

Optimization of Process Parameters of Pressure Die Casting using Taguchi Methodology

Satish Kumar, Arun Kumar Gupta, Pankaj Chandna

Abstract—The present work analyses different parameters of pressure die casting to minimize the casting defects. Pressure die casting is usually applied for casting of aluminium alloys. Good surface finish with required tolerances and dimensional accuracy can be achieved by optimization of controllable process parameters such as solidification time, molten temperature, filling time, injection pressure and plunger velocity. Moreover, by selection of optimum process parameters the pressure die casting defects such as porosity, insufficient spread of molten material, flash etc. are also minimized. Therefore, a pressure die casting component, carburetor housing of aluminium alloy ($Al_2Si_2O_5$) has been considered. The effects of selected process parameters on casting defects and subsequent setting of parameters with the levels have been accomplished by Taguchi's parameter design approach. The experiments have been performed as per the combination of levels of different process parameters suggested by L18 orthogonal array. Analyses of variance have been performed for mean and signal-to-noise ratio to estimate the percent contribution of different process parameters. Confidence interval has also been estimated for 95% consistency level and three conformational experiments have been performed to validate the optimum level of different parameters. Overall 2.352% reduction in defects has been observed with the help of suggested optimum process parameters.

Keywords—Aluminium Casting, Pressure Die Casting, Taguchi Methodology, Design of Experiments

I. INTRODUCTION

PRESSURE die casting in aluminium alloy provides rapid production of engineering and other related components of even or intricate design. The technique becomes important when mass production is required. Aluminum is comparably easy to cast and recyclable, therefore, aluminum is still the most widely processed metal in the field of die casting for engineering components such as aeronautic space, defence and automotive applications etc. It is therefore essential that the optimum casting technique with minimum defects be adopted to reduce the manufacturing cost of die casting component during mass production. Pressure die casting is primarily affected by the process parameters such as solidification time, molten temperature, Filling time, injection pressure and plunger velocity. In pressure die casting process molten metal is injected with the help of plunger and there is no need of riser and runner, therefore lesser amount of machining is required and to prevent metal reaction lesser solidification time is required.

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Hence, the time is reduced with the help of water cooled die. For appropriate spread of molten material into the die cavity for aluminium alloy, higher injection pressure and lower molten temperature is required. The filling process is completed in short time snap to prevent iron contamination due to entrapped air [10].

II. LITERATURE REVIEW

On reviewing of literature, it has been found that most of the researchers over the years, have dealt with various process parameters such as metal temperature, piston velocity, filling time, hydraulic pressure etc. for optimization of the objectives like maximum casting density, minimum porosity, minimum flashes, sufficient spread of molten material etc. [7] Noorul *et al.*, 2009 demonstrated the optimization of sand casting process parameters such as weight of CO_2 gas, mould hardness number, sand particle size, sand mixing time, filling time etc with their effects on casting using Taguchi method. Anastasiou, 2005 investigated the effects of process parameters on porosity formation in the pressure die casting process to improve casting quality using Taguchi method. Process parameter like plunger velocity & Die temperature were optimized to improve quality and to reduce cost using Taguchi method by Tsoukalas *et al.*, 2004. Guharaja *et al.*, 2006 accomplished optimal settings of various significant process parameters like green strength, moisture content, permeability and mould hardness for minimizing green sand casting defects using Taguchi's parameter design approach. Oktem *et al.*, 2006 developed a Taguchi optimization method for low surface roughness for milling an aluminium alloy. Janudom *et al.*, 2010 have minimized the porosity and shrinkage defects of aluminum alloy (ADC12) for gas-induced semi-solid (GISS) die casting.

Taguchi has developed a methodology for the application of designed experiments, including a practitioner's handbook [9]. This methodology has taken the design of experiments from the exclusive world of the statistician and brought it more fully into the world of manufacturing. Taguchi methodology had also been applied to analyze the various significant process parameter i.e. piston velocity, hydraulic pressure, filling time, and metal temperature to estimate optimum casting density for die casting of $AlSi_9Cu_{13}$ aluminium alloy [10]. Better casting density for pressure die casting was achieved by optimizing process parameters for cast copper rotor [4]. This technique design was also be applied for minimizing the surface roughness of an end milling operation by optimizing cutting parameters depth of cut, width of cut, tool diameter [13].

III. PROCESS PARAMETERS OF PDC

A cause and effect diagram (Ishikawa diagram) has been illustrated in Fig. 1 to identify the casting process parameters

that may affect pressure die casting defects. The process parameters have been segmented and listed in four categories [9].

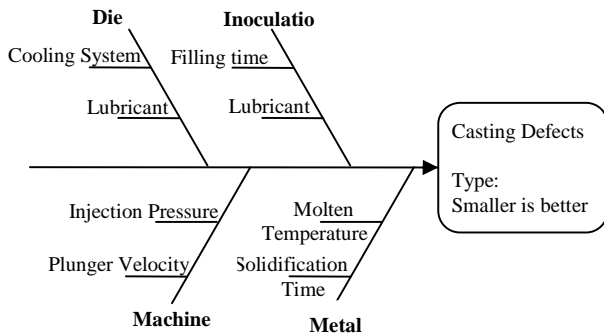


Fig. 3 Cause effect diagram

The range of molten temperature is selected as 570°C to 620 °C, the solidification time is selected as 2 to 6 sec, whereas the range of filling and injection pressure time is considered as 0.5 to 1 sec and 300 to 340bar. The range plunger velocity is taken as 100 to 120 m/s. The selected carburetor casting process parameters, along with their ranges, are presented in Table I.

TABLE I
 PROCESS PARAMETERS WITH THEIR RANGES AND VALUES AT THEIR LEVELS

Parameter Designation	Parameters	Range	Levels		
			1	2	3
ST	Solidification Time	3.0 – 6.0	3	6	
MT	Molten Temperature	570 - 620	570	595	620
Pr	Injection Pressure	300 - 340	300	320	340
FT	Filling time	0.5 – 1.0	0.5	0.75	1.0
VI	Velocity	100 - 120	100	110	120

IV. EXPERIMENTAL DESIGN

The experimental region has been decided as per Taguchi design approach [11]. The number of levels for each controllable process parameter has been defined by table 1. A wide experimental region has been covered so that sensitivity to noise factors does not alter with small changes in these factors settings and to obtain optimum regions for the process parameters. Therefore, each parameter was analyzed at different levels of the process parameters. Effect of interaction among the dependent parameters has also been studied for the output [2].

As per the study conducted to know the parameter interactions [9], it is inferred that there are significant interactions of solidification time with molten temperature and filling time. Therefore, the interaction of solidification time with the molten temperature (ST X MT), and the solidification time with filling time (ST X FT) have been considered. The total degrees of freedom (v) for five factors, one at two levels and remaining four at three levels, and therefore the interactions is 13.

TABLE II
 L18 EXPERIMENTAL COMBINATIONS

S. No	Solidification Time	Molten Temperature	Pressure	Filling time	Velocity
1	3	570	300	0.50	100
2	3	570	320	0.75	110
3	3	570	340	1.00	120
4	3	595	300	0.50	110
5	3	595	320	0.75	120
6	3	595	340	1.00	100
7	3	620	300	0.75	100
8	3	620	320	1.00	110
9	3	620	340	0.50	120
10	6	570	300	1.00	120
11	6	570	320	0.50	100
12	6	570	340	0.75	110
13	6	595	300	0.75	120
14	6	595	320	1.00	100
15	6	595	340	0.50	110
16	6	620	300	1.00	110
17	6	620	320	0.50	120
18	6	620	340	0.75	100

The L18 orthogonal array is selected for present work, as the required degrees of freedom is 13 and the available degrees of freedom (v_{LN}) is 17 (v_{LN} > v required, 17 > 13). The 18 experimental runs have been performed as per the L18 orthogonal array developed by the Taguchi design approach [2], [3]. The percent defected components in a lot of 500 components has been considered as response for the designed input process parameters and shown in table II.

V. ANALYSIS AND INTERPRETATION

The experiments are conducted thrice for the same set of parameters using a single-repetition randomization technique [9]. The casting defects that occur in each trial conditions have been measured. The percentage of defects for each repetition is calculated by relation (1) and averages of casting defects are determined for each trial conditions [10] as shown in Table III.

$$\text{Percentage of Defects} = \frac{\text{No. of defected pieces}}{\text{Total no. of pieces in a Batch}} \quad (1)$$

TABLE III
 RESPONSE TABLE WITH MEAN AND S/N RATIO FOR PERCENTAGE CASTING DEFECTS

S. No.	% defects in experiment				
	R1	R2	R3	SNRA4	MEAN4
1	10.10	8.91	10.01	-19.7251	9.6733
2	12.12	12.48	12.64	-21.8791	12.4133
3	12.28	11.56	10.77	-21.2540	11.5367
4	7.24	6.25	7.15	-16.7701	6.8800
5	9.65	10.16	9.81	-19.8913	9.8733
6	7.33	8.08	7.2	-17.5551	7.5367
7	10.73	10.36	10.14	-20.3514	10.4100
8	12.25	11.49	12.42	-21.6270	12.0533
9	8.98	8.56	8.74	-18.8518	8.7600
10	10.87	10.76	11.11	-20.7599	10.9133
11	3.63	4.87	4.04	-12.4892	4.1800
12	5.77	5.99	4.56	-14.7696	5.4400
13	6.26	5.3	6.53	-15.6395	6.0300
14	6.46	6.61	6.56	-16.3164	6.5433
15	5.10	5.46	5.57	-14.6163	5.3767
16	6.74	5.59	6.46	-15.9626	6.2633
17	5.72	4.46	4.67	-13.9456	4.9500
18	5.16	5.82	4.68	-14.3881	5.2200

To study the process parameter characteristics and optimum setting signal-to-noise ratio has been calculated instead of average in Taguchi method for the results of different trials based on L18 orthogonal array. Average and the variation of the quality characteristics both are replicated by S/N ratio. Since the problem is of minimization of defects in pressure die casting, therefore, the relation “lower is better” is selected to calculate S/N ratio by relation 2. [5].

$$S/N \text{ ratio} = -10 \log \left[\frac{1}{3} (10.1^2 + 8.91^2 + 10.01^2) \right] \quad (2)$$

$$S/N \text{ ratio} = -19.275 \quad (2a)$$

Figure 2 and 3 show the mean and S/N ratio plot respectively for the average of three trials of percent defects in pressure die casting for a given size batches. It has been found maximum at the same levels of the parameters (*ST2*, *MT2*, *Pr3*, *PT1*, *VII*).

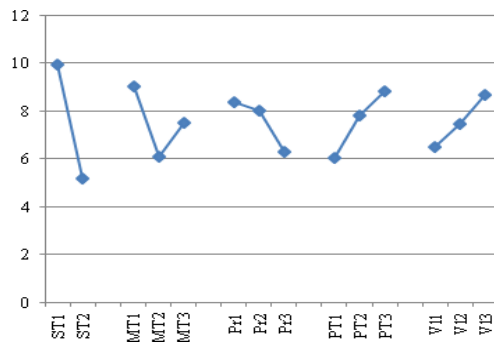


Fig. 2 Mean values of casting defects for each parameter at different levels

An optimum level of the process parameters have been obtained from these plots i.e. the second level of parameter solidification time (*ST2*), the second level of parameter Molten temperature (*MT2*), the third level of parameter injection pressure (*Pr3*), the first level of parameter Filling time (*PT1*) and the first level of parameter plunger velocity time (*VII*). The plot of S/N ratio as shown by fig 3 has also been indicated about the similar results.

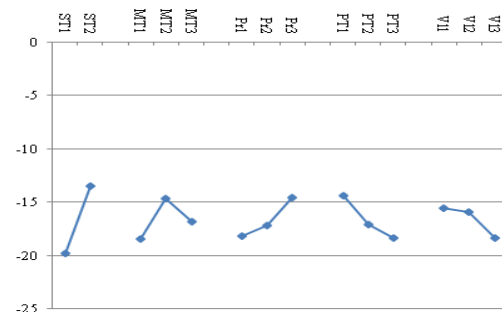


Fig. 3 Average values of S/N ratios for each parameter at different levels

A. ANOVA for mean and S/N ratio

In order to study the significance of these process parameters, three way analysis of variance (ANOVA) has been

performed for mean casting defects and S/N ratios and the results have been shown in Table IV. It is clearly illustrated that parameters *ST*, *MT* and *PT* are significantly affected both the mean and variation in the casting defects.

The results obtained by average plot, S/N ratio plot and ANOVA table have not sufficient enough to find the optimum parameters in order to minimize the casting defects. Therefore, to be more confident about the optimum combination of process parameters, percent contribution and confidence interval have also been estimated. In addition to this, some conformational experiments have also been performed and check the existence of the results between these intervals.

TABLE IV
 ANOVA FOR PERCENT CASTING DEFECTS AND S/N RATIOS

Source	Sum of Squares (SS)		Degree of freedom (v)		Variance (V)		F-ratio	
	Casting defects	S/N ratio	Casting defects	S/N ratio	Casting defects	S/N ratio	Casting defects	S/N ratio
<i>ST</i>	65.056	84.576	1	1	65.056	84.576	28.06	33.11
<i>MT</i>	11.867	8.537	2	2	5.933	4.2685	2.56	1.67
<i>Pr</i>	4.303	5.112	2	2	2.151	2.556	0.15	0.13
<i>PT</i>	19.285	24.739	2	2	9.642	12.3695	4.16	4.84
<i>VI</i>	6.063	7.548	2	2	3.031	3.774	1.31	1.48
<i>STXMT</i>	6.659	7.426	2	2	3.329	3.713	1.44	1.45
<i>STXPT</i>	2.637	4.182	2	2	1.318	2.091	0.606	0.82
Residual Error	2.6373	10.217	42	42	0.062	0.2432	2.318	0.50
Total	125.14	152.33	53	53				

B. Percent Contribution

The percent contribution is the portion of the total variation observed in an experiment attributed to each significant factor and/or interaction which is reflected. The percent contribution is a function of the sums of squares for each significant item [10]. The variation due to a factor contains some amount due to error (V_{error}) and can be obtained by the relation (3)

$$V = V' + V_{error} \quad (3)$$

Where, V' is the expected amount of variation. Expected sum of square (SS') due to variation in the process parameters and percent contribution for each related parameter is computed with the help of relations (4 to 7).

TABLE V
 ANOVA FOR PERCENT CASTING DEFECTS, INCLUDING PERCENT CONTRIBUTION

Source	Sum of squares (ss)	Degree of freedom (v)	Variance (V)	F-ratio	Expected (ss')	Percent Contribution (P)
<i>ST</i>	65.056	1	65.056	28.06	64.993	51.935
<i>MT</i>	11.867	2	5.933	2.56	11.741	9.382
<i>Pr</i>	4.303	2	2.151	0.15	4.177	3.338
<i>PT</i>	19.285	2	9.642	4.16	19.159	15.310
<i>VI</i>	6.063	2	3.031	1.31	5.937	4.744
<i>STXMT</i>	6.659	2	3.329	1.44	6.533	5.221
<i>STXPT</i>	2.637	2	1.318	0.606	2.511	2.007
Residual Error	2.637	42	0.063	2.318		
Total	125.144	53			125.144	

$$V = SS' / v \quad (4)$$

$$V = SS' / v \quad (5)$$

$$SS' = SS - (V_{error})(v) \quad (6)$$

Present Contribution

$$P = \left(\frac{SS'}{SS_T} \right) \times 100 \quad (7)$$

Where P is the percent contribution for each process parameters and SS_T is the total sum of square. ANOVA table for mean casting defects and S/N ratio including percent contribution has been shown in Tables V and VI respectively.

TABLE VI
ANOVA FOR S/N RATIO, INCLUDING PERCENT CONTRIBUTION

Source	Sum of squares (ss)	Degree of freedom (v)	Variance (V)	F-ratio	Expected (ss')	Percent Contribution (P)
ST	84.576	1	84.576	33.11	84.333	55.360
MT	8.537	2	4.268	1.67	8.050	5.285
Pr	5.112	2	2.556	0.13	4.625	3.036
PT	24.739	2	12.369	4.84	24.252	15.920
VI	7.548	2	3.774	1.48	7.548	4.955
ST X MT	7.426	2	3.713	1.45	6.939	4.555
ST X PT	4.182	2	2.091	0.82	3.695	2.426
Residual						
Error	10.217	42	0.2432			
Total	152.336	53			152.336	55.360

C. Confidence Interval

Confidence interval (CI) has been calculated for 95% consistency level and some conformational experiments have been conducted at optimum level of the process parameters for testing the adequacy of the Taguchi methodology. The mean percentage defect (μ) has been obtained by equation (8)

$$\mu = T + (ST2 - T) + (MT2 - T) + (Pr3 - T) + (PT1 - T) + (VII - T) \quad (8)$$

Where, T is the average values of casting defects at different levels. The mean percentage defect calculated for selected trial condition (ST2, MT2, Pr3, PT1, VII) is 2.352%. To verify predictions, the confidence levels i.e. the maximum and minimum values have been calculated, between which the value of confirmational experiments should fall. This interval has been obtained by the set of equations 9 to 12:

$$CI = \left[F(\alpha, 1, v_e) V_e \left[\frac{1}{\eta} + \frac{1}{r} \right] \right]^2 \quad (9)$$

$$\eta = \frac{54}{(1+13)} = 3.87 \quad (10)$$

$$F_{ratio}(1, 0.05, 4) = 7.7086 \quad (11)$$

Where α is the level of risk, V_e is the error variance, v_e is the error degrees of freedom, η is the effective number of replications and r is number of test trials. Using the values in Table V, the CI was calculated as follows:

$$CI = \pm 0.372 \quad (9a)$$

The 95% confidence interval of the predicted optimum of the casting defect is:

$$[\mu - CI] < \mu < [\mu + CI], 1.979\% < \mu < 2.724\% \quad (12)$$

VI. CONCLUSION

Experiments have been performed at different combination of process parameters as suggested by L18 orthogonal array by Taguchi methodology for the pressure die casting of a carburetor of Al alloy. Contribution of process parameters for minimization of defects in the components and the consistency of the experiments have been estimated using statistical techniques.

The results are summarized as under

- 1) Optimum combination of process parameters (ST2 MT2 PT1 VT1) for minimum casting defects has been calculated using Taguchi methods.
- 2) It has been found that the solidification time contributes more than 50% in minimization of casting defects, whereas, filling time is also affect the die casting process to some extent. However, the remaining parameters such as molten temperature, plunger velocity and injection pressure do not affect the process to an appreciable amount.
- 3) The predicted range of percent casting defects is $1.98\% < \mu < 2.72\%$ at 95% constancy level for optimum combination of process parameters. Three conformational experiments have also been performed at the optimum combination of process parameters and all the results are found within the calculated range of percent casting

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