Experimental Study on Abrasive Water Jet Machining of PZT Ceramic

Ajit Dhanawade¹, Ravi Upadhyai¹, Arunkumar Rouniyar¹ and Shailendra Kumar¹,a

¹Department of Mechanical Engineering, S V National Institute of Technology, Surat-395007, India
²skbudhwar@med.svnit.ac.in

Abstract. This paper presents research work involved in abrasive water jet machining of PZT ceramic material. Process parameters namely stand-off distance, water pressure and traverse rate are considered in the present study. Response surface methodology approach is used to design the experiments. Relative significance of process parameters and their influence on kerf properties are identified on the basis of analysis of variance. It is found that water pressure and traverse rate are most significant parameters followed by stand-off distance. On the basis of experimental analysis, regression models are developed to predict kerf taper and depth of cut. The models are developed with respect to significant parameters, interaction and quadratic terms. It is found that model predictions are in congruence with experimental results. Multi-response optimization of process parameters is also performed using desirability approach in order to minimize kerf taper and maximize depth of cut. Kerf wall features of machined surfaces are observed using scanning electron microscope. The findings of present study are useful to improve kerf properties in abrasive water jet machining of PZT ceramic materials.

1. Introduction

Lead Zirconate Titanate (PZT) is a metallic oxide based piezoelectric material. It has excellent piezoelectric properties including high piezoelectricity, Curie temperature, spontaneous polarization, sensitivity, dielectric constants, wear and corrosion resistance, thermal resistance, etc. [1]. It is widely used in ultrasonic cleaners, ultrasonic imaging, sensors, actuators, dielectrics for capacitors, buzzers, accelerometer, hydrophones, and ultrasonic motors, etc. [2]. Many of these applications demand intricate shapes, tolerances, and precise dimensions. However, machining of this material is difficult due to its brittle nature and temperature sensitivity. Traditional machining such as turning, milling, drilling, and diamond saw cutting has many difficulties including high tool wear due to high hardness and strength, friction and vibration, poor surface quality and breakage of material during machining [3]. Also, low material removal rate by traditional machining results in high processing cost. Abrasive water jet machining (AWJM) is one of non-traditional machining processes extensively used in the manufacturing industries for material processing. The unwanted material of work piece is removed by the combined action of high speed abrasive water jet (AWJ). AWJ impinges on the surface of the workpiece and removes the material by means of erosion. The major difficulty in AWJM of ceramics is improper kerf properties [4]. Kerf properties include kerf top width, kerf bottom width, kerf walls...
and kerf taper. The kerf of AWJ machined workpiece is characterised by wide kerf top and narrow kerf bottom [5]. Consequently it results in high kerf taper as depicted in Figure 1.

Some researchers have applied their efforts to improve cutting performance of AWJM of ceramic materials. For example, Hocheng and Chang [6] experimentally studied mechanism of material removal, attainable depth of cut, kerf shape and surface roughness in AWJM of alumina oxide and silicon nitride ceramics. Chen et al. [7] investigated the influence of process parameters on the attainable depth of cut, depth of upper zone, kerf quality in AWJM of alumina ceramic. Mombör et al. [8] investigated material removal process and specific removal energy in AWJM of refractory ceramics. A set of process parameters was optimized for depth of cut and MRR. Gudimeta et al. [9] studied material removal mechanism and kerf characteristics in AWJM of alumina ceramic. Wang and Guo [10] experimentally studied multi-pass cutting in AWJM of alumina ceramic. Effect of number of passes, traverse rate and traverse direction on kerf profile, depth of cut, and surface roughness was studied. Wang and Liu [11] developed predictive models to estimate kerf taper angle, depth of cut, and kerf top width in AWJM of alumina ceramic. The effect of process parameters on kerf quality of alumina ceramic by using kerf taper compensation technique is investigated by Shanmugam and Masood [12]. Srinivasu and Axinte [13] experimentally studied the effect of jet impingement angle on kerf top width in AWJM of silicon carbide ceramic. Annoni et al. [14] experimentally studied the influence of process parameters on kerf taper and surface roughness in AWJM of thin PZT ceramic sheets. Huang et al. [15] studied effect of AWJM process parameters on surface quality of polished aluminium nitride ceramic material. Ghosh et al. [16] experimentally studied the effect of process parameters on surface roughness in AWJM of silicon nitride ceramic. Dittrich et al. [17] investigated influence of process parameters on kerf characteristics, attainable depth of cut and material removal rate in AWJM of alumina ceramic. Chithirai et al. [18] experimentally studied influence of process parameters on surface quality of AWJ machined alumina ceramic.

From the literature review, it is clear that most of the researchers have studied AWJM of ceramic materials including alumina ceramic, silicon nitride ceramic and aluminium nitride ceramic. Researchers have focused on influence of process parameters namely pressure, traverse rate, stand-off distance, abrasive mass flow rate etc. on kerf properties, material removal rate, machinability, etc. Very few researchers have applied their efforts to study kerf properties of AWJ machined PZT ceramic. In the present study, AWJM of PZT ceramic is carried out to investigate effect of process parameters on kerf taper and depth of cut. Second order mathematical models are developed to predict kerf taper and attainable depth of cut on the basis of analysis of variance (ANOVA) results. Also optimization of process parameters is performed to minimize kerf taper and maximize depth of cut.
2. Experimental work

A computer controlled flying arm AWJ machine is used for experiments. Pressure is controlled by dial indicator on pump having maximum pressure of 220 MPa. Throughout the experiments garnet abrasives of mesh #80 size are used, delivered through gravity feed hopper to the nozzle. The nozzle diameter, orifice diameter, impingement angle and focusing length were kept constant at 0.76 mm, 0.25 mm, 90° and 70 mm respectively. The properties of workpiece material (PZT-5H) are given in Table 1. The thickness of workpiece material was 16 mm. This material is used further to manufacture ceramic matrix composite of around 14-15 mm thickness.

| Table 1. Properties of workpiece material |
| Property         | Value |
|------------------|-------|
| Density (kg/m³)  | ρ     | 7500 |
| Elastic compliance (x 10⁻¹² m²/N) | E₁₁ | 15 |
| Dielectric constant | K₃   | 3250 |
| Mechanical quality factor | Q_M | 65 |
| Electrical quality factor | Q_E | 40 |
| Curie Temp. (°C) | T_c  | 190 |

2.1 Experimental design

Central composite design (CCD) of response surface methodology (RSM) is used to design experiments. Experimental design includes 8 factorial runs, 6 axial runs and 6 centre points. Therefore, total 20 experiments are carried out according to the combinations suggested by Design Expert v10 software. Process parameters namely stand-off distance, water pressure and traverse rate are considered. Levels of process parameters as listed in Table 2 are selected on the basis of literature review, trial experiments and available machine setup range. Experiments are performed according to given parameter combinations [19].

| Table 2. Machining Parameters and selected levels |
| Parameter                     | Level |
|-------------------------------|-------|
| Stand-off distance (SOD) mm   | -1 0 1 |
| Water pressure (WP) MPa       | 140 150 160 |
| Traverse rate (TR) mm/min     | 310 320 330 |

2.2 Measurement of kerf taper and depth of cut

After experimentation kerf widths and depth of cut are measured by using vision measurement system (Model- Sipcon SDM-TRZ 5300). Further kerf taper angle is calculated by using equation (1).

\[ \theta = \tan^{-1} \left( \frac{W_t - W_b}{2t} \right) \]  

(1)

Where, \( W_t \) = Top kerf width (mm)
\( W_b \) = Bottom kerf width (mm)
\( t \) = Thickness (mm)

3. Predictive models

The regression models are developed to predict kerf taper and depth of cut.
3.1 Kerf taper

3.1.1 ANOVA. Table 3 gives the ANOVA results for kerf taper. The analysis is carried out at 95% confidence level. The model is significant with F-value of 185.48. Traverse rate and water pressure are found most significant parameters followed by stand-off distance. Interactions between SOD-WP and WP-TR are significant. Likewise, quadratic terms of SOD and TR are significant.

| Source   | SS   | DoF | MS   | F       | p     |
|----------|------|-----|------|---------|-------|
| Model    | 3.46 | 7   | 0.49 | 185.48  | < 0.0001|
| A-SOD    | 0.94 | 1   | 0.94 | 351.81  | < 0.0001|
| B-WP     | 1.03 | 1   | 1.03 | 387.36  | < 0.0001|
| C-TR     | 1.21 | 1   | 1.21 | 452.96  | < 0.0001|
| AB       | 0.029| 1   | 0.029| 10.72   | 0.0067 |
| BC       | 0.035| 1   | 0.035| 12.94   | 0.0037 |
| A²       | 0.15 | 1   | 0.15 | 56.09   | < 0.0001|
| C²       | 0.11 | 1   | 0.11 | 40.82   | < 0.0001|
| Residual | 0.032| 12  | 2.667 x 10⁻³ |       |       |
| Lack of Fit | 0.020 | 7 | 2.925 x 10⁻³ | 1.27   | 0.4103 |
| Pure Error | 0.012 | 5 | 2.305 x 10⁻³ |       |       |
| Corrected Total | 3.49 | 19 | | | |

The regression model is developed with respect to significant terms. The final regression equation for kerf taper in terms of coded factors is as given in equation (2).

\[
\text{Kerf taper} = 91.481 + 0.686 \text{SOD} - 0.218 \text{WP} - 0.482 \text{TR} - 5.976 \times 10^{-3} \text{SOD WP} + 6.568 \times 10^{-4} \text{WP TR} + 0.0753 \text{SOD}^2 + 6.43 \times 10^{-4} \text{TR}^2
\]  

(2)

The predicted and adjusted R² value of 0.9720 and 0.9855 reveals reasonable agreement. It is found that predicted results are in congruence with the experimental results as depicted in the Figure 2. The equation is useful to predict kerf taper.

![Figure 2. Predicted vs actual values of kerf taper](image)
3.1.2 Influence of process parameters on kerf taper. Figure 3 depicts effect of water pressure and stand-off distance on kerf taper. It is observed that increasing water pressure causes decrease in kerf taper. Increase in pressure results in increase in kinetic energy. The jet with increased kinetic energy cuts the material at bottom region which results in minimum kerf taper. Also it causes increase in effective diameter of the jet. It results in wide bottom width which consequently reduces kerf taper. It is observed that kerf taper increases with increase in stand-off distance. It is due to the fact that flaring of water jet occurs when it comes out of nozzle. It reduces cutting ability of jet and results in increased kerf taper.

![Figure 3. Effect of SOD and WP on kerf taper](image)

Effect of water pressure and traverse rate on kerf taper is shown in Figure 4. It is observed that kerf taper increases with an increase in traverse rate. The reason behind this is high traverse rate reduces jet interaction on a given area of material. It causes material erosion by less number of abrasive particles and results in high kerf taper.

![Figure 4. Effect of WP and TR on kerf taper](image)

3.1.3 Kerf quality. Kerf geometries of four samples machined by setting parameters as given in Table 4 are shown in Figure 5. It is observed that kerf geometry of samples is characterized by round top edge. However, it is observed that roundness of top edge of sample 2 is more as compared to sample 1. This is due to an increase in stand-off distance which increases flaring of jet and results in rounding of top edge. It is also observed that rounding of top edge is more in sample 3 as compared to sample 4. This is due to increase in water pressure of sample 4. Kinetic energy increases with increase in pressure and minimizes stray abrasive particles, which results in sharp kerf edges. In non-through cuts,
ballooning effect is observed at bottom region. This effect occurs due to jet deflection, as there is no passage for water jet to flow.

Table 4. Parametric combinations of samples 1 to 4

| Sample | SOD (mm) | WP (MPa) | TR (mm/min) |
|--------|----------|----------|-------------|
| 1      | 1        | 150      | 320         |
| 2      | 5        | 150      | 320         |
| 3      | 2        | 140      | 330         |
| 4      | 2        | 160      | 330         |

Figure 5. Kerf geometry of (a) Sample 1 (b) Sample 2 (c) Sample 3 (d) Sample 4

3.2 Depth of cut

3.2.1 ANOVA. Table 5 gives ANOVA results of depth of cut.

Table 5. ANOVA for depth of cut

| Source    | SS   | DoF | MS   | F     | p      |
|-----------|------|-----|------|-------|--------|
| Model     | 7.86 | 4   | 1.97 | 103.01| < 0.0001|
| A-SOD     | 0.86 | 1   | 0.86 | 45.11 | < 0.0001|
| B-WP      | 5.12 | 1   | 5.12 | 268.10| < 0.0001|
| C-TR      | 1.63 | 1   | 1.63 | 85.63 | < 0.0001|
| B²        | 0.25 | 1   | 0.25 | 13.20 | 0.0025 |
| Residual  | 0.29 | 15  | 0.019|       |        |
| Lack of Fit| 0.17 | 10  | 0.017| 0.75  | 0.6716 |
| Pure Error| 0.11 | 5   | 0.023|       |        |
| Cor Total | 8.15 | 19  |      |       |        |

From ANOVA results, it is observed that model is significant with F value of 103.01. It is found that water pressure is most significant parameter followed by traverse rate and stand-off distance. Quadratic term of water pressure is also significant. No interaction term is significant. From ANOVA results, a regression model is developed with respect to significant terms. The final regression in terms of actual factors is given in equation (3).

\[
\text{Depth of cut} = -4.345507352941 - 0.2319375 \times \text{SOD} + 0.34518345588235 \times \text{WP} - 0.0319562 \times \text{TR} - 0.00096213235294117 \times \text{WP}^2
\]  

(3)
The predicted $R^2$ value of 0.9260 is in reasonable agreement with adjusted $R^2$ value of 0.9555. The equation is useful to predict depth of cut. The predicted values of depth of cut are in congruence with experimental values as shown in Figure 6.

3.2.2 Influence of process parameters on depth of cut. The variation in depth of cut according to experimental combinations is shown in Figure 7.

Figure 8 depicts effect of water pressure and stand-off distance on depth of cut. Increase in water pressure results in increase in kinetic energy of jet. The jet with high kinetic energy penetrates deep in the material. It increases the depth of cut. Increase in stand-off distance results in flaring of AWJ. It reduces the cutting ability of jet. Therefore increase in stand-off distance reduces depth of cut. Figure 9 shows effect of traverse rate and water pressure on depth of cut. High traverse rate reduces number of abrasive particles impingement on material. It also results in less overlapping of machining action. Therefore increase in traverse rate results in decrease in depth of cut.
3.2.3 *Kerf wall features.* Scanning electron microscope (SEM) is used to analyse kerf wall features of machined samples. SEM image of machined surface at three different regions i.e. top, middle and bottom are shown in Figure 10 [20]. It is observed that surface is damaged at jet entry; however it becomes smooth in middle. At jet exit, surface is rough along with striations. Wear tracks in the form of brittle fracture are observed in top region as shown in Figure 10. Also some damages are observed in the form of micro cracking and inter-granular fracture. This is due to low impact angle of AWJ. Also jet deflection results in micro cracking at this region. Smooth surface is observed in bottom region as shown in Figure 10. Some abrasive wear tracks are observed at this region due to stray abrasive particles. Minimum surface waviness is observed in this region due to steady AWJ. Long wear tracks are observed in bottom region of machined sample as shown in Figure 10. The damage of surface is observed along with micro cracks. Striations are observed at this region. This is due to the low kinetic energy of AWJ which tends to follow the path with least resistance.
4. Multi-response optimization using desirability function

In the present study, a set of process parameters is optimized to minimize kerf taper and maximize depth of cut. The optimization is performed on the basis of desirability function. A dimensionless measure of response i.e. composite desirability function on the basis of desirability analysis technique is used for multiple responses. In this approach each response is converted into a desirability function \(d_f\) and it is bounded by \(0 \leq d_f \leq 1\). The optimum values of stand-off distance, water pressure and traverse rate are obtained on the basis of statistical analysis in Design Expert v10 software. Optimized set of these process parameters gives a combination of levels which simultaneously fulfils optimization criteria for each response. Table 6 gives criteria for optimization.

| Factor     | Goal  | Lower limit | Upper limit | Optimized value |
|------------|-------|-------------|-------------|-----------------|
| SOD        | In range | 2           | 4           | 2               |
| WP         | In range | 140         | 160         | 160             |
| TR         | In range | 310         | 330         | 310             |
| Kerf taper | Minimize | 1.1983      | 2.802       | 1.223           |
| Depth of cut | Maximize | 13.415      | 16.015      | 15.883           |
Bar graph for desirability of all factors and responses is shown Figure 11. This graph shows how well each factor satisfies the criteria and desirability of responses. Desirability value of all factors is 1. Desirability values of kerf taper, depth of cut and combined are 0.985, 0.949 and 0.967 respectively. Desirability variations with respect to WP and SOD are shown in Figure 12, when TR is at optimum level. Predicted value of desirability is 0.967 (approximately 1) which shows that process is most efficient at these operating conditions. Figures 13 and 14 show predicted values of kerf taper (1.223) and depth of cut (15.883) respectively at optimum levels. These figures are very useful to check how individual response behaves in the vicinity of optimum condition.
5. Conclusion

Plausible trends of kerf taper and depth of cut in AWJM of PZT ceramic have been analysed in the present work. Following are the findings of the present study-

(i) Traverse rate and water pressure are the most significant factors followed by stand-off distance to control kerf taper.

(ii) Kerf taper decreases with increase in water pressure and decrease in traverse rate and stand-off distance.

(iii) Water pressure is most significant parameter followed by traverse rate and stand-off distance to control depth of cut.

(iv) Depth of cut increases with increase in water pressure and decrease in stand-off distance and traverse rate.

Regression models are developed to predict kerf taper and depth of cut. It is found that model predictions are in good agreement with experimental results. The percentage error between predicted and experimental results is around 5. Further multi-response optimization of process parameters is performed to minimize kerf taper and maximize depth of cut.

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