A Closed-form Expression for an Abrasive Waterjet Cutting Model for Ceramic Materials

Adel A. Abdel-Rahman

Abstract— The abrasive waterjet cutting technique is a controlled erosive process in which the impact of high velocity water and abrasives cause cutting of the target material. Advanced engineering ceramics materials have been used in many applications. Cutting of such materials by abrasive waterjet is becoming the recent cutting technique. In the present study, an elastic-plastic erosion model was adopted to develop an abrasive waterjet model for cutting brittle materials. As a result, a closed-form cutting model based on fracture mechanics was derived and introduced. The suggested model predicts the maximum depth of cut of the target material as a function of the fracture toughness and hardness, as well as process parameters. The maximum depth of cut predicted by the suggested model was compared with published experimental results for AD99.5 ceramic material. The effect of process parameters on the maximum depth of cut for the AD99.5 ceramic material is also studied and compared with experimental work. The comparison reveals that there is a good agreement between the model predictions and experimental results, where the difference between the predicted and experimental values of the maximum depth of cut was found to take an average value of **3.9**%. The predicted depth of cut of the present model for 7 different ceramic materials was also compared with that by a previous model, where the two models were found to predict the same maximum depth of cut within an average value of 4%.

Keywords—Abrasive Waterjet, Cutting ceramics, Waterjet cutting, Waterjet modeling.

NOMENCLATURE

C = abrasive efficiency factor
c = erosion model constant, $B = c/\frac{4}{3}\pi$
d_j = nozzle diameter
$f_1(\alpha_e)$ = function defined by equation (2)
$f_2(\alpha_e)$ = function defined by equation (3)
$g(\alpha_e)$ = $f_1(\alpha_e)/f_2^2(\alpha_e)$
H = vickers hardness of the target material
h = maximum depth of cut
K_c = fracture toughness of target material
k = kerf constant
$\dot{m}_a$ = abrasive mass flow rate
r = particle radius
u = traverse speed
$\dot{V}$ = material volume removal rate (erosion rate)
δV = idealized volume removal by an individual abrasive particle
v = particle impact velocity
v_o = initial abrasive particle velocity
α = local kerf angle
α_e = jet exit angle at the bottom of the workpiece
ρ = particle density

A. A. Abdel-Rahman is with the Mechanical Engineering Department, Beirut Arab University, Debbeih Campus, Beirut, Lebanon, on leave from Mechanical Engineering Department, Alexandria University, Egypt (e-mail: adel.abdel-rahman@eng.alex.edu.eg).

I. INTRODUCTION

A water jet as an erosive agent, without abrasives, has been used to cut materials such as composites, paperboard, asphalt-based materials, foamed plastics, rubber, nylon, mineral fibers, fiberglass, high-pressure laminates, plywood, gypsum board, automotive fabrics, and food products, see figure (1). The major advantages of waterjet cutting over other cutting techniques can be found in [1].

Successful applications have been reported for cutting, slitting, and trimming in the aerospace, automotive, building products, disposables, electronics, food, paper, steel industries, and many others, [2]-[5].

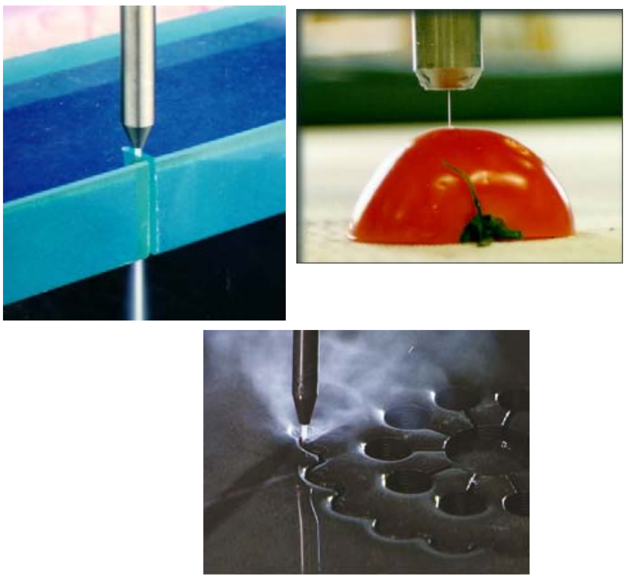

Fig. 1 Water jet is used in cutting different materials

Material cutting using abrasive waterjets (AWJS) is a new process technology that is becoming increasingly used and rapidly spread in much industrial application. Details of the cutting technique including its limitations and applications are also given in [1]. The advantages offered by the abrasive waterjet as a new cutting technique make it well suited to compete and even replace many traditional and non-traditional cutting techniques. The potential of abrasive waterjet cutting technique in turning, milling and drilling has been demonstrated.

Abrasive waterjet cutting operates by the impingement of a high-velocity abrasive-laden water jet against the work-piece. It produces no heat, and therefore no heat-affected zone, to degrade metals or other materials. The finished edge obtained by the process often eliminates the need for postmachining to improve surface finish.

A coherent waterjet is formed by forcing high-pressure abrasive-laden water through a tiny sapphire orifice (figure 2). The momentum transfer between the water and the abrasives creates a focused high-velocity stream of particles that exits the nozzle at more than twice the speed of sound and cuts as it passes through the workpiece. Cuts can be initiated at any point on the workpiece and can be made in any direction of contour, linear, or tangential. The narrow kerf produced by the stream results in neither delamination nor thermal or nonthermal stresses along the cutting path.

In addition to applications in the machining of superalloys; armor plate; titanium; and high-nickel, chromium, and molybdenum alloys, abrasive waterjet machining can also be used to cut concrete, rock, glass, ceramics, composites, and plastics. The ability of the abrasive waterjet to cut most metals without any thermal or mechanical distortion places this innovate process on the leading edge of material cutting technology and has accelerated its development. The primary components of an abrasive waterjet cutting system are the dual intensifying pump, the nozzle assembly and the abrasive catcher assembly. These components are connected by a network of hoses and swivels and are controlled by a system of control valves and sensors. A block diagram of an abrasive waterjet cutting system components is shown in figure (3), while figure (4) shows a block diagram of a new generation of AWJ cutting system.

Advanced ceramics have been increasingly used in optical, electronic, mechanical and biological industries due to their inherent superior high temperature strength, hardness, wear and corrosion resistance. Since ceramics are extremely hard, high cost and dimension accuracy are two main problems encountered in the cutting process. Abrasive waterjet cutting technique has emerged as a promising machining method for ceramics and hard materials, in general.

Machining performance, including depth of cut and cut quality is a major technological challenge to the AWJ machining technology. Machinability of ceramics by abrasive waterjets has been studied by Hocheng and Chang [6]. They tried to correlate between the quality of aluminum oxide and silicon nitride ceramics in slotting and the major machining parameters of the abrasive waterjet. Their experimental results for slot cutting were evaluated in terms of material removal rate, kerf shape and surface roughness. They concluded that a sufficient supply of hydraulic energy as well as fine-mesh abrasives at moderate traverse speed produce a smooth kerf surface. Ramulu and Arola [7] have undertaken an experimental investigation to determine the influence of the cutting parameters on the surface roughness and kerf taper of a graphite / epoxy laminate, machined by an abrasive waterjet system.

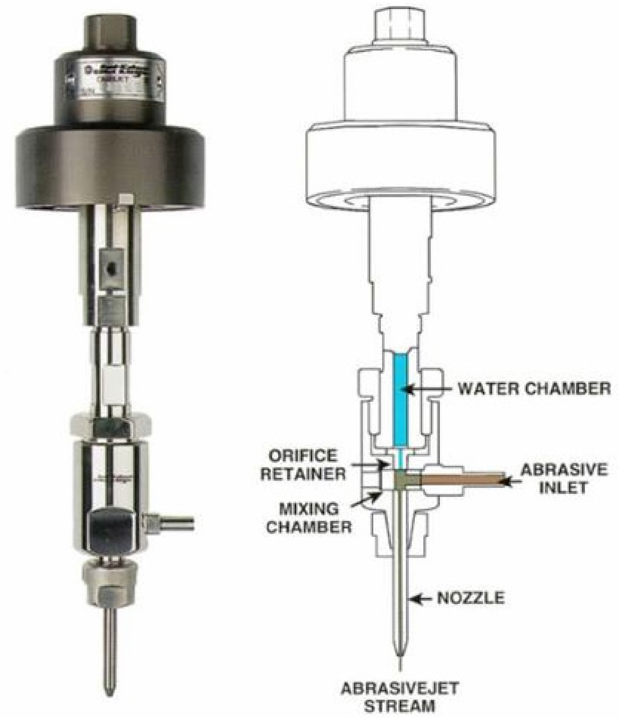

Fig. 2 Typical nozzle configuration for mixing abrasive with waterjet in an abrasive waterjet cutting head

The feasibility of using abrasive waterjets for precision drilling of small diameter holes in a ceramic-coated components has also been studied by [8]. The results obtained indicate that the hole quality can be controlled by controlling the jet dwell time and feed rate. Chen et al. [9] have studied experimentally the effect of jet impact angle on the cutting quality. They also applied new oscillation technique for the cutting head to better cutting ceramic materials. Liu et al. [10] carried out a computational fluid dynamics study to understand the jet and particle dynamic characteristics so as to optimize the jetting and process parameters for enhancing the cutting performance. Wang and Liu [11] developed a jet characteristics model that enabled to evaluate the particle velocity distribution along and across an AWJ. Srinivasa et al. [12] have studied the influence of impingement angle and feed rate on the kerf geometry of silicon carbide. As a result, they established a good basis for developing strategies for controlled 3D AWJ machining of complex shapes. Other research works were done to improve the cut surface, observe the effect of process parameters on the cut surface and depth of cut, [13]-[16].

In order to effectively control and optimize the AWJ cutting process, predictive models for the depth of cut, are required.

Yang et al. [17] used a neural network approach in modeling the surface roughness, while Saxena and Paul [18] developed numerical models for the various kerf characteristics. A number of mathematical models for the material removal rate and depth of cut have been reported, including those using solid particle erosive theories ([19], [20]), an energy conservation approach ([9], [21]), fracture mechanics ([22], [23]), and dimensional analysis [24].

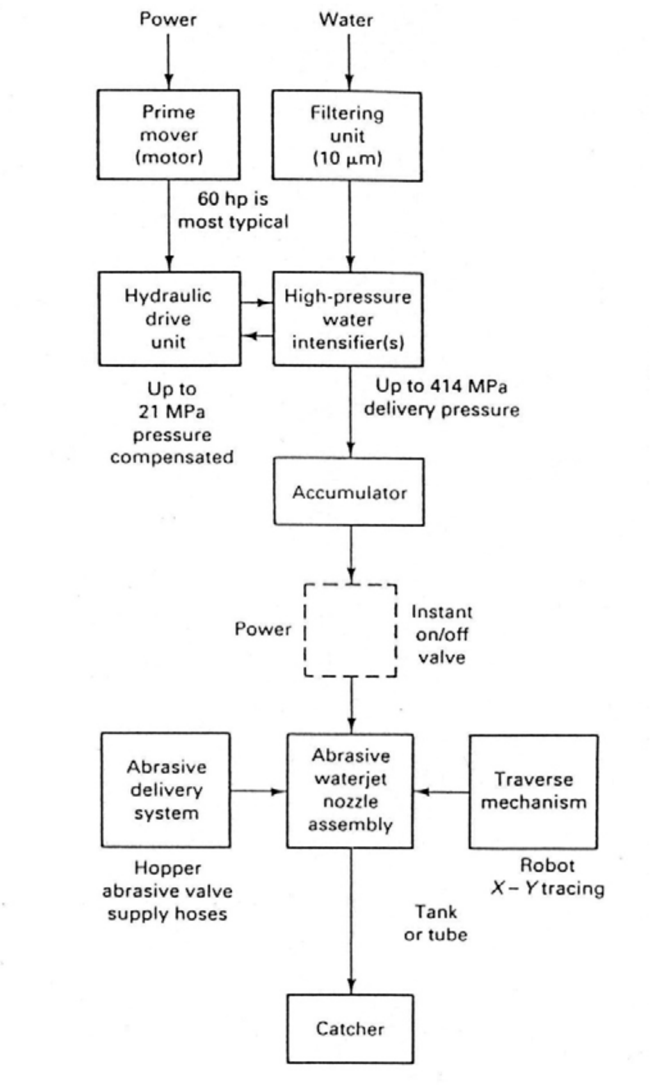

Fig. 3 Block diagram of abrasive waterjet system components

Erosion of ceramic materials has been generally viewed as a brittle fracture process, which occurs mainly by chipping. A more modern view of ceramic erosion is based on the assumption that plastic deformation plays a crucial role in the chipping process (e.g [25]-[27]). The morphology of fractures formed in ceramic materials during impact can be divided into two classes depending on whether the impacting particle is blunt or sharp ([28], [29]). The distinction between blunt and sharp particle impact is a distinction that depends on the role of plastic deformation in the impact process. The particle velocity that characterizes the transition between the formation of Hertzian cracks and the formation of radial cracks depends on the hardness, fracture toughness, and surface structure of the target material.

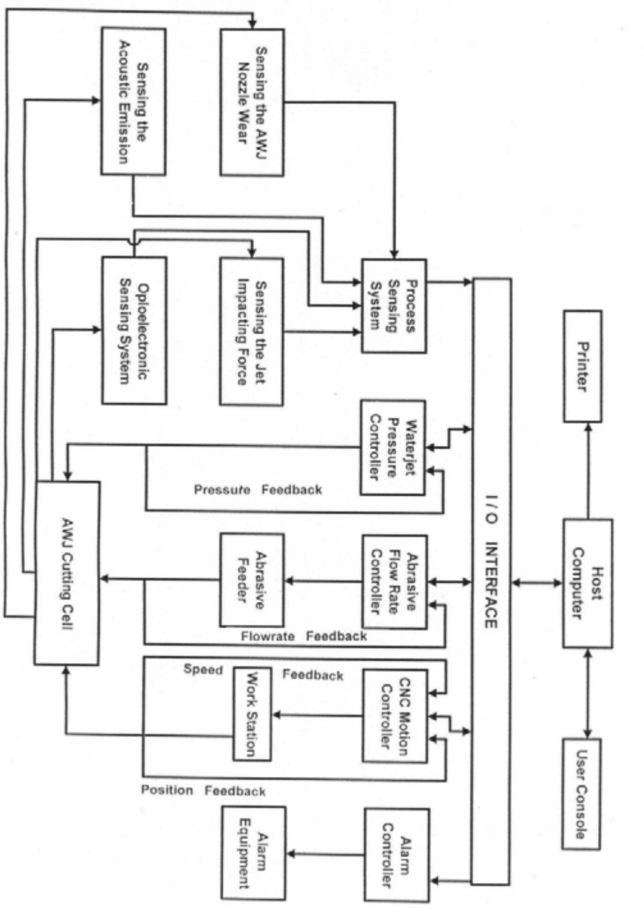

Fig. 4 Block diagram of abrasive waterjet system components

II. THE WATERJET CUTTING MODEL

In the present section, an AWJ cutting model is developed and presented. The model is based on an erosion model for brittle materials [30] and given by:

$$\delta V = c\, v^{22/9}\, r^{11/3}\, \rho^{11/9}\, K_c^{-4/3}\, H^{1/9} \qquad (1)$$

Where δV is the volume removal rate by an individual particle, c is the proportionality constant, v is the particle impact velocity, r is the particle radius, ρ is the particle density, K_c is the fracture toughness, and H is the vickers hardness of the target material. It is worth mentioning at this point that the erosion model, given by equation (1), suggests that the material volume removal depends, among others, on the fracture toughness of the target material, K_c. The model is based on the assumption that the lateral crack size is proportional to the radial crack size, and that the depth of the lateral crack is proportional to the maximum particle penetration.

The idea of the modeling is to relate the macro material removal rate to the accumulated effect of micro cutting of the individual abrasive particles. Therefore, to determine the erosion rate for multiparticle, the volume removal by a single particle as given by equation (1) is to be multiplied by the total number of impacts suffered by the target material. But since not all abrasive particles participate in the erosion process, only a fraction of this total volume is actually eroded. This can be accounted for by introducing an abrasive efficiency factor C [31]. It is now possible to express the accumulated volume material removal rate as;

$$\dot{V}=\int C\left(\frac{\dot{m}_a}{m}\right)(\delta V) \tag{2}$$

Assuming that the abrasive particles are of spherical shapes, the mass of a single particle is thus given by

$$m=\tfrac{4}{3}\pi r^3 \rho \tag{3}$$

Substituting for δV and m from equations (1) and (3) into equation (2), the volume removal rate is given by;

$$\dot{V}=\int C\frac{c}{\frac{4}{3}\pi}\left(\dot{m}_a\ v^{22/9}\ r^{2/3}\ \rho^{2/9}\ K_c^{-4/3}\ H^{1/9}\right) \tag{4}$$

The particle impact velocity v can be related to the initial particle velocity [31]as:

$$v=v_o\cos^2\alpha \tag{5}$$

Substituting for v from equation (5) into equation (4) and integrating along the kerf length (from $\alpha = 0$ to $\alpha = \alpha_e$), one gets:

$$\dot{V}=C\frac{c}{\frac{4}{3}\pi}\left(\dot{m}_a\ v_o^{22/9}\ r^{2/3}\ \rho^{2/9}\ K_c^{-4/3}\ H^{1/9}\right)f_1(\alpha_e) \tag{6}$$

Where

$$f_1(\alpha_e)=\frac{1}{5}\left(\sin\alpha_e\cos^4\alpha_e\right)-\frac{4}{15}\left(\sin^3\alpha_e\right)+\frac{4}{5}\left(\sin\alpha_e\right)$$

In equation (6), it was assumed that the cutting front is parabolic, $x=ky^2$ (figure 5), and the particle velocity v varies according to $v= v_0\cos^2\alpha$. Details on these assumptions can be found in [31]. The abrasive efficiency factor, C, was also introduced [17]. It is to be noted that the particles have been assumed to have spherical shapes. It was further shown in [31] that the material removal rate may be given by:

$$\dot{V}=u\,d_j\,h\,f_2(\alpha_e) \tag{7}$$

where

$$h=\frac{\tan\alpha_e}{2k}$$

and

$$f_2(\alpha_e)=\frac{1}{2\tan\alpha_e}\left[\frac{\tan\alpha_e}{\cos\alpha_e}+\ln\left\{\tan\left(\frac{\pi}{4}+\frac{\alpha_e}{2}\right)\right\}\right]$$

Now, equating (7) to (6), one gets:

$$h=B\,g(\alpha_e)\left(\frac{1}{u\,d_j}\right)\left(\dot{m}_a\ v_o^{22/9}\ r^{2/3}\ \rho^{2/9}\ K_c^{-4/3}\ H^{1/9}\right) \tag{8}$$

Where the following substitutions were made:

$\frac{1}{f_2(\alpha_e)}$ for C , B for $\frac{c}{\frac{4}{3}\pi}$, and $g(\alpha_e)$ for $\frac{f_1(\alpha_e)}{f_2^2(\alpha_e)}$

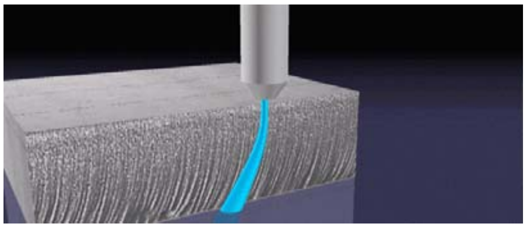

Fig. 5 Water jet cutting front

Equation (8) now represents the proposed cutting model for brittle materials.

If the waterjet models are to include the water pressure, P, as a parameter, the following relation between v_o and P can be used:

$$v_o=\frac{1}{1+R}\sqrt{\frac{2P}{\rho_w}} \tag{9}$$

Equation (9) is derived from basic fluid mechanics and conservation of momentum where R is given by:

$$R=\frac{\dot{m}_a}{\dot{m}_w} \tag{10}$$

Further, the conservation of mass is used to give the relation between $\dot{m}_w$ and P as:

$$\dot{m}_w=\frac{\pi}{4}\rho_w\,d_j^2\sqrt{\frac{2P}{\rho_w}} \tag{11}$$

III. MODEL PREDICTIONS

The cutting model given by equation (4) relates the maximum depth of cut, h, to the target material properties and the major process parameters. The only unknowns in the model are the constant B and the function $g(\alpha_e)$. The exit angle, α_e , as illustrated in [17], would be in the range of 70° to 90°. The value of g (α_e) for an average value of $\alpha_e = 80^{\circ}$ is calculated and found to take a value of 0.05571 (see table 1). The experimental results of the maximum depth of cut of Zeng and Kim [32], were used to calculate the model constant B. The value of this constant is calculated and given also in table (1). It is interesting to find that the constant B is practically independent of the material type and process parameters. Therefore, the constant reported in table (1) is actually an average value of all the constants which have been obtained from using the three ceramic materials (AD 85, AD 94, and AD 99.5) and the 15 different process parameters used in [32].

Having determined the constant B and the function g(α_e) , the present cutting model can now be used to determine the maximum depth of cut. It is worth mentioning here that in an earlier work by the author, [17], a waterjet cutting model has been developed which was based on a different erosion model than the one used here. A comparison between the two models will be made as we demonstrate the predictive capability of the present model.

The predicted depth of cut of the present model for 7 different ceramic materials are shown in figure (6), refer to table (2) for the ceramic materials used and their properties. For the sake of comparison, prediction results of the previous model (1998) are also included in figure (6). The figure clearly displays a good agreement between the predictions of both models. The two models are found to predict the same maximum depth of cut for all materials used (except for silicon carbide) within an average value of 3.9%.

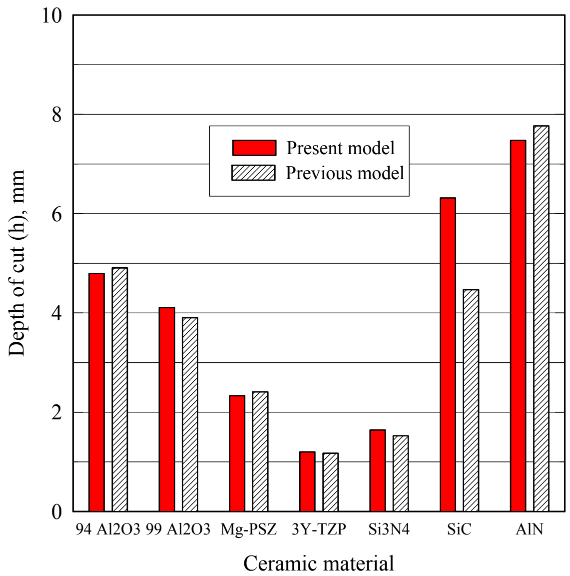

Fig. 6 Depth of cut for different ceramic materials
(450 g/min abrasive flow rate; 1.25 mm nozzle diameter; 70 mm/min traverse speed; 200 MPa water pressure;)

TABLE 1
. VALUE OF THE FUNCTION g(α_e) AND THE CONSTANT B USED IN THE MODEL EQUATION

MODEL	
$h = B\, g(\alpha_e) \left(\frac{1}{u\, d_j} \right) \left(\dot{m}_a\; v_o^{22/9}\; r^{2/3}\; \rho^{2/9}\; K_c^{-4/3}\; H^{1/9} \right)$	
g (α_e)	0.05571 at $\alpha_e = 80^o$
B	1.003×10^{-2} , 1×10^{-3} st. dev. and 2.2×10^{-4} st. error

TABLE 2
PROPERTIES OF CERAMIC MATERIALS

Ceramic material	Alumina ceramic		Zirconia ceramic		Silicon Nitride	Silicon Carbide	Aluminum Nitride
	94% Al_2O_3	99.5% Al_2O_3	*Mg-PSZ*	*3Y-TZP*	Si_3N_4	*SiC*	*AlN*
Density (kg/m^3)	3690	3890	5600	6050	3250	3160	3260
Hardness (GPa)	11.5	14.1	11.2	13	15	32	11
Compressive stress (MPa)	2100	2620	1800	2100	2000	2000	2100
Fracture toughness (MPa$\sqrt{m}$)	3.5	4	6	10	8	3.1	2.5
Thermal conductivity (W/m K)	18	35	2.5	2	25	114	140
Coeff. of thermal expansion (1/°C)	8.1×10^{-6}	8.4×10^{-6}	10×10^{-6}	10×10^{-6}	3×10^{-6}	1.1×10^{-6}	4.5×10^{-6}
Specific heat (J/kg K)	880	880	400	400	800	715	740

Figure (7) represents the variation of the depth of cut with the traverse speed for two water pressures, namely; 100 and 400 MPa. It can be seen that both models predict the same maximum depth of cut within an average of 13% difference for the 100 MPa pressure, and 18% difference for the 400 MPa. However, it is to be noted that the present model predicts values of depth of cut higher than those predicted by the previous model for the 100 MPa pressure. But, the opposite can be seen for the 400 MPa pressure, where the previous model predicts a larger depth of cut.

Figure (8) represents the effect of the abrasive flow rate on the maximum depth of cut for the same two pressure values; 100 and 400 MPa. For the low water pressure (100 MPa) the increase of the abrasive flow rate does not significantly contribute to the increase in the depth of cut. On the other hand, the depth of cut is observed to increase significantly with the abrasive flow rate for the high water pressure (400 MPa). As can be seen from the figure, the present model still predicts higher values for the maximum depth of cut than the previous model does for the low water pressure, and lower values for the high water pressure.

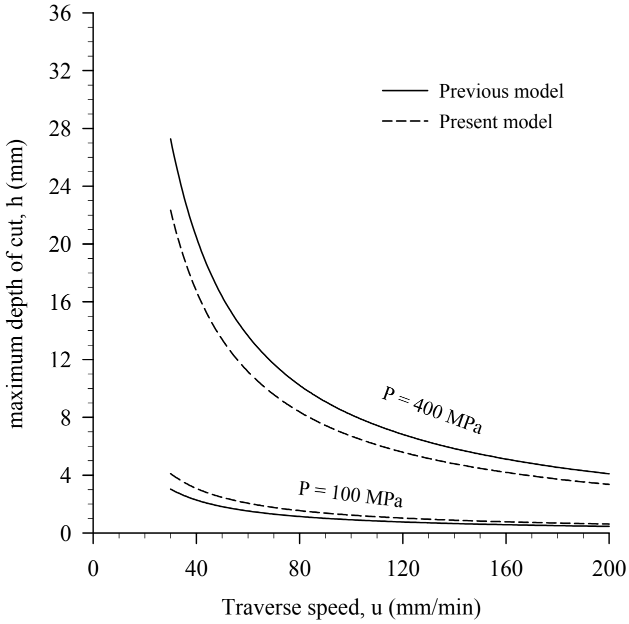

Fig.7 Effect of traverse speed on depth of cut
(mesh 80 garnet abrasive; 450 g/min abrasive flow rate; 1.25 mm nozzle diameter; Al_2O_3 ceramic target material)

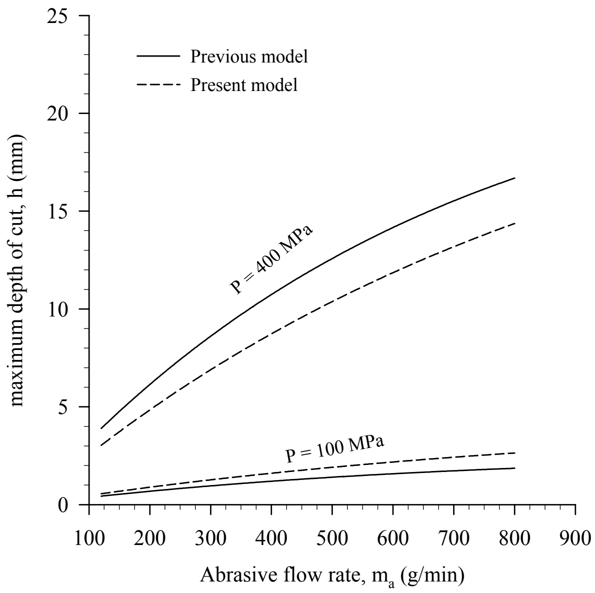

Fig.8 Effect of abrasive flow rate on depth of cut
(mesh 80 garnet abrasive; 70 mm/min traverse speed; 1.25 mm nozzle diameter; Al_2O_3 ceramic target material)

IV. COMPARISON WITH EXPERIMENTAL WORK

Comparison of the present model with the experimental results of Zeng and Kim [32] for two process parameters (traverse speed and abrasive flow rate) are shown in figures (9) and (10) for the AD99.5 ceramic. The range of process parameters used in these figures is the same as that used in [32].

The effect of jet traverse speed on the maximum depth of cut is shown in figure (9), where the experimental results of Zing and Kim are included for comparison. The figure is seen to display a good agreement between the present model predictions and the experimental data for the maximum depth of cut, particularly for the range of traverse speeds between 25 mm/min and 125 mm/min. Table (3) reports the percentage difference between the predicted and the experimental values of the depth of cut.

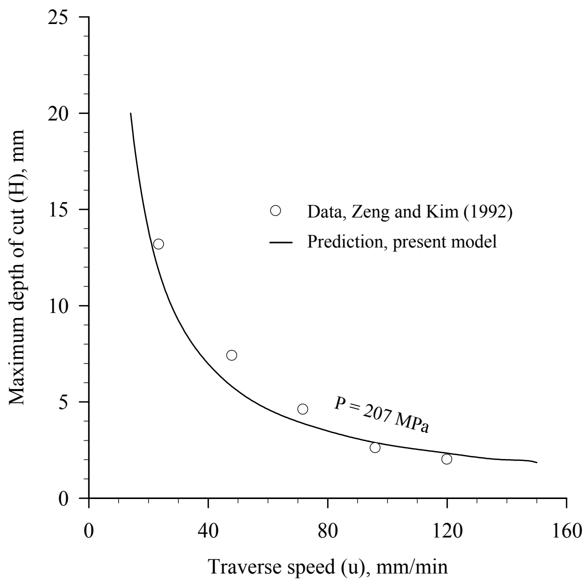

Fig.9 Variation of maximum depth cut with traverse speed (comparison)
(mesh 80 garnet abrasive; 453.6 g/min abrasive flow rate; 1.27 mm nozzle diameter; AD 99.5 target material)

TABLE 3
%ge DIFFERENCE OF MAXIMUM DEPTH OF CUT FOR DIFFERENT TRAVERSE SPEEDS

Traverse speed (mm/min.)	22	48	70	95	120
%ge difference	≈ 0%	- 1.2%	-5.5%	1.6%	2.3%

Comparison of the model with experiments at different abrasive flow rates is presented in figure (10). The model is seen to predict the experimental results reasonably well, within a maximum of 8.3%. Percentage differences between the predicted and experimental results are given in table (4) for the different abrasive flow rates.

TABLE 4
%ge DIFFERENCE OF MAXIMUM DEPTH OF CUT FOR DIFFERENT ABRASIVE FLOW RATES

Flow rate (g/min.)	340	450	550	670	800
%ge difference	6.2 %	-8.3 %	-3.3%	-2.2%	4.3%

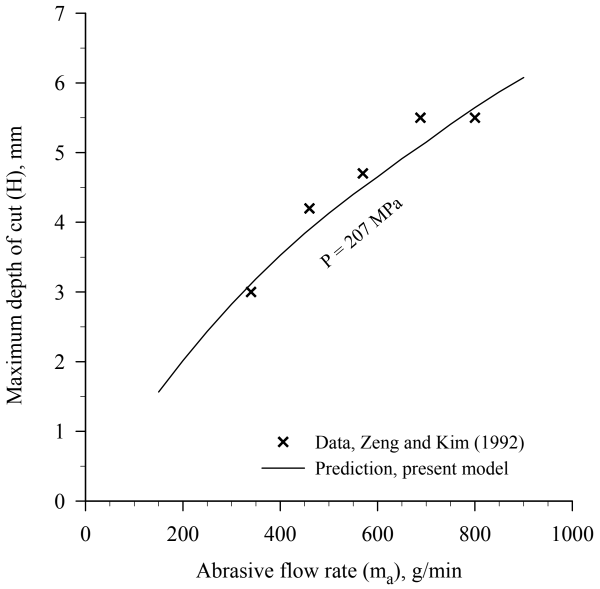

Fig. 10 Variation of maximum depth cut with abrasive flow rate (comparison)

(mesh 80 garnet abrasive; 72 mm/min traverse speed; 1.27 mm nozzle diameter; AD 99.5 target material)

V. CONCLUSIONS

The accurate and efficient use of the AWJ for cutting many engineering materials depends, to a great extent, on the right choice of the process parameters. This right choice could either be based on available experimental data or reliable mathematical model correlating all parameters involved. In the present work, a cutting model for brittle materials has been introduced and its predictions are discussed and compared with experimental results. The cutting model is based on an available erosion model which contain the property of fracture toughness, among other properties, of the target material. It is established that an erosion model containing the property of the fracture toughness is suitable for brittle materials such as ceramics.

The proposed model offers simple and closed form equation that can be used to predict the maximum depth of cut for brittle materials.

The cutting model is found to predict the experimental maximum depth of cut within an average value around 10%; averaging over all process parameters. It is also found that the predicted values of the maximum depth of cut correlate with the experimental results with a correlation coefficient of ≈ 0.95.

REFERENCES

[1] R. K. Miller, *Waterjet Cutting*. The Fairmont Press, Inc. 1991, ch. 1.

[2] A. Deaconescu and T. Deaconescu, "Performance of Macining by Waterjet Erosion", *WSEAS International Conference Proceedings*. Mathematics and Computers in Science and Engineering. Vol. 2, no. 1, ISBN: 978-960-474-122-9.

[3] F. Yuefeng and W. Xiaoyong, "Mechanism Disquisition of De-rusting by Ultra-high Pressure Waterjet", *Proceedings of the 6th WSEAS International Conference on Heat and Mass Transfer (HMT'09)*, ISBN: 978-960-474-39-0.

[4] F. Yuefeng, "Study on the Applications of Extra-high Pressure Water Jet Technology", *WSEAS Transactions on Electronics, in press*.

[5] H. El-Hofy and H. Youssef, "Environmental Hazards of Nontraditional Machining", *Proceedings of the 4th IASME/WSEAS International Conference on Energy & Environment (EE'09)*, ISBN: 978-960-474-055-0.

[6] H. Hocheng, and K.R. Chang, "Material removal analysis in abrasive waterjet cutting of ceramic plates", *J. Mater. Process. Technol*, 40, pp. 287-304, 1994.

[7] M. Ramulu, and D. Arola, "Influence of abrasive waterjet cutting conditions on the surface quality of graphite/epoxy laminate", *Int. J. Mach. Tools Manuf*. 34, pp. 295-313, 1994.

[8] M. Hashish, and J. Whalen, "Precision drilling of ceramic-coated components with abrasive-waterjets", *J. Engineering of Gas Turbines and Power, Trans., ASME*, 115, pp. 148-154, 1993.

[9] L. Chen, E. Siores, and W.C.K. Wong, "Optimising abrasive waterjet cutting of ceramic materials", *J. Mater. Process. Technol*. 74, pp. 251-254, 1998.

[10] H. Liu, J. Wang, N. Kelson, and R. Brown, "CFD simulation and mathematical models of the abrasive waterjet characteristics", *J. Mater. Process. Technol*. 153–154, pp. 488–493, 2004.

[11] J. Wang, and H. Liu, "Profile cutting on alumina ceramics by abrasive waterjet. II. Cutting performance models", *Proc. Inst. Mech. Engrs. Part C: J. Mech. Eng. Sci*. 220, pp. 715–725, 2006.

[12] D.S. Srinivasu, D.A. Axinte, P.H. Shipway, and J. Folks, "Influence of kinematic operating parameters on kerf geometry in abrasive waterjet machining of silicon carbide ceramics", *Int. J. Mach. Tools Manuf.*, 49, pp. 1077-1088, 2009.

[13] R. Balasubramanian, J. Krishnan, and N. Ramakrishnan, "A study on the shape of the surface generated by abrasive jet machining", *J. Mater. Process. Technol*. 121, pp. 102-106, 2002.

[14] G. Vikram, and N.R. Babu, "Modelling and analysis of abrasive water jet cut surface topography", *Int. J. Mach. Tools Manuf*. 42, pp. 1345-1354, 2002.

[15] R.T. Deam, E. Lemma, and D.H. Ahmed, "Modelling of the abrasive water jet cutting process", *Wear* 257, pp. 877-891, 2004.

[16] M. Junkar, B. Jurisevic, M. Fajdiga, and M. Grah, "Finite element analysis of single-particle impact in abrasive waterjet machining", *Int. J. Impact Engineering*, 32, pp. 1095–1112, 2006.

[17] L. Yang, J. Song, and B. Hu, "Neural Network parametric modeling of abrasive waterjet cutting quality", *Int. J. Abrasive Technol*. 1, pp. 198-207, 2007.

[18] A. Saxena, and S. Paul, "Numerical modelling of kerf geometry in abrasive water jet machining", *Int. J. Abrasive Technol*. 1, pp. 208–230, 2007.

[19] M. Hashish, "A modeling study of metal cutting with abrasive waterjet", *J. Eng. Mater. Technol*. 106, pp. 88-100, 1984.

[20] R.J. Wilkins, and E. Graham, "An erosion model for waterjet cutting", *J. Eng. Ind*., 115, pp. 67-61, 1993.

[21] J. Wang, and D.M. Guo, D.M., "A predictive depth of penetration model for abrasive waterjet cutting of polymer matrix composites", *J. Mater. Process. Technol*. 121, pp. 390–394, 2002.

[22] A.A. Abdel-Rahman, and A. A. El-Domiaty, "Maximum depth of cut for ceramics using abrasive water jet technique", *Wear*, 218, pp. 216-222, 1998.

[23] S. Paul, A.M. Hoogstrate, C.A. Van Luttervelt, and J.J. Kales, "Energy partitioning in elastro-plastic impact by sharp abrasive particles in the abrasive water jet machining of brittle materials", *J. Mater. Process. Technol*. 73, pp. 200–205, 1998.

[24] J. Wang, "A new model for predicting the depth of cut in abrasive waterjet contouring of alumina ceramics", *J. Mater. Process. Technol*. 209, pp. 2314-2320, 2009.

[25] A.W. Ruff, and S.M. Wiederhorn, "Erosion by solid particle impact", in *Treatise on material science and technology*, 16, *Erosion*, C. Preece, Ed, New York: Academic Press, 1979, p.69.

[26] S.M. Wiederhorn, and B.J. Hockey, "Effect of material parameters on the erosin resistence of brittle materials", *J.Material Science*,18,pp. 766-780, 1983.

[27] J.E. Ritter, "Erosion damage in structural ceramics", *Material Sci. Eng*., 71, pp. 195-207, 1985.

[28] B.R. Lawn, and T.R. Wilshaw, "Fracture of brittle solids, *J. Material Science"*, 10, pp. 1049-1081, 1975.

[29] B.R. Lawn, and D.B. Marshall, "Flaw and testing", in *Fracture mechanics of ceramics*, B. C. Bradt, D. P. H. Hasselman, and F. F. Lange, Eds, 3, New York: Plenum Press, 1978.

[30] S.M. Wiederhorn, and B.R. Lawn, "Erosion of brittle materials by solid particle impact", *J. American Ceramic Society*, 62, pp. 66-70, 1979.

[31] A.A. El-Domiaty, M. A. Shabara, A.A. Abdel-Rahman, and A.K. Al-Sabeeh, "On the modeling of abrasive waterjet cutting", *Int. J. Adv. Manuf. Technol*, 12, pp. 255-265, 1996.

[32] J. Zeng, and T.J. Kim, "Development of an abrasive waterjet kerf cutting model for brittle materials", *11th Int. Conference on Jet Cutting Technology*, St. Andrews, Scotland, September 8-10, 1992, pp. 483-501.

Adel A. Abdel-Rahman received his B.Sc. (distinction, honors), M.Sc. (1981) in mechanical engineering from Alexandria University, Egypt, and Ph.D. (1987) in mechanical engineering from University of Waterloo, Waterloo, Canada.

He is a professor of mechanical engineering at Alexandria University, Egypt (currently on leave at Beirut Arab University, Lebanon). He spent a few years as a faculty member in the mechanical engineering department at university of Kuwait. He was a visiting professor at the Institute of Turbomachinery & Gas Turbines in Hanover, Germany in January, 1997. He has given public lectures to the engineering communities in Lebanon, Germany, Kuwait, and Egypt. He has published over 55 research papers in refereed journals and conference proceedings; e.g.: Diffusion Characteristics of a Plane Jet Discharged in a Wavy Crossflowing Stream (UK, IMechE 2004), The Effect of Carbon Dioxide in Non-air inlet Mixture on Combustion Performance in Diesel Engine (Italy, IREME, Praise Worthy Prize 2009), On the Atmospheric Dispersion and Gaussian Plume Model (Greece, Corfu, 2nd WSEAS/IASME conf., WWAI '08, 2008). He is a reviewer to two international journals on turbulent jet flows and hot-wire anemometer. His current research interests are in the areas of Turbulent jets, Waterjet cutting processes, ICE, and environmental pollution.

Prof. Abdel-Rahman has been awarded an outstanding achievement awards from the Egyptian and Canadian Governments. He has been active over the past 15 years in the fields of Safety and fire protection with governmental, private sector and petroleum agencies. He has given many short and training courses in the fields of Hazard Identification, Workplace Safety, Risk Assessment, Emergency Preparedness, Automatic Fire-fighting systems, and many others in Lebanon, UAE, Egypt, and Kuwait. He is a member of ASME, AIAA, SES (Society of Engineering Science-USA), ISWJT (International Society of Water Jet Technology), and ESE (Egyptian Syndicate of Engineers), Egypt.