# Parameters Optimization of Rotary Ultrasonic Machining of Glass Lens for Surface Roughness Using Statistical Taguchi's Experimental Design

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*Abstract:* An experiment was conducted to compare the effects of ultrasonic and non-ultrasonic on glass lens using rotary ultrasonic machining (RUM) technology. The primary objective of this study is to analyze the experimental results of the grinding operations using Taguchi method. Feed rate and frequency are the main process parameters to be tested in this experiment. A three-level orthogonal array table had been used to determine the signal-to-noise (S/N) ratios based on Taguchi's design of experiments and analysis of variance (ANOVA) was performed to study the relative significance of both factors in affecting the surface roughness of glass lens. The final results showed that the process output is greatly influenced by the feed rate rather than the frequency and low feed rate without frequency is identified to be the most optimum factor settings. The data of the confirmation run are provided to verify the effectiveness of Taguchi's approach.

*Key–Words:* Taguchi approach, analysis of variances, parameters optimization, rotary ultrasonic machining technology, surface roughness, glass lens, SAS JMP.

## 1 Introduction

RUM is recognized as one of the reliable and cost-effective machining methods used in a number of critical engineering applications among the other non-traditional machining processes. This machining method was invented in 1964 by Percy Legge [1], a technical officer at United Kingdom Atomic Energy Authority. It combines material removal mechanisms of grinding and ultrasonic machining resulting in a higher material removal rates (MRR).

Glass is an important material for optical industries, but it is also one of the most difficult-to-cut materials due to its superior qualities. An experiment was conducted to study the effects of process parameters (feed rate, frequency) upon the surface quality of glass lens by using RUM method. Surface roughness is considered to be a measure of the technological quality of a product. A methodology for the application of designed experiments, which is namely Taguchi method, was used to determine the optimal level combination of the selected process parameters for better surface quality of glass lens in this research.

There were mainly three main objectives for this study. The first was to demonstrate a systematic procedure of using Taguchi's Parameter design in RUM of glass lens. The second was to obtain the optimal process parameters for better process performance and the final purpose is to examine the effectiveness of Taguchi method in the optimization of RUM process parameters.

This paper focuses on the application of Taguchi method in RUM of glass lens. Orthogonal array was employed to plan a Taguchi's version of experimental design while signal-to-noise (S/N) ratio and analysis of variance (ANOVA) method were used to analyze the experiment's result by using statistical software,

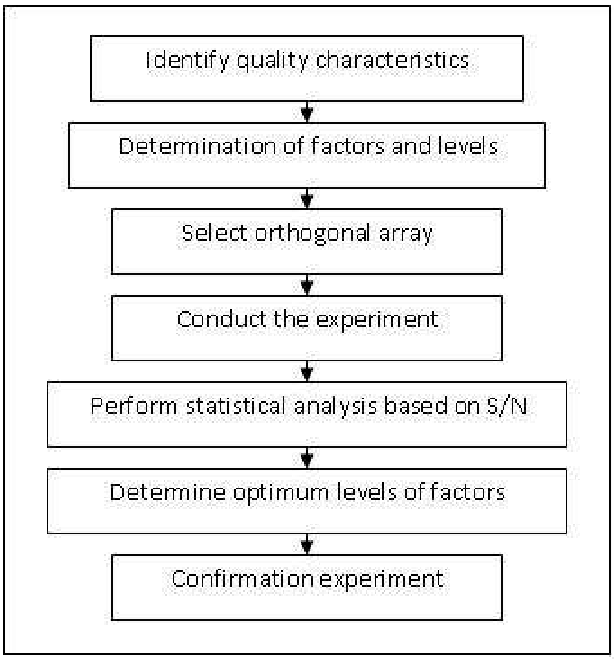


Figure 1: Process flow of the experimentation strategy

SAS JMP version 7.

## 2 Methods

Taguchi method [2] is a set of experimentation techniques based on statistical principles and utilizing engineering knowledge developed by Japanese quality expert, Dr. Genichi Taguchi. The first phase of Taguchi's engineering design methodology is system design which is the conceptual design stage of any new product development or process innovation. Secondly, the innovation in system design is used to optimize the manufacturing processes by making effective use of experimental design and statistical techniques. Lastly, the acceptable range of variability around the nominal settings obtained in parameter design will be determined in tolerance design stage.

Parameter design [3] determines the product parameter values and process factor levels which are less sensitive to change in environmental conditions in the second phase. The step-by-step approach of Taguchi's procedure is as shown in Figure 1.

Orthogonal arrays [4] are special arrangements of factor settings widely used in the design of experiments to gain maximum amount of information by using the least number of experiments. Types of orthogonal tables can be identified as $L_x(Z^y)$, where $y$ is the number of input parameters, $Z$ is the number of level settings and $x$ is the number of experiments that must be run to complete the matrix.

Another significance of Taguchi method is S/N ratio [5], which is the essential component of Taguchi's parameter design because its' equation is tied to interpreting the signal or numerator of the ratio as the ability of the process to build a good product, or of the process to perform correctly. There are mainly three kinds of quality characteristics used to measure the performance, which are smaller-the-better, nominal-the-best and larger-the-better.

For smaller-the-better, the S/N ratio is defined as,

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

For nominal-the-best, the S/N ratio is defined as,

$$\eta = -10 \log \left( \frac{\bar{y}^2}{s_y^2} \right) \tag{2}$$

For larger-the-better, the S/N ratio is defined as,

$$\eta = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \tag{3}$$

where $\bar{y}$ is the average of the observed data, $s_y^2$ is the variance of $y$, $n$ is the number of observations and $y$ is the observed data.

A larger S/N ratio corresponds to a better performance characteristic. With the analysis of S/N ratio, conclusions are not based only on the effect on the mean results for the quality characteristic of interest because the calculations take into consideration both the mean and the variation from one result to the next. Hence, S/N ratio analysis [6] can be viewed as being two-dimensional as opposed to regular analysis being only one-dimensional. Therefore, S/N ratio analysis is usually used to compare performances when variation is of major concern, especially when there is more than one sample in each trial condition.

Confirmation experiment is the final step of Taguchi's data analysis procedure. This is because it is essential to run another experiment to validate the predicted values of the optimal factor level combination. If the result doesn't match the predicted outcomes, the experimenter might need to re-consider the planning of the experiment and re-study the selected factors at the initial phase.

## 3 RUM Experiment

RUM tests are performed on an ultrasonic machine of Sonic Mill Series 10 using diamond wheel [7] which is specifically designed to grind advanced materials. The experimental setup consists of an ultrasonic spindle system, a data acquisition system, and a coolant

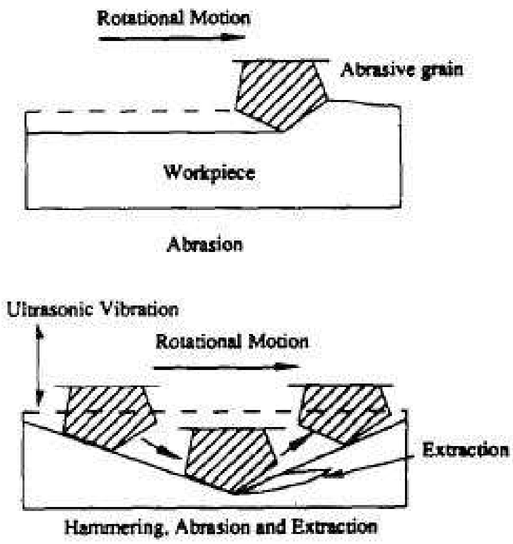


Figure 2: Material removal mechanisms of RUM

system. The work piece material (BK7 glass) with the size of 16mm × 16mm was examined by running under different operating conditions in this experiment. Then, Mitutoyo Formtracer C5000 was finally used to measure the surface roughness of the BK7 glass after the grinding operation.

RUM technology [8] combines the material removal mechanisms of ultrasonic machining process and the conventional diamond grinding process. These include hammering (indentation and crushing under impact of the ultrasonic vibrations), abrasion (the rotational motion of the cutting tool can be modeled as a grinding process) and extraction (produced by the simultaneous action of ultrasonic vibration and rotational motion of the tool). The material removal mechanisms of RUM with and without frequency are schematically illustrated in Figure 2.

## 4 Results and Discussion

The experiments were carried out to examine the effects of ultrasonic (with frequency) and non-ultrasonic machining (without frequency) on the surface quality of glass lens as well as to test different inputs of feed rate using both machining methods. Hence, feed rate (mm/min) and frequency (kHz) were selected as the main factors of this experiment. The desired output of the machining of glass lens is smaller value of surface roughness $(R_a)$ in the unit of $\mu$m . Thus, the quality characteristic of the output was identified to be smaller-the-better. The selected factors and levels are as shown in Table 1.

Firstly, the total degrees of freedom were computed before selecting an appropriate orthogonal array to fit the specific task because each orthogonal array has a specific number of degrees of freedom within its structure as shown in Table 2.

Table 1: Levels of RUM parameters

| Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Feed rate (mm/min) | 0.5 | 1.5 | 2.5 |
| Frequency (kHz) | 0 | 30 | 40 |

Table 2: Number of degrees of freedom

| Factor | Total number of levels | Degrees of freedom |
|---|---|---|
| Feed rate | 3 | $3-1=2$ |
| Frequency | 3 | $3-1=2$ |
| Total | | $2+2=4$ |

Since feed rate and frequency were both studied at three levels, this means each factor required two comparisons or degrees of freedom. Therefore, there are a total of four degrees of freedom for the two RUM parameters in the grinding operations. An $L_9$ orthogonal array was used as the experimental layout of the grinding process because it can accommodate up to a maximum number of four 3-level factors with eight degrees of freedom. Table **??** shows the experimental results and S/N ratio of the surface roughness.

S/N ratios obtained from the experimental results are analyzed with the level average technique. Average effects of each level for both feed rate and frequency are computed in order to construct main effects chart as shown in Figure 3. Taguchi's approach on S/N ratio reveals that higher S/N ratio is always the desired output for smaller-the-better quality characteristic.

According to Figure 3, the average S/N ratio of feed rate and frequency at each level is getting lower and lower. This result indicates that the surface of the glass materials becomes rougher at higher level of both feed rate and frequency. Thus, the most optimum factor level combination is both feed rate and frequency at level 1.

ANOVA is essential to determine the various relative quality effects as well as to study the contribution ratio of the process parameters. In addition, ANOVA computation was performed for evaluating the significance of RUM parameters over surface roughness. Table 4 displays the ANOVA table which was used to show the values of sum of squares, mean squares and the percentage contribution of each factor.

Further analysis on the data is performed by us-

Table 3: Experimental results for surface roughness

| Number of runs | Feed rate | Frequency | Surface Roughness 1 | 2 | 3 | Mean | S/N ratio |
|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0 | .29 | .28 | .31 | .30 | 10.58 |
| 2 | 0.5 | 30 | .32 | .30 | .32 | .31 | 10.11 |
| 3 | 0.5 | 40 | .37 | .35 | .34 | .35 | 9.11 |
| 4 | 1.5 | 0 | .35 | .38 | .37 | .37 | 8.75 |
| 5 | 1.5 | 30 | .45 | .45 | .45 | .45 | 6.94 |
| 6 | 1.5 | 40 | .42 | .42 | .40 | .41 | 7.74 |
| 7 | 2.5 | 0 | .43 | .42 | .41 | .42 | 7.56 |
| 8 | 2.5 | 30 | .49 | .47 | .54 | .50 | 5.98 |
| 9 | 2.5 | 40 | .69 | .59 | .53 | .61 | 4.32 |

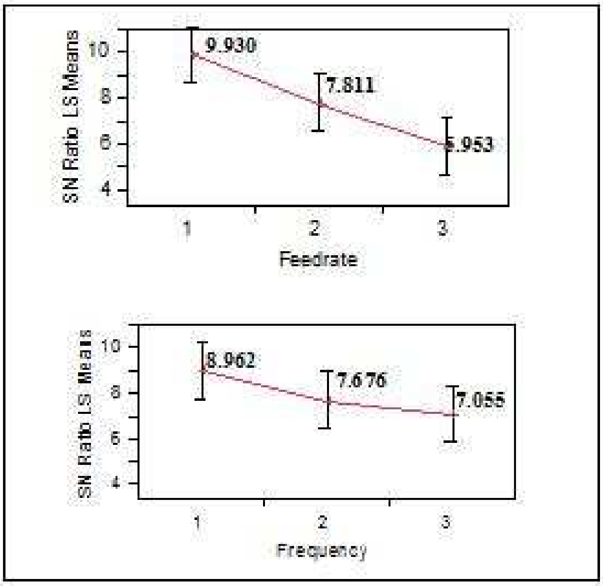


Figure 3: Output from SAS JMP: S/N ratio response graph for feed rate and frequency

Table 4: Analysis of variance table

| Source | *df* | SS | MS | Percentage |
|---|---|---|---|---|
| Feed rate | 2 | 23.755 | 11.878 | 74.734 |
| Frequency | 2 | 5.680 | 2.840 | 17.870 |
| Error | 4 | 2.351 | 0.588 | 7.396 |
| Total | 8 | 31.786 | 3.793 | 100.000 |

Table 5: Results of the confirmation run for surface roughness

| | Initial Assumptions | Optimum Condition Prediction | Experiment |
|---|---|---|---|
| | mm/min, kHz | mm/min, kHz | |
| Level | 0.5, 40 | 0.5, 0 | 0.5, 0 |
| $R_a(\mu\text{m})$ | 0.379 | 0.282 | 0.263 |
| S/N ratio | 8.427 | 10.997 | 11.604 |

ing t-test in order to compare the parameter levels with one another for a better understanding on which pair of comparisons is significantly different with each other. According to the t-test, all the levels of feed rate are significantly different with each other. However, the results for frequency are exactly the opposite of feed rate since all the differences between the levels of frequency are very small. Thus, feed rate is proved to be the main factor which influenced the surface quality of the glass materials in this experiment with the significant difference between high feed rate and low feed rate based on the multiple comparisons results.

Since the optimum factor level combination [8] is identified to be feed rate at 0.5 mm/min without any frequency input (0 kHz), the predicted S/N ratio can be computed by using Eq. (4).

$$\widehat{\eta} = \eta_m + \sum_{i-1}^{q} (\overline{\eta}_i - \eta_m) \quad (4)$$

where $\eta_m$ is the total mean of S/N ratio and $\overline{\eta}_i$ is the mean S/N ratio at the optimal level and $q$ is the number of the process parameters that significantly affect the performance characteristic.

Then, a confirmation experiment was conducted under the recommended optimum settings to see whether the actual result matched the estimated S/N ratio or not. However, there are no references of the previous RUM settings used to machine BK7 glass since this research is new in this field. But, higher frequency input was assumed to be able to produce a better surface roughness initially, so an additional test is conducted under low feed rate with high frequency (40 kHz) in order to confirm which parameter levels yield the best results. Table 5 shows the result of the confirmation run.

The optimal parameter levels are able to produce an even better surface roughness than the predicted result. In addition, the actual S/N ratio of the surface roughness is also found out to be falling within the predicted range from 7.500 until 10.674 under a 95% confidence level [9] by using Eq. (5).

$$\hat{\eta} \pm \sqrt{F(1, df_e; \alpha) \times MS_e \times \left(\frac{1}{n_e}\right)} \qquad (5)$$

where $MS_e$ is the mean sum of squares for error variance in the ANOVA table, $df_e$ is the residual degrees of freedom (*df* associated with the error sum of squares), $F(1, df_e; \alpha)$ is the critical value from the $F$-table depending on 1 and $df_e$ is the degree of freedom at level significance $\alpha$ and $n_e =$ (Total no. of S/N ratio) / (*df* of mean $(= 1) + df$ of all factors included in estimating the optimum performance).

Furthermore, the improvement of the S/N ratio is as high as 3.174 and the surface roughness is decreased 1.441 times as a result of better machining performance under the optimum settings. Thus, the experimental results confirm the prior parameter design for the optimal RUM parameters in grinding operations.

## 5 Conclusion

The research has fully demonstrated Taguchi's data analysis procedure which draws the conclusion as below:

(a) The orthogonal array method introduced by Taguchi is suitable in selecting the right design with lesser number of runs.

(b) Taguchi method provides a simple, systematic and efficient methodology with a step by step approach in analyzing the experimental data.

(c) The measured surface roughness is decreasing with the increment of feed rate and frequency settings.

(d) Feed rate, which measures how fast the tool travels through the work piece is the main factor which influenced the machining performance with a high percentage of contribution (74.734%) while frequency only contributed 17.870%.

(e) The combination of feed rate and frequency at level 1 produced the most optimum result which the mean S/N ratios of feed rate and frequency at this level are 9.930 and 8.962 respectively.

(f) The difference between level 1 and level 3 of feed rate is identified to be the most significant as compared to the other comparisons made among each factor level.

(g) The machining method without ultrasonic vibration is proved to be better in terms of the surface quality of BK 7 glass with an improvement of S/N ratio which valued 3.174 as compared to the machining at 40 kHz in the confirmation test.

(h) The actual S/N ratio falls within the 95% confidence interval between 7.5000 and 10.674 which match the prediction of the optimum factor level combination using Taguchi method.

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