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Numerical Optimization of the Spin Casting Process Parameters

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Abstract: The Philippine metals industry is envisioned at transforming the Philippines into a world-class and a reliable supplier of metal components, machineries and parts and other finished metal products. Development of other applications of spin casting could be of significant contribution to the growth of the metals industry in the Philippines. The objective of this study is to determine the optimum process parameters that will improve the quality of spin castings. Design parameters that have significant contributions in the improvement of the quality of spin casting products are identified which can serve as guidelines for researchers, designers and practitioners in the area of spin casting technology. A design of experiment optimization technique is applied to determine the optimal process parameters in the spin casting of zinc-based alloys. A polynomial regression model defining the relationship between the spin casting process parameters and the casting dimensions is used. An analysis of variance test was conducted to identify the process parameters that are statistically significant. The best results of the dimensional accuracy of the spin casting part were obtained when low values of runner length, runner diameter and disk closing pressure were used. The length of the mold runner as well as the interaction between the mold disk closing pressure and the runner length showed significant influence on the dimensional accuracy of the spin casting part.

Key words: Spin Casting · Design of Experiments · Numerical Optimization · Dimensional Accuracy · Process Parameters

INTRODUCTION

The Philippine metals industry is a vibrant industry that serves the requirements of the various industries of the country such as agricultural machinery, appliances, automotive, industrial, mining, construction, furniture, fabrication and repair of machineries. Export competitiveness in metal products can be built in the Philippine metals industry because of its inherent comparative advantages in operating management and labor skills. The potentials of the Philippine metals industry sector to gain higher niche in the world market aside from its local role as "backbone" of the industrial firms has led the government to support the growth and strengthen the metals and engineering industry in the country. Included in the export development strategy is the modernization of production processes. Strengthening the metal casting sector would also strengthen the machinery manufacturing sector and would stimulate the faster growth of other manufacturing sectors of the country.

Spin casting is a process of pouring and solidifying low melting point alloys in a mould using the principle of centrifugal force. It is a variation of the centrifugal casting process. It is used to cast a variety of small parts. The spin casting process may be used as an alternative to pressure die-casting and other casting techniques for manufacturing either functional or decorative parts [1]. In spin casting, a cured silicon rubber mold is spun in a centrifuge while low temperature metals such as zinc, tin or lead are poured into the center of the mould. For these metals, spin casting is the easiest, cheapest and fastest casting method. Centrifugal force pushes the liquid metal through the mould's runner system, completely filling every section, corner, detail and surface in each mould cavity. Once the metal has undergone solidification, the parts are removed from the mould.

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Manufacturing is not the only area benefiting from spin casting. Rapid prototyping and product development are quickly finding spin casting as an alternate method. Some research activities employed spin casting in combination with rapid prototyping such as for the construction of mold inserts for plastic injection in standard, commercial-grade pressure die casting zinc [2]. Positive results were obtained in the case of geometry analyses. Rapid prototyping technologies have been mostly used to generate prototypes of new products that are not always fully functional. These technologies have also been used to create production prototype tools for various casting and molding processes [3, 4]. A research effort was made to investigate the feasibility of rapid tooling for spin casting using stereolithography (SL) and arc metal spray technologies. Intermediate ceramic tools made of materials used in metal casting were successfully used to make the master metal patterns [5]. Balingit and Maglaya [6] evaluated the viability of using spin casting technology as a rapid prototyping process.

Research activities have been developed on the spin casting cooling process by investigating the effectiveness of different cooling media that includes plain carbon steel, beeswax, casting wax and candle wax, enclosed in the mold close to the casting cavity. The highlight in the research was the necessity to extend the mould life, which is limited by the thermal stress involved in the process and to reduce the production cycle [7]. The importance of the spin casting cooling process and its correlation with the different cast geometries and their quality lead to the formulation of a finite element numerical model for the simulation of the cooling process in spin casting [8]. The study investigated thru simulation, the effects of the clamping time, intensity of convection heat transfer, the use of a mold processing table with a metal surface and the mixing of copper powder on the silicone rubber mold. An air-based cooling system has been designed and studied in order to understand how it could improve the thermal behavior of the mould. A system to optimize the thermal process during casting, utilizing the theoretical analysis of the air-flow characteristics in a cooling tube submerged in a silicon mould and the characteristics of convection heat transfer associated with the mould and cast part was developed [9].

Optimization techniques have been widely used in different manufacturing industries for the improvement of their production processes. Balingit *et al*. [10] presented a comprehensive review of the various studies for the determination of optimum process parameters of the die casting manufacturing method. These techniques can also be utilized in the optimization of the spin casting design and process parameters. In the search of the best combinations of process parameters, changing quantities, levels and combinations, the design of experiments (DOE) has been used as an experimental technique. DOE is a systematic route that may be followed so as to find solutions to industrial process problems with greater objectivity by means of experimental and statistical techniques [11]. Ronald A. Fisher of England developed the traditional design of experiments that was first applied in the rationalization of agricultural experimentation [12]. A design of experiment is the simultaneous evaluation of two or more factors or parameters for their ability to affect the resultant average or variability of particular product or process characteristics [13]. The levels of the factors are varied in a strategic manner, the results of the particular test combinations are observed and the complete set of results is analyzed to determine the influential factors and preferred levels and whether increases or decreases of those levels will potentially lead to further improvement.

In spin-casting, there are factors influencing the quality and integrity of the casting. The objective of this study is to determine the optimum process parameters that will improve the quality of spin castings. Higher accuracy parts can be produced using spin casting which can be an alternative method for die-casting and other metal casting and metalworking processes. Using the optimum process parameters, wastage of energy, materials and labor due to trial and error procedures in the production will be minimized.

MATERIALS AND METHODS

In this paper, the methodology design of experiments (DOE) is employed to study the influence of process parameters on the quality of spin casting parts. The identification and selection of the process parameters that may influence the spin casting quality were conducted with the aid of an Ishikawa diagram or cause and effect diagram. Figure 1 presents the Ishikawa diagram adapted from [14]. Spin casting process parameters that may affect the dimensional accuracy of the casting product were identified. The disk closing pressure and runner dimensions were selected as the most significant parameters that can cause variations of the quality characteristic. Runner dimensions include the diameter of the runner cross-section and the runner length which is the distance between the disk center and the location of the master imprint.

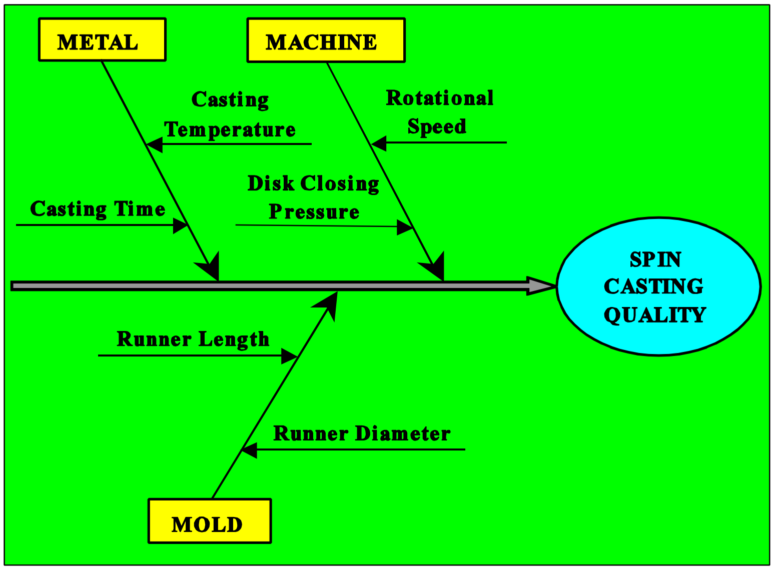

Fig. 1: Ishikawa diagram to identify spin casting process parameters

Table 1: Values of constant process parameters

	Fixed Factors	
Factor	Value	Unit
Casting temperature	450	°C
Casting time	80	s
Rotational speed	550	rpm

Table 2: Values of variable process parameters at three levels

	Control Factors				
Factor	Symbol	Level 1	Level 2	Level 3	Unit
Disk closing pressure	A	2.0	2.5	3.0	bar
Runner diameter	B	6.0	7.5	9.0	mm
Runner length	C	220	240	260	mm

The objective of the optimization is to minimize the amount of dimensional error in the spin casting products that can be used in components or parts requiring higher dimensional accuracy. Percentage change in length of the casting has been selected as the most representative quality characteristic.

The selected spin casting process parameters and their values at different levels are given in Table 1 and Table 2. The range of values of the significant process parameters considered in this study was based on the results of the spin casting characterization experiments conducted by Vezzetti [15]. The range of the disk closing pressure was selected as 2.5-3.0 bars. The runner diameter was selected as 6.0-9.0 mm. The range of the runner length was chosen to be 220-260 mm. The casting temperature, casting time and rotational speed were treated as fixed factors. The assigned values for the casting temperature and the casting time were based on the optimal casting properties of the zinc-based alloy provided by the producer [15]. The rotational speed was found in a previous study to have a minimal relative power to effect variation in the spin casting quality [16].

A polynomial regression model developed by Vezzetti (Equation 1) [15], that defines the relationship between the spin casting process parameters and the casting dimensions, was utilized in this study. Vezzetti [15] presented a structured experimental analysis of the spin casting process that is focused on runner design. Several experimental tests were performed with different process parameters using one type of zinc alloy and one type of silicone rubber mould. The casting time was made constant at 1’ 20”. Casting temperature was also fixed at 450°C. Vezzetti [15] analyzed the experimental results in order to derive the process parameters, the runner dimensions and the cast objects relations by means of a standard deviation analysis and a polynomial regression. A regressive polynomial function (Equation 1) has been obtained for the dimensions of the cast parallelepiped with dimensions of 20 mm x 15 mm x 10 mm. The polynomial regression model [15] is given by:

$$y = 12.12 + 0.970p - 0.225p^2 - 0.0142d^2 \\ - 0.0000144l^2 + 0.0000152wl + 0.000937dl$$

where y is the dimension of the cast parallelepiped with a target value of 15.00 mm, p is the disk closing pressure, d is the runner diameter, l is the runner length and w is the rotational speed.

Table 3: Levels of control factors for each combination

Combination No.	A	B	C
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

A DOE was formulated employing full factorial arrangements. The experimental design comprised all possible combination of factors using the selected significant process parameters considering three levels for each factor. The levels of control factors for each combination are given in Table 3. The quality assessment of the spin casting was carried out by assessing the dimensional accuracy in terms of the percentage change in length from the target dimensional value. The correlation of the significant process parameters with the percentage change in length values was evaluated.

The level of importance of the process parameters on the dimensional accuracy of the spin casting product was determined using the analysis of variance (ANOVA) test. The relative importance of the spin casting parameters with respect to the dimensional accuracy, represented herein as the percentage change in length, was investigated to determine more accurately the optimum combinations of the spin casting process parameters. The ANOVA was established on the sum of squares (*SS*), the degree of freedom (*DOF*), the variance (*V*), the F ratio (*F*) and the percentage contribution (*P*). The sum of squares can be calculated using Equation 2 for the total variation and Equation 3 for the variation due to a factor [13].

$$SS_T = \left[\sum_{i=1}^{N} y_i^2\right] - \frac{T^2}{N}$$

$$SS_A = \left[\sum_{i=1}^{k_A}\left(\frac{A_i^2}{n_{A_i}}\right)\right] - \frac{T^2}{N}$$

where SS_T is the total sums of squares, y is the response, N is the total number of observations, T is the sum of all observations, SS_A is the sum of squares of a factor, k_A is the number of levels of a factor, A_i is the sum of observations under A_i level and n_{Ai} is the number of observations under A_i level.

The percentage contribution P denotes the percentage of the total variance of each individual factor and is computed by Equation 4.

$$P(\%) = \frac{SS'}{SS_T} \text{ x } 100$$

where SS' is the corrected sum of squares and is computed as the sum of squares of factors minus the error variance times the degree of freedom of each factor [17].

RESULTS AND DISCUSSION

The computed percentage change in length for each of the 27 trial conditions are shown in Figure 2. The best results were obtained at combination number 10 followed very closely by combinations 7 and 13. The worst results were obtained at combination number 9. The average values of dimensional accuracy for each parameter at three levels are given in Table 4 and plotted in Figure 3. The main effects of the process parameters when changed from the lower to the higher level are also shown in Table 4.

The results of the analysis of variance are presented in Table 5. The percent contribution P indicates the relative power of a parameter or factor to reduce variation.

Table 4: Average values of percentage change in length at different levels and their main effects

Process Parameter	Level	Percentage Change in Length A	B	C
Average Values	L1	1.331	0.938	0.381
	L2	1.210	1.238	0.965
	L3	0.861	1.227	2.057
Main Effects	L2 - L1	-0.121	0.300	0.584
	L3 - L2	-0.349	-0.011	1.092

Table 5: Results of Analysis of Variance

Process Parameter	*SS*	*DOF*	*V*	*F*	*P(%)*
A	1.0718	2	0.5359	74.3367	5.7
B	0.5200	2	0.2600	36.0639	2.7
C	13.0277	2	6.5138	903.5531	69.6
A x B	0.0288	4	0.0072	1.0000	1.0
A x C	3.6741	4	0.9185	127.4127	19.5
B x C	0.3123	4	0.0781	10.8309	1.5
Error	0.0577	8	0.0072		
Total	18.6924	26			100.0

For a parameter with a high percent contribution, a small variation will have a great influence on the performance. The percentage contribution for each parameter and their interactions are shown in Figure 4. Included in the analysis were the three factors: disk closing pressure (A), runner diameter (B) and runner length (C) and the interactions between these factors (A x B, A x C, B x C).

The resulting optimal combination from the design of experiments method has values of 2.5 bars of disk closing pressure, 6.0 mm diameter of runner cross section and 220 mm runner length. These correspond to level 2 of the closing pressure and level 1 for the runner dimensions. The results are related to low values of the selected significant process parameters. With this combination, the dimensional error of the length has a value of 0.007 mm only. The worst combination has an error value of 0.403 mm. Such worst results are related to low closing pressure of disk and high values of runner dimensions. All of the results were at constant rotational speed of 550 rpm.

The mean response of performance characteristics for one level was calculated as the average of all responses that were obtained with that level. With the average values of percentage change in length (Figure 3) for the three parameters investigated, it is possible to observe that the three process parameters have correlation with the dimensional accuracy of the casting.

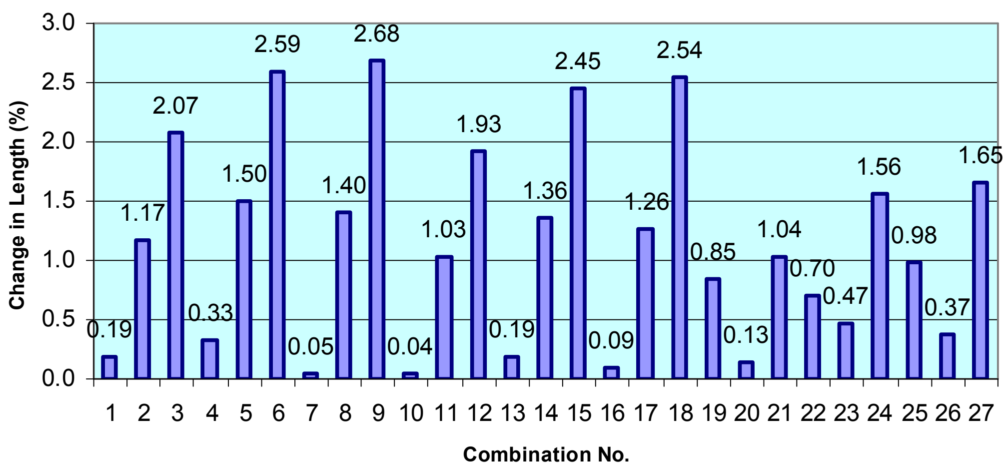

Fig. 2: Dimensional accuracy results in terms of percentage change in length

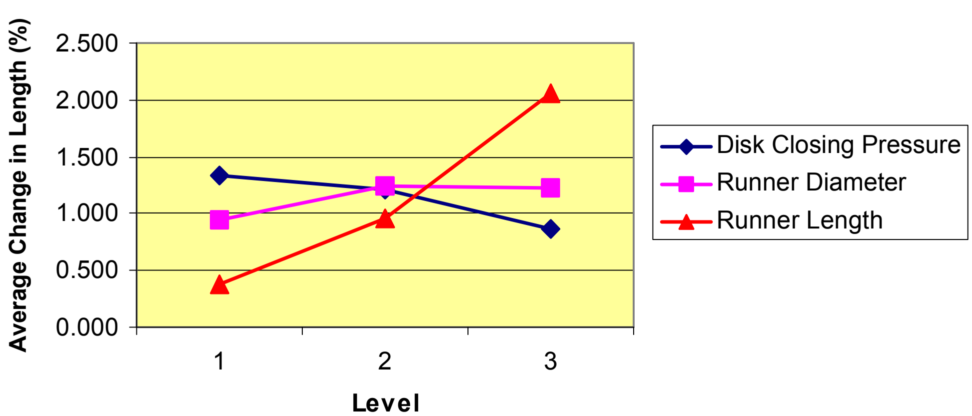

Fig. 3: Graphical representation of the average values of percentage change in length for the parameters under study at three levels

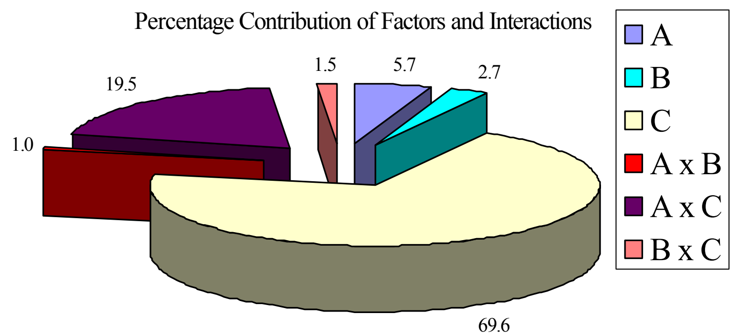

Fig. 4: Percentage contribution for each parameter and their interactions

The percentage change in length varies according to the spin casting process parameter variation. Both the runner diameter and runner length showed positive correlation, while the disk closing pressure showed a negative correlation.

An analysis of variance test was conducted to identify the process parameters that are statistically significant. As per the results of the analysis of variance, runner length (C) was found to be the major factor affecting the dimensional accuracy of the spin casting part with a computed percentage contribution of 69.6% (Figure 4). It was followed by the interaction between the disk closing pressure and the runner length (A x C). The third most significant factor was the disk closing pressure (A) and the fourth was the runner diameter (B). The least significant was the interaction between the factors disk closing pressure and runner diameter (A x B) having a percentage contribution of 1.0% only followed by the interaction between runner diameter and runner length (B x C).

CONCLUSIONS

This study presented an investigation on the optimization and the effect of the process parameters on the dimensional accuracy of the spin casting utilizing a polynomial regression model with a design of experiment approach. The best results of the dimensional accuracy of the spin casting part were obtained when low values of runner length (220 mm), runner diameter (6.0 mm) and disk closing pressure (2.5 bars) were used at constant casting time (1’ 20”), casting temperature (450°C) and rotational speed (550 rpm). The length of the mold runner as well as the interaction between the mold disk closing pressure and the runner length showed significant influence on the dimensional accuracy of the spin casting part. This study showed that a design of experiment methodology can be useful in search of the optimal combination of the process parameters in order to improve the quality of the spin casting products.

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