Application of Taguchi Design Approach in the Optimization of Die Design Parameters of a Two Cavity Injection Molding Tool for a Fan Blade Back Cover

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Abstract

Injection molding methods are widely used in plastic industries for the production of intricate and complex shapes of plastic, FRP parts with higher dimensional accuracy and greater reliability. In the present work an attempt has been made to improve the quality characteristic such as shrinkage of a two cavity injection molding tool for a fan blade back cover made from polypropylene (PP) by optimizing the die design parameters of injection molding tool using the Taguchi design approach. The performance of Fan Blade Back Cover is evaluated in terms of its shrinkage behavior by using the above measured data, Taguchi technique has been employed in optimization of various parameters, which controls the shrinkage, like injection and holding pressure, injection speed, melting temperature, cooling and holding time, with their significance in respect of shrinkage using orthogonal array, S/N ratio and ANOVA with their confirmation tests. Optimal combination of parameters is found out. A good agreement has been found between the estimated and experimental results within the preferred significant level. The optimum combination was verified experimentally and it was confirmed that Taguchi method successfully improved the quality of injection molding of polypropylene material as per customer's specifications.

Keywords: ***Design of Experiments (DOE), Taguchi Method, Signal to Noise (S/N) Ratio, Optimization, injection molding, Polypropylene (PP), shrinkage test.***

1. INTRODUCTION:

Due to enormous popularity of plastics in a wide range of industrial applications, excellent properties exhibited by plastics and their ease of processing, products ranging from sophisticated products, such as consumer goods, disposable food containers, luggage shells, household equipment, telephone handsets, automotive, safety helmets, electrical, computer housings to prosthetic hip and knee joints are used in our day to day life [1]. Injection molding methods are extensively used in plastic industries for the production of intricate and complex shapes of plastic, FRP parts with higher dimensional accuracy and greater reliability [2]. It is based on the ability of polypropylene materials to be softened by heat and to harden when cooled [3]. The injection molding used to produce fan blade back cover conceptually simple; the plastic in the form of granules is melted first and then forced into the cavity of a closed mold which gives shape to the plastic after solidification. Once it is solidified by cooling, the injection mold tool is opened and the part can be produced from it and closed. It will be used repeatedly to complete the cycle [4]. They are influenced by the control factors such as injection speed and pressure, holding pressure, melting temperature, holding and cooling time and etc. required to be optimized so that good quality of finished parts can be assured. Numerous studies have been performed to improve upon or optimizing the quality characteristic for production of high quality commercial plastic product on injection molding machine [5]-[9], yet, work has to be carried out to consider the effect of interaction between parameters on the quality characteristic of the products to know their significant role.

We have made an attempt to describe the optimization of the injection molding process parameters for optimum shrinkage performance of a fan blade back cover plate into two stages. In the first stage, the effect of injection molding tool die design parameters such as injection speed and pressure, melting temperature, holding pressure and time and cooling time on shrinkage was investigated to obtain most and least significant parameters. In the second stage, effect of control parameters namely melting temperature, injection pressure and speed, holding pressure and time, cooling time and two interactions: between melting temperature and injection pressure, between injection pressure and holding pressure was explored to determine optimal combination of parameters for lowest shrinkage. In the following, the Taguchi method, ANOVA and confirmation test for obtaining optimal combination of parameters are discussed [18]-[19].

1.2. Taguchi method:

Taguchi method is a most powerful and popular statistical method used for the design of experiments (DOE) can be effectively employed in optimizing the process / product by using number of steps such as planning, conducting and evaluating results of orthogonal array (OA) experiments to determine the optimum levels of control parameters under very noisy environment[11]- [12]. The prime objective goal is to maintain the variance in the results very minimal even in the presence of noise inputs to make robust design process against all variations. Generally its focus is to optimize the quality characteristic of a process economically and for determining the optimal parameter settings of a process and thereby achieving improved process performance with reduced process variability. Taguchi's method involves use of specially constructed tables called "orthogonal array" (OA) [14] required for very less number of experimental runs in designing which are consistent and easy to apply. It is successfully used in the various fields of Engineering especially in manufacturing industries. The paper deals with implementation of Taguchi's DOE methodology and technique in respect of shrinkage and optimization of process parameters. To find the optimal levels of usage parameters the following step by step procedure is followed for the DOE [15], [19].

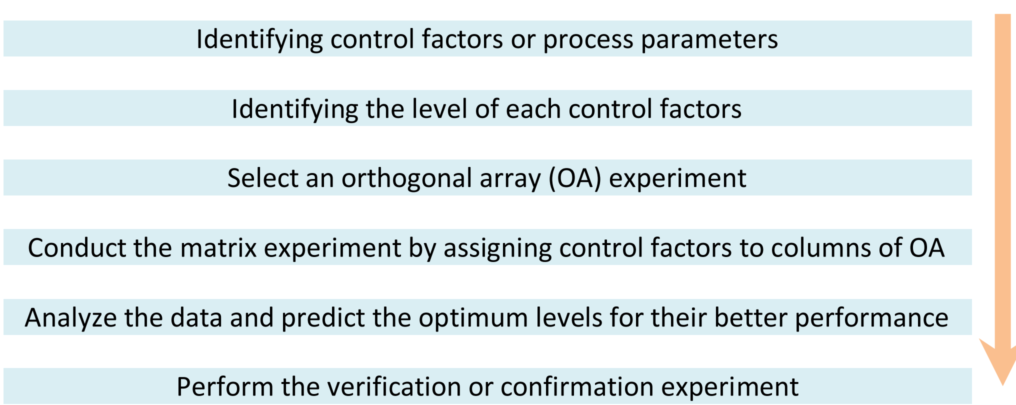

Figure 1: Taguchi methodology

2. EXPERMENTAL METHODOLOGY:

The use of these OA tables make the design of experiments very easy and consistent and it needs relatively less number of experimental trials to study the entire parameter space [14]. Time, cost, and labor saving can be achieved by using this technique. These results can be transformed into a signal-to-noise (S/N) ratio. Usually, there are three categories of quality characteristic deviating from the desired values by measuring S/N ratio, i.e. the-lower-the-better, the-higher-the-better, and the nominal-the-better. The S/N ratio for each level of process parameters is computed. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. Also, analysis of variance (ANOVA) is performed to see which process parameters are most and least significant. The optimal combination of the process parameters can be predicted using S/N and ANOVA analyses. Finally, a confirmation test is conducted to verify the optimal process parameters obtained from the total shrinkage. Shrinkage is the difference between the dimensions of mould and molding. When designing the plastic mould it is important to specify the proper material shrinkage in order to achieve a part that meets the dimensional requirement. So shrinkage for the polypropylene material is 0.01-0.015mm/mm. But according to customer specification the shrinkage factor taken for molding is 0.015mm/mm. Selection of the injection molding tool parameters and their levels were defined by varying the injection speed in the range 75 – 90 rpm (%), the melting temperature in the range 185 – 200 °C, the injection pressure in the range 120–150 bar, the holding pressure in the range 80 – 96 bar, the holding time in the range 5 – 10 sec and the cooling time in the range 5 – 10 sec were selected with available literature, machine technical data, plastics injection molding handbooks and consumer's specification. Two levels of the first parameter and three levels each of the other five parameters were selected as shown in Table 1.

Table 1: Usage parameters and levels of the experimental design

Factor	Parameter	Unit	Level 1	Level 2	Level 3
A	Injection Speed	rpm (%)	75	95	-
B	Melting Temperature	°C	185	195	200
C	Injection Pressure	bar	120	140	150
D	Holding Pressure	bar	80	88	96
E	Holding Time	sec.	5	8	10
F	Cooling Time	sec.	5	8	10

2.1. Selection of Orthogonal Array

An appropriate selection of an orthogonal array (OA) based on the total degrees of freedom of the parameters. In this study, we have each parameter at three levels except injection speed which is at two levels, therefore the total degrees of freedom (DOF) for the parameters are equal to 11. Generally, the degrees of freedom for the OA should be greater than or at least equal to those for the control factors. Hence, mixed level 2-3 DOE using an *L*18 (2^1 × 3^5) orthogonal array with six columns and eighteen rows were used in this study as shown in table 2 using Minitab software such that, each row represents an experiment with different combination of parameters and their levels.

2.2. Signal to Noise (S/N) Ratio

To measure the sensitivity of the quality characteristic in a controlled way can be investigated by determination of signal to noise ratio (S/N ratio) as term 'signal' represents the desirable effect (mean) and the term ‘noise' represents the undesirable effect (signal disturbance, S.D) for the output characteristic which influence the output due to external factors namely noise factors. The objective of any experiment is always to find the highest possible S/N ratio for the result which implies that the signal is much higher than the random effects of the noise factors or minimum variance. As mentioned earlier, there are three categories of quality characteristics, i.e. the-lower-the-better, the higher-the-better, and the-nominal-the-better [8]-[10] [12]-[15]. To obtain optimal molding performance, the-lower-the-better quality characteristic for shrinkage must be taken. Table 3 shows the experimental results for total shrinkage and the corresponding S/N ratio.

The mean S/N ratio for each level of the parameters is summarized along with delta and rank for total shrinkage as shown in table 4.

Table 2: Experimental plan using an *L*18 orthogonal array

Tasks/ Trials/ Experiments	A	B	C	D	E	F
1	1	1	1	1	1	1
2	1	1	2	2	2	2
3	1	1	3	3	3	3
4	1	2	1	1	2	2
5	1	2	2	2	3	3
6	1	2	3	3	1	1
7	1	3	1	2	1	3
8	1	3	2	3	2	1
9	1	3	3	1	3	2
10	2	1	1	3	3	2
11	2	1	2	1	1	3
12	2	1	3	2	2	1
13	2	2	1	2	3	1
14	2	2	2	3	1	2
15	2	2	3	1	2	3
16	2	3	1	3	2	3
17	2	3	2	1	3	1
18	2	3	3	2	1	2

Table 3: Experimental layout and summary of results for total shrinkage of mold

A	B	C	D	E	F	Total Shrinkage	S/N Ratio
75	185	120	80	5	5	0.013136	37.6307
75	185	140	88	8	8	0.013914	37.1310
75	185	150	96	10	10	0.014036	37.0551
75	195	120	80	8	8	0.013654	37.2948
75	195	140	88	10	10	0.013019	37.7084
75	195	150	96	5	5	0.013839	37.1779
75	200	120	88	5	10	0.012534	38.0382
75	200	140	96	8	5	0.012823	37.8402
75	200	150	80	10	8	0.012722	37.9089
90	185	120	96	10	8	0.013881	37.1516

90	185	140	80	5	10	0.013230	37.5688
90	185	150	88	8	5	0.013639	37.3043
90	195	120	88	10	5	0.014245	36.9268
90	195	140	96	5	8	0.013256	37.5518
90	195	150	80	8	10	0.012758	37.8843
90	200	120	96	8	10	0.012576	38.0091
90	200	140	80	10	5	0.012839	37.8294
90	200	150	88	5	8	0.013017	37.7098

Table 4: The average response of S/N ratio for total shrinkage of mold

Level	A	B	C	D	E	F
1	37.53	37.31	37.51	37.69	37.61	37.45
2	37.55	37.42	37.60	37.47	37.58	37.46
3	-	37.89	37.51	37.46	37.43	37.71
Delta	0.02	0.58	0.10	0.22	0.18	0.26
Rank	6	1	5	3	4	2

3. RESULTS & DISCUSSION:

There are eighteen different tests were conducted using the process parameter combinations in the specified orthogonal array table to measure the sensitivity of quality characteristics of output from desired value. Taguchi method uses the S/N (signal-to-noise) ratio to determine the most significant parameter. To get the better performance, smaller shrinkage is desired. Hence smaller is better criteria has been selected and. A sample calculation for one parameter is shown below.

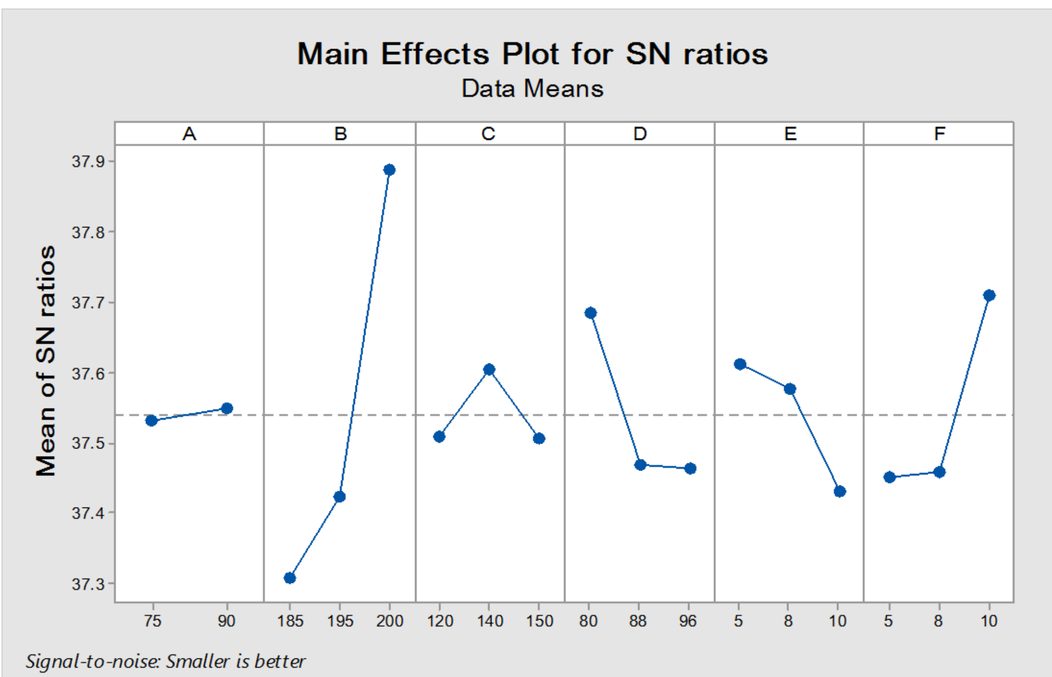

Figure 2: Average response S/N ratio graph for mold shrinkage

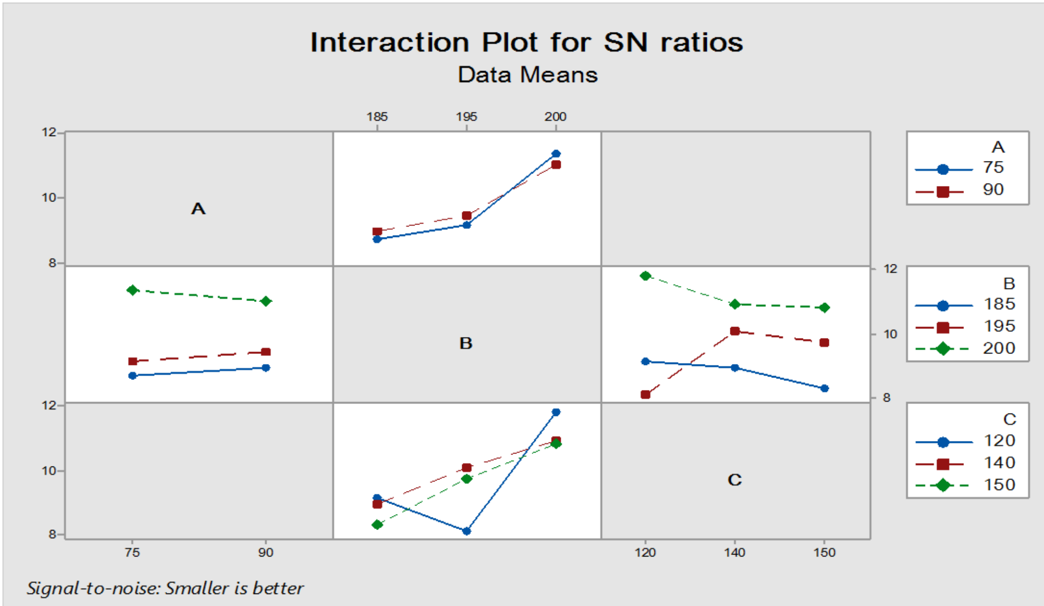

Figure 3: Average response S/N ratio of interaction of AXB and BXC graph for mold shrinkage

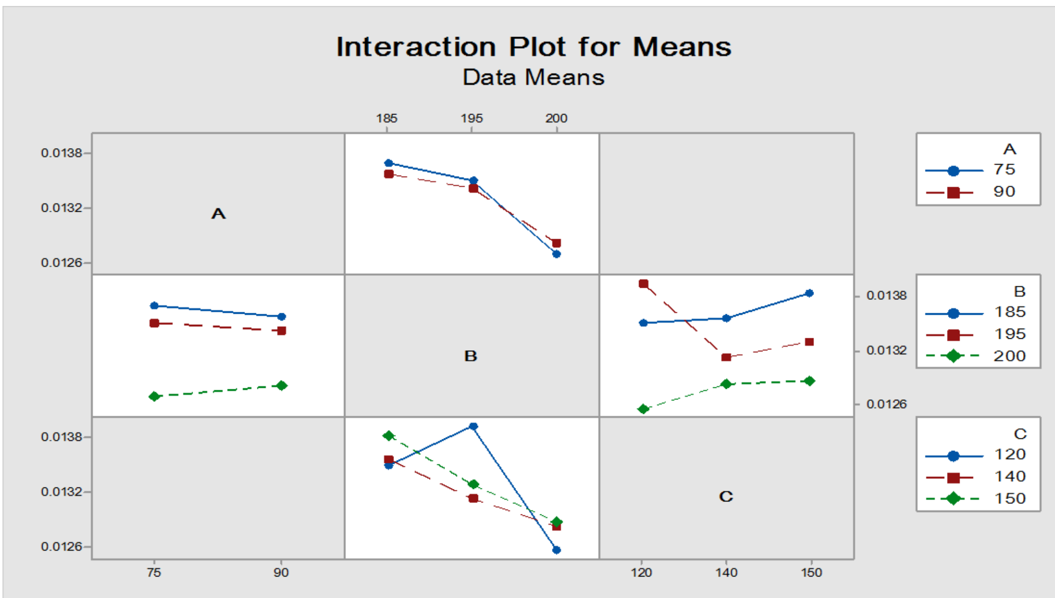

Figure 4: Average response of mean of interaction of AXB and BXC graph for mold shrinkage

Table 5: The optimal set of parameters for shrinkage characteristic of a mold

Symbols	Parameter	Optimum Setting
A	Injection Speed	90 % rpm
B	Melting Temperature	200 ^{0}C
C	Injection Pressure	140 bar
D	Holding Pressure	80 bar
E	Holding Time	5 sec.
F	Cooling Time	10 sec.

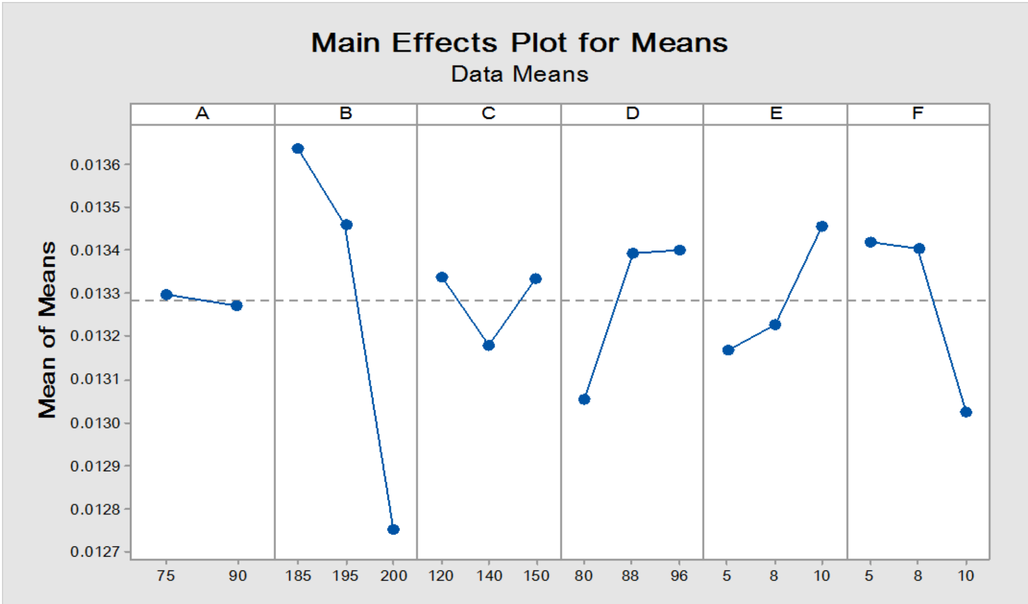

Figure 5: Average response mean of means for factors graph for mold shrinkage

From the above table 4 and figure 1 it is seen that most significant parameters can be determined by the Larger difference of S/N ratio. The experimental results have been compared with optimal parameters obtained by Taguchi Technique, it is found that most significant parameter that decreases total shrinkage is melting temperature (B) followed by cooling time (F), holding pressure (D), holding time (E), Injection pressure (C) and injection speed (A).

3.1 Analysis of Variance (ANOVA):

ANOVA is used to determine the most significant parameter affecting the output quality and characteristic [13]-[15] using the quantities such as degree of freedom (f), sum of squares (SS), variance (V), percent contribution of each parameter (F-ratio) and then contribution ratio or contribution of variance is determined. From the table 5 it is observed that highest contribution ratio is for Melting temperature (B) while Injection speed (A) is the lowest and cooling time (F), holding pressure (D), holding time (E), Injection pressure (C) have moderate value between the other two.

Table 6: ANOVA results for shrinkage characteristic of a mold

Source	DoF	Seq SS	Adj SS	Adj MS	F	P
A	1	0.000031	0.000031	0.000031	0.02	0.893
B	2	0.026465	0.026465	0.013233	8.35	0.018
C	2	0.000977	0.000977	0.000488	0.31	0.746
D	2	0.004673	0.004673	0.002337	1.47	0.301
E	2	0.002786	0.002786	0.001393	0.88	0.462
F	2	0.006034	0.006034	0.003017	1.90	0.229
Error	6	0.009505	0.009505	0.001584	-	-
Total	17	0.050472	-	-	-	-

3.2 Confirmation test:

For the verification of results the confirmation test is conducted [10] and an optimum condition at the selected levels of significant parameters can be predicted such as A2, B3,C2, D1, E1 and F3. The final optimal set of combination of parameters is found out. The predicted average (M) of the response shrinkage of mold can be expressed as [14]-[19].

M = (A2-T) + (B3-T) + (C2-T) +(D1-T) + (E1-T) + (F3-T) +T, where T=overall average of S/N ratio.

M = (37.5484-37.6754) + (37.8893- 37.6754) + (37.6049.63- 37.6754)+ (37.6862- 37.6754) + (37.6129-37.6754) + (37.7107- 37.6754) + 37.6754=37.675463 dB. A confidence interval (C.I) is evaluated = 0.33. Using

$$N_f = \frac{Number\ of\ Trials}{1 + Total\ DoF\ of\ total\ number\ of\ factors} = \frac{18}{1+17}$$

R = number of trials to run confirmation test, from ANOVA table v_e and f_e = 6 and F_α (1, 6) = 12.11 at 95% confidence level and tabulated. At the 95% confidence level the estimated / predicted average of the shrinkage found to be in the range of 37.345463 dB < Shrinkage > 38.005463dB.

Table 7: The comparison of estimated and experimental results of shrinkage of a mold

Particulars	**Optimum Level**		
	Estimation	**Experimental**	**Difference**
Level	$A_2B_3C_2D_1E_1F_3$	$A_2B_3C_2D_1E_1F_3$	-
Shrinkage of mold mm/mm	0.0135745	0.0131289	0.0004455
S/N Ratio in dB	37.3454	37.6354	0.29

4. CONCLUSIONS

The following observations were made from the experiment / Taguchi analysis, for better performance of Injection molding tool die design. From the analysis of the Taguchi approach, the following can be concluded from the present work:

[1] The optimum conditions are A2, B3, C2, D1, E1, F3 i.e. injection speed (90 %rpm), melting temperature
(200°C), injection pressure (140 bar), holding pressure (80 bar), holding time (5 sec), and cooling time (10 sec).

[2] The optimum total shrinkage is 0.012534 mm/mm of mold.

[3] Melting temperature is the most significant factor while injection speed is the insignificant or least significant factor.

[4] The contribution of parameters is melting temperature (52.4%), holding pressure (3.6%), holding time (0.9%) and cooling time (6.9%).

[5] The suspected interaction between factors injection pressure and holding pressure is not found whereas; the interaction between melting temperature and injection pressure does exist.

[6] The optimal shrinkage is 0.013575mm/mm.

[7] From the ANOVA, contribution ratios in case of shrinkage characteristic optimization are tabulated.

[8] The estimated range for optimum shrinkage is 37.345463 dB < Shrinkage > 38.005463dB. The experimental results are in good agreement within the specified range.

[9] It is noticed that, there was a good agreement between predicted and the actual values in respect of shrinkage within the preferred significant level.

Parameters	Contribution Ratio
A	-
B	52.4%
C	-
D	3.6
E	0.9
F	6.9

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