Parameter optimization by Taguchi Methods for finishing advanced ceramic balls using a novel eccentric lapping machine

J. Kang and M. Hadfield

Bournemouth University, School of Design, Engineering & Computing,

Tribology Design Research Unit, Studland House, 12 Christchurch Road,

Bournemouth, Dorset, BH1 3NA, United Kingdom.

Email: jkang@bournemouth.ac.uk; mhadfiel@bournemouth.ac.uk

Abstract: The final finishing process of advanced ceramic balls used in hybrid precision bearings constitutes two thirds of the total manufacturing cost, hence the effective and economic finishing methods and processes are critical to their widespread application. A novel eccentric lapping machine is designed and manufactured, Hot Isostatically Pressed (HIPed) silicon nitride ball blanks (diameter 13.25 mm) are used to investigate the feasibility of accelerating the ball finishing process while maintaining high surface quality. Taguchi Methods are used during the first step of finishing to optimise lapping parameters, the L9 (3^4) Four-Parameter, Three-Level Orthogonal Array is used to design the experiment. Experimental results reveal that this novel eccentric lapping method is very promising, a material removal rate of 40 μm/hour is achievable. The optimum lapping condition is found to be high speed, high load and high paste concentration with 60 μm diamond particles. The analysis of variance (ANOVA) shows that the most significant lapping parameter is lapping load, which accounts for 50% of the total, followed by lapping speed (31%), the particle size and paste concentration parameters only account for 12% and 7% respectively. A comparison with previous lapping experiments and the mechanism of material removal are also discussed briefly.

Keywords: lapping, polishing, finishing, eccentric lapping, ceramic ball finishing, Taguchi Methods, silicon nitride, hybrid bearings

NOTATION

$GTSS$	grand total sum of squares of Signal-to-Noise ratio
MSD	mean square deviation
n_{Ai}	number of tests conducted at level i of parameter A
S/N	Signal-to-Noise ratio
S/N_{LTB}	Signal-to-Noise ratio (larger-the-better)
$\overline{S/N}$	overall mean of Signal-to-Noise ratios
$\overline{S/N}_{Ai}$	the level average S/N of parameter A at level i
SS_A	the sum of the squares of the S/N variation induced by parameter A around overall mean.
SS_B	the sum of the squares of the S/N variation induced by parameter B around overall mean.
SS_C	the sum of the squares of the S/N variation induced by parameter C around overall mean.
SS_D	the sum of the squares of the S/N variation induced by parameter D around overall mean.
SS_{mean}	the sum of the squares due to overall mean of S/N
$SS_{variation}$	the sum of the squares due to variation around overall mean of S/N
y_i	the individually measured response value at measurement *i*
σ_T^2	the total sum of the squares of the standard deviation
σ_A^2	square of the standard deviation caused by parameter A
σ_B^2	square of the standard deviation caused by parameter B
σ_C^2	square of the standard deviation caused by parameter C
σ_D^2	square of the standard deviation caused by parameter D

1 INTRODUCTION

Ceramic ball hybrid bearings which are now used extensively in precision machine tools and aerospace engineering have shown advantages because of thermal resistance, corrosion resistance, low density, high elastic modulus and low friction [**1**]. The only restriction that prevents its widespread application is the high manufacturing cost of ceramic balls. It is estimated that the final finishing process and associated handling and inspection of advanced ceramic balls constitutes two thirds of the total manufacturing cost. Finishing advanced ceramic balls at low cost and efficiency while maintaining high surface quality to ensure long fatigue life is critical to its widespread application.

The finishing process of advanced ceramic balls can be divided into two steps, firstly rough lapping (grinding), and secondly fine lapping (polishing). In the first step, the lapping speed and load are relatively high, and diamond particle size used in the paste or suspension is larger. Ceramic ball surface skin produced in previous manufacturing stages which is compositionally and microstructurally different from core of the ball has to be removed during this step. For a final dimension 12.7mm (0.5″) diameter HIPed ball, 500-800 μm stock in diameter has to be removed from ball surface. The maximum material removal rate in this step is desirable while maintaining roundness and no substantial surface damage. In the second step, the lapping speed and load are relatively low, and diamond particle size used in the paste or suspension is much smaller. The ball surface roughness, waviness, and roundness for precision bearing application are achieved during second step. A novel eccentric lapping machine was designed by authors and manufactured in house. A preliminary lapping test series has been conducted using this machine [**2**]. The current study is focused on the first step of the finishing process by altering different lapping parameters and their combinations to achieve optimum finishing rate.

There are several approaches to investigate the effects of different testing parameters. The most simple one is the single-parameter by single-parameter approach, i.e., only one parameter is changed for a given test run. This is of course the most time consuming and costly approach as the testing parameter number increases. To overcome this, the experimental design [**3**] and dimensional analysis theory [**4**] were introduced. The Taguchi Methods [**5,6**], by developing a set of standard Orthogonal Arrays (OA) and a methodology for the analysis of results, can extract information from experiment more precisely and more efficiently than other approaches, also fewer number of tests are needed even when the number of parameters being investigated is quite large.

Since Taguchi Methods have been proved successful for many manufacturing circumstances [**7,8**], it is chosen in this study. The purpose of this study is to systematically investigate the effects of different lapping parameters and to find out the finishing rate potential on this novel eccentric lapping machine.

2 EXPERIMENTAL SET UP

2.1 Machine

This novel eccentric lapping machine allows the finishing of advanced ceramic balls at a small batch (about 15 balls each time for diameter 13.2~13.4 mm ball blanks). It was deliberately designed for small batch by the authors to enable the investigation of various lapping conditions without consuming too many balls. It is found the performance of this machine is superior both in the first step of finishing (grinding), and in the second step of finishing (polishing). Fig 1 is the photograph of this eccentric lapping machine. A AC motor and gearbox combination connected by a pulleys-belt system drives the lower plate. This lower plate has an eccentric circular V-groove machined on it and rotates at a set speed to promote the sliding/rolling contact of the balls with plates. The top plate which has a flat lapping surface is stationary. Ceramic balls are lapped between the top plate and the V-groove of lower plate (Fig. 2). Because of the eccentricity between the centre of circular V-groove and the rotational axis of the lower plate, there will be an acceleration of ball angular velocity, a skid between the balls and lapping plates, and the ball spin angle will change constantly. Description on the design of this eccentric lapping machine can be found in reference [**2**].

2.2 Procedure

Table 1 summarises the materials used in this experimental investigation. Before and after each lapping test run, balls and lapping plates were cleaned using an ultra-sonic bath, each ball diameter was measured to 1.0 μm and the total weight of the batch (15 balls) was measured to 9.8×10^{-6} N (1.0 mg). Microscope observations on ball surfaces were also conducted after each lapping test run to monitor any exceptional ball surface damage. The diamond paste and lapping fluid were mixed according to paste concentration parameter, 9.8mN:3×10^{-5}m^3 (1g:30ml), 9.8mN:6×10^{-5}m^3 (1g:60ml) and 9.8mN:1.2×10^{-4}m^3 (1g:120ml), and stirred magnetically to make diamond paste fully dissipated in the lapping fluid. A quantity of 5ml such fluid mixture containing diamond particle was dissipated onto the V-groove of lower plate before each test. The lapping speed parameter was set by choosing different pulley combination, and each lapping test was carried for 1 hour duration. After each test, each of the 15 balls was measured across the diameter and the

15 ball diameters were documented in a row of a spreadsheet program in descending order. The individual ball within the batch was not distinguished, the change of each ball diameter (Measured material removal rate on each individual ball (μ/hour)) was deduced from two adjacent rows in the spreadsheet (presuming the diameter descending order of the 15 balls was not changed after each test run). This is an acceptable method as the batch diameter scatter after each test is normally very small (1~2 μm), as well as the individual ball roundness error (ovality) generated from this eccentric lapping is only 0.4~1.1μm. The average weight lost per ball per hour were deduced from the whole batch (15 balls) after each test run and only for monitoring purpose. STDEVP (standard deviation based on the entire population) is also calculated for each test run to monitor the ball diameter scatter.

3 EXPERIMENTAL DESIGN

A standard Taguchi L9 (3^4) Orthogonal Array (OA) is chosen for this investigation as it can operate four parameters, each at three levels. This format is chosen from a preliminary work, that identified four parameters--(A) lapping speed; (B) lapping load; (C) diamond particle size in paste; (D) paste concentration in lapping fluid as important lapping variables which affect the finishing rate. Sufficient details of the effect of different parameter values on experimental results can be obtained by choosing three levels for each parameter to investigate.

The criteria used for choosing the three parameter levels is based to explore a maximum range of experimental variable, but not to include the range which is already known will be out of interest. In addition, it is unnecessary to have uniformly spaced levels because of the counterbalance property of the OA [**9**]. Previous lapping experiments have shown that when the lapping speed range is 8.5~80 rpm, the material removal rate is low, so for this investigation the speed level range is 120~270 rpm. Previous lapping experiments also showed that the material removal rate is fairly high when using 6 μm diamond particles, smaller than this will greatly reduce the finishing rate, but the optimum material removal rate was achieved by using 60 μm diamond particles [**2**]. So for this investigation, the three levels of diamond particle size parameter are chosen as 6 μm, 60 μm and 90 μm. The three levels for lapping load parameter and paste concentration parameter are selected also according to previous lapping experiences but extended to see their effects. The chosen parameters and their levels are shown in Table 3.

The test run is designated by replacing the level number 1, 2, 3 of parameters A, B, C, D in L9 OA with the chosen parameters level values in Table 3. Each row of the array represents a test run parameter setting condition. Table 4 is the test run design.

4 DATA EVALUATION AND ANALYSIS

4.1 Evaluation of Signal-to-Noise ratio

Taguchi Methods use the S/N (signal-to-noise) ratio to analyse the test run results because the S/N ratio represents both the average (mean) and variation (scatter) of the experimental results. The S/N ratio is also used in Analysis of Variance (ANONA). The term S/N ratio is borrowed from signal processing technology, but has different meanings here. A number of S/N ratios are available in Taguchi Methods, e.g., smaller-the-better, larger-the-better, operating window, and nominal-the-best. The standard S/N ratios can be customised to fit specific applications and new S/N ratios can be developed for particular applications. Selecting the proper S/N ratio depends on the physical properties of the problem, the engineering insight, the pursuing experiment results, etc.. In this study the maximum material removal rate is the objective function, so that the larger-the-better S/N ratio is chosen. The basic formulas and notations used in this study can be found in reference [**9**].

$$S/N_{LTB} = -10\log[MSD] = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i^2}\right)\right] \tag{1}$$

Where S/N_{LTB} stands for larger-the-better Signal-to-Noise ratio, *MSD* is the mean square deviation around the target (infinity in this case), y_i is the individually measured response value (experiment result), n is the number of measurements taken in one test run.

Table 5 shows the results of each test run by the measurement of 15 balls being lapped (y_i), the average value of the batch, and the S/N_{LTB} value calculated from equation (1).

4.2 Level average response analysis

The level average response analysis is based on averaging the experiment results achieved at each level for each parameter. In this study, each level for each parameter contains three test runs. It can be seen from Table 4 that while the level 1 of parameter A occurs, in test run 1, 2 and 3, all three levels of parameters B, C and D appear once in these three test runs. The level 2 of parameter A occurs in test run 4, 5 and 6, whilst all three levels of parameter B, C and D also appear once in these three test runs. The level 3 of parameter A is the same. Other levels of other parameters are the same, for example, level 1 of parameter B occurs at test runs 1, 4 and 7, at these three test runs, all three levels of parameter A, C and D also appear once. When performing level average response analysis for one level of one parameter, all the influences from different levels of other parameters will be counterbalanced because every other parameter will appear at different level once. So the effect of one parameter at one level on the experiment results can be separated from other parameters. In this way, the effect of each level of every parameter can be viewed independently.

The level average response analysis is carried out by averaging the experimental results from three test runs corresponding to each level of each parameter, one by one, which is shown in Table 6 and plotted in Fig. 2. Table 7 and Fig. 3 give the results of level average response analysis by S/N ratio.

4.3 Analysis of Variance (ANOVA)

Analysis of variance is a computational technique to quantitatively estimate the relative contribution, which each controlled parameter makes to the overall measured response and expressing it as a percentage. Thus the information about how significant the effect of each controlled parameter is on the experimental results can be obtained. ANOVA uses S/N ratio responses to calculate. The basic idea of ANOVA is $\sigma_T^2 = \sigma_A^2 + \sigma_B^2 + \sigma_C^2 + \sigma_D^2$, that the total sum of the squares of the standard deviation (σ_T^2, total variation) is equal to sum of the squares of the standard deviation caused by each parameter σ_A^2, σ_B^2, σ_C^2, σ_D^2.

The overall mean from which all the variation (standard deviation) is calculated is given by

$$\overline{S/N} = \frac{1}{n}\sum_{i=1}^{n} S/N_i \qquad (2)$$

In this study,

$$\overline{S/N}_{LTB} = \frac{1}{9}\sum_{i=1}^{9}(S/N_{LTB})_i \;=\; \frac{1}{9}(19.20 + 23.11 + 25.87 + 23.45 + \ldots\ldots\ldots + 32.06) = 25.513$$

The grand total sum of squares GTSS is given by

$$GTSS = \sum_{i=1}^{n}(S/N_i)^2 \qquad (3)$$

In this case,

$$GTSS = \sum_{i=1}^{9}(S/N_{LTB})_i^{\,2} = (19.20)^2 + (23.11)^2 + (25.87)^2 + \ldots\ldots\ldots + (32.06)^2 = 5970.844$$

The GTSS can be decomposed into two parts, the sum of the squares due to overall mean and the sum of the squares due to variation around overall mean:

$$GTSS = SS_{mean} + SS_{variation} \qquad (4)$$

1. The sum of the squares due to overall mean:

$$SS_{mean} = n \times (\overline{S/N})^2 \qquad (5)$$

Where n is the number of total test runs.

In this case,

$$SS_{mean} = 9 \times (\overline{S/N}_{LTB})^2 = 9 \times (25.513)^2 = 5858.245$$

2. The sum of the squares due to variation around overall mean:

$$SS_{variation} = \frac{1}{n}\sum_{i=1}^{n}(S/N_i - \overline{S/N})^2$$

(6)

In this study,

$$SS_{variation} = \frac{1}{9}\sum_{i=1}^{9}((S/N_{LTB})_i - \overline{S/N}_{LTB})^2 = (19.20 - 25.513)^2 + (23.11 - 25.513)^2 + (25.87 - 25.513)^2 + . \quad \ldots\ldots\ldots\ldots\ldots\ldots + (32.06 - 25.513)^2 = 112.6$$

The $SS_{variation}$ can be further decomposed into the sums of the squares of the variation induced by individual parameter effects around overall mean. From 4.2, it is known that when doing level average response analysis for one level of one parameter, all the influences from different levels of other parameters will be counterbalanced. So, the level average S/N minus overall mean S/N is the variation caused by that parameter at that level.

For parameter A, the sum of the squares due to variation around overall mean is

$$SS_A = n_{A1}\times(\overline{S/N}_{A1} - \overline{S/N})^2 + n_{A2}\times(\overline{S/N}_{A2} - \overline{S/N})^2 + n_{A3}\times(\overline{S/N}_{A3} - \overline{S/N})^2 \quad (7)$$

Where n_{Ai} is number of tests conducted at level i of parameter A

Where $\overline{S/N}_{Ai}$ is the level average S/N of parameter A at level i

In this case,

$$SS_A = 3\times(22.73 - 25.513)^2 + 3\times(26.75 - 25.513)^2 + 3\times(27.06 - 25.513)^2 = 35.095(dB)^2$$

Similarly,

$SS_B = 56.379\ (dB)^2$

$SS_C = 13.237\ (dB)^2$

$SS_D = 7.895\ (dB)^2$

The percentage contribution of each parameter is found:

$$\text{Percentage contribution of Parameter j} = (SS_{\text{parameter j}} / SS_{\text{variation}}) \quad (8)$$

In this study,

Parameter A, Lapping Speed: $(35.095/112.6) \times 100 = 31.17\%$

Parameter B, Lapping Load: $(56.379/112.6) \times 100 = 50.07\%$

Parameter C, Particle Size: $(13.237 /112.6) \times 100 = 11.76\%$

Parameter D, Paste Concentration: $(7.895 /112.6) \times 100 = 7.01\%$

The percentage contributions for parameters A, B, C, and D are shown in Fig. 5.

5 RESULTS DISCUSSION

Table 5 shows the experimental results for the lapping program. The influences of individual lapping parameters on the material removal rate can be clearly seen in Fig. 3. Generally, the material removal rate increases as the lapping speed, lapping load and paste concentration increase. For the lapping speed parameter, the material removal rate increases sharply as the speed increases from 118.42 rpm to 168.75 rpm, an increase of 57%. From 168.75 rpm to 270 rpm, although the speed increase is 60%, the material removal rate increases only 9%. This is consistent with a previous single parameter experiment which ranged from 8.5 rpm to 168.75 rpm and showed that the material removal rate is quite low when speed below 80 rpm [**2**]. It seems that there is a threshold for the lapping speed, below which the material removal rate is very low. The speed below this threshold is proper for polishing (fine lapping), but not for grinding (rough lapping). The abrasive wear process above this speed threshold is predominantly by the micro-fracture. This view is supported by the microscope and SEM observations on previous lapping samples by the authors [**10**]. This kind of micro-fracture will increase as the lapping speed increase, but to a certain amount the increase will slow down.

Surprisingly, the material removal rate increases almost linear with the increase of lapping load at a slope of 15 μm × lapping load (9.8N/ball). This is true also in the level average analysis by S/N ratio in Fig.4 B. This information is extremely useful when establishing a theoretical lapping model about the diamond particles ploughing against ceramic working material by contact mechanics and fracture mechanics. The lapping parameter also is the most significant factor influencing the finishing rate, accounts for 50% in ANOVA. These valuable information could not be drawn from a simple one-parameter changing experiment.

The material removal rate increases by 38% with the increasing of diamond particle size from 6 μm to 60 μm, but decreases 6% from 60 μm to 90 μm. The result from the level average analysis by S/N ratio showed in Fig. 4 C for 60 μm to 90 μm is the same. To verify this, two more test runs were arranged afterwards with diamond particle sizes 60 μm and 90 μm respectively, all other three parameters were set at highest (load 18.13N/ball (1.85kg/ball), speed 270 rpm, paste concentration 9.8mN:$3\times10^{-5}m^3$ (1g:30ml)). The results are consistent, for 60 μm diamond particles, the material removal rate is around 40 μm/hour, for 90 μm diamond particles, around 36 μm/hour. So for diamond particle size parameter, 60 μm is considered as optimum. This is also because the two highest standard deviation values (STDEVP) are found in test run No. 5 (0.980) and test run No. 7 (0.735) which are associated with 90 μm diamond particles. This implies that too large diamond particles will cause ball diameter scatter, especially under medium and higher load.

For parameter D, diamond paste concentration, the material removal rate increases as the paste concentration increasing. The increase is higher from 1.6366×10^4N/m^3 (1.67 g/ml) to 3.2634×10^4N/m^3 (3.33 g/ml) than from 8.134×10^3N/m^3 (0.83 g/ml) to 1.6366×10^4N/m^3 (1.67 g/ml) shown in Fig. 3 D. The level average analysis by S/N ratio shown in Fig. 4 D is the same.

The level average response analysis by S/N ratio is shown in Table 7 and Fig. 4. Although the physical meaning of S/N ratio (dB) is not as straight forward as simple level average response analysis by values (μm/hour). It is more objective towards the target because the S/N ratio reflects both the average (mean) and the scatter (variance). The line trends in Fig. 4 A, B, D is the same as in Fig 3 A, B, D, this gives a kind of confidence about the conclusions drawn from the experiment. The line trend in Fig. 4 C is a little different from Fig 3 C which is confirmed by further investigation, as discussed previously.

From the level average response analysis, the optimum lapping parameter combination is found to be lapping speed 270 rpm, lapping load 18.13N/ball (1.85kg/ball), diamond particle 60 μm and paste concentrations 9.8mN:3×10^{-5}m^3 (1g:30ml or 3.33 g/ml %). This is verified by further lapping test run arranged immediately afterwards. The achieved material removal rate of 40 μm/hour is much higher than by conventional concentric lapping, in which the material removal rate usually is only a few μm/hour. This indicates that this novel eccentric lapping is very promising.

The analysis of variance (ANOVA) shows that within the experimental level ranges, the most significant lapping parameter is lapping load, which accounts for 50% of the total, followed by lapping speed (31%), particle size and the paste concentration parameters only account for 12% and 7% respectively. It should be noted that this percentage contribution of each lapping parameter to the material removal rate is only valid within the experimental parameter setting level ranges, that is, the lapping speed from 118.42 rpm to 270 rpm, the lapping load from 8.82N/ball (0.9kg/ball) to 18.13N/ball (1.85kg/ball), the particle size from 6 μm to 90 μm and the paste concentration from 9.8mN:3×10^{-5}m^3 (1g:30ml) to 9.8mN:1.2×10^{-4}m^3 (1g:120ml), An earlier single parameter changing experiment concerning the lapping speed ranging from 8.5 rpm to 168.75 rpm showed the material removal rate is quite low when speed below 80 rpm. If the lower level of lapping speed chosen in the L9 OA in this study were low, the percentage contribution of lapping speed would be much higher.

The overall results from the application of Taguchi Methods experimental design and data analysis are satisfactory. Only nine test runs are conducted and much more and precise information about the parameters at the experimental levels affecting the finishing rate found. This gives a clear overall picture about the influences of the four important parameters on this novel eccentric lapping of advanced ceramic balls.

6 CONCLUSION

(1) Taguchi Methods have been successfully applied to eccentric lapping of HIPed silicon nitride balls for parameter optimisation in the first step of finishing.

(2) Increasing the lapping load, lapping speed and paste concentration parameters causes a corresponding increase in material removal rate. The increase of material removal rate is most significant as the lapping speed parameter increases from 118.42 rpm to 168.75 rpm. The increase of material removal rate is almost linear (proportional) with the increase of lapping load throughout the parameter range. The increase of material removal rate is higher for paste concentration parameter changing from $1.6366\times10^{4}N/m^{3}$ (1.67g/ml) to $3.2634\times10^{4}N/m^{3}$ (3.33g/ml).

(3) The optimum lapping parameter combination within the experimental level ranges is found to be high speed, high load, 60 μm diamond particles and high paste concentration.

(4) The achieved material removal rate of 40 μm/hour is much higher than by conventional concentric lapping, indicates that this novel eccentric lapping is very promising.

(5) Within the experimental level ranges, the most significant influencing parameter is lapping load, which accounts for 50% of the total effect, followed by lapping speed (31%), particle size and the paste concentration parameters only account for 12% and 7% respectively.

ACKNOWLEDGEMENT

The authors would like to thank the financial support of the project from SKF Engineering & Research Centre B. V. in the Netherlands, in particular the technical advice from Dr Robin Cundill.

REFERENCES

1 **Cundill, R. T.**, Light-weight material for the rolling elements of aircraft bearings, *Ball Bearing Journal,* 1983, **216,** 33-36.

2 **Kang, J.** and **Hadfield, M.**, A study on the lapping of ceramic ball, *Surface treatment for computer methods and experimental measurements*, Assisi, Italy, 1999, pp. 389-398 (Computational Mechanics Publications, Southampton).

3 **Cochran, W. G.** and **Cox, G. M.**, *Experimental designs*, 2nd 1968, (Wiley, New York; London).

4 **Buckingham, E.**, Model experiments and the form of empirical equations, *Trans. ASME,* 1915, **37.**

5 **Taguchi, G.**, *Taguchi Methods ---- Research and Development*, 1992, (ASI Press, Dearborn, MI).

6 **Taguchi, G.**, *Taguchi on robust technology development, bringing quality engineering upstream* 1992, (ASME Press, New York).

7 **Wu, Y.**, *Taguchi methods case studies from the US and Europe,* 1989, (ASI Press, Dearborn, MI).

8 **Bendell, T.**, *Taguchi methods 1st European conference Papers,* 1989, (Elsevier).

9 **Fowlkes, W. Y.** and **Creveling, C. M.**, *Engineering methods for robust product design, Using Taguchi Methods in technology and product development* 1995, (Addison-Wesley Publishing Company).

10 **Kang, J.** and **Hadfield, M.**, The loose abrasive process in the eccentric lapping and polishing of advanced ceramic balls, *in preparation*

LIST OF CAPTIONS FOR THE TABLES AND ILLUSTRATIONS

TABLES

Table 1 Summary of testing materials

Lapping plates	material: grey cast iron (grade 12) upper plate flat lower plate with eccentric V-groove V-groove angle 90° symmetric axis parallel to rotating axis diameter of circular V-groove 65 mm eccentricity (distance between centre of circular V-groove and rotating axis) 8 mm
Ball being lapped	HIPed silicon nitride ball blanks (CERBEC NBD200) diameter: 13.255 mm
Diamond Paste	Kemet diamond compound (90μ) 90-KD-C2, (60μ) 60-KD-C2 Metadi II diamond paste (6μ) 40-6250UK
Lapping Fluid	Metadi fluid (water based) 40-6064UK

Table 2 Standard L9 (3^4) Orthogonal Array used in Taguchi Method

Run	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 3 The chosen parameters and their levels

Level	Parameters			
	A: Lapping Speed	B: Lapping Load	C: Particle Size	D: Paste Concentration
1	118.42 rpm	8.82N/ball (0.9kg/ball)	6 μ	9.8mN:3×10^{-5}m^{3} (1g:30ml)
2	168.75 rpm	13.034N/ball (1.33kg/ball)	60 μ	9.8mN:6×10^{-5}m^{3} (1g:60ml)
3	270 rpm	18.13N/ball (1.85kg/ball)	90 μ	9.8mN:1.2×10^{-4}m^{3} (1g:120ml)

Table 4 The test run design

Test No.	Parameters			
	A: Lapping Speed	B: Lapping Load	C: Particle Size	D: Paste Concentration
1	118.42 rpm	8.82N/ball (0.9kg/ball)	6 μ	9.8mN:3×10^{-5}m^{3} (1g:30ml)
2	118.42 rpm	13.034N/ball (1.33kg/ball)	60 μ	9.8mN:6×10^{-5}m^{3} (1g:60ml)
3	118.42 rpm	18.13N/ball (1.85kg/ball)	90 μ	9.8mN:1.2×10^{-4}m^{3} (1g:120ml)
4	168.75 rpm	8.82N/ball (0.9kg/ball)	60 μ	9.8mN:1.2×10^{-4}m^{3} (1g:120ml)
5	168.75 rpm	13.034N/ball (1.33kg/ball)	90 μ	9.8mN:3×10^{-5}m^{3} (1g:30ml)
6	168.75 rpm	18.13N/ball (1.85kg/ball)	6 μ	9.8mN:6×10^{-5}m^{3} (1g:60ml)
7	270 rpm	8.82N/ball (0.9kg/ball)	90 μ	9.8mN:6×10^{-5}m^{3} (1g:60ml)
8	270 rpm	13.034N/ball (1.33kg/ball)	6 μ	9.8mN:1.2×10^{-4}m^{3} (1g:120ml)
9	270 rpm	18.13N/ball (1.85kg/ball)	60 μ	9.8mN:3×10^{-5}m^{3} (1g:30ml)

Table 5 Experimental results

Test No.	Measured material removal rate on each individual ball (μ/hour)															Average (μ/hour)	S/N_{LTB} (dB)	Weigh 10^{-6}N/
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15			
1	10	9.5	9.5	9	9	9	9	9	9	9	9	9	9	9	9	9.13	19.20	79
2	15	15	15	15	15	14.5	14.5	14	14	14	14	14	14	13.5	13.5	14.33	23.11	11
3	20	20	20	20	20	20	20	20	19.5	19.5	19.5	19.5	19	19	19	19.67	25.87	16
4	16	15	15	15	15	15	15	15	15	15	15	15	14.5	14	14	14.9	23.45	104
5	30	30	30	30	29	29	29	29	29	29	28	28	28	27	27	28.8	29.17	222
6	25	25	25	25	25	24	24	24	24	24	24	23	23	23	24	24.13	27.64	163
7	17	17	17.5	18	18	18	17	17	16	16	16	16	16	17	17	16.9	24.53	143
8	16.8	16.8	17.3	16.8	16.8	15.9	16.8	16.8	16.8	16.8	16.8	17.8	17.8	16.8	16.8	16.96	24.58	133
9	40	40	39	39	39	40	41	40.5	41	41	41	40	40	40	40	40.1	32.06	336

Table 6 Level average response analysis

	Test Run No.	Average of each run (μ/hour)	Level Average Response (μ/hour)
Parameter A, Lapping Speed			
Level 1, 118.42 rpm	1	9.13	14.38
	2	14.33	
	3	19.67	
Level 2, 168.75 rpm	4	14.9	22.61
	5	28.8	
	6	24.13	
Level 3, 270 rpm	7	16.9	24.65
	8	16.96	
	9	40.1	
Parameter B, Lapping Load			
Level 1, 8.82N/ball (0.9kg/ball)	1	9.13	13.64
	4	14.9	
	7	16.9	
Level 2, 13.034N/ball (1.33kg/ball)	2	14.33	20.03
	5	28.8	
	8	16.96	
Level 3, 18.13N/ball (1.85kg/ball)	3	19.67	27.97
	6	24.13	
	9	40.1	
Parameter C, Particle Size			
Level 1, 6 μ	1	9.13	16.74
	6	24.13	
	8	16.966	
Level 2, 60 μ	2	14.33	23.11
	4	14.9	
	9	40.1	
Level 3, 90 μ	3	19.67	21.79
	5	28.8	
	7	16.9	
Parameter D, Paste Concentration			
Level 1, 9.8mN:$3\times10^{-5}m^3$ (1g:30ml)	1	9.13	26.01
	5	28.8	
	9	40.1	

Level 2, 9.8mN:$6\times10^{-5}m^3$ (1g:60ml)	2	14.33	18.46
	6	24.13	
	7	16.9	
Level 3, 9.8mN:$1.2\times10^{-4}m^3$ (1g:120ml)	3	19.67	17.18
	4	14.9	
	8	16.966	

Table 7 Level average response analysis using S/N_{LTB} ratio

	Test Run No.	S/N_{LTB} of each run (dB)	Level Average S/N_{LTB} (dB)
Parameter A, Lapping Speed			
Level 1, 118.42 rpm	1	19.20	22.73
	2	23.11	
	3	25.87	
Level 2, 168.75 rpm	4	23.45	26.75
	5	29.17	
	6	27.64	
Level 3, 270 rpm	7	24.53	27.06
	8	24.58	
	9	32.06	
Parameter B, Lapping Load			
Level 1, 8.82N/ball (0.9kg/ball)	1	19.20	22.40
	4	23.45	
	7	24.53	
Level 2, 13.034N/ball (1.33kg/ball)	2	23.11	25.62
	5	29.17	
	8	24.58	
Level 3, 18.13N/ball (1.85kg/ball)	3	25.87	28.52
	6	27.64	
	9	32.06	
Parameter C, Particle Size			
Level 1, 6 μ	1	19.20	23.81
	6	27.64	
	8	24.58	
Level 2, 60 μ	2	23.11	26.21
	4	23.45	
	9	32.06	
Level 3, 90 μ	3	25.87	26.52
	5	29.17	
	7	24.53	
Parameter D, Paste Concentration			
Level 1, 9.8mN:3×10^{-5}m^3 (1g:30ml)	1	19.20	26.81
	5	29.17	
	9	32.06	
Level 2, 9.8mN:6×10^{-5}m^3 (1g:60ml)	2	23.11	25.09
	6	27.64	
	7	24.53	
Level 3, 9.8mN:1.2×10^{-4}m^3 (1g:120ml)	3	25.87	24.63
	4	23.45	
	8	24.58	

ILLUSTRATIONS

Fig. 1 Overview photograph of the eccentric lapping machine

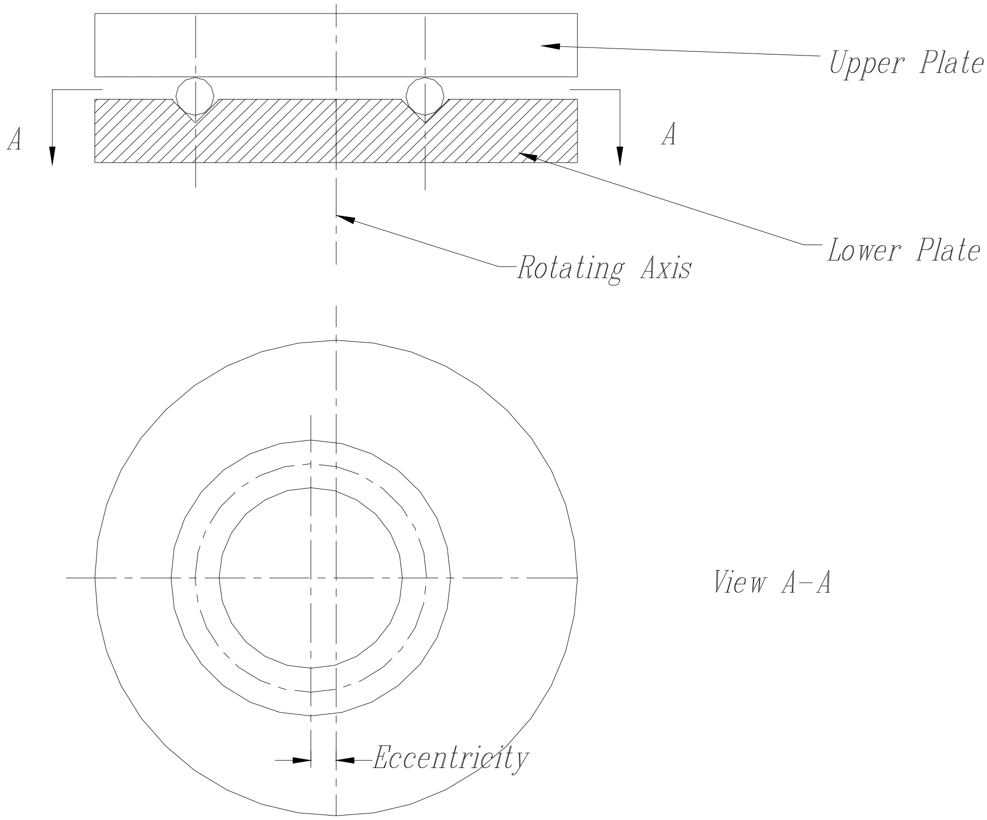

Fig. 2 Schematic of the eccentric lapping plate

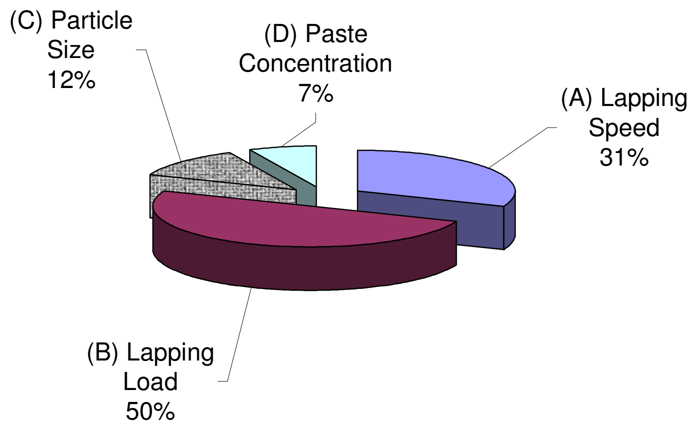

Fig. 5 Percentage contributions for parameters A, B, C, and D by ANOVA

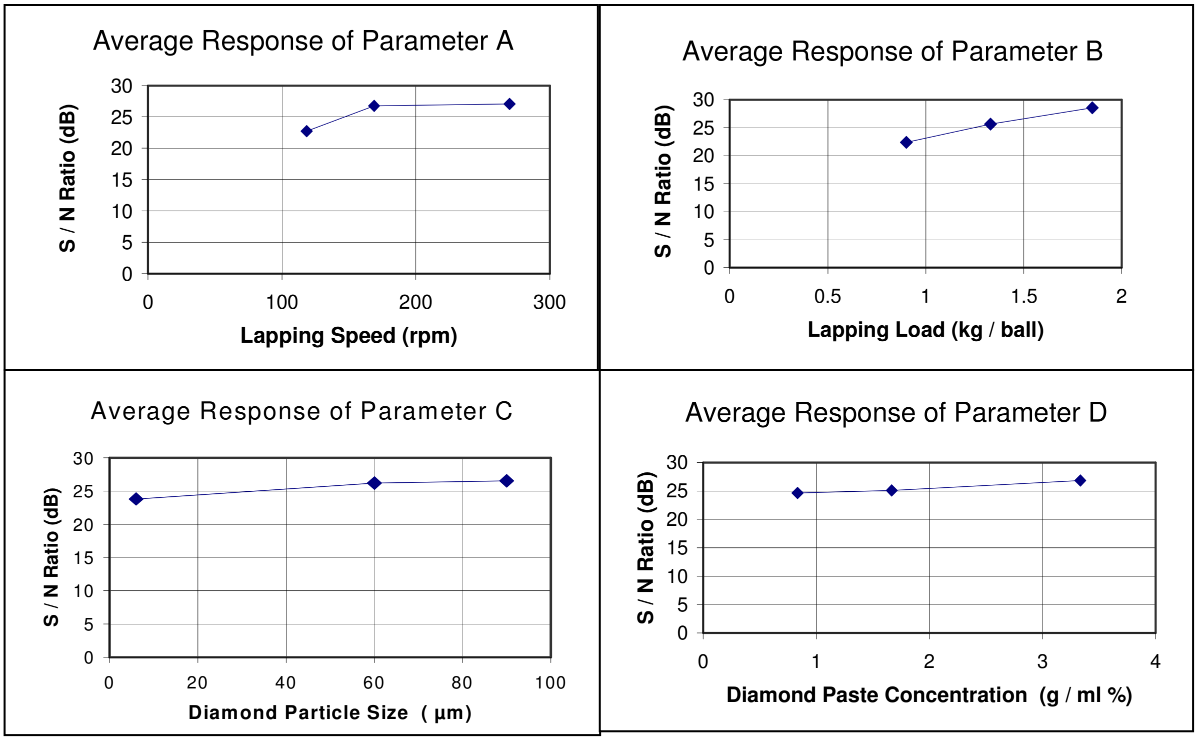

Fig. 4 Level average responses for parameters A, B, C, and D by S/N ratios

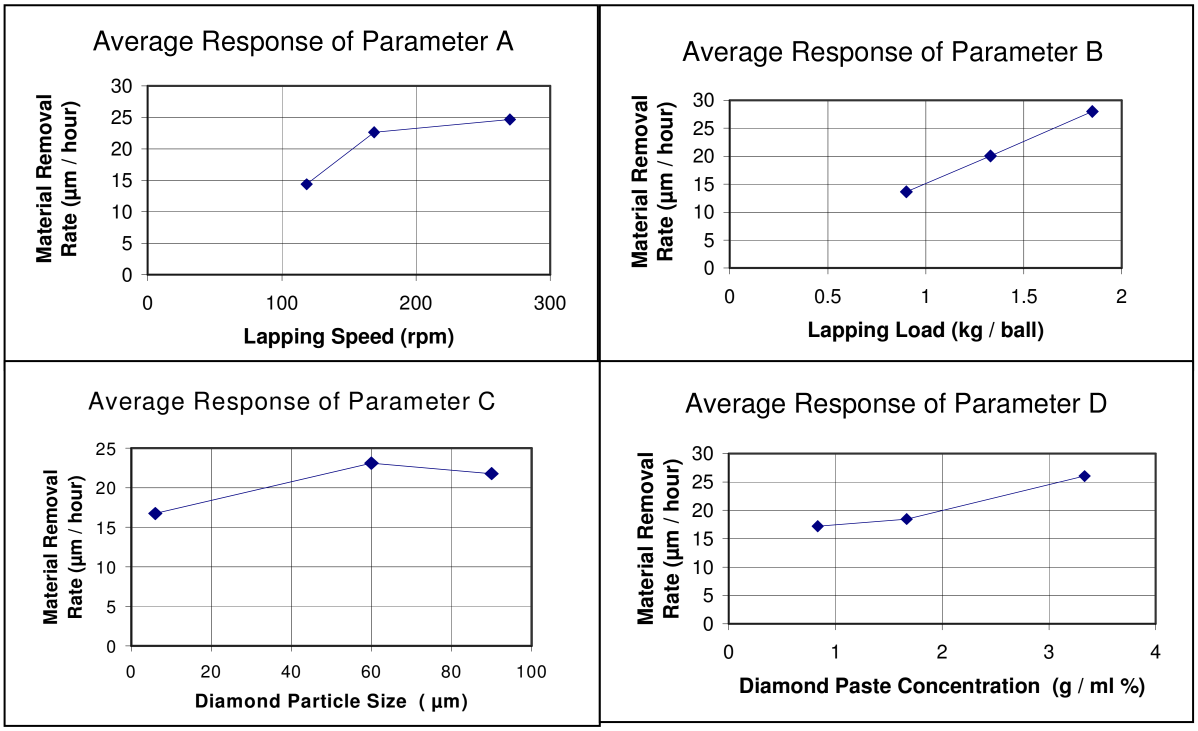

Fig. 3 Level average responses for parameters A, B, C, and D