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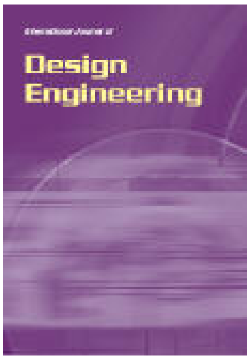

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Analysis of dimensional accuracy of RP pattern and RTV mould inserts using DOE technique

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Abstract: This paper presents the dimensional accuracy of the wax replicas generated by room temperature vulcanisation (RTV) silicon rubber moulding for stepped bar pattern to be used in investment casting. The main purpose of this research work is to investigate the effect of process parameters on dimensional accuracy and test its practical implication in RTV moulding technique. To study the influence of process factors, a 3-factor 4-level (L16) orthogonal array experiment is designed as per Taguchi method and the result is reported. A case study for research of dimensional accuracy of wax patterns created by RTV silicone rubber mould had not been attempted as earlier for stepped bars. As this appends an additional stage in the tooling process, it is evident to estimate and predict the dimensional deviation from RP model and its wax replica. Experimental results show the dimensional accuracy in RTV technique is accurately the same as in traditional moulding. It was realised that RTV tooling technique can be used efficiently to produce wax patterns at optimum condition in investment casting.

Keywords: design of experiments; rapid tooling; RT; rapid prototyping; RP; soft tooling; room temperature vulcanised silicone; RTV mould shrinkage; shrinkage variation in X, Y, Z directions.

Reference to this paper should be made as follows: Kumar, S. (2023) ‘Analysis of dimensional accuracy of RP pattern and RTV mould inserts using DOE technique’, *Int. J. Design Engineering*, Vol. 12, No. 1, pp.1–10.

Biographical notes: Sagar Kumar received his BE (Mechanical) degree from Sir MVIT Bangalore in 2010. He qualified GATE 2010 and completed his MTech (CAD/CAM) from Visvesvaraya National Institute of Technology, Nagpur (India) in 2012. After that, he received his PhD (Mechanical) from Malaviya National Institute of Technology, Jaipur, (India) in 2019. He worked for more than five years as an Associate Professor in the Department of Mechanical Engineering at Poornima College of Engineering, Jaipur. He also worked as a Guest Lecturer at BIT Mesra, Jaipur. He has published over 12 peer reviewed research papers in highly reputed journals. Currently he is working as an Associate Professor in Mechanical Engineering Department at Dr. K.N. Modi University, Newai, Rajasthan India 304021. His research interests include CAD/CAM/CAE, additive manufacturing, product design, RT and reverse engineering.

1 Introduction

The term RP is coming at the phase from 'feel – fit' status to 'feel –fit and function 'status. Rapid tooling (RT) is the link between rapid prototyping (RP) and rapid manufacturing. Researchers across the globe have reported various RT techniques by integrating RP with conventional precision manufacturing, leading to rapid manufacturing systems, like Rapid Investment casting, rapid injection moulding, etc. (Blake and Gouldsen, 1998; Lee et al., 2004; Chua et al., 2005; Idris et al., 2008; Kumar and Singh, 2020, 2018a, 2018b; Sai et al., 2020). The effective integration opens up challenges and endless scope for researchers in this area (Tromans, 2003; Hilton and Jacobs, 2001). RP is valuable in generating the models digitally and directly from the CAD data without having the necessity of elaborate tooling, cutting process time and cost. However RP machines are inherently designed for one or a few runs; it is uneconomical as the number of replicas exceeds four or five numbers or still higher. As an example, Integration of RP with Investment casting is reported but it is successful for small run production if enough number of patterns (say 50 or more numbers) are available. However commercial RP machines are incapable of printing this quantity economically. As a typical case, one RP model (Pattern) of 1' cube approximately requires one hr. time and cost 200–300/INR. This leads us to using RP model as a master pattern for multiplication! Hence replication techniques of RP models become an urgent need of the rapid manufacturing realm and obviously attract global researcher's imagination.

In the case of Rapid investment casting the pattern replication technique is envisaged through the use of room-temperature-vulcanising (RTV) silicon rubber moulds. (Chaudhari1 et al., 2013; Kuo and Chen, 2013). This is also known as soft tooling. RTV mould captures remarkable detail of the pattern due to the flexibility of the silicone. The soft tools can be used to cast materials including wax, gypsum, low melt alloys/metals, urethane, and epoxy or polyester resins with maximum working temperature up to 300°C www.smooth-on.com and there are a variety of RTV compounds available commercially. But a few publications is available on silicone rubber soft tooling technique and dimensional accuracy of wax replicas of RP pattern. Yarlagadda and Teo (2003) compared accuracy of wax patterns created by hard tools (polyurethane mould) and soft tools (RTV mould). They found that for the soft tool, the injection pressure and holding time have little effect on the accuracy of wax patterns and the injection temperature is the only parameter that has an effect on dimensional accuracy. They considered the deviation between mould and the replicas not between RP and its replicas www.stockwell.com. Rahmati and Akbari (2007) worked on Dimensional accuracy of wax patterns created by RTV moulds and concluded RTV silicone rubber mould is a useful alternative of metallic mould to produce wax patterns for investment casting (Yarlagadda and Teo, 2003). They used stereolithography (SLA) patterns not fused deposition modelling (FDM) patterns. Present paper is on acrylonitrile butadiene styrene (ABS) master pattern.

In the present work RP pattern replication technique using RTV mould is explored and its accuracy in X, Y and Z dimensions on the wax replica is reported. DOE is also carriedwith injection temperature (T), injection pressure (P) and mould hold time after injection (t) as factors and its influence on the replica's dimensional deviation is also studied.

2 Experimental set up

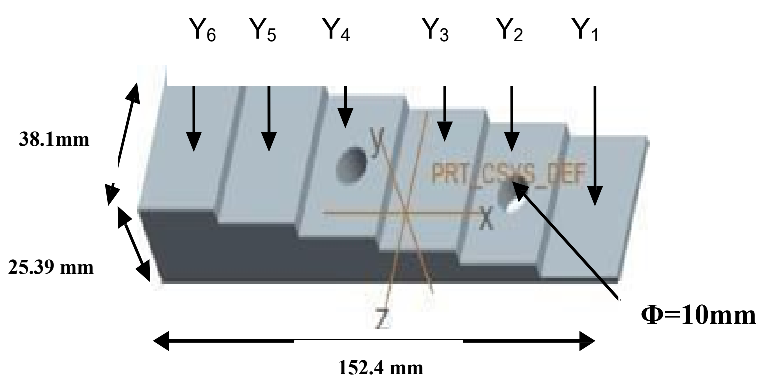
The FDM based native RP machine was used for modelling the pattern (shrinkage stepped bar). This needed only one pattern. The build material used was ABS wires of 1.7mm. RTV moulds were planned and made with mould max 60 Part A and Part B supplied by smooth-on products distributors Mumbai. A wax injector 2.5 kg was used for injecting the wax into the silicon rubber moulds. The respective wax replicas dimensions were recorded for calculating dimensional deviations and ANOVA.

3 Methodology

3.1 Selection of test pattern (Model)

In order to win the acceptance of precision casting industries, it was decided to use the most popular test pattern used by the industry, hence the stepped shrink test bar was selected. The important dimensions to be observed in X, Y and Z directions and a cylindrical hole were included for dimensional deviation study, as in the Figure 1. It is a good choice for its shape, size, manufacturability, etc.

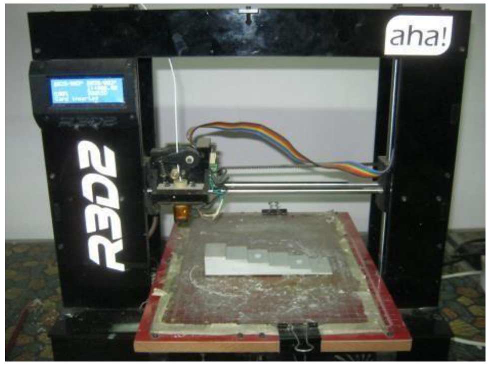
Figure 1 RP stepped bar pattern



3.2 Generation of RP model

The STL file of the test bar is prepared and printed on the 3D printer, with appropriate bed and extruder temperatures, layer thickness, speed, internal fill, etc. The native 3D printer is as shown in Figure 2.

Figure 2 3D printer (see online version for colours)



3.2.1 Selection of RTV Silicone compound

MouldMax60 RTV compounds were selected for its relatively high Shore hardness (60), low linear shrinkage 0.0015 in/in, high mixed viscosity (20,000cps), thermal conductivity (0.347W/mK), pot life (40min), cure time (24hrs), etc.

3.2.2 Mould preparation

The mould box was readied as cope and drag as in the Figure (3a) and Figure (3b). Required weight of the compound A and B are mixed in a jar and bottom mould was made. After 24 hrs. of curing time top mould was also made. Mould alignment and guide pins are very important and were taken care of. The pattern was removed and mould was ready for filling (Zaragoza et al., 2021; Hajare and Gajbhiye, 2022).

Figure 3 (a) silicon core and (b) cavity (see online version for colours)

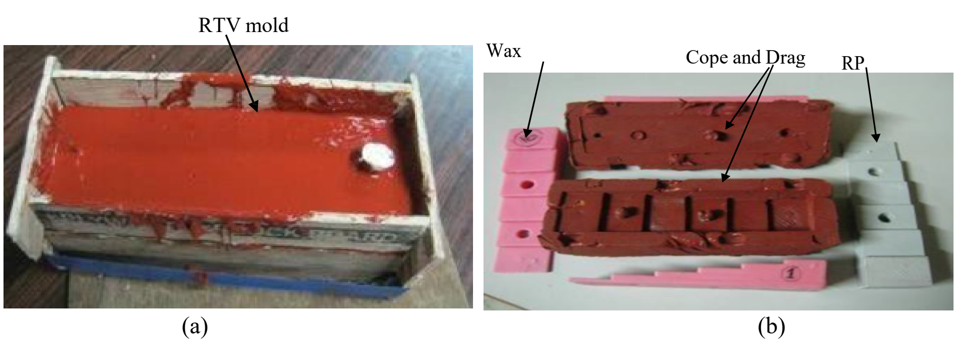


Figure 4 Wax injector (see online version for colours)

It is advised to

1 Use an appropriate mould release agent.

2 Conduct a compatibility test between the rubber mix and the plastic RP pattern: just observe whether the rubber is becoming gummy on smearing on a small non critical area of the pattern

3 Use safety wear – nose mask, sleeves, gloves, safety glasses are compulsory. Care! If the mix is spilled it spoils the work area too. Mould filling- It was decided to use a wax injector of 2.5kg, with temperature (range 30°C –150°C PID controller) and pressure (range 0–2Kg/cm^2) control provisions. Refer Figure 4. Adequate number of runs were performed before getting the injector stabilised. Further trial runs were also tried to understand the process parameters suitable for the proposed test bar. Then the factor and levels were decided to perform DOE. Sixteen combinations were tried and wax replicas were identified as 1 to 16.

4 Experiment and observation

Dimensions of the RP replicas m Wax patterns) were measured and compared with respective CAD dimensions and RP contraction was calculated as in the Table 1. A four level three factor DOE was planned as in the Table 2 and Taguchi L16 orthogonal array experimentation procedures were performed to generate the respective responses. The responses; The linear dimensional deviation in X, Y, Z and Hole diameter were calculated taking the respective RP dimensions as references. The percentage deviations were calculated as given in the Table 1. In most of the cases it was shrinkage and hardly expansion was noticed. The S/N ratios were calculated, trend graphs were plotted for temperature, pressure and time. The responses were used for calculating the ANOVA using MINITAB16.

Table 1 Response table

Dimensions (Refer Figure 1)			*Responses for L16 Taguchi experiment combinations (Dimensional variations)*															
	CAD	*RP*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Y2	7.11	7.26	7.8	6.92	7.2	6.7	6.92	6.98	7.1	7.11	6.9	6.92	7.1	7.9	6.90	7.2	7.17	6.72
Y3	11.68	11.64	11.00	10.9	11	10.8	10.94	11	10.9	11.08	10.78	11	11.04	11.28	11.02	11.1	11.1	11.02
Y4	16.25	15.80	14.92	14.88	14.8	14.82	14.82	15	14.8	14.92	14.9	14.98	14.92	15.1	15.22	15.32	14.74	14.96
Y5	20.82	20.58	19.38	19.32	19.28	19.48	19.42	19.52	19.34	19.56	19.4	19.48	19.4	19.72	19.84	19.62	19.4	19.74
Y6	25.39	24.52	23.96	24.0	24	24	23.7	23.9	24.12	24.1	23.9	24.14	24.02	24.22	24.20	24.42	24.06	24.22
X7	152.40	152.2	147.96	147.6	147.3	147.92	147.22	147.48	147.66	148.76	147.4	147.58	147.5	147.5	148.06	147.6	148.4	148
Z	38.10	38.2	36.7	36.74	36.48	36.7	36.62	36.78	36.72	36.66	36.60	36.56	36.72	36.60	36.58	36.78	36.98	36.96
H	10.00	9.26	9.21	9.34	9.42	9.63	9.26	9.29	9.19	9.32	9.23	9.25	9.35	9.32	9.27	9.31	9.31	9.12
Percentage shrinkage calculated from above responses																		
Y(Y2 to Y5)			5.09	5.74	4.73	6.61	5.63	4.88	3.64	4.09	5.93	5.17	4.66	3.12	4.38	3.28	4.57	5.5
X(X7)			2.78	3.02	3.21	2.81	3.27	3.10	2.98	2.26	3.15	3.03	3.08	3.08	2.72	3.02	2.49	2.75
Z			3.92	3.82	4.50	3.92	4.13	3.71	3.87	4.03	4.18	4.29	3.87	4.18	4.24	3.92	3.19	3.24
H			0.53	–0.86	–1.72	–1.72	0	–0.32	0.75	–0.64	0.32	0.10	–0.97	–0.43	–0.10	–0.53	–0.53	–1.72

Table 2 Operating parameters

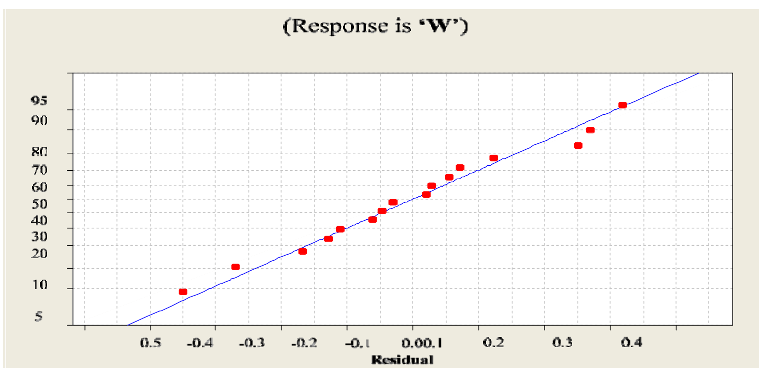
SI. no	*Factors*	*Levels*			
		1	*2*	*3*	*4*
A	Temperature (°C). T	75	80	85	90
B	Pressure (Kg/cm^2). P	0.8	0.9	1.0	1.1
C	Time (min).t	4	6	8	10

5 Results and discussion

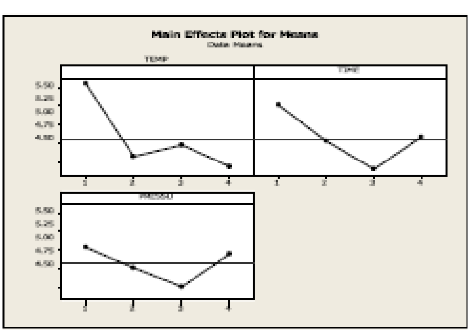
For the sake of simplicity the dimensional deviation of RP replica with reference to RP pattern is termed as shrinkage. Then percentage shrinkage is estimated in X, Y, Z directions. The selected test bars for study in this paper is the one being regularly used in the precision casting sector. This might enhance the adaptability and acceptance from the end users and hence linking the findings with the industry might become easy. Since FDM models (patterns) have contraction in X, Y, Z directions it was advised to quantify the contraction compensation of wax (RP replicas) also in X, Y, Z directions. This might help when it decides to providing total (cumulative) compensation on CAD drawing stage. It can avoid estimating individual contraction of RTV mould provided the combined contraction relevant to 'RP Model to its replica' is estimated. This will prove helpful to the shop floor as dimensions of the flexible moulds are often hard to estimate compared to making measurements on RP and Replica . Hence total compensation is RP contraction (% dimensional deviation, it could be + or –) + RP to Replica contraction + Alloy contraction.

It can be read out from the Taguchi response that the shrinkage in Y direction is 3.5%–6% Z Direction is 3.5% to 4.5% X direction is 2.5% to 3.5 % Shrinkage on one typical internal dimension (Hole dia) is an example for restricted dimensions, and it is clear that when the wax is restricted by the mould it hardly shrinks. The shrink value observed is +0.50 to –1.7%. One can well assume the average value as approximately –1.0%. ie., it has an apparent expansion on the restricted dimensions; this is a complex phenomenon, it may even explore the thermal expansion of the RTV, accuracy of RP on cylindrical dimensions, etc. to explain it. Above values reported represents 'RP to Replica contraction'' and above stated alloy contraction always is available with the shop floor for different alloys cast. But the RP contraction is quite a controversial in spite of several technical publications. However academia agrees with RP models behaviour that it shrinksin X, Y and Z directions differently and it tends to expand in its z direction. The typical values found to represent RP contraction is 0.34 to –3.0% –0.2% and 0.13% respectively in Y, Z and X direction. Once it is put together all the three contraction components can quantify the compensation required on the CAD. It's worth to recall now that wax contraction is hardly 1% in metallic mould ,it shows wax behaves differently in metal moulds and in RTV moulds .This may be due to the difference in the respective thermal conductivity (thermal diffusivity) and modulus. In the precision castings sector the above findings are unacceptable and remain irrelevant as it is quoted without reference and limits. It is very important to notice that in X direction which is taken along the direction of wax flow/wax injection the wax replica has a tendency to shrink less compared to Z direction which is taken to be perpendicular to the wax flow. This conforms to the technical literature published by RTV suppliers that it shrinks less in the flow direction [www.xiameter.com]. The applicability of above shrinkage values is 0mm–150mm, 0mm–40mm and 0–25 mm for X, Z and Y axes respectively. The Taguchi experiment S/N ratio and trend charts gives us the impact of wax temperature(T), Hold time (t) and wax injection pressure (p) on the output that is measured in the form of shrinkage. It is may be inappropriate to term the response as shrinkage; it is shear dimensional deviation since It is not attributed to just a phase change, in fact there appears an interplay of thermo physical properties of RTV compound and process factors involved in mould making, like thermal diffusivity, thermal conductivity, mould wall thickness, modulus (strength), wax flow direction, size and geometry besides the process factors that considered. It can state from the trend graph that 80 – 900C wax temperature, Pressure 1 bar and hold time 8minutes give best result in Y direction where in Z direction pressure is not very impactful. Temperature and Hold time is more impactful and it is more evident as values are increased and the Injection temperature is more impactful in all the cases. It was observed that impact of pressure is very different in Z and X directions, in Z direction it is found more impactful, may be, the hydrodynamic pressure is more on across the flow, i.e., perpendicular to X (injection) direction.

Figure 5 (a) Normal probability plot (b) Y2-Y5 (Y direction) (c) (X- direction) (d) (Z direction) (e) (Hole) (see online version for colours)



(a)



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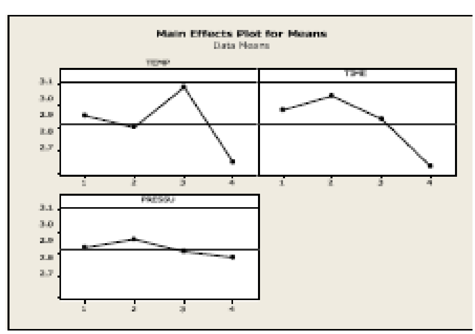
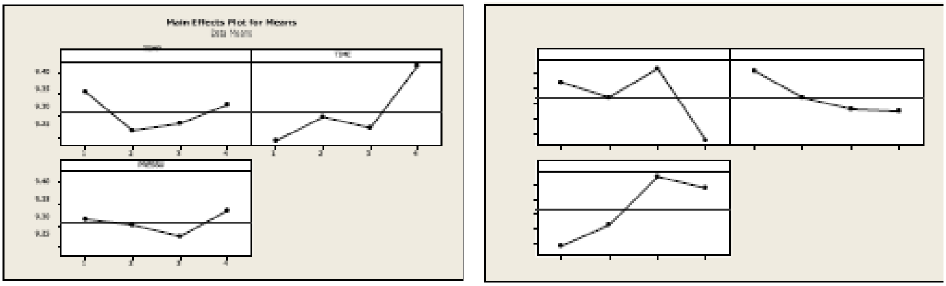


(b)

Figure 5 (a) Normal probability plot (b) Y2–Y5 (Y direction) (c) (X- direction) (d) (Z direction) (e) (hole) (continued) (see online version for colours)



(a) (b)

Table 3 General linear model: W versus temp, time, pressure

Factor	*Type*	*Levels*	*Values*
Temp.(°C)	Random	4	75, 80, 85, 90
Time (min)	Random	4	4, 6, 8, 9
Pressure (bar)	Random	4	0.8, 0.9, 1.0, 1.1

Table 4 Analysis of variance (ANOVA) for W, using adjusted SS for tests

Source	*DF*	*Seq. SS*	*Adj. SS*	*Adj. MS*	*F*	*P*
Temp (°C)	3	0.52667	0.52667	0.17556	2.02	0.213
Time (min)	3	0.19132	0.19132	0.06377	0.73	0.569
Pressure (bar)	3	0.57607	0.57607	0.19202	2.21	0.188
Error %	6	0.52219	0.52219	0.08703		
Total	15	1.81624				

Note: S = 0.295011, R-Sq. = 71.25%, R-Sq. (adj.) = 28.12%.

6 Conclusions

This work reports shrinkage behaviour of wax in the RTV silicone rubber compounds under the influence of wax injection temperature, Mould hold time and Wax injection pressure. This work helps open up the black box of ‘cumulative shrinkage compensation‟ required on the CAD drawing when integration of RP with precision castings is attempted. This is the need of the present day precision casters but unfortunately it is a complex issue and a live challenge to the academic community and researchers. Though the wax pattern generated by RTV demonstrates its capability to be an alternative to metallic moulds its full potential can be realised only when RTV and RP go hand. Though sporadic commercialisation of RTV and RP integration is being reported a comprehensive optimisation and standardisation is essential before it could win the trust of precision cast houses.

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