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Optimization of squeeze casting parameters for non symmetrical AC2A aluminium alloy castings through Taguchi method†

P. Senthil[1,*] and K. S. Amirthagadeswaran[2]

[1]*Department of Mechanical Engineering, Coimbatore Institute of Engineering & Technology, Coimbatore-641109, India*
[2]*Department of Mechanical Engineering, Government College of Technology, Coimbatore-641013, India*

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Abstract

This paper reports a research in which an attempt was made to prepare AC2A aluminium alloy castings of a non symmetrical component through squeeze casting process. The primary objective was to investigate the influence of process parameters on mechanical properties of the castings. Experiments were conducted based on orthogonal array suggested in Taguchi's offline quality control concept. The experimental results showed that squeeze pressure, die preheating temperature and compression holding time were the parameters making significant improvement in mechanical properties. The optimal squeeze casting condition was found and mathematical models were also developed for the process.

Keywords: Squeeze casting; AC2A aluminium alloy; Non symmetrical castings; Taguchi method

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1. Introduction

The squeeze casting process has been widely used to produce quality castings of automotive parts. Because of high pressure applied during solidification of molten metal in the mould, porosities caused by both gas and shrinkage can be eliminated. The contact between the molten metal and the mould is improved by pressurization, which results in a pore free, finer, grain-size and close dendrite arm spacing components with improved mechanical properties. Light metal alloys are widely used in automotive and aero space industries because of their interesting properties such as high strength to weight ratio, good formability, desirable corrosion resistance and high castability or low viscosity at molten state. Especially in automobile sectors, use of aluminium alloy components has been increased during the last two decades due to the light weight requirements of transportation systems. This would in turn lead to reduced energy consumption and better environmental protection. Yue and Chadwick [1] stated that squeeze casting process was an ideal process to produce high quality light metal components with near net shape. Yue [2] compared the tensile properties of the squeeze cast AA7010 aluminium alloy with its wrought product counterparts and reported that squeeze castings were better than their wrought counterparts. Kim et al. [3] reported that squeeze casting accounted for 15-40% improvement of mechanical properties than gravity die casting process. Ghomashchi and Vikhrov [4] summarized the overall advantages and disadvantages of squeeze casting process based on the previous research works and pointed out that further development was yet required to produce complex shaped and thin sectioned components through squeeze casting process. Yong and Clegg [5] investigated the optimal combination of process parameters for squeeze cast magnesium alloy components. Vijian and Arunachalam [6] studied that squeeze casting exhibited remarkable grain refinement and substantial improvement in mechanical properties while processing gun metal. The effect of applied pressure dominated in the improvement of mechanical properties of squeeze cast aluminium alloys such as LM6, LM13, LM24 aluminium alloys [7-9]. Vijian and Arunachalam [10] found the optimum squeeze casting condition for LM24 aluminium alloy for the production of cylindrical components with improved mechanical properties. Many research people investigated the effects of various casting parameters on microstructure and mechanical properties of squeeze cast aluminium alloy components and reported that mechanical properties were improved with the application of pressure [11-14].

Though many research works on squeeze cast aluminium alloys have been reported in literature, authors have not found any published data regarding the squeeze casting of AC2A aluminum alloy for a non-symmetrical component with respect to the axis of squeeze load. On considering the impor-

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[*] Corresponding author. Tel.: +919585174522, Fax.: +914222455230
E-mail address: senth.ksa@gmail.com
[†] Recommended by Associate Editor Dae-Eun Kim Editor Mohammad Abdul Aziz

Table 1. Chemical composition of AC2A aluminium alloy.

Element	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
JIS AC2A std (wt%)	3.0-4.5	<0.25	4.0-6.0	<0.75	<0.55	<0.30	<0.55	<0.15	<0.05	<0.2	Rest
Ingot analysis (wt%)	3.69	0.16	4.81	0.24	0.11	0.011	0.02	0.027	0.009	0.04	Rest

Table 2. Control factors and levels.

Factor	Control factor	Level 1	Level 2	Level 3	Level 4
A	Squeeze pressure (MPa)	50	75	100	125
B	Melt temperature (^{0}C)	675	700	725	750
C	Die preheating temperature (^{0}C)	150	200	250	300
D	Die insert material	copper	stainless steel	brass	hot die steel
E	Compression holding time (seconds)	15	30	45	60

tance of aluminium alloys, AC2A aluminium alloy was processed for the production of a non symmetrical component in this study. The chemical composition of AC2A alloy as per Japanese specification is shown in the Table 1. Currently gravity die casting and pressure die casting processes are widely employed for the manufacture of wheel cylinder, a non symmetrical automotive component with high rejection rate used in brake assembly of light vehicles. However, these processes include several casting defects such as shrinkage porosities, hot tears etc and need post processes for the improvement of mechanical properties. In order to overcome the above said defects and drawbacks in the process itself, squeeze casting process was employed in this study. Casting variables such as squeeze pressure, melt temperature, die preheating temperature, die insert material and compression holding time were taken into account while conducting experiments based on $L_{16}(4^5)$ orthogonal array. Hardness and tensile tests were carried out so that the optimal squeeze casting condition could be found by Taguchi method.

2. Wheel cylinder

Wheel cylinder is a non symmetrical component used in brake system, provided on each wheel of vehicle. It consists of two pistons attached to the brake shoes by means of links. Master cylinder in the brake system converts the force of the operator's foot into fluid pressure to operate the wheel cylinders. When the fluid in master cylinder enters into the wheel cylinder under pressure, it forces the pistons outwards, thereby pushing the brake shoes against the drum and applying the brakes.

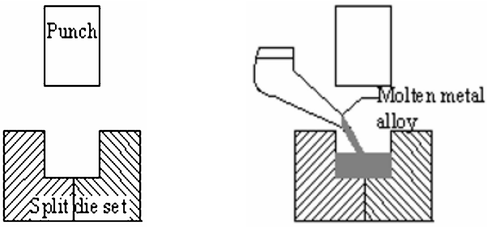
The manufacturer reports that wheel cylinder components produced by gravity and pressure die casting processes are more defective and life of components is also less due to higher wear rate between the cylinder and piston. Hence, higher hardness and ultimate strength are required to resist wear of components and to increase life of components. As an effective braking system is highly closed with prevention of accidents, the components used in brake system must be defects free, strong, wear resistant and more durable. Keeping all points in mind, squeeze casting process was employed in this study for the production of AC2A aluminium alloy wheel cylinder.

3. Taguchi method

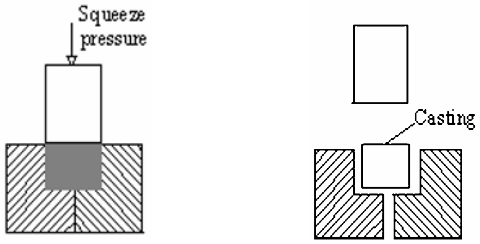
Taguchi method is an efficient problem solving tool, which can improve the performance of the product, process, design and system with a significant reduction in experimental time and cost. This method that combines the experimental design theory and quality loss function concept has been applied for carrying out robust design of processes and products and solving several complex problems in manufacturing industries. The number of experiments generally increases with the increase of process parameters. To solve this complexity, Taguchi method uses a special design of orthogonal array to study the entire process parameter space with a small number of experiments only. Taguchi defines three categories of quality characteristics such as the lower-the-better, the larger-the-better and the nominal-the-best. The signal to noise (S/N) ratio for each parametric setting is computed. Regardless of the category of the quality characteristics, a larger S/N ratio corresponds to better quality characteristic. Therefore, the optimal level of process parameters promotes highest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) can be performed to see which process parameter is statistically significant for each quality characteristic.

In order to observe the influencing process parameters in squeeze casting, five process parameters namely squeeze pressure, melt temperature, die preheating temperature, die insert material and compression holding time each at four levels were considered as listed in Table 2. A four level $L_{16}(4^5)$ orthogonal array with sixteen experimental runs was selected. Hardness and tensile strength were considered as quality characteristics with the concept of the "larger the better". The S/N ratio used for these types of response is given in Eq. (1).

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



(a) Preheat die and punch (b) Pour molten metal alloy into die cavity



(c) Apply pressure through punch (d) Withdraw punch and separate casting

Fig. 1. Squeeze casting process steps.

where i=1, 2,…, n and R_i is the response value for an experimental condition repeated n times.

4. Experiments

4.1 Experimental set up

A 40 tonne universal testing machine was employed for the application of pressure. A ceramic electrical heater of capacity 400°C was used to preheat the die. SG400 spheroidal graphite iron (die material), EN8 alloy steel (punch material) and DYCOTE D140 (die coat material) were used during the conduct of experiments. AC2A aluminium alloy was melted in an electric resistance crucible furnace. After degassing the melt, a metered quantity of molten metal alloy was poured into the preheated die cavity. Through the punch, pressure was directly applied on the molten metal alloy and was maintained for predetermined time. Punch was then withdrawn and the casting was separated from die. All process steps are clearly indicated through a schematic diagram shown in Fig. 1. The experimental set up used for direct squeeze casting is shown in Fig. 2. A set of experiments were conducted based on $L_{16}(4^5)$ orthogonal array. The photograph of squeeze cast samples of wheel cylinder made under experimental conditions is shown in Fig. 3.

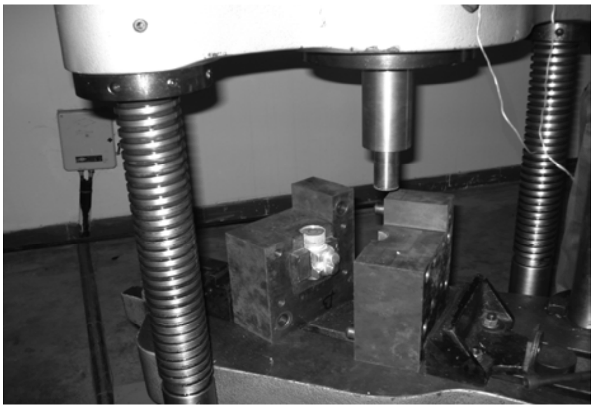


Fig. 2. Experimental set up.

Fig. 3. Squeeze cast samples.

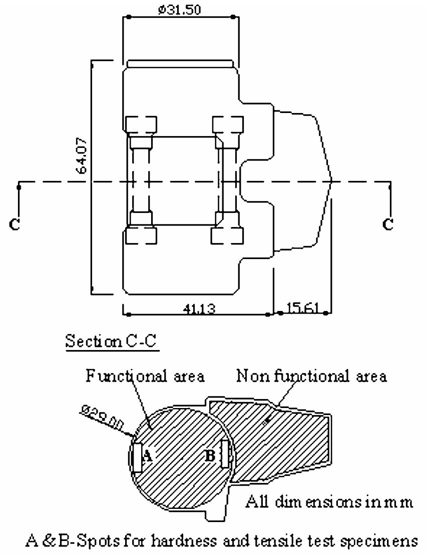


Fig. 4. Functional and non functional areas of wheel cylinder.

4.2 Hardness and tensile testing

Hardness and tensile specimens were machined in the functional volume of wheel cylinder samples made under experimental conditions. For each experimental condition and each type of test, two specimen samples were prepared. For Brinell hardness (BHN) test, 250 kg load was applied through a ball indentor of 5 mm diameter on the polished specimen surface and hardness values were measured in two spots of functional areas as shown in Fig. 4. INSTRON universal testing machine was used for performing tensile test on the specimens of 4.53 mm diameter with a gauge length of 16 mm.

Table 3. Experimental observations and S/N ratio.

Ex.no	A	B	C	D	E	Hardness (BHN)		Tensile strength (MPa)		S/N Ratio for hardness	S/N Ratio for tensile strength
						R_1	R_2	R_1	R_2	Y_1(dB)	Y_2(dB)
1	1	1	1	1	1	84	78	239	225	38.15	47.30
2	1	2	2	2	2	88	82	251	234	38.57	47.68
3	1	3	3	3	3	92	85	262	242	38.92	48.01
4	1	4	4	4	4	86	80	245	228	38.36	47.46
5	2	1	2	3	4	97	90	276	256	39.40	48.48
6	2	2	1	4	3	95	88	271	251	39.21	48.31
7	2	3	4	1	2	89	81	254	231	38.56	47.66
8	2	4	3	2	1	95	89	271	253	39.26	48.35
9	3	1	3	4	2	102	95	291	270	39.85	48.94
10	3	2	4	3	1	100	93	285	265	39.67	48.77
11	3	3	1	2	4	102	95	291	270	39.85	48.94
12	3	4	2	1	3	112	105	321	301	40.70	49.84
13	4	1	4	2	3	97	89	276	253	39.35	48.42
14	4	2	3	1	4	101	94	288	268	39.76	48.86
15	4	3	2	4	1	106	100	302	289	40.25	49.40
16	4	4	1	3	2	95	88	271	250	39.21	48.29
									Mean	$\overline{Y_1} = 39.32$	$\overline{Y_2} = 48.42$

5. Results and discussion

The squeeze casting process parameters, namely squeeze pressure (A), melt temperature (B), die preheating temperature (C), die insert material (D) and compression holding time (E) were assigned to the 1st, 2nd, 3rd , 4th and 5th columns of $L_{16}(4^5)$ array, respectively. The S/N ratios were computed for hardness and tensile strength in each of the sixteen experimental conditions and their values are given in Table 3. In order to find ranking and optimum level of the process parameters, S/N ratio response was estimated for hardness and tensile strength. The details are given in Tables 4 and 5. The response curves for hardness and tensile strength are shown in Figs. 5 and 6, which depict the pictorial view of variation of each factor and describe the effect on the system performance. The optimum levels were A_3 (squeeze pressure of 100 MPa), B_3 (melt temperature of 725°C), C_2 (die preheating temperature of 200°C), D_4 (die insert of hot die steel) and E_3 (compression holding time of 45 seconds).

In order to study the significance of parameters, ANOVA was performed for hardness and tensile strength. Tables 6 and 7 show that the significant factors which affect the hardness and tensile strength are squeeze pressure (A), die preheating temperature (C) and compression holding time (E). Based on the highest values of the S/N ratio levels for the significant factors A, C and E, the overall optimum condition thus obtained were A_3, C_2 and E_3. The percentage contribution of significant factors is shown in Fig. 7.

5.1 Estimation of predicted mean and confidence interval

At the overall optimum condition, predicted mean (μ) for hardness and tensile strength was estimated as follows [15]:

Table 4. S/N ratio response table for hardness.

	A	B	C	D	E
Level 1	38.50	39.19	39.11	39.29	39.33
Level 2	39.11	39.30	39.73	39.26	39.05
Level 3	40.02	39.39	39.45	39.30	39.54
Level 4	39.64	39.38	38.99	39.42	39.34
Max-Min	1.52	0.20	0.74	0.16	0.49
Rank	1	4	2	5	3
Optimum level	A_3	B_3	C_2	D_4	E_3

Table 5. S/N ratio response table for tensile strength.

	A	B	C	D	E
Level1	47.61	48.29	48.21	48.42	48.46
Level2	48.20	48.41	48.85	48.35	48.14
Level3	49.12	48.50	48.54	48.39	48.65
Level4	48.75	48.49	48.08	48.53	48.44
Max-Min	1.51	0.21	0.77	0.18	0.51
Rank	1	4	2	5	3
Optimum level	A_3	B_3	C_2	D_4	E_3

$$\begin{aligned}\mu_{\text{hardness}} &= \overline{A_3} + \overline{C_2} + \overline{E_3} - 2\overline{Y_1}\\ &= 40.02 + 39.73 + 39.54 - 2 \times 39.32\\ &= 40.65\ \text{dB}\\ \mu_{\text{tensile strength}} &= \overline{A_3} + \overline{C_2} + \overline{E_3} - 2\overline{Y_2}\\ &= 49.12 + 48.85 + 48.65 - 2 \times 48.42\\ &= 49.78\ \text{dB}\end{aligned}$$

The confidence interval (CI) of the predicted mean was cal-

Table 6. ANOVA for hardness.

Source	Pool	Sq	DOF	Mq	F-ratio	Sq'	%
A		5.221	3	1.74	62.3	5.138	70.9
B	yes	0.109	3	0.036	-	-	-
C		1.362	3	0.454	16.25	1.278	17.6
D	yes	0.058	3	0.019	-	-	-
E		0.496	3	0.165	5.913	0.412	5.68
Pooled e		0.168	6	0.028	-	0.419	5.78
St		7.246				7.246	

Table 7. ANOVA for tensile strength.

Source	Pool	Sq	DOF	Mq	F ratio	Sq'	%
A		5.213	3	1.738	54.17	5.117	69.5
B	yes	0.120	3	0.040			
C		1.439	3	0.480	14.95	1.342	18.2
D	yes	0.073	3	0.024			
E		0.515	3	0.172	5.351	0.419	5.69
Pooled e		0.192	6	0.032		0.481	6.54
St		7.36				7.36	

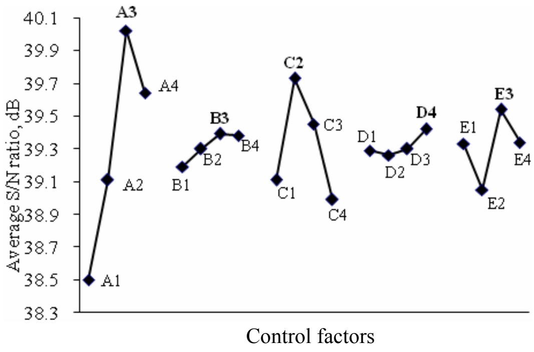


Fig. 5. Response curve of hardness.

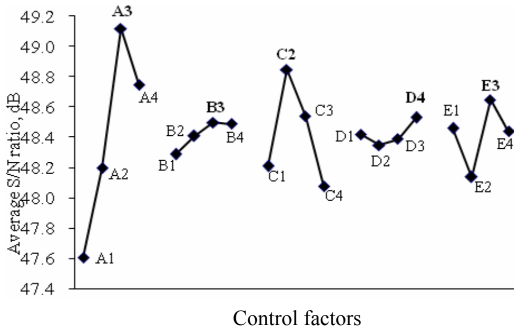


Fig. 6. Response curve of tensile strength.

culated as under Eq. (2).

$$CI = \pm\sqrt{F_{0.05,1,6} \times V_e \times \frac{1}{N_{eff}}} \tag{2}$$

where $V_e = \frac{\text{Total pooled variation}}{\text{Total pooled DOF}}$ and $N_{eff} = \frac{\text{Number of experiments}}{1+\text{Total DOF associated with } \mu}$.

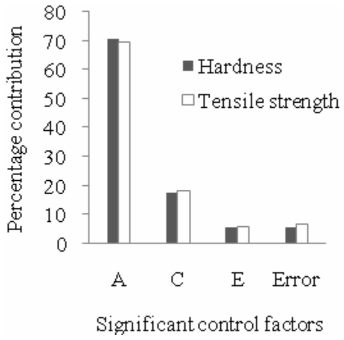


Fig. 7. Percentage contribution of significant control factors.

At 5% level of significance, the confidence interval for predicted mean of hardness was found to be 40.65 ± 0.32 dB. It varies from 40.33 to 40.97 dB.

At 5% level of significance, the confidence interval for predicted mean of tensile strength was found to be 49.78 ± 0.35 dB. It varies from 49.43 to 50.13 dB.

5.2 Confirmation test

A confirmation test was conducted based on the optimum level of process parameter settings as determined through Taguchi method. The values of hardness and tensile strength measured in the functional volume were found to be 115,107 BHN and 328,308 MPa respectively and their S/N ratios were 40.89 dB and 50.04 dB, respectively. These values were found to be within the confidence interval limits.

5.3 Development of mathematical models

Using non-linear regression analysis method with the help of MINITAB 14 software, the relationships between mechanical properties such as average hardness $(\overline{H})$, average tensile strength $(\overline{T})$ and the significant control factors were modeled in Eqs. (3) and (4).

$$\begin{aligned}\overline{H} = &-3.82542 + 0.8787A + 0.46587C + 0.30411E - 0.00393A^2 \\ &- 0.00116C^2 + 0.00097E^2 + 0.00051AC \\ &- 0.00333AE - 0.00018CE\end{aligned} \tag{3}$$

$$\begin{aligned}\overline{T} = &-11.2606 + 2.5778A + 1.3316C + 0.7552E - 0.0116A^2 \\ &- 0.0034C^2 + 0.0031E^2 + 0.0015AC \\ &- 0.0097AE - 0.001CE\end{aligned} \tag{4}$$

The square value of correlation coefficient (R) for the above two cases is as follows.

$R^2 = 0.84$ for the modeling equation of average hardness

$R^2 = 0.83$ for the modeling equation of average tensile strength.

The value of R^2 indicates the closeness of the model representing the process.

5.4 Future scope

Significant scope exists to improve the quality of AC2A aluminium alloy castings through the exhaustive combination of factors and levels by including other squeeze casting parameters like die material, die coat material, delay time to achieve maximum pressure, melt superheat and punch temperature. This would enable to find the optimum parametric condition for the production of squeeze cast AC2A aluminium alloy components with improved mechanical properties. It is understood that the addition of ceramic materials will enhance the mechanical properties and life of components. Future studies on production of composites by reinforcing suitable ceramic materials with this alloy are also required in this direction.

6. Conclusion

In this work, Taguchi's off-line quality control concept was applied for the determination of optimum squeeze casting condition which was used for producing non symmetrical AC2A aluminium alloy casting with improved mechanical properties. The optimum level of process parameters was found as follows:

Squeeze pressure : 100 MPa
Melt temperature : 725°C
Die preheating temperature : 200°C
Die insert material : hot die steel
Compression holding time : 45 seconds

Squeeze pressure, die preheating temperature and compression holding time were identified as significant control process parameters from ANOVA. The optimum settings were checked through the confirmation test. From the percentage contribution analysis, it is noted that squeeze pressure is the major contributing factor for the improvement of mechanical properties. The defects reported by manufacturer were completely eliminated and the components produced with the optimum condition were found to be defects free and sound. Mathematical models have been developed for hardness and tensile strength as function of squeeze cast parameters. These models can be taken as objective function for the application of optimization algorithms through which better parameter settings can be found.

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Nomenclature

R_1 : Readings measured in spot A
R_2 : Readings measured in spot B
Sq : Sum of squares
St : Total sum of squares
DOF : Degree of freedom
Mq : Mean square
Sq' : Pure sum of squares
% : Percentage contribution

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P. Senthil received his B.E degree in Mechanical Engineering and M.E degree in Production Engineering from Bharathiar University, India in 1998 and 2002 respectively. He is currently an Assistant Professor at the Department of Mechanical Engineering, Coimbatore Institute of Engineering and Technology, Coimbatore, India.

K. S. Amirthagadeswaran received his B.E degree in Mechanical Engineering from Madras University, India in 1980 and M.E degree in Production Engineering from Bharathiar University, India in 1988. He then received his Ph.D degree from Bharathiar University, Coimbatore, India in 2007. He is currently a Professor at the Department of Mechanical Engineering, Government College of Technology, Coimbatore, India. His publications are over 25 in different journals and conferences. His current research interests include Scheduling, Cellular Manufacturing Systems, Non-traditional Optimization Algorithms, Robotics, Squeeze Casting and Electro Discharge Machining.