Journal of Mechanical Engineering and Sciences (JMES)
ISSN (Print): 2289-4659; e-ISSN: 2231-8380
Volume 10, Issue 2, pp. 2200-2213, September 2016

DOI: https://doi.org/10.15282/jmes.10.2.2016.22.0206

Quality improvement using Taguchi method in shot blasting process

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ABSTRACT

This paper presents the reliability of the Taguchi Method for improving the product and process quality in the industrial environment. The purpose is to signify the applicability of the Taguchi method in process optimization. The application of the Taguchi design of experiment (DOE) is widely reported and published but the success of the Taguchi method as a prominent tool in solving the industrial problem is not disclosed. In this study, the shot blasting process was chosen with two control factors of blasting speed and turntable speed; both factors were set at three levels. The rotor blasting speed and turntable speed were set between 2500-2900 rpm and 35-45 rpm respectively. From the result obtained, it was found that the surface roughness capability index improved from Cpk -0.14 to 1.06, i.e. an improvement in the S/N ratio of 113% (from 12.78 dB to 27.21 dB). The main factor that significantly affected the surface roughness variation was rotor blasting speed which contributed 56.9% of the total effects. The optimum setting was by setting the rotor blasting speed at 2900 RPM and the turntable speed at 39 RPM. The estimated tolerance setting was found to be 1% and 2% for the rotor blasting speed and turntable speed respectively. The optimum setting resulted in the improvement of the surface roughness, i.e. the quality of the part. Taguchi method is an effective way to determine optimum performance through the analysis of optimum combination parameter setting.

Keywords: Quality improvement; Taguchi method; blasting process; capability index; tolerance setting

INTRODUCTION

The massive competition in the world market is to satisfy customers' need and the expectation has triggered manufacturers to improve the product design and cost of manufacturing [1]. In reality, the application of statistical techniques and experimentation are not widely being used in the industrial organization. In such situation, companies that were unable to overcome the challenging demand have to close operation and the worst scenario is if the organizations are engaged with millions of debts and are facing difficulty in paying back. In general, many manufacturers are not able to use the design of experiment to improve the quality of product faster in the product development process at lower manufacturing cost. In replacement, trial and error are still the popular approaches to be employed. As a result, excessive loss and waste are encountered during the development and processing of the intended goods to be sold in the market. The conventional design of the experiment is known as a very complicated and highly disciplined process which required competent resources and will accrue high experimental cost. It is complex and not easy to use, especially when a large number of experiments have to be carried out when the number of the process parameters increase [2, 3]. The time required to complete an experiment is extremely long especially for investigating and evaluating the large quantity of factors that affecting the desired quality characteristics. In the Taguchi method, model development is not required to satisfy the needs in design optimization as well as in problem solving [4]. Taguchi method is based on actual practice and not on complicated statistics [5, 6]. Previous work that utilized the Taguchi method in order to reduce experimental run yet withdraw a valid conclusion are listed [7-11].

To achieve the desirable product quality by design, Dr. Taguchi recommends a three-stage process; system, parameter and tolerance designs [12-14]. The Taguchi methodology has taken the design of experiments from exclusive world of the statistician and brought it more fully into the world of manufacturing [2]. It emphasizes the importance of designing quality control into manufacturing processes [12, 15]. Robust design is an engineering methodology for optimizing the product and process conditions which minimally sensitive to the various causes of variation, and which produce high quality of product with low development and manufacturing costs [16]. The robust design and indeed any statistical analysis need to be carried out with the engineering aims of the study clearly in mind [17].The shot blasting process in this case study is for a mechanical surface treatment. The workpiece was shot repeatedly with a cast steel ball or iron shot, which made overlapping indentations on the surface [18]. Although the main reason for this process is to achieve a designated surface roughness for the subsequent finishing process, the result of the shot blasting process was actually developing a plastic surface deformation which has improved the fatigue life by delaying the fatigue crack initiation [19]. The essence of Taguchi approach is its contribution to the excellent quality control in the manufacturing industries. His concept has developed engineers to see quality as a yardstick in their design of product and process. The philosophy which based on three fundamental concepts has greatly caused the better application and development of technology and techniques in many industries. The three concepts are [12];

i) Quality should be designed into the product and not in its inspection.
ii) To achieve the quality it is best to minimize the deviation from the target and product shall be designed to be insensitive to the uncontrollable environmental factors.
iii) The cost of quality is measured as a function of deviation from the standard and the losses should measure system-wide.

Robust design is an engineering methodology for optimizing the product and process conditions which minimally sensitive to the various causes of variation, and produce high quality of product with low development and manufacturing costs [16, 20]. The Taguchi parameter design is an important tool for robust design. In this method, the tolerance design can be also classified as a robust design. Specifically, the robust design is identical to the parameter design but a wider sense parameter design is a subset of a robust design. Two major tools used in the robust design are [21, 22];

i) Signal-to-noise ratio which measures quality with the emphasis on variation.
ii) Orthogonal arrays which accommodate many design factors (parameters) simultaneously.

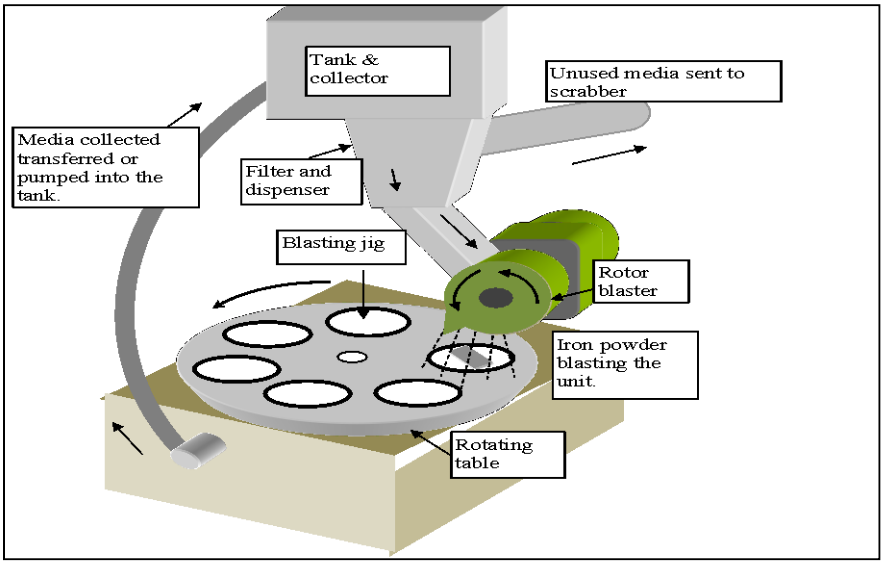
The shot blasting process which is also known as an airless blasting process operates when the abrasive is hurled centrifugally upon the work by means of one or more rotating bladed wheels which are strategically mounted to get the abrasive coverage of the surfaces to be cleaned or blasted. In the industrial application of the abrasive blasting process, the objectives are [23] cleaning the casting residue, removing scale from forging process, cleaning and removing welding spatter and flux, removing foreign materials and preparing a surface texture for galvanizing, painting, metalizing and anodizing process. In this study, how the quality improvement is made possible by using the Taguchi method in the actual manufacturing environment is presented. In addition, the effectiveness of Taguchi method is evaluated. The screening of process parameters is a method to achieve high quality without increasing the number of experiments and cost.

METHODS AND MATERIALS

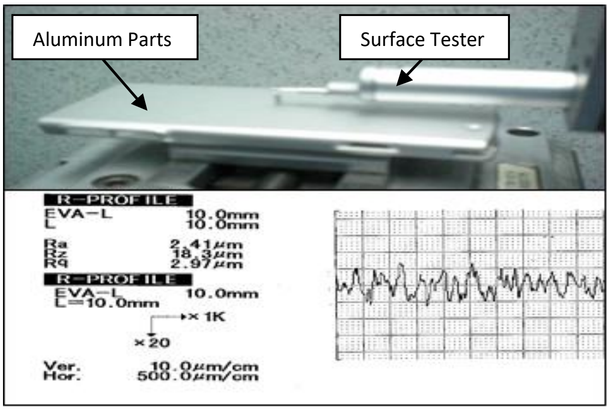
Since it is important to verify the effectiveness of the Taguchi method the study has been focused on knowing the procedures and methodology applied in this approach are consistent with the objective of the project. It is necessary to experience the experimentation and its difficulties such that are coming from external factors and in the experimentation itself. The instrument in this study was the experiment methodology which was conducted at the production of the mechanical assembly line and surface treatment process. The experimentation was conducted for the static case in the production of shot blasting process and the response variable was the surface roughness. The purpose is to identify the significant process parameters and tolerance setting for shot blasting process. Taguchi design matrix L9 was used to run the experiment and the main effect of each factor was calculated. In this investigation, the focus was to apply the pure approach of the Taguchi method in the design of the experiment and the interactions in this study was not anticipated as a significant effect. The current performance of these quality characteristics shall be measured as a baseline for future comparison. The next stage was to identify factors that potentially affect the quality performance of the response variable. The level for each factor to be tested was determined as this led to the selection of appropriate Taguchi orthogonal array. The dominant and significant effects of factors were to be confirmed with the ANOVA results. The optimum combination setting from the ANOVA results was determined by a review of the main effect plots as ANOVA will show the significant factors but not the levels of all factors.

Shot Blasting Process: Single Response

Blasting process is a process to form a surface texture on the metal as preparation for the next finishing process such as spraying and anodizing. In addition, blasting process will increase the plain fatigue stress [24]. The process is by blasting an iron powder onto aluminium alloy to generate a surface which provides a gripping force as well as the desired surface texture for cosmetic quality. Once the blasting process finishes the specimen is checked by a surface tester. The response variable for the blasting process is the surface roughness measured in Ra (an arithmetic mean of the absolute values of the profile deviations from the mean line). The measurement of the surface roughness was done using the surface tester machine made by Mitutoyo Corporation. The blasting machine number 5 of the production line was chosen for the whole experiment activities. Below are the blasting machine and blasting process used in the experiment. The blasting process, equipment and inspection method of the surface roughness are shown in Figure 1.



(a)



(b) (c)

Figure 1 (a) Schematic diagram of the blasting machine, (b) The front side of the machine, and (c) The surface tester and the specimen

DOE using Taguchi Method

The objective of this experiment is to determine the optimum response variable of the surface roughness through the optimum parameter setting. Therefore, the following formula was used [16]:

$$\text{Nominal the best: } S/N = 10 \log [y^2\text{mean}/s^2] \quad (1)$$

The experiment was conducted with two noise factors at two levels; the first factor is a condition after filling up 5 kg of blasting media and before the topping up of media, the second-factor experiment was conducted by two experimenters. There were two controllable factors tested in this experiment: Both blasting (rotor) speed and turntable speed were measured in rotation per minutes (R.P.M) as depicted in Table 1. Taguchi L9 orthogonal array was used to run the experiment as shown in Table 2. There were nine experimental runs conducted at three different levels with two noise factors [25, 26].

Table 1. Factors and levels set for experiment at the blasting machine.

Controlled Factor	Units	Level 1	Level 2	Level 3
A. Rotor Blasting speed	R.P.M	2500	2700	2900
B. TurnTable speed	R.P.M	35	39	45
Noise factors				
1- Media Top Up	-	Before Top Up	After Top Up	-
2- Experimenter	-	Person -1	Person -2	-

Table 2. The L9 orthogonal array and its combination setting for factor A and B.

	Control Factors					Noise Factors			S/N
Expt.No	A	B	Empty	Empty	T1S1	T1S2	T2S1	T2S2	
1	2500	35	1	1	Result1	Result2	Result3	Result4	
2	2500	39	2	2	Result1	Result2	Result3	Result4	
3	2500	45	3	3	Result1	Result2	Result3	Result4	
4	2700	35	2	3	Result1	Result2	Result3	Result4	
5	2700	39	3	1	Result1	Result2	Result3	Result4	
6	2700	45	1	2	Result1	Result2	Result3	Result4	
7	2900	35	3	2	Result1	Result2	Result3	Result4	
8	2900	39	1	3	Result1	Result2	Result3	Result4	
9	2900	45	2	1	Result1	Result2	Result3	Result4	
A = Blasting speed – Rpm					Noise factor i) T – Before and after top up material				
B = Table speed – Rpm					Noise factor ii) S – Experimenter 1 and Experimenter 2				

Figure 2 is the block diagram for the blasting process indicating the relationship between the controllable and noise factors and the response variable.

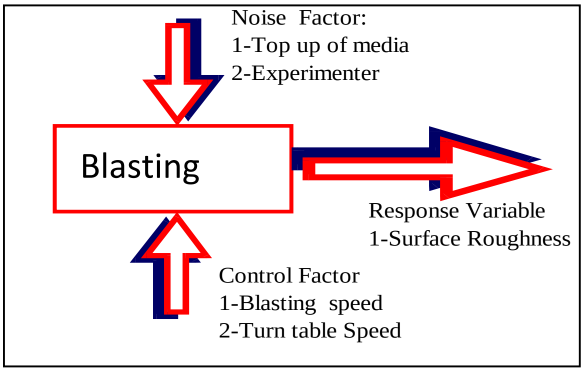


Figure 2. Block diagram for blasting process (a static problem).

RESULTS AND DISCUSSION

Analysis of Result using S/N ratio

The experiment conducted at blasting process was a single response variable with two controllable factors; factor A was the rotor blasting speed and factor B the table speed. This experiment was conducted under two noise levels to ensure the robustness of the design of experiment process. There were conditions of before and after topping up the material, and two different experimenters carried out the experiments. The result of the experiment is shown in Table 3.

Table 3. The results of surface roughness in the experiments.

Factors			Noise Factor						
Run	Blasting Speed (rpm)	Table Speed (rpm)	T1S1	T1S2	T2S1	T2S2	Mean	Variance	S/N ratio (Nominal the best)
1	2500	35	2.42	2.05	2.15	2.60	2.31	0.06	19.253
2	2500	39	2.42	2.32	2.51	2.18	2.36	0.02	24.433
3	2500	45	2.05	2.50	2.37	2.26	2.30	0.04	21.617
4	2700	35	2.38	2.58	2.81	2.35	2.53	0.05	21.505
5	2700	39	2.51	2.59	2.60	2.65	2.59	0.00	32.996
6	2700	45	2.76	2.32	2.61	2.31	2.50	0.05	21.022
7	2900	35	2.68	2.81	2.72	2.74	2.74	0.00	34.037
8	2900	39	2.78	2.70	2.54	2.71	2.68	0.01	28.446
9	2900	45	2.54	2.60	2.50	2.60	2.56	0.00	34.363

The experiment resulted in the overall mean of the S/N ratio as 26.4 dB. The calculation of the main effect in S/N ratio was made from the experimental result and plotted in the graph as shown in Figure 3. The graph shows that factor A, the blasting speed was the main factor affecting the bigger variation to the quality performance of the surface roughness. The most significant level of factor A was at the level 3, i.e. 2900 R.P.M, the highest S/N ratio value indicated. There was only a slight effect from factor B; table speed and the highest S/N ratio value were at the level 2. The factors affecting the surface roughness in blasting process were justified by performing the ANOVA in which the significant process parameters are statistically determined [4, 27].

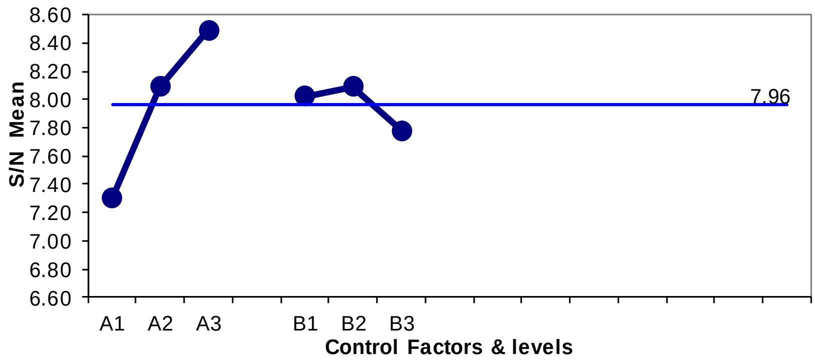


Figure 3. Factors affecting the surface roughness.

The main effect graph for blasting has shown the similar view on how factors are affecting the surface roughness. In this single response variable experiment, the graph gave definite information on factor A as the key factor affecting the quality performance of the surface roughness. Subsequently, the optimal level of the process parameters was determined by the combination of individual parameters with levels having the highest signal to noise ratio [28]. This was agreeable with Apte [29] and Radhakumari [25] on the important of the main plot in determining the optimum condition. Phadke [16] also used the main effect plot to calculate the optimum result of the experiment. The result in ANOVA table has determined and confirmed the significant of factors accordingly [30]. The blasting speed contributed 57.53% of the total variation in the quality performance and its *F* value was 3.30. Whereas the second factor, table speed contributed 7.64% with *F* value of 0.44. This result shows that factor A was the most significant factor and factor B was subjected for pooling as its *F* value was very small and the contribution was less than 10%. This result is shown in Table 4.

Table 4. The ANOVA calculation for factor affecting the surface roughness.

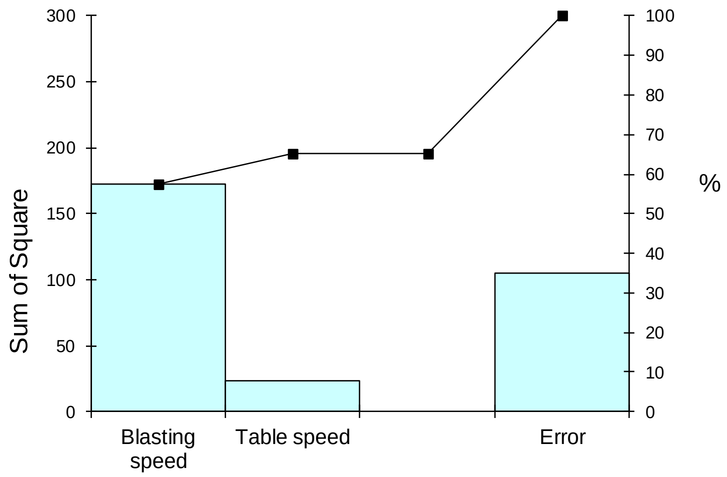
Factors	Degree of freedom	Sum of squares	Mean squares	Mean square ratio-F	x' = is Pooled variance	Pure sum of square	Percent contribution %
A-Blasting Speed (rpm)	2	172.67	86.33	4.06		130.18	43.37
B-Table Speed (rpm)					X		
Error	6	127.47	21.25			169.96	56.63
Total	8	300.14					100.00
Effective Df factors	2						

Table 5. The ANOVA table after the pooling of factor B.

Factors	Degree of freedom	Sum of squares	Mean squares	Mean square ratio-F	x' = is Pooled variance	Pure sum of square	Percent contribution %
A-Blasting Speed (rpm)	2	172.67	86.33	4.06		130.18	43.37
B-Table Speed rpm)					X		
Error	6	127.47	21.25			169.96	56.63
Total	8	300.14					100.00
Effective Df factors	2						

Pareto Diagram was constructed from the result of ANOVA in Table 4. The figure shows that the blasting speed was the major contributor, and therefore indicates that the focus and control of this factor were significantly important to maintain the variation to the quality performance. The ANOVA in Table 5 displays the value of factors affected after the pooling of the factor B. The optimum result was calculated based on only factor A at the most significant level that affects variation in the quality performance. The optimum result was 32.82 dB. In this study, ANOVA revealed that the blasting speed of factor A was the most significant factors affecting the surface roughness compared to the table speed of factor B. The result was similar to the finding of Maghsoodloo et al. [31].

They justified that a weak factor (factor B) has no effect on the mean or variability of the response variable. The other important feedback of the ANOVA table was the amount of error before pooling any variance. In several examples, when the error was near to 30%, the data collected were not accurate as the probability of this source of error may come from factors that were not addressed in the experiments or due to variation coming from experimental error, and this information is important to review the experiment before wrong conclusion and decision are being made [32].



NO	Factor	Sum of Square	%
1	Blasting speed	172.67	57.53
2	Table speed	22.94	7.64
	Error	104.54	34.83
	TOTAL	300.15	100.00

Figure 4. Pareto diagram for factors affecting the surface roughness.

The calculation of the confidence interval quantities was determined and calculated using the following equations [29]:

1. S/N opt = mean + (selected MA3-mean) + (selected MB2-mean) (2)

The overall mean value from the experiment was 26.41 dB. The S/N opt calculated was 32.282 dB when the effect of factor B was pooled.

2. The optimum response variable in the scale unit was determined below;

$$\text{Variance Y optimum} = 10^{-(\frac{S}{Nopt})/10} = \text{MSD} \Rightarrow 0.00059\ \mu m \tag{3}$$

Y optimum square root of variance MSD $= \sqrt{MSD}$ => 0.02432 µm

Estimated result from S/N in scale unit;

$$Y_{opt} = Y_{mean} \pm \sqrt{MSD} \tag{4}$$

$$Y_{mean} = 2.5500$$

$$Y_{opt} = \text{ from } 2.525 \text{ to } 2.547\ \mu m$$

3. Confidence Interval

$$\text{C.I} = \pm\sqrt{(F(1,n2) \times \frac{Ve}{Ne})} \tag{5}$$

$$Ne = \frac{\textit{total number of results}}{\textit{dF of mean (=1, always) + dF of all factors included in the estimate of mean}} \quad (6)$$

= 9/(1+2)
= 3.00
Ve = 21.245
Ne = 3.00
dF n2 = 6.00 for the error
F(1,n2) = 3.776 at 90% confidence
Confidence Interval (*C.I.*) in S/N ratio was = 5.171 dB where S/N opt. was 32.282 dB

4. Upper value was S/N opt. + C.I = 37.453 dB, converted into the scale unit
Y optimum = *(Yo or Ymean)* $\pm \sqrt{MSD}$
MSD S/N upper = $10^{-(\frac{S}{N_{upper}})/10}$ = 0.00018
Y optimum at S/N high; minimum = 2.53 µm, and maximum = 2.56 µm
5. Lower value was S/N opt. – C.I = 27.111 dB, converted into scale unit
Y optimum = (*Yo or Ymean*)$\pm \sqrt{MSD}$
MSD S/N lower = $10^{-(\frac{S}{N_{lower}})/10}$ = 0.00194
Y optimum at S/N lower; minimum = 2.50 µm, and maximum = 2.59 µm

Table 6. Improvement result for blasting process.

	Initial stage	Optimum	Confirmation
Control factors	Initial Condition	Predicted	Observed
Parameter Setting A,B	A2 B2	A3 B2	A3 B2
S/N ratio (dB)	12.78	32.28	27.21
% Improvement S/N ratio -	153%	113%	
Surface Roughness	2.35	2.53	2.55
Cpk value	-0.14	-	1.06

The optimum result from this experiment obtained was 32.8 dB. The conversion of this value into scale unit gave two estimated result as 2.52 micron for the lower S/N value and 2.54 micron at the higher S/N value. The confidence interval for the upper limit was 37.45 dB and the lower limit was 27.11 dB. The conversion of this confidence level into scale value gave two estimated result at the upper and lower bound of the S/N ratios. The selection of the applicable confidence interval was from the lower bound as it provided larger limits for the mean to fall. The confidence interval is used to manage the expectation within estimated probability of error [33]. The validation of the experiment was confirmed with the S/N ratio value obtained from the verification run which was 27.21 dB. According to Zhang et al. [34], the confirmation run indicates that the selection of the optimal levels for all parameters will produce the best quality characteristic [35]. In this case study, the final combination of parameter setting was determined as A3 and B2; factor A was set at 2900 RPM and the factor B was at 39 RPM. The higher blasting speed was expected to produce the larger size of grains [36] reflected by the higher value of the surface roughness. The optimum condition suggested by the experiment indicates improvement in the S/N ratio was 153% compared to before experiment and 113% in the verification run after the experiment. The Cpk value of the surface roughness was increased to 1.06 from -0.14 against a specification of 2.4 to 2.7µm set for the surface roughness. The improvement result of the experiment is shown in Table 6.

The standard deviations determined from the experiments were used to quantify the capability of process under normal and student distribution. For example, the variations of the quality performance before and after experiment were visualized through the plus minus 3-sigma distribution. This is more important when the target of the quality is known. Statistically, the improvement can be visualized through the sample distribution as depicted in Figure 5, a comparison before and after experiment for surface roughness.

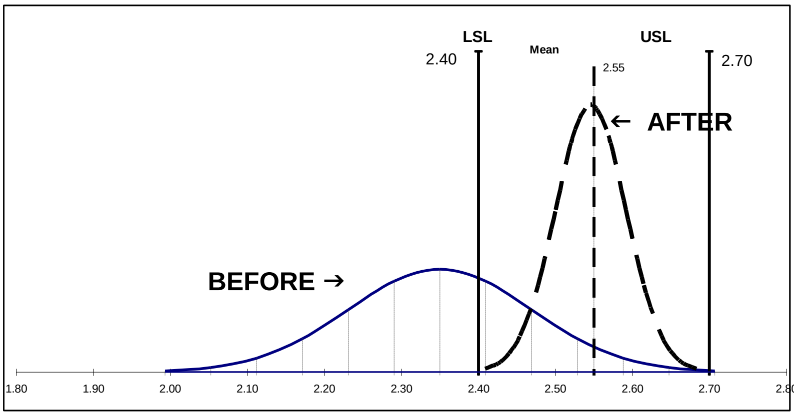


Figure 5. The statistical comparison before and after experiment for surface roughness.

The Cpk of the performance was calculated to understand the process capability against the expected target and this was the second verification to justify the result is in accordance with the objective target and customer expectation [37]. The Cpk value of the surface roughness in blasting process was 1.06 which indicates a strong improvement compared to the previous performance of -0.14. The Cpk of 1.06 means further improvement is required to ensure the process is highly robust to customer specifications. This analysis will raise the necessity to execute the design of experiment for continuous improvement activity.

Table 7. Tolerance setting off for factor blasting speed and table speed.

	Factors			Noise or repetition				
Trial (No.Exp)	A	B	Empty	R1	R2	Mean	Variance	Nominal the best
1	2871.00	38.22	0.00	2.57	2.58	2.575	0.0001	51.23
2	2871.00	39.78	0.0	2.52	2.43	2.475	0.0041	31.80
3	2929.00	38.22	0.00	2.62	2.63	2.635	0.0000	51.39
4	2929.00	39.78	0.00	2.59	2.46	2.525	0.0084	28.78

Parameter Tolerance Setting for Blasting Process

The tolerance setting of the experiment was determined according to the optimum parameter setting [13]. The tolerance was found applicable when the blasting speed of factor A at level 3 was set from 2871 RPM to 2929 RPM and the table speed at level 2 was set at 38.22 RPM to 39.78 RPM. All units tested with the L4 combination arrays fall within the desired specification limit of 2.4 – 2.7 µm. The selection of the tolerance range is shown in Table 7 and the result of the combination runs is shown in Table 8.

Table 8. Result of the combination run for tolerance setting.

Comparison item	Min	Max	Unit
1. Target value	2.400	2.700	µm
Data spread from predictive interval	2.419	2.681	µm
2.Target value	2.400	2.700	µm
Mean spread from predictive interval	2.414	2.686	µm

The acceptance was confirmed from the result of the predictive interval limits for overall data and the mean fell within specification limits [38]. It was obtained that the predictive interval for overall samples was from 2.42 until 2.68 µm. The predictive interval for the mean was from 2.41 until 2.69 µm. These results are shown in Table 9. The tolerance limits were found suitable to maintain the surface roughness to be within the engineering specification.

Table 9. Confirmation result of the applicable tolerance limits.

Factors	Selected level	Level value	Estimated tolerance	Min (L1)	Max (L2)
Blasting Speed (rpm)	A3	2900	1%	2871.00	2929.00
Table Speed (rpm)	B2	39	2%	38.22	39.78

CONCLUSIONS

In this study, the Taguchi method was proven to be a practical way of determining the optimum parameter through analysis of combination parameter setting. The approach of the Taguchi method was able to improve the process performance when the optimum parameter setting used in the process gave better output performance in terms of quality and productivity. The success of the Taguchi L9 orthogonal arrays in determining the processing parameters has led to the determination of appropriate tolerance for the process to improve its insensitivity to the noise factors. The outcome of the experiment in the blasting process revealed that the surface roughness is greatly influenced by the changes in the blasting speed from a rotor blaster. The experiment noticed a higher reading in surface roughness (Ra) with a stronger blasting speed. The blasting speed contributed (57%) over the total variation effect. It was found that the Taguchi method needs to be trained to the experimenter prior to conducting the experiment. This will make the execution of the experiment be more interesting to the workers and engineers. In this study, it was observed that with proper understanding on the Taguchi basic concept, people are motivated to apply this important tool in their project development and solve inline quality problems.

ACKNOWLEDGEMENTS

The authors would like to thank the Company A for giving an opportunity to demonstrate the application of Taguchi Method design of experiment in improving quality performance that finally increased the efficiency of its production line. This project as part of my master thesis and it was conducted with facilities provided by the company. Finally, authors would like to acknowledge and thank Universiti Kebangsaan Malaysia for the support and guidance in this successful project.

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