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The effect of injection parameters on dimensional accuracy of wax patterns for investment casting

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Abstract

Thermal expansion and hot deformation are two phenomena that cause dimensional errors in investment casting. This error occur in dimensions between the die pattern and the wax pattern. Therefore, the wax's thermo-physical and thermo-mechanical properties, the metal die features, and the process parameters affect the dimensions of the wax pattern. Some important effective process parameters are the injection temperature, the injection temperature, the die temperature and the holding time. In this paper, the effect of injection parameters on dimensional accuracy of wax models created by a metallic die has been studied. The Taguchi formulation based on design of experiments has been applied in order to obtain the optimum condition to achieve the best dimensional accuracy. The studied specimen with "F" shape has 10 dimensions. The root mean square (RMS) of dimensional differences has been considered for accuracy analysis. The results has shown that if the injection temperature, the injection pressure and the holding time be considered as 80ºC, 20 bar, and 2.5 minute, respectively, the best accuracy may be achieved.

Nomenclature

A, B, C	Serial of factors
A_i	Total results that include factor A
F	F-ratio
f	Degree of freedom
N	Number of experiments
N_{Ai}	Total number of experiments in which level i of factor A is present
P	Percent influence
S_T	Total variation
S'	Pure sum of squares
T	Total results
V	Mean of squares
V_e	Variance of error term
Y_i	Data results
$\bar{Y}$	Mean of data results

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1. Introduction

One of the oldest and the most accurate manufacturing processes is the investment casting. Because of more time consuming and more expensive factors of investment casting with respect to other manufacturing processes, this process should be used for creating the parts which need more accuracy. Turbine blades and airplane parts under high temperature situations, are some components that the investment casting

may be used [1]. Investment casting starts from creating a mold. The mold cavity has the desired shape and dimensions. Then the mold be used for injection of the wax in order to produce a wax part. The wax part is a sacrificed part and be melted in pouring the melt. Dimensional errors between the die cavity and the wax pattern is an important factors affect the dimensional accuracy of the final specimen. This dimensional errors influences by injection parameters. Therefore, it is necessary to select the optimum conditions of injection parameters in order to achieve the best accuracy in wax specimens.
Dimensional accuracy analysis is one of the most research interest in recent [2-7]. Sabau and Viswanathan [8] studied the wax material properties, in order to better predict the dimensional errors in the step of wax pattern creation of the investment casting process. Some experiments on the wax pattern of the gas turbine blade have been carried out by Rezavand and Behravesh [9]. They obtained the best value for injection temperature and holding time in order to achieve the predictable dimensional errors. They concluded that the holding time is more effective parameter than injection temperature in dimensional accuracy. hard (polyurethane) and soft Room Temperature Vulcanization (RTV) tools have been used by Yarlagadda and Hock [10]. They compared the dimensional accuracy of the wax specimens created by these two molds and optimized the injection parameters on them. Centrifugal casting and argon vacuum casting machines for creating the better wax dimensions have been compared by Cheng, et al, [11]. The factors affects the wax shrinkage and determination of the best values for injection parameters, are the goals of a paper written by Bonilla, et al, [12]. In two separate works Gebelin, et al, [13, 14] modeled the wax injection process for investment casting. The biomedical implant and developments of its casting process to create the FDM pattern have been reviewed by Singh et al, [15]. Hybrid investment casting and its wax dimensions and final specimen dimensions were the main aim of a research reported by Kumar et. al. [16]. In some papers, the surface finish and the accuracy of some biomedical implants manufactured by investment casting process have been studied by Singh et. al. [17-19]. The Bukingham's Pi approach has been used in another paper written by Singh, et. al. [20] in order to model accuracy of the wax patterns. The shrinkage of the thin-walled hollow turbine blade has been modeled by Dong et al, [21]. Barbosa and Puga [22] studied on ultrasonic melt processing of investment casting of aluminum alloys at low pressure.
The Taguchi approach can also reduce the number of experiments and assess the optimum conditions for investment casting. Park et al, [23] studied the Taguchi procedure outputs for less dimensional errors on powder-binder separation. They obtained the better material properties and process parameters than before. Valinejad and Soleymani [24] used the Taguchi approach for prediction of the best values of the operating factors in deposition of the wax. Sun et al, [25] used the Taguchi approach for parametric optimization of selective laser melting.
In this paper the effect of three injection parameters namely injection pressure, injection temperature, and holding time on dimensional accuracy of wax patterns of investment casting are analyzed. For determination of the optimum values of injection parameters in creation of the wax patterns, the Taguchi approach based on design of experiments (DOE) are used. The interaction between factors has also been evaluated.

2. Theoretical Background

2.1. The design of experiments (DOE)

Two separate design methods named full factorial and fractional factorial design are developed in recent years in order to obtain more accurate and further results from experimental procedures. In these two methods, the input parameters influencing the output parameter are studied by programming the experimental process. The Full factorial design method are appropriate where the number of input parameters (named factors) and their effective values (named levels) are few. The number of experiments using the full factorial design method will be the number of levels powered by the number of factors. So, if the number of factors and their levels be greater, the full

factorial design method will be more expensive and time consuming. In this situation, the fractional factorial design method may be better choice.
One of the best methods based on fractional factorial design procedure is the Taguchi approach proposed by Dr. Taguchi after World War II in Japan. He prepared some standard tables, in order to design the experiments. These standard tables is known as Orthogonal Arrays. By using these orthogonal arrays and caring out only few experiments out of full factorial experiments, it is possible to standardize the optimum results [26].

2.2. Performing the analysis of variance in Taguchi method

The first step in design of experiments is determination of the input parameters (factors) and their well-defined values (levels). In another step, an appropriate orthogonal array should be selected based on the number of factors and the number of their levels using the Taguchi method. After using an orthogonal array in Taguchi method and caring out the experiments, the analysis of variance should be performed [27].
If the results of experiments be Y_1; Y_2; . . .Y_N, the first step of performing the analysis of variance is calculating the mean of the results named $\bar{Y}$. the total variation can be evaluated by:

$$S_T = \sum_{i=1}^{N} \left(Y_i - \bar{Y}\right)^2 \quad (1)$$

After that, the variation caused by each input parameter, named sum of squares should be evaluated. For example for input parameter named "A", the formulation is:

$$S_A = \frac{A_1^2}{N_{A_1}} + \frac{A_2^2}{N_{A_2}} + \ldots - \frac{T^2}{N} \quad (2)$$

In above formulation, N_{A2} is the total number of experiments where include the level 2 of the input parameter A. The parameter A_1 is the sum of the results that the level 1 of the input parameter A is present. The parameter T is the total number of results.

The mean squares (or variance) of the results may be evaluated by the following equation:

$$V_A = \frac{S_A}{f_A} \quad (3)$$

The F-ratio of the results can be calculated by equation 4, as follows:

$$F_A = \frac{V_A}{V_e} \quad (4)$$

In above equation, V_e is the variance of the error term. This parameter should be calculated by dividing the S_A by the errors degrees of freedom. The pure sum of squares for each input parameter may be evaluated by:

$$S'_A = S_A - \left(V_e \times f_A\right) \quad (5)$$

Where, f_A is the degrees of freedom for input parameter A.
The percent influence of each factor may be evaluated separately by the following formulae [27]:

$$P_A = \frac{S'_A}{S_T} \quad (6)$$

2.3. Interaction of the input parameters

In some orthogonal arrays, only the factors and their levels can be studied. However, it is realized that the input parameters (factors) may interact to each other. So, some other orthogonal arrays have been developed considering these interaction between the factors. By studying the interactions of the input parameters, the exact and real value for each individual input parameter may be evaluated [28]. Therefore, one should use the developed orthogonal arrays in order to study the interaction between the factors.

2.4. Determination the optimum values for input parameters

After evaluating the effect of each individual factors on output parameter and their interactions between them, the final step of the design of experiments using the Taguchi method is the determination of the optimum values of each factors (input parameters). In Taguchi approach, the less main effects of each factor, performs the optimum values for input parameters.

3. Experimental Program

3.1. Design of appropriate model for analyzing the dimensional accuracy

Design or determination of a pattern is one of the important step in study of the dimensional accuracy of the wax models used in investment casting. The model should have various lengths in order to study various values of length on dimensional accuracy. Also, the model should have various thicknesses in order to study the thickness shrinkages in wax. However, the model should be easy enough in order to remove the wax model from the die, easily. Therefore, a model of F-shape has been selected as a case study model in this paper, considering these above factors. This model is shown in Fig. 1.

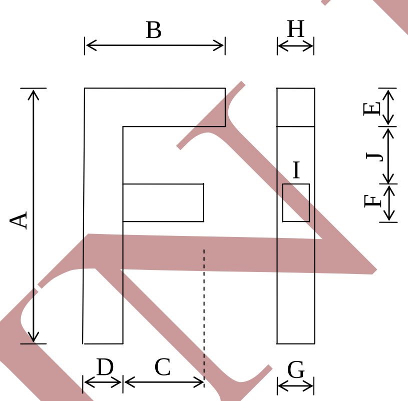

Fig. 1. Geometry of the pattern.

As can be observed from Fig. 1, there are ten sections (named A to J) on the pattern, which the dimensional errors of between the metallic die cavity and the wax model should be evaluated. However, the output parameter (named dimensional accuracy) should be only one data according to the Taguchi orthogonal arrays. So, one should define a characteristic parameter that contains all ten dimensions. In this paper, the root mean square of the dimensional errors of ten sections has been considered as characteristic value. It is evident that if the characteristic value for each experiment be smaller, more accuracy will be achieved and the dimensional errors becomes smaller.

3.2. Design of experiment using the Taguchi method and performing the experiments

Three factors named injection temperature, injection pressure, and holding time were considered as input parameters which are affect the output parameter named dimensional accuracy. It should be noted that the selection of these input parameters has been carried out based on performing good experimental program. Some other input parameters may have insignificant effect on output parameter, such as room humidity. Also, some other input parameters may have significant effect on dimensional accuracy, but they are not measurable or controllable during the tests. For example, the used machine for creating the wax pattern could not measure and control the injection speed during the test. So, it is not possible to consider the injection speed as input parameter affecting the output parameter.
Four different values for each input parameter were selected. These values (levels) is well-defined based on the authors' previous experiences. The input parameters (factors) and their values (levels) are listed in Table 1.

Table 1. Factors and their levels

Serial	Factors	Levels			
		1	2	3	4
A	Injection Temperature (°C)	70	75	80	85
B	Holding Time (min)	1	1.5	2	2.5
C	Injection Pressure (Bar)	20	25	30	35

If the full factorial design method be used, the total number of 4^3 experiments should be carried out. However, by using the Taguchi method based on fractional factorial design method, the total number of required experiments may be reduced to 16. In this reduction procedure, the modified L16 orthogonal array proposed by Taguchi has been used. The other ambient and process parameters were assumed to be constant during the tests.

An aluminum die was used to produce the wax patterns under different injection conditions. The applied die is shown in Fig. 2.

Fig. 2. An aluminum die used to produce of wax patterns under different conditions

This die was produced by a CNC machine. Two guides were designed in order to achieve the alignments. The die temperature was assumed to be constant and equal to 5°C in all experiments. No cooling procedure has been considered in all experiments. So, the wax injected to the die will cooled by heat transfer with ambient. When the upper part of the die is mounting on the lower part, a pressure about 5 MPa has been carried out by the machine, in order to keep the parts of the die and avoid them from separating.

The wax properties are listed in Table 2.

Table 2. Properties of wax used in this research

Name	Filled wax B417
Manufacturer	Remet, England
Filler type	Polystyren
Melting point	75°C
Glassy point	61°C
Viscosity (at 80°C)	1000 cpa
Filler content	38 % wt.
Ash content	0.03 % wt.
Color	Green

The dimensions of various sections of the die cavity are listed in Table 3. Note that these dimensions, selected arbitrarily, are the nominal dimensions of the die cavity.

Table 3. The dimensions of selected pattern

Section	A	B	C	D	E	F	G	H	I	J
Dimension (mm)	110	60	35	15	15	15	12	12	8	30

The modified L16 (M16) orthogonal array based on Taguchi approach are listed in Table 4. After determination of 16 experiments thorough all 64 experiments (based on full factorial design method), the selected experiments were carried out. In each experiment, the dimensions of each sections (A to J) were measured and compared by nominal data reported in Table 3. Then the mean root squares of errors was evaluated. It should be noted that for repeatability, each row in Table 4 (each experiment with specific input parameter values) has been carried out twice. Therefore, two columns named "Result1" and "Result2" have been introduced in Table 4, reporting the root mean squares of experiments for each row.

In order to evaluate the effect of interactions between factors, eight experiments were carried out using the L8 orthogonal array. The levels 1 and 4 of each input parameter were chosen. The L8 orthogonal array are listed in Table 5. Same as in Table 4, there are two columns named

Result1 and Result 2 indicating the root mean squares of each experiments.

Table 4. Modified L16 (M16) orthogonal array of the Taguchi approach and the results of experiment

Trial	Factor A	Factor B		Factor C		Result 1	Result 2
	1	2	3	4	5		
1	1	1	1	1	1	0.6498	0.6395
2	1	2	2	2	2	0.5755	0.6387
3	1	3	3	3	3	0.5643	0.5799
4	1	4	4	4	4	0.6230	0.5603
5	2	1	2	3	4	0.5765	0.5991
6	2	2	1	4	3	0.6967	0.6516
7	2	3	4	1	2	0.5773	0.5036
8	2	4	3	2	1	0.6406	0.5866
9	3	1	3	4	2	0.7304	0.6860
10	3	2	4	3	1	0.5424	0.5749
11	3	3	1	2	4	0.5655	0.6339
12	3	4	2	1	3	0.4738	0.4933
13	4	1	4	2	3	0.6705	0.6758
14	4	2	3	1	4	0.6186	0.6141
15	4	3	2	4	1	0.6264	0.6845
16	4	4	1	3	2	0.5877	0.6527

Table 5. The L8 orthogonal array of the Taguchi approach to evaluate the interactions between factors and the results of experiments

Trial	A	B	A*B	C	A*C	B*C		Result 1	Result 2
	1	2	3	4	5	6	7		
1	1	1	1	1	1	1	1	0.6624	0.6477
2	1	1	1	2	2	2	2	0.6843	0.5877
3	1	2	2	1	1	2	2	0.6203	0.5420
4	1	2	2	2	2	1	1	0.6334	0.5603
5	2	1	2	1	2	1	2	0.6152	0.6678
6	2	1	2	2	1	2	1	0.5722	0.6150
7	2	2	1	1	2	2	1	0.5672	0.6037
8	2	2	1	2	1	1	2	0.5681	0.6374

4. Discussion

By determination of the results (output parameter) and using the equations 1 to 6, the main effects of each input parameter are listed in Table 6.
In order to observe the effects of factors easier, the main effects of each input parameter are shown in Fig. 3. The analysis of variance of the experiments using equations 1-6 are listed in Table 7.

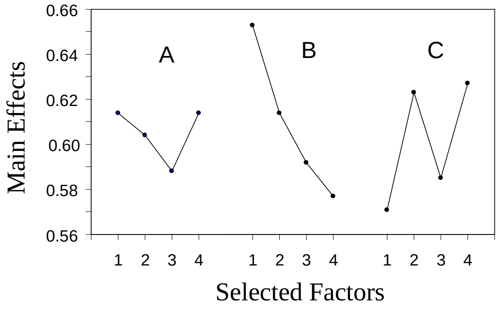

Fig. 3. Main effects of selected factors

Table 6. Main effects of selected factors

Serial	Factor	Level 1	Level 2	Level 3	Level 4
A	Injection Temperature (°C)	0.614	0.604	0.588	0.641
B	Holding Time (min)	0.653	0.614	0.592	0.577
C	Injection Pressure (Bar)	0.571	0.623	0.585	0.627

Table 7. Analysis of variance (ANOVA) of the main factors

Factors	DOF	Sum of squares	Variance	F-ratio	Pure sum	Percent
A	3	0.0124	0.0041	2.5256	0.0117	10.5
B	3	0.0264	0.0081	5.3620	0.0299	26.8
C	3	0.0365	0.0122	7.4104	0.0316	28.3
Other/error	22	0.0361	0.0016			34.4
Total	31					100.0

It can be observed from Table 7 that the influence of *other/error* term is 34.4%. One of the reasons of this significant number is the effects of interactions between the input parameters which has not been considered in Table 7. Another reason may be the experimental errors and the errors caused by measuring apparatus. However, one can determine the effect of interactions between the factors and eliminate that from the term other/error listed in Table 7. Using L8 orthogonal array, 8 experiments were carried out and the results are listed in Table 5. The main effects of input parameters and the analysis of variance of the results using L8 array are reported in Tables 8 and 9, respectively.

Table 8. The main effects of input parameters and the interactions between them

Factor	Level 1	Level 2	L1 – L2
A	0.617	0.606	0.011
B	0.632	0.592	0.040
A * B	0.620	0.603	0.017
C	0.616	0.607	0.009
A * C	0.608	0.615	-0.007
B * C	0.609	0.614	-0.005

Table 9. The analysis of variance of the main factors and their interactions

Factors	DOF	Sum of squares	Variance	F-ratio	Pure sum	Percent
A	1	0.0005	0.0005	0.2536	0.0033	12.1
B	1	0.0064	0.0064	3.1090	0.0062	22.8
A * B	1	0.0011	0.0011	0.5308	0.0010	3.7
C	1	0.0003	0.0003	0.1394	0.0073	26.9
A * C	1	0.0002	0.0002	0.0910	0.0019	7.1
B * C	1	0.0001	0.0001	0.0529	0.0028	10.4
Other/error	1	0.0185	0.0021			17.0
Total	7	0.0271	0.0106			100.0

It is interesting to compare the main effects of the input parameters reported in Tables 7 and 9. It can be observed that the results are close to each other. For example, the percent influence of the factor C from Tables 7 and 8 are 28.3% and 26.9%, respectively. Therefore, the results of Table 9 are in agreement with those reported in Table 7.

One can evaluated the percent influence of interactions of the factors by summing the interactions of each two factors from Table 9 (i.e. 3.7+7.1+10.4 = 21.2%).

The results of Table 9 show that the factor C (injection pressure) is more dominant in dimensional accuracy of wax models created by the studied metallic mold.

Using the Taguchi approach, it was concluded that the optimum levels of input parameters in order to achieve the best dimensional accuracy of wax patterns is 80°C for injection temperature, 2.5 minute for holding time, and 20 bar for injection pressure. The optimum levels of input parameters and their contribution on the overall results are listed in Table 10.

Table 10. Optimum point of factor to achieve good dimensional accuracy and their contribution

Serial	Factors	Value	Level	Contribution
A	Injection temperature	80°C	3	-0.02165
B	Holding time	2.5min	4	-0.03192
C	Injection pressure	20bar	1	-0.03792
Total contribution from all factors				-0.0915
Current grand average performance				0.6092
Expected result at optimum condition				0.5177

It can be observed from Table 4 that the optimum point is 12^{th} trial of the experiments. The characteristic values of this point are 0.4738 and 0.4933. It can be observed from the results listed in Table 4 that, Taguchi procedure can predict the optimum conditions accruable, since the 12^{th} trial of the experiments has smaller root mean square of the dimensional errors.

It should be noted that the dimensional errors of the wax specimen created under optimum levels of input parameters are in the range of the permissible tolerance of investment casting. According to investment casting references, the permissible tolerance for straight dimensions is 0.005 inch per inch or 0.5%. The RMS of the dimensions is 137.3 (dimensions listed in Table 3). So, the permissible tolerance of whole dimensions is 137.3*0.005=0.686. The RMS of dimensional differences of the model produced at optimum conditions is 0.4738 and 0.4933 in two tries. Therefore, the errors are acceptable.

Rezavand and Behravesh [9] studied the effect of injection temperature and holding time on dimensional accuracy of wax patterns in gas turbine blade. They found that the effect of holding time has further effect on dimensional accuracy compared with injection temperature. The results of this paper are in agreement with their results. However, in this paper, the effect of injection pressure has also been studied on dimensional errors of wax specimens. The results have shown that this parameter is the most effective parameter among studied parameters on dimensional accuracy.

5. Summary and Conclusions

Dimensional accuracy of wax specimens used as sacrificed specimen in investment casting may influenced by some input parameters such as injection temperature, holding time, and injection pressure. The effects of each input parameters was studied in this paper. It was concluded that the injection pressure is the most effective parameter on dimensional errors of wax specimens created by the metallic mold. The Taguchi procedure base on fractional factorial design method in design in experiments showed that the optimum values of input parameters in order to achieve the best dimensional accuracy may be 80°C for injection temperature, 2.5 min for holding time, and 20 bar for injection pressure. The dimensional errors of the wax pattern created under these optimum values are in the range of permissible tolerance of investment casting manufacturing procedure.

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