DOE in Solving Industrial Problem: Case Study of the Application of Taguchi Method in Riveting Process

Jaharah A. Ghani, Haris Jamaluddin, Rizauddin Ramli, Mohd Nizam Ab Rahman,
Baba Md Deros and Che Hassan Che Haron
Department of Mechanical and Materials Engineering
Faculty of Engineering and Built Environment
Universiti Kebangsaan Malaysia
43600 Bangi, Malaysia

Abstract

Recently, in manufacturing industries, the ability and knowledge in solving production problems have become a distinct capability that should be developed within the available manpower resources to anticipate and resolve upfront conflicts. Ensuring that the corporate goal is clearly defined and that strategic planning is successfully implemented in the right direction is very important. Optimization of the technology employed must not be hindered by the incompetence of key personnel in executing design of experiment (DOE) to identify the magnitude and areas for improvements. Understanding the fundamental experimentation will be a starting point in improving process yields, product performances, and productivity from company-wide operation. Thus, a more reliable and effective experimental approach will definitely be the proper option to study possible design factors that satisfy customer and process compatibility demands. The present study exploits the application of DOE using Taguchi method to solve a riveting process problem at a local Malaysian company. The findings revealed that the Taguchi method is an effective method of determining the optimum parameter setting and, finally, to quantify the achieved improvement. The riveting strength was found to have improved by 40%. In addition, the Taguchi method has successfully determined that the stroke distance is a significant factor that affects the performance of the riveting strength. Conclusion was drawn that the stroke distance is a critical factor because it will cause significant effects in the variations in quality and performance. The sensitivity of this stroke distance has triggered greater precaution in monitoring and controlling this parameter.

Keywords

DOE, Taguchi method, riveting process, quality, performance improvement

1. Introduction

In the recent market and global requirements, the desire to provide higher quality level of products and services to increase market shares has continued competitively among manufacturers to ensure customer satisfaction and assure consumer return orders. The importance of product and process optimization has prompted manufacturers to focus greater attention to design optimization to stay competitive in the world market.

Conventional design of experiment (DOE) has been known to be a very complicated and a highly disciplined process, which requires competent resources and demands high experimental cost. It is complex and not easy to implement, especially when a large number of experiments need to be conducted when the number of process parameters increases [1]. The time required to complete an experiment is extremely long, especially in investigating and evaluating a large quantity of factors that affects the desired quality characteristics. Difficulties are further aggravated when the experiments have to be repeated for several modeling and verification purposes until accurate and validated results are obtained. Therefore, the DOE Taguchi method has become an alternative in solving these problems and is chosen as an appropriate solution for any industrial organization in improving its product and process design. The Taguchi method, designed to reduce engineering experimental time and cost, stimulates the initiative and effort for product improvement and assists in continuous improvement of processing capability. The practicability of DOE, with its simplified data collection, has made its practical implementation possible in any organization and business operation for product and process improvement.

The dilemma confronting most manufacturing industries is the lack of competent and skilled personnel to implement DOE, also a similar problem with the Taguchi method, although it has been the most recommended method for application in the industry. In most manufacturing industries, only a handful of personnel may be capable of implementing DOE. Nevertheless, organizational policies kept on highlighting the importance of DOE in product and process design. Some organizations, which have realized the importance of product improvement to stay competitive in the market place, have capitalized on producing better quality products at lower cost and shorter period for new product development, as well as started investing in human capital by educating and improving their employees' skills and knowledge in DOE.

The Taguchi method emphasizes the importance of designing quality control in the manufacturing processes [2]. Robust design is an engineering methodology employed to optimize product and process conditions, which are minimally sensitive to various causes of variations and which produce high product quality with low development and manufacturing costs [3]. The Taguchi parameters and tolerance design are important tools for robust design. Robust design and, indeed, any statistical analysis need to be done to conform to the engineering aims of the study [4]. The design process in real and feasible DOE is a combination of statistical theorem and engineering practices. The overall target of quality engineering is to make products that are robust with respect to all noise factors [5]. According to Apte [6], the variations that represent the noise factors are categorized under the following three sources:

i) Unit to unit variation: caused by the variation in material, equipment performance, and workmanship
ii) Environment (external factor): arises from environmental conditions surrounding the processes
iii) Deterioration (internal factor): wear and tear of the components and expendable items used in the process

Often, in an industrial setting, totally eliminating the source of variations can be very expensive [2]. A low-cost solution can be achieved by adjusting the levels of variation. Figure 1 shows the Taguchi design procedure that represents the three stages: system, parameter, and tolerance designs [7].

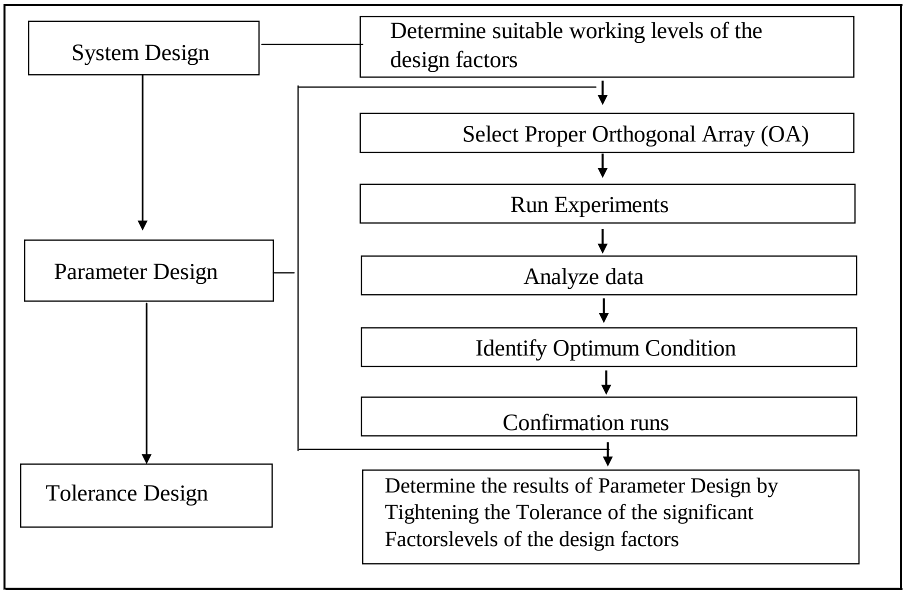

Figure 1: Taguchi design procedure [7]

2. **Methodology**

The effectiveness of the Taguchi method has been verified by the procedures and methodology used in this approach, where experiments were conducted for a static case in the production line. The experimentation was based on dual-response variables for "nominal-the-best" and "larger-the-better" quality characteristics in a precision riveting process.

In this case study, only the "larger-the-better" and "nominal-the-best" characteristics were studied in the experiment. The process started with the identification of the problem nature that occurred at the workplace. To execute the experiments, the related quality characteristic was identified for project selection, and the current performance of this quality characteristic was used as a baseline for comparison. The next stage was the identification of the factors that can possibly affect the quality performance of the response variable. Each factor level was tested and determined to select the appropriate Taguchi orthogonal array.

In this study, the Taguchi L9 array was selected as the best array. The noise factors were identified and included in the experiment, as their potential effects on the performance characteristic could be significant. The experiment was then conducted at the actual production floor according to the sequence of the Taguchi L9 array to capture all potential variations from the controllable and uncontrollable factors during the process. The results of the experiments during the observation period were recorded in matrix columns.

2.1 Riveting Process: Dual-response Quality Characteristics

The riveting process in this case study was implemented using a radial riveting machine, which applied radial force to press the guide shaft to form a snap head that will hold the shaft to the lever plate. Figure 2 shows the radial riveting machine used to join the pin and the plate lever, and Fig. 3 shows the schematic diagram of the radial riveting process and the workpiece. The response variables are riveting strength (N·cm) and riveting snap height (mm). The expected minimum force required for this riveting strength was specified at 4 N·cm by the customer, and the riveting snap height was set from 0 mm to 0.9 mm. The guide shaft is made from SUS (SF20x) steel, and the lever is made from SUS430-Cx steel.

Figure 2: Radial riveting machine used to join the pin and plate lever [8]

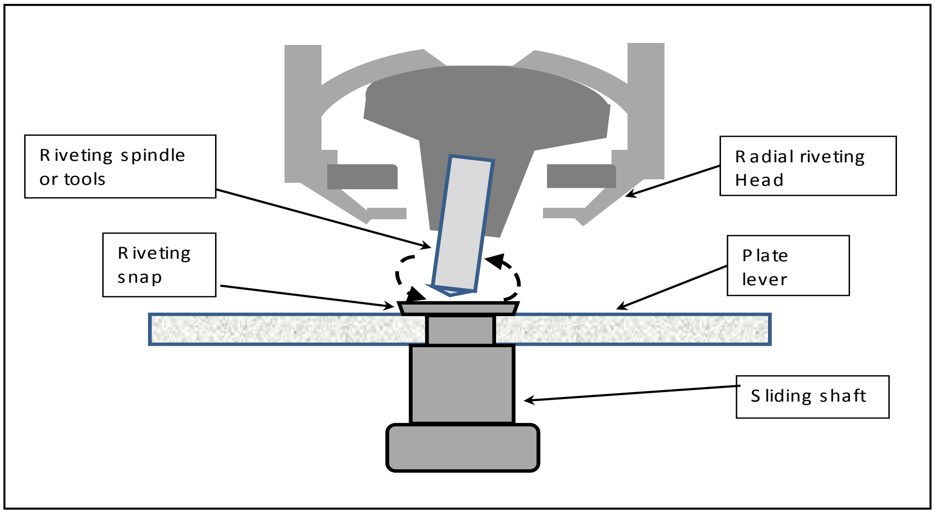

Figure 3. Schematic diagram of the radial riveting process and the work piece [8]

Radial forming displaces a material in a uniform way, at a constant speed, and in three directions, namely, radially outward, radially inward, and tangentially overlapping. The tool moves in an overlapping radial motion pattern, causing gentle displacement of the material.

The experiment was conducted employing two noise factors: thickness of the plate and height of the shaft, which were produced by external source. The thickness and height of each noise factor were classified into high and low values. The relationship among the controllable factors, the noise factors, and the quality characteristics in the riveting process is shown in Fig. 4.

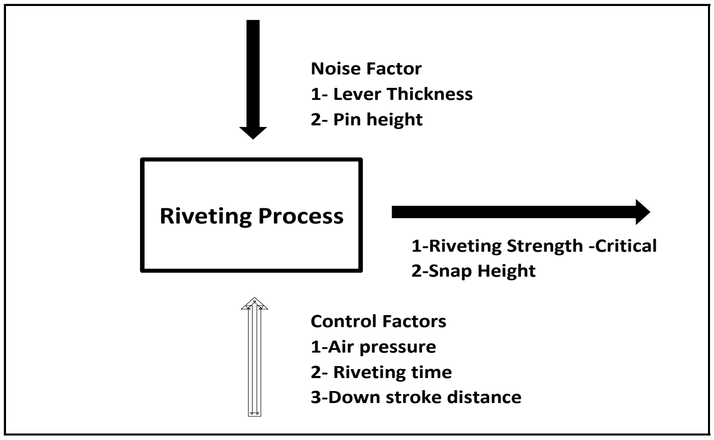

Figure 4. Block diagram of the riveting process for a static problem

The control factors and their levels tested in the experiment are shown in Table 1.

Table 1. Control factors and their levels for the riveting experiment

Factor	Units	Level 1	Level 2	Level 3
A. Cylinder air pressure	Mpa	0.3	0.4	0.5
B. Caulking time	Second	1.5	2	2.5
C. Stroke distance	mm	2	2.05	2.15

The combination setting of the experiments used for the riveting strength and snap height is shown in Table 2.

Table 2. The L9 array with combination setting and result column used in riveting process

	Control Factors				Noise Factors				
Expt. No.	**A**	**B**	**C**	**empty**	T1H1	T1H2	T2H1	T2H2	S/N
1	0.3	1.5	2	1	Result1	Result2	Result3	Result4	
2	0.3	2	2.05	2	Result1	Result2	Result3	Result4	
3	0.3	2.5	2.15	3	Result1	Result2	Result3	Result4	
4	0.4	1.5	2.05	3	Result1	Result2	Result3	Result4	
5	0.4	2	2.15	1	Result1	Result2	Result3	Result4	
6	0.4	2.5	2	2	Result1	Result2	Result3	Result4	
7	0.5	1.5	2.15	2	Result1	Result2	Result3	Result4	
8	0.5	2	2	3	Result1	Result2	Result3	Result4	
9	0.5	2.5	2.05	1	Result1	Result2	Result3	Result4	

A = Air pressure
B = Riveting time
C = Stroke Distance
Noise factor i) T- Lever thickness 1 and 2.
Noise factor ii) H- Pin Height 1 and 2.

The measurement of the quality characteristics was done using a manual torque meter for the strength and a digital indicator for the snap height.

3. Results and Discussions

The riveting process for the "larger-the-better" and "nominal-the-best" characteristics was chosen for optimum parameter setting. The Taguchi method was employed in the experiments for selected quality characteristics. The experiment was conducted based on L9 array with nine trials, repeated four times for the two noise factors at two levels.

In the riveting process, the L9 array was used to determine the effect of three process parameters: A—cylinder air pressure; B—riveting time; and C—downstroke. The two noise levels were identified as thickness of the lever and height of the guide shaft. The result of the experiment for the "larger-the-better" quality characteristic is shown in Table 3.

Table 3. The result of the riveting strength

	FACTORS			NOISE FACTOR						
RUN	**Air pressure**	**Riveting time**	**Stroke distance**	**T1S1**	**T1S2**	**T2S1**	**T2S2**	**Sum of squares of reciprocals**	**Mean of sum of squares of reciprocals**	**SN ratio (larger the better) N**
1	0.3	1.5	2	0.10	1.00	0.10	0.50	205.000	51.250	-17.10
2	0.3	2	2.05	2.50	3.00	3.50	4.00	0.4152	0.1038	9.84
3	0.3	2.5	2.15	4.50	6.50	7.00	7.00	0.1139	0.0285	15.46
4	0.4	1.5	2	4.00	4.50	3.25	4.00	0.2691	0.0673	11.72
5	0.4	2	2.15	6.50	7.00	7.00	7.00	0.0849	0.0212	16.73
6	0.4	2.5	2	5.00	6.00	5.00	6.00	0.1356	0.0339	14.70
7	0.5	1.5	2.15	7.00	7.50	6.00	6.50	0.0896	0.0224	16.50
8	0.5	2	2	1.00	3.00	1.00	2.00	2.3611	0.5903	2.29
9	0.5	2.5	2.05	3.00	4.75	3.00	4.50	0.3159	0.0790	11.02

Figure 5 shows the main-effect graph, which indicates that factor C is the major possible contributor to the effect on the quality characteristics because the gradient of its line graph is the highest among all factors. However, this visual observation and this phenomenon have yet to be confirmed by ANOVA.

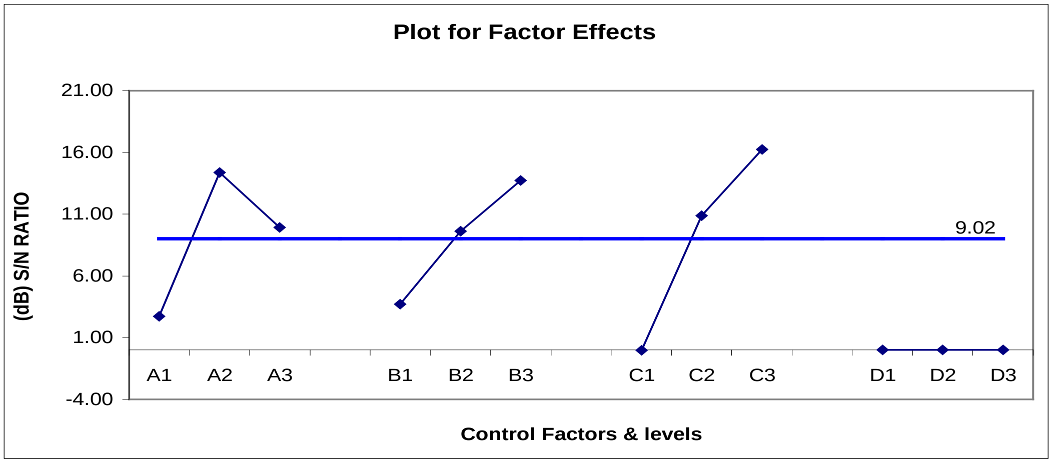

Figure 5. S/N ratio and main-effect plot for each factor. A and C represent the riveting strength experiment

Table 4 shows the ANOVA that calculates and estimates the effect of each factor and its contribution to quality performance. The ANOVA table reveals that factor C (stroke distance) contributes the most significant effect on the performance characteristic. The stroke-distance factor has the largest *F* value at 2.63 and contributes 44.8% to the variation of the riveting strength. Factor A (air pressure) contributes 22.3% and an *F* value of 1.32. The contribution of Factor B (riveting time) is not significant, and its *F* value is 0.97; although its contribution is 16.4%, the effect is very minimal to the performance characteristic. The *F* values of factors A and B are less than 1.5; therefore, they are pooled for optimum response calculation.

Table 4. The ANOVA for factor effect before pooling

`	Factor/Source	Degree of freedom	Sum of Squares	Mean squares	Mean square ratio - F	Percent contribution %
A	Air pressure	2	207.46	103.73	1.32	22.34
B	Riveting time	2	152.23	76.11	0.97	16.40
C	Stroke distance	2	412.08	206.04	2.63	44.38
	Error	2	156.67	78.3355		16.87
	Total	8	928.43			100

Calculation of the factor effects is further made by calculating and estimating the effect of factor C after pooling factors A and B, as shown in Table 5.

Table 5. ANOVA after pooling factors A and B

	Factor/Source	**Degree of freedom**	**Sum of Squares**	**Mean squares**	**Mean square ratio - F**	**X = not in used or Pooled variance**	**Pure sum of square**	**Percent Contribution %**
A	Air pressure					x		
B	Riveting time					x		
C	Stroke distance	2	412.08	206.04	2.39		239.96	25.846
	Error	6	516.35	86.0588			688.470	74.154
	Total	8	928.43					100.00
	(error)	2						

The experiment has resulted in an optimum S/N ratio value of 16.2 db when only the effect of factor A at level 2 was taken into consideration. The preliminary optimum combination of the parameter setting was set as A2, B3, and B4, selected as suggested by the main effect plots (Fig. 5). As the experiment had two response variables, the final setting was confirmed after the effect of the combination setting on the second response variables was taken into consideration. From the optimum S/N ratio, the confidence interval was computed to be from 5.8 db to 26.5 db. The calculation was made for a 90% confidence level [2]. The overall mean of the experiment was 9.02 db.

The second quality performance in this experiment was the snap height. The L9 array combination result was used to measure the snap height performance, which was measured first prior to the destructive strength test. The result is shown in Table 6, which indicates that the overall mean was 0.0725 mm.

Table 6. The L9 matrix and the experimental results

FACTORS				NOISE FACTOR						
RUN	Air pressure	Riveting time	Stroke Distance	T1S1	T1S2	T2S1	T2S2	Mean	Variance	SN Ratio (Nominal-the-Best)
1	0.3	1.5	2	0.15	0.14	0.14	0.15	0.15	0.00	31.12651161
2	0.3	2	2.05	0.10	0.10	0.10	0.11	0.10	0.00	27.613889
3	0.3	2.5	2.15	0.03	0.03	0.02	0.02	0.02	0.00	11.34742887
4	0.4	1.5	2.05	0.09	0.09	0.09	0.09	0.09	0.00	45.31992741
5	0.4	2	2.15	0.02	0.02	0.03	0.01	0.02	0.00	6.680725715
6	0.4	2.5	2	0.06	0.06	0.05	0.05	0.05	0.00	22.82357725
7	0.5	1.5	2.15	0.01	0.01	0.01	0.01	0.01	0.00	17.87893215
8	0.5	2	2	0.12	0.12	0.14	0.11	0.12	0.00	22.2012404
9	0.5	2.5	2.05	0.08	0.08	0.09	0.09	0.09	0.00	31.31839123

Figure 6 shows the main-effect plots, which indicate that factor C (the stroke distance) contributed the largest effect to the snap height, followed by factor B (the riveting time). Factor A (the air pressure) has shown no significant effect to the snap height. The important role of factor C is to ensure that sufficient force is applied to the riveting guide shaft, and factor B ensures that adequate time is allotted for completion of the riveting process before the radial riveting starts to return to its origin.

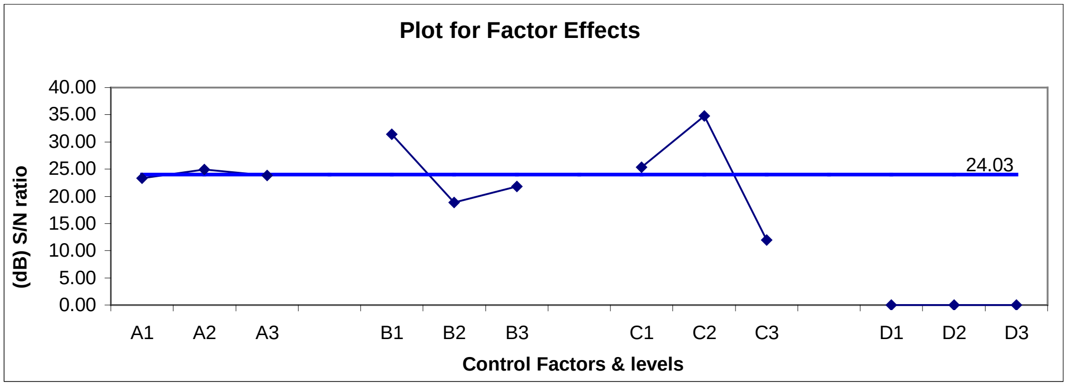

Figure 6. Main-effect plot of each factor level for the snap height

The mean effect of the factors was analyzed using the ANOVA method, and the result verified that factor C (the stroke distance) contributed 73.25% of the variation in snap height, with an *F* value calculated as 34.22. Factor B was the second contributor at 24.2% with an 11.32 *F* value. The non-significant factor A contributed only 0.37 % with an *F* value of 0.17. This result is shown in Table 7. To determine the optimum condition of the response variable, factor A was pooled.

Table 7. ANOVA table for snap height before pooling

	Factors	Degree of freedom	Sum of Squares	Mean squares	Mean square ratio - F	Percent contribution
A	Air pressure	2	3.99	1.99	0.17	0.37
B	Riveting time	2	260.39	130.19	11.32	24.24
C	Stroke Distance	2	786.70	393.35	34.22	73.25
	Error	2	22.99	11.4961		2.14
	Total	8	1074.07			100
	Effective Dof factors	6				

The pooling of factor A resulted in higher *F* values for both the stroke distance and riveting time. This result is shown in Table 8, where the pure sum of squares is calculated.

Table 8. ANOVA table for snap height after pooling factor A

	Factors	Degree of freedom	Sum of Squares	Mean squares	Mean square ratio - F	X = not in used or Pooled variance	Pure sum of square	Percent Contribution %
A	Air pressure					x		
B	Riveting time	2	260.39	130.19	19.30		246.90	22.987
C	Stroke Distance	2	786.70	393.35	58.32		773.21	71.989
	Error	4	26.98	6.7449			53.959	5.024
	Total	8	1074.07					100.00
	Effective Dof factors	4						

The optimum result from this experiment was calculated based on the significant factors at the selected levels that affect the quality performance of the snap height. The optimum S/N ratio value was 42.16 db.
The confidence interval selected was from the lower confidence range, from 0.0598 µm to 0.0850 µm, because the width is large enough for more practical applications of testing for the mean.

The process of eliminating the contribution of the insignificant factors and adjusting the contribution of the other factors is called pooling. In pooling, the sum of squares of the insignificant factor effect is combined with error of the experiment. In this case study, when the two non-significant factors were excluded, the process has increased the mean square error that resulted in a smaller percent contribution value from the significant factors, which occurred after all the errors and their effects were quantified and taken into account in calculating the pure sum of squares. The value of this pure sum of squares represents the actual effect of the significant factor (factors), and this value could be visualized in terms of the percentage contribution amount to the output result. The ANOVA significant factor effect justifies and confirms the decision to determine the optimum result and the confidence interval where the possible estimated process variation shall fall. The increase in error will present a higher degree of freedom of error, and this condition will influence the estimated range of the confidence interval. The higher the error is, the smaller is the range, and this condition is more precise than that at larger range because only the effect from the main significant factor (factors) is being focused on. The optimum results would be inaccurate, and the confidence interval would be too large and impractical if the insignificant factors were not excluded from the calculation of the optimum value (in S/N ratio). The effect of this result can also be seen in the conversion of the S/N ratio into predicted scale values. Statistical inference commonly represents the natural and actual distribution of the data; when the *f* value is small, this method excludes those factors to capture the amount of total error to be considered when estimating a pure relationship between the significant factor (factors) and its (their) effect.

Verification is necessary to justify and validate the experiment. As the snap height is not a critical response variable, emphasis was concentrated more on ensuring that the riveting strength is maintained to attain better results. However, both quality characteristics confirmed that factor C (the stroke distance) is the main contributor to the variation effect. Ten samples were run under recommended combination settings: factor A at A2, 0.4 MPa; factor B at B3, 2.5 sec; and factor C at C3, 2.15 mm. The experiment result was found to be positive when the S/N ratio value for the riveting strength was 16.41 db, where it lay within the range of the calculated confidence interval. The S/N ratio result of the snap height was 28.9 db, better than the 12.06 db value before the experiment. The snap height was not tested with the optimum combination setting because the level set in the final parameter setting was different from the experiment. Priority was focused on ensuring the riveting strength as the main objective.

Comparison of the S/N ratio values was done to understand the achieved experimental result. The first condition was the value of S/N with the setting before the experiment, the optimum condition of the S/N ratio value from the experiment, and the value of the S/N ratio from the confirmatory run. The improvement in riveting strength achieved for the optimum condition in the actual verification run was 39% and 40%. The "nominal-the-best" criterion for snap height was expected to be 250% at the optimum condition; however, its actual improvement following the riveting strength combination setting was only 134%, as explained and shown in Tables 9 and 10.

Table 9. Results and improvement of the experiment for snap height

		Initial stage	**Optimum**	**Actual**
	Control factors	**Initial condition**	**Predicted**	**Observed**
Parameter Setting	A ,B, C	A=0.4Mpa B= 1.5sec, C=2.10mm	A2 B1 C2	A2 B3 C3
S/N ratio (db)		12.06	42.16	28.19
% Improvement S/N ratio			250%	134%
Cpk against expected spec.		-0.075	-	3.512

Table 10. Improvement result of the experiment for critical riveting strength

		Initial stage	**Optimum**	**Confirmation**
	Control factors	**Initial Condition**	**Predicted**	**Observed**
Parameter Setting	**A ,B, C**	**A=0.4Mpa B= 1.5sec, C=2.10mm**	**A2 B3 C3**	**A2 B3 C3**
S/N ratio (db)		11.69	16.23	16.41
Riveting strength (Ncm)		3.84	6.48	6.61
% Improvement S/N ratio			39%	40%
% Improvement in scale unit			69%	72%

4. Conclusions

The Taguchi approach to DOEs is an effective strategy for product and process optimization. In this study, the Taguchi method has been proven to be a practical method to determine the optimum result through optimum combination parameter setting. The Taguchi method approach improved the process performance when optimum parameter settings used in the process resulted in better output performance in terms of quality and productivity. From this study, conclusion was made that the Taguchi method is an effective method in determining the optimum parameter setting and, finally, to quantify the achieved improvement. These results were observed from two experimental results. The actual improvement of the S/N ratio in riveting strength was 40%. The Taguchi method has successfully determined the stroke distance as a significant factor that affected the performance of the riveting strength, technically proving that stroke distance is important in ensuring that sufficient displacement force is applied on the riveting head during the radial riveting process. If the distance is not enough, the amount of force is less, and the riveting process will be incomplete. From the same experiments, the stroke distance was found to be critical in ensuring that the snap height is maintained below 0.11 mm. This result proffered the conclusion that stroke distance is a critical factor because changes in this factor will cause a significant effect in the variation of the two quality performance criteria. The sensitivity of this stroke distance has triggered greater precaution in monitoring and control of this parameter.

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