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Taguchi Approach for the Optimisation of the Bursting Strength of Knitted Fabrics

Abstract
In this paper, the bursting strength of knitted fabrics was optimised using the Taguchi experiment design technique, which is a recently famous approach. In the evaluations, analyses of variance (ANOVA) and the signal to noise ratio were used. 9 experiments were performed with respect to the L_9 orthogonal design for the Taguchi approach. The results show a considerable improvement in the S/N ratio as compared to the initial condition. With the Taguchi processes, we can easily determine optimum conditions for maximising the bursting strength of knitted fabrics with simple experiments.

Key words: *knitted fabrics, bursting strength, experimental design, Taguchi design.*

Designations used

n - total number of experimental runs
j - number of control factor parameters
y_i - response or observed quality value for i^{th} experimental run
η_o - predicted value of S/N ratio at optimal parameter setting.
η_m - average value of S/N ratios of all experimental runs
η_i - average S/N ratio corresponding to i^{th} control factor at the optimum parameter level
$\bar{y}$ - average of data observed
s^2 - the variation

Introduction

Knitting is the process of forming fabric by interloping yarn in a series of connected loops using needles. Knit fabrics provide outstanding comfort qualities and have long been preferred in many types of clothing. In addition to comfort imparted by the extensible looped structure, knits also provide lightweight warmth, wrinkle resistance, and ease of care [1].

The physical and mechanical properties of knitted fabrics are very important in many ways. Among these properties, the bursting strength is extremely important. Bursting strength is the force that must be exerted perpendicularly on the fabric surface to break off fabric. Since measurements of the tensile strength in the wale and course directions in knitted fabrics are not suitable, testing the bursting strength, which is the strength against multi directional forces, becomes important especially for knitted fabrics [2].

Taguchi's methods focus on the effective application of engineering strategies rather than advanced statistical techniques [3].

Taguchi views the design of a product or process as a three-phase program:

1. System design: This phase deals with innovative research. Here, one looks for what each factor and its level should be rather than how to combine many factors to obtain the best result in the selected domain [4].
2. Parameter design: The purpose of parameter design is to investigate the overall variation caused by inner and outer noise when the levels of the control factors are allowed to vary widely. Quality improvement is achievable without incurring much additional cost. This strategy is obviously well suited to the production floor [4, 5].
3. Tolerance design: This phase must be preceded by parameter design activities. This is used to determine the best tolerances for the parameters [4, 6].

Taguchi methodology for optimisation can be divided into four phases: planning, conducting, analysis and validation. Each phase has a separate objective and contributes towards the overall optimisation process. The Taguchi method for optimisation can be presented in the form of a flowchart, as shown in ***Figure 1*** [7 - 9].

The primary goal is to keep the variance in the output very low, even in the presence of noise inputs. Thus, the processes/products are made robust against all variations [8].

Two major tools used in the Taguchi method are the orthogonal array (OA) and the signal to noise ratio (SNR or S/N ratio). OA is a matrix of numbers arranged in rows and columns. A typical OA is shown in ***Figure 2***.

In this array, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur, doing so an equal number of times. Here, there are four parameters: A, B, C, and D, each at three levels. This is called an "L_9" design, the 9 representing the nine rows, configurations or prototypes to be tested. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, $L_9(3^4)$ means that nine experiments are to be carried out to study four variables at three levels. The number of columns of an array represents the maximum number of parameters that can be studied using that array [10].

Taguchi suggests that the response values at each inner array design point be summarised by a performance criterion called the signal to noise ratio. The S/N ratio is expressed in decibels (dB). Conceptually, the S/N ratio (η) is the ratio of signal to noise in terms of power. Another way to look at it is that it represents the ratio of sensitivity to variability [5,

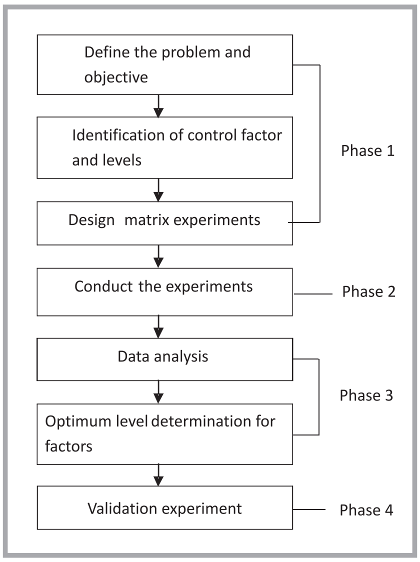

Figure 1. *Flowchart representing the Taguchi method for optimisation; Phase 1 (Planning), Phase 2 (Conducting), Phase 3 (Analysis, Phase 4 (Validation).*

11]. The higher the SNR, the better the quality of the product is. The idea is to maximise the SNR, thereby minimising the effect of random noise factors, which have a significant impact on the process performance [6, 12].

Therefore, the method of calculating the S/N ratio depends on whether the quality characteristic is smaller-the-better, larger-the-better, or nominal-the-best [5, 9, 12, 13].

Lower is better (yarn hairiness, abrasion, etc.).

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Higher is better (strength, air permeability, etc.).

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \tag{2}$$

Where n is the number of experiments in the orthogonal array and y_i the i^{th} value measured.

Nominal is best (dimension, humidity etc.).

$$S/N = 10\log\left(\frac{\overline{y}^2}{s^2}\right) \tag{3}$$

Where $\overline{y}^2$ is the average of data observed and s^2 the variation. Detailed information about the Taguchi method can be found in many articles [5, 9, 13].

Studies on the application of Taguchi design in the textile industry are very new. However, no research has been conducted on the bursting strength of knitted fabrics from yarn and fabric parameters using Taguchi design.

Cheng and Li (2002) used L_{16} Taguchi orthogonal design to examine the effects of different spinning parameters on yarn hairiness in the jet ring spinning system and evaluated optimum spinning conditions for different fiber materials [14]. Using the Taguchi method, Park and Ha (2005) developed a process that is applied to two different fabrics for optimising sewing conditions to minimise seam pucker [4].

Ishtiaque et al. (2006), in their several articles, investigated the effect of drafts at different stages of spinning process variables on some properties of ring, rotor and air-jet viscose yarns using the Taguchi method and analysis of variance [15-20]. Cho and Jeong (2006) predicted the yarn tenacity of a spun-dyed yarn from the spinning conditions, and other properties of the yarn were analysed using the defined parameters by way of the Taguchi method [21].

Experiments	Factors A	Factors B	Factors C	Factors D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1
$L_9(3^4)$				

Figure 2. *$L_9(3^4)$ orthogonal array.*

Webb et al. (2007) conducted the optimisation of the splicer parameters of Nylon 66 yarns with minimum variation using the Taguchi method [22]. Zeydan (2008) analysed the effect of certain fiber, yarn and fabric parameters on the strength of jacquard woven fabric using Taguchi design and an artificial neural network for comparison [6].

In the present paper, the effect of certain yarn and fabric parameters on the bursting strength of knitted fabric was analysed using Taguchi orthogonal design. Firstly, factors which have an effect on the bursting strength of knitted fabrics were chosen from a cause-effect diagram. Taguchi's parameter design approach was used to plan and analyse the experiments.

Determination of design parameters

The cause-effect diagram showed the factors that were expected to have an effect on the bursting strength of the knitted fabrics (***Figure 3***). Due to the difficulty and cost of controlling certain parameters in practical scenarios, this study specifically focused on the factors associated with materials, which can be accepted as the major input.

During relaxation treatment, knitted fabrics tend to go back to their original form by releasing the stress. Relaxation treatment changes the shape of the loop, which affects the fabric performance properties. Moreover, the type of yarn production (ring, compact and open-end) as well as the physical features of yarns and fabrics produced from these yarns would demonstrate different performance properties. If the amount of yarn essential for one stitch is increased, the fabric is looser and its weight decreases. Hence, fabric performance is affected.

Thus, relaxation treatment, yarn type and loop length, which effect bursting strength, are selected as control factors. Here, yarn type is assumed as a yarn parameter, and relaxation treatment and loop length are assumed to be fabric parameters affecting the bursting strength.

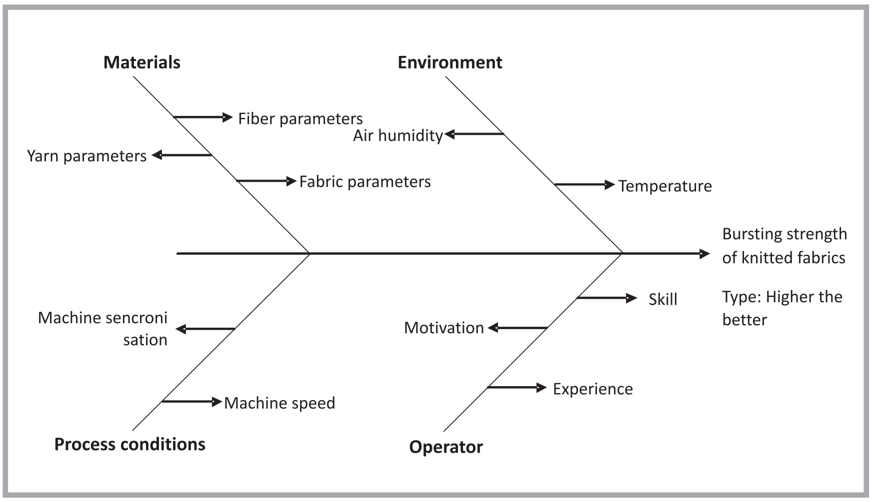

Figure 3. *Cause-effect diagram.*

Table 1. Parameters and their levels.

Parameter	Designation	Levels		
		1	2	3
Relaxation treatment	A	Dry	Washing	-
Yarn type	B	Ring	Compact	Open end
Loop length, cm	C	0.27	0.29	0.31

Materials and method

100% cotton Ne 30/1 yarns were knitted into 1×1 rib structures on an 18-gauge 30-inch circular knitting machine.

The control parameters were selected as follows:
Ring, compact and open-end yarns were selected as the control parameters since they are the most commonly used yarn types in industry. Two levels of relaxation treatment were selected for washing and drying. Three levels of loop length were selected: 0.27, 0.29 and 0.31 cm. The yarns used were produced at nearly closed machine settings .

Table 1 gives the levels of various parameters and their designation.

For dry relaxation, the fabrics were placed on a flat surface in a standard atmosphere (temperature: 20 ± 2 ºC and relative humidity: 65 ± 2%). After dry relaxation, the fabrics were washed in a domestic washing machine at 30 ºC for 45 min using a 0.05% wetting agent. After wetting, the fabrics were briefly hydro extracted. Before tests were performed, the fabrics were conditioned for 48 h in a standard atmosphere.

The fabric bursting strength was tested using a JH Truburst tester machine according to the BS EN 13938-2 (test area: 10 cm^2, diameter: 35.7 mm) testing method [23]. Five samples were tested from each group and expressed in kPa. All the tests were performed under standard atmospheric conditions (temperature: 20 ± 2 ºC and relative humidity: 65 ± 2%).

Taguchi's L_9 orthogonal array was selected for 3 different parameters and their levels. However, since factor A (relaxation treatment) in the design has 2 levels, without the 3rd level of the standard array, one of the 1st or 2nd levels of the parameter must be placed in the array. In this study, the 1st level of factor A is placed instead of the 3rd factor. ***Table 2*** gives the new arrangement of the array.

Thus, in this orthogonal array one of the factors has two stages, whereas the others have three .

As shown in ***Table 2***, the Taguchi design required 9 design experiments.

Table 2. *Orthogonal matrix for sample production; * Level 1 was arranged instead of level 3 in the standard L_9 orthogonal design.*

Order	Parameters		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	1*(3)	1	3
8	1*(3)	2	1
9	1*(3)	3	2

Analysis, results and discussions

In short, the Taguchi optimisation method consists of the following steps: Each S/N ratio can be obtained from observations according to the formula of higher the better. For each significant factor, the level corresponding to the highest S/N ratio is chosen as its optimum level. A search for the factors that have a significant effect on the S/N ratio is then performed through an analysis of variance (ANOVA) of the S/N ratios [4, 5].

Table 3 shows the average value of the bursting strength of the fabrics for each experimental point, as well as S/N ratios calculated by formula 2.

The next step is to determine the average effect of each factor on the multiple quality characteristic at different levels. This is equal to the sum of all S/N ratios corresponding to a factor at a particular level divided by the number of repetitions of the factor level [5]. For example, the average S/N ratio of factor B at level 3 is calculated as being

$$(52.82 + 55.05 + 52.61)/3.$$

The factor levels corresponding to the maximum average effect are selected as the optimum level. The average factor effect is shown in ***Table 4***, and the main effects plotted for SNR are shown in ***Figure 4***.

The delta value was calculated by subtracting the largest value from the lowest from among the values in each column.

The largest S/N ratio for each factor would be preferred. Hence, the optimum (maximum bursting strength) setting of

Table 3. Experimental layout using an L_9 orthogonal array table and S/N ratio of experimental results; DR: Dry relaxation, WR: Washing relaxation, RY: Ring yarn, CY: Compact yarn, OEY: Open end yarn.

Exp. No	Factors and levels			Average fabric bursting strength, kPa	S/N ratio, dB
	A	B	C		
1	DR	RY	0.27	557.28	54.90
2	DR	CY	0.29	645.08	56.12
3	DR	OEY	0.31	443.16	52.82
4	WR	RY	0.29	732.6	57.29
5	WR	CY	0.31	748.78	57.44
6	WR	OEY	0.27	567.44	55.05
7	DR	RY	0.31	540.46	54.55
8	DR	CY	0.27	657.44	56.29
9	DR	OEY	0.29	440.3	52.61

Table 4. *Response table for the S/N ratio; *: Optimum parameter level.*

Factors	Average S/N, dB			
	Level 1	Level 2	Level 3	Delta
A- Relaxation treatment	54.55	56.59*	-	2.04
B- Yarn type	55.58	56.62*	53.49	3.13
C- Loop length	55.41*	55.34	54.94	0.47

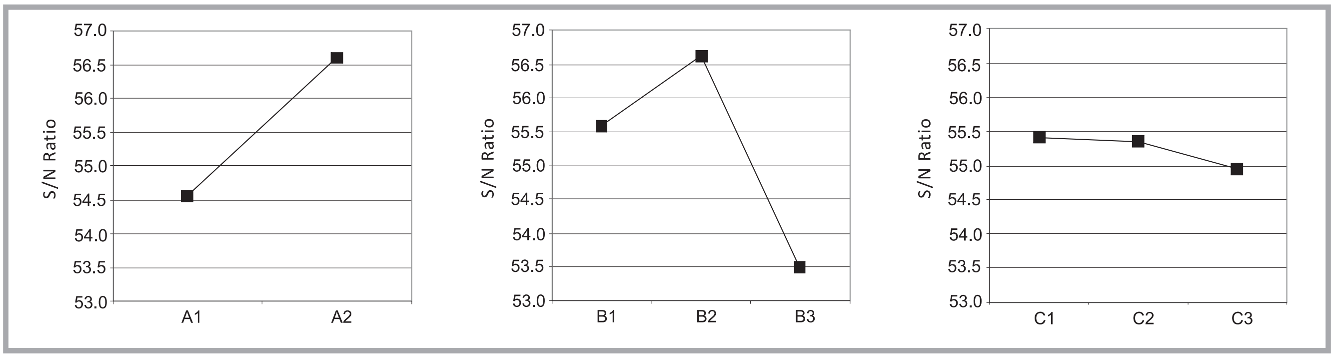

Figure 4. *Main effects plot for S/N – Factor A (relaxation treatment), factor B (yarn type), and factor C (loop length)*

the parameters is $A_2B_2C_1$. Corresponding parameter values are listed in ***Table 5.***

ANOVA analyses

Latter results of the S/N analysis were used for realisation of ANOVA, allowing to define which factor and level influences the final results of experiments [24]. ANOVA was performed for the S/N ratios using a Design Expert 6.0.1 statistical program (α = 0.05). An ANOVA table for the S/N ratio is given in ***Table 6***.

Table 5. *Optimum parameters.*

Factor (level)	Value
A (2) B (2) C (1)	Washing relaxation Compact yarn 0.27 cm

The sum of squares, the mean square, the F value as well as the residual and percentage contribution of each factor are shown in the ANOVA tables. The degree of freedom (df) for each factor is calculated as follows:

df = number of level – 1

With respect to ***Table 6***, prob values lower than 0.05 show that the model established is meaningful. Since the value of R^2 is 0.98, the expressiveness of the model is high. Relaxation treatment (A) and yarn type (B) are found to be significant for the fabric bursting strength at 95 percent confidence levels according to the ANOVA tables. The contribution of different factors in a decreasing order is as follows: yarn type (62.44%), relaxation treatment (34.39%), loop length (1.63%) and undefined parameters (1.54%).

Verification experiment

A verification experiment is the final step of the design of an experiment. Its purpose is to verify that the optimum conditions suggested by the matrix experiment do indeed give the improvement projected. The verification experiment is performed by conducting a test with optimal settings of the factors and levels previously evaluated. The predicted value of the multiple S/N ratio at the optimum level (η_0) is calculated by formula 4.

$$\eta = \eta_m + \sum_{i=1}^{j}(\eta_i - \eta_m) \qquad (4)$$

Where, j is the number of factors, η_m the mean value of multiple S/N ratios in all experimental runs, and η_i are the multiple S/N ratios corresponding to optimum factor levels [13, 25].

The S/N ratio calculated for the optimum level is as follows:

$$\eta_o = \eta_m + (\eta A_2 - \eta_m) + (\eta B_2 - \eta_m) + + (\eta C_1 - \eta_m) \qquad (5)$$

where, η_o is the optimum S/N ratio, η_m the overall mean of S/N values, ηA_2 the average value of S/N at the second level of relaxation treatment, ηB_2 the average value of S/N at the second level of the yarn type and ηC_1 is the average value of S/N at the first level of the loop length.

Substituting the values of various terms in equation (5),

$$\eta_o = 55.23 + (56.59 - 55.23) + + (56.62 - 55.23) + (55.41 - 55.23) = = 58.16 \text{ (dB)}$$

If the S/N is known and we want to learn about the result expected that will make the S/N, the procedure is to back-transform S/N to find the performance value expected [9, 26].

When the value 58.16 dB is placed into formula 2, the value obtained is 808.45 kPa. Values of the bursting strength of other combinations can be derived using the same formula.

Furthermore, the knitted fabric was produced according to the optimum design ($A_2B_2C_1$; 1 × 1 rib fabrics knitted at a 0.27 cm loop length value from compact yarns, performed with washing relaxation). The bursting strength of the fabric was measured at five different places of the fabric. The average of the results was determined as 824.7 kPa (***Table 7***). This result is very close to that estimated by Taguchi design (808.45 kPa)

Table 6. *ANOVA table for the S/N ratio; R-squared: 0.98.*

Factors	Sum of squares	Degree of freedom	Mean square	F value	Prop > F	Percentage contribution, %
Model	23.94	5	4.79	38.19	0.0064 significant	-
A	8.36	1	8.36	66.70	0.0038	34.39
B	15.18	2	7.59	60.54	0.0038	62.44
C	0.40	2	0.20	1.58	0.3405	1.63
Residual	0.38	3	0.13			1.54
Total	24.32	8				100.00

Table 7. Results of optimum and initial design.

Design	Performance values, kPa					Average, kPa	S/N, dB
$A_2B_2C_1$	793.7	794.3	812.6	851.0	871.8	824.7	58.31
$A_1B_1C_1$	575.4	528.1	528.1	583.4	571.4	557.28	54.90

Table 8. Results of verification experiment.

Design	Prediction S/N	Verification S/N
Initial design	55.08	54.90
Optimum design	58.16	58.31
Gain	3.08	3.41

The initial design is accepted as $A_1B_1C_1$, then the S/N ratio is obtained according to the initial and optimum design and how much profit is gained using the Taguchi design (***Table 8***).

As seen in ***Tables 7*** and ***8***, the improvement in the S/N ratio at the optimum level is found to be 3.41 dB. The value of the bursting strength in kPa at the optimum level is 824.7 against an initial parameter setting of 557.28.

Prediction of the bursting strength of other conditions using Taguchi design

According to the Taguchi design, values of the bursting strength of knitted fabrics for seven conditions (order) were predicted using formula 2 and 4. The values predicted are given in ***Table 9*** along with their experimental results.

Furthermore, values of percentage relative error can be evaluated, and by shortening the numbers using a computer, personal mistakes are taken into consideration [27]. ***Figure 5*** shows the measured and calculated values of bursting strength graphically.

As seen from ***Table 9*** and ***Figure 5***, the experimental results and values predicted are much closer.

Table 9. Comparison of experimental results with predicted values from the Taguchi design.

Order	A	B	C	Experimental (measured)	Predicted with Taguchi design (calculated)	Relative error, %
1	2	1	1	772.20	717.96	7.02
2	1	3	1	478.20	446.19	6.69
3	1	1	2	600.24	562.99	6.21
4	2	2	2	714.10	802.70	12.4
5	2	3	2	543.50	559.80	3.00
6	2	1	3	650.10	680.10	4.61
7	1	2	3	590.62	606.12	2.62

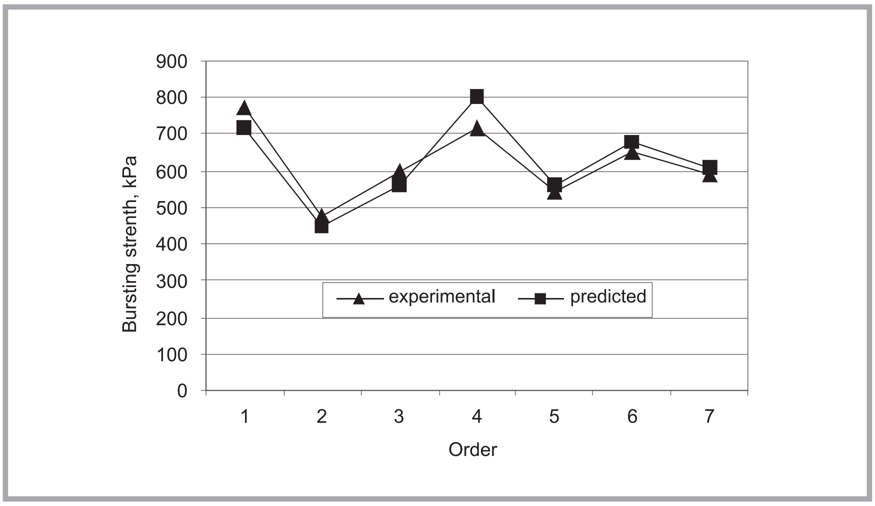

Figure 5. Comparison of experimental results and values predicted.

Conclusions

In this research, we intended to create a process for optimising knitted fabric conditions using Taguchi design to maximise the bursting strength of knitted fabrics. We can conclude from this research that by using the Taguchi design to maximise the bursting strength of knitted fabrics, we can determine the optimal variables.

Based on the S/N ratio and ANOVA analyses, the optimum levels of the various parameters obtained in this study are:

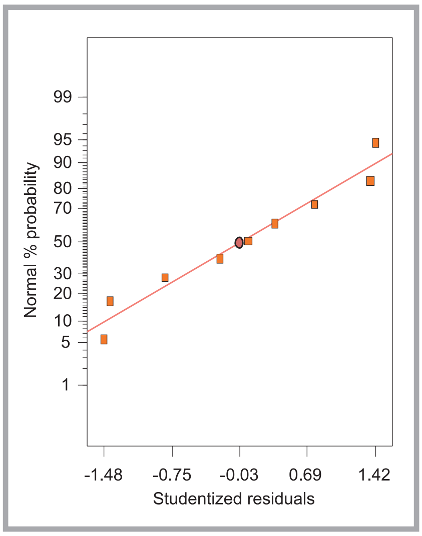

Figure 6. Normal probability plot of residuals.

Relaxation treatment: washing relaxation
Yarn type: compact yarn
Loop length: 0.27 cm.

Moreover, the S/N ratio has been considerably improved as compared to the initial parameter settings of the experiment.

The closeness of the results of predictions based on calculated S/N ratios and experimental values show that the Taguchi experimental design technique can be used successfully for both optimisation and prediction. Normal probability plots of the residuals are shown in ***Figure 6***. An inspection of the plots in the figure revealed that the residuals generally fall in a straight line, implying that the errors are distributed normally.

As a result, the fundamental principle of the Taguchi method is to improve the quality of a product by minimising the effect of the causes of variation without eliminating them. In this methodology, the design desired is finalised by selecting the best performance under conditions that produce a consistent performance. The Taguchi approach provides systematic, simple and efficient methodology for the optimisation of near optimum design parameters with only a few well-defined experimental sets and determines the main factors affecting the process.

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