Optimization of Stereolithography Process Parameters for Part Strength using Taguchi Technique

Raju B. S, Chandra Sekhar U, Drakshayani D. N

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 SL product. The contribution of the identified parameters: i.e., layer thickness(L_t), Orientation(O) and hatch spacing (H_s)which are more significant factors contributing to the strength of an SL product. An attempt has been made in order to study and optimize these process parameters in order to maximize the part strength and also development of an empirical model which depicts the relationship between the process parameters and part strength through taguchi technique and Analysis of variance. The detailed study of the effects of these parameters was carried out over the SLA parts and the data were analyzed by quantitative methods. The optimum levels of the parameter contributing to higher tensile/ impact and flexural strength of the part are the end results of the paper, which is very useful information for machine designers as well as RP machine users. The results obtained were utilized to select the main influencing parameters and the best parameter settings for yielding the optimum objectives.

Index Terms— ANOVA, Hatch space, Layer thickness, Mechanical properties, Orientation, Stereolithography Process, Taguchi Technique.

I. INTRODUCTION

Layered Manufacturing has revolutionized the way products are designed and manufactured today. Over the past few decades, stereolithography has prominently established as one of the leading and master of rapid prototyping (RP) technique among all the commercially available RP process, which posses fast and reliable development of prototype model at competitive cost and time [1]. Stereolithography (SLA) is one of the RP techniques, which involve fabrication of intricate shape of a plastic monomer directly from Computer aided design (CAD) data by depositing material layer by layer by photo polymerization process [2], Since the basic building process is additive in nature where the addition of material layer by layer, which posses some inherent pros and cons.

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The most important advantage is the ability to build almost any three-dimensional complex shape which can be subjected to mechanical dynamic testing. The time needed to build the parts depends on its geometrical intricacy, since the build time is directly affects the cost of the prototypes. Hence in general larger values of layer thickness are assumed to reduce the build time, but it causes form distortion or warpage of build part. One of disadvantage of the SL process is poor surface finish, especially on inclined surface due to the stair-stepping effect. So, it is evident that some kind of conflict exists between part build and part quality while having SLA prototypes. The SLA process involves the following steps as shown in fig 1 which consists of ; creation of the CAD model of the design; conversion of the CAD model to the standard triangulation language (STL) file format; slice the STL file into thin cross sectional layers; constructing the model one layer a top another; clean and finish off the model. SLA prototypes have wide application in aerospace, automobile, and manufacturing sectors especially in rapid tooling. Strength plays a very important role in rapid tooling [3] where the components have to withstand high pressure during the test of fitment and also when used as a die in injection moulding, where the dies prepared through SLA process will be subjected to high tension due to high injection pressure. Taguchi technique is a powerful tool for the design of high quality systems [4, 5], it provides a simple efficient and systematic approach to optimize design for performance, quality and cost. The methodology is valuable when design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristic through the setting of design parameters and reduce the sensitivity of the system performance to source of variation [6]. Dingal *et al.* used Taguchi method to find out the significant factors influencing density, porosity and hardness on selective laser sintering of iron powder [7]. Guharaja *et al.* made an attempt to obtain optimal settings of green sand casting parameters using Taguchi method [8]. Rama Rao and padmanabhan used Taguchi method and ANOVA in optimization of process parameters for material removal rate in electrochemical machining of Al/5% SiC composites [4]. Nataraj *et al.* used risk analysis Taguchi method to find optimum conditions of design parameters [9]. Barua *et al.* used the Taguchi Method to optimize the mechanical properties of V (Vacuum) casting process [10]. Hence, an attempt is made in order to achieve high strength of the prototypes with the specified process parameters which gives prior information of the part strength before fabricating the actual SLA prototypes. Hence, parameter optimization of SLA process is investigated and evaluated through a standard test specimen [11, 12].

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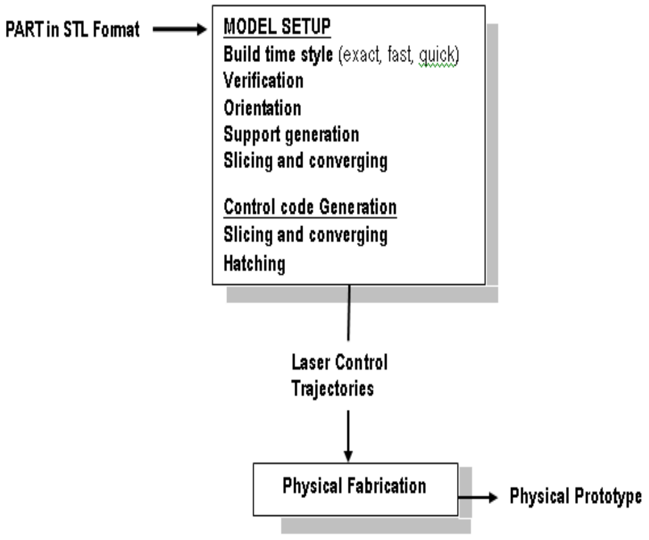

Fig. 1 RP PROCESS

II. EXPERIMENTATION

The experiment was carried out by selecting three levels for each of the identified process parameters called factor as shown in table 1 in order to identify the best level for each factor so that the main objective can be optimized.

Table 1. Description of Factors and its Levels

Control Parameter	LEVEL 1	LEVEL 2	LEVEL 3
LayerThickness(L_t)	0.075	0.1	0.125
Orientations (O)	0^0 (H_X)	45^0 (VH_{XY})	90^0(V_y)
Hatch Spacing (H_s)	0.01	0.015	0.02

The experimental building material adopted is CIBATOOL 5530 epoxy resin. The experimental building models are categorized into three specimens viz: the tensile test, flexural test, and impact test which are characterized using ASTM D638-01 [13], ASTM D790-03 [14] and ASTM D256-04 [15] specifications respectively. The STL format is generated by CATIA V5 R16 and sent to the 3D system SLA 5000 rapid prototyping machine. The various conditions in preprocessing steps such as STL verification, deposition layer thickness, orientation, building interior structure form, supporting method and building deposition direction are incorporated by means of 3D light year software [16] provided by 3D system of Valencia, USA followed by the layer slicing process to generate the building path with ACES™ build style. Building quality characteristics or attributes include the larger-the-better (LB) for the strength of the SLA prototypes.

A. *Experimental Apparatus*

The major experimental apparatus adopted includes:
3D system SLA5000 rapid prototyping machine produced by the Valencia, USA where it uses CIBATOOL 5530 epoxy resin to build geometrical shape of the work piece by photo polymerization process. Similarly, the tensile and flexural tests were conducted using Instron Universal Testing Machine, UK make, Model 5582. The impact test was conducted using impact tester, Aditya Instruments, Bangalore, Model IT-30.

B. *Taguchi Quality Aspect*

The orthogonal array is employed for the Taguchi method as the experimental analysis basis. The experimental factors and their corresponding levels are identified. Then the experimental results are manipulated and validated by analysis of variance (ANOVA), in order to determine each factor effect versus the response variable-strength of the SLA prototypes. The experimental procedures is as given below: Identification of SLA process parameter that influence the response variable, determining the various levels of the factors, Based on the factors and their levels, the degree of freedom is calculated and the suitable orthogonal array is selected, the experiment proceeds according to the variable factor layout of the orthogonal array. The experimental results are obtained and the signal to noise ratio (S/N ratio), the ANOVA and the corresponding contribution are computed, establishment of empirical relationship for the response variable under different parameter settings. The Taguchi method, parameter design converts the objective value to S/N ratio, which is known as quality characteristic evaluation index [17, 18], with the S/N ratio where the least variation and the optimal quality design can be obtained. The S/N ratio is beneficial in increasing factor weighting effect, decreasing mutual action, simultaneously processing the average and variation and improving the quality [19]. The higher the S/N ratio, the more stable quality can be obtained. According to the response variable, larger the better (LB) is used. The LB: the objective optimal value is larger better for the strength of the SLA prototypes.

$$\eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right] \quad \ldots \text{ (Eq 1)}$$

where **η** – S/N ratio; y_i - the i^th^ result of the experiment; n –number of replication. The total number of experiments in full factorial design for “m” parameters each set of “L” levels is L^m and it increases exponentially with L & m. Taguchi suggested the use of orthogonal array which will be used for conducting the fractional factorial experiments [20]. The Taguchi orthogonal array adopted in the research experiment is L_9 for three factors-three level settings.

III. EXPERIMENTATION

A. *Experimental Analysis for Tensile Strength (Ts)*

The nine tensile specimens as per the ASTM standards (ASTM D638-01) were built for L_9 orthogonal array setting using epoxy resin CIBATOOL SL5530 in SL5000 machine of three replications each. The tensile strength is calculated using the ratio of ultimate load to cross sectional area. The experimental results are given in Table 2.

A. 1 Prediction of Optimal Levels of Process Parameters

S/N ratio is an evaluation measure for the process parameters at each of their process level where the signal represents the desirable target (LB of tensile strength) and noise indicates the undesirable value which is defined in equation 1.

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The average S/N ratio for each process parameter (control variable) at each level is an average of n_j at a defined level. The graph represented in Fig 2 shows the variation of average S/N ratio with respect to the various levels. The main objective is to maximize the tensile strength of the parts produced by SLA process, in order to achieve this S/N ratio should be more. Hence, the level having higher S/N ratio is selected as the optimum level, which are contributing higher strength to the part. Therefore, the optimum levels contributing to the higher strength of the part are

Layer thickness : 0.125mm (Level 3, S/N Ratio: **35.34**)
Orientation : 90^0 V_y (Level 3, S/N Ratio: 35.33)
Hatch Spacing : 0.015 (Level 2, S/N Ratio: 35.29)

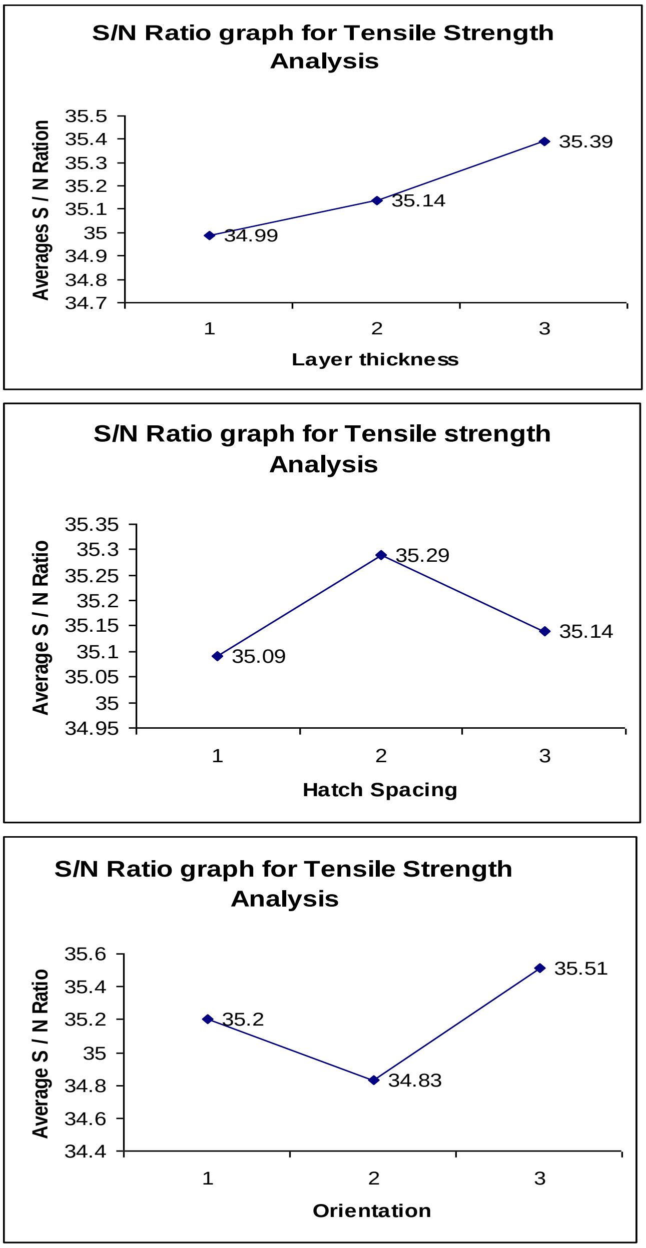

Fig. 2 S/N Ratio Graph for Tensile Strength Analysis

A. 2 Identification of Significant and Percentage of Contribution of Process Parameters

The process parameter (L_t, O & H_s) which influences much on response variable is identified through the percentage of contribution of each parameter. The parameter which has more percentage of contribution is the significant parameter to the response variable [21, 22, 23, 24] have mentioned ANOVA is widely used for determining the significance of the independent variables in influencing the dependent variables and also in determination of percentage of contribution of these dependent variables to the response variable. Table 3 shows the percentage of contribution of the parameters to the response variable with the ANOVA parameters. Hence, from the ANOVA table the significance of each parameter is identified.

B. Experimental Analysis for Flexural Strength (Fs)

The analysis carried out for the flexural strength is identical to the one in section 3.1. The nine flexural test specimen as per the ASTM standards (ASTM D790-03) were built for L_9 orthogonal array setting using epoxy resin CIBATOOL SL5530 in SL5000 machine of three replications each. The flexural specimens are subjected to point load at the midpoint between the supports, which are placed at 190mm apart with a particular load where the fatigue occurs. The flexural strength at fracture (δ) is determined by the following equation 2.

$$\delta = \frac{3WL}{2bd^2} \qquad \text{(Eq 2)}$$

Where W is load in Newton, L is the length of the test specimen in mm, b is the breadth of the test specimen in mm, d is the depth of the test specimen in mm. The experimental results are tabulated in table 4 which shows the flexural strength and fig 3 shows the variation of S/N ratio for all the controllable factors.

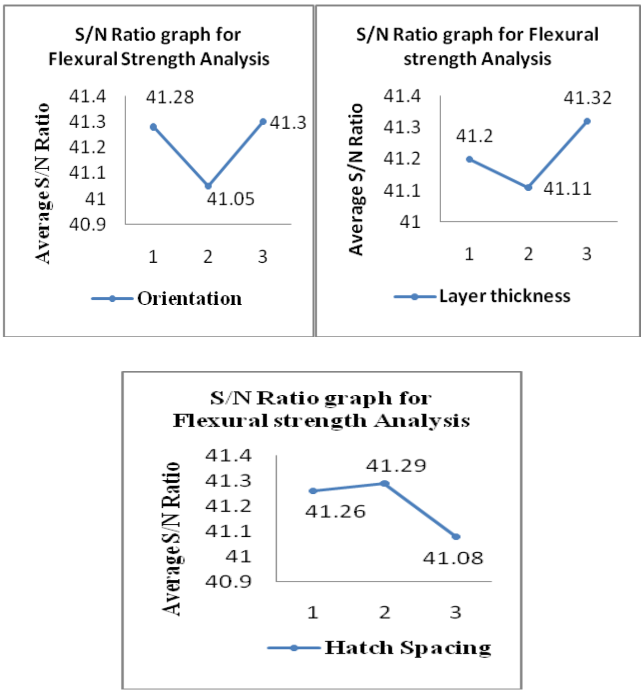

Fig. 3 S/N Ratio Graph for Flexural Strength Analysis

The level which have higher S/N ratio is selected as the optimum level contributing higher flexural strength to the part. Hence the optimal parameters are Layer thickness: 0.125mm (Level 3, S/N Ratio: 41.32)

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Orientation: 90^0 V_y (Level 3, S/N Ratio: 41.3)
Hatch Spacing: 0.015 (Level 2, S/N Ratio: 41.29)
The Table 5 represents the percentage of contribution of each factor for flexural strength along with the estimated ANOVA parameters. From the ANOVA table the significance of each parameter is identified.

C. Experimental Analysis for Impact Strength

The analysis carried out for the impact strength is identical to the one in section 3.1. The nine impact test specimen as per the ASTM standards (ASTM D256-04) are built for L_9 orthogonal array setting using epoxy resin CIBATOOL SL5530 in SL5000 machine of three replications each. In Izod test method, the specimen placed vertically and is broken by a single swing of the pendulum weight with a contact point at a fixed distance from the centerline of the notch. The impact strength obtained through the ratio of energy absorbed by the specimen during the break and the width of the specimen using izod impact tests. The experimental results of impact strength are tabulated in table 6 and fig 4 shows the variation of S/N ratio for all the controllable factors.

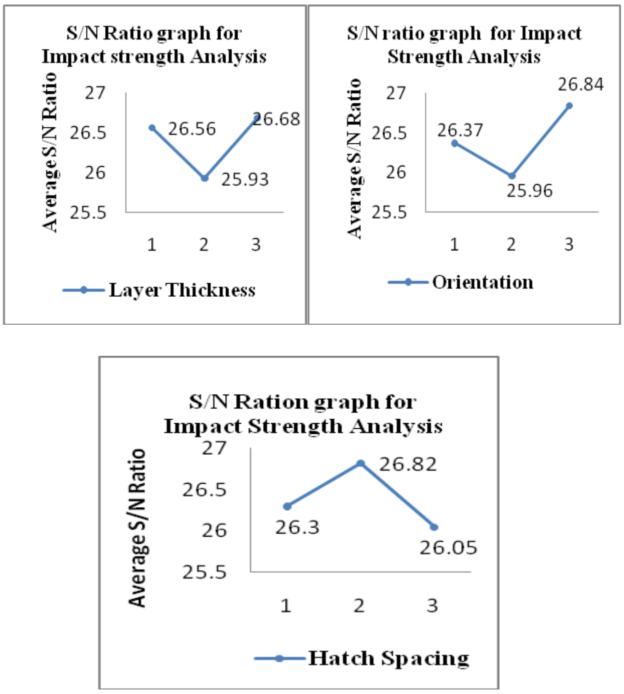

Fig. 4 S/N Ratio Graph for Impact Strength Analysis

The level which have higher S/N ratio is selected as the optimum level contributing higher Impact strength to the part. Hence the optimal parameters are
Layer thickness: 0.125mm (Level 3, S/N Ratio: 26.68)
Orientation: 90^0 V_y (Level 3, S/N Ratio: 26.84)
Hatch Spacing: 0.015 (Level 2, S/N Ratio: 26.82)
The table 7 represents the percentage of contribution of each factor for Impact strength along with the estimated ANOVA parameters. From the ANOVA table the significance of each parameter is identified.

IV. ESTABLISHMENT OF PROCESS MODEL (REGRESSION EQUATION)

ANOVA reveals that the layer thickness, orientation, and hatch spacing are contributing significantly to mechanical properties. Hence, establishment of a process model (empirical relationship / regression model) for mechanical properties (tensile/flexural/impact strength) as a function of process parameters (layer thickness, orientation and hatch spacing) is used to predict the strength for the given set of process parameters, which provides the prior information of the strength before fabricating the SLA prototype and useful for rapid designers as well as RP machine users. Montgomery [25] suggests the orthogonal polynomial which is very much useful for developing the process model with the L9 Orthogonal data. A Quadratic polynomial model is proposed to establish the process model between the response variable and process parameter as shown in equation 3.

$$RV = \beta_0 + \sum_{i=1}^{9}\left[\beta_{1i} P_{1(i)} + \beta_{2i} P_{2(i)}\right] + \epsilon \quad \ldots\ldots\ldots\ldots\ldots\ldots (Eq\ 3)$$

Where RV : Response variable , i: process parameter identifier , β0: constant coefficient, β1i : Linear Coefficient for the ith parameter, β2i: Non linear coefficient for the ith parameter , ∈:Error component , P1(i) : 1st order orthogonal polynomial of parameter , P2(i) : 2nd order orthogonal polynomial of the parameter.

A. Empirical Relation for Tensile Strength Versus Process Parameters.

The process model is established between tensile strength versus process parameter (L_t , O and H_S) is given in eq 4.

$$TS = -0.3714\, L_t^2 + 1.7483\, L_t + 3.19830\, O^2 + 0.4583\, O - 1.9716\, H_s^2 - 0.215\, H_s + 56.37 \ldots\ldots (Eq\ 4)$$

B. Empirical Relation for Flexural Strength Versus Process Parameters.

Similarly the process model is established between flexural strength versus process parameter (L_t , O and H_S) is given in equation 5.

$$FS = 1.8948\, L_t^2 + 0.7716\, L_t + 3.1848 O^2 + 0.035\, O - 1.6149\, H_s^2 - 1.1983\, H_s + 112.7205 \ldots (Eq\ 5)$$

C. Empirical Relation for Impact Strength Versus Process Parameters

In the similar manner the process model is established between Impact strength versus process parameter (L_t , O and H_S) is given in equation 6.

$$IS = 1.6332\, L_t^2 + 0.1666 L_t + 1.4983\, O^2 + 0.5833 O - 1.5666 H_s^2 - 0.2666 H_s + 19.8879 \ldots\ldots (Eq\ 6)$$

V. CONCLUSION

Optimizing the rapid prototyping SLA process by using Taguchi method is proposed. In this paper, an attempt is made to analyze the process parameters that influence the strength aspect of the SLA parts which are useful for various applications of the prototypes in testing and tooling process. The major conclusions are as follows:

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- The parameters L_t , O and H_S influences much on part strength of SLA prototypes.
- The optimal level combination of the process parameters are :

Layer Thickness	: 0.125mm (Level 3)
Orientation	: 90^0 -V_y (Level 3)
Hatch Spacing	: 0.015 (Level 2)

For tensile, Flexural and Impact strength of the SLA prototypes.

- Among the three process parameters the L_t and O are major contributing parameter for the tensile strength , O and H_S are major contributing parameter for the flexural strength and O has more significance among the parameters for the impact strength.
- The empirical relationship (Process model) between the part strength characteristics and the influencing parameters has been established for stereolithography process, which can predict the strength of the SLA prototypes by prior knowledge of part strength before building the prototypes.

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions. The procedure is applied in order to optimize the other rapid prototyping process with different materials.

VI. ACKNOWLEDGMENT

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Table 2. Ultimate Tensile Strength for OA Settings

j	1	2	3	4	5	6	7	8	9
Ts_j (N/mm^2)	55.46	54.57	55.07	58.46	54.51	58.59	58.62	55.34	61.73

Table 3. % of Contribution of the Parameters to the Tensile Strength Along with the Estimated ANOVA Parameter

Parameter "i"	Sum of Squares	Degree of freedom	Mean sum of squares	F Statisitcs	F tabulated $F_{(0.1,2,2)}$	% of contribution
L_t	18.57	2	9.285	9.622*		36.93
O	21.72	2	10.86	11.25*	9	43.19
H_s	8.06	2	4.03	4.176		16.03
Error	1.93	2	0.965			3.83
Total	50.28	8	25.14			
*Significance at 90% confidence Level (F Statistics > F Tabulated)						

Table 4. Flexural Strength for OA Settings

j exp., run	1	2	3	4	5	6	7	8	9
FS_j(N / mm^2)	116.67	113.92	114.08	115.7	110.0	115.6	115.8	114.8	118.7

Table 5. Shows the % of Contribution of the Parameters to the Flexural Strength Along with the Estimated ANOVA Parameter

Parameter "i"	Sum of Squares	Degree of freedom	Mean sum of squares	F Statistics	F tabulated $F_{(0.01,2,2)}$	% of contribution
L_t	10.75	2	5.375	82.69		23.88
O	20.3	2	10.15	156.15*	99	45.09
H_s	13.84	2	6.92	106.45*		30.75
Error	0.13	2	0.065			0.28
Total	45.02	8	22.507			
*Significance at 99% confidence Level (F Statistics > F Tabulated)						

Table 6. Impact Strength for OA Setting

j exp., run	1	2	3	4	5	6	7	8	9
IS_j (J / m)	20.72	22	21.1	20.3	17.9	21.3	21.4	19	23.6

Table 7. Shows the % of Contribution of the Parameters to the IMPACT STRENGTH ALONG with the Estimated ANOVA Parameter

Parameter "i"	Sum of Squares	Degree of freedom	Mean sum of squares	F Statistics	F tabulated $F_{(0.01,2,2)}$	% of contribution
L_t	5.5	2	2.75	2.69		28.47
O	6.44	2	3.22	3.16*	3	33.33
H_s	5.34	2	2.67	2.617		27.64
Error	2.04	2	1.02			10.55
Total	19.32	8	9.66			
*Significance at 75% confidence Level (F Statistics > F Tabulated)						

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