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AN INVESTIGATION ON SURFACE ROUGHNESS IN ABRASIVE WATER JET MACHINING OF PZT CERAMIC

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ABSTRACT

The present paper describes the research work involved in experimental study of abrasive water jet machining (AWJM) of lead zirconate titanate (PZT) ceramic. Influence of three process parameters namely stand-off distance, water pressure and traverse speed on surface roughness of machined samples is studied. Response surface methodology approach is used to plan the design of experiments. Relative significance of process parameters and their influence on surface roughness are identified on the basis of analysis of variance. It is found that water pressure and stand-off distance are most significant parameters followed by traverse speed. Some machined surfaces are observed by using scanning electron microscope. On the basis of experimental analysis, a regression model is developed to predict surface roughness. The model is developed with respect to significant parameters, interaction and quadratic terms. Model predictions are in congruence with experimental results. Optimization of process parameters is also performed on the basis of desirability approach in order to minimize surface roughness.

Keywords: *Abrasive water jet machining, lead zirconate titanate, surface roughness, optimization.*

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1. Introduction

Ceramic materials are inorganic, non-metallic materials made from compounds of metals and non-metals. Ceramic materials are useful due to properties including high hardness and specific strength and wear resistance. Nowadays, ceramics have been used in optical, electronic, mechanical and biological industries [1]. Lead Zirconate Titanate (PZT) ceramic is a metallic oxide-based piezoelectric ceramic. PZT ceramic exhibits high ferroelectric and piezoelectric properties, high Curie temperature, high sensitivity and constant dielectric [2]. It is widely used in science and technology applications such as undersea exploration, aerospace, telecommunication, automotive, oil exploration etc. Traditional machining of PZT ceramic is difficult due to high hardness and compressive strength, brittle and temperature sensitive nature. It leads to machining difficulties such as excessive tool wear, lack of dimensional accuracy, high cutting forces and temperatures and poor surface finish [3]. Abrasive water jet machining (AWJM) is non-traditional machining process used in industry for machining of different hard to cut materials including ceramics and composites. Fig. 1 shows the schematic of AWJM setup.

In AWJM, high velocity abrasive water jet (AWJ) impinges on workpiece and material removal takes place by means of erosion. AWJM offers advantages like no heat generation, reduced setup time, high machining versatility and ability to produce complex 2D contours [4,5]. AWJM process is viable option to machine ceramic materials because of no interface temperature and thermal distortion.

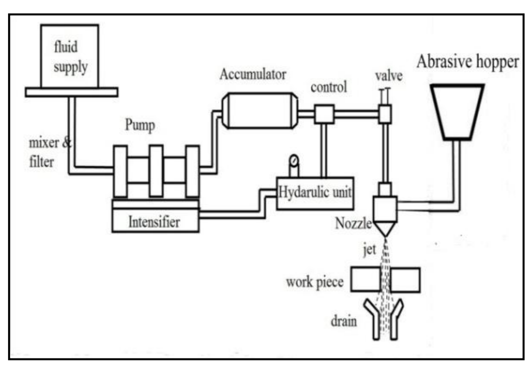

Fig. 1 AWJM setup [6]

Some researchers have carried out AWJM of ceramic materials to investigate the influence of process parameters on cutting performance.

For example, Chen et al. [7] experimentally investigated the influence of process parameters on

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attainable depth of cut in AWJM of alumina ceramic. Paul et al. [8] studied the mechanism of material removal rate in AWJM of polycrystalline ceramic. Kahlman et al. [9] studied the wear behaviour by low impingement angle in AWJM of silicon carbide ceramics. Wang and Liu [10] investigated the effect of process parameters on various cutting performance measures such as depth of cut and kerf taper in AWJ profile cutting of alumina ceramic. Wang and Guo [11] studied the influence of process parameters on kerf quality and depth of cut in multi pass AWJM of alumina ceramics. Srinivasu et al. [12] investigated the effect of process parameters on kerf width and depth of cut in AWJM of silicon carbide ceramic. Wang [5] developed a regression model of attainable depth of cut in AWJ contouring of alumina ceramics. Annoni et al. [13] experimentally studied the influence of process parameters on kerf taper and surface roughness in AWJM of thin PZT ceramic sheets. Filip and Bulea [14] studied the effect of process parameters on surface roughness and deviation in linear AWJ cutting of aluminium oxide ceramic. Yue et al. [15] adapted the experimental procedure of radial mode AWJ turning to minimize surface roughness and improve material removal rate of alumina ceramic. Santhanakumar et al. [16] investigated the influence of process parameters on surface roughness and kerf taper in AWJM of ceramic tiles. Dhanawade and Kumar [17] studied the effect of process parameters on surface roughness in AWJM of carbon fiber reinforced polymer.

Worldwide researchers have investigated AWJM of some ceramic materials including alumina ceramic, silicon carbide ceramic and aluminium oxide ceramic. Researchers have focused on influence of process parameters such as water pressure, stand-off distance, abrasive mass flow rate and traverse speed on kerf properties, material removal rate, depth of cut, etc. Very less work has been reported on AWJM of PZT ceramic. In the present study, influence of process parameters namely water pressure, stand-off distance and traverse speed on surface roughness in AWJM of PZT ceramic is studied. Regression model is developed to predict surface roughness. Scanning electron microscope is used to analyze some machined surfaces. Also a set of process parameters is optimized to minimize surface roughness.

2. Present Experimental Work

For the present study, experiments are performed on a computer controlled flying arm AWJ machine. The machine is equipped with high pressure pump with maximum pressure up to 220 MPa. Garnet abrasives of mesh size #80 are used throughout the experiments. Abrasives are supplied through gravity feed abrasive hopper. The orifice diameter, nozzle diameter, focusing tube and impingement angle were kept constant at 0.25 mm, 0.76 mm, 70 mm and 90^0 respectively. The workpiece used in this experimental work is PZT-5H ceramic. The thickness of workpiece is 16 mm. The properties of PZT-5H ceramic such as density, elastic compliance, mechanical quality factor, electrical quality factor, dielectric constant and Curie temperature are 7500 kg/m^3, 21*10-12 m^2/N, 65, 40, 3250 and 190° C respectively.

2.1 Experimental design

For the present study, machining parameters and their levels as listed in Table 2are selected on the basis of literature review, set-up range of available machine and trial experiments.

Table 2. Selected Machining parameters and their levels

Machining Parameters	Range and Levels				
	-2	**-1**	**0**	**1**	**2**
Stand-off Distance (SOD) (mm)	1	2	3	4	5
Water pressure (WP) (MPa)	140	160	180	200	220
Traverse speed (TS) (mm/min)	30	50	70	90	110

Abrasive mass flow rate was kept constant at 3 g/sec. Central composite design (CCD) of RSM is used to design experiments. CCD gives total 20 experiments according to selected parameters.

Experimental design includes 8 experiments as factorial points, 6 as axial points and 6 as center points experiments, therefore design gives 20 experiments. The machining of samples is performed on AWJM setup for 20 runs given by design of experiments. Further surface roughness of samples at three different region i.e. top, middle and bottom are measured by surface roughness tester.

2.2 Surface roughness measurement

Surface roughness tester SURFTEST (Model-Mitutoyo SJ- 210) is used to measure surface roughness of machined samples. A cone shaped diamond stylus having tip angle of 90^0 and diameter of 5 µm is used. Throughout the measurement cut off length as 0.8 mm, total sampling length as 4 mm and traverse speed as 0.5 mm/s were kept constant. In this process, surface roughness values at three different regions i.e. top, middle and bottom are measured. Further average surface roughness values (Table 3) are taken for analysis.

3. Predictive Model

3.1 ANOVA for surface roughness

Analysis of variance (ANOVA) is performed using Design Expert software v10 to evaluate the statistical significance of process parameters on surface roughness. Table 4 shows the ANOVA for surface roughness. The analysis is carried out at 95% confidence level. From ANOVA results it is clear that model has F-value of 95.60.It indicates that the model is significant. Since p-value of SOD, WP and TS is less than significance level i.e. 0.05, SOD, WP and TS have passed the test of significance for surface roughness. WP and SOD are most significant parameters followed by TS. Among interaction terms, interactions between SOD - WP, WP - TS are significant. Likewise quadratic terms of SOD and WP are significant.

3.2 Predictive model for surface roughness

The regression equation to predict surface roughness is developed in terms of significant terms. The regression equation depends upon linearity and additivity of relationship between dependent and independent variables, statistical independence and homoscedasticity of the errors and normality of the error distribution. Equation 1 gives regression model in terms of coded factors.

Table 3. Experimental and predicted values of surface roughness

Sr. No.	Surface roughness		
	Experimental	Predicted	Percentage Deviation
1	2.427	2.435	-0.329
2	3.041	3.028	0.427
3	2.209	2.202	0.317
4	2.280	2.239	1.798
5	2.529	2.583	-2.135
6	3.189	3.177	0.376
7	2.527	2.553	-1.029
8	2.617	2.591	0.994
9	2.480	2.438	1.694
10	3.023	3.068	-1.488
11	2.871	2.851	0.697
12	2.010	2.032	-1.095
13	2.382	2.355	1.133
14	2.928	2.855	2.493
15	2.623	2.605	0.686
16	2.542	2.605	-2.478
17	2.654	2.605	1.846
18	2.568	2.605	-1.441
19	2.555	2.605	-1.957
20	2.582	2.605	-0.891

Surface roughness (SR) = $+2.61 + 0.16A - 0.20B + 0.12C - 0.14AB + 0.051BC + 0.037A^2 - 0.041B^2$ ----- 1

R^2 predicted value of 0.9386 is in reasonable agreement with the R^2 adjusted value of 0.9721. The R2 values indicate that the model is adequate in predicting the surface roughness. The model predictions are found in good agreement with the experimental results as given in Table 3.

Table 4. ANOVA for surface roughness

Source	Sum of Squares	DF	Mean squares	F-value	p-value	Remarks
Model	1.59	7	0.23	95.60	< 0.0001	Significant
A-SOD	0.40	1	0.40	167.42	< 0.0001	
B-WP	0.67	1	0.67	282.07	< 0.0001	
C-TS	0.25	1	0.25	105.06	< 0.0001	
AB	0.15	1	0.15	65.14	< 0.0001	
BC	0.021	1	0.021	8.64	0.0124	
A^2	0.036	1	0.036	15.18	0.0021	
B^2	0.044	1	0.044	18.50	0.0010	
Residual	0.029	12	2.376×10^{-003}			
Lack of Fit	0.019	7	2.740×10^{-003}	1.47	0.3478	Insignificant
Pure Error	9.336×10^{-003}	5	1.867×10^{-003}			
Cor Total	1.62	19				

4. Result and Discussion

The effect of water pressure and stand-off distance on surface roughness is plotted by design expert software as shown in Fig. 2. Decrease in surface roughness is observed with increase in water pressure. Increase in water pressure causes increase in kinetic energy. Therefore brittle abrasive particles break down into smaller pieces and as a result of decreased size of abrasive particles the surface roughness decreases. Increase in surface roughness is observed 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 increasing surface roughness. Also stray abrasive particles from outer layer of jet deteriorate the surface. The effect of water pressure and traverse speed on surface roughness is plotted as shown in Fig. 3. Increase in surface roughness is observed with increase in traverse speed. The reason behind this is high traverse speed reduces jet interaction on a given area of material. It causes material erosion by less number of abrasive particles and results in high surface roughness. Smooth machined surface was observed near to the jet entry while it becomes rough towards the jet exit.

This is due to reason that when jet penetrates into material, it loses its kinetic energy and cutting ability. It results in striations and uncut portion at jet exit region. Abrasive mass flow rate and type of abrasives are kept constant in the present work. These parameters may be varied to investigate their influence on surface roughness.

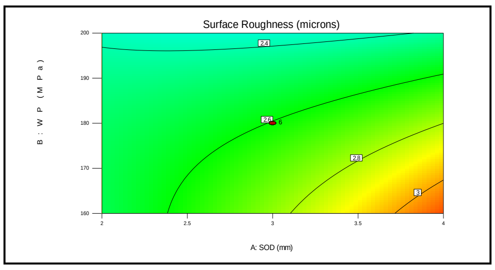

Fig. 2 Contour plot showing effect of WP and SOD

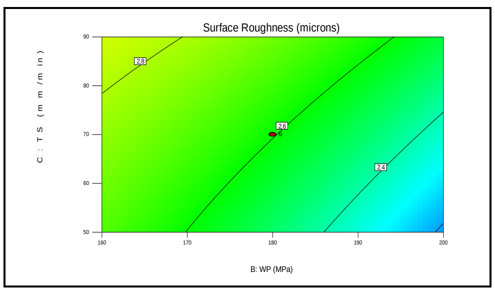

Fig. 3 Contour plot showing effect of WP and TS

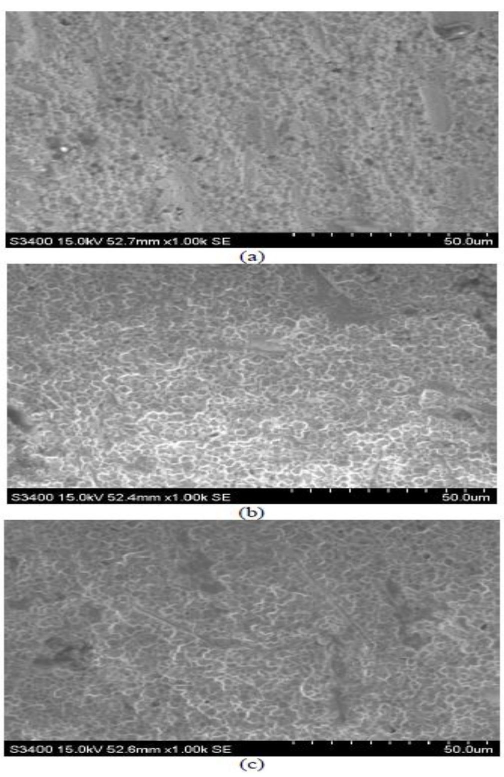

Fig. 4 SEM image of (a) top (b) middle (c) bottom region of machined surface

5. SEM Analysis

Scanning electron microscope (SEM) is used to analyze few machined surfaces. SEM image of machined surface at three different regions i.e. top, middle and bottom are shown in Fig. 4 (a), (b) and (c). 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 Fig. 4 (a). Also some damages are observed in the form of micro cracking and intergranular 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 Fig. 4 (b). Some abrasive wear tracks are observed at this region due to some 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 Fig. 4 (c). 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.

6. Optimization of process parameters

Optimization of process parameters on the basis of desirability approach is performed in order to minimize surface roughness. Goals and limits are set for each response separately to determine their impact on individual desirability. Upper and lower limit are provided for each parameters and response to be optimized. The optimum levels of process parameters are obtained as given in Table 5

Table 5. criteria for optimization

Parameters and responses	Goal	Lower Limit	Upper Limit	Optimized value
SOD	in range	2	4	2.782
WP	in range	160	200	200
TS	in range	50	90	50
Surface roughness	minimize	2.010	3.189	2.182

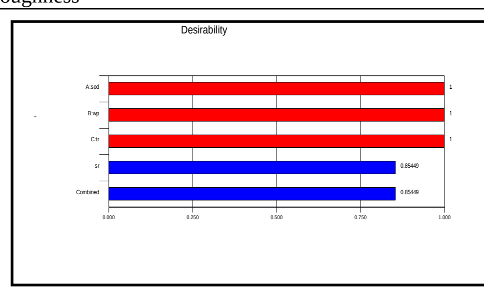

Fig. 5 Desirability bar graph

Desirability bar graph is plotted for optimized level of process parameters as shown in Fig. 5. Desirability bar graph shows the overall desirability function of the responses. Predicted value of desirability is 0.854. The value of desirability is near to 1 and is acceptable. Desirability variation with respect to water pressure and stand-off distance is plotted as shown in Fig. 6. Traverse speed is kept constant at optimum level. Predicted value of desirability is also shown nearly 1. This value of desirability is acceptable.

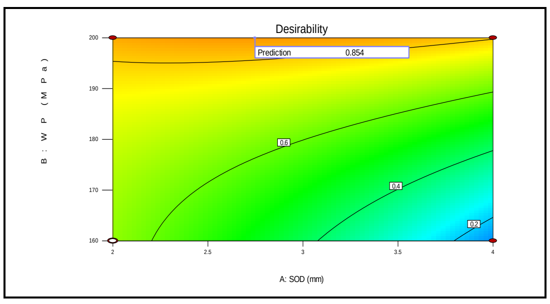

Fig. 6 Desirability value with optimum level

7. Conclusion

Plausible trends of surface roughness with variation in process parameters of AWJM of PZT ceramic have been studied in the present work. Following conclusions are drawn from the present study:

- Water pressure and stand-off distance are most significant parameters followed by traverse speed.
- Surface roughness decreases with increase in water pressure; and decrease in SOD and traverse speed.
- Regression model to predict surface roughness is developed on the basis of experimental results. It is found that model predictions are in congruence with experimental results. Optimization of process parameters is performed to minimize surface roughness.
- Another major concern in AWJM of ceramics is kerf taper and depth of cut which occurs due to decreasing kinetic energy of jet. Therefore, further investigation is required to develop predictive models for kerf taper and depth of cut in AWJM of PZT ceramic material.

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