기술논문
한국정밀공학회지 제15권 제6호 (1998년6월)
Journal of the Korean Society of Precision Engineering Vol. 15. No. 6. June. 1998.

Abrasive Waterjet 세라믹 Drilling가공시 Acoustic Emission 신호를 이용한 On-Line Monitoring에 대한 연구

곽 효 성*, Rodovan Kovacevic**

On-Line Monitoring of Abrasive Water Jet Drilling of Refractory Ceramics Using Acoustic Emission Sensing Technique

Kwak, Hyo-Sung*, Rodovan Kovacevic**

ABSTRACT

Abrasive waterjet(AWJ)은 가공시 열에 의한 가공경화가 없기 때문에 유리, 세라믹, 타이타늄및 금속복합재료와 같은 난삭재의 가공기술로 사용이 증가되었다. Acoustic emission(AE)신호에 의한 AWJ 세라믹 drilling가공시 On-Line Monitoring의 가능성이 고찰되었다. 기계적인 물성이 서로 상이한 3종류의 세라믹이 본 연구에서 사용되었으며, AE신호는 AWJ drilling의 깊이를 monitoring하는데 유용함을 알 수 있었고 또한 세라믹의 material removal mechanisms을 규명하였다.

Key Words : Abrasive WaterJet(AWJ)(어브레이시브 워러젯), Difficult-to-Machine Materials(난삭재),Acoustic Emission(AE:음향파), AE Root Mean Square(AE-RMS:음향실효치), Drilling Time(드릴링시간), Material Removal Rate(가공율), Damping Effect(감쇠효과), Penetration Rate(페너트레이션 율).

1. Introduction

Abrasive waterjet machining technique can be considered as one of the most recent non-traditional manufacturing processes to be introduced. In this machining technique, the abrasive such as garnet, aluminum oxide (Al_2O_3), or silicon carbide (SiC) is accelerated by high velocity waterjet and directed through an abrasive waterjet nozzle at the target material to be machined. Abrasive waterjet machining was first introduced as a commercial technique in 1983 for cutting glass. Absence of heat-affected zone and thermal distortion, and ability to cut difficult-to-machine materials have made abrasive waterjet a versatile tool for cutting applications. Originally, the abrasive waterjet machining technology was applied for linear cutting and shape cutting of materials such as glass, titanium, super-alloy, metal-matrix composites and advanced ceramics. However, recently this technology is used for such machining applications as milling, turning and drilling.

---

* LG-EDS 시스템, CALS/CIM 연구소.
** Department of Mechanical Engineering and Center for Robotics and Manufacturing Systems, University of Kentucky, Lexington, KY 40506, U.S.A.

Drilling difficult-to-machine materials presents significant challenges to conventional techniques. Drilling such materials with solid drill bits is often not possible due to large difference in the nature of material properties and their unpredictable response to the drill bit action. In order to expand the possible applications of these materials, machining methods must be developed to allow for successful fabrication of component parts. Recently, it was demonstrated(1-4) ceramics and metal matrix composites can be effectively machined by non-traditional methods such as lasers, electrodischarge machining (EDM), Electrochemical machining (ECM), and abrasive water-jet machining. EDM is used for fragile tungsten parts. A practical material remove rate (MRR) for EDM ranges from 20 to 200 mm^3 /hour (1). This relative low volume removal rate translates into an excessively high machining cost for the drilling operation. ECM has also been used for these materials. However, ECM is an extremely slow process with poor dimensional stability. Additional, the hazardous wastes generated in the process are harmful. The use of lasers results in undesirable surface characteristics, considerable heating of the workpiece and need for additional processing, which significantly increases the cost of machining. Among the various non-traditional machining techniques, it appears that AWJ drilling shows big promise in machining these materials.

The increasing need to conduct an in-depth study into the mechanisms involved in AWJ drilling process is necessitated by the unique capability of AWJ to machine the previously mentioned exotic materials with least material distortion/failure. Even though several investigations have been conducted to explore the mechanisms involved in AWJ cutting process, the differences in the physical phenomena involved in these two processes warrant a separate study of the AWJ drilling process. The results of this investigation will also aid a better understanding and control of the AWJ drilling process.

In the AWJ drilling process, a combination of parameters, such as stand-off-distance, abrasive flow rate, pump pressure, abrasive material and grain size, back flow of water, jet impact angle, drilling time, etc., determines the process effectiveness. Of these parameters, the back flow of the rebounded jet from the bottom of blind holes causes turbulence inside the drilled hole, reduces the particle velocity and interferes with the drilling process. The cross-section of the hole drilled with AWJ indicating the impinging jet and the rebounded jet is shown in Fig.1. Fig. 2 shows general scheme of drilling concept. Holes drilled with stationary jet and stationary workpiece are characterized by small diameters and larger h/d ratio (h-depth, d-diameter). This process is con-

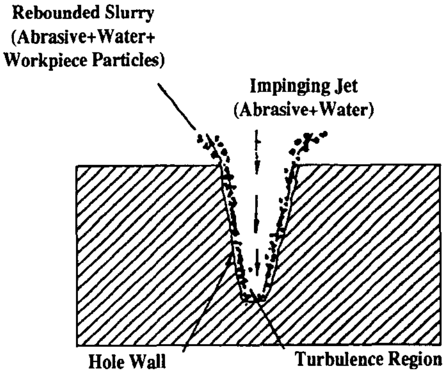
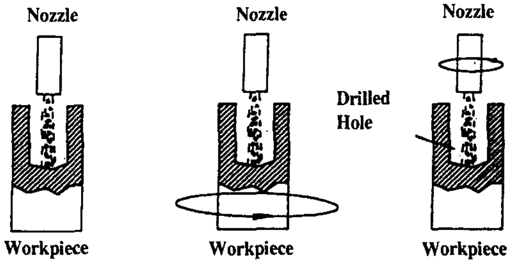


Fig. 1 Typical Cross-Section of a Drilled Hole



Case 1 Case 2 Case 3

Fig. 2 General Scheme of AWJ Drilling Concept.

ventionally called "piercing". However, the cases 2, and 3 mentioned above are characterized by large diameters and relatively smaller h/d ratios. Drilling a rotating workpiece with a stationary jet or a stationary workpiece with a rotary jet are conventionally called "drilling". In this study the primary focus is on AWJ drilling of stationary workpiece with stationary jet (case 1) and hence the term "AWJ drilling" implies "drilling stationary workpiece with stationary jets". A brief description of the investigations already performed in this field is given below.

Hashish[5] investigated AWJ drilling of glass and laminated composites and found that low pressures (about 30 to 40 MPa) should be used in glass piercing for good results. High pressure piercing resulted in fracture or cracking due to the shock loading of water or hole hydrodynamic pressurization. AWJ rock drill has been developed by Savanick and Krawza[6] and Hashish[7] for drilling quartzite with compressive strength as high as 503 MPa. The investigators suggested that the rotary dual (or multiple) drill is the most promising technique because high-efficiency jets can be used at optimum mixing conditions. Hole quality and hole size control through pressure ramping in precision drilling of ceramic coated components was attempted by Hashish and Whalen[8] using an open-loop approach. Raju and Ramulu[9] have reported a semi-empirical transient numerical model for prediction of the depth of AWJ drilling. However, the experimental results were not closely matching the model predictions especially at extremely low or high drilling depths.

To produce a small diameter hole with controlled depth is a basic problem of the AWJ drilling operation. The methods used to detect the drilling depth of AWJ could be categorized into two groups, namely direct and indirect. Direct methods provide a measurement of the drilling depth by interrupting the drilling process. Obviously, this method is not suitable for on-line control of the uniformity of drilling depth. Indirect methods could be based on the measurement of some parameters that are correlated to the depth of AWJ drilling, such as the average workpiece normal force or acoustic emission .

Acoustic emission has been widely used in monitoring manufacturing processes[10-12]. Liu et al.[10] found that AE-RMS signal is a good candidate to monitor the actual depth of cut in precision machining operations such as single point diamond turning.

They also reported that other information from the zero crossing rate and kurtosis of AE signal could be related to changes in the cutting mechanism in micro-machining. Work has been done in sensing tool wear in milling and grinding processes using AE signals[13,14]. Pandit et al. [14]proposed possible use of data dependent system analysis in correlating the AE modes with different cutting conditions, such as depth of cut, grinding wheel grade, cutting speed, or workpiece. AE technique was also used for in-process control of laser drilling[15] through depth regulation and beam break-through control. In the field of abrasive water jet cutting technology, Mohan et al.[16] have applied AE technique for monitoring of depth of cut in grey cast iron. They found that the power spectrum density of the auto regressive moving average model, representing the time domain AE signals, gave a good indication of the depth of penetration.

Above literature review indicates that there has been one attempt[8] at developing a control scheme for open-loop control of depth in AWJ drilling process. However, even though there is a need for closed-loop monitoring and controlling of AWJ drilling process, its feasibility has not been established till date. The current research work is aimed at understanding the underlying principles and mechanisms involved in AWJ drilling process and develops a suitable technique for on-line monitoring of AWJ drilling depth using AE sensing technique.

2. Experimental Setup and Procedure

The experimental setup consists of an AWJ system, AE sensor, pre-amplifier, A/D convertor, AE monitoring system, PC with suitable software and workpieces. The AWJ system used for performing the experiment consists of a high pressure intensifier pump, AWJ cutting head, abrasive metering and delivery system, abrasive hopper with garnet as abrasive, catcher tank and X-Y-Z positioning system controlled by a CNC controller. A schematic of the experimental setup is shown in Fig. 3. The generated AE signals were detected and processed by Model AET 5500 Acoustic Emission Monitoring System which consists basically of AET 5500 mainframe (signal processing unit), graphics terminal (interface, data storage and display) and the accessories (sensors, pre-amplifier). When acoustic emission caused by an induced stress occurs in a test specimen, the sensors (resonant frequency 2 MHz) convert this acoustic wave into a voltage signal which is amplified by the pre-amplifier and sent to the mainframe (16-bit microprocessor) for post processing. For detecting the AE signals from the AWJ drilling process, a sensor was fixed on the side wall of the workpieces with a water resistant epoxy-gum. Three types of non-homogeneous refractory ceramics namely magnesia chromite, sintered magnesia, and bauxite of 51 mm thickness were used for this investigation. The workpiece material properties are shown in Table 1. Different holes were drilled on the workpiece materials for the same process parameters. AE signals were acquired at a sampling frequency of 1 MHz (at 5.0 gain) with progressive drilling time. Signals were monitored during three stages of the drilling process namely pure water impingement stage, drilling stage, where the target material is subjected to erosion by abrasive waterjet mixture, and dwelling stage which is after full penetration of the target material. The time domain AE signal was acquired in several data sets over the entire drilling process. Each

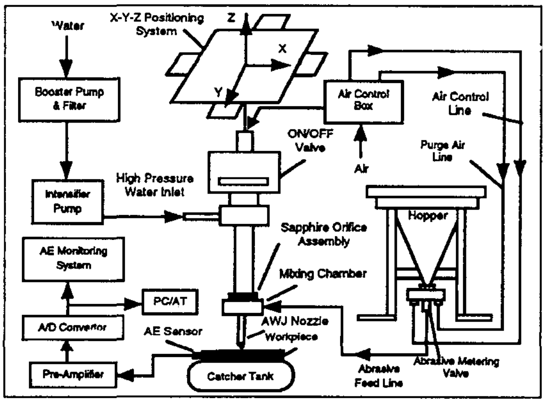


Fig. 3 Experimental Setup

Table 1. Material Properties

	Density (g/cm^3)	Porosity (%)	Cold Compressive Strength (MPa)	Cold Bending Tensile Strength (MPa)	Young's Modulus (MPa)
Magnesia Chromite	3.26	15.2	30	3.5	13,000
Sintered Magnesia	3.00	15.2	40	14	85,000
Bauxite	2.89	15.0	126	19	59,000

Table 2. Process Parameters

Constant Parameters

Abrasive material :Garnet
Abrasive mesh size :80
Abrasive particle shape :Angular(random)
AWJ orifice material : Sapphire
AWJ orifice diameter : 0.457 mm
Mixing nozzle diameter : 1.27 mm
Mixing nozzle length : 88.9 mm
Method of feed : Suction
Condition of abrasive : dry
Angle of jet : 90 degree

Variable Parameters

Material : Magnesia chromite,
Sintered magnesia, Bauxite
Material thickness : 51 mm
Waterjet pressure : 206 MPa
Abrasive flow rate : 5.75 g/s
Stand-off-distance : 5 mm

data set consists of 1024 data points representing the AE signal generated at a particular instant of time. Several holes of different depths were also drilled and the time taken was noted to determine the material removal rate and penetration rate. All these experiments were performed several times for the same set of process parameters and workpiece materials to verify the repeatability of the results. The process parameters are given in Table 2.

3. Results and Discussion

Acoustic emission, also called stress wave emissions, are produced by microscopic deformations occurring in materials as they are stressed. It contains part of the elastic energy released during deformation. Acoustic emission is associated with dislocation movements, crack growth, deformations of inclusions and with other mechanisms. These are sources which are related to the machined materials. Other type of sources depend on the fluid dynamics of the AWJ such as turbulence, vortex and cavitation. The characteristic of the AE signal generated during the machining process depend on the source of generation and the material properties.

Acoustic emission signals can be classified into continuous and burst type. Continuous type acoustic emission signals are associated with plastic deformation in ductile materials, and erosion process in brittle materials[18], while burst type signals are observed in unsteady processes such as crack growth in the material[17] and transgranular spalling fracture[18]. However, it must be noted that at any instant of time, there could be more than one source generating the AE signal and hence the general characteristics of the signal is determined by the dominant source. Information about dominant source can be obtained through several means such as identification of the type of AE signal.

The major features contained in the raw AE signal are energy, spectrum distribution, and amplitude distribution. The first one can be represented by the RMS voltage, the second is reflected in the zero crossing rate, and the last will be reflected in the kurtosis which represents the sharpness of the AE signal. Features of the AE signals such as peak amplitude, rise time, event counts, event duration etc, can also be used to represent the AE signal.

It has been found by Mohan et al.[19] that AE signal energy represented by area enclosed by power spectrum density curve is capable of providing a quantified measure of the energy dissipated in the workpiece during AWJ cutting. Hence it is reasonable to expect that AE-RMS which is again a measure of AE signal energy can provide an indication of the depth of penetration in AWJ drilling process. AE-RMS is given by,

$$AE_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (1)$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

Where, n is the number of data points, and y_i is the amplitude of the AE signal.

Typical time domain AE signal and the corresponding Fast Fourier Transform(FFT) for different stages of the drilling process and for materials of different mechanical properties are shown in Fig. 4 and 5, respectively. The signal representing partial penetration condition is indicated by "drilling" stage and full penetration condition is indicated by "dwelling" stage. It can be seen that respective amplitudes for pure water impingement stage is about three to four times higher than drilling condition. It is also interesting to note that amplitude of magnesia chromite in pure water stage is lower than those of sintered magnesia and bauxite. When pure waterjet impinges on the workpiece, part of the energy is used for

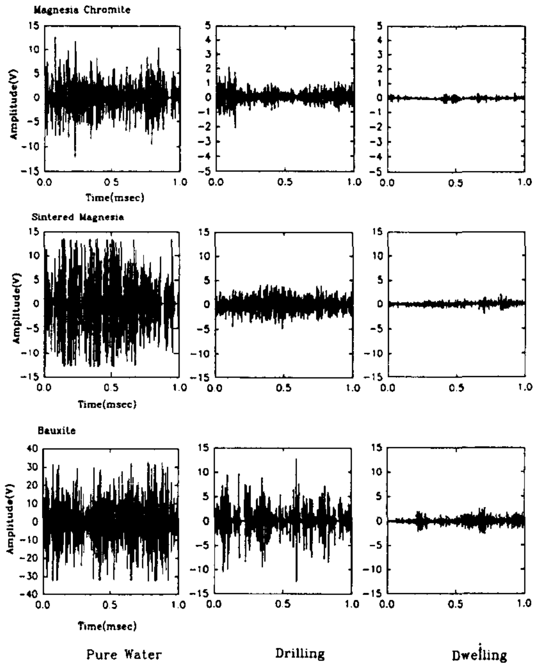


Fig. 4 Typical Time Domain AE Signals for Different Process Stages

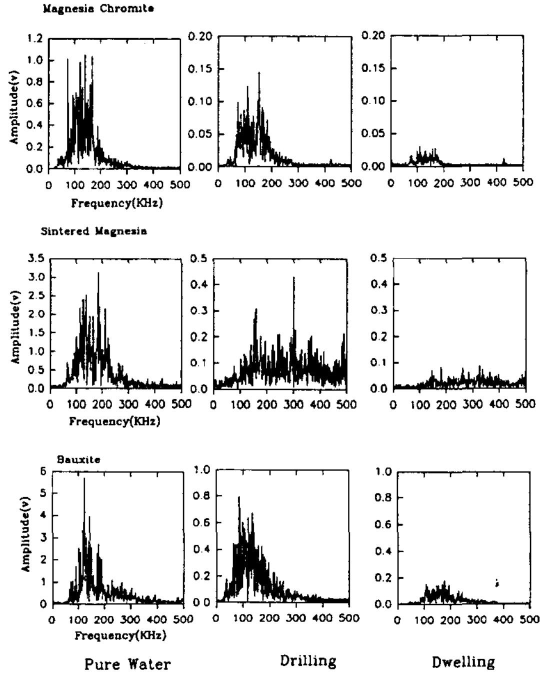


Fig. 5 Typical Frequency Domain AE Signals for Different Process Stages

penetration if the material properties allow it to happen, and part of the energy is lost in the damping phenomena due to factors like turbulence, cavitation, etc. Deeper the penetration, higher the effect of damping is and higher the energy dissipated. For the above materials, the pure waterjet penetrates less and hence less energy is dissipated in the material removal as well as in damping. As a result, the entire energy of the impinging jet is transmitted to the sensor through the workpiece. This could be the reason for higher amplitude of AE signal for pure waterjet conditions. As noted above, less energy is dissipated in the material removal process when impinged by pure waterjet in the case of bauxite due to lower penetration. This is the reason for the presence of relatively higher amplitude AE signal in bauxite.

AE signal during drilling stage is generated primarily by phenomena related to target material such as erosion, crack generations, crack propagation, turbulence, etc. The AE signal in bauxite material is of burst type indicating material removal mode due to transgranular fracture, which is observed in comparatively high strength materials(See Fig.4). Visual observation of the kerf wall of AWJ cutting of this material supports the view that in both drilling as well as AWJ cutting the material removal takes place simultaneously in the hard inclusions as well as the matrix with equal significance. While other materials show continuous type signal which indicates material removal mechanism caused by intergranular erosion(See Fig.4). This result may suggest that the mechanisms involved in drilling are principally at steady state. However, it is not easy to predict the response due to non-homogeneous nature of material. It is observed from corresponding FFT graph that for magnesia chromite and bauxite, frequency is concentrated between 70 KHz and 170 KHz during drilling stage. However, frequency in sintered magnesia is spread between 100 KHz and 500 KHz. Weak AE signal is detected after penetration (dwelling stage) due to AWJ impact on the hole wall surface. It may also be noted that dwelling time is an important factor which affects the hole geometry and hole quality.

Material removal rate was measured for each ceramic material with progressive drilling time and is indicated in Fig. 6. It can be noted that material removal rate does not change much with drilling time. As the drilling is performed by a stationary jet on a stationary workpiece, the jet continuously removes the workpiece material from the drilled hole and is displaced by jet back flow(See Fig.1). The newly exposed workpiece material in the hole is subjected to fresh AWJ mixture impingement. As a result, the local energy of the impinging jet is almost the same throughout the drilling depth. This is the reason for near constant material removal rate with progressive drilling time. As the compressive strength of the material increases the material removal rate reduces due to higher resistance of the target material. It is interesting to compare the material removal rate of above materials with the penetration rate during AWJ drilling process. Fig. 7 gives a plot of penetration rate for each material with progressive drilling time. Similar to material removal rate, penetration rate is also lower for material with higher compressive strength. However, with increase in time, the penetration rate drops down quadratically. The trends shown by Fig. 6 and 7 indicate that with progressive time, the AWJ mixture removes more material from the walls of hole than from the bottom, producing a diverging hole. This also supports the view that the back flow of the jet has sufficient potential energy to remove material in above ceramics.

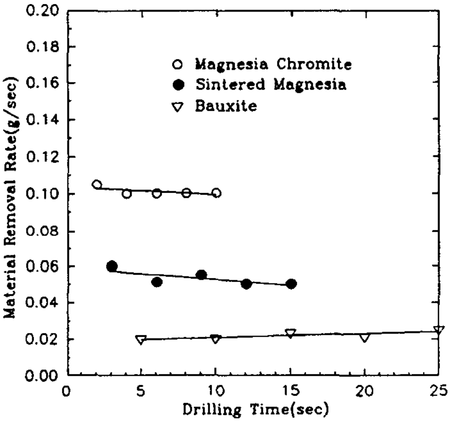


Fig. 6 Material Removal Rate for Different Ceramic Materials

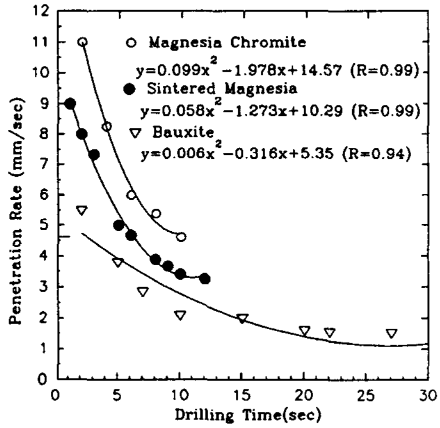


Fig. 7 Penetration Rate for Different Ceramic Materials

Fig. 8 shows the plots of the drilling depth vs. drilling time for different materials. The drilling depth has an exponential relationship with the drilling time as given by,

$$h = h_{\max}(1 - e^{-at}) \qquad (2)$$

Where, $h_{\max}$ is theoretically maximum possible drilling depth, and 'a' is time constant. It may be noted that $h_{\max}$ depends on the process parameters, mechanical properties of the material and material removal mechanism. The time constant 'a' depends on compressive strength of ceramic materials. Higher the compressive strength is, lower the time constant becomes. Drilling depth exhibits initially a linear trend as drilling time increases and then shows non-linear trend which indicates less efficient material removal. Similar

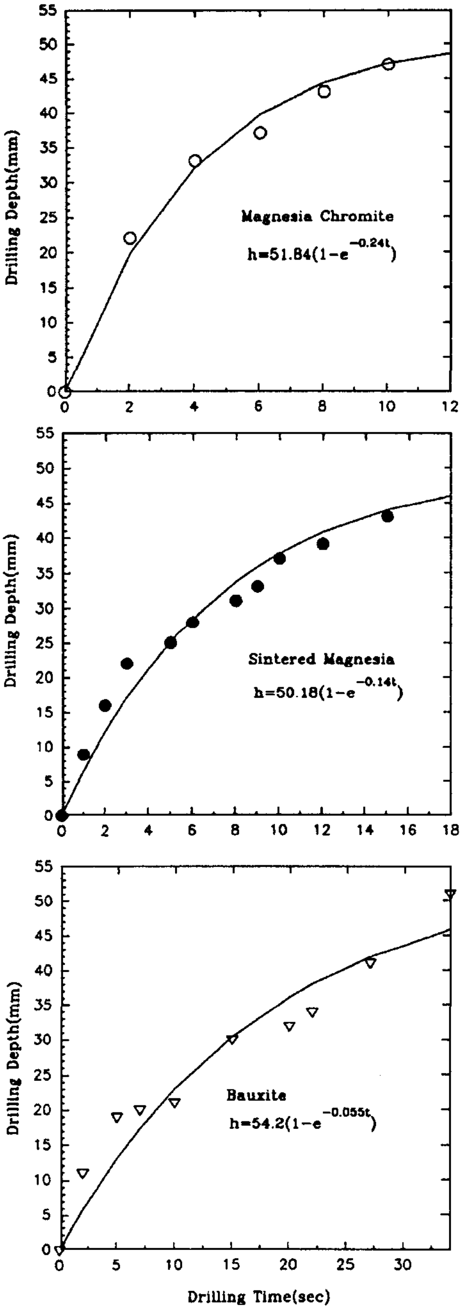


Fig. 8 Drilling Depth vs. Drilling Time

results were obtained by Hashish[5] and Raju and Ramulu[9] for other materials.

A plot of AE-RMS against drilling time is given in Fig. 9. AE-RMS decreases as the drilling time increases. Small diameter hole drilling has damping effects on the generated AE signal due to the presence of turbulence and back flow of water. Damping effects increase in deeper holes due to more abrasive water debris collected in cavity. This could be the reason for the decrease of amplitude of the AE signal for higher drilling depth. In addition, RMS values vary linearly for relatively soft materials and linear regression fitted very well (R=0.95 and 0.93, respectively). A second order polynomial regression was used for bauxite ceramic which has relatively higher compressive strength (126 MPa). Compared to magnesia chromite, bauxite has more variance in AE-RMS. This could be due to the presence of more hard inclusions. This trend in AE-RMS for all the three materials with progressive time indicates that AE-RMS can be effectively used for monitoring drilling depth.

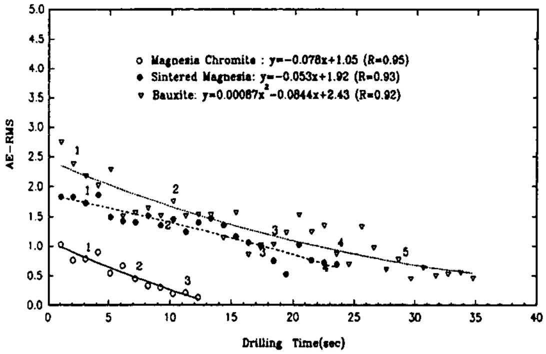


Fig. 9 AE-RMS vs. Drilling Time for Different Ceramic Materials

4. Conclusions

Acoustic emission sensing technique provides critical information about the material removal mechanism in AWJ drilling process. Material failure in bauxite with high compressive strength is caused by transgranular fracture indicated by a predominantly burst emission signal.

AE signal amplitude is about three to four times higher in the case of pure water impingement stage compared to drilling stage. Material removal rate and penetration rate studies indicate that the back flow of the jet has sufficient kinetic energy to remove material from the walls of the drilled hole in the case of the analyzed materials causing hole divergence. Decrease in penetration rate and increase in damping effect caused by jet turbulence are responsible for reduction in AE signal amplitude with progressive drilling time.

Material removal rate during AWJ drilling of ceramic materials decreases with increase in the material compressive strength. Higher energy dissipation during material removal process of high compressive strength materials causes higher AE-RMS.

AE-RMS is a useful indicator of depth of AWJ drilling and hence can be used as a potential parameters for on-line monitoring of drilling depth.

References

1. Yih. S. W. H., and Wang. C. T., Tungsten: Source, Metallurgy, Properties, and Application, Plenum Press, New York, New York, 1979.
2. Hunt. D. C., Kim. T. J. and Sylvia.J. G., "A Parametric Study of Abrasive Waterjet Processes by Piercing Experiment," 8th Int'l Symposium on Jet Cutting Technology," England. pp. 287-295. Sept. 1986.
3. Kim.T.J., Sylvia. J. G. and Posner.L. "Piercing and Cutting of Ceramics by Abrasive Water," Machining of Ceramics Materials and Components. PED Vol. 17 pp. 19-24. 1985.
4. Hamatani. G. and Ramulu. M., "Machinability of High Temperature Composites by Abrasive Waterjet," ASME Tranc. J. of Engineering Material and Technology, Vol. 112. pp. 381-386.
5. Hashish. M., "Turning, Milling, and Drilling with Abrasive Waterjets," 9th Int'l Symposium on Jet Cutting Technology. Japan. pp. 113-131. Oct. 1988.
6. Savanick. G. A., and Krawza. W. G., "An Abrasive Water Jet Rock Drill," Proc. of the 4th U. S Waterjet Conference. pp.129-132. Aug. 1987.
7. Hashish. M., "The Potential of an Ultra-high-Pressure Abrasive Waterjet Rock Drill," 5th American Water Jet Conference. Canada. pp. 321-332. Aug. 1989.
8. Hashish.M., and Whalen. J., "Precision Drilling of Ceramic-Coated Components with Abrasive-Waterjets," ASME. J. of Engr. for Gas turbines and Power. Vol. 115. pp. 148-154. 1993.
9. Raju. S. P., and Ramulu, M. "A Transient Model for Material Removal in the Abrasive Waterjet Machining Process," Proc. of 7th American Water Jet Conference. Seattle, Washington. pp. 141-155. Aug. 1993.
10. Liu. J. J., and Dornfeld. D. A., " Monitoring of Micromachining Process using Acoustic Emission," Transaction of NAMRI/SME. Vol. XX. pp. 189-195. 1992.
11. T. Blum and Inasaki.I., "A study on Acoustic Emission from the Orthogonal Cutting Process," ASME. J. of Engineering for Ind. Vol. 112. pp. 203-211. Aug. 1990.
12. Emel. E., and Kannatey-Asibu. E., "Acoustic Emission Monitoring of the Cutting Process-Negating the Influence of Varying Conditions," ASME. J. of Engineering Materials and Technology. Vol. 113. pp. 456-464. Oct. 1991.
13. Sturges. R. H., "Monitoring Milling Processes Through AE and Tool/ Part Geometry," ASME. J. of Engineering for Ind. Vol. 114, pp. 8-14. 1992.
14. Pandit. S. M., and Stacey. J. D., "Data Dependent System Analysis of Acoustic

Emission in Grinding," ASME. PED-Vol. 64, pp. 437-444. 1993.

15. Chryssolouris.G., Sheng. P., Anastasia. N., and Domroese. M., "Investigation of Acoustic Sensing for Laser Drilling," Trans. of NAMRI/SME. Vol.XX. pp. 227-233. 1992.
16. Mohan. R., Momber. A., and Kovacevic. R., "On-Line Monitoring of Depth of AWJ Penetration Using Acoustic Emission Technique," Waterjet Cutting Technology, Mechanical Engineering Publication. Suffolk. pp. 649-664. 1995.
17. Schofield. B.H., "Research on the Sources and Characteristics of Acoustic Emission," ASTM STP 505, pp. 11-19. 1972.
18. Momber. A., Mohan. R., and Kovacevic. R., "Acoustic Emission Measurements on Brittle Materials during Abrasive Waterjet Cutting," First Int'l Machining and Grinding Conference, MR95-184, pp. 439-458, Dearborn, MI. Sept. 1995.
19. Mohan. R., Momber. A., and Kovacevic. R., "Detection of Energy Absorption During Abrasive Waterjet Machining Using Acoustic Emission Technique," ASME Manufacturing Science and Engineering MED. Vol. 2-1, pp. 69-85, 1995.