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ORIGINAL ARTICLE

Enhancement and verification of a machined surface quality for glass milling operation using CBN grinding tool—Taguchi approach

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Abstract Nowadays, the demand for high product quality focuses extensive attention to the quality of machined surface. The (CNC) milling machine facilities provides a wide variety of parameters set-up, making the machining process on the glass excellent in manufacturing complicated special products compared with other machining processes. However, the application of grinding process on the CNC milling machine could be an ideal solution to improve the product quality, but adopting the right machining parameters is required. Taguchi optimization method was used to estimate optimum machining parameters with standard orthogonal array L_{16} (4^4) to replace the conventional trial and error method as it is time-consuming. Moreover, analyses on surface roughness and cutting force are applied which are partial determinant of the quality of surface and cutting process. These analyses are conducted using signal to noise (S/N) response analysis and the analysis of variance (Pareto ANOVA) to determine which process parameters are statistically significant. In glass milling operation, several machining parameters are considered to be significant in affecting surface roughness and cutting forces. These parameters include the lubrication pressure, spindle speed, feed rate, and depth of cut as control factors. While, the lubrication direction is considered as a noise factor in the experiments. Finally, verification tests are carried out to investigate the improvement of the optimization. The results showed an improvement of 49.02% and 26.28% in the surface roughness and cutting force performance, respectively.

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1 Introduction

Glass is generally known as a hard, brittle, solid, and transparent material. The optical and physical properties of glass play an essential role for many different industrial applications. Soda-lime glass is one of the most prevalent types of glass, which is widely used and can easily be found on the market. In industry, this type of glass is the most commonly produced since it is easy to make with better cost-effectiveness compared with other types of glass [1]. In addition, it also has good mechanical properties in terms of hardness, refractive index, and melting temperature [2]. In silicone industry as an example, soda-lime glass has been used as a mold with a very good precision in terms of dimensional accuracy even at elevated temperatures. While using a very high precision glass mold, the shape varieties of the silicone product lead to many different complicated shapes of glass molds to be developed [1]. However, unique properties of soda-lime glass, such as compressive hardness and brittleness, make any machining of glass a very challenging process [3–8]. Glass milling would be a good process required especially in producing varieties shape of slot on glass surface. The capability of the CNC milling machine to make batch production would be a noteworthy advantage for glass machining. However, the demand for high quality focuses

Table 1 The control factors and experimental condition levels

Control factors		Control factor levels (i)			
		i=1	i=2	i=3	i=4
A	Lubrication pressure (MPa)	0.4	0.6	0.8	1.0
B	Spindle speed (min^{-1})	5,000	10,000	15,000	20,000
C	Feed rate (mm/min)	0.5	1	1.5	2
D	Axial depth of cut (mm)	0.25	0.5	0.75	1

attention on the surface condition and the quality of the product, especially the roughness of the machined surface, because of its effect on product appearance, function, and reliability [9, 10]. Hence, the application of grinding process on the CNC milling machine is found to be an ideal solution in manufacturing complicated special products, making the machined surface quality on the glass mold superlative compared with other machining.

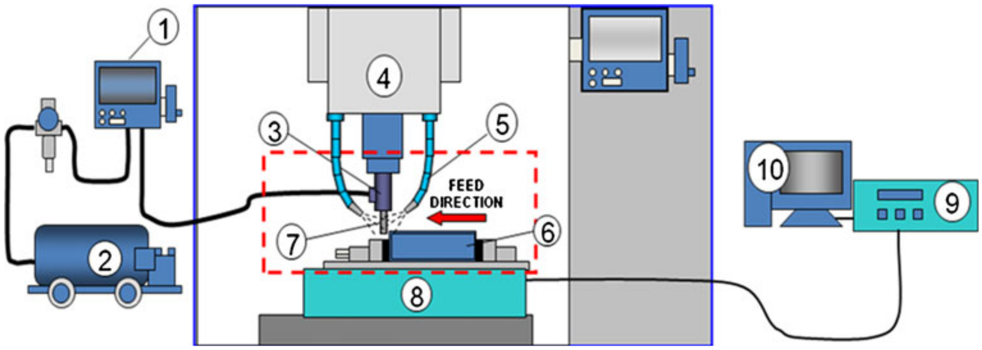
Surface roughness is defined as a group of irregular waves in the surface, measured in micrometers (μm). The roughness data obtained by measurement can be manipulated to determine the roughness parameter. There are many different roughness parameters in use, but R_a is the most common. Other common parameters include R_z, R_q, and R_{sk}. Surface roughness is mainly affected by different controlled machining parameters that can be set up in advance, such as spindle speed, feed rate, depth of cut, and lubrication pressure. However, it is also affected by other uncontrolled variables such as the mechanical properties of the workpiece material, the type of the cutter, and the vibration produced during the process [11]. In metal machining, the use of higher cutting speed and lower feed rate and depth of cut produced a better surface finish and this is mainly attributed to the high temperature generated in the interface [9, 12]. However, in glass machining, the effect of these parameters needs to be investigated, but in general, with higher cutting speed and higher temperature, special rapid tooling is needed to increase abrasion resistance and hence produce good surface roughness. Cubic boron nitride (CBN) grinding tools are traditionally expected to play multiple roles, such as reducing cutting temperatures and cutting forces and increasing abrasion resistance. The cutting temperature is a key factor, which directly affects tool quality, workpiece surface integrity, and machining precision according to the relative motion between the tool and workpiece. The amount of heat generated varies with the type of workpiece material being machined and machining parameters used especially cutting speed, which had the most influence on the temperature [13]. Therefore, the implementations of cutting fluid, which not only act as a lubricant, but also work as a coolant, are very crucial to control the temperature for better surface finish.

Following the literature above, for optimization of glass milling process in minimizing the surface roughness and cutting force, this study has been conducted by anticipating lubrication pressure, spindle speed, feed rate, and depth of cut as control variables. In addition, the lubrication direction is another important factor impacting the surface quality. It is considered as a noise factor as it is hard to categorize its degree of performance to control the cutting temperature. The main objective of this research work is to find the best combination of these parameters in glass milling operation using CBN grinding tool to get lower cutting force and best surface roughness. The conventional method to achieve that is to use the "trial and error" approach. However, "trial and error" approach is very time-consuming due to the requirement of a large number of experiments. Hence, a reliable systematic approach for optimizing the machining parameters is thus required. Taguchi optimization method is an efficient, effective, reliable, and simpler approach, in which the response

Table 2 Standard $L_{16}(4)^4$ orthogonal array

Exp. no.	Control factors and levels (i)			
	A	*B*	*C*	*D*
1	i=1	1	1	1
2	i=1	2	2	2
3	i=1	3	3	3
4	i=1	4	4	4
5	i=2	1	2	3
6	i=2	2	1	4
7	i=2	3	4	1
8	i=2	4	3	2
9	i=3	1	3	4
10	i=3	2	4	3
11	i=3	3	1	2
12	i=3	4	2	1
13	i=4	1	4	2
14	i=4	2	3	1
15	i=4	3	2	4
16	i=4	4	1	3

The 16 experiments with the details of the combination levels



No	Item
1)	High Speed Spindle Controller
2)	Air Compressor
3)	High Speed Spindle(HSS)
4)	CNC Milling Centre
5)	Lubrication Nozzle
6)	Workpiece
7)	Tool
8)	Kistler Dynamometer
9)	Kistler Charge Amplifier
10)	Data acquisition system

Fig. 1 The experimental set-up

parameters affecting surface roughness and cutting forces can be optimized [9]. The steps in the Taguchi optimization method include: selecting the orthogonal array (OA) according to the numbers of controllable factors, running experiments based on that OA, analyzing data, identifying the optimum parameters, and conducting verification test with the optimal levels of all parameters.

In this research work, Taguchi optimized approach is applied and the following items are investigated to get better (i.e., low value) surface roughness and cutting force in glass milling operation:

- The relationship between the controllable factors (lubrication pressure, spindle speed, feed rate, and depth of cut) and the response factors (surface roughness and cutting forces) to obtain the best combination of controllable factor
- The effect of the noise factors (lubrication direction) on the response factor to obtain the optimal condition for better surface quality

2 Design of experiment

The most important thing of experiment design lies in the selection of control factors. All possible factors should be included so that identification of non-significant variables

Table 3 Soda-lime glass chemical composition [1]

Chemical composition	Weight %
SiO_2	73
Na_2O	14
CaO	9
Al_2O_3	0.15
K_2O	0.03
MgO	4
TiO_2	0.02
Fe_2O_3	0.1

Table 4 Soda-lime glass mechanical properties [1]

Properties	Value
Density at 20°C, g/cm^3	2.53
Refractive index nD at 20°C	1.52
Young's modulus at 20°C, Gpa	74
Liquidus temperature, °C	1,000
Thermal conductivity, W/m·K	0.9–1.3
Hardness (Mohs scale)	6–7
Knoop hardness, kg/mm^2+20	585

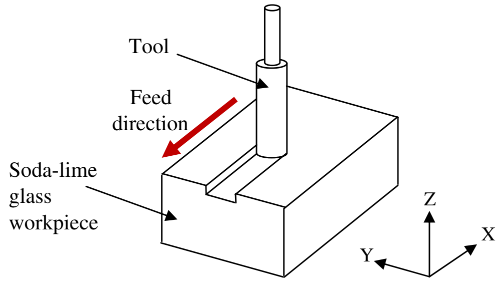


Fig. 2 The workpiece and tool paths

could be done easily by Taguchi method, which is the best method to offer such facility. The control factors and experimental condition levels used are shown in Table 1. The spindle speed values are selected to investigate the surface roughness in both normal and high-speed modes. While, the axial depth of cut and feed rate values are selected based on the grinding tool's capability as per suggested by suppliers to avoid critical damage and also for safety reasons. With the four control factors at four levels each, the Taguchi fractional factorial design used is a standard L_{16} (4^4) orthogonal array. This orthogonal array is chosen due to its capability to check the interactions among factors. The 16 experiments with the details of the combination of the experimental condition levels for each control factor (*A*–*D*) are shown in Table 2. Each row of the matrix represents one trial. However, the sequence in which these trials are carried out is randomized. The four levels of each factor are represented by "1," "2," "3," or "4" in the matrix.

In this experiment, lubrication direction is considered as a noise factor due to the researchers' inability to reproduce the exactly same lubrication direction situation. The lubrication direction effect on the experiment is investigated in two different lubrication direction modes. The first mode is to deliver lubrication in the front and back directions of the workpiece simultaneously, referred to as P_1, while the second mode is to deliver lubrication from both sides of the workpiece, assigned as P_2.

Table 5 The properties of Shell Dromus BL lubricant oil

Brand	Shell
Name	Dromus BL—8 000 021 138/R 0665/DOM 06 032 006
Specification	Emulsion appearance: Milky White, Opaque
	pH at 5%—8.9
	Refractometer factor—1
	Density at 15°C kg/L: 0.889 » 889 kg/m^3
	Viscosity at 40°C centistokes—37 » 3.7×10^{-5} m^2/s (kinematics viscosity)

3 Experiment set-up and procedure

The second step in the Taguchi optimization method is to run the experiments based on the selected OA. The 32 experiments at the two different lubrication direction modes (P_1 and P_2) were carried out in a random sequence to eliminate any other invisible factors, which might also contribute to the surface roughness. The experimental set-up is shown in Fig. 1. The machine used in this study is a vertical-type machining center (Cincinnati Milacron Saber TNC750 VMC); the spindle has constant position pre-loaded bearings with oil–air lubrication with the maximum rotational speed of 12,000 min^{-1}. The cutting process of a rectangular workpiece of soda-lime glass 80×50×25 mm is selected as a case study. The glass chemical composition and mechanical properties are shown in Tables 3 and 4, respectively. While Fig. 2 shows the workpiece and the tool paths used in the cutting tests. The tool moves in +*X* direction to cut 30 mm stroke with a fixed axial depth of cut. The tool type used in the glass milling operation is an internal CBN grinding tool. The tool diameter is 4.5 mm with a no. 150 grit size. To investigate the surface roughness in both normal and high-speed modes, an attachable high-speed spindle unit (Model NSK HES510 BT40) with 50,000 min^{-1} maximum rotational speed is attached to the machine spindle using a built-in rigid holder to maintain the machining accuracy. The cutting forces are measured using a Kistler three-axis dynamometer (type 9275). The measured cutting force signals in *X*-, *Y*-, and *Z*-axis directions are captured and filtered with low path filters (10 Hz cutoff frequency). The sampling frequency was set so that 20 points per one spindle revolution can be obtained. To measure the machined workpiece surface roughness R_a, a portable surface meter (Mitutoyo SJ-201P) was used with a cutoff distance and the sampling length of 0.8 and 4 mm, respectively. In addition, the polished granite surface for more stable and accurate surface roughness measurements was used. Finally, the lubricant system was used to control the cutting temperature and to reduce the friction between the tool and workpiece. The Shell Dromus BL lubricant type has been selected since it has a good lubrication quality characteristic. The properties of the lubricant used are shown in Table 5.

4 Results, analysis, and discussion

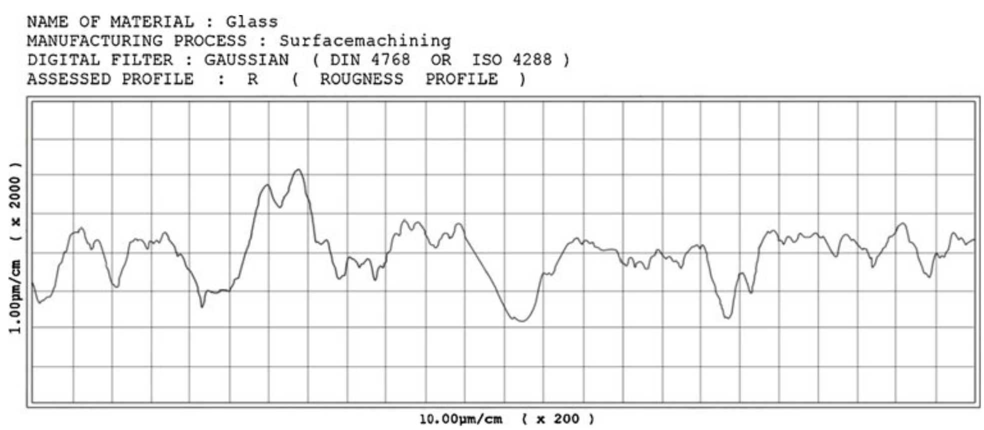
4.1 The experimental results

The experimental tests are carried out using the proposed experimental set-up. The measured values of surface roughness and cutting forces at the different lubrication direction

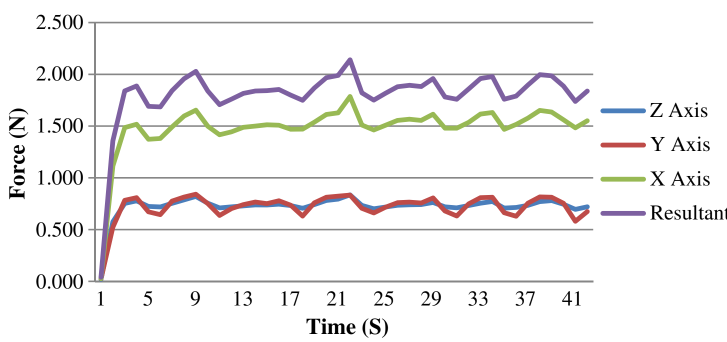
Table 6 The measured values of surface roughness and cutting force with the calculated TPM and S/N ratio

Test levels (j)	Control factor and levels (i)				Measured surface roughness, R_a (μm)		Calculated parameters		Measured cutting force (N)		Calculated parameters	
	A	B	C	D	P_1	P_2	TPM (μm)	S/N (dB)	P_1	P_2	TPM (μm)	S/N (dB)
1	i=1	1	1	1	0.52	0.55	0.53	5.46	1.37	1.42	1.39	−2.89
2	i=1	2	2	2	0.60	0.59	0.60	4.49	1.64	1.63	1.63	−4.25
3	i=1	3	3	3	0.85	0.85	0.85	1.43	1.81	1.81	1.81	−5.14
4	i=1	4	4	4	1.02	1.03	1.03	−0.21	1.97	1.94	1.96	−5.82
5	i=2	1	2	3	0.84	0.87	0.86	1.36	1.82	1.81	1.82	−5.18
6	i=2	2	1	4	1.08	1.06	1.07	−0.60	2.20	2.08	2.14	−6.61
7	i=2	3	4	1	0.74	0.83	0.79	2.09	1.74	1.76	1.75	−4.86
8	i=2	4	3	2	0.72	0.67	0.69	3.17	1.59	1.60	1.59	−4.03
9	i=3	1	3	4	0.87	0.84	0.85	1.37	2.10	1.84	1.97	−5.92
10	i=3	2	4	3	1.14	0.97	1.06	−0.52	1.99	1.91	1.95	−5.79
11	i=3	3	1	2	0.73	0.73	0.73	2.73	1.73	1.67	1.70	−4.62
12	i=3	4	2	1	0.72	0.46	0.59	4.38	1.63	1.58	1.60	−4.11
13	i=4	1	4	2	0.91	0.89	0.90	0.90	1.85	1.89	1.87	−5.43
14	i=4	2	3	1	0.56	0.34	0.45	6.68	1.41	1.31	1.36	−2.68
15	i=4	3	2	4	0.73	0.80	0.77	2.30	1.79	1.80	1.79	−5.07
16	i=4	4	1	3	0.49	0.46	0.47	6.52	1.45	1.44	1.45	−3.21

modes (P_1 and P_2) are summarized in Table 6. As the average of three experimental runs for each test level (j), Fig. 3a, b shows an example of the measured surface roughness and measured cutting forces in X-, Y-, and Z-axis directions at 0.8 MPa lubrication pressure, 20,000 min^{-1} spindle speed, 0.25 mm/min feed rate, and 1 mm axial depth of cut.



(a) Measured surface roughness



(b) Measured cutting force

Fig. 3 An example of measured surface roughness and cutting force at 0.8 Mpa lubrication pressure, 20,000 min^{-1} spindle speed, 0.25 mm/min feed rate, and 1 mm axial depth of cut. **a** Measured surface roughness. **b** Measured cutting force

Table 7 The S/N response data for surface roughness

Factor and interaction	Levels (i)	S/N response data (dB)			
		Lubrication pressure (A_i)	Spindle speed (B_i)	Feed rates (C_i)	Depth of cut (D_i)
Summation at the same control factor level	Level 1	2.79	2.27	3.53	4.65
	Level 2	1.51	2.51	3.13	2.82
	Level 3	1.99	2.14	3.16	2.20
	Level 4	4.10	3.47	0.56	0.71
Difference		2.60	1.33	2.96	3.94
Rank		3	4	2	1

4.2 The analyze of the results

The procedure after the experimental runs is to analyze the results to optimize the parameters and to identify which process parameters are statistically significant. The analyis of the data was conducted using S/N response analysis and Pareto ANOVA.

4.2.1 (S/N) response analysis

Taguchi used the S/N ratio as the quality characteristic of choice to analyze the data. S/N ratio is used as a measurable value instead of standard deviation due to the fact that as the mean decreases, the standard deviation also decreases and vice versa [9]. The methods for calculating the S/N ratio are classified into three main categories, depending on whether the desired quality characteristics are smaller the better, larger the better, or nominal the better. In the case of surface roughness and cutting force analysis, the smaller values are always preferred. The equation for calculating the S/N ratio for the "smaller the better" a characteristic (in dB) is as follows [9]:

$$\frac{\mathrm{S}}{\mathrm{N}} = -10\log\frac{1}{n}\left(P_1^2 + P_2^2\right) \qquad (1)$$

Where (j) is the test levels from 1 to 16 and n is the number of noise factors, in this case n is equal to 2. The S/N values function shown in Eq. 1 is a performance measurement parameter to develop processes insensitive to noise factors. The degree of predictable performance of a process in the presence of noise factors could be defined from S/N ratios in which, for each factor, the higher the S/N ratio the better the result. The calculated S/N ratio and TPM values are summarized in Table 6, where TPM is the target performance measurement, which is equal to the average of the measured surface roughness and cutting forces under both of P_1 and P_2 at the same test level (j).

Furthermore, the S/N and TPM response data for the surface roughness are calculated and summarized in Tables 7 and 8, respectively. While, the S/N and TPM response data for the cutting forces are calculated and summarized in Tables 9 and 10, respectively. As an example of S/N or TPM response calculation, A_i is the average of all S/N or TPM values corresponding to the same control factor level (i) under A in Table 6. In this case, (i) is equal to 1, 2, 3, or 4. The difference under A_i column is equal to the maximum minus the minimum of the S/N or TPM response values. Similarly, the S/N, TPM response values, and the differences are calculated for B_i, C_i, and D_i. The rank is given in order from the highest to the lowest difference values. The significance of each factor is determined based on the value of the difference of both S/N and TPM.

Figures 4a–d and 5a–d show the S/N and TPM response graphs for selecting the best combination levels for lowest

Table 8 The TPM response data for surface roughness

Factor and interaction	Levels (i)	TPM response data (μm)			
		Lubrication pressure (A_i)	Spindle speed (B_i)	Feed rates (C_i)	Depth of cut (D_i)
Summation at the same control factor level	Level 1	0.75	0.79	0.70	0.59
	Level 2	0.85	0.79	0.70	0.73
	Level 3	0.81	0.78	0.71	0.81
	Level 4	0.65	0.70	0.94	0.93
Difference		0.20	0.10	0.24	0.34
Rank		3	4	2	1

Table 9 The S/N response data for cutting force

Factor and interaction	Levels (i)	S/N response data (dB)			
		Lubrication pressure (A_i)	Spindle speed (B_i)	Feed rates (C_i)	Depth of cut (D_i)
Summation at the same control factor level	Level 1	−4.53	−4.86	−4.33	−3.64
	Level 2	−5.17	−4.83	−4.65	−4.58
	Level 3	−5.11	−4.92	−4.44	−4.83
	Level 4	−4.10	−4.29	−5.48	−5.18
Difference		1.07	0.63	1.15	1.55
Rank		3	4	2	1

surface roughness and cutting forces values, respectively. The desired "smaller the better" criteria implies that the lowest TPM response would be the ideal result, while the largest S/N response would reflect the best response which results in the lowest noise. This is the criteria employed in this study to determine the optimal machining parameters. Based upon the criteria of smaller TPM and larger S/N response, the axial depth of cut (factor D) shown in Fig. 4d is found to be of most significant factor affecting surface roughness. The feed rate (factor C) is found to be the second most significant factor followed by the lubrication pressure (factor A) and cutting speed (factor B), shown in Fig. 4c, a, b, respectively. The highest lubrication pressure (A_4, 1 MPa), with the highest cutting speed (B_4, 20,000 min^{-1}), lowest feed rate (C_1, 0.5 mm/min), and lowest axial depth of cut (D_1, 0.25 mm), is determined to be the best choices for obtaining the best surface roughness. Therefore, the optimal parameters for the best surface roughness are set as A_4 B_4 C_1 D_1.

On the other hand, the axial depth of cut (factor D) shown in Fig. 5d is found as most significant factor affecting cutting force. The feed rate (factor C) is found to be the second most significant factor followed by the lubrication pressure (factor A) and cutting speed (factor B), shown in Fig. 5c, a, b, respectively. The highest lubrication pressure (A_4, 1 MPa), with the highest cutting speed (B_4, 20,000 min^{-1}), lowest feed rate (C_1, 0.5 mm/min), and lowest axial depth of cut (D_1, 0.25 mm), is determined to be the best choices for obtaining the cutting force. Therefore, the optimal parameters are set as A_4 B_4 C_1 D_1.

4.2.2 Pareto ANOVA: an alternative analysis

Pareto ANOVA is an alternative method used to analyze the data for process optimization. It exhibits the percentage of factor influence for each parameter in a very simple way [9]. Pareto ANOVA for surface roughness and cutting force are constructed in Tables 11 and 12, respectively, using the S/N response data in Tables 7 and 9. The summation of squares of differences (S) for each control factor is calculated such that, for example, S_A can be obtained by the Eq. 2 as follows:

$$S_A = (A_1 - A_2)^2 + (A_1 - A_3)^2 + (A_1 - A_4)^2 + (A_2 - A_3)^2 + (A_2 - A_4)^2 + (A_3 - A_4)^2 \quad (2)$$

Similarly, S_B, S_C, and S_D are calculated. The contribution ratio for each factor is calculated as the percentage of summation of squares of differences for each factor to the total summation of the squares of differences. A Pareto diagram is plotted using the contribution ratio and the cumulative contribution.

For surface roughness analysis, as presented in Table 11, the significant factors are chosen from the left-hand side of

Table 10 The TPM response data for cutting force

Factor and interaction	Levels (i)	TPM response data (μm)			
		Lubrication pressure (A_i)	Spindle speed (B_i)	Feed rates (C_i)	Depth of cut (D_i)
Summation at the same control factor level	Level 1	1.70	1.76	1.67	1.53
	Level 2	1.82	1.77	1.71	1.70
	Level 3	1.81	1.76	1.68	1.75
	Level 4	1.62	1.65	1.88	1.96
Difference		0.20	0.12	0.21	0.44
Rank		3	4	2	1

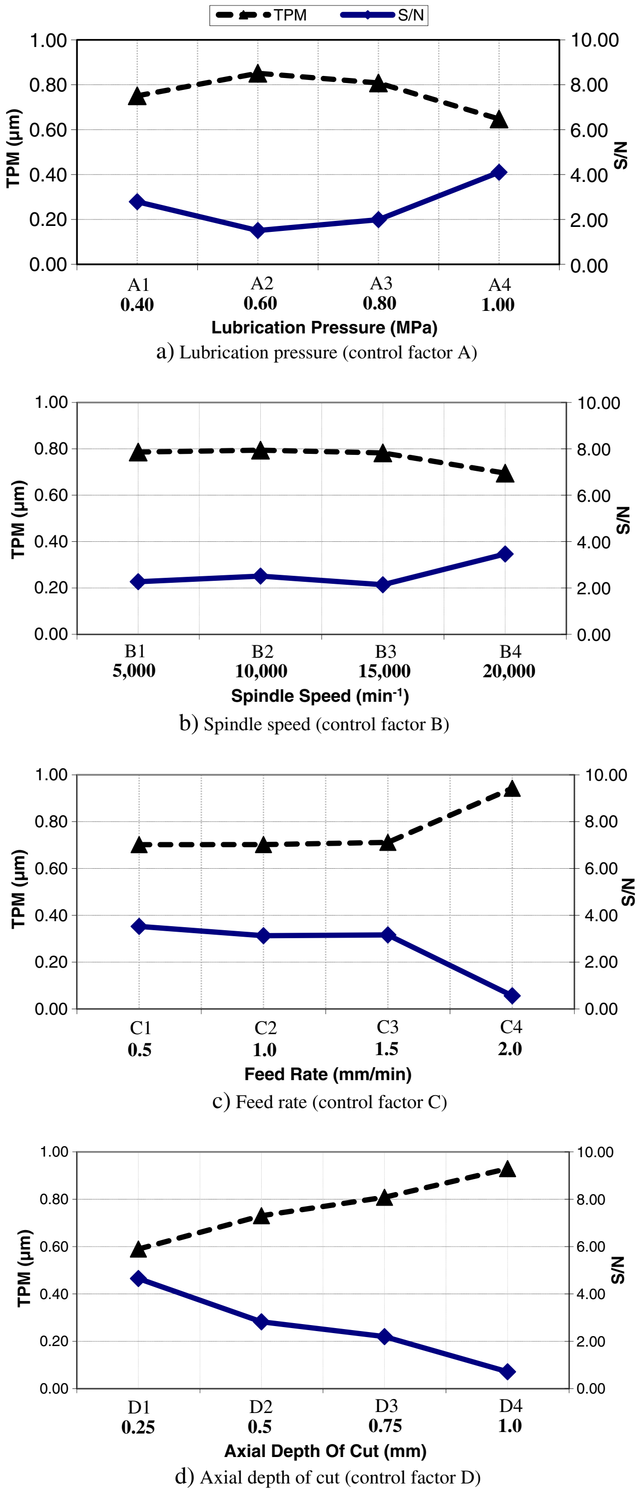


Fig. 4 S/N and TPM response graph for selecting best combination levels for lowest surface roughness value. **a** Lubrication pressure (control factor *A*). **b** Spindle speed (control factor *B*). **c** Feed rate (control factor *C*). **d** Axial depth of cut (control factor *D*)

the Pareto diagram. The best levels of factor combination for minimum surface roughness are obtained in the following: the depth of cut (*D*) 43.08%, the feed rate (*C*)

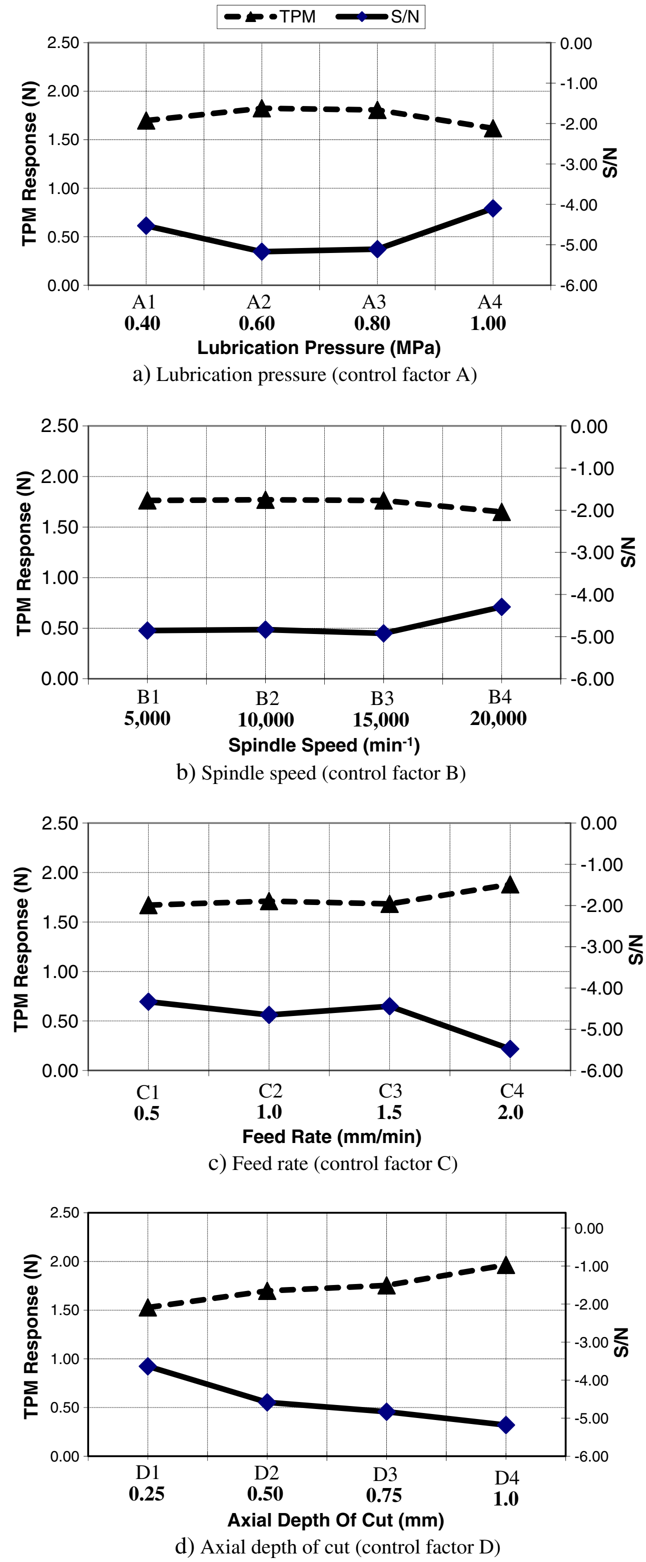
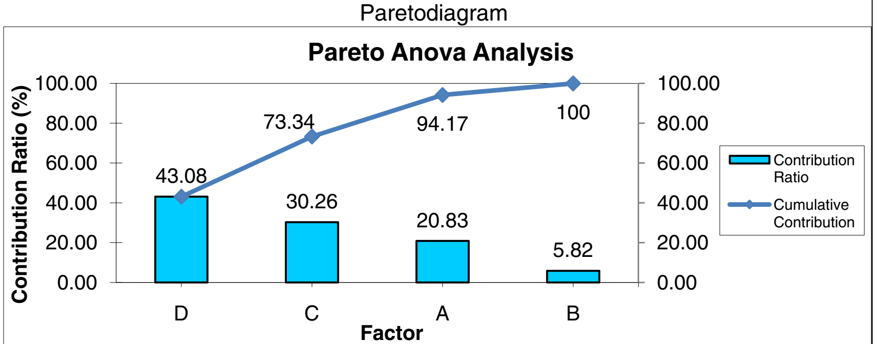


Fig. 5 S/N and TPM response graph for selecting best combination levels for minimum cutting force. **a** Lubrication pressure (control factor *A*). **b** Spindle speed (control factor *B*). **c** Feed rate (control factor *C*). **d** Axial depth of cut (control factor *D*)

Table 11 Pareto ANOVA analysis for surface roughness

Control factor levels (*i*)	S/N response data(dB)			
	A_i Lubrication pressure	B_i Spindle speed	C_i Feed rate	D_i Depth of cut
Level 1	2.79	2.27	3.53	4.65
Level 2	1.51	2.51	3.13	2.82
Level 3	1.99	2.14	3.16	2.20
Level 4	4.10	3.47	0.56	0.71
Total of summation	10.39	10.39	10.39	10.39
Summation of squares of differences (S)	$S_A = 15.4378$	$S_B = 4.3125$	$S_C = 22.4280$	$S_D = 31.9290$
Total summation of squares of differences $St = S_A + S_B + S_C + S_D$	74.14			
Contribution ratio (%)	20.83	5.82	30.26	43.08
Paretodiagram				



Cumulative contribution	43.08	73.35	94.18	100.00
Optimum combination	D1	C1	A4	B4
Overall optimum conditions for all factors	A4 B4 C1 D1			

30.26%, the lubrication pressure (*A*) 20.83%, and finally the spindle speed (*B*) 5.82%. The recommended optimal parameter combination for best surface roughness is A_4 B_4 C_1 D_1. This result is similar to the result obtained from S/N response analysis.

As for the cutting forces analysis shown in Table 12, the best levels of factor combination for minimum cutting force are found in the following: the depth of cut (*D*) 41.72%, the feed rate (*C*) 25.57%, the lubrication pressure (*A*) 24.65%, and finally the spindle speed (*B*) 8.05%. The depth of cut, feed rates, and lubrication pressure are considered prominent factors, having a cumulative contribution of 91.95%. The Pareto ANOVA analysis determines essentially that A_4 B_4 C_1 D_1 are the best combination parameters to adhered the lowest value of cutting forces, which is also similar to the optimum result obtained from the S/N response analysis.

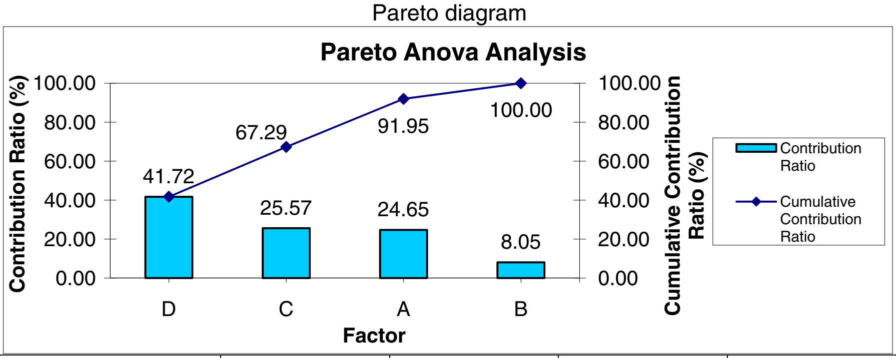
4.3 The discussion

In this study, two data analysis techniques were used to analyze the results of the cutting forces and surface roughness. It was observed that both techniques delivered similar results. The axial depth of cut is found to be the most prominent factor followed by feed rate and lubrication pressure, while the spindle speed has a less significant effect. Thus for better surface roughness and for lower cutting force, the recommended setting is the lowest values of the depth of cut and feed rate, and the highest values of the lubrication pressure and spindle speed. However it was noted that the interactions of the factors produce a significant impact on the cutting forces and surface roughness. This is because the combination of feed rate and depth of cut determines the undeformed chip section and hence influences the amount of cutting forces required to remove a specified volume of material. The greater the feed rate and depth of cut the larger the cross-sectional area of the uncut chip and the volume of the deformed workpiece. Consequently, the greater is the resistance of the workpiece to chip formation and the larger is the cutting force leading to a contact overload between the cutting tool and the workpiece producing bad surface quality. That would also cause instantaneous fracture of the glass

Table 12 Pareto ANOVA analysis for cutting force

Control factor levels (*i*)	S/Nresponse data (dB)			
	A_i Lubrication pressure	B_i Spindle speed	C_i Feed rate	D_i Depth of cut
Level 1	−4.53	−4.86	−4.33	−3.64
Level 2	−5.17	−4.83	−4.65	−4.58
Level 3	−5.11	−4.92	−4.44	−4.83
Level 4	−4.10	−4.29	−5.48	−5.18
Total of summation	−18.91	−18.91	−18.91	−18.91
Summation of squares dfferences (S)	$S_A = 3.1057$	$S_B = 1.0146$	$S_C = 3.2215$	$S_D = 5.2554$
Total summation of squares of differences $St = S_A + S_B + S_C + S_D$	12.5972			
Contribution ratio (%)	24.65	8.05	25.57	41.72

Pareto diagram



Cumulative contribution	41.72	67.29	91.95	100.00
Optimum combination	D1	C1	A4	B4
Overall optimum conditions for all factors	A4 B4 C1 D1			

workpiece if the cutting tool at high cutting force is severely damaged [14]. This could be also explained in terms of stress produced due to the cutting forces at each point in the cutting zone of the glass cutting process, obtained using FEM simulation [15]. Areas of high stress are present at the tool–chip and tool–workpiece interface therefore the high force associated with high depth of cut and feed rate would increase the fracture probability for these areas [16]. In other words, feed rate and depth of cut serve as key role in obtaining lowest cutting force and smaller surface roughness [15].

On the other hand, the experimental results show that the cutting force is low at higher cutting speed and comparatively high at low cutting speed. The cutting force exhibit an almost linear increasing trend, independent of cutting speed shown in Fig. 5b. The reason for the drop of cutting force with an increase of cutting speed is due to the decrease in chip thickness. This means that at higher speed, thinner chips are produced. It has also been suggested that the drop in these forces is partly caused by decrease in contact area of flow and

Table 13 The results of the confirmation run

Sample no.	R_a	Resultant cutting force
1	0.24	0.97
2	0.22	1.01
3	0.23	0.99
4	0.23	0.98
5	0.21	1.03
6	0.22	1.01
7	0.25	0.99
8	0.20	0.97
9	0.21	1.04
10	0.21	1.01
11	0.23	1.02
12	0.20	0.99
13	0.25	0.99
14	0.22	1.02
15	0.23	0.97
16	0.22	1.02
Mean	0.22	1.00

partly by a drop in shear strength in the flow zone. As cutting speed increases, the chips become thinner and shear angle increases. Such an increment of shear angle decreases chip reduction coefficient and chip strains, which means the plastic deformation takes place with less strain, so the force and power consumptions are lowered. The coefficient of friction decreases and consequently main cutting force decrease, which in turn preserves the machined surface properties leading to better surface roughness [17]. Another possible reason is given by Ghani et al. [10] that, when the spindle speed is increased accordingly, cutting energy input to the machine tools and generated machining compressive stresses grow correspondingly higher and lead to increased chip–tool interface temperatures. The generated heat in the machining zone helps to soften workpiece material, reducing cutting forces required to cut the material leading to better surface quality. However, it is believed that the spindle speed should be controlled at an optimum value, as the influence of temperature, especially for low thermal conductive materials such as glass, would significantly affect the chip formation mode, cutting forces, tool life, and surface quality. Thus the implementation of cutting fluid, which acts as a coolant, is very crucial. In addition, cutting fluid would not only work as a coolant, but also to facilitate relative movement between two contacting surfaces leading to reduce the cutting force and surface roughness of the machined workpiece. This would also explain why the minimum surface roughness is obtained at the highest lubrication pressure even though the gradient of the curve is very small and does not show a fixed trend. Finally, the noise factor, which is the lubricant direction, is found to have no effect on the response of the experiment. The large value of S/N response indicates that the signal is considerably strong as compared to the noise factor.

5 Verification test

After the optimal levels of all control factors are identified, the last step in the Taguchi optimization method is to conduct a verification test using the optimal parameters A_4 B_4 C_1 D_1 to validate the recommendation. This test is repeated 16 times and the average of 16 TPM values of measured surface roughness and cutting forces is calculated. The result in the Table 13 shows an improvement of 49.02% and 26.28% in mean of surface roughness and cutting force compared to the smallest values obtained in TPM during the initial experiments, shown in Table 6.

6 Conclusion

In this study, enhancement and verification of a machined surface quality for glass milling operation using an internal CBN grinding tool were investigated using Taguchi optimization method. This research work is contributing to the enhancement of machined surface quality of glass material particularly in mold making industries which require high accuracy of component dimension. With the L_{16} (4^4) orthogonal array, a total of 32 experiments are carried out with four different factors, four different experimental condition levels, and two noise factors. The results are analyzed in two different techniques, the S/N and Pareto ANOVA response analysis. However, both techniques delivered similar results. The depth of cut is found to be more significant followed by the feed rate, lubrication pressure, and cutting speed. While the lubrication direction as a noise factor was found to be statistically insignificant. Finally, verification tests with the optimal levels of all the parameters were carried out to investigate the improvement of the optimization. The result shows an improvement of 49.02% and 26.28% in the surface roughness and cutting force measurement; respectively. This was accomplished with a relatively small number of experimental runs.

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