization of aluminium alloy components has been increased in the recent years. Among various aluminium alloys, aluminium silicon (Al–Si) alloys are widely processed for producing automotive components due to their interesting properties such as low coefficient of thermal expansion, high heat transfer rate, high strength, desirable resistance to hot tear and wear behaviour [2]. However, their relatively low melting point and low hardness compared to other engineering alloys reduces their applications. Generally, die casting techniques exhibit several casting defects such as porosity, segregation, hot tears and cracks while processing Al-Si alloys for making intricate shaped parts. Squeeze casting is a novel casting technique capable of producing components of pore free, fine grain sized and improved mechanical properties [3].

Squeeze casting is an emerging metal forming process that has been widely employed for the production of light metal alloy components with near net shaping [4, 5]. The applied pressure during solidification of the melt activated multidirectional feeding mechanisms throughout die cavity and hindered the formation of porosities caused by both gas and shrinkage [6, 7]. The applied pressure led to grain refinement in microstructure of squeeze cast aluminium alloys such as AC8A, LM6, LM13 and A356 [8-12]. When processing AA7010 wrought aluminium alloy through squeeze casting, Yue [13] observed that high pouring temperature and high pressure were undesirable as they led to poor tensile property. Kim et al [14] reported that squeeze cast 7050 wrought aluminium alloy parts exhibited superior quality than gravity die cast parts. Many research people investigated the effects of various casting parameters on mechanical properties of squeeze cast aluminium alloys such as Al-Cu based alloy, Al-Zn-Mg-Cu alloy, Al-13.5%Si alloy, EN-AB46000, LM25, Al 2124, Al-7Si-0.7Mg and Al-7%wt Si [15-23] and reported that mechanical properties were improved with the application of squeeze pressure. The optimum squeeze casting condition exhibited a significant improvement in mechanical properties of aluminium alloys like LM24,AC2A, A2017, AlSi7Mg, etc [24-31]. Ghomashchi and Vikhrov [2] insisted that development in squeeze casting process was still required to produce complex shaped and thin-walled components.

From the literature, it was noted that squeeze casting process has been widely employed for processing Al-Si alloys in the production of solid castings and generally not employed in the production of thin walled (hollow) components. Squeeze casting is practicable for processing Al- Si alloys for castings by means of high-level pressure along with certain process parameter settings. An attempt was made in this direction for processing LM24 such an Al-Si alloy through squeeze casting. The chemical composition of LM24 as per Japanese specification (JIS) is given in Table 1. LM24 alloy is widely used for producing automotive components such as carburetor, cylinder, cylinder lid, absorber, engine gear box, side cover, gear box, crank case lid, upper lid and lower lid of gas adjuster, etc. This alloy is generally processed through gravity and low pressure die casting processes in aluminium foundries. LM24 alloy was processed for making hollow casting through squeeze casting process and optimization techniques like Taguchi method and genetic algorithm were employed for finding optimum parametric condition for improving hardness of the castings in this study.

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Table 1 Chemical composition of LM24

Element	Si	Cu	Fe	Ni	Mn	Mg	Sn	Zn	Al
JIS (wt%)	9.6-12	1.5-3.5	0.9 max	0.5 max	0.5 max	0.3 max	0.3 max	0.1 max	rest
Ingot (wt%)	11.82	2.35	0.81	0.04	0.18	0.17	0.1	0.05	85.5

EXPERIMENTS AND TEST

Squeeze Casting Experimental Setup

The experimental setup shown in Figure 1 consists of bottom pouring electric furnace, preheaters, split die set, punch and hydraulic circuit. The furnace capable of heating upto 1200°C was used to melt the metal at the desired temperature. A pathway with a preheater arrangement of 400°C capacity is inbuilt in this setup to maintain the fluidity of the molten metal during transferring from the furnace to the die cavity. A permanent split die set specially made of H13 die steel and core of mild steel were designed for making hollow cylindrical sample of 50 mm outer diameter and 200 mm height. A preheater of 500°C capacity with thermocouple arrangement was used to preheat the die which enables uniform heating.

The inner sides of the stainless-steel crucible and die cavity were coated with graphite suspension. LM24 ingots were charged into the crucible in the furnace and the required temperature was maintained. The molten metal was degassed fully using hexachloroethane tablets to remove the entrapped gases and other impurities present. The molten slurry was transferred from the bottom pouring furnace into the preheated die through the preheated pathway which connects the melting furnace with the die. A hydraulic press of 40-ton capacity was used to apply squeeze load on the molten metal by means of a punch which is an integral part of the hydraulic unit. Squeeze load was applied on the melt through the punch and maintained until solidification was completed. Punch was then moved up and the casting was separated from the die assembly.

Fig. 1 Experimental Setup

Fig. 2 Casting samples

Melt temperature of 575°C was required for effective filling of molten metal into the die cavity. When the melt temperature was raised to above 625°C, gases evolved from die coating were entrapped in the melt, leading to pin holes. With the aid of a four-blade stirrer, a satisfactory homogeneous distribution of particles through the matrix material was achieved. Throughout the experiment, the mechanical stirring speed of 400-600 rpm is maintained. The die assembly was designed to withstand maximum squeeze load of 40 ton. It was observed that there was an existence of micro pores in the castings made at squeeze load of 20 ton. The die temperature below 180°C resulted inpremature solidification of the castings and temperature above 220°C increased solidification time leading to loss in production and decreased life of the die assembly. Hence, the bounds for all these process parameters were set as follows.

Stirring speed, A (mm) : $400 \leq A \leq 600$
Melt temperature, B (°C) : $575 \leq B \leq 625$
Squeeze load, C (ton) : $20 \leq C \leq 40$
Die temperature, D (°C) : $180 \leq E \leq 220$

All process parameters were fixed at three levels within the above bounds to conduct experiments based on the $L_9(3)^4$ orthogonal array. The details of all parameters and their levels are given in Table 2. For each experimental condition, the casting samples were cast and are shown in Figure 2.

Table 2 Process parameters and their levels

Notation	Process Parameter	Level		
		1	2	3
A	Stirring speed (rpm)	4000	500	600
B	Melt Temperature (°C)	575	600	625
C	Squeeze Load (ton)	20	30	40
D	Die Temperature (°C)	180	200	220

Hardness Test

Hardness specimens were machined in the middle of casting samples cast under each experimental condition. The cut surfaces of specimen samples were ground and polished for performing Brinell hardness test. A 250 kg load was applied through a steel ball indentor of 5 mm diameter on the polished surface of specimen and Brinell hardness (BHN) values were measured in the four spots.

RESULTS AND DISCUSSION

Taguchi Method

S/N Ratio Response

Hardness was treated as an output response with the category of quality characteristics "larger-the-better". The impact strength was treated as an output response with the category of quality characteristics "larger-the-better". The S/N ratio for this response was estimated by using Equation (1) for each experimental condition and their values are given in Table 3.

$$S/N(dB) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{R_i^2}\right)$$

where i = 1,2,…, n (here n = 4) and R_i is the response value for an experimental condition. Mean value ($\bar{Y}$) of S/N ratios was also calculated using Equation (2) and is given in Table 3.

$$\text{Mean}, \bar{Y} = \frac{1}{N}\left(\sum_{j=1}^{N} Y_j\right)$$

where j = 1, 2… N (here N = 9) and Y_j is S/N ratio for j^{th} parametric setting.

In order to find optimum level of the process parameters, average S/N ratio response was estimated for every level of the parameters and the corresponding details are given in Table 4. Based on the highest value of S/N ratio, an optimum level for each parameter (A: 1st level; B: 2nd level; C: 3rd level; D: 2nd level) was noted. Thus, the optimum parametric setting $A_1B_2C_3D_2$ (stirring speed of 400 rpm, melt temperature 600°C, squeeze load of 40 ton and die temperature of 200°C) was obtained for the output response.

The response graph shown in Figure 3 described the variation of each process control parameter on the output response of the squeeze casting process. From the response graph, it was observed that parameters B and D showed lesser variations on the output response compared to other parameters. Therefore, analysis of variance (ANOVA) and F test were used to analyze the experimental data [33-36] for predicting the significant parameters influencing squeeze casting process in this study.

Table 3 Experimental observations and S/N ratio

EX. No	Experimental Condition	Hardness					S/N ratio (dB)
		R_1	R_2	R_3	R_4	R_{avg}	
1	$A_1B_1C_1D_1$	96	97	96	95	96	39.6447
2	$A_1B_2C_2D_2$	97	99	98	98	98	39.8238
3	$A_1B_3C_3D_3$	102	103	103	104	103	40.2561
4	$A_2B_1C_2D_3$	93	92	91	92	92	39.2750

5	$A_2B_2C_3D_1$	99	100	99	100	99.5	39.9561
6	$A_2B_3C_1D_2$	92	91	90	91	91	39.1800
7	$A_3B_1C_3D_2$	98	97	99	98	98	39.8238
8	$A_3B_2C_1D_3$	92	93	91	92	92	39.2750
9	$A_3B_3C_2D_1$	91	89	90	90	90	39.0840
							39.5910

Table 4 Average S/N ratio response

Category	**A**	**B**	**C**	**D**
level 1	39.9082	39.5812	39.3666	39.5616
level 2	39.4704	39.6850	39.3943	39.6092
level 3	39.3943	39.5067	40.0120	39.6020
Max-Min	0.5139	0.1782	0.6455	0.0476
Rank	2	4	1	3
Optimum	A_1	B_2	C_3	D_2

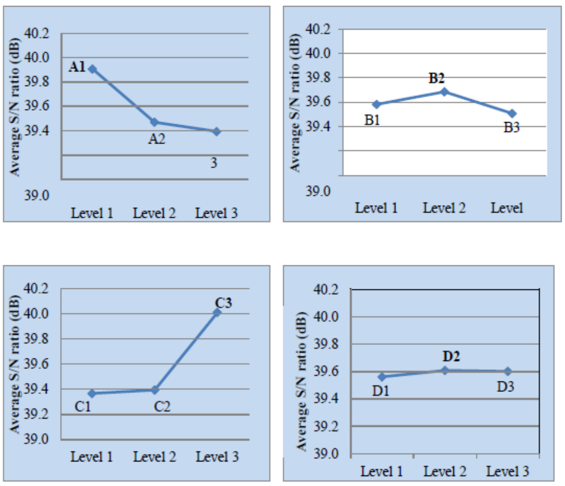


Figure 3 Response graph

Analysis of Variance

Analysis of variance was performed on signal-to-noise ratios to find the relative significance of the process control parameters and their contribution in the process performance. The following terms were calculated by using Equations (3-10) and their values are given in Tables 5 and 6.

(i) Sum of squares due to mean, $SS_m = N\bar{Y}^2$ (3)

(ii) Sum of squares due to parameter A,

$$SS_A = n_{A1}\times\overline{A_1}^2 + n_{A2}\times\overline{A_2}^2 + n_{A3}\times\overline{A_3}^2 - SS_m \quad (4)$$

Similarly, sum of squares due to parameters B, C and D were calculated. Sum of squares due to parameters B and D were found to be very less in this study. Therefore, their effects on the output response were assumed to be insignificant and considered as an error (pooled error). Sum of squares due to pooled error was also calculated as follows.

$$SS_{\text{pooled error}} = SS_B + SS_D \quad (5)$$

(iii) Total sum of squares,

$$TSS = SS_A + SS_B + SS_C + SS_D \quad (6)$$

(iv) Degree of freedom for parameter,

$DOF_{\text{parameter}}$ = Number of parameter levels – 1

Degree of freedom for pooled error,

$DOF_{\text{pooled error}} = DOF_B + DOF_D$

(v) Mean sum of squares due to parameter A,

$$MSS_A = \frac{SS_A}{DOF_A} \quad (7)$$

Likewise, mean sum of squares for all other parameters and pooled error were calculated.

(vi) F ratio for parameter A,

$$F_A = \frac{MSS_A}{MSS_{\text{pooled error}}} \quad (8)$$

Similarly, F ratio was calculated for parameter C. The calculated F ratio for parameters A and C was found to be greater than the F distribution value ($F_{1,4} = 7.71$ at 5% level of significance). Therefore, the parameters A and C were confirmed as significant parameters in this study.

(vii) Pure sum of squares due to parameter A,

$$PSS_A = MSS_A - DOF_A \times MSS_{\text{pooled error}}$$

(viii) Percentage contribution of parameter A,

$$PC_A = \frac{PSS_A}{TSS} \times 100\ \% \quad (10)$$

Similarly, pure sum of squares and percentage contribution of parameters C and pooled error were calculated. The percentage contribution of pooled error was noted to be less than 8% in this study. The percentage contribution of all significant parameters is clearly shown in Figure

4. Taguchi method was used to find better level of process parameters from among the set levels. In order to tune the parameter setting between the set levels, metaheuristic technique namely genetic algorithm was also used in this study.

Table 5 First level ANOVA

Source	Pool	SS	DOF	MSS	F Ratio	PSS	PC (%)
A	-	0.4616	2	0.2308	16.8367	0.4577	34.8666
B	-	0.0481	2	0.0240	12.1713	0.0441	3.3626
C	-	0.7990	2	0.3995	02.2198	0.7950	60.5668
D	Yes	0.0040	2	0.0020	-	-	-
Pooled	-	0.0040	2	0.0020	-	0.0158	1.2040
T	-	1.3127	-	-	-	-	-

Table 6 Second level ANOVA

Source	Pool	SS	DOF	MSS	F ratio	PSS	PC (%)
A	-	0.4616	2	0.2308	17.7411	0.4356	33.1854
B	Yes	0.0481	2	0.0240	-	-	-
C	-	0.7990	2	0.3995	30.7061	0.7730	58.8855
D	Yes	0.0040	2	0.0020	-	-	-
Pooled	-	0.0520	4	0.0130	-	0.1041	7.9291
TSS	-	1.3127	-	-	-	-	-

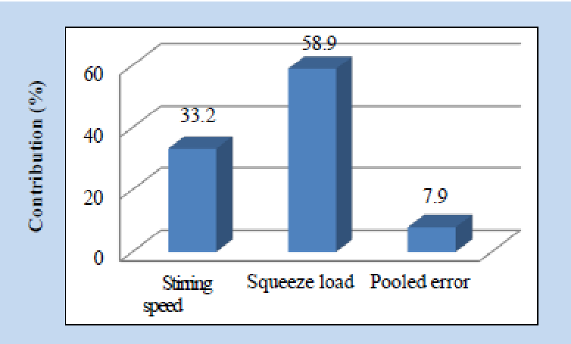


Figure 4 Percentage contribution

Genetic Algorithm

Mathematical Model

The relationship between the control parameters and their effect on average hardness (R_{avg}) was modeled by using non-linear regression analysis with the help of statistical software MINITAB 14.

$$R_{avg} = 91.8333+7.8333A-1.3333B-21.0833C+19.9167D-2.6667A^2+0.8333B^2+5.5833C^2-4.9167D^2 \quad (11)$$

For this regression model, it was found that $r^2 = 0.99$ where r is the co-efficient of correlation. The value of r^2 indicates the closeness of the model representing the process. As r^2 is nearing unity, this model can be taken as objective function for the application of genetic algorithm.

Inputs to GA

Genetic algorithm solver available in the MATLAB software was used to find the optimum parametric setting for the maximization of average hardness of squeeze cast hollow castings (R_{avg}) in this study. The regression model given in Equation (11) was used as fitness function (objective function). The bounds with coded condition for the process parameters (constraints) are given in Table 7.

Table 7 Bounds for control parameters

Process parameter	Lower bound	Upper bound
Stirring speed	1	3
Melt temperature	1	3
Squeeze load	1	3
Die temperature	1	3

Genetic algorithm was run for the evolutionary parameters such as population type (double vector), population size (20), fitness selection function (stochastic), probability of crossover (0.8) and probability of mutation (0.03). It was observed that the fitness value was decreased through generations as shown in Figure 5 and an optimized average hardness (108.25 BHN) was obtained in the 53rd generation. The optimum parametric setting in the last generation is given in Table 8.

Table 8 Optimum parametric setting

Control parameter	Coded Condition	Uncoded Condition
Stirring speed	1.468	11.936
Melt temperature	3	625
Squeeze load	3	40
Die temperature	2.024	200

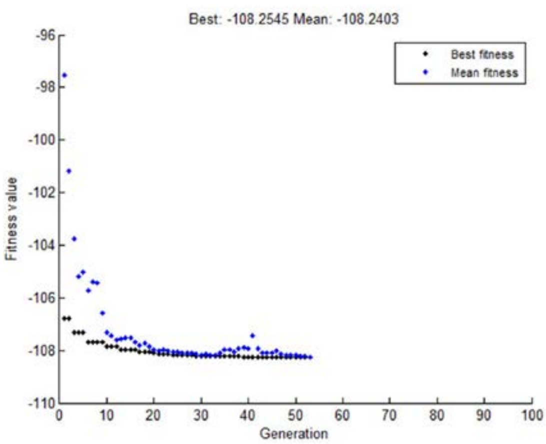


Figure 5 GA result

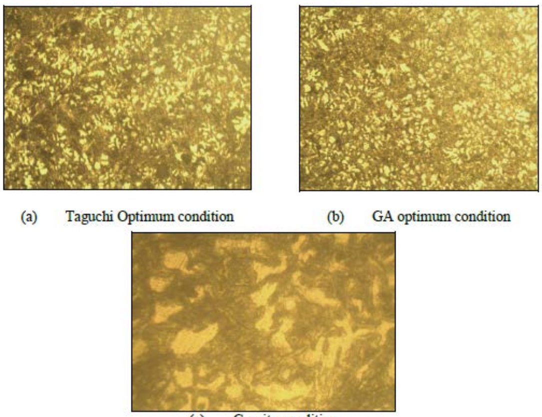
Confirmation Experiments

Confirmation experiments were conducted for the optimum parametric condition suggested by Taguchi Method and genetic algorithm. The average hardness (predicted and tested) values are given in Table 9. It is evident that there is a good agreement between the predicted average hardness and actual average hardness of the castings since the error is less than 1%. An experiment was also conducted for gravity die casting condition (A: 400 rpm; B: 600°C; D: 200°C) using the same set up without the application of squeeze load. The specimens for hardness test and microstructural analysis were prepared from the casting samples. For micro examination, the specimens were etched with Keller's reagent and Ziess microscope was used for making photomicrographs. Comparisons were made between the optimum squeeze casting condition and gravity die casting condition in the aspects of microstructure and hardness, and clearly shown in Figure 6.

Table 9 Confirmation test results

Optimization technique	**Optimum parametric condition**			**Hardness (BHN)**		**Error (%)**
	Process parameter	**Coded**	**Uncoded**	**Predicted**	**Tested**	
Taguchi method	Stirring speed	1	400 rpm	104.83	105	0.16
	Melt temperature	2	600℃			
	Squeeze load	3	40ton			
	Die temperature	2	200℃			
Genetic algorithm	Stirring speed	1.468	500 rpm	108.25	108	0.23
	Melt temperature	3	625℃			
	Squeeze load	3	40ton			
	Die temperature	2	200℃			

The castings obtained for the optimum squeeze casting condition showed better grain refinement in the microstructure and nearly 25% improvement in hardness than the castings obtained for gravity die casting condition. Due to high level squeeze load, heat transfer increased considerably between the melt and the die, which led to an increase in solidification rate. High heat transfer or cooling was the reason for good grain refinement in microstructure and improvement in hardness.



(a) Taguchi Optimum condition (b) GA optimum condition (c) Gravity condition

Figure 6 Microstructure (100X)

CONCLUSION

The following are the conclusions drawn based on the parametric optimization for improving hardness of squeeze cast LM24 hollow castings.

(i) From the ANOVA, stirring speed and squeeze load were identified as significant process control parameters in this study.

ii) From the percentage contribution analysis, it was noted that squeeze load was the most important parameter over the control of squeeze casting process.

iii) A regression model has been developed for the squeeze casting process based on the experiment results. The average hardness of the castings can be predicted using this model if the values of stirring speed and squeeze load are known.

iv) It is evident that there is a good agreement between the predicted average hardness and actual average hardness of the castings since the error is less than 1%.

v) The castings obtained for the optimum squeeze casting condition showed better grain refinement in the microstructure and nearly 25% improvement in hardness than the castings obtained for gravity die casting condition.

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