Drilling of Engineering Ceramics using Combination of Ultrasonic Vibrations and Diamond Slurry

S. M. Hoseini *
Department of Mechanical Engineering,
Science and Research Branch, Islamic Azad University, Tehran, Iran
E-mail: sm.hoseini@srbiau.ac.ir
*Corresponding author

J. Akbari
Center of Excellence in Design, Robotics and Automation,
School of Mechanical Engineering, Sharif University of Technology,
Tehran, Iran

Received: 8 January 2012, Revised: 30 May 2012, Accepted: 8 June 2012

Abstract: Engineering ceramics due to their high strength-to-weight ratio, wear resistance, corrosion resistance, and thermal resistance have widely been used in the industries especially in aerospace, automobile, electronics and computers. In spite of their extensive application, however using conventional machining methods for manufacturing of complex and desired shapes are not suitable. Accordingly drilling holes with desired accuracy are difficult to be achieved. Ultrasonic machining (UM) is a modern machining method that is appropriate for creating holes in hard and brittle materials through ultrasonic vibrating applied to work piece by tools. Furthermore, abrasive slurry is applied through the gap between the tool and workpiece. In this paper modal analysis is used to choose the best shape for wave amplitude magnification and concentration. A desktop CNC milling machine is used for controlling feed motion of ultrasonic head upon a ceramic sample. Effect of input factors such as power, abrasive grit size, slurry concentration and feed rate are obtained on the material removal rate (MRR), tool wear rate (TWR) and hole over size (HOS) by Taguchi method. The results showed that between the input parameters, power is the most effective factor on MRR. Furthermore, grit size and feed rate are the most effective factors on TWR and HOS.

Keywords: Engineering Ceramic, Ultrasonic Machining, Taguchi Method, Modal Analysis

Reference: Hoseini, S. M., and Akbari. J, “Drilling of engineering ceramics using combination of ultrasonic vibration and diamond slurry”, Int J of Advanced Design and Manufacturing Technology, Vol. 6/ No. 2, 2013, pp. 29-35.

Biographical notes: S. M. Hoseini received his MSc in mechanical engineering from Islamic Azad University, Science and Research Branch, Tehran, Iran in 2011. His current research focuses on advanced ceramics machining via ultrasonic vibration and abrasive grits. **J. Akbari** is an associate professor at School of Mechanical Engineering, Sharif University of Technology, Iran. He received his PhD from Chiba University (Chiba, Japan) in 1993. His field of research is on monitoring of grinding process of ceramic parts using acoustic emission. During 1993-95 he has been working in Seiko Instruments Inc., CNC Machine Tool Design Department. He has published more than 125 technical articles in these fields.

1 INTRODUCTION

Engineering ceramics due to their great properties such as high hardness, corrosion resistance, high wear resistance and chemical stability are superior among the common engineering materials which are good choice for industrial applications such as aerospace, automobile, electronics and computers [1]. Conventional machining of ceramics is difficult and uneconomical [2]. Processes like EDM and ECM that are depended on the electrical conductivity of the part, cannot be used for this kind of materials, therefore finding a new process for machining engineering ceramic which are very brittle is necessary.

Ultrasonic machining is a non-traditional process which is used for machining of both conductive and non-metallic materials by using abrasive grits. Meanwhile, UM does not make any changes in the metallurgical structure of material and is suitable for machining of materials with hardness higher than 40HRC [3, 4]. In this process an ultrasonic head accelerates the grits, which are commonly artificial diamond; so by striking to the workpiece surface with high speed, leads to material removal. Fig. 1 schematically shows the major components of an ultrasonic head in a drilling process. Precision drilling by use of ultrasonic method contains both the dimensional and shape precision, which is influenced by tool wear, grit size and machining time.

Adithan and Venkatesh reported that to a large extent the machining precision depends on grit size and to lesser extent on amplitude and static load; in addition, the hole over-size increases with increase in power and external slurry flow rate. They showed that oversize of the produced holes at the entry face were greater than at the exit face [5,6]. Zhang and Sun have investigated the effect of static load on MRR for alumina and zirconia ceramics and have suggested an optimal value. Generally, with increasing the static load, the MMR increases to some extent and then it decreases [7].

Kainth et al. in their work used another experimental setup, and achieved very similar results [8]. Jadoun et al. [2] investigated that high amplitude due to increasing power, increases TWR and HOS. Guzzo and Shinohara [9] showed that the material removal rate (MRR) decreased with increasing depth of cut for alumina. Kumar and Khamba demonstrated that the power and grit size were the most effective factors on MRR and TWR [10].

Up to now all research works on UM are concentrated on the constant load, nevertheless in this study the "constant feed rate" is used for the drilling of alumina ceramic. An acoustic head was installed on the ahead of a desktop CNC milling machine type DN333 produced by KAFA, used for drilling process. To determine the effects of input factors and their contribution and achieve optimum values, Taguchi technique is implemented for design of experiments as well as data analysis.

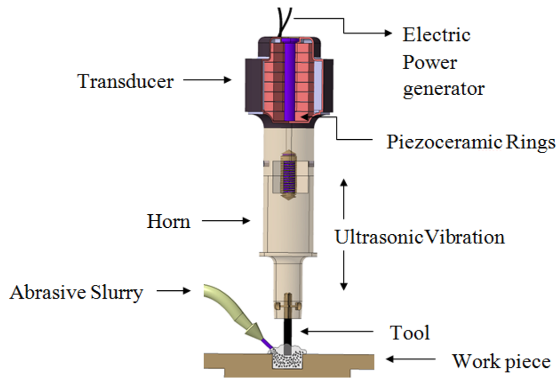

Fig. 1 Schematic view of a USM setup

2 EXPERIMENTAL PROCEDURES

2.1 Experimental setup and procedure

In this research, alumina ceramic which is created by hot iso-static pressing (HIP) method is used for the purpose of drilling process. Mechanical properties of the ceramic workpieces are presented in Table 1.

Table 1 Properties of alumina ceramic workpiece

Material	Al_2O_3
Hardness (HRC)	55
Density (g/cm^3)	3.1
Young module (GPa)	210-380
Dimensions (mm)	27.1 × 27.1 × 5

Drilling tool, consist of a high speed steel rod with 6mm in diameter and flat tip that is placed at the end of the ultrasonic head (Fig. 1). Tool tip is reshaped after each test by grinding process for insuring the tip flatness. Water which is a proper coolant is used as the intermediate liquid; water removes the debris from the machining area as well. Continuous flow of synthetic diamond particles slurry with different grain sizes between the tool gap and work piece were accelerated through the vibration tool. Accelerated abrasive grits via vibration tool causes material removing through impacting work piece. Concentration of abrasive slurry is chosen to be 3, 7 and 10 % respectively.

2.2 Modal analysis and horn design

For performing ultrasonic machining experiments, a horn and related fixture are designed and fabricated. Fig. 2 shows the experimental set-up fixed on the CNC machine tool. For electrical wave generation, MSG. 1200.IX Master Sonic generator is used. This generator changes the normal electrical power frequency of 60Hz to high frequency electrical pulses. The high frequency voltage is transformed to mechanical vibrations trough a piezoelectric transducer. The amplitude and energy is magnified and concentrated by horn, while it may be adjusted by changing the electrical power. Generator frequency ranges are between 17500 to 27500 Hz with the steps of 1Hz. To find the resonance frequency and optimum setup dimensions, FEM modal analysis is applied. Fig. 3 shows the longitudinal displacement diagram of the horn. Aluminum 7075-T6, due to its superior acoustic characteristics and fatigue resistance is used as the horn's material. In order to measure the vibration amplitude at the tool tip, a dial indicator with two micron accuracy is used. Fig. 4 shows the method of measuring vibration amplitude.

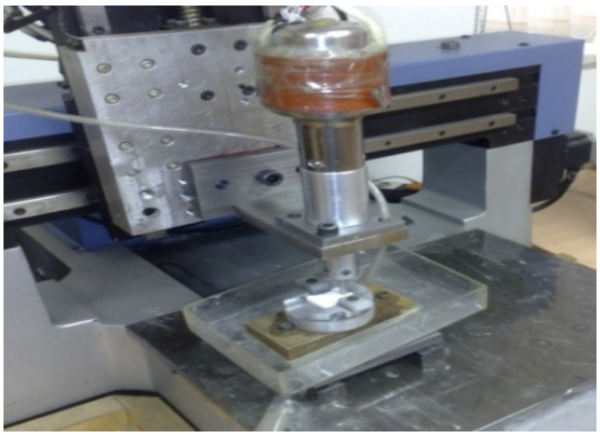

Fig. 2 Experimental set-up for ultrasonic machining

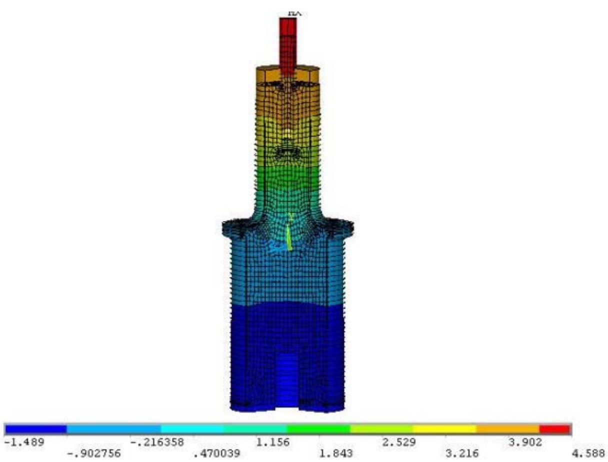

Fig. 3 Longitudinal amplification diagram of ultrasonic head

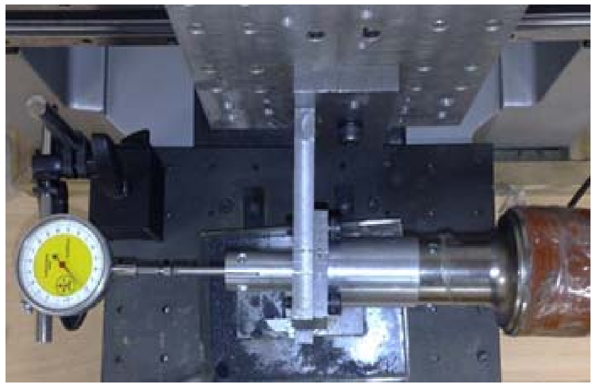

Fig. 4 Measuring method of vibration amplitude

2.3. Design of experiments (Taguchi´s technique)

In this study Taguchi method is used for the purpose of design of experiment and data analyses. Taguchi presents orthogonal arrays for planning of experiments. Minimum number of required experiments is determined by these arrays [11]. In this study, input factors are power (C1), grit size (C2), slurry concentration (C3), and feed rate (C4), which are presented in Table 2. According to the number of factors and levels, L9 orthogonal array is selected and the experiments are performed. Each test is repeated three times. The experimental results are shown in Table 3. Meanwhile the response diagrams of signal-to-noise ratio (S/N) for MRR, TWR, and HOS are presented in Figs. 5 to 7 respectively. These diagrams present the influence of simultaneous factors of machining process. The amounts of MRR and TWR are calculated through the reduction volume per unit time. Equations (1) and (2) are used so as to facilitate more accurate calculations under varying process conditions [10].

$$MRR= W_1-W_2/\rho.t \quad (1)$$

$$TWR= W_{t1}-W_{t2}/\rho_t.t \quad (2)$$

In the above equations, W_1 and W_2 are the initial weight and machined weight of workpiece respectively. W_{t1}, and W_{t2} indicate initial weight and the tool weight after erosion. ρ, ρ_t are density of the workpiece and tool in g/mm^3 respectively. Furthermore, t is the machining time. The entrance diameter of hole is measured by olympus tool maker. "Hole over-size" is the difference between the tool diameter and the hole diameter measured at the hole entry.

2.4. Data Analysis

The average quantities of results and signal-to-noise ratio are calculated for MRR, TWR and HOS in three levels, respectively. Signal-to-noise ratio plots for these three parameters are shown in Figures 5 to 7. In this research Minitab software is used for statistical analysis.

2.5. Analysis of variance

Tables 4 to 6 show the results of analysis of variance (ANOVA) for the MRR, TWR and HOS, respectively. ANOVA is a statistical analysis method which uses inspecting of the obtained results of variation, for predicting the best conditions of performance. ANOVA establishes the relative significance factors in terms of their percentage of contribution to the response. ANOVA is also needed for estimating the error variance for the effects and variance of the prediction error. This analysis is performed on signal-to-noise ratios to obtain the contribution of each of the factors. In these tables, SS is the sum of squares, DOF is the degrees of freedom, V is the variance, and P stands for the contribution percent [7]. According to the obtained results of quality characteristics, optimal values are determined and verified by the experimental tests shown in Table 7. Degree of freedom, Sum of Squares, Variance, Percent contribution of each factor are calculated by variance analysis and are organized as standard table shown in tables 4 to 6.

Table 2 Process parameters and their values at different levels

Parameters symbols	Process parameter	Level 1	Level 2	Level 3
C1	Power rating, W	16	22	35
C2	Grit size, μm	90	170	250
C3	Slurry concentration %	3	7	10
C4	Feed rate, mm/min	0.15	0.2	0.25

Table 3 Experimental results and related S/N ratios

Expt. no	Average of three responses			Signal-to-noise ratio (S/N)		
	MRR	TWR	HOS	MRR	TWR	HOS
T1	1.703	0.497	0.073	0.206	1.471	22.365
T2	2.081	0.013	0.133	5.712	36.154	17.243
T3	2.236	0.024	0.186	2.957	31.973	13.513
T4	3.8	0.054	0.146	9.214	23.666	16.589
T5	5.065	0.042	0.346	13.991	27.416	9.141
T6	5.881	0.054	0.3	14.940	24.024	10.219
T7	5.149	0.091	0.146	14.227	20.748	16.149
T8	3.401	0.027	0.226	10.541	31.057	12.025
T9	4.182	0.069	0.393	12.313	23.094	8.087

Table 4 Response diagram of S/N ratio for MRR

Summary of ANOVA for Material removal rate				
factors	DOF	SS	V	P %
A	2	183/706	91/851	81/83
B	2	9/621	4/810	4/29
C	2	5/336	2/668	2/38
D	2	25/835	12/917	11/5
Error	18	0	-	-
Total	26	224/499	28/062	100 %

Table 5 Response diagram of S/N ratio for TWR

Summary of ANOVA for Tool wear rate				
factors	DOF	SS	V	P %
A	2	6/498	3/240	0/82
B	2	413/324	206/662	52/3
C	2	139/881	69/940	17/70
D	2	230/685	115/342	29/18
Error	18	0	-	-
Total	26	790/389	98/796	100%

Table 6 Response diagram of S/N ratio for HOS

Summary of ANOVA for Hole over size				
factors	DOF	SS	V	P %
A	2	64/358	32/179	38/13
B	2	96/034	48/017	56/91
C	2	5/628	2/814	3/33
D	2	2/752	1/376	1/63
Error	18	0	-	-
Total	26	168/774	21/096	100%

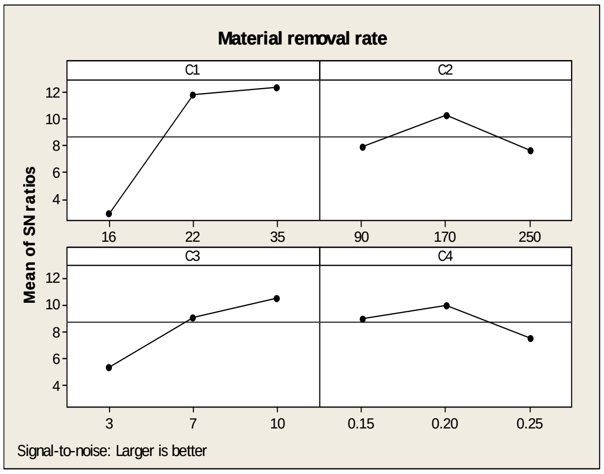

Fig. 5 Response diagram of S/N ratio for MRR

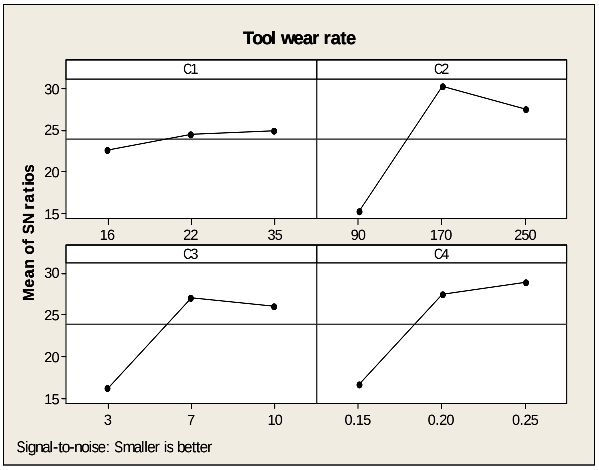

Fig. 6 Response diagram of S/N ratio for TWR

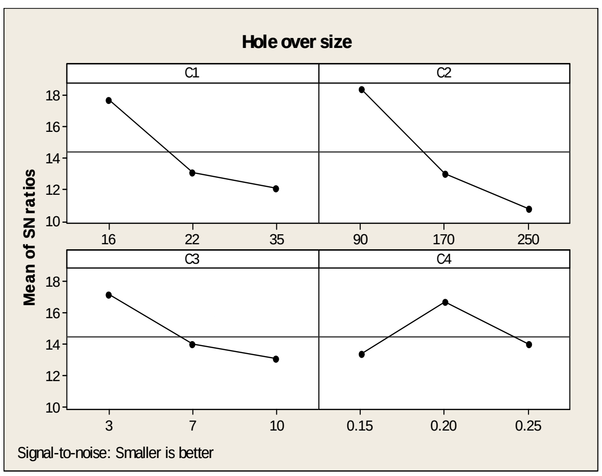

Fig. 7 Response diagram of S/N ratio for HOS

3 RESULTS AND DISCUSSION

In the ultrasonic machining of alumina ceramics, MRR, TWR and HOS are the main concerns. This article is based on the optimum condition for each factor with reference to Table 7 and Fig. 8 (a-b-c). According to the Fig. 5, increasing the power and abrasive particle concentration, the MRR increases, nevertheless this increase is dependent on feed rate. Increasing feed rate leads to more contact between the tool's tip and the workpiece. More contact causes losing gap between workpiece and tool, which necessitates spending more time to form gap again, which leads to increase in machining time.

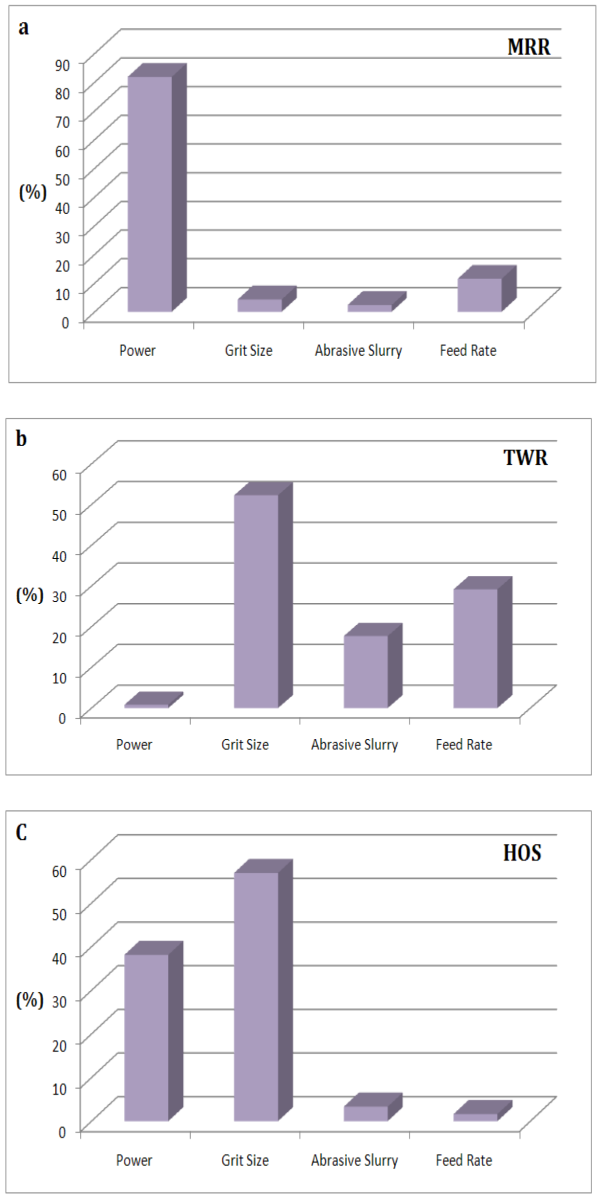

Fig. 8 Bar graphs showing percentage contributions of significant process parameters for MRR (a), TWR (b) and HOS (c)

Fig. 8-a shows significant contribution percentage of power and feed rate on MRR compared with other

factors. Fig. 8-a clearly shows that power and feed rate have the most contribution on the MRR. By increasing the feed rate, the MRR reduces because abrasive particles hardly reach to the machining area due to gap elimination. This also causes lateral material removing which results in hole over size. Therefore an optimal value for feed rate is necessary for reaching to the best MRR, where lower and higher feed rates may increase machining time.

As shown in Fig. 8-b, the greatest contributions are related to grit size and feed rate. As a matter of fact striking the abrasive particles to the tool, leads to tool erosion, however when the grit size is small, less tool wear is expected. Meanwhile, increasing the feed rate increases the contact between tool and workpiece, which results in higher TWR. By decreasing the feed rate, the contact between tool and workpiece becomes less, thus higher wear by the abrasive particles occurs.

Increasing slurry concentration causes increase in tool wear due to more abrasive particles. Higher abrasive particles in the slurry increase the contact between particles with each other and lead to more wear among particles. Therefore there is a certain level for particle concentration to provide a suitable tradeoff between TWR and the MRR.

In case of HOS, as shown in Fig. 8-c, higher contributions are related to grit size and power. HOS continuously increases with increase in power. This is due to the fact that power rating causes increasing lateral vibration. The impact of coarse abrasives with the tool results in higher wear rate that causes higher HOS.

Table 7 Optimal values of experimental results

Optimum Result	Power W	Grit size µm	Slurry concentration %	Feed rate mm/min
MRR = 4.964	35	170	10	0.2
TWR = 0.044	16	90	3	0.15
HOS = 0.120	16	90	7	0.15

4 CONCLUSION

In this study, the machining of alumina ceramic with the aid of ultrasonic vibrations and abrasive slurry is investigated. The FEM modal analysis is applied to find the resonance frequency and optimum dimensional setup as well as appropriate tool length. A desktop CNC milling machine is used to apply feed motion control on the ultrasonic head. The design and experiments analysis with Taguchi method is done and effects of each factor, percentage of contribution and the optimal levels in machining process are determined. The results are stated as follows:

- From ANOVA analysis, it is clear that feed rate has second significant effect on MRR and TWR.
- Appropriate feed rate along with increasing power, result in higher material removal rate. As indicated in Fig. 8-a, higher percentage of contribution relates to power and feed rate subsequently. The percentage contributions of factors in descending order for MRR are power rating: 81.83%, feed rate: 11.5%, grit size: 4.29 % and slurry concentration: 2.38%, respectively.
- As shown in Fig. 8-b abrasive grit size and feed rate have the most significant effect on TWR. The percentage contributions of factors in descending order for TWR are grit size: 52. 3%, feed rate: 29.18%, slurry concentration: 17.70% and power: 0.82 %, respectively.
- According to Fig. 8-c power and grit size are the most effective on HOS. The percentage contributions of factors in descending order for HOS are Grit size: 56. 91%, power: 38.13 %, slurry concentration: 3.33%, and feed rate: 1.63%, respectively.
- The specific amount of abrasive slurry concentration for MRR, TWR and HOS in machining process of alumina ceramic is shown in Figure 8.
- The optimal levels and conditions of various process parameters for maximum MRR, minimum TWR and HOS along with results are shown in table 7.

REFERENCES

[1] Deng, J., and Lee, T., “Ultrasonic machining of alumina-based ceramic composites”, Journal of the European Ceramic Society”, Vol. 22, 2002, pp. 1235-1241.

[2] Jadoun, R. S., Pradeep, Kumar, and Mishra, B. K., “Taguchi’s optimization of process parameters for production accuracy in ultrasonic drilling of, engineering ceramics”, Production Engineering, Vol. 3, No. 3, 2009, pp. 243-253.

[3] Ghahramani, B., and Wang, Z. Y., “Precision ultrasonic machining process: a case study of stress analysis of ceramic (Al2O3)”, Int. Journal of Machine Tools & Manufacture, Vol. 41, No. 3, 2001, pp. 1189-1208.

[4] Thoe, T. B., Apinwall, D. K., and Wise, M. L. H., “Review on ultrasonic machining”, Int. Journal Mach. Tools Manufacture, Vol. 38, No. 4, 1998, pp. 239-255.

[5] Adithan, M., and Venkatesh, V. C., “Production accuracy of holes in ultrasonic drilling”, Department of Mechanical Engineering Tribology, Vol. 40, 1976, Issue 3, pp. 309-318.

[6] Adithan, M. and Venkatesh, V. C., “Parameter influence on tool wear in ultrasonic drilling”, Department of Mechanical Engineering Tribology, Vol. 7, Issue 6, 1974, pp. 260-264.

[7] Zhang, Q. H., Zhang, J. H., Jia, Z. X., and Sun, J. L., “ Material removal rate analysis in the ultrasonic machining of engineering ceramics”, Journal of Materials Processing Technology, Vol. 88, Issue 1-3, 1999, pp. 180-184.

[8] Kainth, G. S., Nandy, Amitav and Singh, Kuldeep, “On the mechanics of material removal in ultrasonic machining”, Int. Journal MTDR, Pergamon, Vol. 19, 1979, pp. 33-41.

[9] Guzzo, P. L., and Shinohara, A. H., “A Comparative Study on Ultrasonic Machining of Hard and Brittle Materials”, Brazilian Manufacturing Congress, Vol. 26, No. 1, 2003, pp. 56-61.

[10] Kumar, V., and Khamba, J. S., “Parametric optimization of ultrasonic machining of co-based super alloy using the Taguchi multi-objective approach”, Production Engineering, Vol. 3, No. 4-5, 2009, pp. 417-425.

[11] Ranjit, R., “Design of experiments using the Taguchi approach: 16 steps to product and process improvement”, John Wiley & Sons, 2001, Chaps 5-6.