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Optimizing Blend of Wax Pattern in the Investment Casting Process Using Grey Relational Analysis

Aragaw Mulu Muhaba[1,*]

1 Faculty of Mechanical and Industrial Engineering, Bahir Dar University, Bahir Dar, Ethiopia.

Abstract: Nowadays investment casting is one of the most essential kinds of metal casting, it showed its effectiveness for casting materials with complicated, irregular shapes that are expensive and difficult to machine. The role of this technology is negligible in Ethiopia. This is due to the cost for importation of the wax and refractory materials. In the investment casting, poor surface finish, hardness and too much shrinkage of the wax pattern often yield poor quality of the finished casting. This paper presents optimum blend of wax for investment casting wax pattern. An optimum blend of wax could provide better surface finish, least shrinkage and enough hardness to manufacture intricate part. The test was performed generally with different types of waxes namely vegetable wax, bee wax, Paraffin wax, tree resin and Vaseline, varying their proportions and process parameter. The assessment of the influence of each blend wax on basic properties of wax pattern like surface finish, percentage shrinkage and hardness has been enriched. An attempt was made to find out the set of input parameters, which could offer a set of ideal properties of the wax blend using Grey relational Analysis. From Grey relational analysis, it is found optimum result that the local blend of wax with the vegetable wax type of Candellila, its quantity of 5%, bee wax of 30%, paraffin wax of 60%, tree resin of 10%, Vaseline of 4%, injection temperature of 70°C and the Holding time of 2 hours. The confirmation experiments were carried out to validate the optimal results. Thus, the optimum investment mould compositions were optimized for achieving the combined objectives of higher compression strength of material, lower linear and volumetric expansion value on the dried mould considered in this work.

Keywords: Investment, Dewaxing, Wax pattern, Taguchi, Grey relation, ANOVA.

1. Introduction

Investment casting is one of the oldest manufacturing processes, dating back thousands of years, in which molten metal is poured into an expendable ceramic mold. The mold is formed by using a wax pattern - a disposable piece in the shape of the desired part. The pattern is surrounded, or "invested", into ceramic slurry that hardens into the mold. Investment casting is often referred to as "lost-wax casting" because the wax pattern is melted out of the mold after it has been formed. Lox-wax processes are one-to-one (one pattern creates one part), which increases production time and costs relative to other casting processes. However, since the mold is destroyed during the process, parts with complex geometries and intricate details can be created.

The resulting refractory shell is further hardened by heating and then filled with molten metal to produce the finished part. The working efficiency of investment casting depends largely upon the quality of the disposable pattern since its surface and dimensional characteristics are transferred to the ceramic shell and so to the final casting. Wax is the most widely used pattern material but blends containing different types of waxes need to be modified in terms of their properties through the addition of some materials called additives and fillers. Continuing efforts are always underway to improve the properties of pattern waxes though numerous additives and fillers.

* E-mail: aragmulu@gmail.com

A pattern wax must have the following characteristics. It should have lowest possible thermal expansion so that it can form a pattern with the highest dimensional accuracy. Its melting point is not much higher than the ambient temperature so that the expansion during the injection and the energy consumption can be minimized. After the injection, it should solidify in the mold in a short while. This improves the cycle time in the die and minimizes the solidification shrinkage which leads to the distortion of the patterns on thick sections and to the surface cavitation. It should be resistant to breakage, i.e. it is of sufficient strength and hard enough at room temperature such that the patterns can be self-supporting and handled without damage. It should have a smooth and wettable surface so that a finished part with a smooth surface can be obtained and that the ceramic slurry can adhere to its surface. It should have a low viscosity when melted to simplify its injection and, flow into and fill the thinnest sections of the die. It should be released from the mold easily after formation. It should have very low ash content so that it does not leave any ash inside the ceramic shell. It should be environmentally safe, i.e. it does not lead to the formation of environmentally hazardous or carcinogenic materials upon combustion.

Costs, availability, easy of recycling, toxicity, resistance to binders or solvents are the other important factors in selecting the ingredients of pattern wax compositions. The working efficiency of investment casting can be increased by improving one or more characteristics of the pattern wax, mentioned above, without spoiling the others. [1] In the present study, an attempt is made to produce a wax blend that would offer optimum properties.

The Past investigations show that there is some focusing on blend of wax pattern for investment casting process. Waxes are the complex mixtures of many compounds including natural or synthetic wax, solid fillers and even water. [2]They made tests like penetration, specific gravity, viscosity to determine quality of the wax mixture. The effect of the injection process parameters on the dimensional stability of the wax patterns made using silicon rubber mold has been studied and the optimum injection process parameters to reduce the shrinkage of wax patterns have been suggested. The wax injection processing parameters considered for experimentation were injection temperature, injection pressure and injection time and taguchi approach is applied to optimize the process parameter. The analysis of experimental results showed that the injection temperature and injection pressure greatly influenced the dimensional stability of wax patterns.

The various waxes used in the IC process are of animal type, vegetable type, petroleum type, mineral type, and synthetic type. But many researchers have found that the blends containing only waxes lack the following two properties [3]: (1) strength and rigidity; (2) dimensional control, with regards to surface cavitations resulting from solidification shrinkage during and after pattern injection. So they need to be modified in terms of their properties through the addition of some materials called additives and fillers .[4]Other researchers [5] investigated the effect of addition of the additives to the wax. Additives used for making investment casting waxes included a variety of materials such as resins, plastics, fillers, oils and plasticizers. They concluded that dimensional changes between the pattern tooling and its corresponding cast part occur as a result of thermal expansion, shrinkage, hot deformation, and creep of the pattern material (wax), mold material (shell), and solidifying alloy during the processing. Okhuysen et al. [6] found that shrinkage of the wax is largest components of the overall dimensional changes between the pattern and its corresponding cast part. He used the computer model to predict the wax dimensions and concluded that, one of the main difficulties in using computer models for the prediction of wax dimensions is the lack of constitutive equations and material properties of the wax. He reported the results of a survey of 18 investment casting companies to determine the tooling allowance practices. It appears that there is no consistency in the way investment casters decide on the application of their tooling shrinkage allowances. Gebelin and Jolly [7] explained that the accuracy of the wax patterns used has a direct bearing on the accuracy achievable in the final cast part. They also concluded that, it is usual for the investment caster to use precision-machined full –metal dies for producing wax patterns when large numbers of highly accurate components are required. Rezavand and Behravesh [8] made an experimental study on dimensional stability of simplified wax models. The dimensional accuracy of wax pattern can be determined during injection step which introduces a great influence on the final dimension and thus on finishing process. The focus of this experimental work was on the injection stage, investigating the effects of processing parameters and the shrinkage of critical dimensions. They had chosen injection temperature and holding time as variable processing parameters and concluded that, the final dimensions of wax pattern are affected by: (i) type of wax; (ii) geometry of part and (iii) process parameters.

The wax blend, to be used in the investment casting process, is prepared by mixing different waxes and starch as filler material to reduce the shrinkage of wax patterns. The effect of the injection process parameters on the dimensional stability of the wax patterns made using silicon rubber mould has been studied and the optimum injection process parameters to reduce the shrinkage of wax patterns have been suggested. The wax injection processing parameters considered for experimentation were injection temperature, injection pressure and injection time and taguchi approach is applied to optimize the process parameter. The analysis of experimental results showed that the injection temperature and injection pressure greatly influenced the dimensional stability of wax patterns. [9] And other Author [10] studied on Taguchi concept with better example studied in order to analyze the effects of various input parameters on output response of a process. He worked on designed orthogonal arrays and explained different values in ANOVA table.

In the present study, an attempt has been made to produce a Wax blend which could offer better surface finish, minimum shrinkage and moderate hardness. Experiments were conducted with different types of waxes namely Paraffin wax, Bees wax, Vegetable wax, Tree resin and Vaseline varying their proportions. In each case properties of wax pattern like surface roughness and percentage shrinkage (linear/volumetric) were determined. Using the data obtained from the experiments an attempt is made to find out the set of input parameters, which could offer a set of ideal properties of the wax blend. GREY RELATION method was used to optimize the process parameters.

2. Materials and Methods

A. Materials and testing specimens

In the experimental test, the blend of wax pattern was castoff as the test specimens. After the designed mixture is melted, pour the melted mixture in to the mold having a shape of the stepped cylinder. In the quality testing, the wax blend was mixed, molded. And the wax pattern is used as specimens for volumetric and linear expansion and surface roughness. The wax pattern is prepared from blend of different wax that is being mixed by using the local bee wax, paraffin wax, tree resin and Vaseline. Figure 1 shows the wax pattern using the mixture of local bee wax and blend of waxes respectively. Prior to the experiment, the control factors and their levels should first be determined. This is shown in Table I.

Figure 1. **Blend wax pattern for the Experiment**

Control factors	Level		
	1	2	3
A. Vegetable Wax type	Carnauba	Candellila	-
Vegetable wax percentage	5	10	20
C. Bee wax percentage	10	20	30
D. Paraffin percentage	50	60	70
E. Tree resin percentage	5	10	20
F. Vaseline percentage	2	3	4
G. Injection Temperature (C°)	66	68	70
H. Holding Time(hr)	2	3	4

Table 1. **The control factors and their levels in wax blend experiments**

B. Experimental details

A Taguchi design or an orthogonal array the method is designing the experimental procedure using different types of design like, two, three, four, five, and mixed level [11]. In the study, a three factor mixed level setup is chosen with a total of eighteen numbers of experiments to be conducted and hence the OA L18 was chosen. By giving the parameters and levels for MINITAB [12], the software shows the experimental design layout as seen in table II. A total of 18 groups of experiments were conducted in accordance with the orthogonal array. Each group of experiment should follow the inspecting methods required by Optical profiling machine, Volume measuring flask and Viernier caliper to test surface roughness, volumetric shrinkage as well as linear shrinkage respectively.

(1). *Linear expansion:* Linear shrinkage can be calculated by measuring the difference between die dimensions and pattern dimensions produced.

(2). *Volumetric expansion:* Firstly fill the water in measuring flask and take the initial reading then place the wax pattern in the measuring flask, now the volume of the water raises and take the final reading. The difference between the two readings gives the volume of pattern. Finally the percentage of volumetric contraction of the pattern is given by

$$\left(\frac{Volume\ of\ the\ wax\ pattern - volume\ of\ casting}{Volume\ of\ the\ wax\ pattern}\right) * 100 \tag{1}$$

(3). *Surface roughness:* Surface roughness of the each pattern is measured by using Optical Profiling System device which is of the type Veeco WYKO NTI 100.

Ex. No.	Veg. Wax Types	Veg Wax %	Bee Wax %	Paraffin Wax %	Tree Resin %	Vaseline %	Injection Temp (C)	Holding Time (min)
1	Carnauba	5	10	50	5	2	66	2
2	Carnauba	10	20	60	10	3	68	2
3	Carnauba	20	30	70	20	4	70	2
4	Carnauba	5	10	60	10	4	70	3
5	Carnauba	10	20	70	20	2	66	3
6	Carnauba	20	30	50	5	3	68	3
7	Carnauba	5	20	50	20	3	70	4
8	Carnauba	10	30	60	5	4	66	4
9	Carnauba	20	10	70	10	2	68	4
10	Candellila	5	30	70	10	3	66	2
11	Candellila	10	10	50	20	4	68	2
12	Candellila	20	20	60	5	2	70	2
13	Candellila	5	20	70	5	4	68	3
14	Candellila	10	30	50	10	2	70	3

Ex. No.	Veg. Wax Types	Veg Wax %	Bee Wax %	Paraffin Wax %	Tree Resin %	Vaseline %	Injection Temp (C)	Holding Time (min)
15	Candellila	20	10	60	20	3	66	3
16	Candellila	5	30	60	20	2	68	4
17	Candellila	10	10	70	5	3	70	4
18	Candellila	20	20	50	10	4	66	4

Table 2. **The L18 orthogonal array layout for MINITAB**

3. Analysis of Experiment

The experiments were conducted based on varying the wax pattern parameters, which affect properties to obtain the required quality characteristics. Quality characteristics are the response values or output values expected out of the experiments. There are 64 such quality characteristics. The most commonly used are: 1) Larger the better, 2) Smaller the better, 3) Nominal the best, 4) Classified attribute, 5) Signed target.

A. Experimental Result

The response table for compression strength, linear and volumetric expansion of mould is shown in Table III. A total of 18 groups of experiments were conducted in accordance with the orthogonal array. Taguchi method S/N ratios for linear and volumetric shrinkage and surface roughness are also calculated to analysis the result of response of wax pattern parameter is smaller-the better criteria.

B. Optimization using Grey Relational Analysis

Taguchi's method [13] is focused on the effective application of engineering strategies rather than advanced statistical techniques. The primary goals of Taguchi method are

- A reduction in the variation of a product design to improve quality and lower the loss imparted to society.
- A proper product or process implementation strategy, which can further reduce the level of variation.

The steps involved in Taguchi's Grey Relational Analysis are:

Step 1: The collected experimental data were used to calculate the SN ratio for each group of experiment in accordance with Equation 2 and 3. This is shown in table III.

$$\text{lower-the-better} - 10\log\frac{1}{n}\sum y^2, \tag{2}$$

$$\text{Higher-the-better} - 10\log\frac{1}{n}\sum\frac{1}{y^2} \tag{3}$$

Where n is the number of observations and y is the observed data.

Step 2: In the grey relational analysis [14, 15], data preprocessing is first performed in order to normalize the raw data for analysis. A linear data preprocessing method for raw data can be expressed as

$$x^*{}_i\,(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)}, \quad i = 1, 2\ldots, m; \quad k = 1, 2\ldots, n \tag{4}$$

Where m is the number of experiments, n is the number of response variables. Where $x_i(k)$ is the original sequence of the response, $x_i^*(k)$ is the comparable sequence after data normalization, $\max x_i(k)$ and $\min x_i(k)$ are the largest value and smallest value of $x_i(k)$ in this paper, $m = 18$, $n = 3$ is taken.

No	Linear expansion		Volumetric expansion		Surface Roughness	
	Response (%)	*SN ratio (dB)*	*Response (%)*	*SN ratio (dB)*	*Response (um)*	*SN ratio (dB)*
1	3.00	-9.54243	9.0	-19.0849	2.5	-7.95880
2	2.90	-9.24796	3.5	-10.8814	1.9	-5.57507
3	2.40	-7.60422	2.8	-8.9432	0.9	0.91515
4	3.00	-9.54243	4.0	-12.0412	2.4	-7.60422
5	2.70	-8.62728	3.0	-9.5424	1.8	-5.10545
6	2.50	-7.95880	9.5	-19.5545	1.9	-5.57507
7	3.00	-9.54243	10.0	-20.0000	2.0	-6.02060
8	2.80	-8.94316	9.5	-19.5545	2.3	-7.23456
9	2.00	-6.02060	9.0	-19.0849	1.8	-5.10545
10	2.90	-9.24796	9.8	-19.8245	1.0	0.00000
11	1.80	-5.10545	3.0	-9.5424	1.7	-4.60898
12	1.00	0.00000	2.8	-8.9432	0.7	3.09804
13	2.40	-7.60422	6.1	-15.7066	0.8	1.93820
14	1.60	-4.08240	5.0	-13.9794	1.7	-4.60898
15	0.75	2.49877	2.7	-8.6273	0.7	3.09804
16	3.10	-9.82723	2.5	-7.9588	0.9	0.91515
17	2.50	-7.95880	5.0	-13.9794	1.7	-4.60898
18	0.90	0.91515	2.6	-8.2995	2.0	-6.02060

Table 3. **The responses and SN ratio of L18 orthogonal array**

Step 3: The grey relational coefficient [18] is calculated to express the relationship between the ideal (best) and actual normalized experimental results. After normalization of the original sequence, the grey relational coefficient is calculated using Equation (5). It can be expressed as

$$\gamma\left(x^{*}{}_{0}\left(k\right), x^{*}{}_{i}(k)\right) = \frac{\Delta_{\min} + \tau\Delta_{\max}}{\Delta_{oi}\left(k\right) + \tau\Delta_{\max}} \tag{5}$$

ζ is the distinguishing coefficient and $\zeta \in [0, 1]$. ζ is set at 0.5.

$$\Delta_{min} = \min_{\forall_i} 1 \min_{\forall_k} \Delta_{oi}\ (k)$$

$$\Delta_{max} = \max_{\forall_i} 1 \max_{\forall_k} \Delta_{oi}\ (k)$$

Based on Equation (5) the Grey relational coefficient is given in Table 4.

Step 4: Principal component analysis is specially introduced here to determine the corresponding weighting values for each performance characteristic. The Eigenvalue and Eigenvector are calculated using MINITAB software. There is one of three Eigenvalue larger than one. The eigenvector that corresponded to the largest Eigenvalue 2.0066 was [-0.596, -0.567, and -0.568]. Hence, for this study, the squares of its corresponding eigenvectors are selected as the weighting values of the related performance characteristic. The contributions of compression strength, linear expansion, and volumetric expansion of the mould are indicated as 0.3564, 0.2949, and 0.3493.

Step 5: The grey relational grade represents the level of correlation between the reference sequence and Comparability sequence [16]. It is determined as

$$\Psi\left(x^{*}{}_{o}, x^{*}{}_{i}\right) = \sum_{k=1}^{n} \omega_{k}\gamma\left(x^{*}{}_{o}\left(k\right), x^{*}{}_{i}\left(k\right)\right) \tag{6}$$

Where Ψ is the weight of the kth performance characteristics. Based on Equation (6) and the grey relational coefficient, the grey relational grade can be calculated as follows:

$$\Psi\left(x^{*}{}_{0}, x^{*}{}_{1}\right) = 0.3564 \times 0.333333 + 0.2949 \times 0.375067 + 0.3493 \times 0.406682$$

$= 0.372662$

Step 6: Determination of the Optimal Factor and its Level provides best combination for multiple performance characteristics using Minitab. It is clear from the experiments that experiment no. 15 has large value of grade. Therefore, it provides best combination for multiple performance characteristics. In order to separate out of effects of each process variable on grey relational grade at different levels using Taguchi methodology. Grey relational graph is plotted as shown in Figure 3. Mean value of Grey relational grade is 0.59. Basically, the larger the Grey relational grade, the better is the multiple performance characteristics. Combination of A2B1C3D2E2F3G3 and H1 showed larger value of Grey relational grade for factors A, B, C, D, E, F, G and H respectively. Therefore, A2B1C3D2E2F3G3 is optimal parameter combination for three performance characteristics. However, significant contributions of process parameters still need to be known to predict optimal values of performance characteristics.

Step 7: Analysis of variance (ANOVA) of the overall grade is done to show the significant parameters. This is accomplished by setting the experimental response in Minitab. It shows that the seven parameters A, C, D, E, F, G and H are found to be the major factors with the selected multiple performance characteristics, because their corresponding P ratio is less than 0.05.

Comparability sequence, No	**Grey relational coefficient**			**Overall Grey Relational Grade**
	Linear expansion	***Volumetric expansion***	***Surface Roughness***	
1	0.338548	0.351123	0.333333	0.340681
2	0.344115	0.673204	0.389283	0.464255
3	0.378889	0.859472	0.716924	0.642195
4	0.338548	0.595922	0.340615	0.421731
5	0.356468	0.791747	0.402597	0.511048
6	0.370806	0.341763	0.389283	0.367181
7	0.338548	0.333333	0.377442	0.349193
8	0.350072	0.341763	0.348554	0.346676
9	0.419755	0.351123	0.402597	0.391873
10	0.344115	0.336604	0.640868	0.437209
11	0.447658	0.791747	0.417698	0.548312
12	0.711517	0.859472	1	0.851677
13	0.378889	0.437277	0.826586	0.541843
14	0.483594	0.5	0.417698	0.467284
15	1	0.900061	1	0.9672
16	0.333333	1	0.716924	0.671191
17	0.370806	0.5	0.417698	0.42722
18	0.795573	0.946442	0.377442	0.708643

Table 4. **Grey relational coefficients for 18 comparability sequence**

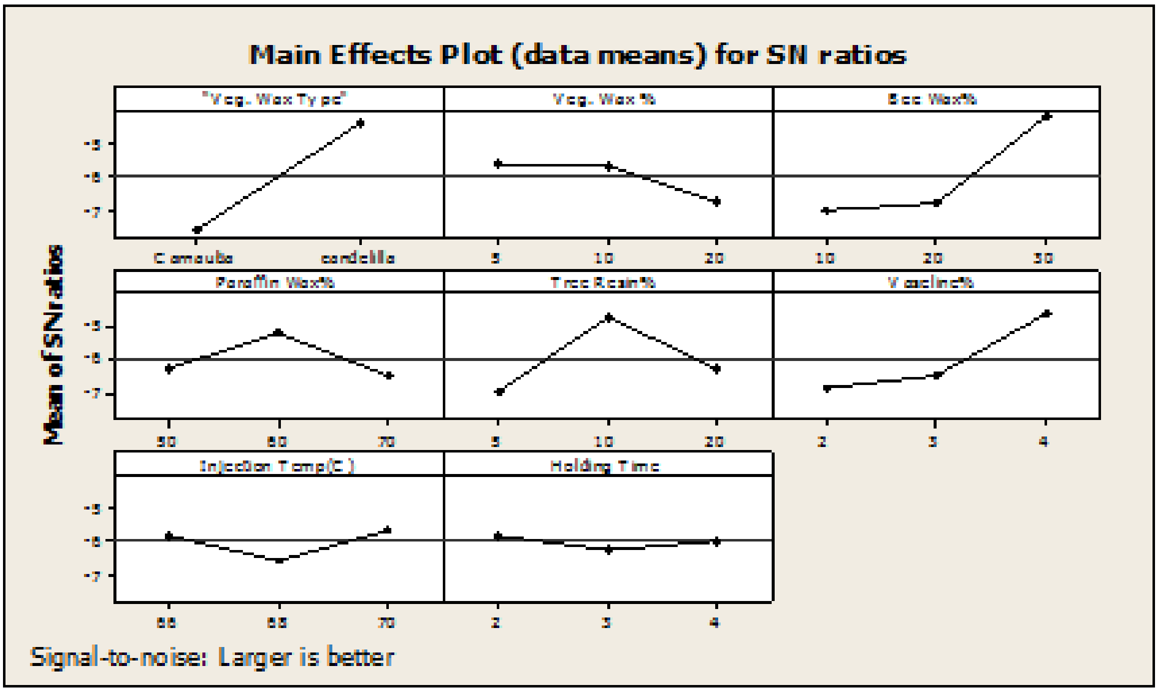

Figure 2. **The plots of the control factor effects for grey relation grade**

Step 8: The optimal grey relational grade (μGRG) is predicted at the selected optimal setting of process parameters. The significant parameters with optimal levels are already selected as: A2, C2, D2, E3, F1, G3 and H3. The estimated mean of the response characteristic is computed as Equation (7) [11].

$$\mu_{GRG} = \overline{T}_{GRG} + \left(A_2 - \overline{T}_{GRG}\right) + \left(C_2 - \overline{T}_{GRG}\right) + \left(D_2 - \overline{T}_{GRG}\right) + \left(E_3 - \overline{T}_{GRG}\right) + \left(F_1 - \overline{T}_{GRG}\right) + \left(G_3 - \overline{T}_{GRG}\right) + \left(H_3 - \overline{T}_{GRG}\right) \tag{7}$$

A confidence interval for the predicted mean on a confirmation run is ±3.32. The 95% confidence interval of the predicted optimal grey relational grade is:

$$[\mu_{GRG} - CI] < \mu_{GRG} < [\mu_{GRG} + CI] \quad i.e. \quad -1.69 < \mu_{GRG} < 4.949$$

Step 9: After the optimal level of pattern parameters has been identified, a verification test needs to be carried out in order to check the accuracy of analysis. Predicting value for multiple performance characteristics at optimal setting of process parameters are confirmed through experimental results.

Then three experiments on optimal combination of multiple quality characteristics are conducted. The result of verification experiment in terms of SN ratio, surface roughness, linear shrinkage and volumetric shrinkage are 30.71dB, -8.71 dB, and -14.45 dB, respectively. It can be seen from the above that SN ratio of each quality characteristic falls into 95% confidence interval, which therefore bears out the reliability of the optimal combination of processing parameters for multiple quality characteristics.

4. Conclusions

Taguchi's Signal-to-Noise ratio and Grey Relational Analysis were applied in this work to improve the multi-response characteristics such as surface roughness, linear and volumetric shrinkage during development process of blend of wax pattern. The conclusions of this work are summarized as follows:

- The optimal parameters combination was determined as A2B2C2D2E3F1G3H3. Namely, the vegetable wax type of Candellila, its quantity of 5%, bee wax of 30%, paraffin wax of 60%, tree resin of 10%, Vaseline of 4%, injection temperature of 700C and the Holding time of 2 hours.
- The predicted results were checked with experimental results and a good agreement was found.
- This work demonstrates the method of using Taguchi methods for optimizing blend of wax pattern for multiple response characteristics.
- The component produced by the lost wax mould has a tolerance of ±0.78 mm/m and a very good surface

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