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Condition Monitoring of Focusing Nozzle Exit Diameter in Abrasive Waterjet Machining using Multiple Sensors

K R Sunilkumar[1], **M Kanthababu**[2*], **S Gowri**[3] , **R Prabhakaran**[4] and **J John Rozario Jegaraj**[5]

[1]Research Scholar, [2,3]Professor, [4]PG Student
Department of Manufacturing Engineering, College of Engineering Guindy,
Anna University, Chennai, India.
[5]Scientist,
Defence Research and Development Laboratory, Hyderabad, India.

Abstract

Recently, Abrasive Waterjet Machining (AWJM) is extensively used for cutting difficult to machine materials. The focusing nozzle in the AWJM system is an important component, which requires condition monitoring. Therefore, in this work, an attempt has been made to monitor the focusing nozzles with different exit diameters (0.76, 0.83, 0.89, 1.01 and 1.21mm) during AWJM of five different materials namely Stainless Steel 304 (SS 304), Stainless Steel 316 (SS 316), EN8 Steel (EN-8), Aluminium 6061 (AA 6061) and Aluminium 8011 (AA 8011) using signals acquired from multiple sensors such as acoustic emission (AE) and accelerometer (ACC). Signal processing is carried out in both time domain (Root Mean Square (RMS)) and frequency domain (dominant frequency). From time domain analysis, it is observed that the RMS of the AE signal (AE_{RMS}) increases with increase in focusing nozzle exit diameters. However, the RMS acquired from the accelerometer signal (ACC_{RMS}) shows decreasing trend with the focusing nozzle exit diameters. In the case of frequency domain analysis, the amplitude of the dominant frequency of AE signal is found to be uniformly increasing with respect to increase in the focusing nozzle exit diameters, while the amplitude of the dominant frequency of ACC signal is uniformly decreasing with increase in the focusing nozzle exit diameters. It is observed that the dominant frequencies of the AE and ACC signals are found in between 30-50 kHz and 3.5-8 kHz respectively. The variations in the dominant frequencies are observed due to differences in the hardness of the materials studied. This study is useful for the manufacturers, for monitoring the focusing nozzle during AWJM of different materials using multiple sensors approach.

Keywords: Abrasive waterjet machining, Focusing nozzle, Acoustic emission, Accelerometer, Signal processing.

1. INTRODUCTION

Abrasive Waterjet Machining (AWJM) is found to be effective in machining difficult to machine materials. In AWJM, a stream of high pressure water is mixed with abrasives such as garnet, aluminium oxide, silicon carbide etc., which are accelerated as abrasive waterjet and directed towards the target materials [1]. The abrasive waterjet cutting head consists of orifice, abrasive inlet, mixing chamber, focusing nozzle, etc. The role of the focusing nozzle in the cutting head is important. The focusing nozzle is subjected to constant wear as the machining time progresses due to the interaction between the high pressure waterjet and abrasives on the inner surface of the focusing nozzle. As a result, the exit diameter of the focusing nozzle increases gradually, which leads to poor quality in the finished component in terms of surface roughness (R_a), kerf width (K_w), etc,. The condition of the focusing nozzle can be monitored by acquiring and processing the signals using different sensors. However, it is observed that only few researchers have made attempts to study the effects of variation in the focusing nozzle with respect to the time [2,3]. Therefore, in this work, condition monitoring is carried out on the focusing nozzle of AWJM system using the signals acquired from multiple sensors such as acoustic emission (AE) and accelerometer (ACC) while machining different materials.

*Author to whom correspondence should be made, Email: kb@annauniv.edu

2. LITERATURE REVIEW

Literature review related to monitoring of AWJM using different sensors is briefly presented here. Hassan et al [4] has proposed a model for monitoring on-line depth of cut using AE signals. From the signal analysis (wavelet transform) they have observed that the dominant frequency increases with the increase in the depth of cut. Mikler [5] monitored AWJ milling using AE sensor. It is found that AE parameters such as standard deviation, skewness, and kurtosis does not shows any significant changes with the increase in the nozzle wear. Axinte and Kong [6] developed an integrated energy-based monitoring of AWJM system using AE sensor. Significant variations were observed in the AE signals during the machining operations such as cutting and milling. Hreha and Radvanska [7] monitored the vibration signals while machining of stainless steel. Experiments were carried out for two sets of abrasive flow rate (400 g/min and 250 g/min) along with different settings of traverse rate (50, 75, 100, 150 mm/min) and focusing tube diameters (0.8 mm and 1.4 mm). They have observed that the peak values in the frequency spectrum are found to be shifting towards the higher level as the abrasive flow rate increases. Higher peaks are also recorded in the high frequency spectrum. They have also observed that at higher abrasive flow rates lowers the RMS values of the vibration signals. Radvanska [8] has studied the focusing nozzle wear and its influence on the vibrations and surface roughness (R_a). It is found that surface roughness (R_a) increases with

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focusing nozzle exit diameter. Kinik and Ganovska [9] have developed an on-line monitoring method for surface roughness in AWJM using vibration signals. They have observed the significant variations in the vibration signals as the traverse rate increases. From the literature review, it is observed that the AE and accelerometer (ACC) are widely used sensors in condition monitoring individually. However, multi sensory approach for monitoring the focusing nozzle exit diameter is limited. In this work, an attempt has been made to monitor the focusing nozzle exit diameter different sensor signals using multi-sensory approach with senors such as AE sensor and ACC, while machining different materials. Output parameters such as the surface roughness (R_a) and kerf width (K_w) during machining of five different materials are also correlated with exit diameters of the focusing nozzles.

3. EXPERIMENTAL DETAILS

The experiments were carried using a commercially available AWJM system (Make: OMAX; Model: 2626). The photograph of the experimental work is shown in Figure 1. Five focusing nozzles made of tungsten carbide (Make: Kennametal; Model: Roctec 500) of length 102 mm and having different exit diameters 0.76, 0.83, 0.89, 1.01 and 1.21 mm were used. The AWJM process parameters such as abrasive mass flow rate (240 g min-1), water jet pressure (210 MPa), Jet traverse speed (120 mm min-1), orifice diameter (0.3 mm), abrasive type (garnet), mesh size (#80) and standoff distance (2 mm) were kept statistically constant during machining. The length of cut for each trial is 40 mm.

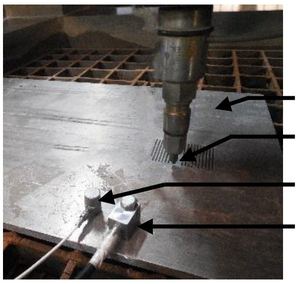

Figure 1 Experimental Setup

The condition monitoring of the focusing nozzle is carried out using two different sensors namely AE and ACC. A description of the sensor arrangements are briefly presented here:

AE signals were acquired using Piezotron AE Sensor (Make: Kistler; Model: 8152) with a frequency range of 50 to 400 kHz. A compatible coupler (Make: Kistler; Model: 5125B) is used to amplify the AE signals obtained from the AE sensor. Thereafter, the amplified AE signals are converted into digital signals using the 16 bit multi-channel analog to digital (A/D) conversion card (Make: National instruments, Model: PCI-6133). The sampling frequency of the AE signal is 2 MHz. Piezoelectric accelerometer is used to collect the vibration that arises due to the variation in the focusing nozzle exit diameter (Make: Kistler, Model: 8702B), with a frequency range of 1 Hz to 10 kHz. A compatible coupler (Make: Kistler, Type: 5110) is used to amplify the vibration signals and converted into digital signals by conversion card (Make: National instruments, Model: PCI-6143). The sampling rate of the vibration signal is 250 kHz. Both the sensors were attached to the workpiece with a thin layer of silica gel, which acts as a couplant, in order to avoid air gap between workpiece and sensors. Data acquisition system specially designed is used to collect and process the data collected from multiple sensors. It consists of a PC with compatible expansion boards and a custom software, which is designed to allow the PC to act as a dual-channel FFT signal analyser. The data collected from the AE and ACC sensors are transferred to the PC and then analyzed off-line in the time domain and frequency domain to derive the necessary information. From the signals collected from each sensor, the first 65,536 data points were used for the time domain analysis whereas the first 8192 data points were used for the frequency domain analysis. Both time domain and frequency domain analysis are carried out during each machining trial, using MATLAB R2010a.

The five workpiece materials used in this work are Stainless steel 304 (SS 304) Stainless steel 316 (SS 316), EN8 Steel (EN-8),Aluminium 6061 (AA 6061) and Aluminium 8011 (AA 8011) whose hardness values are 296 HV, 246 HV, 241 HV, 145 HV and 61 HV respectively with dimension of 300x300x10 mm each. The surface roughness (Ra) of the machined material is measured using a computer controlled surface roughness tester (Make: Kosaka Laboratory, Model: SC 3500) with a probe radius of 2.5 μm, cutoff wavelength of 0.8 mm and traverse length of 5.6 mm. The exit diameter of the focusing nozzle and top kerf width is measured using the non-contact video measuring system (VMS) (Make: Rational instruments, Model: VMS-2010F).

4. RESULTS AND DISCUSSION

The following section deals with the analysis of AE and ACC signals in time and frequency domains with respect to variation in the focusing nozzle exit diameters during AWJM of five different materials. The focusing nozzle exit diameters are also correlated with R_a and K_w. In time domain analysis, root mean square (RMS) values are obtained. For the frequency domain analysis, the fast fourier transform (FFT) technique is used to get the power spectra from the sensor signal.

4.1. Analysis of AE signal

Figure 2 indicates the response of AE_{RMS} of different materials for the five different focusing nozzle exit diameters. From the time domain analysis (Figure 2), it is observed that AE_{RMS} shows a uniform increasing trend with the increase in focusing nozzle exit diameter in all the materials studied. It is observed that higher the hardness, lower the AE_{RMS}. The variation in the AE_{RMS} values may be due to the differences in the hardness of the materials. A polynomial regression of 3rd order is used to fit an equation for focusing nozzle exit diameter with respect to AE_{RMS} for every material studied. Equation (1) shows the regression equation obtained for SS 316.

$$d_e = 2.001 - 3.197x + 2.447x^2 - 0.494x^3 \qquad (R^2=0.998) \qquad (1)$$

In the above equation, 'd_e' represents exit diameter (mm) and 'x' represents AE_{RMS} (V). Using equation (1), the exit diameter of the focusing nozzle can be predicted using the AE_{RMS} values obtained during machining. Similar equations were obtained for other materials and presented in Table 1. Figure 3 indicates the typical power spectra of AE signals obtained for the SS 316. From the Figure 3, it is observed that the dominant frequency of AE signal is found to be between 38 and 42 kHz. Similar power spectral graphs were obtained for other materials and the dominant frequencies were found to be varying from 36 to 49 kHz for SS 304, 32 to 42 kHz for AA 6061, 31 to 43 kHz for AA 8011 and 31 to 40 kHz for EN-8. However, the amplitude at the corresponding dominant frequency were found to be increasing with respect to increase in focusing nozzle exit diameters.

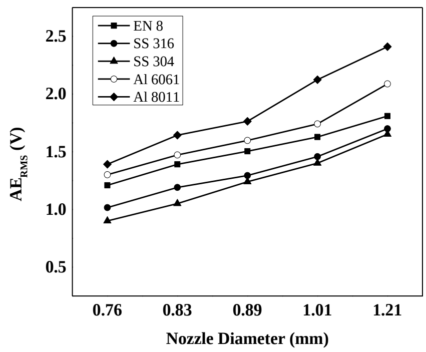

Figure 2 AE$_{RMS}$ Vs. Nozzle Diameter

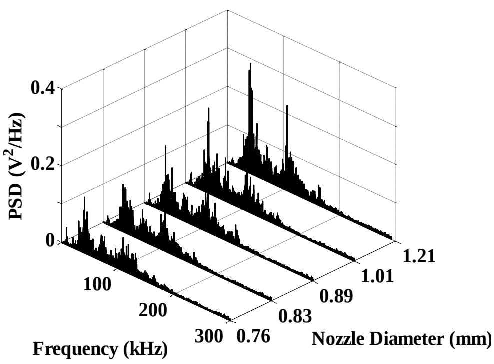

Figure 3 Power spectra of the AE Signal (SS 316)

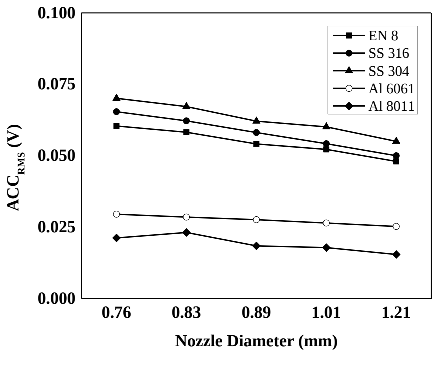

Figure 4 ACC$_{RMS}$ Vs. Nozzle Diameter

Similar observations in AE signal analysis were also observed by Kovacevic [10].

4.2. Analysis of ACC signal

Figure 4 indicates the ACC$_{RMS}$ of different materials with varying focusing nozzle exit diameters. From the time domain analysis (Figure 4), it is observed that the ACC$_{RMS}$ shows a decreasing trend with the increase in the focusing nozzle exit diameters in all the materials studied. The variation in the RMS values may be due to the differences in the hardness of the materials. Higher the hardness, higher are the ACC$_{RMS}$ values. The polynomial regression of 3rd order is used to fit an equation for focusing nozzle exit diameter with respect to AE$_{RMS}$ for every material. Equation (2) shows the regression equation for SS 316.

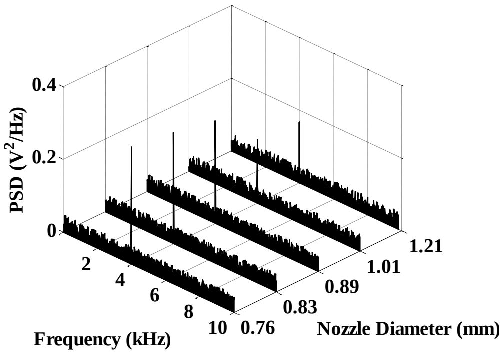

Figure 5 Power spectra of the ACC Signal (SS 316)

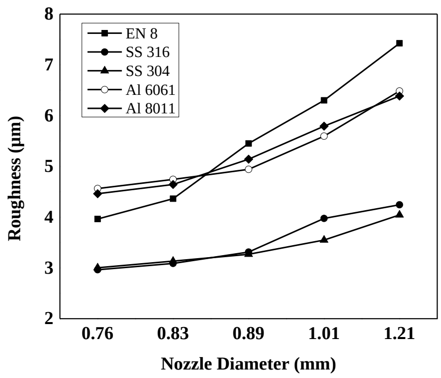

Figure 6 Surface Roughness (R$_a$) Vs. Nozzle Diameter

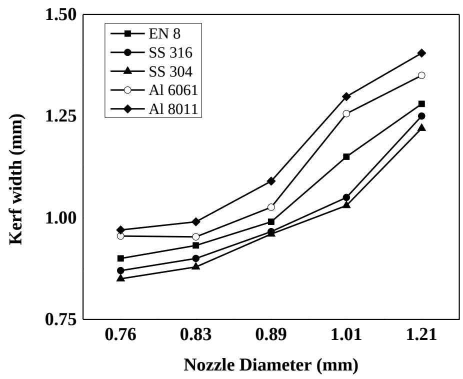

Figure 7 Kerf width (K$_w$) Vs. Nozzle Diameter

$$d_e = 30.293-1406.24y+22642.5y^2-123008y^3 \quad (R^2=0.999) \qquad (2)$$

In the above equation, 'y' represents ACC$_{RMS}$ (V). Using equation (2), the exit diameter of the focusing nozzle can be predicted using ACC$_{RMS}$ values obtained during machining.

Similar equations were obtained for other materials and presented in Table 1. Figure 5 indicates a typical power spectra of the vibration signal obtained while machining SS 316. From Figure 5, it is observed that the dominant frequency of the ACC signal is found to be 4 kHz. Similarly for other materials, the dominant frequency was found to be around 3.985 kHz for SS 304, 8 kHz for AA 6061, 3.969 kHz for AA 8011 and 3.5 KHz

Table 1
3rd order polynomial equations predicting the focusing nozzle diameter while machining different materials

Material	AE_{RMS} (V)		ACC_{RMS} (V)	
	3rd order polynomial equation	R^2	3rd order polynomial equation	R^2
SS 304	$d_e = 0.287 + 0.963x - 0.768x^2 + 0.317x^3$	0.996	$d_e = 25.300 - 1033.378y + 14749.24y^2 - 71336.58y^3$	0.983
AA 6061	$d_e = 5.495 - 9.331x + 5.846x^2 - 1.130x^3$	0.996	$d_e = 106.410 - 10966.82y + 381922y^2 - 4459907y^3$	0.990
AA 8011	$d_e = -1.499 + 3.593x - 1.952x^2 + 0.384x^3$	0.997	$d_e = -7.581 + 1698.931y - 104162.6y^2 + 2007919y^3$	0.984
EN-8	$d_e = 2.463 - 3.232x + 1.720x^2 - 0.174x^3$	0.999	$d_e = 27.981 - 1332.56y + 22108.48y^2 - 124274.3y^3$	0.986

However, the peak amplitude of dominant frequency was decreasing with respect to increase in focusing nozzle exit diameters for all materials. From the power spectra of all five materials, the amplitude of the ACC signals shows a decreasing trend with respect to increase in the focusing nozzle exit diameter. Similar observation in ACC signal analysis were observed by Hreha [7].

4.3. Analysis of surface roughness (R_a) and kerf width (K_w)

Figure 6 indicates the analysis of surface roughness (R_a) with respect to nozzle exit diameter while machining different materials. It is observed that the surface roughness (R_a) is found to be increasing with focusing nozzle exit diameter. This may be due to the fact that lesser the diameter of the focusing nozzle, the concentration of the abrasive particles on the peripheral part of the stream will be higher, which will cut the material smoothly. Similar observations were made by Radvanska [8]. Figure 7 shows the increasing trend of K_w with the increase in the focusing nozzle diameter for different materials. It is observed that the K_w increases almost linearly with the increase in the focusing nozzle diameters.

5. CONCLUSION

In this work, condition monitoring of focusing nozzle exit diameter in AWJM using multiple sensors during machining of five different materials is carried out. The signals are analyzed in the time and frequency domains. The AE_{RMS} shows increasing trend with increase in the nozzle dimeter and also varies with the increase in the hardness of the material. While, a decreasing trend is observed in case of ACC_{RMS} with increase in nozzle diameter. In case of frequency domain, the dominant frequency of the AE and ACC signals are found to be between 30-50 kHz and 3.5-8 kHz respectively. Peak amplitude of AE sensor signals increases with the increase in nozzle diameter, while peak amplitude of ACC signal decreases with the increase in focusing nozzle exit diameters. The increase in focusing nozzle exit diameter leads to increase of both R_a and K_w in all the materials studied in this work. The regression equations were obtained for the materials studied in this work. The regression equations were obtained based on the RMS values for the focusing nozzle exit diameters.

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