Int J Adv Manuf Technol (2006) 29: 79–88
DOI 10.1007/s00170-004-2307-0

ORIGINAL ARTICLE

K. Chockalingam · N. Jawahar · K.N. Ramanathan · P.S. Banerjee

Optimization of stereolithography process parameters for part strength using design of experiments

Received: 8 March 2004 / Accepted: 15 June 2004 / Published online: 9 March 2005

Abstract Rapid prototyping (RP) is an emerging technology that has been implemented in many spheres of industry – particularly in the area of new product development. Growth of this field has been rapid in recent years. Stereolithography (SL) is one of the most popular RP process used for rapid tooling applications. There are several process parameters contributing to the strength of an SL product. The contribution of three parameters; namely, layer thickness, post curing time and orientation are most significant. In light of this concern, an attempt has been made to study and optimize these process parameters for maximum part strength, and develop an empirical relationship between process parameters and part strength through design of experiments (DOE). The proposed DOE is verified with the data of experiments conducted under standard conditions.

Keywords Design of experiments · Process optimization · Rapid prototyping · Rapid tooling · Stereolithography · Taguchi method

Notation and nomenclature

A_1, A_2, A_3	Regression coefficients of layer thickness
ANOVA	Analysis of variance
B_1, B_2, B_3	Regression coefficients of post-curing time
C	Sum of constants
C_1, C_2, C_3	Regression coefficients of orientation
CF	Correction factor
CS	Cross-sectional area
D_1, D_2	Regression coefficients of $Lt.Pc$
DOE	Design of experiments
f	Degrees of freedom
F	Variance ratio
i	Level identifier of Lt
j	Level identifier of Pc
k	Level identifier of O
Lt	Layer thickness
Lt_i	Effect of the ith level of Lt on tensile strength
$(Lt.Pc)_{ij}$	Interaction effect of Lt and Pc on tensile strength
$(Lt.O)_{ik}$	Interaction effect of Lt and O on tensile strength
$(Lt.Pc.O)_{ijk}$	Interaction effect of Lt, Pc and O on tensile strength
n	Number of experiments at level i
N	Total number of experiments
O	Orientation
O_k	Effect of the kth level of O on tensile strength
OA	Orthogonal array
P	Percentage of contribution
Pc	Post-curing time
Pc_j	Effect of jth level of Pc on tensile strength
$(PcO)_{jk}$	Interaction effect of Pc and O on tensile strength
RP	Rapid prototyping
SL	Stereolithography
SLA	Stereolithography apparatus
S/N	Signal-to-noise ratio
SS	Sum of squares
SS_f	Factor sum of squares
SS_T	Total sum of squares
t	Thickness
T	Sum of TS_{ijk} of 18 experiments
TS	Regression value of response variable (tensile strength)
TS_{ijk}	Tensile strength at the ith level of Lt, jth level of Pc and kth level of O
UV	Ultraviolet
UL	Ultimate load
V	Variance
V_e	Error variance
V_f	Variance of factor
w	Width

K. Chockalingam · N. Jawahar (✉) · K.N. Ramanathan
Department of Mechanical Engineering,
Thiagarajar College of Engineering,
Madurai 625 015, India
E-mail: jawahartce@yahoo.co.uk
Tel.: +91-452-2482240
Fax: +91-452-2483427

P.S. Banerjee
Central Mechanical Engineering Research Institute,
Durgapur 713209, India

y	Response variable
ε_{ijk}	Random error
η	Average S/N ratio
μ	Average value of the response variable
ι_I	Average value of tensile strength at the ith level of Lt
$(\iota\beta)_{ij}$	Average value of tensile strength at the ith level of Lt and jth level of Pc
$(\iota\gamma)_{ik}$	Average value of tensile strength at the ith level of Lt and kth level of O
β_j	Average value of tensile strength at the jth level of Pc
$(\beta\gamma)_{jk}$	Average value of tensile strength at the jth level of Pc and kth level of O
γ_k	Average value of tensile strength at the kth level of O

1 Introduction

In a customer-driven market, each and every manufacturer has to produce its products in a very short span of time. This is a prerequisite to survive in the global market. A decrease in product development cycle time and an increase in product complexity requires new ways to realize innovative ideas. In response to these challenges, a spectrum of new technologies has evolved that helps develop new products and broaden the number of product alternatives. One such technology is layered manufacturing, which produces parts by deposition of material, layer by layer. Today, the key benefits of layered manufacturing are mostly derived from its ability to create physical models – regardless of their shapes and complexities – directly from CAD models. In addition, models built with the help of layered manufacturing processes are used as tools for casting and moulding, i.e. dies for an injection moulding process and patterns for a casting process. This is a member of the set of time compression technologies and is popularly known as rapid prototyping (RP). It shortens the product development cycle time to a great extent. It is also known as a solid freeform fabrication technique, which allows the transformation of digital design into a 3D solid object for production of models, prototypes and tooling [1]. RP is essentially an additive fabrication technique, which builds the products by adding/depositing raw material, layer by layer, replacing a conventional metal removal process [2]. The representatives of RP processes are selective laser sintering (SLS), laminated object manufacturing (LOM), three-dimensional printing (3DP), fused deposition modeling (FDM) and stereolithography (SL) [1, 3]. This paper considers the SL process and addresses its part strength characteristics. Though SL is being recognized as an innovative technology, it still cannot be fully utilized in practical applications since lacks in SL Part quality characteristics compared to conventional processes. These characteristics can be divided into physical characteristics and mechanical characteristics. The physical characteristics are surface finish, dimensional accuracy, curl and distortion, whereas the mechanical characteristics are flexural, tensile, compressive and impact strength. Part strength is crucial in the case of rapid tooling since the models have to withstand pressures during test of fitment and also during use as dies for injection moulding. The dies made through the SL process are subjected to high tension due to high injection pressure. Various attempts made to increase the strength of dies in the tooling application of SL technology include using a minimum ejection force [4] and different compositions of epoxy resins [1, 5, 6]. This work aims to further increase the tensile strength of the SL component by identifying and optimizing the process parameters that influence the part strength apart from other considerations attempted earlier. In this paper, an attempt has been made to identify the process parameters that influence the strength of parts made by the SL process – one of the processes used for rapid tooling, optimize the parameter levels and evolve an empirical regression equation between tensile strength and their influencing parameters. A statistical tool DOE is used for the above purposes of identification of process parameters, optimization of selected levels and establishment of regression equation. The proposed methodology is verified with the data of experiments conducted under standard conditions. The rest of the paper is organized as follows: Sect. 2 gives overview of the SL process; problem definition is dealt in Sect. 3; optimization of SL part strength is described in Sect. 4; Sect. 5 deals with performance evaluation; and conclusions and scope for future research are delineated in Sect. 6.

2 Stereolithography process

When time is critical and competition is fierce, SL provides a clear decisive edge over other conventional prototype manufacturing techniques. SL uses an ultraviolet (UV) laser beam to cure a photosensitive monomer resin layer by layer to build prototypes having complex shapes. In the SL process, a tessellated CAD model (STL file) is first sliced into very thin cross sections and then the resulting slice data is for part building in a stereolithography apparatus (SLA). SLA uses a computer-controlled laser to cure a photosensitive resin (epoxy or acrylate) layer by layer to create a 3D part. The schematic diagram of the SL process is shown in Fig. 1.

Here, the prototype is built on a platform positioned just below the surface of liquid epoxy or acrylate resin contained in a vat. A low-power highly focused UV laser beam traces out the first layer, selectively solidifying the resin while leaving the excess area liquid. Next, an elevator incrementally lowers the platform into the vat by a distance equal to the layer thickness value chosen. Since the photo-curable resin is relatively viscous, simply lowering the elevator by the small distance (equal to layer thickness) down into the vat does not permit the liquid to instantly cover the whole of the upper surface of the cured part in a uniform manner. A recoating mechanism is therefore required to facilitate this process. For that purpose, the elevator is raised to the desired height and a wiper arm traverses over its surface to quickly level the excess viscous material. After a short wait (z wait) for the resin to get stabilized, the laser traces the next layer above the first layer. The process is continued till the final layer is built. Then, the solid part is removed from the vat and rinsed to

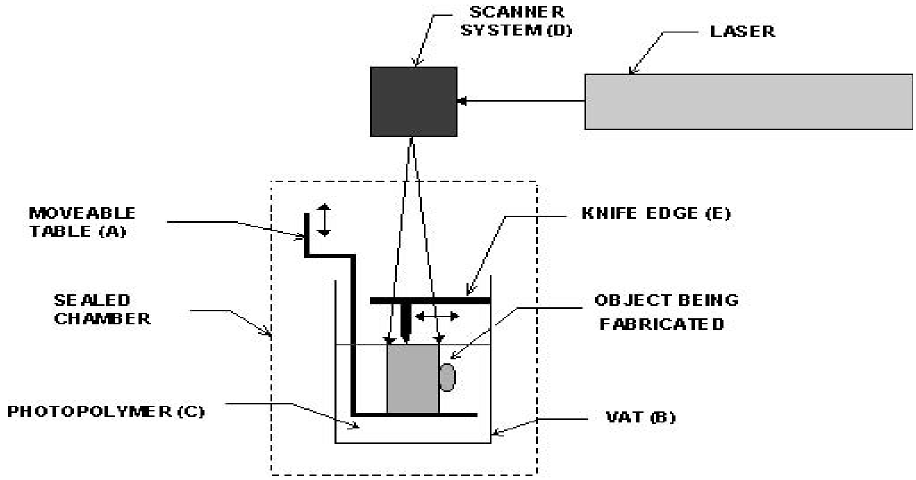


Fig. 1. Stereolithography process

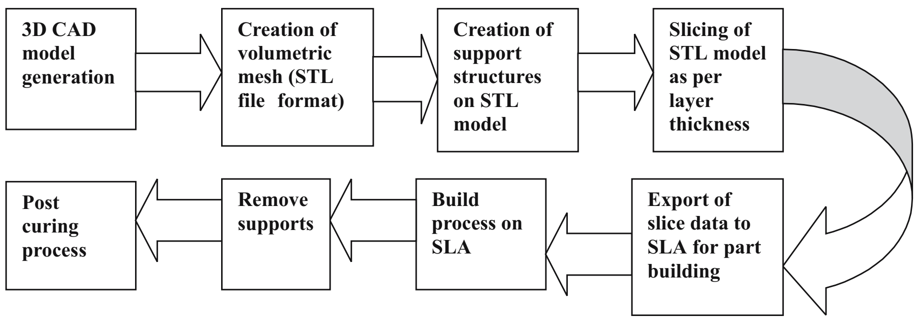


Fig. 2. Stereolithography process sequence

remove excess liquid. Supports are broken off and the part is subjected to a post-curing operation. In the post-curing process, the part is placed in a UV oven to complete the curing after nearly 97% of liquid polymer gets solidified during the build process. The flow diagram given in Fig. 2 explains the sequence of steps involved in 3D-model-generation through SL.

3 Problem definition

Part strength is crucial in the case of rapid tooling, since the models have to withstand pressures during test of fitment and also during use as dies for injection moulding. The dies made through the SL process are subjected to high tension due to high injection pressure. Harris et al. [4] conducted finite element analysis (FEA) on the ejection forces in injection mould tooling (insert) made with an SL process and concluded that smaller layer thickness and greater draft angle of the insert resulted in lower ejection forces. Besides this, it is pointed out that the adjustment of built layer thickness has a greater effect on ejection force than the adjustment of draft angle. However, the focus of the work of Harris et al. [4] is on minimization of the ejection force involved in the injection moulding process to avoid premature failure of tooling. Increasing the strength (tensile) of the die in addition to minimization of the ejection force would further increase the tool life. In this context, this paper addresses the strength aspects of the SL parts, which will increase the tooling application potential of the SL process. The strength of SL parts has improved significantly in recent years with the advent of new resins [1]. Geiger and Ozel [7] discussed that the main problem associated with injection moulding inserts made with an SL process is low thermal conductivity and low physical strength. They proposed a methodology to overcome the problem by adding a low melting-point metal alloy to the SL resin and supplementing with copper cooling lines. Rahmathi and Dickens [5] compared the life of inserts made of epoxy resin (SL 5170) and Zeneca-filled resin and concluded that tool inserts made with epoxy resins yielded a higher strength and achieved more than 500 successful injections without tool failure. Pang et al. [6] discussed that the introduction of new SL epoxy resins significantly improved the overall part accuracy, dimensional stability and mechanical properties relative to the earlier acrylate SL resins. They compared the mechanical properties of SL 5170 resin and SL 5180 resin and concluded that parts made through SL 5180 resin possess better tensile, flexural and impact strength. The above literature review reveals that the strength of the SL component is highly important in its applications and better strength could be achieved by selecting the proper resin, by adding metals in epoxy resins and by introducing cooling lines in the SL part. This work aims to further increase the tensile strength of the SL component by identifying and optimizing the process parameters that influence the part strength apart from other considerations attempted earlier.

4 Optimization of SL part strength

Optimization, in general, is defined as the selection of the best course of action (decision) for (a) specific objective(s) among the many possible choices that depend on resource availability specified as constraints. This paper considers maximization of part strength of the SL process given a set of operating environments. The objective function for the optimization problem is the relationship between the part strength and process parameters that could be used for the selection of optimal settings, which differ with environments, applications and specific requirements. This section describes the procedure for establishing the relationship between part tensile strength and process parameters, which could be used as objective function in process optimization studies. In this paper, Design of Experiments (DOE) is used as the optimizing tool to optimize the influencing parameters. DOE is a series of ordered tests in which purposeful changes are made to the input variables of a process or system to identify the corresponding changes in the output response variable. DOE is a powerful statistical technique used to study the effect on the outcome of multi variables simultaneously [8, 9]. The process or system is usually influenced by two sets of process variables namely controllable variables and uncontrollable variables (noise factor). The objectives of the experiment include the determination of:

- the most influencing (controllable) variable on the output response,
- the significant setting of these influential variables so as to minimize the variability in the output,
- the percentage of contribution of variables and
- the relationship between performance parameters and response variables.

The Taguchi method, which is outlined in Fig. 3, is adopted for SL part strength optimization. The Taguchi technique is a more refined and advanced version of the fractional factorial experiment in DOE [8]. This Taguchi technique is the most efficient problem-solving tool, which can improve the performance of the product, process, design and system with a significant slash in experimental time and cost [10]. This technique increases the power of analysis of experimental data by complex ANOVAs. This technique is also an efficient way to determine the optimum factor level combination to keep the variation at a minimum while keeping the mean on target.

4.1 Identification of process parameters

Process parameters of the SL process number more than fifty [11]. However, not all of the parameters influence the strength characteristics. This section discusses the various pa-

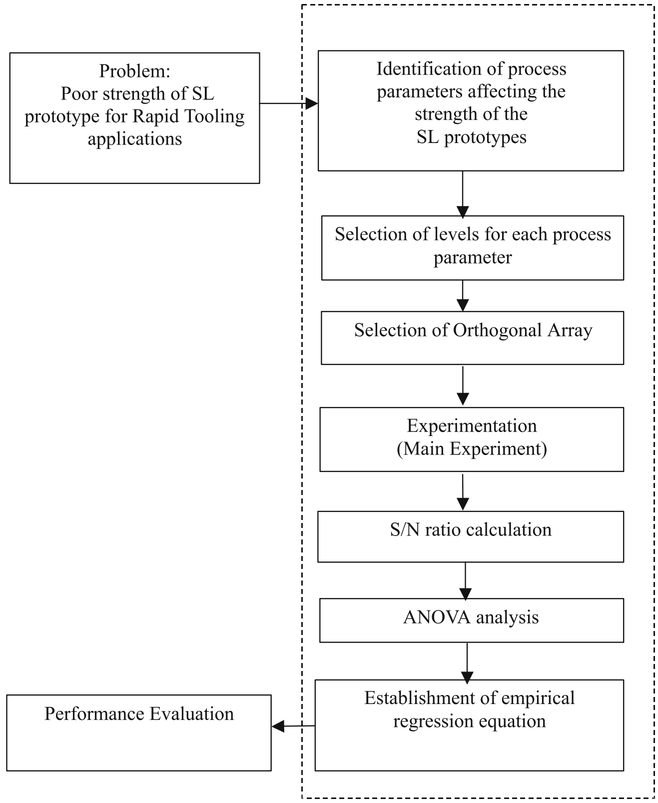


Fig. 3. SL process parameter optimization using the Taguchi method

rameters that are considered in recent research for part strength analysis and optimization. Schuab et al. [11] identified layer thickness, part orientation and over-cure depth as the important SL process parameters that affect accuracy and strength. Jacobs [1] proposed that layer thickness, laser power, scanning velocity and orientation are the important process parameters affecting part strength and the mechanical properties of SL prototypes. Banerjee et al. [12] conducted a study on the mechanical strength of the prototypes made by an SL process. They found that layer thickness, orientation and post-curing time are the most important SL process parameters expected to impart maximum influence upon the ultimate tensile strength (UTS) of the prototype. Chockalingam et al. [13] made an attempt to identify and study the various process parameters governing the SL system related to part characteristics (mechanical characteristics) and identified layer thickness as one of the most influencing parameters. Cheng et al. [14] proposed a multi-objective approach for determining optimal part build orientation in order to have higher accuracy and shorter build time. They found that the orientation of the part during fabrication in the SL process is a critical parameter and the strength of the prototype depends on the orientation in which the part is built. Table 1 summarizes the parameters that influence the strength of the SL parts.

The summary reveals that two parameters – namely, layer thickness and orientation – are considered important SL process parameters that influence the part strength. The complete solidification of the part built through an SL process takes place after

Table 1. Parameters considered for SL part strength analysis

Year	Author	Layer thickness	Orientation	Post-curing time	Laser power	Over cure depth	Scanning velocity
1992	Jacobs [1]	✓	✓	×	✓	×	✓
1995	Cheng et al. [14]	×	✓	×	×	×	×
1997	Schuab et al. [11]	✓	✓	×	×	✓	×
1997	Rahmati et al. [5]	✓	×	×	×	×	×
2002	Banerjee et al. [12]	✓	✓	✓	×	×	×
2002	Harris et al. [4]	✓	×	×	×	×	×
2003	Chockalingam et al. [13]	✓	×	×	×	×	×

✓ = Considered × = Not Considered

the post-curing process. The strength of the part is improved after post-curing. Thus, post-curing time is an important parameter that affects the strength of the part. Considering the above factors, the following parameters are identified as the most significant with respect to strength and they are described below:

Layer thickness (Lt): This is the specified thickness that the model is sliced in the z direction.
Orientation (O): This is the position in which the part is built.
Post curing time (Pc): This is the time for which the prototype is placed in a UV oven for complete solidification.

4.2 Selection of levels for each process parameter

The levels for each process parameter are selected after conducting a screening experiment. They are usually fixed by analyzing the ranges of each process parameter in the SL machine. In DOE, it is crucial to select the proper level values for the chosen controllable factors; namely, layer thickness (Lt), post-curing time (Pc) and orientation (O). Normally, the number of levels of each factor depends on the behaviour of response variable (say tensile strength) to the factor under consideration. Two levels, usually minimum and maximum limits of the factor, are set for linear pattern. To find non-linear effects, a minimum of three levels of each factor should be considered. The lower value, middle value and higher value of each factor are considered to be level 1, 2 and 3 respectively. These levels depend on the machine and material specifications. The levels set for the above three parameters to produce an SL part on an SLA 250/50 machine with CIBATOOL SL 5210 resin are shown in Table 2.

4.3 Selection of orthogonal array (OA)

Any process gives the best possible output when all of the influencing parameters operate at the optimum level. If m parameters are selected with n levels, the total number of experiments to be conducted is n^m. If the total number of parameters and levels involved is greater, the number of experiments to be conducted becomes very large. Taguchi suggested the use of an orthogonal array (OA), which is the basis for conducting fractional factorial experiments [8, 9]. The orthogonal array is selected based on the number of factors, interactions between them and the number of levels of each factor. Table 3 shows L_{18} standard OA used for the three factors, each set at three levels.

Table 2. Levels of process parameters

Parameter	Range	Level 1	Level 2	Level 3
Lt	0.1–0.15 mm	0.1	0.125	0.15
Pc	60–120 min	60	90	120
O	HX, VX, HY, VY	HX	VX	HY

4.4 Experimentation (main experiment)

After completing the screening experiment to select the level values of the controllable factors, 18 experiments were conducted with the process parameters set at appropriate levels using OA L_{18} shown in Table 3. Tensile specimens have been built as per American Society for Testing and Materials (ASTM) standards for resin ASTM D638 as shown in Fig. 4 [15].

Table 4 shows the tensile strength (TS_{ijk}) of all OA settings found through the exact dimensions measured with a coordinate measuring machine (CMM) and the ultimate load obtained with universal testing machine (UTM).

Table 3. Orthogonal array (L_{18})

Experiment number	Level		
	Layer thickness (Lt)	Post-curing time (Pc)	Orientation (O)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	1
5	2	2	2
6	2	3	3
7	3	1	2
8	3	2	3
9	3	3	1
10	1	1	3
11	1	2	1
12	1	3	2
13	2	1	2
14	2	2	3
15	2	3	1
16	3	1	3
17	3	2	1
18	3	3	2

Table 4. Ultimate tensile strength for OA settings

Experiment number	Width (w) (mm)	Thickness (t) (mm)	Cross-sectional area (CS) (mm^2)	Ultimate load (UL) (kg)	Tensile strength (TS_{ijk}) (kg/mm^2)
1	12.937	3.311	42.8344	314.5	7.34223
2	13.162	2.94	38.69628	266.5	6.88697
3	13.059	3.748	48.94513	324.0	6.61966
4	13.007	3.321	43.19625	296.0	6.85245
5	13.141	3.008	39.52813	287.5	7.27330
6	13.08	3.434	44.91672	276.0	6.14470
7	13.174	3.0	39.52200	276.0	6.98345
8	13.078	3.598	47.05464	289.0	6.14179
9	13.048	3.37	43.97176	273.5	6.21990
10	13.013	3.499	45.52899	315.0	6.91867
11	13.041	3.446	44.93928	280.5	6.24175
12	13.174	2.957	38.95552	294.0	7.54707
13	13.249	3.006	39.82649	293.5	7.36947
14	13.046	3.097	40.40346	249.0	6.16284
15	12.992	3.369	43.77005	247.5	5.65455
16	13.105	3.335	43.70517	309.0	7.07010
17	13.027	3.396	44.23969	284.0	6.41957
18	13.156	2.964	38.99438	259.0	6.64198

4.5 Signal to noise (S/N) ratio calculation

As an evaluation tool for determining the robustness of the design, signal-to-noise (S/N) ratio is the most important component of the parameter design [8, 9]. In the Taguchi method, the term "signal" represents the desirable target (higher tensile strength) and "noise" represents the undesirable value. The S/N ratio for each parameter level is calculated using Eq. 1 [8].

Table 5. S/N ratio values at each level

Levels	*Lt*	*Pc*	*O*
1	16.76	17.00	16.11
2	16.24	16.24	17.02
3	16.33	16.16	16.23

$$\eta = -10 \log_{10} \left(1/n \sum_{i=1}^{n} 1/y_i^2 \right) \tag{1}$$

where η is the average S/N ratio, n is the number of experiments conducted at level i and y_i is the measured value (here, tensile strength (TS_{ijk})).

A robust system will have a high S/N ratio. As the objective is to maximize the tensile strength of the parts produced by the SL process, a "larger-the-better" quality characteristic is to be considered. Thus, the S/N ratio should be as large as possible for higher values of tensile strength. Table 5 shows the S/N ratio for each level in each factor and the graph shown in Fig. 5 shows the variation of the S/N ratio for all of the controllable factors.

The level having the higher S/N ratio is selected as the optimum level contributing higher strength to the part. They are:

layer thickness: 0.1 mm (level 1, S/N: 16.76),
post-curing time: 60 min (level 1, S/N: 17.00) and
orientation: VX (level 2, S/N: 17.02).

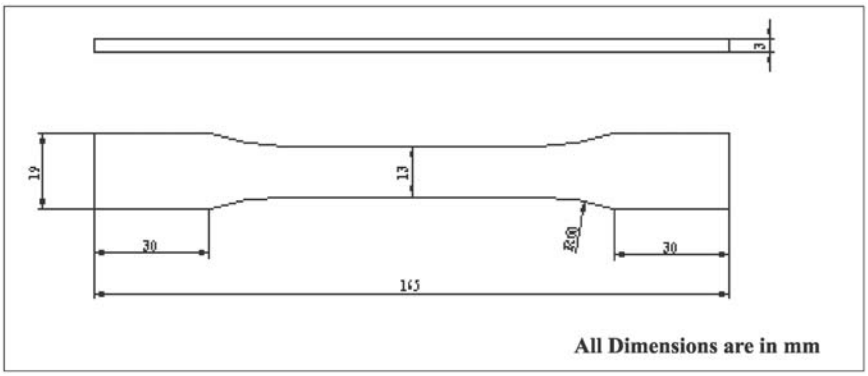


Fig. 4. ASTM D638 tensile specimen

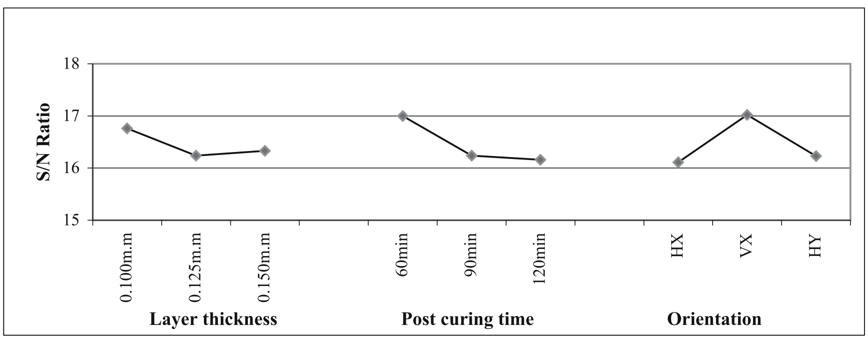


Fig. 5. S/N ratio graph

4.6 Analysis of results (ANOVA analysis)

Analysis of variance (ANOVA) is an analytical method to square the dispersion of specific numbers. This uses the sum of squares of each experiment-related factor to the factor's contribution to evaluate response variable (say tensile strength). The following are ANOVA terms used for analyzing the experimental results [8, 9, 16]:

Sum of squares (SS): It is the sum of squares of all the trial run results.

Total sum of squares (SS_T): It is the difference between the sums of squares of all the trial run results and Correction Factor (CF).

Correction factor (CF): the term that reduces the variation of the process.

$$CF = T^2/N$$

Degrees of freedom (f): the number of degrees of freedom for a factor is equal to one less than the number of levels of that factor.

Variance (V): the variance of each factor is determined by the sum of the squares of each trial sum of results involving the factor divided by the degrees of freedom of the factor.

$$V = SS_f/f$$

Variance ratio (F): it is the ratio of variance of each factor to the error variance.

$$F = V_f/V_e$$

Percentage of contribution (P): the percentage of the contribution of each factor is the ratio of the factor sum of squares to the total sum of squares.

$$P = [SS_f - (fxV_e)]/SS_T$$

Table 6 shows the percentage of the contribution of each factor for tensile strength (TS_{ijk}) along with the estimated ANOVA parameters before pooling.

Table 6. Percentage contribution of factors for tensile strength (before pooling)

Source	Sum of squares (SS)	Degrees of freedom (f)	Variance (V)	Variance ratio (F)	Percentage of contribution (P)
L_t	0.481	2	0.2405	1.647	3.97
Pc	1.411	2	0.7055	4.832	23.51
O	1.616	2	0.808	5.534	27.82
$Lt.Pc$	1.134	4	0.2835	1.94	11.56
$Lt.O$	0.55	4	0.1375	0.94	−0.714
Error	−0.438	3	0.146		33.14
Total	4.759	17			100

When the contribution of a factor is small, the sum of squares for that factor is combined with the error. This process of disregarding the contribution of a selected factor and subsequently adjusting the contribution of the other factor is known as pooling [8, 9]. Here, the percentage of contribution of $Lt.O$ is very small and hence its sum of squares and degrees of freedom is combined with the error term. Then, the ANOVA calculations are performed again to find the new percentage of contribution. Table 7 shows the percentage of contribution of each factor on tensile strength after pooling.

From the ANOVA table, the significance of each parameter after pooling is identified and given as a pie chart in Fig. 6.

The observations of the parameters on tensile strength are:

- orientation has maximum influence of 33.28%;
- post-curing time contributes 28.97%;
- layer thickness contributes 9.43%; and
- interaction between layer thickness and post-curing time contributes 22.48%.

4.7 Establishment of the empirical regression equation

The relationship between response variable(s) and influencing parameters provide a platform to predict, optimize and control the process. The regression equation for the response variable with three parameters (Lt, Pc and O) and three levels (1, 2 and 3) is modelled and is given in Eq. 2 [8].

$$TS = \mu + Lt_i + Pc_j + O_k + (Lt.Pc)_{ij} + (Lt.O)_{ik} + (Pc.O)_{jk} + (Lt.Pc.O)_{ijk} + \varepsilon_{ijk} \quad (2)$$

Table 7. Percentage contribution of factors for tensile strength (after pooling)

Source	Sum of squares (SS)	Degrees of freedom (f)	Variance (V)	Variance ratio (F)	Percentage of contribution (P)
L_t	0.481	2	0.2405	15.03	9.43
Pc	1.411	2	0.7055	44.09	28.97
O	1.616	2	0.808	50.5	33.28
$Lt.Pc$	1.134	4	0.2835	17.72	22.48
Error	0.117	7	0.016		5.84
Total	4.759	17			100

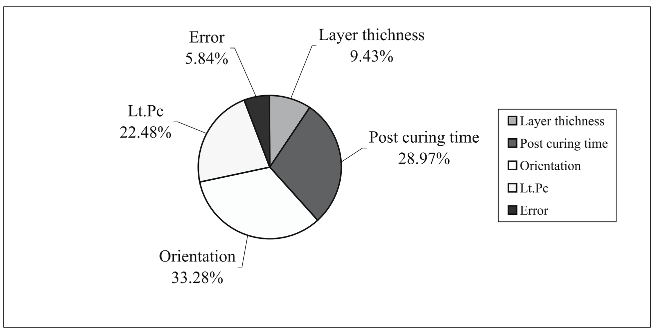


Fig. 6. Pie chart showing percentage of contribution

where TS is the regression value of the response variable (tensile strength) and μ is the average value of the response variable:

$$\mu = 1/18 \sum_{i=1}^{3} \sum_{j=1}^{3} \sum_{k=1}^{3} TS_{ijk}.$$

Lt_i is the effect of the ith level of Lt on the tensile strength:

$$Lt_i = [\iota_i - \mu].$$
$$\iota_i = 1/6(TS_{ijk}),\ \forall j \text{ and } \forall k.$$

ι_i is the average value of tensile strength at the ith level of Lt. Pc_j is the effect of the jth level of Pc on tensile strength:

$$Pc_j = [\beta_j - \mu].$$
$$\beta_j = 1/6(TS_{ijk}),\ \forall i \text{ and } \forall k.$$

β_j is the average value of tensile strength at the jth level of Pc. O_k is the effect of the kth level of orientation on tensile strength.

$$O_k = [\gamma_k - \mu].$$
$$\gamma_k = 1/6(TS_{ijk}),\ \forall i \text{ and } \forall j.$$

γ_k is the average value of tensile strength at the kth level of O. $(Lt.Pc)_{ij}$ is the interaction effect of Lt and Pc on tensile strength:

$$(Lt.Pc)_{ij} = [(\iota\beta)_{ij} - \mu].$$
$$(\iota\beta)_{ij} = 1/2(TS_{ijk}),\ \forall k.$$

$(\iota\beta)_{ij}$ is the average value of tensile strength at the ith level of Lt and the jth level of Pc. $(Lt.O)_{ik}$ is the interaction effect of Lt and O on tensile strength:

$$(Lt.O)_{ik} = [(\iota\gamma)_{ik} - \mu].$$
$$(\iota\gamma)_{ik} = 1/2(TS_{ijk}),\ \forall j$$

$(\iota\gamma)_{ik}$ is the average value of tensile strength at the ith level of Lt and the kth level of O. $(Pc.O)_{jk}$ is the interaction effect of Pc and O on tensile strength:

$$(Pc.O)_{jk} = [(\beta\gamma)_{jk} - \mu].$$
$$(\beta\gamma)_{jk} = 1/2(TS_{ijk}),\ \forall i.$$

$(\beta\gamma)_{jk}$ is the average value of tensile strength at the jth level of Pc and the kth level of O. $(Lt.Pc.O)_{ijk}$ is the interaction effect of Lt, Pc and O on tensile strength. Finally, ε_{ijk} is the random error, and i, j, k are the level identifiers of Lt, Pc and O.

Since the interaction effect between Lt and O, Pc and O and Lt, Pc and O is negligible, the regression Eq. 2 thus becomes:

$$TS = \mu + Lt_i + Pc_j + O_k + (Lt.Pc)_{ij} + \varepsilon_{ijk} \tag{3}$$

The values of ι_i, β_j, γ_k and $(\iota\beta)_{ij}$ are modelled with second-order polynomial equations and is given by Eq. 4.

$$\begin{aligned} TS =& \mu + (A_1 Lt^2 + A_2 Lt + A_3 - \mu) \\ &+ (B_1 Pc^2 + B_2 Pc + B_3 - \mu) \\ &+ (C_1 O^2 + C_2 O + C_3 - \mu) \\ &+ (D_1 Lt.Pc + D_2 - \mu) + \varepsilon_{ijk} \end{aligned} \tag{4}$$

Table 8. Average response of parameter levels

Parameter	Levels	Average response (mm)
Lt	0.1	6.926
	0.125	6.576
	.15	6.580
Pc	60	7.089
	90	6.521
	120	6.471
O	HX	6.455
	VX	7.117
	HY	6.510

Eq. 4 is rewritten as

$$\begin{aligned} TS =& A_1 Lt^2 + A_2 Lt + B_1 Pc^2 + B_2 Pc \\ &+ C_1 O^2 + C_2 O + D_1 Lt.Pc + C \end{aligned} \tag{5}$$

Where A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3, D_1 and D_2 are the regression coefficients.

$$C = A_3 + B_3 + C_3 + D_2 - 3\mu + \varepsilon_{ijk}$$

The regression coefficients are determined with regression analysis, which uses the average response of all parameter levels of L18 OA shown in Table 8, employing the least mean square error as a criterion [8].

By substituting the regression coefficients obtained, the regression Eq. 5 becomes:

$$\begin{aligned} TS =& (-89.878) Lt^2 + (16.8) Lt + (2.88 \times 10^{-4}) Pc^2 - (0.062) Pc \\ &- (0.6345) O^2 + (2.5655) O - 0.068(Lt.Pc) + 7.667 \end{aligned} \tag{6}$$

5 Performance evaluation

The final step in the process parameter design is to validate the regression equation with selected optimum process parameters. Table 9 shows the comparison between the experiment value and regression value of the tensile strength at various levels of process parameters (18 OA settings and 9 non-OA settings). Also, the percentage of deviation of the regression value from the experimental value for various combinations is shown in Table 9.

The graph shown in Fig. 7 illustrates the percentage deviation of tensile strength (regression equation value) from the experimental value.

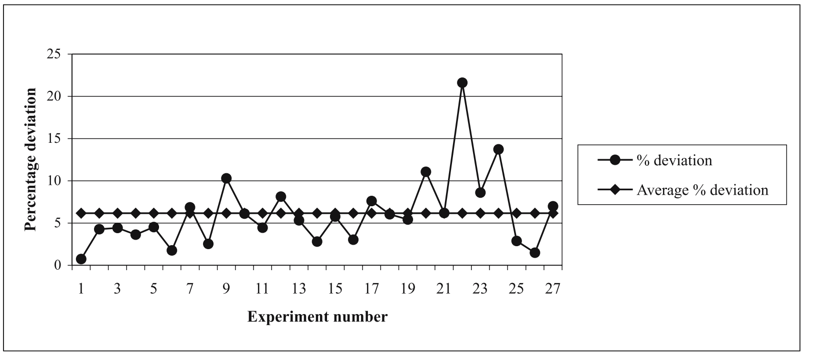
6 Conclusions and scope for future research

Part strength is an important characteristic in rapid tooling and it is necessary to determine and optimize the process parameters for maximum strength. This paper attempted to identify the process parameters that influence the strength of parts made by

Table 9. Comparison between experimental value and regression value

	Experiment Number	Lt (mm)	Pc (min)	O	Experiment value (TS_{ijk})	Regression value (TS)	Percentage of deviation $\|(TS_{ijk} - TS)/(TS_{ijk})\| \times 100$
OA settings	1	0.1	60	HX	7.34223	7.28802	0.74
	2	0.1	90	VX	6.88697	7.18202	4.28
	3	0.1	120	HY	6.61966	6.32542	4.44
	4	0.125	60	HX	6.85245	7.10046	3.62
	5	0.125	90	VX	7.27330	6.94346	4.53
	6	0.125	120	HY	6.14470	6.03586	1.77
	7	0.15	60	VX	6.98345	7.46255	6.86
	8	0.15	90	HY	6.14179	5.98554	2.54
	9	0.15	120	HX	6.21990	5.57895	10.30
	10	0.1	60	HY	6.91867	7.34302	6.13
	11	0.1	90	HX	6.24175	6.52002	4.45
	12	0.1	120	VX	7.54707	6.93242	8.14
	13	0.125	60	VX	7.36947	7.76245	5.33
	14	0.125	90	HY	6.16284	6.33645	2.82
	15	0.125	120	HX	5.65455	5.98086	5.77
	16	0.15	60	HY	7.07010	6.85554	3.03
	17	0.15	90	HX	6.41987	5.93055	7.62
	18	0.15	120	VX	6.64198	6.24095	6.04
non-OA settings	19	0.1	60	VX	7.54120	7.95002	5.42
	20	0.1	90	HY	5.91968	6.57502	11.07
	21	0.1	120	HX	6.68517	6.27042	6.20
	22	0.125	60	HY	5.88318	7.15546	21.62
	23	0.125	90	HX	6.87263	6.28146	8.60
	24	0.125	120	VX	5.84079	6.64286	13.73
	25	0.15	60	HX	7.00279	6.80055	2.89
	26	0.15	90	VX	6.69297	6.59255	1.50
	27	0.15	120	HY	6.05789	5.63395	6.99

Fig. 7. Performance graph for percentage of deviation



an SL process – one of the processes used for rapid tooling, optimize the parameter levels and evolve an empirical regression equation between tensile strength and their influencing parameters. A statistical tool DOE is used for the above purposes of identification of process parameters, optimization of selected levels and establishment of the regression equation. Conclusions of the DOE study are as follows:

- Lt, Pc and O have a large influence on part strength.
- Among the process parameters, orientation has the maximum influence on part strength.
- The optimal combination of process parameters is 0.1 mm layer thickness, 60 min post-curing time and vertical orientation (VX).
- The average percentage deviation of tensile strength (obtained from regression equation) from the experimental value is reasonable (6.16%).

This procedure could be employed for impact, compression and flexural strength analysis. This work could be extended with different OA settings for more accuracy in optimal level settings and regression equation.

Acknowledgement The authors thank the management, principal and head of the Mechanical Engineering Department of the Thiagarajar College of Engineering for the facility and support extended to prepare this research paper.

The authors are grateful to the director of CMERI for his kind permission to publish the paper. They are also thankful to the staff members of the

Material Testing Group of CMERI for their assistance in carrying out this investigative work.

References

1. Jacobs PF (1992) Rapid prototyping and manufacturing: fundamentals of stereolithography. Society of Manufacturing Engineers, Dearborn
2. Pham DT, Dimov SS (2001) Rapid manufacturing. Springer, Berlin Heidelberg New York
3. Jacobs PF (1996) Stereolithography and other RP&M technologies. American Society of Mechanical Engineers, New York
4. Harris R, Hopkinso N, Newlyn H, Hague R, Dickens P (2002) Layer thickness and draft angle selection for stereolithography injection mould tooling. Int J Prod Res 40(3):719–729
5. Rahmate S, Dickens P (1997) Stereolithography for injection mould tooling. Rapid Prototyp J 3(2):53–60
6. Pang, TH (1994) Stereolithography epoxy resins SL 5170 and SL 5180: accuracy, dimensional stability and mechanical properties. In: Solid free form fabrication proceedings, pp 204–224
7. Geiger M, Ozel T (2001) Development of rapid tooling for injection molding with metal filled stereolithography(SLA) cavity inserts. In: Proceedings of the 2nd International Conference on Design and production of Dies and Molds, pp 109–113
8. Montgomery C (2001) Introduction to statistical quality control, 3rd edn. Wiley, New York
9. Ross PJ (1996) Taguchi techniques for quality engineering, 2nd edn. McGraw-Hill, New York
10. Onuch SO, Hon KK (1998) Application of Taguchi method and new style for quality improvement on stereolithography. In: Proceedings of the institution of mechanical engineers 212(B):461–472
11. Schaub DA, Chu KR, Montegomery DC (1997) Optimizing stereolithography throughput. J Manuf Syst 6(4):290–303
12. Banerjee PS, Sinha A, Banerjee MK (2002) A study on effect of variation of SLA process parameters over strength of Built model. In: Proceedings of the 2nd National Symposium on Rapid Prototyping & Rapid Tooling Technologies, pp 79–84
13. Chockalingam K, Bharadwaj S, Chandrasekar U, Jawahar N (2003) Influence of layer thickness on mechanical properties in stereolithography process. In: Proceedings of INCARF, IIT New Delhi in CD, paper code: 139
14. Cheng W, Fuh JYH, Nee AYC, Wong YS, Miyazawa T (1995) Multi objective optimization of part building orientation in stereolithography. Rapid Prototyp J 1(4):12–23
15. ASTM (1996) Annual book of ASTM standards 2001 08.02. ASTM, West Conshohocken
16. Jagadeesh KA, Sivakumar M, Prasad R, Radhakrishnan P (1995) Optimization of process parameters using Taguchi method for PSG – RP machine, pp 709–716