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Modeling and Experimental Investigation of Abrasive Jet Machining of Glass

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Abstract

This paper presents a modeling approach implemented to consider the effects of the process parameters of Abrasive Jet Machining (AJM), namely applied pressure (Pr), standoff distance (SoD), nozzle diameter (dn) and particle grain size (dg) on machining performance. In particular, a previously reported model of the AJM was adapted to improve its capability to predict material removal rate (MRR) more accurately. In order to validate the developed model experimentally and at the same time to examine the influence of the machining conditions on the MRR, a series of drilling tests have been carried out on glass workpieces using sand as an abrasive powder. After each cutting trial, the MRR was quantified which enabled characterizing the influence of the applied process parameters on the machining performance in terms of resultant MRR. In addition, the experimental results were compared with those obtained by the proposed model, where a relatively acceptable agreement between both results was achieved with an average error of 39%. Also, the experimental results have revealed that MRR is highly dependent on the kinetic energy of the abrasive particles and the applied pressure was found to be the most significant parameter that dominated the material removal rate.

Keywords: AJM, MRR, process conditions, modeling, experimental validation

1. Introduction

In abrasive jet machining, the material is removed from the wokpiece by mechanical abrasion. Particularly, a focused stream of fine abrasive particles carried by highly pressurized air, are accelerated to hit the workpiece surface. The high pressure of air or gas generates high kinetic energy of the particles which pass from the nozzle with high velocity to impact the workpiece. As the particles get in contact with the workpiece, they cause small fractures, and the gas stream carries both the abrasive particles and the fractured particles away [1, 2, 3]. AJM is an effective machining method for hard and brittle materials. Moreover, in addition to its wide applications at macro-scale, it recently plays a significant role in micro-machining, especially micro sized features such as micro-channels; micro-holes for the manufacture of micro-devices. For high efficiency of AJM process, it is necessary to optimize input parameters to increase its material removal rate (MRR) while obtaining good quality of the generated surface. However, up to the knowledge of the author, there has been no adequate and comprehensive investigation that enables further advancement of this technology. Therefore, the motivation for this research study was to address the lack of scientific understanding via carrying out a systematic study to investigate the abrasive jet machining process by assessing the influence of the process parameters and thus to control them for the best possible performance of the process. In particular, the aim of this study was to modify a pre-existing model of the AJM to enable precise prediction of MRR for different process parameters. The proposed approach was experimentally validated via experimental trials under a range of applied pressure (Pr), standoff distance (SoD), nozzle diameter (dn), and particle grain size (dg) and thus to identify the process input/output relationships.

2. Related Work

A considerable number of investigations have been carried out on AJM to explain various erosion mechanisms and to study the factors influencing performance of the process in matters such as material removal rate (MRR), dimensional accuracy and obtainable surface quality. Two erosion modes have been often illustrious in the literature: brittle and ductile erosion. In brittle fracture, the material removal occurs due to the formation of cracks and their propagation [4-6]. When the particles impact the workpiece with high force, the contact area is plastically deformed by high compression. It generates large tensile stresses in target material that results in radial and lateral crack formation [7-13]. The material removal takes place when the lateral crack reaches the surface [7] as shown in Fig.1. The volume of cracks depends mainly on the mechanical properties of the target material and the kinetic energy of the particle [9-11].

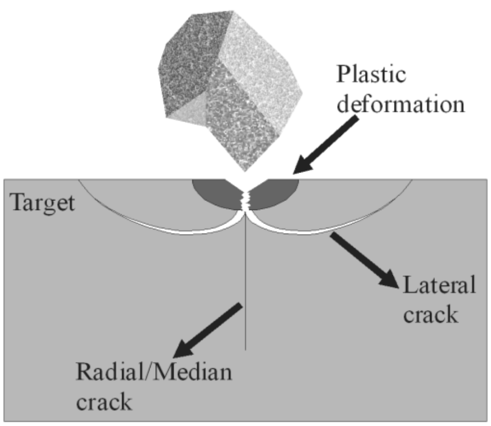


Fig.1. Mechanism of brittle erosion by solid particle impact [7]

In ductile mechanism, the material removal takes place by plastic deformation due to shearing stresses. Ductile materials show the maximum erosion rate at a small impact angle [14-17]. At low angles, the particles sweep into the surface and leave again with amount of residual kinetic energy, however at higher angles the particle comes to rest in the surface during cutting [16]. Maximum erosion rate for brittle materials is occurred at 90° impact angle, while maximum erosion rate for ductile martial is occurred at 15°-30° impact angle [15, 17 and 18].

The effect of process parameters on erosion rate for impact with solid particles are major topics of many research works in the recent years. Sundararajan and Roy [17] investigated the effects of particle shape on the erosion rate. It was found that angular particles caused higher erosion than round ones at small impact angle. Also, Desale, et al. [19] reported that the increase in density, hardness and angularity of the impact particles causes an increased wear. Moreover, the abrasive size effect has been reported in many researches [20-23]. These results showed that increasing in particle size leads to large and deeper indentation, which in turn results in higher erosion rate. Hutchings [24] conducted an experimental investigation of the AJM where he measured the erosion rate for both ductile and brittle material under different values of particles' velocities. It was found that the erosion rate increased by increasing the particles velocities. Muju [25] reported that increasing the standoff distance leads to an increase in the erosion. This is valid up to a certain value, however, beyond this value, the erosion rate decreases again. This is mainly attributed to the effect of standoff distance on velocity of particles and its associated kinetic energy. Wakuda et al. [26] investigated the effect of properties of workpiece and abrasive powder when machining ceramic materials by AJM. It was found that material removal rate was affected by fracture toughness and hardness of the target materials. Moreover, the type of abrasive significantly influenced the material removal rate.

A number of experimental studies on the machining of glass by AJM have been studied [27-35]. El-Domiaty et al. [27] experimentally studied the AJM via conducting a series of drilling experiments using sand as abrasive with different values of process parameters. They found that the MRR increased by increasing the particle size, pressure and nozzle diameter. Chandra and Kandpal et al. (2011) [28-29] also carried out drilling tests of glass by AJM. Their results showed that as the pressure is increased the MRR increased. Besides, the top diameter and bottom diameter of holes increased with increasing the standoff distance. Vadgama et al. [30] and Padhy et al. [31] used Taguchi method to design experiments for drilling glass by AJM. It was found also that MRR increased with the increase of both pressure and standoff distance up to a certain limit and then the curve returns to reveal the decrease of MRR. Sharma et al. [32] found that the taper cut and over cut of produced holes decreased by increasing pressure and nozzle diameter and decreasing standoff distance. Grover et al. [33] used Taguchi method and ANOVA to analyze the process parameters on AJM. It was found that MRR decreased by decreasing the impact angle and grain size. Fan et al. [34] developed predictive mathematical models for the material removal rate in micro-machining of holes and channels on glasses by AJM. It was found that the MRR increased with the increase in air pressure and standoff distance and slightly decreased with the increase in abrasive mass flow rate and machining time. Lei Zhang, et al. [35] investigated micro abrasive intermittent jet machining for drilling small holes. This technique was utilized to ensure removing the abrasive particles regularly and thus to prevent system blockage during the process.

3. Material Removal Rate Modeling

As previously stated, when the particles impact the workpiece with adequate force to cause deformation, the contact area is plastically deformed resulting in lateral crack formation. The material removal takes place when the lateral crack reaches the surface [7-13]. According to Jafar's theory [36], each particle impact is assumed to remove a spherical cap of material with a radius and depth equal to that of the predicted lateral crack (C_L). The author assumed that the lateral cracks are initiated at the bottom of the indentation (a) rather than assuming it initiated at the bottom of the plastic zone (b) as shown in Fig. 2.

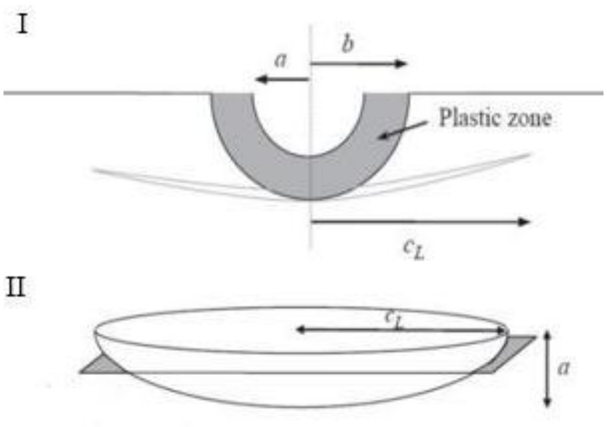


Fig.2 (I) Cross-section of hemispherical indented zone with radius, (a) Generated by a particle impact, the corresponding plastic deformation zone of radius, and (b) the cross section of a circular lateral crack radius, (C_L). (II) Spherical cap representing [36]

a and C_L can be determined in terms of mechanical properties of the target material and the kinetic energy of the particle (U), respectively as shown in Eq.1 and Eq.2 [36].

$$a = [\frac{3U}{2\pi H}]\ 1/3 \qquad (1)$$

$$C_L = \left[\frac{18^{\frac{5}{24}}\sqrt{0.025}\,E^{\frac{3}{8}}\,U^{\frac{5}{12}}}{0.75^{\frac{1}{4}}\,H^{\frac{7}{24}}\,Kc^{\frac{1}{2}}}\right] * \left[1 - \frac{1200^{\frac{1}{4}}\,E^{\frac{1}{4}}\,Kc}{18^{\frac{1}{12}}\sqrt{0.75}\,H^{\frac{13}{12}}\,U^{\frac{1}{6}}}\right]^{0.5} \qquad (2)$$

where, H is the hardness of the target in (Pa), E is the elastic modulus in (Pa), Kc is the fracture toughness in ($Pa.m^{0.5}$) and U is the kinetic energy in (N.m). The kinetic energy of the particle (U) is determined by;

$$U = \frac{1}{2} m_p v^2 \qquad (3)$$

where m_p and v are the mass and velocity of the particle, respectively. Since the particle assumed to have a spherical shape, its mass can be calculated as follows;

$$m_p = \frac{4}{3}\pi\, d_g^3\, \rho_p \qquad (4)$$

where, d_g is particle grain average diameter and ρ_p is the particles density.

The velocity of the abrasive particles, which are carried by air, can be determined by applying Bernoulli equation as the following;

$$v = \frac{d_c^2}{d_n^2} v_c \qquad (5)$$

$$v_c = \sqrt{\frac{2p}{\rho_t}} \qquad (6)$$

where, v is the velocity of particles' stream, which carried by air exit from the nozzle, v_c is the velocity of air stream in compressor tube, d_c is the compressor tube diameter, d_n is the nozzle diameter, and p is the applied pressure.

However, according to Jafar assumption [36], his developed model estimated the volume of the material removed by a single impact as;

$$E_P = \frac{\pi}{6}\rho_t\, a(a^2 + C_L^2)^2 \quad g_{material}/_{particle} \qquad (7)$$

where, ρ_t is the target density. So, to estimate the metal removal rate per second from the previous formula, Eq.8 has to be multiplied by the number of impacts per second, N_p. The number of impacts can be calculating from the following equation;

$$N_p = \frac{\dot{m}_a}{m_p} \qquad (8)$$

where, $\dot{m}_a$ is abrasive mass flow rate, which can be obtained form;

$$\dot{m}_a = \rho_p . A . v = \frac{\pi \, d_n^2 \, v \, \rho_p}{4} \quad g_{particle} / _{min} \qquad (9)$$

Thus, the material removal rate from the surface of the target material can be obtained form;

$$MRR = E_P \times N_p \quad \text{g/min} \qquad (10)$$

As a result, MRR can be predicted using the modified deterministic model, as shown in Eq.10, at different values of kinetic energy of the particles by changing the values of the particles' grain size (dg), applied pressure (Pr) and nozzle diameter (dn).

4. Experimental Investigation

4.1 Machining Setup

In order to carry out the experimental work, the following setup was developed. A ready to use CNC machine with three axis capability was adapted to enable fixing the AJM tool. The machine has a work-table with the following dimensions 150cm * 250cm * 25cm in x-axis, y-axis and z-axis, respectively, with a maximum traverse speed of 120 m/min.

An air compressor with a maximum pressure of 10 bar was used to achieve a range of applied pressure. A number of nozzles were manufactured with 4mm, 5mm and 6mm inner diameters to be utilized in cutting process. Sand was chosen as abrasives particles during the experiments of this study. The nominal aperture sizes of sand (Mesh sizes) were 150, 300 and 600, µm.

Glass was selected as a target material in the experiments. Each sample of glass has a square shape with 50 mm*50 mm edge length and a thickness of 3 mm. The procedure of the experimental work was carried out by fixing the glass sheet on the table of the CNC machine. The gun nozzle is attached in a perpendicular position of the specimen surface as shown in Fig.3. However, the fixture of the blasting gun was allowed to move the gun in tilted angles through the adjustment holder way. Fig.4. illustrates the layout drawing of the AJM preparation. The properties of abrasive (sand) and the workpiece (glass) are as follows [37];

Abrasive density (ρ_p) = 2.3 g/cm3
Glass hardness (H) = 5.5 GPa
Glass fracture toughness (Kc) = .76 MPa √m
Glass elastic modulus (E) = 72 GPa
Glass density ((ρ_t) = 2.5 g/min

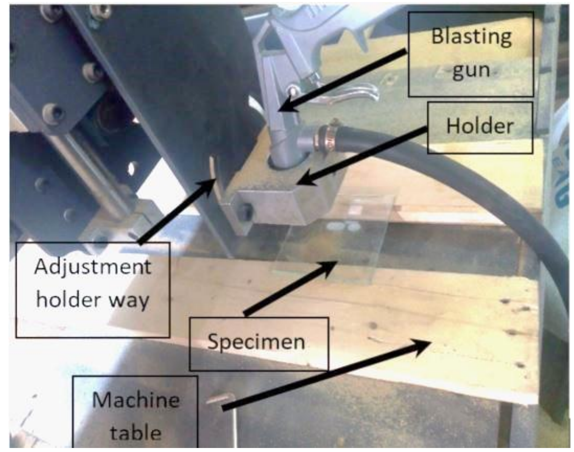


Fig.3. Fixture of the blasting gun against the specimen

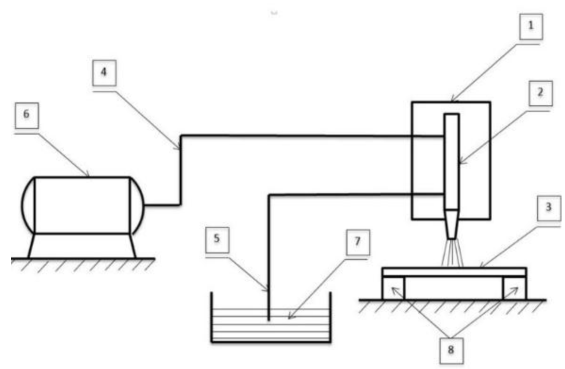


Fig.4. Layout drawing of the AJM preparation with following components;
(1) crosshead machine, (2) blasting gun, (3) specimen, (4) compressor tube, (5) sand tube, (6) compressor, (7) sand, (8) machine table

4.2 Experiment setup

The major parameters varied to assess their influence were air pressure (Pr), standoff distance (SoD), nozzle diameter (dn) and abrasive grain size (dg). Each factor was investigated via applying three levels, as shown in the Table.1.

Table.1. AJM process parameters for drilling holes

Parameters	Levels
Pressure (Pr)	0.3, 0.6, 0.9 MPa
Standoff distance (SoD)	4, 6, 10 mm
Nozzle diameters (dn)	4, 5, 6 mm
Abrasive grain size (dg)	150, 300, 600 µm

Full factorial design was used to propose the design of the experiment using the parameters previously stated. When changing one parameter, the remaining parameters will be kept constant. All pervious experiments were conducted at impact angle equal to 90º. However, following to this set of experiment, other tests were carried out at different impact angles to estimate its effect on the machining performance; particularly impact angles of 70º and 50º were practiced. However, it is worth emphasizing that prior to adopting the experiments, the mass flow rate has to be calculated experimentally at different levels of the applied process parameters.

4.3 MRR Evaluation

MRR can be evaluated by measuring the weight of the workpiece before and after machining and then dividing the difference by the machining time of the process, Eq.11. The weight was measured for glass sheet before and after each experiment by sensitive digital balance that has a sensitivity of 0.01 gm.

$$MRR = (wb - wa) / t \quad \text{(g/min)} \qquad (11)$$

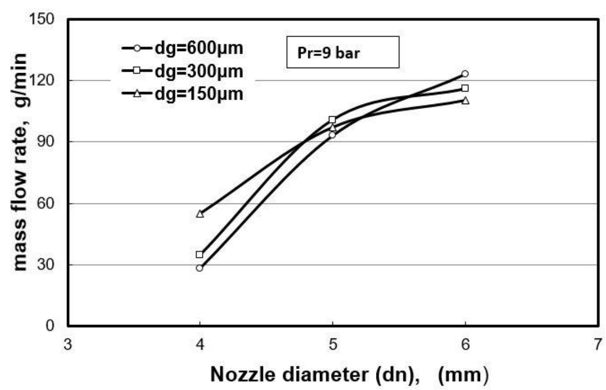
where wb is the weight of work piece before the process (g) and wa is the weight of workpiece after the process (g) and t is the machining time in min.

The machining time was recorded by a stop watch during each experiment. The machining time for each trial was the time consumed to obtain a complete through hole which varied based on the applied cutting conditions. Therefore, the machining time was varies for each experiment.

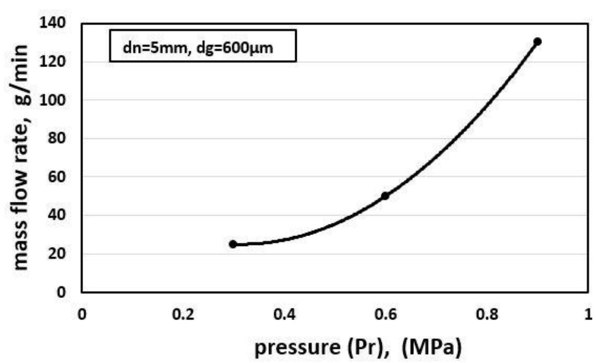
5. Results and Discussions

5.1 Effect of Process Parameters on Mass Flow Rate

Figure.5. (a and b) illustrates the relationship between process parameters (pressure, particles grain size and nozzle diameters) and the obtainable mass flow rate. The results have demonstrated that mass flow rate increased with the increase in nozzle diameter. At small nozzle diameter, high pressure caused random scramble of the particles which prevented the majority of particles to leave the nozzle exit and in turn reduced the mass flow rate. It was observed that the mass flow rate for different sizes of the particles is significantly associated with the using of appropriate nozzle diameter. The results indicated that the highest mass flow rate for nozzle diameter equal to 6mm while using a grain size of 600 µm than other different sizes. At nozzle diameter of 5mm, the highest mass flow rate occurred was observed when using particle grain size of 300µm. However, at a nozzle diameter of 4mm, the highest mass flow rate occurred at a particle grain size of 150µm. So, one can argue that the grain size had no significant effect on the mass flow Rate. Also, it was found that applied pressure was the most significant parameter that influenced the mass flow rate. In particular, mass flow rate was proportional with the applied pressure. That is mainly due to the fact that high pressure caused higher velocity of particles that exit from the nozzle and thus increased the overall mass flow rate.



(a) *Effect of nozzle diameter on mass flow rate with different particles' grain sizes*



(b) Effect of pressure on mass flow rate

Fig.5. Effect of process parameters on mass flow rate of particles

5.2 Effect of Process Parameters on the Material Removal Rate

5.2.1 Effect of Applied Pressure

Figure.6. Shows the relationship between nozzle pressure (Pr) and material removal rate (MRR) for various particles' grain size. It was found that the material removal rate increased by the increase in pressure. This can be explained by the increase in kinetic energy of abrasive particles at high pressure which leads to removal of large volume of material.

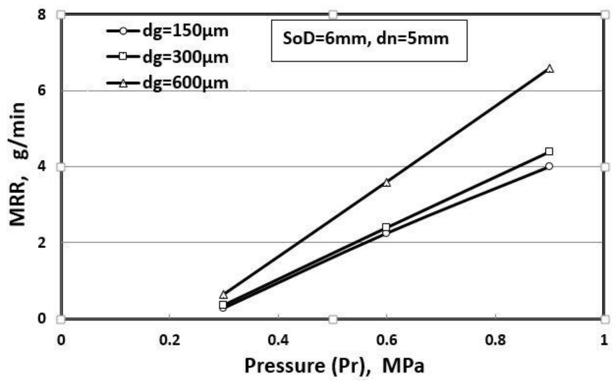
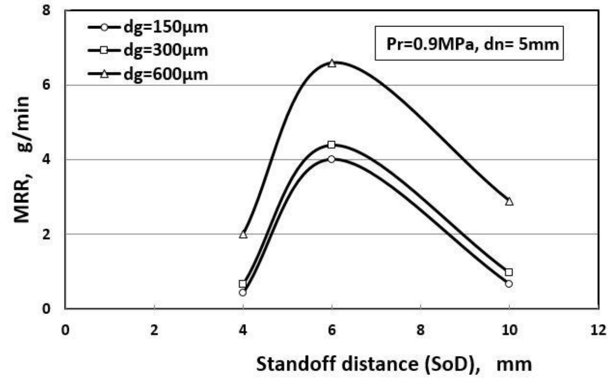


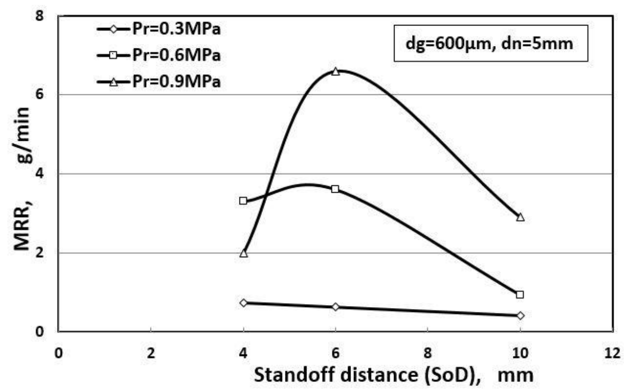
Fig. 6. Effect of pressure (Pr) on material removal rate (MRR) at different particles grain size (dg)

5.2.2 Effect of standoff distance

Figure.7. (a, b) illustrates the relationship between standoff distance (SoD) and material removal rate (MRR) at altering values of particles' grain size and nozzle pressure. It was found that the material removal rate increased with increasing in the standoff distance up to 6 mm, nevertheless then the trend of the curve changed which clearly shows a reduction of the material removal rate for the values of the standoff distance above 6 mm. Therefore, one can conclude that the optimum value of standoff distance that gave the maximum material removal rate was 6 mm for various process parameters as shown in Fig.7. The varying trend of the MRR against the applied cutting parameters is mainly due to the fact that a small standoff distance caused an inter-collision of particles against the particles themselves and hence caused a loss of kinetic energy. Also, the random scramble of particles makes it difficult to move away after impingement as the particles collide with the exit of the nozzle also especially at higher pressure. However, this is not the case at low pressure as shown in Fig.7-b. Moreover, when the standoff distance is increased, the kinetic energy of the particles decreased therefore the material removal rate decreased as well.



(a) Effect of standoff distance on material removal rate at different particles' grain size (dg)



(b) Effect of standoff distance on material removal rate at different pressure (Pr)

Fig.7. Effect of standoff distance (SoD) on material removal rate (MRR)

5.2.3 Effect of Nozzle Diameter

Figure.8. reveals the relationship between nozzle diameter (dn) and material removal rate (MRR) for different particle grain sizes. It was found that when the nozzle diameter increased, the material removal rate increased also up to a certain limit, then the material removal rate decreased. This increase in MRR is because of the increasing in flow rate of abrasive in a large nozzle diameter as a higher number of particles exit from the nozzle which results in a large volume of material to be removed. This linear relationship was detected up to a nozzle diameter of 5 mm, and then the curve tends to decrease in the material removal rate at nozzle diameter equal to 6mm as shown in Fig.8. This is due to the velocity of particles' stream that are reduced at larger nozzle diameter than that in case of smaller diameter, which in turn leads to reduce the kinetic energy of the jet and thus the material removal rate decreases consequently.

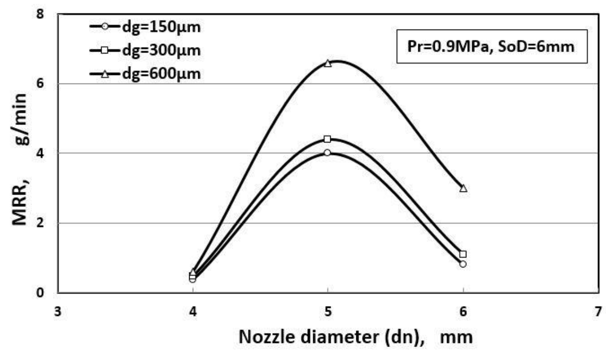


Fig.8. Effect of nozzle diameter (dn) on material removal rate (MRR) at different particles' grain size (dg)

5.2.4 Effect of Particles Grain Size

The results was show that the increase in the particles' grain sizes resulted in increasing the material removal rate at different values of the other parameters as shown in Fig(6, 7 and 8). In particular, the increase in the mass of the abrasive particles resulted in increasing their kinetic energy, therefore the material removal rate increased. Moreover, it was observed that the ability influence of the grain size on machining was based on using the appropriate nozzle diameter. Therefore, the material removal rate in particles grain sizes equals 600 µm with a nozzle diameter of 4 mm was too small compared to other grain sizes and other nozzle diameters in low pressure as shown in Fig.9. This can be explained as follows; when the nozzle diameter is too small, it obstacles the flow of the particles with large particles, so the abrasive flow rate decreases especially in low pressure and material removal rate decreases.

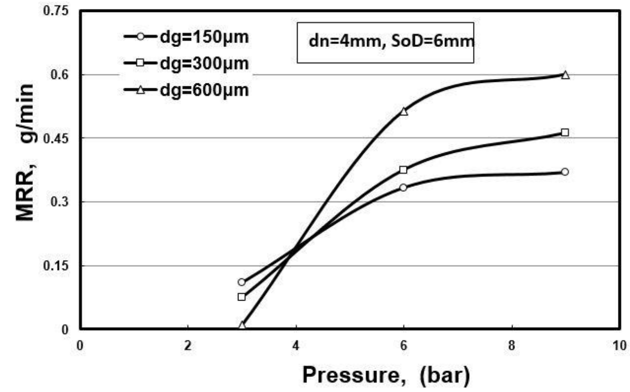


Fig.9. Effect of pressure on material removal rate for different particles grain size (dg) at dn =4mm

5.2.5 Effect of Impact Angle

Figure.10. presents the relationship between the material removal rate and impact angle. It was found that the material removal rate increased with increasing the impact angle. That is due to the increase in normal kinetic energy of particles at higher impact angle, which caused deeper crack formation and leads to large volume removal of material. This is based on the fact that material removal on brittle erosion occurs due to normal impact [19].

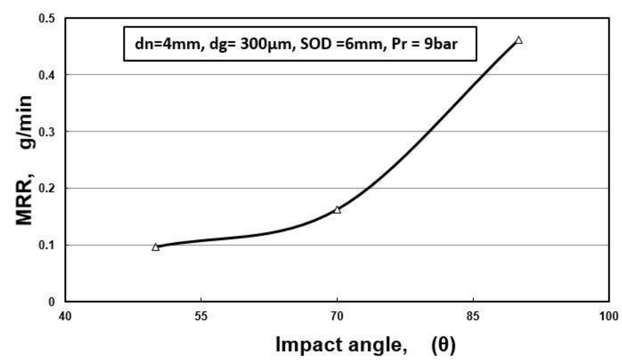
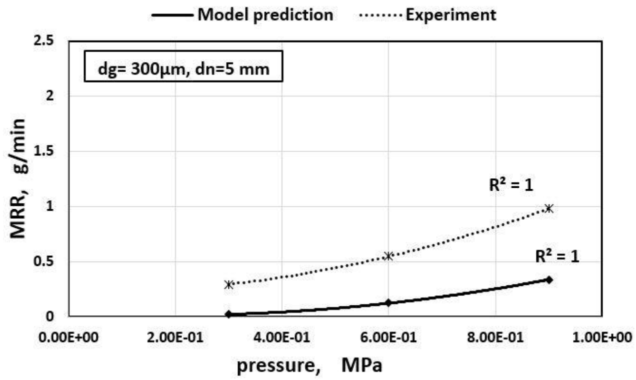


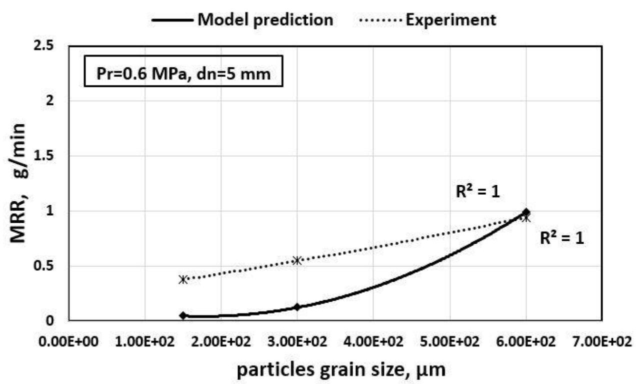
Fig.10. Effect of impact angle on material removal rate

5.3 Modeling Experimental Validation

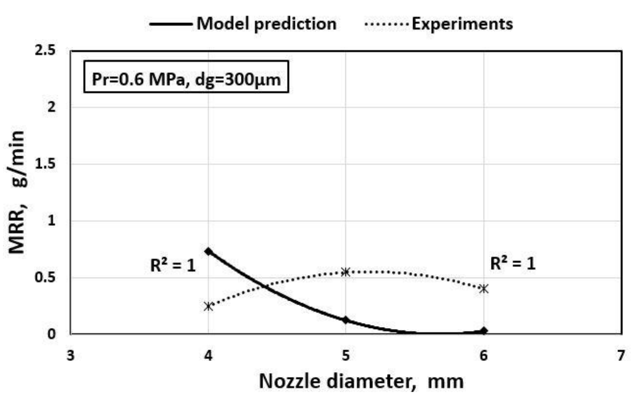
Fig.11. illustrates the theoretical results calculated from E.q.10 compared with those obtained from the experimental work. The experimental work was carried out at constant standoff distance, particularly 10 mm using a compressor with exit tube diameter of 6 mm.



(a) Material removal rate versus pressure



(b) Material removal rate versus particle grain size



(c) Material removal rate versus nozzle diameter

Fig.11. comparison between experimental and theoretical results; the dashed line indicates the trend of experimental data while the solid line shows the model predictions.

It was found that the experimental results are nearly close with the theoretical predictions at different pressure and particles' grain size as shown in Fig. 11-a and Fig. 11-b. However, there were noticeable differences between the experimental and theoretical results, especially in Fig. 11-c. This can be explained as follows; the increase in nozzle diameter reduced the velocity of particles that exit from the nozzle end and in turn leads to a reduction in the kinetic energy of the particles which finally decreases the material removal rate. So, material removal rate increases with the decrease in nozzle diameter as shown in theoretical results. However, this is not the case at the smallest nozzle diameter in experiments (4 mm) due to random scramble of particles at high velocity that prevents smooth exit and reduces mass flow rate. Therefore, it was found that the material removal rate was affected by the kinetic energy of particles. Fig.12. shows the effect of kinetic energy of partagainst MRR for the model predictions and experimental results.

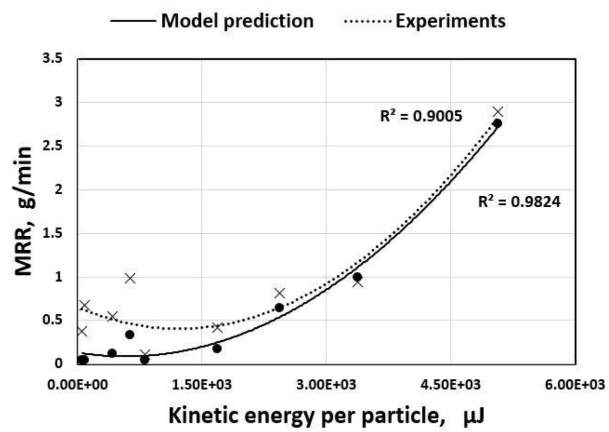


Fig.12. Material removal rate versus the kinetic energy, the dashed line indicates the trend of experimental data while the solid line shows that of the model predictions.

It is not so difficult to see a relatively acceptable agreement between the experimental results and the theoretical ones, especially at the higher values of the kinetic energy. An average error of 39% was obtained over the entire range of study.

6. Conclusion

In this paper, a detailed study of the AJM has been undertaken that involved modeling and experimental investigation of the process parameters that governing MRR. The experimental and theoretical results are in a relatively acceptable agreement within an average error of 39%.

The following are specific conclusions made based on the results and discussions.

- The investigation has demonstrated that material removal rate was proportional to the kinetic energy of the abrasive particles.
- It was found that nozzle pressure was the most significant parameter that influenced the MRR.
- In addition, nozzle diameter has a considerable effect on MRR. It was found that at a large nozzle diameter, the MRR decreased.
- Moreover, it was concluded that MRR increased with the increase in standoff distance up to a certain limit and then the MRR decreased with the increase of standoff distance.
- Furthermore, abrasive grain size was proportional to MRR.
- Finally, it was detected that the higher value of material removal rate was occurred at impact angle of 90º, as the nozzle was at a right angle to the target surface where oblique impact gave lower rate of material removal.

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