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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 causing dimensional errors in investment casting. This error occurs in dimensions between the die and 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, die temperature, and holding time. In this paper, the effect of injection parameters on the dimensional accuracy of the wax model created by a metallic die is studied. The Taguchi formulation based on the design of experiments is applied to obtain the optimum condition in achieving the best dimensional accuracy. The studied specimen has an "F" shape with 10 dimensions. The root mean square (RMS) of dimensional differences is considered for accuracy analysis. The results show that if the injection temperature, injection pressure, and holding time are considered as 80°C, 20 bar, and 2.5 min, 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

1. Introduction

One of the oldest and most accurate manufacturing processes is 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 which can be produced by investment casting [1]. This casting process starts with making a mold. The mold cavity has the desired shape and dimensions. Then the mold is injected by wax to produce a wax part. The wax part is a sacrificed part which is melted

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through pouring the melt. Dimensional errors between the die cavity and the wax pattern is an important factors affecting the dimensional accuracy of the final specimen. This dimensional error is influenced by the 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 years [2-7]. Sabau and Viswanathan [8] studied the wax material properties to better predict the dimensional errors in the step of wax pattern making. Some experiments on the wax pattern of gas turbine blade have been carried out by Rezavand and Behravesh [9]. They obtained the best value for injection temperature and holding time to achieve predictable dimensional errors. They concluded that the holding time is more effective parameter than the 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 made by these two molds and optimized the injection parameters on them. Centrifugal casting and argon vacuum casting machines for making better wax dimensions have been compared by Cheng et al. [11]. The factors affecting 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 development of its casting process to make the FDM pattern have been reviewed by Singh et al. [15]. Hybrid investment casting and its wax dimensions, as well as final specimen dimensions, were the main aim of the research reported by Kumar et al. [16]. In some papers, the surface finish and 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] to model the 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 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 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 the 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 the dimensional accuracy of wax patterns of investment casting are analyzed. For determination of the optimum values of injection parameters in making the wax patterns, the Taguchi approach based on the design of experiments (DOE) is used. The interaction between factors is also evaluated.

2. Theoretical background

2.1. The design of experiments (DOE)

Two separate design methods named full factorial and fractional factorial designs are developed in recent years 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 is 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 is greater, the full factorial design method will be more expensive and time consuming. In this situation, the fractional factorial design method may be a 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 are known as orthogonal arrays. By using these orthogonal arrays and caring out only a 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 the design of experiments is the 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 the experiments are 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:

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

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

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

In the above formulation, N_{A2} is the total number of experiments including 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:

$$V_A = \frac{S_A}{f_A} \tag{3}$$

The F-ratio of the results can be calculated by Eq. (4) as follows:

$$F_A = \frac{V_A}{V_e} \tag{4}$$

In the 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:

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

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 equation [27]:

$$P_A = \frac{S'_A}{S_T} \tag{6}$$

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 with each other. So, some other orthogonal arrays have been developed considering these interactions 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 interactions 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, the final step of the design of experiments using the Taguchi method is the determination of the optimum values of each factor (input parameters). In Taguchi approach, the less main effects of each factor perform 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 steps in the study of the dimensional accuracy of the wax models used in investment casting. The model should have different lengths to study various values of length on dimensional accuracy. Also, the model should have various thicknesses to study the thickness shrinkages in wax. However, the model should be simple enough to remove the wax model from the die, easily. Therefore, a model of F-shape (Fig. 1) is selected as the case study model in this paper, considering the above factors.

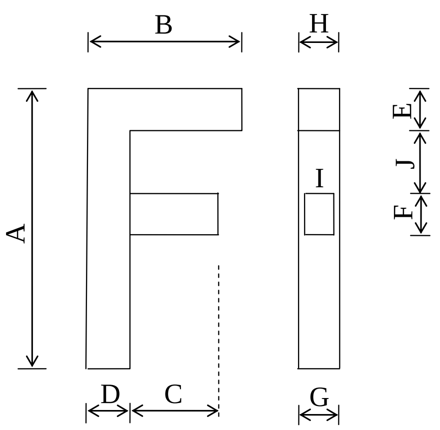

Fig. 1. Geometry of the pattern.

As can be observed from Fig. 1, there are ten sections (named A to J) on the pattern, in which the dimensional errors 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 is considered as the characteristic value. It is evident that if the characteristic value for each experiment is smaller, more accuracy is 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 are considered as input parameters affecting the output parameter named dimensional accuracy. It should be noted that the selection of these input parameters is carried out based on performing a good experimental program. Some other input parameters may have an insignificant effect on the output parameter, such as room humidity. Also, some other input parameters may have a significant effect on dimensional accuracy, but they are not measurable or controllable during the tests. For example, the used machine for making 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 an input parameter affecting the output parameter.
Four different values for each input parameter are 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.
If the full factorial design method is 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.

Table 1. Factors and their levels.

Serial	Factors	Level			
		1	2	3	4
A	Injection temperature (ºC)	70	75	80	85
B	Holding time (min)	1	1.5	2	2.5
C	Injection pressure (bar)	20	25	30	35

In this reduction procedure, the modified L16 orthogonal array proposed by Taguchi is used. The other ambient and process parameters are assumed to be constant during the tests.

An aluminum die (Fig. 2) is used to produce the wax patterns under different injection conditions. This die is produced by a CNC machine. Two guides are designed in order to achieve the alignments. The die temperature is assumed to be constant and equal to 5ºC in all experiments. No cooling procedure is considered in all experiments. So, the wax injected to the die is cooled by heat transfer with ambient. When the upper part of the die is mounting on the lower part, a pressure of about 5 MPa is carried out by the machine to keep the parts of the die and avoid them from separating. The wax properties are listed in Table 2. 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.

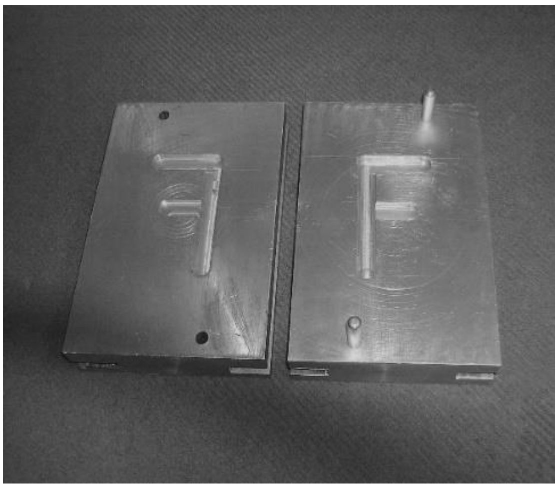

Fig. 2. An aluminum die used to produce wax patterns under different conditions.

Table 2. Properties of wax used in this research.

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

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 the Taguchi approach are listed in Table 4. After determination of 16 experiments out of all 64 experiments (based on full factorial design method), the selected experiments are carried out. In each experiment, the dimensions of each section (A to J) are measured and compared by nominal data reported in Table 3. Then the mean root squares of errors are evaluated. It should be noted that for repeatability, each row in Table 4 (each experiment with specific input parameter values) is carried out twice. Therefore, two columns named "Result 1" and "Result 2" are 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 are carried out using the L8 orthogonal array. The levels 1 and 4 of each input parameter are chosen. The L8 orthogonal array is listed in Table 5. Similar to Table 4, there are two columns named Result 1 and Result 2 indicating the root mean squares of each experiment.

4. Results and discussion

By determination of the results (output parameter) and using Eqs. (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 variance analysis of the experiments using Eqs. (1 to 6) are listed in Table 7. It can be observed that the influence of other/error term is 34.4%. One of the reasons for this significant number is the effects of interactions between the input parameters which is not considered in Table 7. Another reason may be the experimental errors and other errors caused by the 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.

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

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

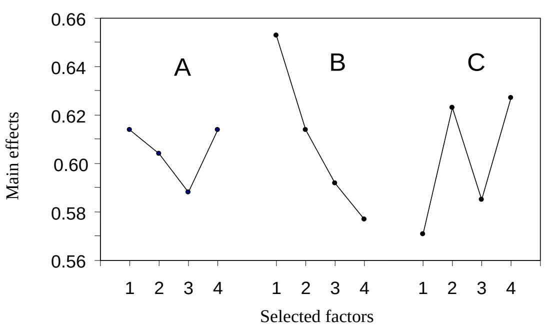

Fig. 3. Main effects of selected factors.

Using L8 orthogonal array, 8 experiments are carried out, and the results are listed in Table 5. The main effects of input parameters and the variance analysis of the results using L8 array are reported in Tables 8 and 9, respectively. 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.

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

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

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

Serial	Factors	Value	Level	Contribution
A	Injection temperature	80^{o}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

Therefore, the results of Table 9 are in agreement with those reported in Table 7. One can evaluate 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 the dimensional accuracy of wax models made by the studied metallic mold.

Using the Taguchi approach, it is concluded that the optimum levels of input parameters in order to achieve the best dimensional accuracy of wax patterns is 80^{o}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 to the overall results are listed in Table 10.

It can be observed from Table 4 that the optimum point is 12th 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 12th trial of the experiments has a smaller root mean square of the dimensional errors.

It should be noted that the dimensional errors of the wax specimen made 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 the dimensional accuracy of wax patterns in a gas turbine blade. They found that the effect of holding time has a further effect on dimensional accuracy compared with injection temperature. The results of this paper are in agreement with their results. However, in the present paper, the effect of injection pressure on dimensional errors of wax specimens is also studied. The results show that this parameter is the most effective parameter among studied parameters on dimensional accuracy.

5. Conclusions

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

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