Proceedings of the 17th Int. ***AMME*** *Conference, 19-21 April, 2016*

Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.

17th International Conference
on Applied Mechanics and
Mechanical Engineering.

EXPERIMENTAL INVESTIGATION OF ABRASIVE JET MACHINING OF GLASS

E. Abdelnasser*, A. Elkaseer** and A. Nassef***

ABSTRACT

This paper presents an experimental investigation of Abrasive Jet Machining aiming to characterize the effect of process parameters on the quality of the machined surfaces. In particular, a series of drilling holes and machining channels have been carried out on glass workpieces using sand as abrasive powder. The research examined the effects of the process parameters, namely applied pressure (Pr), standoff distance (SoD), nozzle diameter (dn), particle grain size (dg) and impact angle on the dimensional accuracy of the machined surface in terms of generated kerf taper of the produced holes. In additions, Taguchi method was utilized to determine surface roughness (Ra) of the machined slots by AJM. The results have revealed that the surface roughness was proportional to the kinetic energy of particles, the particles grain sizes and applied pressure. Moreover, although, a proportional relationship was detected between the kerf taper and applied standoff distance, the generated kerf taper reduced by applying axial feed to maintain the standoff distance at constant level during the entire process.

KEYWORDS

AJM, kerf taper, axial feed, surface roughness, process condition.

---

* Demonstrator of Production Eng., Faculty of Eng., Port Said University; Email: aisegy@hotmail.com.

** Lecturer of Production Eng., Faculty of Eng., Port Said University; Email: elkaseeram@gmail.com.

*** Prof. of Production Eng., Faculty of Eng., Port Said University; Email: nassef12@hotmail.com.

INTRODUCTION

In abrasive jet machining (AJM), the material removal process takes place through the action of a focused stream of fine abrasive particles, carried by highly pressurized air accelerated towards the workpiece. 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 [1-3]. A considerable number of investigations on AJM to examine the effect of process parameters on material removal rate (MRR). However, one of the challenges that still needs addressing is the geometrical accuracy of the generated features by AJM and how to improve its quality. Therefore, the aim of this investigation was to study the factors influencing the performance of AJM process in matters such as dimensional accuracy and surface roughness of machined surface. In particular, a series of drilling holes and machining channels have been carried out under various values of air pressure, nozzle diameters, particles grain sizes, standoff distance and impact angle to obtain best possible performance of the process. Machining performance has been assessed by quantifying the following parameters; dimensional accuracy of the machined surface as measurement the generated kerf taper of produced holes and quality of generated surface as measurement the surface roughness of machined slots.

RELATED WORK

The shape and of generated surface by AJM have been discussed by many investigators [4-14] to estimate the effect of process parameters on its quality. Chandra and Kandpal et al [4-5] carried out drilling tests of glass by AJM. Their results showed that the top diameter and bottom diameter of holes increased by increasing the standoff distance. Liao et al. [6] studied drilling holes by AJM. The authors found that the AJM generate kerf taper on machined holes due to difference between the upper and lower diameters of holes. Sharma et al [7] found that the kerf taper and over cut of produced holes decreased by increasing pressure and nozzle diameter and decreasing standoff distance. Balasubramaniam et al [8] [9] [10] investigated the shape of the machined surface by AJM. He found the surface generation was given revers bell mouthed shape with entry side diameter in target material and entry side edge radius depends on the values of process parameters. It was found that standoff distance and nozzle diameter were the most significant parameter on the shape of the machined surface. It was reported that increasing in standoff distance caused the increasing in the edge radius, and as the nozzle diameter increased the edge radius increased and the difference on entry side, and exit side diameter decreased. Chastagner et al [11] studied the ability of abrasive jet machining for deburring edge of 90°. It was found that as the impact angle increased, the edge radius decreased and the depth increased, for small in depth damage and large edge radius, along standoff distance was applied. Achtsnick et al [12] investigated the effect of shape of nozzle on abrasive jet machining using two different types of nozzles one of them was a converging cylindrical nozzle and the other was a line shaped Laval nozzle. It was found that the profile shape of the machined surface was uniform in the case of Laval nozzle more than the other case. Slatineanu et al [13] investigated the abrasive jet machining on surface roughness. It was found from that there was no effect of the standoff distance and the impact angle on surface roughness. Besides, the particles grain size affected the obtainable surface roughness. Jafar et al [14] studied the effect of process parameters on surface roughness by abrasive jet machining. It was found that the surface roughness increased by increasing in kinetic energy of particles as increasing in particles grain size and its velocities. Moreover, as the impact angle increased the surface roughness increased.

EXPERIMENTAL SETUP

Machining Setup

The experimental work was carried out using axial and transvers feed. So, it was necessary to use CNC machine with a three axis capability. Glass was selected as a target material in the experiments with 3 mm thickness and Sand was chosen as abrasives. The procedure of the experimental work was carried out by fixing the glass sheet on the table of the CNC machine. The gun nozzle attached in a perpendicular position of the specimen surface. However, the fixture of the blasting gun was allowed to move the gun in tilted angles through the adjustment holder way as shown in Fig.1.

Design of the Experiment

Drilling through holes

Initially, the first set of experiments was carried out aiming at investigating the performance of drilling through holes on glass sheets under different machining parameters**.** 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. Full factorial design was used to propose the design of the experiment using the parameters previously stated.

Drilling holes with axial feed

Because of the nozzle was kept constant during each drilling trial, the stand of distance unintentionally varied over the cutting time over the entire thickness to be cut, which could lead to inaccurate results of the dimensional accuracy. In order to avoid this limitation, in the second set of experiments, axial feeding motion of the nozzle (axial feed in direction of depth of cut) was applied during the process. The results from this procedure will be compared with those from the first one and thus to estimate the effect of such variation on the efficiency of cutting process. The axial feed of the nozzle towards the target surface was applied for 3 mm distance equivalent to the thickness of glass sheet, where the machining time was already known when drilling the corresponding hole of each pervious experiment. That is in order to make sure that the hole was opened in this time where the exit nozzle was moved the distance of glass thickness. It is obvious that each hole drilling with different feed value of other holes. This is mainly because of varies machining time for each experiment based on the applied cutting conditions. Fig.2 illustrated the difference of drilling holes technique without feed and with feed.

Machining channel

In the third setup of experiments, channels were machined on the glass sheets in order to measure the surface roughness produced by AJM. The channels machined by moving the nozzle in x- direction with constant scan speed (Traverse speed) Vs= 300 mm/min. Experiments was designed based on Taguchi method to optimize the surface roughness for variable process parameters. Taguchi method uses special design of orthogonal arrays to study the entire parameter space with a small number of experiments. Taguchi methods consist of a plan of experiments with the objective of getting data in a controlled way to obtain the behavior of a given process [15]. L9 orthogonal array was used. This array consists of three control parameters, (pressure, particles grain size and standoff distance) with three levels using constant nozzle diameter (dn) = 5mm.

Measurement

Kerf taper measurement

During cutting a hole, the AJM may generate kerf taper due to the difference between the upper and lower diameters of the hole [16] as shown in Fig.3, where, Wu= upper kerf width, W_L= lower kerf width, ϴ= kerf taper angle, tn= material thickness. The kerf taper is measured as the ratio of the difference of upper and lower radius for hole to the sheet thickness, Eq. 1

$$Kerf\ taper\ =\ tan\,\theta\ = \frac{wu - w_L}{2tn} \qquad \text{mm/mm} \quad \text{(Eq. 1) [16]}$$

Surface roughness measurement

In order to measure, the average surface roughness (Ra) of AJM machined channels, Surtronic (3 stylus) profilometer was used. The cutoff length was selected to be 0.8 mm as it was indicated in profilometer's operation manual. Due to the variability of surface finish data, three measurements for each specimen on each cut were made close to the centerline of the machined slot (smooth zone) of the cut surface and the average was taken as the final reading for the surface roughness (Ra). The measurements were taken at a distance of 5mm from the top of the cut surface. Before applying any measurements on glass specimens calibration by standard specimen related to the profilometer was conducted.

RESULTS AND DISCUSSIONS

The Effect of Process Parameters on Kerf Taper

Effects of standoff distance

Figure 4 reveals the relationship between standoff distance and kerf taper for different pressures. It was found that difference between the upper diameter and the lower diameter increased as the standoff distance increased, which led the kerf taper to increase. Obviously, higher standoff distance allows the jet to diverge before impingement, which may reduce resistance to external drag from the surrounding environment. Therefore, material removal at periphery decreased more than that in centerline of the jet and increase in kerf taper. Standoff distance has a major effect on kerf taper of holes in AJM.

Effect of pressure

It was noticed that increasing in pressure resulted in a reduction of the difference between top and bottom diameters of holes which eventually gave low kerf taper as shown in Fig.4. That is due to a higher kinetic energy of particles at high pressure which can remove a large volume of material along axial distance of hole and increases the lower diameter. Moreover, the material removal rate increased in peripheral area as the peripheral velocity was high at high velocity of particles stream, therefore the difference between the upper and the lower diameters decreased and the kerf taper decreased.

Effect of nozzle diameter

Fig.5. Demonstrates the relationship between nozzle diameter (dn) and kerf taper for different particles grain sizes. It was observed that increasing in nozzle diameter resulted in reduced differences between top and bottom diameters of holes which ultimately give low kerf taper as shown in Fig.5. This is due to nozzle jet expansion in small nozzle diameter and increasing in peak velocity more than that in larger nozzle diameter that causes increasing in material removal rate in centerline more than obtained in the periphery which leads to an increase in difference between the upper and lower diameters of the produced hole. Besides, the variation of velocity profile in case of larger diameter decreased the difference of material removal rate in centerline and periphery and decreased also the difference between upper and lower diameter of hole. Moreover, this observation was only detected when the nozzle diameter was limited up to 5mm. However, at larger nozzle diameter the kerf taper slightly increased as shown in Fig.5. which can be attributed to the reduction in kinetic energy of particles for large nozzle diameter and the velocity decreased in periphery areas.

Effect of particles grain size

It was found from results that the difference between the upper and the lower diameter reduced with increasing in particles grain size, therefore the kerf taper decreased as shown in Fig.5. At larger mass of particles, the stream has higher kinetic energy and consequently results higher capability to penetrate into the workpiece surface. Moreover, at larger mass of particles, more concentrated is expected at the center of the stream than that at the periphery. On the contrary, the particles with smaller mass is expanded to periphery and results in increasing in the difference of material removal rate between the center and periphery of holes. Therefore, the kerf taper increases when using small particle. However, it was found that the particle size has slightly effect on kerf taper.

Effect of Axial Feed on Kerf Taper

Fig. 6 illustrates the performance of the cutting process in terms of resultant kerf taper when drilling holes with and without feed for different values of pressure. It was observed a significant influence of applying feed on dramatically reduction of the produced kerf taper of machined holes. The set SoD prevented jet expansion during cutting which enabled high rate of material removal at periphery which in turn reduced the kerf taper. Fig.7 illustrated the difference between the shape of hole generated by AJM with feed and without feed. Fig.8 shows the relationship between feed rate and kerf taper. The effect of the feed rate on kerf taper generated is presented with different values of feed rate, 7 mm/min, 14 mm/min and 17mm/min. It was found that reducing in feed rate caused reducing in kerf taper that due to the increase in material removal rate in peripheral area as the machining time was increased.

The Surface Roughness Results

In the following section, the experimental results of surface roughness generation on machined channel by AJM are discussed. Taguchi method was used to design the experiments. The measured values of Ra from the experiments are shown in Table.2. It was found that the minimum value of surface roughness was 2.8 µm which was achieved at pressure of 0.3 MPa, standoff distance 4 mm with particle grain size 150 µm. Same result was obtained also at pressure of 0.6 MPa, standoff distance of 10 mm with particle grain size of 150 µm and similarly at 0.3 MPa pressure, 6 mm standoff distance and with 300 µm particle grain size. The machining parameters, namely standoff distance, and pressure and particle size have been found having significant effect on surface roughness as shown in the main effect plot for surface roughness (Ra) in Fig.9.

Effect of standoff distance on surface roughness

Figure 9-a shows the effect of standoff distance on the resultant surface roughness. Although no clear trend of the relationship between both parameters was detected, one can say that standoff distance has relatively small effect on the surface roughness. This is clearly obtained when looking at the small variation of the generated roughness corresponding to the range of applied standoff distance. However, it can be summed up that the mid-range value of the applied standoff distance, 6 mm has the most positive influence on the obtained surface roughness. Following are some explanations of such conclusion; the jet divergence at higher standoff distance leads to a large reduction of the kinetic energy density of the jet at impingement. Besides, the separating and dispersion of particles at large standoff distance may prevent overlap machining action leads to rougher surface. Alternatively, Inversion at relatively smaller standoff distance where the particles are concentrated at the axial path of the stream, it leads to over-lapping in particles leads to reduce surface roughness. However, the surface roughness increased at very small standoff distance due to the dramatic increase in kinetic energy of particles and the scramble of particles caused the particle impinging with each other and with the nozzle exit causing rougher surface.

Effect of applied pressure on surface roughness

Figure 9-b shows the effect of applied pressure on the obtainable surface roughness. It was found that surface roughness is dramatically increased by the increase in applied pressure. This can be explained as the higher pressure accompanying with high kinetic energy of the particles that leads to impact the target material with large impact force. This cause's large volume removal of material and finally rougher surface is expected.

Effect of particles grain sizes on surface roughness

Figure 9-c shows the effect of particle grain size on the resultant surface roughness.

Similarly, to what found in case of applied pressure, it is clearly detect a proportional relationship between the particle grain size and generated roughness. This can be understandable when considering the geometry of the particles. In particular, large size of particle associated with has higher kinetic energy during the impact than the small particle which in turn leads to larger volume removal of material that ultimately results higher rougher surface.

Effect of impact angle on surface roughness

Figure 10 shows the relationship between the impact angle and surface roughness. It was found that the surface roughness increased by increasing the impact angle. This is due to the related increase in normal kinetic energy of particles at higher impact angle, which causes deeper crack formation. It results in large volume removal of material leads to rougher surface which again due to the fact that material removal on erosion impact occur due to normal impact [17].

Effect of scan speed on surface roughness

Figure 11 shows the relationship between the surface feed rate, which also so-called scan speed (Vs), and the surface roughness. The effect of scan speed on surface roughness is examined by applying altering values vs varies between 100 mm/min, 300 mm/min, 600 mm/min and 1000 mm/min. It was found that there was a reverse relationship between the surface roughness the applied scan speed. Increasing in scan speed caused less overlap machining action and fewer particles impinged the surface caused rougher surface.

CONCLUSIONS

In this paper, an experimental investigation has been carried out on abrasive jet machining of glass. A reliable setup was developed that offered an accurate test rig for the experimental trials by using CNC machine with three axis capability. The investigation focused on major machining performance factors, such as dimensional accuracy of machined surface in term of the kerf taper of drilled holes and surface roughness of machined channels. Followings are some specific conclusions drawn based on the results obtained.

- Standoff distance has the major effect on the kerf taper generated for drilled holes. As the standoff distance was proportional with kerf taper and large one resulted in boor dimensional accuracy.
- Nozzle diameter was the second operational parameter that has substantial effect on kerf taper. On the other hand, abrasive grain size and nozzle pressure had relatively minor effect on kerf taper
- However, it was possible to improve the kerf taper by applying pre-calculated axial feed motion of the blasting gun during the process. It was found that the kerf taper reduced when applying axial feed and the best results were obtained with small feed rate.
- Surface roughness was influenced by the kinetic energy of the abrasive particles. The most important parameters that had a significant effect on surface roughness were the abrasive grain size and nozzle pressure. Standoff distance had a slight effect on surface roughness compared with other parameters.
- Besides, it was found that the scan speed (traverse speed) had a large effect on surface roughness, the surface roughness reduced at smaller scan speed.

Finally, it was found that the surface roughness increased by increasing the impact angle.

ACKNOWLEDGMENTS

The authors would like to thank Eng. Mohamed Negm the co-founder of Becatronics Co. for allowing the author to conduct the experimental work in his factory and using the facilities of Becatronics.

REFERENCES

[1] Marinov. V, 2012, "Manufacturing process design" Kendall/Hunt, pp. 129-148, Available at: http://www.amazon.com last accessed 17/7/2015.

[2] Kharagpur, 2015, "Module 9 non-conventional machining", Version_2_ME_IIT_Kharagpur, Available at http://www.academia, last accessed 17/7/2015.

[3] Jagadeesha T, 2015, "Non-traditional machining", Mechanical Engineering Department, National Institute of Technology, Calicut, Available at: http://www.nitc.ac.in last accessed 22/7/2015.

[4] Chandra. B, 2011, "A Study of effect of Process Parameters of Abrasive jet machining, International" Journal of Engineering Science and technology, Vol. 3 No. 1, pp. 504-513.

[5] Kandpal. B. C, Kumar. N, Kumar. R, Sharma. R and Deswal. S, 2011, "Machining of glass and ceramic with alumina and silicon carbide in abrasive jet machining", International Journal of Advanced Engineering Technology, Vol. II, Issue IV, pp. 251-256.

[6] Liao. Y. S and Chen. L. C, 2006, "Determination of mask opening size in creating a fluid hole on brittle material by double-side sand blasting", International Journal of Advanced Manufacturing Technology, Vol. 29, Issue. 5, pp. 511-517.

[7] Sharma. P. K and Deol. G. S, 2014, "A comparative analysis of process parameters during machining of glass fiber reinforced plastic by abrasive jet machining", International Journal of Advance Foundation and Research in Science and Engineering (IJAFRSE), Vol. 1, Issue 3, pp. 28-37.

[8] Balasubramaniam. R, Krishnan. J, Ramakrishnan. N, 2002, "A study on the shape of the surface generated by abrasive jet machining", Journal of Material Processing Technology, Vol. 121, Issue. 1, pp.102–106.

[9] Balasubramaniam. R, Krishnan. J and Ramakrishnan. N, 2000, "An empirical study on the generation of an edge radius in abrasive jet external deburring (AJED)", Journal of Materials Processing technology, Vol. 99, Issues. 1–3, pp. 49–53.

[10] Balasubramaniam. R, Krishnan. J and Ramakrishnan. N, 1998, "Investigation of AJM for deburring", Journal of Materials Processing Technology, Vol. 79, Issues. 1–3, pp. 52–58.

[11] Chastagner. M. W and Shih. A. J, 2007, "Abrasive jet machining for edge generation", Transactions of the North American Manufacturing Research Institution of SME, Vol. 35, pp. 359-366.

[12] Achtsnick. M, Geelhoed. P. F, Hoogstrate. A. M. and Karpuschewski. B, 2005, “Modelling and evaluation of the micro abrasive blasting process”, Wear, Vol. 259, Issues. 1–6, pp. 84–94.

[13] Slatineanu. L, Potarniche. S, Coteaţa. M, Beşliu. I. G, Gherman. L and NEGOESCU. F, 2001, “Surface roughness at aluminum parts sand blasting”, Proceedings in Manufacturing Systems, Vol. 6, Issue 2, pp. 69- 74.

[14] Jafar. R. H. M, 2013, “Erosion and roughness modeling in abrasive jet micro-machining of brittle materials,” Ph.D. Thesis, University of Toronto.

[15] Roy. R. K, 2001, “Design of experiments using the Taguchi approach: 16 steps to product and process improvement”, Available at: http://www.amazon.com, last accessed 22/8/2015

[16] Maros. Z, 2012, “Taper of cut at abrasive waterjet cutting of an aluminum alloy”, Production Processes and Systems, Vol.5, No. 1, pp. 55-60.

[17] Wensink. H, Miko and Elwenspoek. C, 2002, “A closer look at the ductile–brittle transition in solid particle erosion”, Wear, Vol 253, pp.1035–1043.

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

Table.2. Measured values of Ra form the experiments.

No. of experiment	SOD (mm)	Pr (MPa)	dg (μm)	Ra (μm)
1	4	0.3	150	2.8
2	4	0.6	300	3.3
3	4	0.9	600	5.3
4	6	0.3	300	2.8
5	6	0.6	600	3.9
6	6	0.9	150	3.8
7	10	0.3	600	4.3
8	10	0.6	150	2.8
9	10	0.9	300	3.9

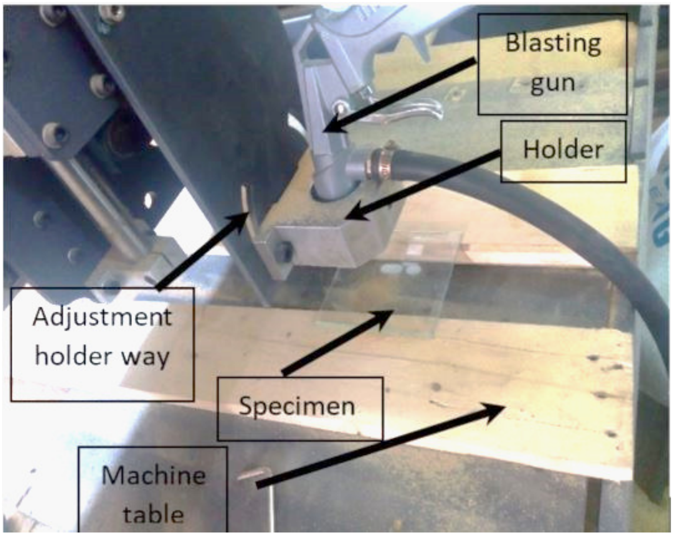
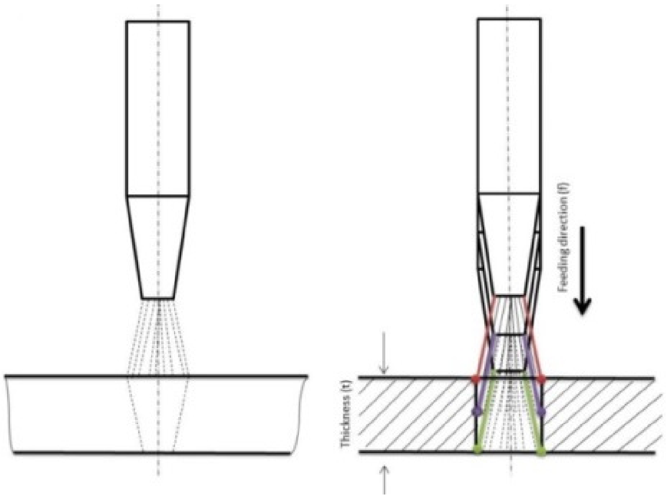


Fig.1. Fixture of the blasting gun against the specimen.



(a) drilling hole without feed (b) drilling hole with feed

Fig. 2. the difference of drilling holes technique without feed and with feed.

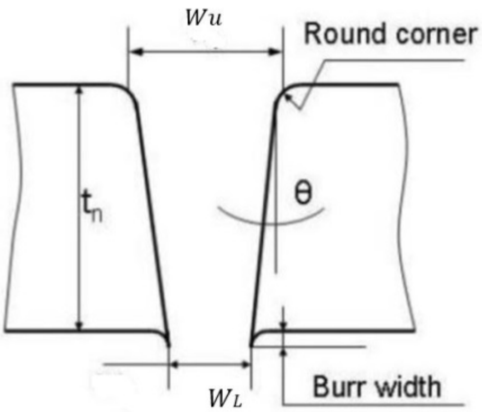


Fig. 3. Cross-sections of hole generated of AJM process [14].

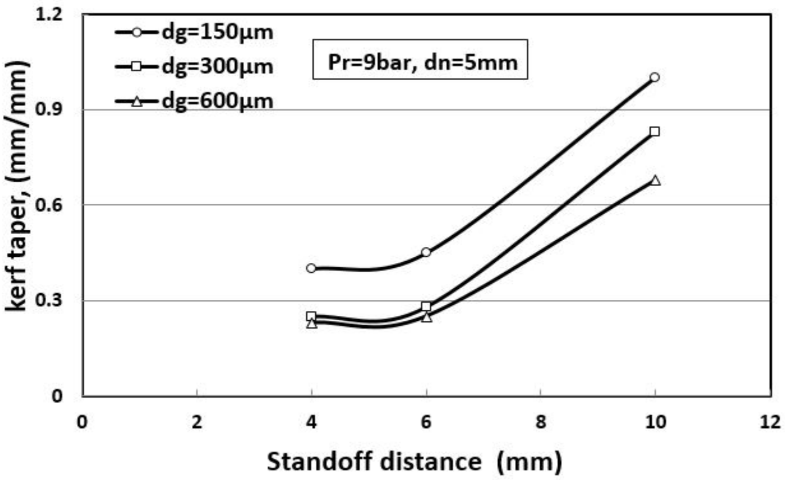


Fig. 4. Effect of standoff distance on kerf taper at different pressure (Pr).

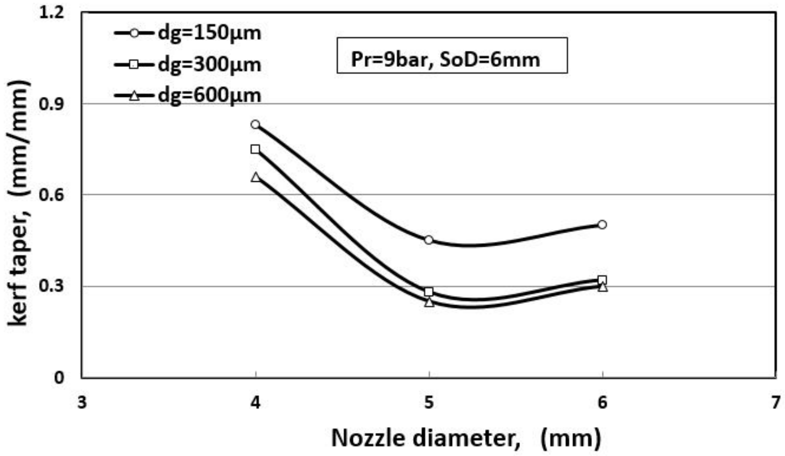


Fig.5. Effect of nozzle diameter (dn) on kerf taper at different particles grain size (dg).

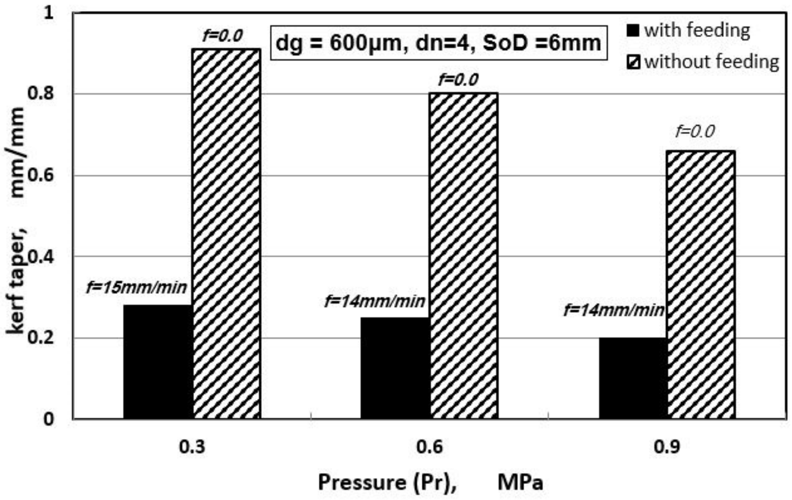
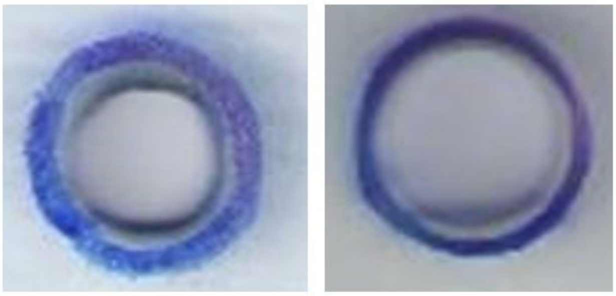


Fig. 6 Comparison between kerf taper generated for drilling holes with feed and without feed for number of experiments with different nozzle pressure.



(a) without feed *(b) with feed*

Fig. 7. Comparison between holes generated by AJM for drilling hole with feed and without feed at dn=5mm, dg=600µm, Pr=0.9MPa and SoD=6mm.

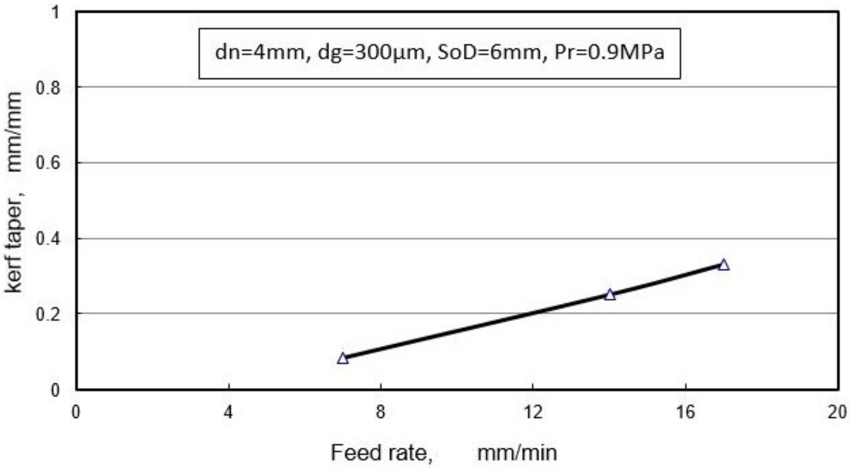


Fig. 8. Effect of feed rate on kerf taper.

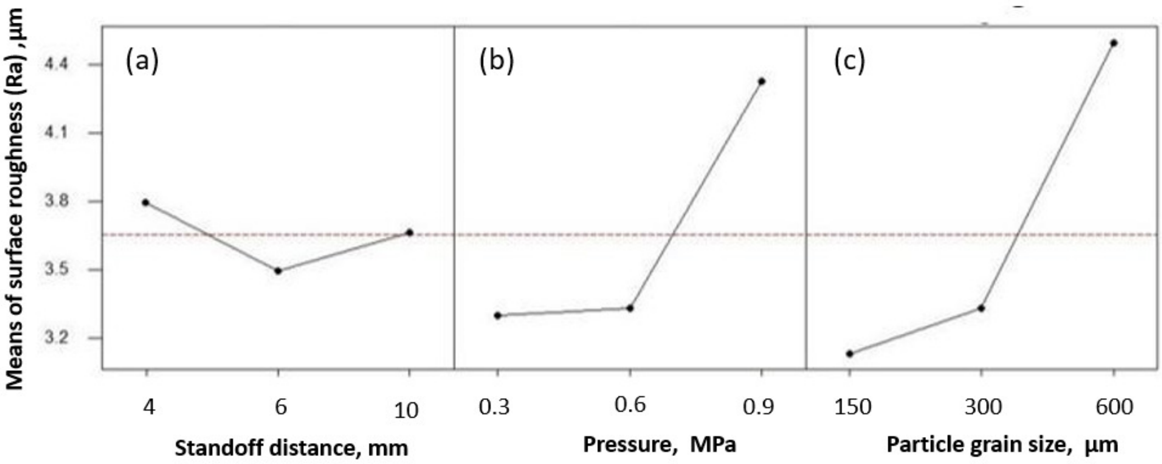


Fig. 9. Main effect plot for means of surface roughness (Ra) (a) the standoff distance effect, (b) the pressure effect and (c) the particles grain size effect.

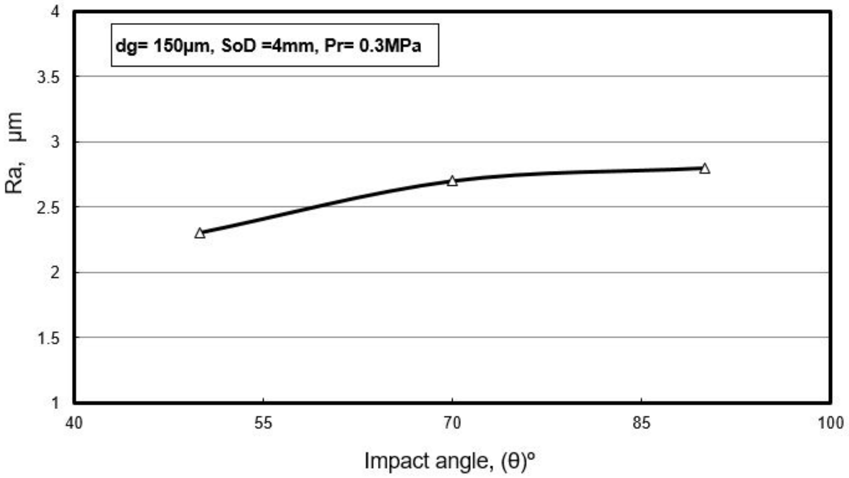


Fig. 10. Effect of impact angle on surface roughness (Ra).

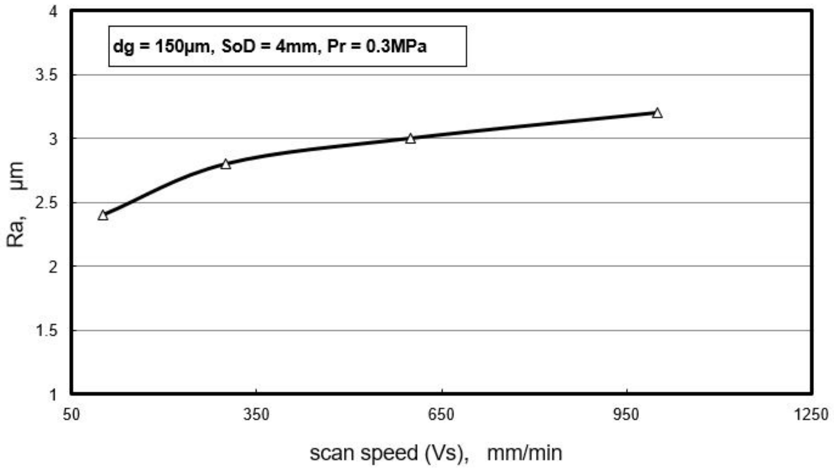


Fig. 11. Effect of scan speed (Vs) on surface roughness (Ra).