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Taguchi Approach for Optimization of Parameters that Reduce Dimensional Variation in Investment Casting

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Abstract

Variation in final casting dimensions is a major challenge in the investment casting industry. Additional correction operations such as die tool reworking as well as coining operations affect foundry productivity significantly. In this paper influence of basic parameters such as wax material, mould material, number of ceramic coats and feed location on the dimensional accuracy of stainless-steel casting has been investigated. Two levels of each factor were chosen for experimental study. Taguchi approach has been used to design the experiment and to identify the optimal condition of each parameter for reduced dimensional deviation. Analysis of variance has been carried out to determine the contribution of each process parameter. The result reports that selected parameters have significant effect on the dimensional variability of investment casting. Mould material is the dominant parameter with the largest contribution followed by number of ceramic coats and wax material whereas feed location is having negligible contribution.

Keywords: Innovative foundry technology and materials, Investment casting, Dimensional accuracy, Taguchi method, Optimisation

1. Introduction

Investment casting (IC) process produces components consisting of complex geometrical shape with high degree of dimensional accuracy and excellent surface finish however dimensional deviations from specified tolerances in final casting component is one of the key challenges in this technology. The major stages of investment casting process are: producing wax pattern, ceramic mould forming, dewaxing, sintering and metal casting. Each stage has great influence on the final casting dimension, but having major influence of wax pattern and casting stage [1]. The pattern material should exhibit characteristics such as low melting point, low viscosity, excellent surface finish, fast setting rate, ease in release from mould surface and easy availability at low cost [2]. Wax material is the preferred choice as offers above characteristics. Wax dimensions are affected by type of wax, geometry, and process parameters. Shrinkage of wax, is one of the major components of the overall dimensional change in casting [3]. Impact of different types of waxes on linear and volumetric shrinkage has been studied by Pattnaik et al. [4]. Influence of wax injection process parameters such as injection pressure, temperature and time on dimensional accuracy of wax pattern is the common topic of several researchers [4-8]. Ceramic mould has to pass through various heating and cooling stages such as drying, dewaxing, sintering, pouring, solidification and cooling of castings, thus affected the mould dimensions significantly. Dimensional changes are also occurring due to type of stucco material and binder used and the number of coats applied [9]. Yan et al. [10] investigated the influence of different IC shells formed by varying binder and stucco material on dimensional accuracy of casting. Influence of number of ceramic coats on dimensional accuracy of hybrid investment casting and rapid casting has been studied by Kumar et al. [11] and Singh et al. [12] respectively. Selection of ceramic mould material is crucial and properties such as high melting point, low coefficient of thermal expansion, good permeability, sufficient strength to hold metallostatic pressure and low modulus of rupture for easy removal of shell must be considered [13-14]. Impact of refractory material with varying proportions of zircon and silica, on dimensional variability of thin walled casting has been examined by Bates et al. [15]. The contraction of the cast alloy is determined by the pouring temperature and chemical composition. Influence of different metal grade on casting dimensional accuracy has been studied by several researchers [16-17]. Casting residual stresses and strains developed from dimensional changes and distortions has been studied by Farhangi et al. [18]. Their work reports the effects of various parameters namely mould geometry, chemical composition, pouring temperature and melt superheat temperature on residual stress and strain. In experimental research work, increase in number of parameters and levels to be studied results multiple increase in number of experiments to be conducted. The experimentation work become tedious and expensive and to overcome this Taguchi technique is used which provides simple and efficient experimental design. Several researchers [4-5,11-12,16-17] have applied Taguchi technique to determine the optimized condition of selected parameters and conducted ANOVA analysis to determine the contribution of parameters in variability of results.

In IC processs shrinkage occurred at wax, mould and casting stage affects final casting dimensions significantly. In the present work influence of four basic parameters namely wax type, mould material, number of coats and feed location on shrinkage variation of investment casting has been studied. Taguchi technique is used to determine the individual effects and optimized condition of selected parameter to reduce shrinkage deviation in IC process, which results improvement in dimensional accuracy of casting. Analysis of variance (ANOVA) has been carried out to estimate the contribution of these parameters in variability of results. This differentiates significant and insignificant parameter affecting dimensional discrepancy. This study helps in selecting the specific levels of these parameters to improve the dimensional accuracy by minimizing the shrinkage deviation with reduced experimentation.

2. Experimental work

In the present work selection of process parameter, design of experiment, conduction of experiment and analysis of results has been done using Taguchi approach. The clear steps conducted in Taguchi method has been presented in Fig.1.

2.1 Taguchi approach

Design of experiment (DoE) is the technique of establishing and exploring all possible conditions in an experiment involving several factors. When the number of factors increases, required experimentation grows significantly and conducting large number of experiments becomes expensive and tedious. Taguchi technique uses standard orthogonal array corresponding to levels and factors, which limits the number of experiments with high level of result accuracy. This approach provides systematic, simple but efficient methodology which saves significant amount of time and cost. The methodology of the research work using Taguchi approach is shown in Fig.1.below.

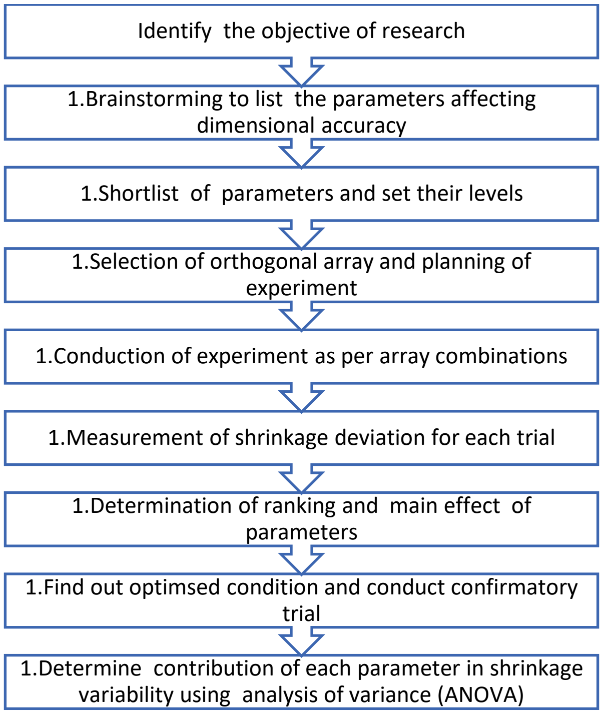

Fig. 1. Methodology of Taguchi approach

2.2. Selection of process parameters

In this experimental study, various parameters from major stages of investment casting such as wax stage, mould stage and casting stage, which affects dimensional accuracy of investment casting have been listed and represented in Ishikawa diagram shown in Fig.2.

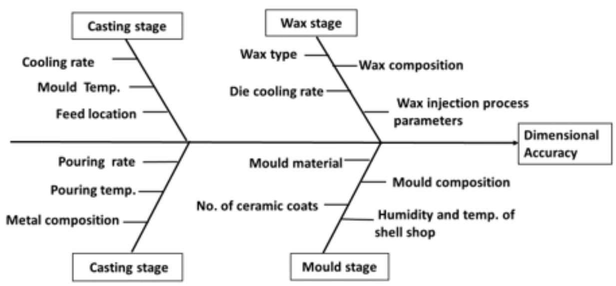

Fig. 2. Factors affecting dimensional accuracy of IC process

The wax stage is the second most important stage affecting the casting dimensions significantly due to heavy shrinkage of wax [3,5]. Process capability study of different stages of investment casting [20] reports that wax pattern dimensions for selected wax type are uniform and consistent. Process parameters such as wax injection pressure, temperature and time from the wax stage are easily controllable by automatic wax injection machine. Thus, to understand the effect of wax type on casting dimension it has been selected for the study. Although ceramic mould has to pass through various heating and cooling stages, dimensional changes in shell are negligible due to low coefficient of expansion of refractory material used for mould [3]. Aluminum silicate and fused silica are the two different types of refractory material generally used in secondary coats of shell forming, to study the impact of these two-mould material on mould dimensions, these have been selected. During casting a large amount of heat has to be transferred through thin shell of mould. Number of ceramic coats determine mould thickness and is a significant parameter as affects heat transfer rate. This is considered as one of the parameters in affecting casting dimensions by several researchers [13-18]. Improper location of feed in complex part, affecting casting dimensional accuracy [21] and thus selected as one of the parameters. The selected parameters and their two common levels used in foundry is shown in Table 1.

Table 1.
Selected parameters and levels for experimentation

Symbol	Factor	Level 1	Level 2
A	Wax type	Filled Wax	Unfilled wax
B	Feed location	Centre	Corner
C	No. of ceramic coats	Lower (6)	Higher (8)
D	Mould material	Fused silica	Alum. silicate

Wax type: In investment casting, conventionally two types of wax: unfilled or filled wax are used for making wax patterns. To produce thin and intricate components, unfilled wax is preferred as produces smooth surface finish and sharpness of minute details. In thick section component unfilled wax causes depressions over surface due to heavy shrinkage of wax material. Thus, to avoid such depressions, filler powder (styrene) has been added to unfilled wax which is referred as filled wax. The filled wax is widely used in industry due to fast setting rate, less shrinkage. To understand the influence of type of wax on casting dimensional stability, these two types of waxes have been selected for study and their composition is as shown in Table 2.

Table 2.
Composition of wax material

	Content in %					
Wax	Paraffin	Resin	Micro wax	Carnoba	Castor oil	Filler
Filled	17	45	2	6	5	25
Un-filled	25	55	5	10	5	-

Mould material: In IC process, ceramic mould is made up of ceramic slurry and stucco. Conventionally zircon slurry and stucco has been used for the primary coat, and fused silica or aluminum silicate for secondary coats. Permeability, hardness and modulus of rupture are the key characteristics of mould which is influenced by the selection of secondary material. Aluminium silicate belongs to the oxide-based engineering ceramics classification, while fused silica (fused quartz) belongs to the glass and glass-ceramics. Fused silica as a mould material provides increase in permeability, easy to handle due to light in weight and good collapsibility compared to aluminum silicate except high in cost. These two mould material; fused silica and aluminum silicate represents two levels. Composition of both the mould material are given in Table 3.

Feed location: During casting stage, location of feed (ingate) plays major role in producing sound casting. In this research work, the selected thin walled rectangular part is considered as one of the complex geometries as it needs multiple feeds (ingates) to produce sound casting. Attached feed restrains the free shrinkage of the component and may results in dimensional changes. The component requires four feeds hence two alternative locations center and corner are identified for the study; as shown in Fig. 3a and 3b respectively. Soundness of casting, for the designed feed size and location, has been ensured by using casting simulation software ‘Softcast’.

Table 3.
Composition of mould material

Mould material	Contents in %			
	SiO_2	Al_2O_3	FE_2O_3	TiO_2
Alum.silicate	55	42	1.5	1.5
Fused silica	99.8	Traces	Traces	Traces

Number of ceramic coats: The primary layer contributes to surface finish where as other coats such as secondary, intermediate, back up and seal provides thickness and strength to mould. Ceramic mould having lower thickness (coats) can result in leakage and bulging defect due to lower breaking strength to sustain metallostatic pressure at high temperature of inside metal. Higher number of coats increases the mould cost due to longer process times and more material consumption. Thick mould provides higher strength to mould but causes difficulty in shell removal. In the present experimental work, number of coats have been selected at two levels (6/9) to study the influence on final casting dimensions.

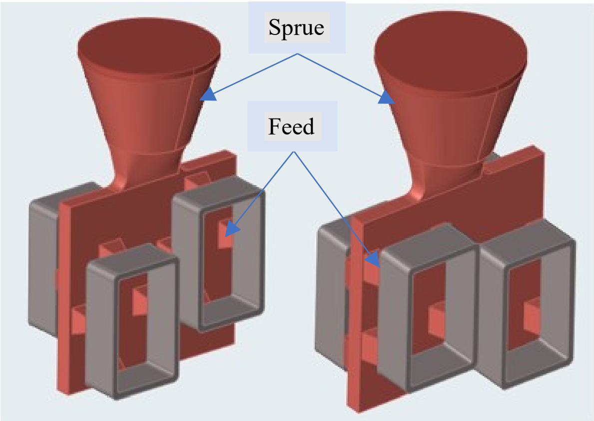

Fig. 3. (a) Centre feed Fig. 3. (b) Corner feed

2.3 Orthogonal array (OA)

Selected four parameters and their two levels are shown in Table 1. Appropriate orthogonal array selection is the next stage. Orthogonal array is the smallest possible design of combinations in which all the parameters are varied simultaneously and their effect is examined concurrently. The $L_8\,2^7$ array is selected for for this experimental research. This array has eight rows i.e. experiments to be conducted and seven columns for assigning factors and their interactions as shown in Table 4. In present case each of the four factors has been varied at two levels and no consideration has given to interaction effect of the parameters. Thus, four factors have been assigned sequentially to first four columns of L_8 OA while as remaining three kept un assigned as explained by Roy [2].

Table 4.
Orthogonal array L_8 (2^7)

Factor	A	B	C	D
Trial				
1	1	1	1	1
2	1	1	1	2
3	1	2	2	1
4	1	2	2	2
5	2	1	2	1
6	2	1	2	2
7	2	2	1	1
8	2	2	1	2

2.4 Experimentation

Details of the component

A thin rectangular, tubular shaped stainless-steel component has been selected as a bench mark for this study. This geometry is a representative of rectangular enclosures which is one of the running industrial components used in food processing industry to cover the various electrical and mechanical parts. This thin wall rectangular component requires multiple feed to produce sound casting and is considered as one of the complex casting in foundries.

The geometry is having outer size (120 mm X 80 mm X 40 mm) with thickness of 6 mm as shown in Figure 4. Critical dimensions of this component are inside width, height, diagonal and flatness which has to maintain in the tolerances provided by reference data sheet. In this work, the height =108 ± 0.88 mm and width = 68 ± 0.55 mm of the rectangular cavity of component has been considered for study.

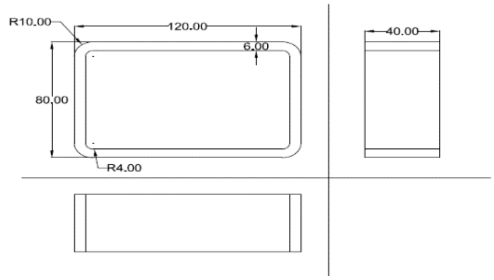

Fig. 4. Dimensions of selected component

Investment casting process

In investment casting, wax pattern making is the first stage, two types of waxes such as filled and unfilled wax has been used to produce wax patterns by injecting wax at set pressure, temperature and holding time. Ejected wax patterns then immediately submersed in chilled water (12°C ±1°C) with insertion of a metallic gauge to avoid deformation of the pattern. Each pattern has been engraved with unique number for identification. The critical dimensions (width and height) of all wax patterns has been measured and recorded. The wax tree is formed by attaching total four wax patterns on vertical riser plate, two on each side. Feed location for each tree has been selected as per L_8 OA. Each wax tree assembly has been attached with a unique shaped wax piece to differentiate the eight assemblies till end. Standard test piece has also been attached opposite to sprue end. Eight ceramic mould has been formed by initially dipping all wax tree assembly in zircon slurry and stuccoes with zircon sand for application of the prime coat. Different mould assemblies are formed by applying varying secondary coats and using fused silica or aluminum silicate as per L_8 OA. These mould assemblies then dried under moisture-controlled environment followed by dewaxing at set pressure and temperature. Stainless steel alloy (austenitic) charge of required composition as shown in Table 5. is prepared and tested on optical emission spectrometer for ensuring the composition. The superheated stainless-steel alloy at 1590°C is then poured in preheated (1100°C) mould.

Table 5.
Chemical composition of Austenitic stainless steel

Element	C	Si	Mn	P	S
%	0.07	1.5	1.5	0.04	0.03
Element	Cr	Ni	Cu	Al	Fe
%	18-20	8-11	0.5	0.05	Balance

After solidification and cooling, knockout operation is done to remove ceramic shell of component, followed by degating to separate the castings from feeding system. Finishing operation like feed grinding and tumblasting has been done. Critical dimensions of casting components (width and height) has been measured to find out the shrinkage from wax dimensions using Equation 1. Shrinkage deviation of component is calculated by comparing with the standard shrinkage value of cast metal using Equation 2.

$$S = 100\,[(l_{wax} - l_{cast})/l_{cast}] \quad (1)$$

$$S_{dev} = S_{component} - S_{standard} \quad (2)$$

Shrinkage deviation (S_{dev}) is the response for the L_8 OA and entered in Table 6.

2.5 Analysis procedure

As per the Taguchi design, eight experiments have been conducted. Taguchi technique designed the orthogonal array in specific combination of trials from which average (main) effect of selected parameters on response can be obtained. The total average effect of each parameter has been calculated by adding the results of the selected parameter at particular level. The lowest value of shrinkage deviation corresponding to main (average) results represents optimized condition of parameters which corresponds to maximum dimensional accuracy. Shrinkage deviation (S_{dev}) at optimum condition has been calculated by using Equation (3) and (4).

$$S_{dev\ opt} = \bar{T} + (\bar{A}_l - \bar{T}) + (\bar{B}_l - \bar{T}) + (\bar{C}_l - \bar{T}) + (\bar{D}_l - \bar{T}) \quad (3)$$

$$where\ \bar{T} = Grand\ average\ performance = \frac{\sum S_{dev}}{n} \quad (4)$$

$$n = no.of\ experiments$$

$$\bar{A}_l, \bar{B}_l \ \ldots\ldots = lower\ value\ of\ shrinkage\ deviation$$

ANOVA of means is carried out on the experimental results to distinguish between the significant and insignificant parameters and to determine the percentage contribution of each parameter which influences the variability of results. Derived ANOVA Table has important terms such as degree of freedom, sum of squares, percentage contribution, F value and P value and is obtained by using following Equations 5-11.

$$DF\ for\ each\ factor\ is\ one\ as\ each\ factor\ has\ two\ levels$$

$$Total\ DF = (trial\ X\ repetitions) - 1 \quad (5)$$

$$S_T = Sum\ of\ squares\ of\ all\ exp.result - contributing\ factor\ (C.F.)$$

$$S_T = \sum_{i=1}^{n} (Y_i)^2 - C.F \quad (6)$$

$$where\ C.F. = \frac{T^2}{n}, T = \sum Y_i \quad (7)$$

$$Contribution\ of\ factor\ A = S_A = \left(\frac{A_1 - A_2}{4}\right)^2 \quad (8)$$

$$S_e = error\ contribution\ = S_T - (S_A + S_B + S_C + S_D) \quad (9)$$

$$F_A = varaince\ ratio\ = \frac{V_A}{V_e} \quad (10)$$

$$P_A = \frac{S_A}{S_T} X\ 100 \quad (11)$$

All the calculated values have been checked using statistical software Minitab17.

3. Results and discussions

The shrinkage deviation of all the casting trials conducted as per the orthogonal array for width as well as height has been measured and is shown in Table 6 as response of L_8 Orthogonal array. This is further analyzed using Taguchi technique to find out the main effect of the individual parameter. Optimized condition of parameters has been predicted from the main effect. Confirmation trial has been conducted using optimized condition of parameter for verifying the predicted optimized condition. ANOVA has been carried out to find out percentage contribution of each parameter and to determine the significant and non-significant parameters contributing variability of result.

Table 6.
Taguchi's orthogonal array L_8 (2^7)

	Process Parameter				Shrinkage deviation	
Expt. No	A	B	C	D	S_{dev} (W)	S_{dev} (H)
1	1	1	1	1	0.163	0.145
2	1	1	1	2	0.203	0.193
3	1	2	2	1	0.198	0.187
4	1	2	2	2	0.262	0.259
5	2	1	2	1	0.219	0.230
6	2	1	2	2	0.289	0.274
7	2	2	1	1	0.180	0.167
8	2	2	1	2	0.249	0.260

Parameters: A-Wax material, B-Feed location , C-No. of ceramic coats, D-Mould material

3.1 Main effect of selected parameters

Main effects of the selected parameters are presented in the response Table 7 and 8 for width and height respectively. The column L_1 and L_2 represent the main effects of level 1 and level 2 of each parameter. The column delta shows the impact of level variation which is ranked from higher to lower in the last column. Higher the delta value more is the significance of the factor thus assigned highest rank. Observation of Table 7 and Table 8 indicates that mould material possess the highest rank 1 and is the greatest significant factor followed by number of coats, wax type and feed location.

The main effect plot for level 1 and level 2 for each process parameter is shown in Fig. 5 and Fig. 6 graphically. This shows that level variation effect on shrinkage deviation is maximum for the parameter D (mould material) for both the dimensions width and height. The level 1 of mould material represents 'fused silica' which produces more accurate dimensions than 'aluminum silicate' level 2. The low coefficient of expansions and high melting point properties of the fused silica produces dimensionally stable components.

Table 7.
Average shrinkage deviation values for width

	L_1	L_2	Delta	Rank
$\bar{A}$	0.2065	0.2342	0.0277	3
$\bar{B}$	0.2185	0.2223	0.0038	4
$\bar{C}$	0.1988	0.242	0.0432	2
$\bar{D}$	0.19	0.2508	0.0608	1

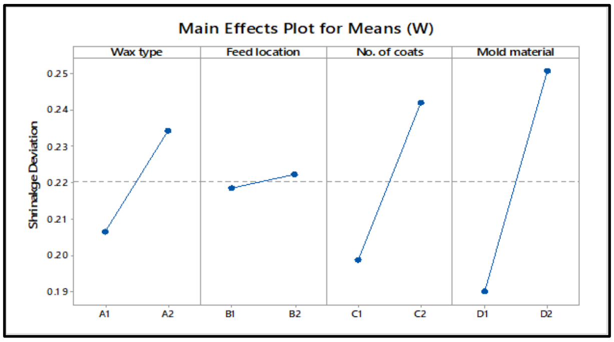

Fig. 5. Main effect of factors on shrinkage deviation of width

Table 8.
Average shrinkage deviation values for height

	L_1	L_2	Delta	Rank
$\bar{A}$	0.196	0.2328	0.0368	3
$\bar{B}$	0.2105	0.2183	0.0078	4
$\bar{C}$	0.191	0.2375	0.0463	2
$\bar{D}$	0.1823	0.2465	0.0643	1

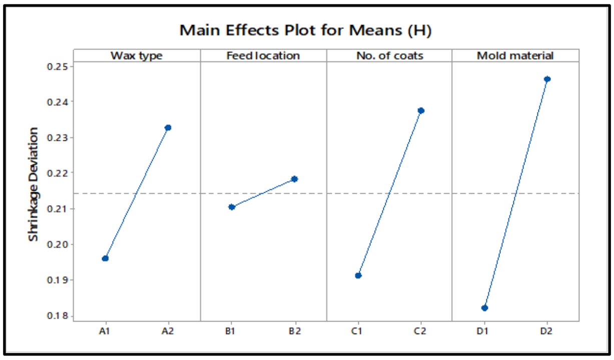

Fig. 6. Main effect of factors on shrinkage deviation of height

The second ranked parameter is 'number of ceramic coats' which is parameter C. Fig. 5. and Fig. 6. depicts that shrinkage deviation is lesser for lower number of coats compared to higher number of coats. Thus thin shell produces dimensionally more accurate component compared to thick mould. Increase in number of ceramic coats makes the shell stronger and provides higher constraint to free shrinkage of metal. Level variation in the parameter A which is 'wax material' has less impact whereas the parameter B 'feed location' have negligible influence in shrinkage deviation. Applied feeds are balanced feeds thus cause uniform shrinkage deviation in investment casting component. Center location of feed pad is better than diagonal as provides uniform constraint. Filled wax produce more dimensional accurate part than unfilled wax as filled wax compensate heavy shrinkage of unfilled wax. This can be observed from plots 5and 6.

3.2 Optimized condition and confirmation trial

In this research work 'deviation in shrinkage' is the output (response) and for this research work quality characteristic 'lower the better' preferred which results improvement in dimensional accuracy. Observation from Figure 5 and Figure 6 depicts that $\bar{A}_1\bar{B}_1\bar{C}_1\bar{D}_1$ is the optimum condition which results in lower shrinkage deviation and thus produces more dimensionally accurate components. Optimized condition is the Trial 1 from Taguchi's orthogonal array. This can be described as use of 'filled wax' for wax pattern, selecting 'center location' of feed and applying 'lower number of coats' on mould by using 'fused silica' as a mould material which provides minimum shrinkage deviation. The geometry is simple with uniform thickness and having balanced feed. Thus, resulted in similar shrinkage deviations in width as well as height. Results for optimized condition has been predicted by using Equation 3 which is compared with the average results obtained by using Equation 4 to find out the improvement in results. Optimized condition results 27% reduction in shrinkage deviation from average shrinkage deviation. Confirmatory experimental trial has been carried out for optimized condition and observed that experimental results are consistent with predicted shrinkage deviation. Table 9. represents the average, predicted and experimental values of shrinkage deviation.

Table 9.
Comparison of different results of shrinkage deviation

	$S_{dev\ (average)}$	S_{dev} (predicted)	$S_{dev\ (cofirmatory\ trial}$
Width	0.22	0.16	0.15
Height	0.21	0.15	0.14

3.3 Analysis of variance (ANOVA)

The derived values of analysis of variance for means using equation 5-11 has been shown in Table 10 and 11 which depicts that, mould material contributes largest contribution in shrinkage deviation which is above 51-57% followed by number of ceramic coats around 26-28 % for both the critical dimensions. Whereas other factors such as wax material having 11-16% contribution shows moderate effect and feed location less than 1% is insignificant contributors. Error contribution is also less than 5% indicate that selection of parameter is proper and no missing parameters left to consider for this study. The P value corresponding to different factors also represents that parameters A, C and D are significant factor in width as well as height shrinkage deviation as P value is less than < 0.05. The column F value indicates that parameter A, C and D is having F values greater than Tabular F value thus these parameters are significant. These calculated values have been verified with statistical software MiniTab 17.

Table 10
Analysis of variance (width shrinkage)

Source	DF	Seq SS	%Contribution	F-Value	P-Value
A	1	0.001540	11.86	15.54	0.029
B	1	0.000028	0.22	0.28	0.631
C	1	0.003741	28.80	37.74	0.009
D	1	0.007381	56.83	74.46	0.003
Error	3	0.000297	2.29		
Total	7	0.012988	100.00		

Table 11.
Analysis of variance (height shrinkage)

Source	DF	Seq SS	%Contribution	F-Value	P-Value
A	1	0.002701	16.74	10.38	0.048
B	1	0.000120	0.74	0.46	0.546
C	1	0.004278	26.51	16.45	0.027
D	1	0.008256	51.17	31.74	0.011
Error	3	0.000780	4.84		
Total	7	0.016136	100.00		

4. Conclusions

1. The influence of wax type, mould material, feed location, and number of ceramic coats on dimensional accuracy of austenitic stainless-steel casting have been investigated using Taguchi approach. In this work shrinkage deviation has been considered as measure of dimensional accuracy. The experimental results were analysed using statistical software Minitab and ANOVA report that use of fused silica as a material for ceramic mould had the most significant influence over improvement in dimensional accuracy followed by selecting minimum number of ceramic coats for mould formation. Filled wax over unfilled wax has moderate effect while as change of feed location from center feed to corner feed had negligible influence on dimensional stability.
2. The minimum shrinkage deviation which corresponds to maximum dimensional accuracy has been observed in stainless steel component which was casted by using filled wax for pattern, fused silica for mould formed with lower number of ceramic coats and locating feed on center of each side was 0.15-0.16 deviation for critical dimensions.While as the maximum shrinkage deviation corresponds to minimum dimensional accuracy were found by producing casting with unfilled wax type, aluminum silicate mould material, with more number of ceramic coats and center location of feed results 0.27-0.29 deviation.
3. Optimized conditions reduce shrinkage deviation by 27 % as compared to average value. Filled wax reduces the heavy shrinkage of wax, fused silica provides stable dimensions due to low coefficient of expansion, center feed balances the shrinkage pull whereas a smaller number of coats offers less restrain to free shrinkage of metal thus resulted less shrinkage deviation i.e. improved dimensional accuracy.

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