Prod. Eng. Res. Devel. (2009) 3:243–253
DOI 10.1007/s11740-009-0164-2

PRODUCTION PROCESS

Taguchi's optimization of process parameters for production accuracy in ultrasonic drilling of engineering ceramics

R. S. Jadoun · Pradeep Kumar · B. K. Mishra

Received: 26 September 2008 / Accepted: 10 July 2009 / Published online: 26 August 2009

Abstract This paper presents a study of the effect of process parameters on production accuracy obtained through ultrasonic drilling of holes in alumina based ceramics using silicon carbide abrasive. Production accuracy in ultrasonic drilling involves both dimensional accuracy (hole oversize) and form accuracy (out-of-roundness and conicity). The parameters considered are workpiece material, tool material, grit size of the abrasive, power rating and slurry concentration. Taguchi's optimization approach is used to obtain the optimal parameters. The significant parameters are also identified and their effect on oversize, out-of-roundness and conicity are studied. The results obtained are validated by conducting the confirmation experiments.

Keywords Ultrasonic drilling · Alumina based ceramics · Engineering ceramics · Hole-oversize · Out-of-roundness · Conicity · Taguchi method · Optimization

1 Introduction

Engineering ceramics have excellent material properties such as high hardness, wear and corrosion resistance, stiffness and high strength even at elevated temperatures. Because of these aforesaid properties, it finds its applications in the modern manufacturing industries especially in aerospace, automobile, electronics and computers [1, 2]. Alumina (Al_2O_3) can be used in these applications because of its high hardness and wear resistance, chemical resistance and smooth surface. Al_2O_3 can also be used extensively for electrical applications such as spark plug insulators, substrates for electronics modules (such as in automobiles) and packages for integrated circuits due to its good electrical insulating characteristics. Because of the large quantity requirements, Al_2O_3 can be considered as the lowest-cost high-performance ceramics. Thus, they should be considered when seeking an alternate material for increased wear resistance, improved surface finish, dimensional stability, decreased friction and higher temperature use.

Unfortunately, the machining of Al_2O_3 by conventional manufacturing processes is extremely difficult and un-economical [3–7]. Not all methods are suitable for all type of machining problems. A careful selection of the process for a given problem is, therefore, essential. Ultrasonic machining is a valuable process for the precision machining of hard, brittle materials because of many of its unique characteristics. This machining process is non-thermal, non-chemical, non-electrical and creates no change in the metallurgical, chemical, or physical properties of the material machined [8]. Thus, in the present investigation, ultrasonic drilling (USD) has been chosen for further exploration as a machining process for alumina based ceramic materials. In modern industry the goal is to manufacture low cost, high quality products.

The Taguchi's method of off-line quality control has been successfully used in design and selection of optimal process parameters in many areas of manufacturing processes.

R. S. Jadoun (✉)
Production Engineering Department,
College of Technology, Pantnagar 263145, India
e-mail: rsjadoun63@yahoo.co.in; rsjadoun@gmail.com

P. Kumar · B. K. Mishra
Mechanical and Industrial Engineering Department,
IIT Roorkee, Roorkee 247667, India
e-mail: kumarfme@iitr.ernet.in

B. K. Mishra
e-mail: bhanufme@iitr.ernet.in

Off-line quality control methods are concerned with those quality control activities at the design stages, which are conducted to improve product manufacturability, reliability and to reduce product development and lifetime costs. Quality achieved by means of design optimization is found by many manufacturers to be cost effective in gaining and maintaining a competitive position in the world market [9–11]. The production accuracy obtainable for ultrasonically drilled holes is affected by the various parameters. Thus, the main thrust of this investigation is parametric optimization (an off-line quality control activity) with regards to production accuracy obtained by USD process.

2 Literature review

Accuracy of holes produced by USD must take into account both dimensional accuracy (over size) and form accuracy (out-of-roundness and conicity) [12]. An increase in the diameter/length ratio increases lateral vibrations causing greater over size [13, 14]. Shaw [15] and others [12–14, 16, 17] have shown that surface roughness improves with increased static load which reduces the abrasive size and suppresses lateral vibrations of the tool, so minimizing the oversize/conicity [out-of-roundness (OOR)] of the holes produced. Adithan and Venkatesh [12] found that the oversize with rectangular holes was greater than that obtained with circular tools. Kennedy and Grieve [18] has reported that the factors affecting accuracy of USD are: the precision of the machine tool (i.e. the accuracy of the feed motion), the accuracy of the fixtures used, the quality of the assembly element, abrasive grit size, tool wear, transverse vibration effects, and depth of cut.

The grain size is one of the main factor which affects the hole oversize (HOS) during drilling [12, 16, 19]. Neppiras [16] stated that the overcut has been found to be about one and a half times the mean grain size. Various investigators as cited in reference [12] have suggested various rules for side clearance being related to the geometry, size and distribution of abrasive grains. The amount of oversize of the holes is greater at entry than at exit resulting in unavoidable conicity due to tool wear. The amount of oversize at the bottom of the hole is of the same order as the smallest abrasive size. Conicity can be reduced by using tungsten carbide and stainless steel tool materials [12], an internal slurry delivery system [12, 13, 20], tools with negative tapering walls or fine abrasives [13, 14, 16, 18]. Dimensional accuracy of the order of ±5 μm can be obtained in most materials. Conicity is reduced at higher static loads and for prolonged operating times since tool wear is less with finer abrasives [12, 16]. Use of combined tools with negative taper improves accuracy [19]. Injection of slurry into machining zone increases precision and decreases conicity [19, 21]. Re-passing with the use of fine abrasives can eliminate conicity [21, 22]. OOR is mainly due to lateral vibrations and inaccuracy in the feed motion at entry, but at the exit, it is due to micro chipping [20] of the work material. It decreases with increase in static pressure and machining time [12, 19].

From the above, it is observed that much of the emphasis is laid on the methods to improve the machining rate and to find out the stress distribution in the work piece. Some of the researchers also made an attempt to study other performance characteristics by varying one factor at a time. Thus, literature lacks in systematic investigation of the effect of process parameters on the quality of drilled hole. Moreover, most of the studies conducted earlier, have not considered the interaction effects of process parameters on quality of drilled hole. However, quality of the drilled hole, which can be estimated from such attributes as the obtainable surface finish, HOS and conicity, is dependent on the complex interaction of process parameters like slurry concentration, grit size, power, work piece material etc. Thus, there is a need to further investigate the effect of different process parameters on the quality of hole drilled by ultrasonic machining. Considering the large number of parameters involved in USD, the experiments need to be designed using some experimental design techniques.

3 Materials and methods

3.1 Means and materials

In order to achieve the objective of the present study, the experiments were conducted on an 'AP-500 model Sonic-Mill' ultrasonic machine. Hot pressed Alumina based ceramic composites were used in this investigation. A monolithic Al_2O_3 was used as the baseline material. Silicon carbide (SiC) particles (average particle size 1 μm) were added to Al_2O_3 matrix according to the combinations listed in Table 1. The Workpieces were cast in the plate form of size 38.1 × 38.1 × 6.35 mm. The morphology and microstructure of the composite is shown in Fig. 1.

The tools made of high carbon steel, high speed steel and tungsten carbide are used in this investigation. The

Table 1 Composition of ceramic composites

Material Designation	Contains % age of weight			
	Al_2O_3	CaO	SiC	MgO
1	50	25	20	5
2	60	15	20	5
3	70	5	20	5

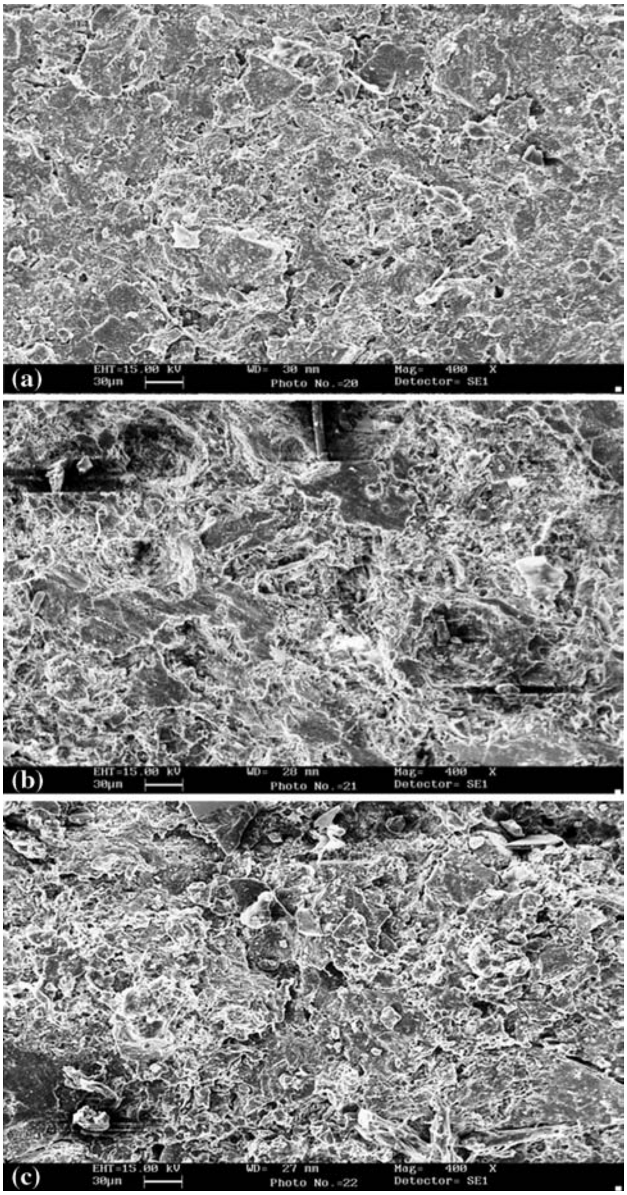

Fig. 1 SEM photographs of workpiece materials before drilling **a** 50% Alumina, **b** 60% Alumina and **c** 70% Alumina

tools were silver brazed to the replaceable threaded tip. Brazing was done at 1,200°F (648°C). Before brazing, the alignment of tool and replaceable threaded tip is ensured and then brazing is done with utmost care, so as to keep the axis of the horn and the axis of the tool in line. The tool geometry is shown in Fig. 2.

Silicon carbide was used as an abrasive to drill the hole by USD process. Silicon carbide is a high quality abrasive available in two type's viz. black ands green. Due to availability of black silicon carbide, the abrasive with properties such as hardness on mohs scale (9.7); fracture toughness (4.5 MPa $m^{1/2}$); specific gravity (3.2 g/cc); Young's modulus (440 GPa); melting point (2,600°C); black color is used in the present investigations. On the basis of pilot experiments the range of the grit size has been decided as # 220, 320 and 500. Water is used as liquid media to make abrasive slurry. The range of the slurry concentration was decided on the basis of literature review and pilot experiments conducted with selected process parameter at different values using one factor at a time approach. The selected concentrations are 25, 30 and 35%.

3.2 Measurements

The measurements of various properties reported in this paper are done as per the procedure specified in ASTM standards [23]. The increase in the size of the hole produced with reference to the size of the tool is known as the oversize of the hole produced. The diameter of the hole at the entry side was measured by using Tool Maker's Microscope. The tool diameter was subtracted from the hole diameter to get the HOS. OOR refers to the errors of geometrical form of the circular holes drilled. Diameter of measuring OOR or circularity is most widely preferred method [24]. For this, diameters at three different places were measured using Tool Maker's Microscope. Thus the 'OOR' was calculated as the difference between highest and lowest diameters of the drilled hole. Conicity (CC) is defined as the difference between the hole diameters at the entry side and exit side per unit length of the hole produced.

3.3 Plan of experiments (Taguchi's technique)

This paper uses Taguchi's method, which is very effective to deal with responses influenced by multi-variables. Taguchi's method of experimental design provides a simple, efficient and systematic approach to determine optimal machining parameters. Taguchi recommends orthogonal arrays (OA) for laying out of experiments. For optimum performance characteristics of the USD process, five process parameters viz. workpiece material (A), tool material (B), grit size (C), power rating (D), slurry concentration (E) and three-two-parameter interactions viz. A × B, B × C, A × C were selected as shown in Table 2. Berne and Taguchi [25] have identified that the non-linear behavior (if any) of the parameters of a process can only be determined if more than two levels are used. As per Ross [26], it is also necessary that the interval between the levels in multi-level experiment must be equal. Hence, it was decided to study each selected parameter at three levels. With five parameters each at three levels and three-second order interactions, the total degrees of freedom (DOF) required is 22 [=5 × (3 − 1) + 3 × 4], since a three level parameter has teo DOF (No. of levels—1) and each two-parameter interaction term has four DOF (2 × 2). Hence, an L_{27} (3^{13}) OA (a standard 3-level OA) has been selected for this phase of experimental work. The L_{27} OA [26] with

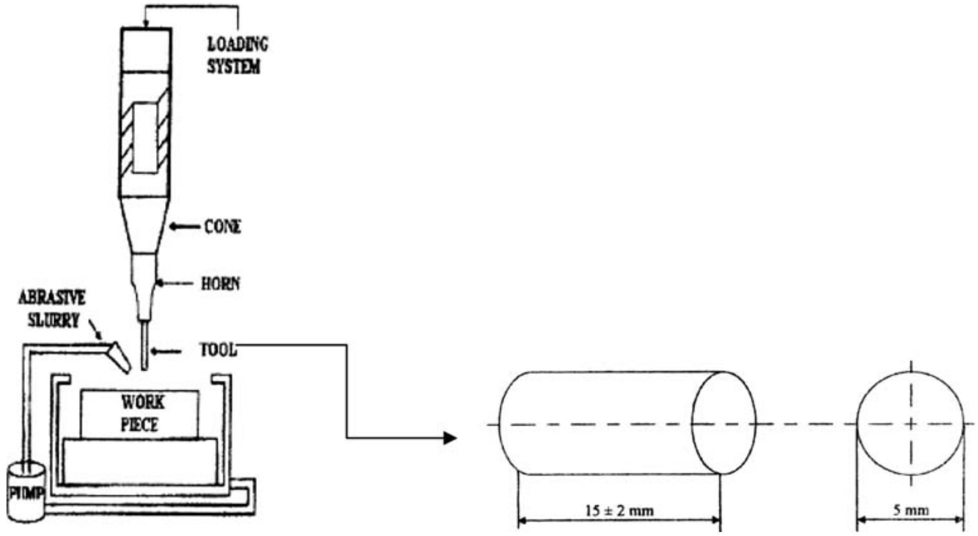

Fig. 2 Schematic diagram of USD process with tool geometry [28]

assignment of parameters and interactions is shown in Table 3. The parameters and interactions have been assigned to specific columns of the OA using the triangular Table [26] and linear graphs [27].

According to the scheme of experimentation outlined in Table 3, holes were drilled in the workpieces. Three repetitions per trial, i.e. three holes were drilled at every trial condition, resulting in a total of 81 tests [28–30]. The experimental results are shown in Table 4.

4 Data analysis

4.1 Evaluation of S/N ratios

The signal to noise ratios is obtained using Taguchi's methodology. Here, the term 'signal' represents the desirable value (mean) and the 'noise' represents the undesirable value (standard deviation). Thus, the S/N ratio represents the amount of variation present in the performance characteristic. Depending upon the objective of the performance characteristic there can be various types of S/N ratios. Here the desirable objective is to obtain lower values of HOS, OOR and CC. Hence, the lower-the-better type S/N ratio, as given below was applied.

$$(\mathrm{S/N})_{\mathrm{LB}} = -10 \log\left[\frac{1}{R}\sum_{j=1}^{R} y_j^2\right] \quad (1)$$

where y_j = value of the characteristic in an observation j, R = number of observation or number of repetitions in a trial.

The S/N ratios for HOS, OOR and CC, calculated from the observed data are shown in Table 4.

Table 2 Process parameters and their values at different levels

Process parameters symbols	Process parameter	Level 1	Level 2	Level 3
A	Work piece	50% Al_2O_3	60% Al2O3	70% Al_2O_3
B	Tool	HCS	HSS	TC
C	Grit size	220	320	500
D	Power rating	40%	50%	60%
E	Slurry concentration	25%	30%	35%
Constant parameters				
Frequency of vibrations	20 kHz			
Static load	1,000 g			
Type of work piece	Alumina based ceramic			
Thickness of work piece	5 mm			
Tool geometry	As shown in figure			
Abrasive type	Silicon carbide			
Liquid media	Water			
Slurry temperature	20°C i.e. near the ambient temperature of tap water			
Flow rate	50×10^3 mm^3/min			

Table 3 Taguchi's L_{27} orthogonal array, with parameters assigned

L_{27} (3^{13}) test	A 1	B 2	A × B 3	A × B 4	C 5	A × C 6	A × C 7	B × C 8	D 9	E 10	B × C 11	Error 12	Error 13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	2	3	1	3	2	3	2	1
27	3	3	2	1	3	1	1	2	1	3	1	3	2

4.2 Level average response analysis

The level average responses from the raw data help in analysing the trend of the quality characteristic with respect to the variation of the factors under study. The level average response plots based on the S/N data help in optimizing the objective under study. The average response plots for raw and S/N data are shown in Fig. 3a–c for HOS, OOR and CC, respectively. The interactions effect of the factors under study have also been considered and plotted as shown in Fig. 4a–i.

4.3 Analysis of variance

Tables 5, 6 and 7 show the results of the pooled ANOVA with the HOS, OOR and CC in workpiece, respectively. This analysis was carried out for a level of confidence of 95%. The last column of the tables previously mentioned shows the percentage contribution of each factor on the total variation which indicates the degree of influence on the result. The percentage contributions of significant parameters are plotted as shown in Fig. 5a–c.

4.4 Selection of optimum levels of process parameters

The optimal levels of process parameters are selected on the basis of average response analysis for S/N data and pooled ANOVA. Whatever may be the objective of quality characteristic, the peak points in the S/N response graph for significant parameters give the optimal combination for the quality characteristic. The optimal settings for HOS, OOR and conicity are given in Table 8.

4.5 Estimation of confidence intervals

After determination of the optimum condition, the mean of the response (μ) at the optimum condition is predicted. This mean is estimated only from the significant parameters.

Table 4 Experimental results of production accuracy and S/N ratios

Expt No.	Average of three responses			Signal to noise ratio (dB) (S/N)		
	HOS (mm)	OOR (mm)	CC	HOS	OOR	CC
1	0.382	0.450	0.048	8.349	6.934	26.446
2	0.351	0.402	0.042	9.082	7.922	27.549
3	0.156	0.368	0.037	16.124	8.673	28.542
4	0.527	0.455	0.041	5.561	6.837	27.786
5	0.339	0.283	0.041	9.401	10.952	27.730
6	0.211	0.242	0.030	13.500	12.333	30.341
7	0.566	0.445	0.039	4.948	7.026	28.089
8	0.311	0.298	0.022	10.144	10.524	33.176
9	0.309	0.307	0.014	10.200	10.266	36.872
10	0.471	0.368	0.057	6.540	8.674	24.882
11	0.307	0.345	0.046	10.266	9.241	26.669
12	0.135	0.363	0.037	17.370	8.810	28.651
13	0.463	0.442	0.050	6.694	7.097	26.019
14	0.455	0.406	0.042	6.844	7.822	27.507
15	0.311	0.391	0.035	10.135	8.164	29.218
16	0.428	0.307	0.039	7.378	10.257	28.075
17	0.390	0.284	0.024	8.186	10.923	32.444
18	0.295	0.240	0.016	10.593	12.391	35.713
19	0.645	0.405	0.068	3.800	7.850	23.349
20	0.397	0.390	0.051	8.031	8.177	25.882
21	0.075	0.350	0.044	22.531	9.116	27.091
22	0.575	0.422	0.053	4.802	7.499	25.558
23	0.313	0.425	0.045	10.089	7.432	27.026
24	0.184	0.200	0.037	14.718	13.978	28.651
25	0.523	0.359	0.065	5.635	8.888	23.706
26	0.348	0.255	0.049	9.176	11.868	26.184
27	0.249	0.212	0.026	12.086	13.459	31.655

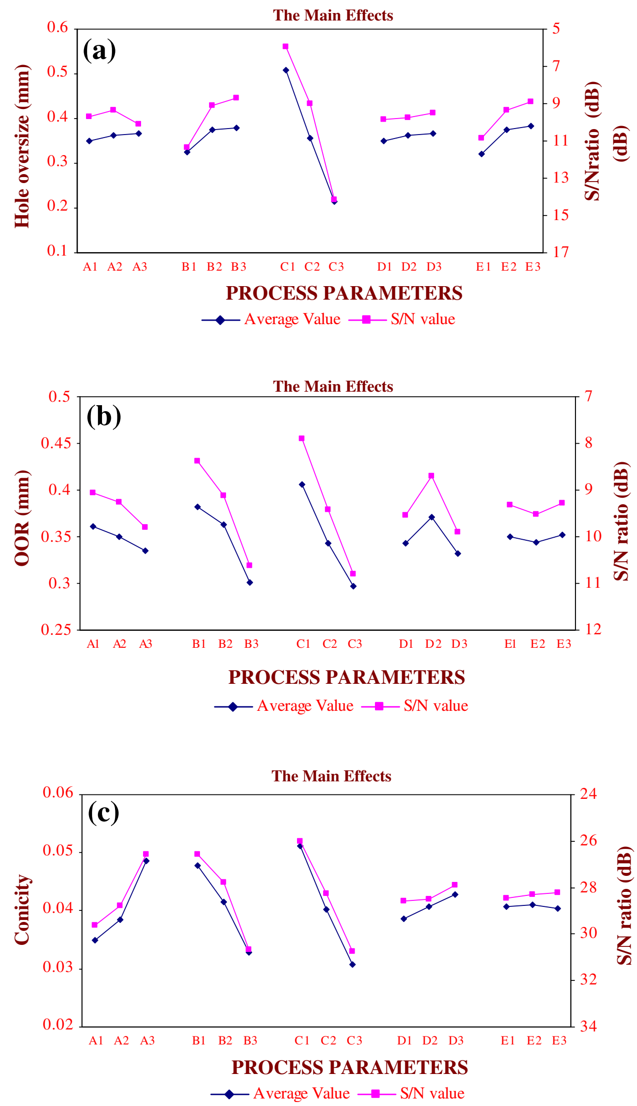

Fig. 3 **a** Effects of process parameters on HOS-raw data and S/N ratio: main effects. **b** Effects of process parameters on OOR-raw data and S/N ratio: main effects. **c** Effects of process parameters on conicity-raw data and S/N ratio: main effects. *A* Workpiece, *B* tool, *C* grit size, *D* power rating, *E* slurry concentration

The estimate of the mean (μ) is only a point estimate based on the average of results obtained from the experiment. Statistically this provides a 50% chance of the true average being greater than μ and a 50% chance of true average being less than μ. It is therefore customary to represent the values of a statistical parameter as a range within which it is likely to fall, for a given level of confidence [26]. This range is termed as the confidence interval (CI). In other words, the confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence [26].

The following two types of confidence intervals are suggested by Taguchi in regards to the estimated mean of the optimal treatment condition [26].

(1) Around the estimated average of a treatment condition predicted from the experiment. This type of confidence interval is designated as CI_{POP} (confidence interval for the population).

(2) Around the estimated average of a treatment condition used in a confirmation experiment to verify predictions. This type of confidence interval is designated as CI_{CE} (confidence interval for a sample group).

The difference between CI_{POP} and CI_{CE} is that CI_{POP} is for the entire population i.e., all parts ever made under the specified conditions, and CI_{CE} is for only a sample group made under the specified conditions. Because of the smaller size (in confirmation experiments) relative to the entire population, CI_{CE} must be slightly wider. The expressions for computing the confidence interval are given below [26, 27].

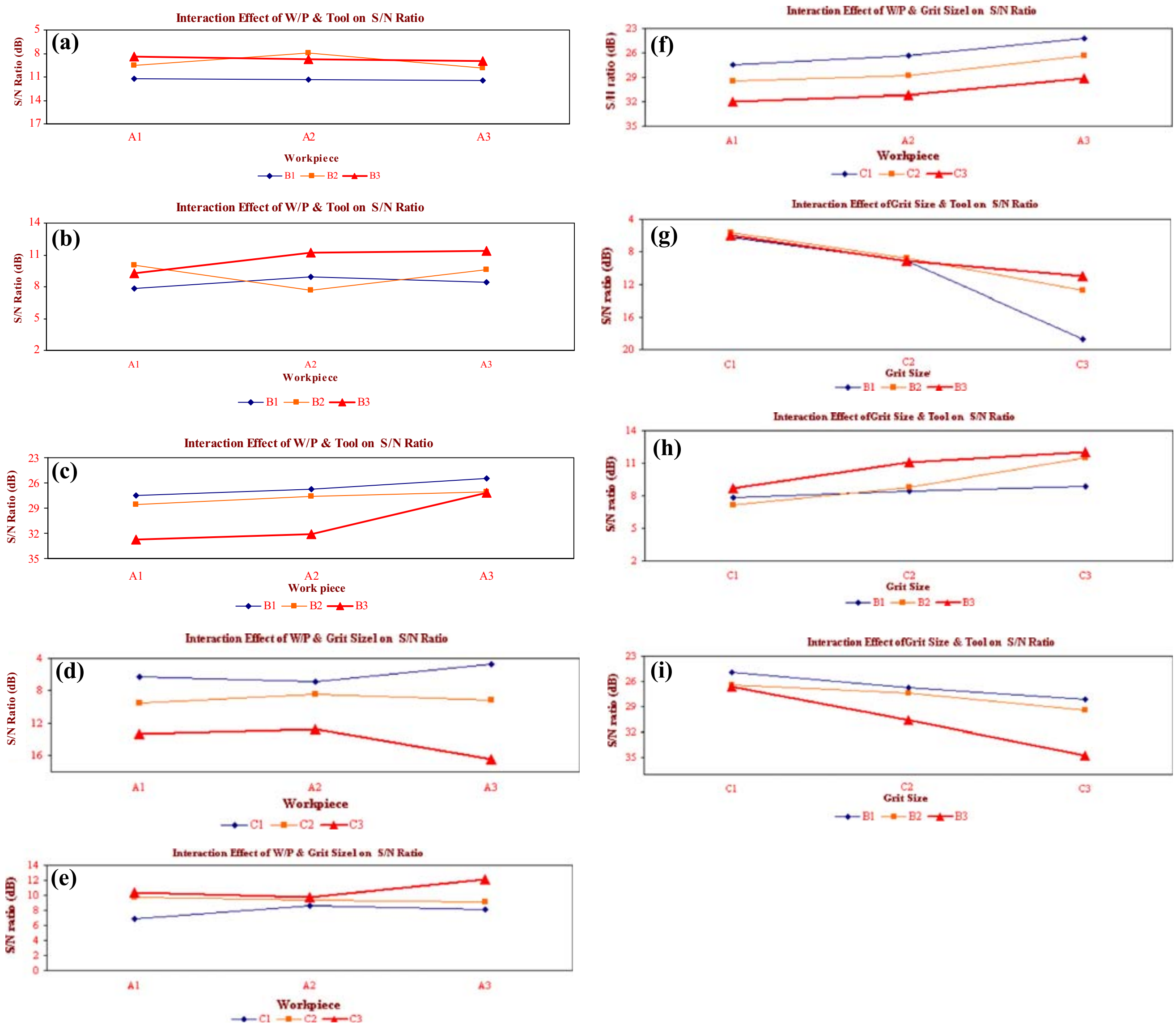

Fig. 4 **a** The interaction effects between workpiece and tool on HOS-S/N data. **b** The interaction effects between workpiece and tool on OOR- S/N data. **c** The interaction effects between workpiece and tool on CC-S/N data. **d** The interaction effects between workpiece and grit size on HOS- S/N data. **e** The interaction effects between workpiece and grit size on OOR-S/N data. **f** The interaction effects between workpiece and grit size on CC-S/N data. **g** The interaction effects between grit size and tool on HOS- S/N data. **h** The interaction effects between grit size and tool on OOR-S/N data. **i** The interaction effects between grit size and tool on CC-S/N data. *A* Workpiece, *B* tool, *C* grit size, *D* power rating, *E* slurry concentration

$$\mathrm{CI}_{\mathrm{pop}} = \sqrt{\frac{F_{\alpha}(1,f_e)V_e}{n_{\mathrm{eff}}}} \tag{2}$$

$$\mathrm{CI}_{\mathrm{CE}} = \sqrt{F_{\alpha}(1,f_e)\,V_e\left[\frac{1}{n_{\mathrm{eff}}}+\frac{1}{R}\right]} \tag{3}$$

where $F_{\alpha}(1, f_e)$ = the *F*-ratio at a confidence level of $(1-\alpha)$ against DOF 1 and error DOF f_e, V_e = error variance (from ANOVA)

$$\mathrm{n}_{\mathrm{eff}} = \frac{N}{1+[\text{Total DOF associated in the estimate of the mean}]} \tag{4}$$

where N = total number of results, R = sample size for confirmation experiment.

In Eq. 3, as R approaches infinity, i.e., the entire population, the value *I/R* approaches zero and $\mathrm{CI}_{\mathrm{CE}} = \mathrm{CI}_{\mathrm{POP}}$. As R approaches 1, the $\mathrm{CI}_{\mathrm{CE}}$ becomes wider. These results are shown in Table 8.

Table 5 Pooled ANOVA—raw data (hole-oversize)

Source	SS	DOF	V	SS′	*F*-ratio	*F*-tab	*P* (%)
A					Pooled		
B	0.0512	2	0.03	0.05	43.70	4.99	3.20*
C	1.1744	2	0.59	1.17	1001.97	4.99	74.96*
D					Pooled		
E	0.0650	2	0.03	0.06	55.47	4.99	4.08*
A × B	0.0462	4	0.01	0.04	19.73	3.69	2.80*
A × C	0.1138	4	0.03	0.11	48.56	3.69	7.12*
B × C	0.0780	4	0.02	0.08	33.29	3.69	4.84*
Error	0.0363	62	0.0006	0.05			3.00
Total	1.5650	80					100.00

SS Sum of squares, *DOF* degrees of freedom, *V* variance, *SS′* pure sum of squares, *P* percent contribution, *A* work piece, *B* tool, *C* grit size, *D* power rating, *E* slurry concentration

* Significant at 95% confidence level

Table 7 Pooled ANOVA—raw data (conicity)

Source	SS	DOF	V	SS′	*F*-ratio	*F*-tab	*P* (%)
A	0.0027	2	0.00135	0.0027	994.80	3.15	20.21*
B	0.0030	2	0.00152	0.0030	1115.84	3.15	22.67*
C	0.0056	2	0.00280	0.0056	2055.09	3.15	41.77*
D	0.0002	2	0.00011	0.0002	81.45	3.15	1.64*
E					Pooled		
A × B	0.0008	4	0.00021	0.0008	154.98	2.53	6.26*
A × C	0.0003	4	0.00007	0.0003	52.39	2.53	2.09*
B × C	0.0006	4	0.00015	0.0006	112.65	2.53	4.54*
Error	0.0001	60	0.000001	0.0001			0.81*
Total	0.0134	80					100.00

SS Sum of squares, *DOF* degrees of freedom, *V* variance, *SS′* pure sum of squares, *P* percent contribution, *A* work piece, *B* tool, *C* grit size, *D* power rating, *E* slurry concentration

* Significant at 95% confidence level

Table 6 Pooled ANOVA—raw data (out-of-roundness)

Source	SS	DOF	V	SS′	*F*-ratio	*F*-tab	*P* (%)
A	0.009	2	0.0045	0.01	26.33	4.99	1.88*
B	0.098	2	0.0489	0.10	287.55	4.99	21.23*
C	0.162	2	0.0808	0.16	475.51	4.99	35.16*
D	0.022	2	0.0112	0.02	66.09	4.99	4.82*
E					Pooled		
A × B	0.070	4	0.0175	0.07	102.93	3.69	15.10*
A × C	0.051	4	0.0128	0.05	75.53	3.69	11.04*
B × C	0.036	4	0.0091	0.04	53.58	3.69	7.79*
Error	0.010	60	0.0002	0.01			2.96
Total	0.459	80					100.00

SS Sum of squares, *DOF* degrees of freedom, *V* variance, *SS′* pure sum of squares, *P* percent contribution, *A* work piece, *B* tool, *C* grit size, *D* power rating, *E* slurry concentration

* Significant at 95% confidence level

4.6 Confirmation experiments

The confirmation experiment is the final step in verifying the conclusions from the previous round of experimentation. The optimum conditions are set for the significant parameters (the insignificant parameters are set at economic levels) and a selected number of tests are run under constant specified conditions [26]. The results are shown in Table 8.

5 Results and discussions

The dimensional accuracy (oversize) is due to the influx of abrasives which cause the hole to be larger than the tool used. It is theoretically equal to twice the mean diameter of the abrasives used [12]. HOS marginally increases with the increase in alumina content in the workpiece as shown in Fig. 3a. However, the effect is insignificant. This can be attributed to the fact that as the alumina content in the ceramics increases, the hardness and fracture toughness also increases. The tool wear increases with the increase in the hardness and toughness of the material, resulting into the oversize of the hole produced. This result is in conformity with the findings of Smith [20] and Adithan and Venkatesh [12]. The OOR decreases with the increase in alumina content in the workpiece as shown in Fig. 3b. OOR depends on the chipping tendency of the workpiece. With tungsten carbide, OOR is a minimum as chipping is absent [12]. The conicity increases with the increase in alumina content in the workpiece (Fig. 3c). This can be attributed to the fact that as the alumina content in the ceramics increases, the hardness and fracture toughness also increases which results into high tool wear. These results are in conformity with the studies of similar nature made earlier by different investigators.

The effect of tool material on HOS can be studied from the trend of variation as shown in Fig. 3a. The average HOS is almost same in case of HSS and TC tools and is greater than that of HCS tool. These results are contrary to the perception that HOS increases with the increase in tool wear. This may be due to the interaction of tool and grit size (B × C) and work piece and grit size (A × C) (see Fig. 4f, g). The average OOR is lowest with TC tool as shown in Fig. 3b. In the present investigation, it has been observed that there is least lateral wear with TC tool and greatest with HCS tool. Also, the grooves were observed on tools used. These observations are in conformity with other investigators like, Adithan and Venkatesh [12]. The tools

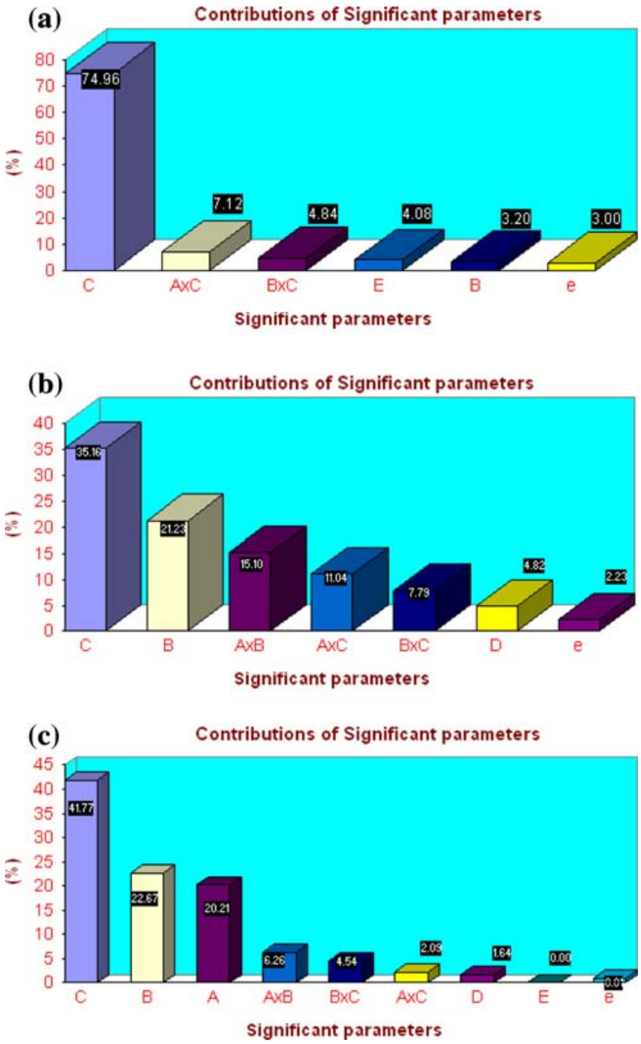

Fig. 5 **a** Bar graphs showing percentage contributions of significant process parameters for hole oversize. **b** Bar graphs showing percentage contributions of significant process parameters for out of roundness data. **c** Bar graphs showing percentage contributions of significant process parameters for conicity. *A* Workpiece, *B* tool, *C* grit size, *D* power rating, *E* slurry concentration

can be ranked in the order of decreasing conicity as: HCS > HSS > TC (see Fig. 3c). Because of the high abrasion resistance, tungsten carbide tool has least wear as compared to high carbon steel and high speed steel. These results are similar to the findings of earlier investigators like Markov [19], Smith [20] and McGough [14].

The HOS increases almost linearly as the grain size increases from third level to second level and then to first level. HOS is the highest at first level (# 220) and lowest for third level (# 500) as shown in Fig. 3a. The OOR increases almost linearly as the grain size increases from third level to second level and then to first level. OOR is the highest at first level and lowest for third level (see Fig. 3b). OOR is caused by the flow of abrasive particles in the gap between the tool and work piece; these particles scour the tool surface and produce lateral or side wear. The lateral or side wear depends on the rate of abrasive flow and as this is not uniform, lateral tool wear is also not uniform. This gives rise to OOR [12]. From Fig. 3c, it can be seen that conicity increases almost linearly as the grain size increases from third level to second level and then to first level. Tool wear rate (TWR) is the highest at first level and lowest for third level. This is due to the fact that the coarser grains cause more extensive damage of tool material during the impact of abrasives. This trend is similar to that of tool wear rate, which is the main cause of conicity in ultrasonically drilled holes.

Hole-oversize increases marginally with the increase in power as shown in Fig. 3a. This is due to the fact that power rating is associated with the amplitude of vibrations. As the amplitude of vibrations increases, the impact of abrasive with the tool also increases, resulting into higher wear rate and consequently producing higher HOS. The OOR is highest for 50% power rating (Fig. 3b). The conicity increases marginally with the increase in power. This is due to the fact that power rating is associated with the amplitude of vibrations. As the amplitude of vibrations increases, the impact of abrasive with the tool also increases, resulting into higher wear rate.

The HOS increases with increase in concentration from 25–30 to 35%. This can be attributed to the fact that the increase of tool wear rate with the increase in concentration results in increased HOS. It can be observed that the effect of concentration on OOR is insignificant. The conicity increases marginally with increase in concentration from 25–30 to 35% but the increment is insignificant. This can be attributed to the fact that the tools used in the present investigation have high resistance to abrasion.

The interaction effects for the S/N data have been plotted and are shown in Fig. 4a–i. There is a significant interaction between tool and work piece, work piece and grit size and tool and grit size with regard to the raw data. However, the interaction between workpiece and tool does not significantly affect the S/N ratio of HOS. There is a significant interaction between tool and workpiece, workpiece and grit size and tool and grit size with regard to the raw data and S/N data both. There is a significant interaction among workpiece, tool and grit size with regard to the raw data. However, the interaction between workpiece and grit size does not significantly affect the S/N ratio of conicity. Percentage contributions of different parameters are plotted and are shown in Fig. 5a–c.

Table 8 Predicted optimal values, confidence intervals and results of confirmation experiments

Performance characteristics	Optimal levels Process parameters	Predicted optimal value	Confidence interval (95%)	Actual value (average of three conformation experiments)
Hole-Oversize (HOS)	A3, B1, C3, D1, E1	0.138 (mm)	CI_{pop}: $0.124 < \mu_{HOS} < 0.152$	0.143
			CI_{CE}: $0.106 < \mu_{HOS} < 0.170$	
Out-of-roundness (OOR)	A3, B3, C3, D1, E2	0.229 (mm)	CI_{pop}: $0.220 < \mu_{OOR} < 0.238$	0.233
			CI_{CE}: $0.210 < \mu_{OOR} < 0.248$	
Conicity (CC)	A1, B3, C3, D1, E1	0.015	CI_{pop}: $0.014 < \mu_{CC} < 0.016$	0.0153
			CI_{CE}: $0.013 < \mu_{CC} < 0.017$	

CI_{pop} Confidence interval for the mean of the population, CI_{CE} confidence interval for the mean of the confirmation experiment, *A* workpiece, *B* tool, *C* grit size, *D* power rating, *E* slurry concentration

6 Conclusions

1. Taguchi's robust design method is suitable to analyze the ultrasonic drilling problem as described in this paper.
2. Hole-oversize marginally increases with the increase in alumina content in the work piece. However, the effect is insignificant as can be seen from ANOVA. The average HOS is almost same in case of HSS and TC tools and is greater than that of HCS tool. The HOS increases with the increase of grain size and concentration. The HOS increases marginally with the increase in power (see Fig. 3a). There is a significant interaction between tool and work piece, work piece and grit size and tool and grit size with regard to the raw data. However, the interaction between work piece and tool does not significantly affect the S/N ratio of HOS (see Fig. 4a). From ANOVA, it is clear that all the individual factors except work piece and power rating have significant effect on HOS (raw data). Percentage contribution of grit size was much more than rest of parameters (see Fig. 5a). The optimal levels of various process parameters for minimum HOS were:

Work piece material	70% Alumina
Tool	High carbon steel
Grit size	#500
Power rating	40%
Slurry concentration	25%

   The predicted optimal range of HOS at 95% confidence level was $0.124 < \text{HOS (mm)} < 0.152$. The optimal results obtained were validated by conducting confirmation experiments.
3. The OOR decreases with the increase in alumina content in the work piece. The average OOR is highest for drilling with HCS tool and lowest with TC tool. The OOR increases almost linearly as the grain size increases. The OOR increases with the increase of power rating; attains maximum and then decreases with further increase of power. The effect of concentration on OOR is insignificant (see Fig. 3b). There is a significant interaction between tool and work piece, work piece and grit size and tool and grit size with regard to the raw data and S/N data both (see Fig. 4b, e, h). From ANOVA, it is clear that all the individual factors except slurry concentration have significant effect on OOR. The percentage contributions of parameters affecting both mean and variation in decreasing order are: grit size (33.10), tool (20.15), interaction A × B (13.05), interaction A × C (08.75), interaction B × C (07.29), and power rating (5.23) (see Fig. 5b). The optimal levels of various process parameters for minimum OOR were:

Work piece material	70% Alumina
Tool	Tungsten carbide
Grit size	#500
Power rating	40%
Slurry concentration	30%

   The predicted optimal range of OOR at 95% confidence level was $0.220 < \text{OOR (mm)} < 0.238$. The optimal results obtained were validated by conducting confirmation experiments.
4. Conicity increases with the increase in alumina content in the work piece. The tools can be ranked in the order of decreasing conicity as: HCS > HSS > TC. The conicity increases almost linearly as the grain size increases. The conicity increases marginally with the increase in power and concentration (see Fig. 3c). There is a significant interaction between tool and work piece, work piece and grit size and tool and grit size with regard to the raw data. However, the interaction between work piece and grit size does not significantly affect the S/N ratio of conicity (see Fig. 4f). From ANOVA, it is clear that all the individual factors except slurry concentration have significant effect on conicity. The percentage

contributions of parameters affecting both mean and variation in decreasing order are: grit size (36.51), tool (28.51), work piece (15.89), interaction B × C (8.88) and interaction A × B (06.86) (see Fig. 5c). The optimal levels of various process parameters for minimum conicity were:

Work piece material	50% Alumina
Tool	Tungsten carbide
Grit size	#500
Power rating	40%
Slurry concentration	25%

The predicted optimal range of conicity at 95% confidence level was $0.014 < CC < 0.016$. The optimal results obtained were validated by conducting confirmation experiments.

7 Limitations

The limitation of present study is that, it considers only the optimization of a single parameter at a time. But in a real practical situation simultaneous optimization of various parameters has to be looked into. Taguchi method has been designed for the optimization of single parameter only.

References

1. Pandey PC, Shan HS (1980) Modern machining processes. TMH, New Delhi, pp 2–3
2. Brook RJ (1991) Concise encyclopedia of advanced ceramic materials. Pergamon press, New York, pp 1–2, 488
3. Weller EJ (1984) Non-traditional machining processes. Society of Manufacturing Engineers, Dearborn, pp 15–71
4. Benedict GF (1987) Nontraditional manufacturing processes. Marcel Decker Inc., New York, pp 2–3, 67–86
5. Boothroyed G, Knight WA (1989) Fundamentals of machining and machine tools. Marcel Decker Inc., New York, pp 468–469
6. Rajurkar KP et al (1999) Micro removal of ceramic material (Al_2O_3) in the precision ultrasonic machining. Precis Eng 23:73–78
7. Zhang QH et al (1999) Material-removal-rate analysis in the ultrasonic machining of engineering ceramics. J Mater Process Technol 88:180–184
8. Bradford JD, Richardson DB (1980) Production engineering technology, 3rd edn. Macmillan, London, pp 74–93
9. Thomas PR (1988) Taguchi approach to experimental design: some concerns. Qual Prog 4:34–36
10. Phadke MS (1989) Quality engineering using robust design. Prentice-Hall, Englewood cliffs
11. Taguchi G (1989) Quality engineering in production systems. Mcgraw-Hill, New York
12. Adithan M, Venkatesh VC (1976) Production accuracy of holes in ultrasonic drilling. Wear 40(3):309–318
13. Kremer D (1981) The state of the art of ultrasonic machining. Ann CRIP 30(1):107–110
14. McGeough JA (1988) Advanced methods of machining. Chapman and Hall, New York, pp 170–198
15. Shaw MC (1956) Ultrasonic grinding. Microtechnic 10(6):257–265
16. Neppiras EA (1956) Report on ultrasonic machining. Metalworking Prod 100: 1283–1288, 1333–1336, 1420–1424, 1599–1604
17. Komaraiah M, Narsimha Reddy P (1993) Relative performance of tool materials in ultrasonic machining. Wear 161:1–10
18. Kennedy DC, Grieve RJ (1975) Ultrasonic machining—a review. Prod Eng 54(9):481–486
19. Markov AI (1966) Ultrasonic machining of intractable materials. Iliffe, London
20. Smith TJ (1973) Parameter influence in ultrasonic machining. Ultrasonics 11(5):196–198
21. Rozenberg LD et al (1964) Ultrasonic cutting. Consultants Bureau, New York
22. Barash M, Watana PD (1970) The effect of ambient pressure on the rate of material removal in ultrasonic machining. J Mach Sci 12:775–779
23. ASTM (2001) C 1161, C 1259, C1326-03 and C 1327, Annual book of ASTM standards, 15.01. American Society for Testing and Materials, West Conshohocken
24. Laroiya SC et al (1992) Machining of advanced ceramics. In: 15th AIMTDR conference, 3–5 December, 1992, pp 571–575
25. Byrne DM, Taguchi S (1987) The Taguchi approach to parameter design. Qual Prog 20(12):19–26
26. Philip JR (1988) Taguchi technique for quality engineering. McGraw-Hill, New York
27. Ranjit KR (1990) A primer on Taguchi method. Van Nostrand Reinhold, New York
28. Jadoun RS, Pradeep K, Mishra BK, Mehta RCS (2006) Optimization of process parameters for ultrasonic drilling (USD) of advanced engineering ceramics using Taguchi approach. Eng Optim 38(7):771–787
29. Jadoun RS, Pradeep K, Mishra BK, Mehta RCS (2006) Manufacturing process optimization for tool wear rate in ultrasonic drilling (USD) of engineering ceramics using Taguchi's method. Int J Mach Mach Mater 1(1):94–114
30. Jadoun RS, Pradeep K, Mishra BK, Mehta RCS (2006) Optimisation of MRR in ultrasonic drilling (USD) based on Taguchi's robust design methodology. Int J Mach Mach Mater 1(4):445–462