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AN EXPERIMENTAL STUDY OF KERF PROPERTIES OF LEAD ZIRCONATE TITANATE CERAMIC MACHINED BY ABRASIVE WATER JET MACHINING

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ABSTRACT

The present paper describes the experimental study of kerf properties in abrasive water jet machining of lead zirconate titanate ceramic material. Process parameters namely traverse rate, water pressure and stand-off distance are considered in the present study. Design of experiments is performed on the basis of response surface methodology to investigate the influence of process parameters on kerf taper. Further, analysis of variance is performed in order to identify significance and influence of process parameters on kerf taper. It is found that traverse rate and water pressure are most significant parameters followed by stand-off distance. On the basis of experimental analysis, a second order mathematical model is developed to predict kerf taper. Model predictions and experimental results are found in reasonable agreement. Lastly optimization of process parameters is performed to minimize kerf taper.

Key words: *Abrasive water jet Machining, lead zirconate titanate ceramics, kerf properties, optimization.*

1. Introduction

Ceramic materials are widely used in high performance applications in various fields including structural, semiconductor, micro electro mechanical systems, medical, defence, aerospace and electronics. Last three decades have seen interest in ceramic materials due to its properties such as high hardness, wear resistance, brittleness, oxidation resistant and specific strength [1]. An unusual property exhibited by few advanced ceramic materials is piezoelectricity such as barium titanate, lead titanate and lead zirconate titanate (PZT). PZT is used in variety of sensors, actuators and transducers. It has excellent piezoelectric properties, high Curie temperature, spontaneous polarization, sensitivity, wear and corrosion resistance [2]. Conventional machining showed limitations such as excessive tool wear, friction, vibration, poor surface quality and chipping-off of material due to its brittle nature, high hardness and strength [3]. AWJM is widely used in industries for machining of different hard to cut materials. It uses a high speed water jet to transfer the momentum and accelerate the abrasive particles.

High speed abrasive water jet (AWJ) impinges on the workpiece to remove the material by means of erosion. Abrasive water jet machining (AWJM) offers various advantages such as low cutting forces, no thermal distortion, environmental friendly and high flexibility [4]. Kerf taper is a major difficulty during AWJM, due to wider kerf at top region than bottom region [5]. A non through cut is characterized by three regions namely upper smooth zone, striation zone and jet upward deflection zone as shown in Fig. 1. In AWJM, hydraulic pressure, traverse rate, stand-off distance, abrasive flow rate are major process parameters. Kerf top width has a higher value as compared to the bottom region.

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] performed

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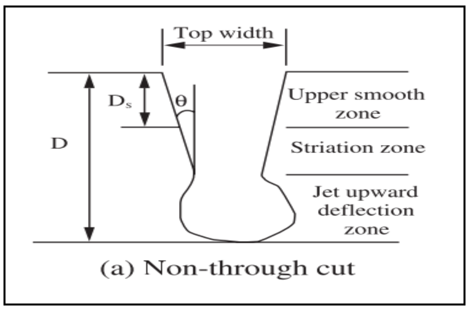

Fig. 1 Schematic diagram of AWJ machine kerf [5]

Experiments to investigate the influence of process parameters on the attainable depth of cut, depth of upper zone, kerf quality in AWJM of alumina ceramic. Momber 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. Gudimetla et al. [9] investigated 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 et al. [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. Dhanawade and Kumar [19] experimentally investigated surface roughness of AWJ machined carbon fiber reinforced polymer.

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. A second order mathematical model is developed to predict kerf taper. Also optimization of selected process parameters is performed to minimize kerf taper. The experiments for present research work are designed by response surface method. Optimization of process parameters is done by desirability approach. Some machined samples are examined under scanning electron microscope and vision measurement system.

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 focussing length were kept constant at 0.76 mm, 0.25 mm, 90^0 and 70 mm respectively. For the present study, workpiece material PZT-5H of 16 mm thickness is taken. The properties of this ceramic material are given in Table 1.

Table 1. Properties of PZT ceramic

Property		Value
Density (kg/m3)	ρ	7500
Elastic compliance	$_SE_{11}$	15
(x 10^{-12} m^2/N)	$_SE_{33}$	21
Dielectric constant	K^T_3	3250
Mechanical quality factor	Q_M	65
Electrical quality factor	Q_E	40
Curie Temp. (°C)	T_c	190

2.1 Experimental design

Response surface methodology (RSM) with central composite design 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 the design suggested by Design expert 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.

Table 2. Machining Parameters and selected levels

Parameter	Level				
	-2	**-1**	**0**	**1**	**2**
SOD (mm)	1	2	3	4	5
WP (MPa)	130	140	150	160	170
TR (mm/min)	300	310	320	330	340

2.2 Measurement of Kerf Taper

After experimentation kerf widths are measured by using vision measurement system (Model- Sipcon SDM-TRZ 5300). Bottom kerf width measurement is taken at the constant height of 9 mm from top to avoid ballooning effect. Further kerf taper angle is calculated by using Equation 1.

$$\theta = \tan^{-1} (W_t - W_b)/2t \qquad \ldots\ldots\ldots\ldots\ldots 1$$

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

3. Predictive Model

3.1 ANOVA for kerf taper

Table 3 shows the ANOVA for kerf taper. The analysis is carried out at 95% confidence level. The significance of model can be verified by 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.

3.2 Predictive Model for Kerf Taper

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.

$$\text{Kerf taper} = 1.86 + 0.24A - 0.25B + 0.27C - 0.060AB + 0.066BC + 0.075A^2 + 0.064C^2 \qquad \ldots\ldots\ldots\ldots 2$$

The predicted and adjusted R^2 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 Fig. 2. The equation is useful to predict kerf taper. It is also useful to identify relative impact of the factors by comparing the factor coefficients.

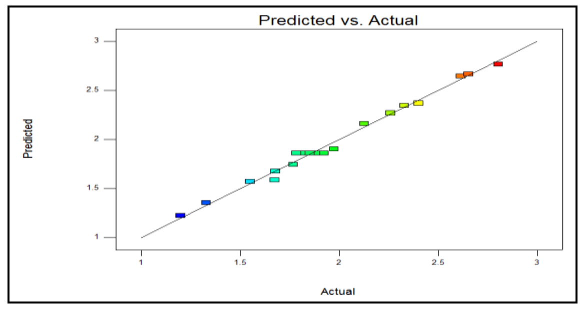

Fig. 2 Predicted vs. Actual values of kerf taper

4. Result and Discussion

Effect of water pressure and stand-off distance on kerf taper as plotted by the software is shown in Fig. 3. 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.

Table 3.ANOVA for kerf taper

Source	Sum of Squares	Degree of freedom	Mean Square	F-value	p-value	Remark
Model	3.46	7	0.49	185.48	< 0.0001	Significant
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	
A^2	0.15	1	0.15	56.09	< 0.0001	
C^2	0.11	1	0.11	40.82	< 0.0001	
Residual	0.032	12	2.667×10^{-003}			
Lack of Fit	0.020	7	2.925×10^{-003}	1.27	0.4103	Insignificant
Pure Error	0.012	5	2.305×10^{-003}			

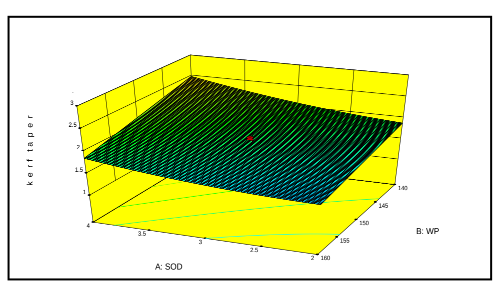

Fig. 3 Effect of SOD and WP on kerf taper

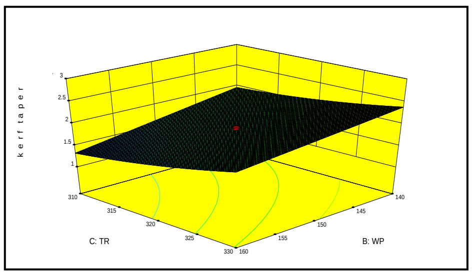

Fig. 4 Effect of WP and TR on kerf taper

Effect of water pressure and traverse rate on kerf taper is plotted as shown in Fig. 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.

5. Kerf Quality

Kerf geometries of four samples machined by setting parameters as given in Table 4 are shown in Fig. 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.

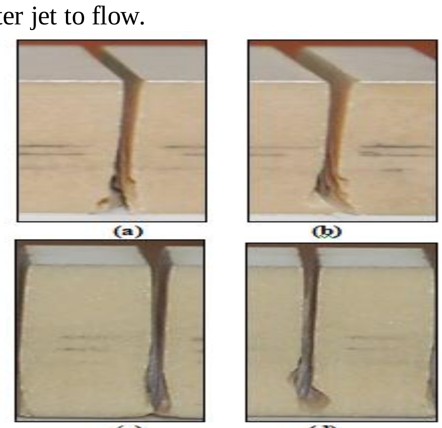

Fig. 5 Kerf geometry of (a) Sample 1 (b) Sample 2 (c) Sample 3 (d) Sample 4

Table 4.Parametric combinations of samples

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

Microscopic images of kerf top of four samples machined by setting parameters as given in Table 5 are shown in Fig. 6. It is observed that increase in stand-off distance deteriorates top edge as shown in Fig. 6. However, it is observed that top edge of sample 6 is more deteriorated as compared to sample 5. This is due to increased stand-off distance of sample 6. Increasing stand-off distance causes increase in stray particles in outer layer of jet, which results in deterioration of the top edge. It is observed that increase in water pressure improves the top edge quality. It is observed that top edge of sample 7 is more deteriorated as compared to sample 8 due to low pressure.

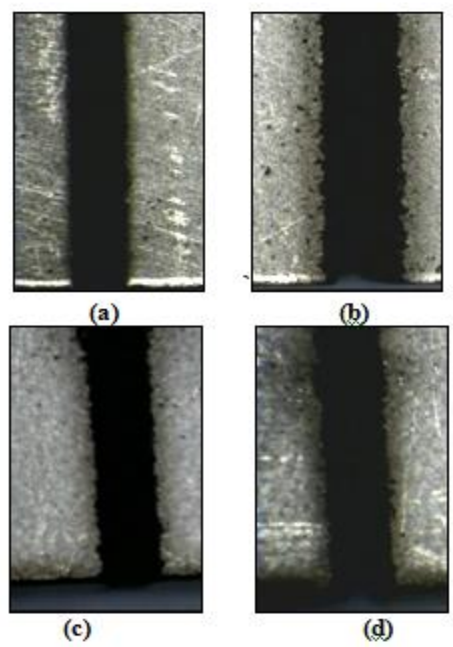

Fig. 6 Microscopic images of kerf top (a) Sample 5 (b) Sample 6 (c) Sample 7 (d) Sample 8

Table 5.Parametric combinations of samples

Sample	SOD (mm)	WP (MPa)	TR (mm/min)
5	1	150	320
6	5	150	320
7	3	130	320
8	3	170	320

Fig. 7 Different machined sample

Some small cracks are observed at jet entry as shown in Fig. 7. The cracks occur due to brittle nature of material. As high speed AWJ impinges on workpiece, due to impact and brittle nature of material small fractures occur at lead in area.

6. Optimization of Process Parameters

In the present study, a set of process parameters is optimized to minimize kerf taper. The optimization is performed on the basis of desirability function. Table 6 shows criteria for optimization.

Table 6.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

Bar graph for desirability of all factors and kerf taper is as shown Fig. 8. This graph shows how well each factor satisfies the criteria and desirability of response. Desirability value of all factors is 1. Desirability value of kerf taper is 0.985.

Desirability variations with respect to WP and SOD are shown in Fig. 9, when TR is at optimum level. Predicted value of desirability is approximately 1 which shows that process is most efficient at these operating conditions.

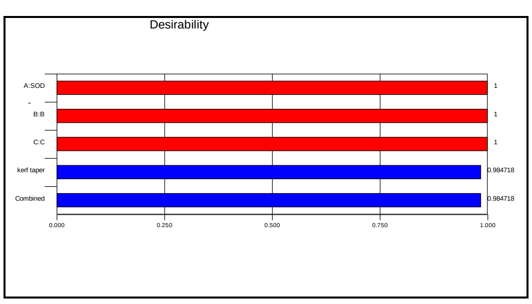

Fig. 8 Bar graph of desirability

7. Conclusions

An experimental study on AWJM of PZT ceramic is performed in the present work. The findings of the present study are following.-

(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.

Predictive model is developed to estimate kerf taper. It is found that model predictions are in good agreement with experimental results. Further optimization of process parameters is performed to minimize kerf taper.

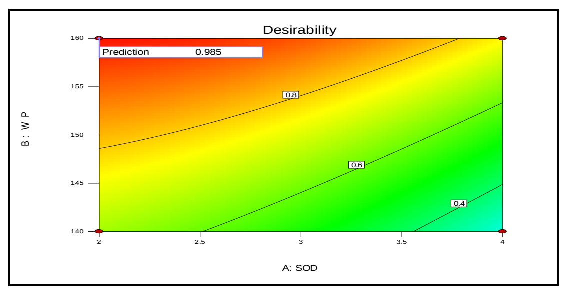

Fig. 9 Desirability value with optimum levels

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