Experimental Investigation and Characterization of Abrasive Waterjet Drilling of Deep Holes

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Abstract: Machining of hard-to-cut materials to high precision level is a prerequisite in fabricating various intricate engineered components in both a macro and micro scale. One of the most common but also a demanding task is the drilling of deep holes having small diameters, to the required degree of accuracy, using abrasive waterjet machining. In this paper, an experimental investigation of drilling high aspect ratio holes with abrasive waterjet machining is presented. A multivariate analysis method was invited to study the effect of different input parameters on various machining performance measures such as material removal rate and kerf characteristics in a full factorial design of experiment. The statistical models to predict the process response variables investigated are as well presented

Key words: Abrasive waterjet, aspect ratio, removal rate, standoff distance, taper angle.

1. Introduction

Deep -hole drilling is the process of machining holes with relatively large depth-to-diameter ratios [1]. In conventional machining processes, double-lip gun drills and twist drills are the commonly used to machine deep-holes [2]. These processes are, however, limited in the realizable depth-to-diameter ratios. Additionally, the drilling tools have to be guided by bushes or using a pilot hole during the material penetration. The processes are also associated with high heat generation which may affect the accuracy of the holes. Subsequent machining processes such as reaming and honing are required during these deep-hole drilling processes. Other critical challenges which are observed in conventional deep-hole drilling is the chip removal [3]. To ensure a successful residue-free chip removal, additional costs such as sufficient feeding of lubricant under pressure are unavoidable. There is a considerable demand for establishing more efficient technologies for precision drilling of complex parts such as engine vanes and shrouds at low costs and environmental pollution.

Abrasive waterjet machining (AWJM) uses relatively high-velocity waterjet containing fine abrasives to machine features such as holes and channels with high accuracy and precision. Compared to other machining technologies, such as electron beam, laser, electro-discharge, electrochemical, and plasma beam machining, AWJM has several unique advantages. For example, the process is capable of machining different materials-both at a micro and macro scale; has minimal or zero heat-affected zones (HAZ) onto the workpiece; its amenability to 3D machining, and relatively cheap operating costs [4]. With the development of harder, structural heterogeneous, and heat sensitive materials there has been an increased demand for identifying appropriate machining methods capable of processing such hard-to-cut materials. Furthermore, the fact that these hard-to-cut materials are used in a wide range of high-value products ranging from medical [5] to aerospace industries, coming up with better machining methods to encompass these demands is imminent. AWJM has found application in solving some of the challenges aforementioned including rock drilling in the mining industry [6]. In regard, many researchers have investigated this promising technology with the aim of making it commercially viable. However, the machining efficiency of this technology in terms of depth of jet penetration and kerf quality is still the major challenges limiting its applications [7]. Further, AWJM is a complex three-phase flow consisting of high-velocity air, liquid, and solid abrasive particles interacting closely to form the jet [8], [9]. The abrasive waterjet drilling is a very complicated process involving both the liquid-solid and solid-solid interactions with the workpiece material. Therefore, it is difficult to fully understand the effects of various input parameters to output variables such as material removal rate, surface roughness, and hole geometry deviations. In the present study, multivariate analysis method in the design of experiment has been invited to investigate the effects of pressure (P), standoff distance (SoD), and machining time (t) on various machining performance measures in deep-hole drilling operation.

2. Experimental Work

The experiments were conducted using a FLOW 3-axis CNC AWJM (MACH 123b series) installed at AlexStone Co., Ltd, Alexandria, Egypt. The machine is fitted with a JETPLEX pump capable of delivering ultrahigh-pressures of up to 55,000 psi (≈ 380 MPa). With a machining envelope of ≈ 3 m x 2 m, the machine has a positioning accuracy of ±0.003 mm and machining accuracy of ±0.01 mm.

The aluminum 7075-T6 alloy specimens were prepared at dimensions of 300 x 60 x 25 mm. The alloy's composition includes 5.7 % zinc, 2.3 % magnesium, 1.43 % copper, and less than 0.5 % silicon, manganese, iron, manganese, titanium, chromium, and other metals giving it a Vicker's hardiness (HV) of 165. Due to the alloy's high strength-to-density ratio, it finds wide applications in automotive, aerospace, and marine industries.

Only the major and controllable parameters were considered in the present design of the experiment. A full factorial design of experiment was developed to study the effect of pressure, standoff distance, and drilling time on the top diameter, hole depth, aspect ratio, penetration rate, taper angle, and material removal rate. Based on preliminary tests, two pressure levels (100 and 350 MPa), two standoff distances (2 and 4 mm), and four levels of machining time (5, 10, 15, and 20 s) were considered making a total of 16 blind holes in the 25 mm thickness aluminum 7075-T6 alloy plate. Each experiment was replicated three times in a randomized manner so as to ensure repeatability through total of 48 experiments. The abrasives flow rate (3g/s), the nozzle diameter (1.02 mm), and the impingement angle (90^o) were kept constant.

During the experiment, the workpiece was placed horizontally to avoid errors in measuring the kerf walls tapers. The drilled holes diameters were measured using a MarVision MM 320 optical microscope. The microscope has a maximum permissible error of less than 1.5 microns. The hole depths were measured using a modified Mitutoyo digital caliper. A fine needle was attached to the tip of the caliper to easily penetrate the small holes drilled as a probe. The measurements were taken at least three times to avoid any measurement and instrumental errors and the averages were used as the final reading. It was anticipated that in abrasive waterjet drilling of blind holes the kerf taper walls might be formed due to the jet spreading phenomenon explained by Hashish and Plessis [10]. The kerf profile was obtained by solidifying Conta glue in the machined holes. The conta glue was considered because of its fast solidifying nature and it can be easily retracted from the holes. The kerf taper was calculated by measuring the kerf wall inclination (Dt - Db) as shown in Fig. 1. The kerf taper angle was calculated from Eq. 1

$$\theta = \tan^{-1}(\frac{D_t - D_b}{2t}) \quad (1)$$

where θ is taper angle, D_t is the top hole diameter, D_b is the bottom hole diameter, and t is the distance between the measured sections.

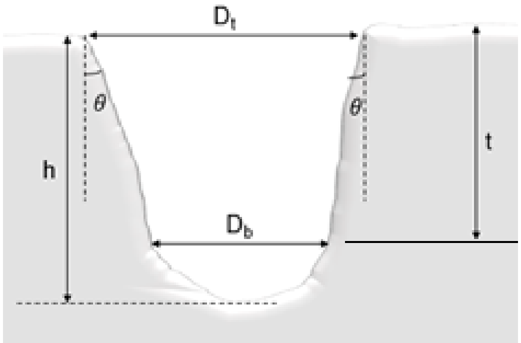

Fig. 1. Schematic diagram of blind deep-hole.

The effects of the selected input parameters on penetration rate (PR) were also studied. Penetration rate was calculated as the rate of change of depth with time (h/t). Eventually, the effects of the parameters on the volumetric material removal rate were investigated. The volume of the machined hole is calculated by double integration using a Matlab code. For the statistical analysis of variance (ANOVA), the Minitab 2018 commercial software was used to deduce the significance of various input parameters effects on the measured and calculated responses as well the regression models of each response are developed. ANOVA is a statistical computational technique in which the mean variations in a set of observations or measurable from an experiment are deduced.

3. Results and Discussion

3.1. Effect of *P*, SoD, and *t* on the top hole diameter (D_t)

The analysis of variance (ANOVA) was carried out and is presented in Table 1. It is evident that pressure (*P*), standoff distance (SoD), two way interaction between *P* and SoD (P*SoD), machining time (*t*), two way interaction between SoD and *t* (SoD*t*), two way interaction between *P* and *t* (*P**t*), and three-way interaction between P, SoD, and t (P*SoD*t*) significantly affect the top hole diameter at a confidence level of 95 %. Pressure is the most significant factor at 48.7209 % followed by SoD at 43.074 %, *P**SoD at 6.0288 %, *t* at 1.94 %, SoD*t* at 0.1395%, *P* * *t* at 0.0585 %, and *P**SoD*t* at 0.039%. The R2 value of the regression coefficient is 0.9985 indicating that most of the variability of the response data of top hole diameter's means have been captured i.e. the model is 99.85 % accurate. Equation (2) predicts the top hole diameter.

$$D_t = 0.8583 + 0.00010\,P + 0.0553\,\mathrm{SoD} + 0.00973\,t + 0.000445\,P * \mathrm{SoD} - 0.000015\,P * t + 0.0002\,\mathrm{SoD} * t + 0.000007\,P * \mathrm{SoD} * t \quad (2)$$

Table 1: Analysis of Variance of Significant Factors Affecting Hole Diameter (Dt)

	P	SoD	t	P*SoD	P*t	SoD*t	P*SoD*t
Mean-Square MS)	1.70253	1.5052	0.06778	0.21068	0.00204	0.00487	0.00136
F-Value	9845.98	8704.82	391.90	1218.36	11.82	28.19	7.89
P-Value	0.000	0.000	0.000	0.000	0.000	0.000	0000
R2				0.9985			

From the mean effect plot in Fig. 2, it can be deduced that D_t increases with the increase in *P*. A higher jet pressure results in an increase in kinetic energy of the abrasive particles leading to a higher erosion rate. D_t also increases with the increase of SoD as well as with an increase in t. As the SoD increases, the abrasive waterjet tends to spread out. Thus it results in an increase in jet diameter and, hence, widening the top hole diameter.

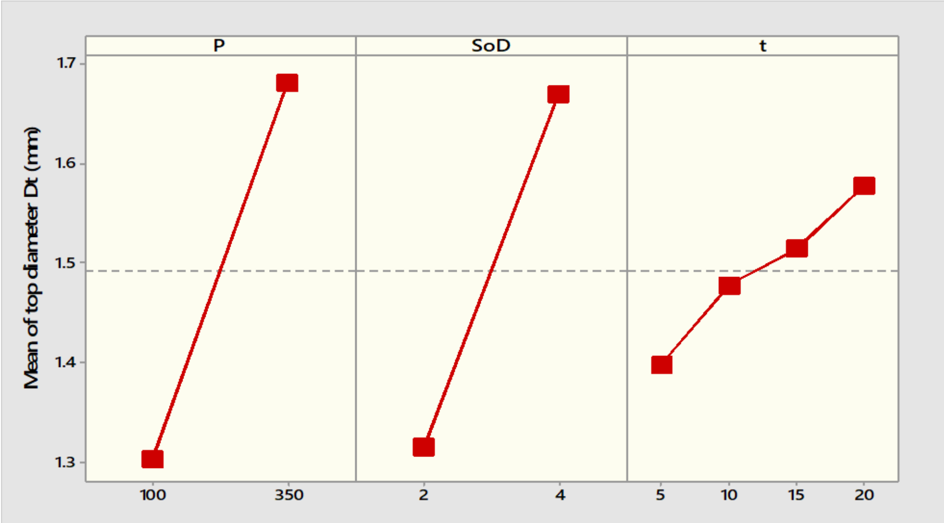

Fig. 2. Mean effect plot of P, SoD, and t on top diameter D_t (mm).

3.2. Effects of *P*, SoD, and *t* on hole depth, *h* (mm)

The ANOVA results on the significance of P, SoD, t, and variables interactions on hole depth (h) are presented in Table 2. According to the results, P, SoD, t, and two-way interaction between P and t as well as between SoD and t significantly affect the hole depth at a confidence level of 95 %. he percentage contribution for each significant factors and interactions was 63.24%, 4.35%, 27.53%, 3.45%, and 1.39%, respectively. Additionally, the two-way interaction P*SoD and three-way interaction P*SoD*t were not significant. Equation (3) predicts the hole depth using the machining conditions investigated.

$$h = 8.304 + 0.00244\,P - 1.482\ \mathrm{SoD} + 0.0919\,t + 0.000972\,P * t + 0.0803\,SoD * \tag{3}$$

Table 2: Analysis of Variance of Significant Factors Affecting Hole Depth (h)

	P	SoD	t	P*SoD	P*t	SoD*t	P*SoD*t
Mean Square (MS)	159.615	10.992	69.494	0.020	8.725	3.504	0.022
F-Value	709.60	48.87	308.95	0.09	38.79	15.58	0.1
P-Value	0.000	0.000	0.000	0.771	0.000	0.000	0.961
R^2				0.983			

Fig. 3 shows the mean effect plot of each factor on the hole depth. From the mean effect plot, it is evident that the hole depth increases with an increase in pressure and machining time but decreases with an increase in standoff distance. Increasing the pressure increases the kinetic energy for the waterjet stream, which consequently increases the velocity of the abrasive particles and thus the material removal rate. The machining time determines the exposure time of the abrasive jet on the workpiece surface. When the exposure time is high i.e. increased t, there is a possibility of secondary abrasive particles impingement resulting in an increase in h with the t. The effect of standoff distance can be explained that at smaller standoff distance, the jet front is characterized by potential core region which tends to have more jet power as compared to the larger standoff distance which is characterized by the main region.

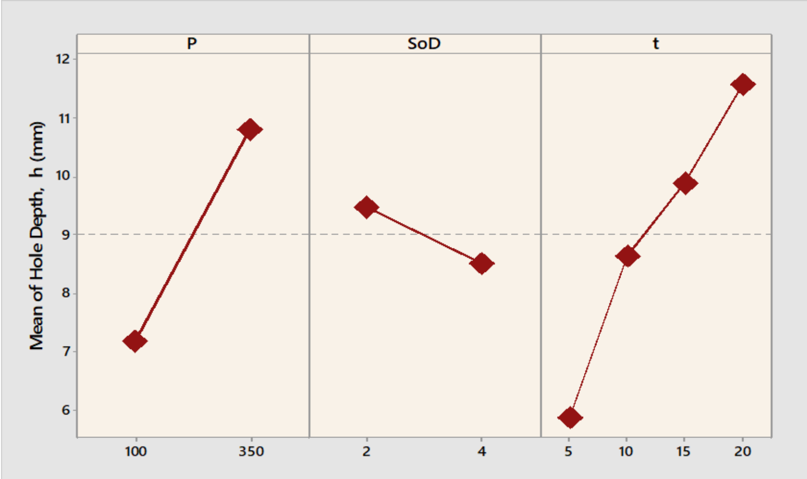

Fig. 3. Mean effect plot of P, SoD, and t on hole depth, h (mm).

3.3. Effects of P, SoD, and t on aspect ratio, (h/D_t)

Drilling high aspect ratio (AR) hole is one of the most challenging machining operations. Hence it is important to understand how various input parameters in AWJM affect the depth-to-diameter ratio so as to produce these holes accurately and in an economical way. Table 3 shows the significance of P, SoD, and t as well as their interaction on the aspect ratio. From the analysis, the most significant factor affecting the aspect ratio at a confidence level of 95 % was the standoff distance at 59.585%, followed by machining time at 21.722%, and the pressure at 14%. The two-way interaction between pressure and standoff distance as well as between pressure and time were significant with percentage effect of 1.8% 2.2%, respectively. The AR can be predicted using Equation (4)

$$AR = 6.127 + 0.00297\ \mathrm{P} - 0.723\ \mathrm{SoD} + 0.0939\ \mathrm{t} - 0.001461\ P * SoD + 0.000439\ P * t \tag{4}$$

Table 3: Analysis of Variance of Significant Factors Affecting AR

	P	SoD	t	P*SoD	P*t	SoD*t	P*SoD*t
Mean Square (MS)	12.458	53.0567	19.3415	1.6013	1.8815	0.4920	0.2124
F-Value	149.26	635.66	231.73	19.18	22.54	5.89	2.54
P-Value	0.000	0.000	0.000	0.000	0.000	0.07	0.73
R^2				0.9803			

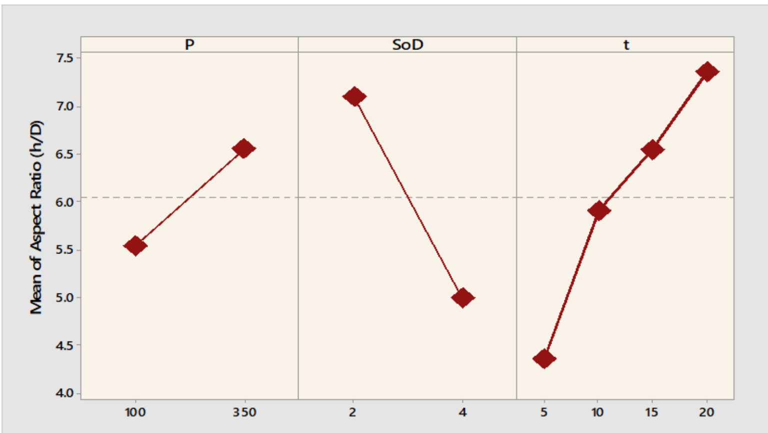

Fig. 4. Mean effect plot of the effect of P, SoD, and t_m on the AR.

Fig. 4 presents the mean effect plot of pressure, standoff distance, and machining time on aspect ratio. The AR increases with an increase in pressure and machining time but decreases with an increase in standoff distance. This phenomenon can be explained by the jet dynamic characteristics. For instance, the effect of standoff distance on the aspect ratio can be explained by the nature of rapid decay of the axial velocity at the jet centerline. The jet decay causes a reduction of the kinetic energy of the jet downstream, thus the decrease of the AR with an increase of the SoD is observed.

3.4. Effect of P, SoD, and t on Taper Angle (θ)

The taper angle was calculated using Eq.1. The taper angle is essential in deducing the hole geometric accuracy which is a machinability index. In machining deep holes, minimized or rather zero tapers are anticipated. The significance of the investigated factors on taper angle is presented in Table 4 and the taper angle θ can be predicted using Equation (5).

$$\theta = 3.5953 - 0.009120\, P + 0.7827\, \mathrm{SoD} - 0.05695\, t - 0.001127\, P * \mathrm{SoD} + 0.000101\, P * t \quad (5)$$

Table 4: Analysis of Variance of Significant Factors Affecting θ

	P	SoD	t	P*SoD	P*t	SoD*t	P*SoD*t
Mean Square (MS)	94.753	13.4408	0.6009	0.19520	0.0813	0.0015	0.0152
F-Value	67984.36	9643.65	431.16	683.07	58.34	1.04	10.89
P-Value	0.000	0.000	0.000	0.000	0.000	0.388	0.73
R^2				0.9996			

According to ANOVA, the pressure is the most significant factors with a percentage effect of 86.26% followed by the standoff distance with a percentage of 12.236%. Although the machining time significantly affects the taper angle at a 95 % confidence level, its effect is small at a percentage of less than 1%. Further, the interaction between pressure and standoff distance is significant although at small percentages of about less than 1 %. The three-way interaction (P*SoD*t) insignificantly affect the taper angle. High pressure, small standoff distance, and more machining time are recommended for small taper angle as it can be deduced from the mean effect plots in Fig. 5.

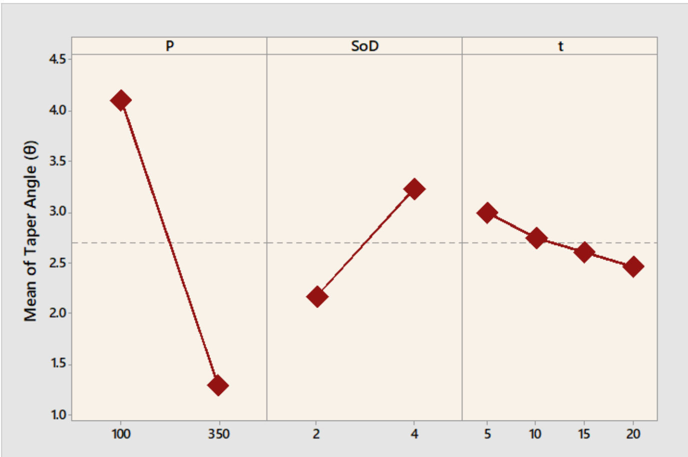

Fig. 5. Mean effect plot of the effect of P, SoD, and t on the taper angle (θ).

The taper angle decreases with an increase in pressure. High pressure increases the energy of the abrasive particles thus facilitating more effective material removal and reducing localized effects of higher penetration rates. It can be deduced that the kerf taper angle increases with an increase in standoff distance. This trend can be explained by the phenomenon of jet divergence at the downstream side. The jet loses its kinetic energy as it penetrates into the workpiece, the outer rim of the diverged abrasive jet lack sufficient energy to perform effective material removal as it goes deeper. As a result, the kerf taper increases with the standoff distance.

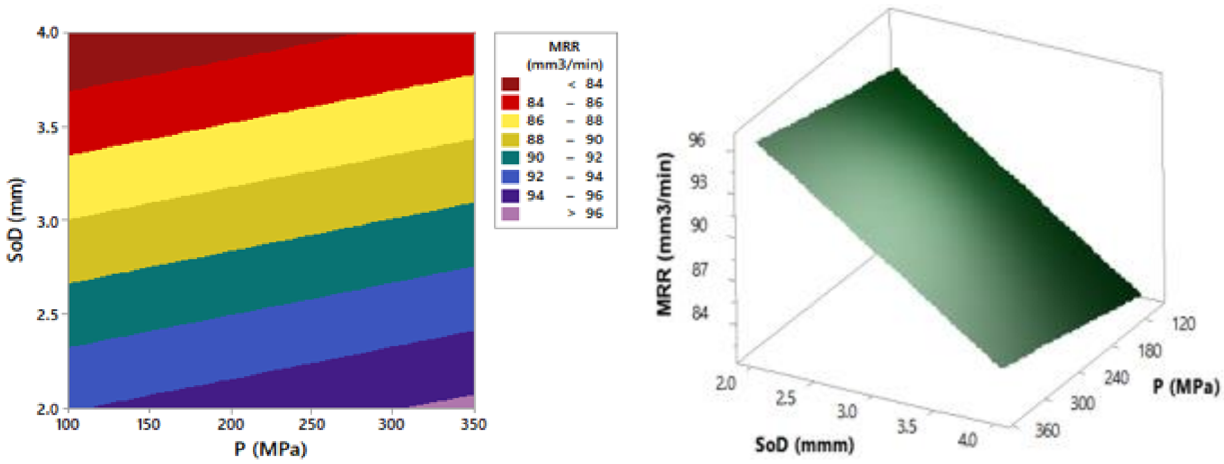

Fig. 4. Contour and surface plots showing the optimal conditions for maximized material removal rate.

3.5. Effect of *P* and SoD on Material Removal Rate

The volumetric material removal rate (VRR) is defined as the volume removed per unit time. Fig. 6 is the contour plot and surface plot, respectively, presenting the effect of P and SoD on volumetric material removal rate. According to the plot, the VRR increases with an increase in pressure but decreases with an increase in the standoff distance. The VRR can be predicted using Equation (6).

$$VRR = 83.3 + 0.0591\ \mathrm{P} - 13.62\ \mathrm{SoD} - 3.492\ t_m + 0.001127\ P * SoD - 0.00392\ P * t_m + 0.62\ SoD *\ t_m \tag{6}$$

Higher pressures result in a higher material removal rate by increasing the kinetic energy of the abrasive particles impinging the workpiece surface. A small standoff distance results in a higher material removal rate because of the dynamic jet characteristics structure. At a small distance, the dynamic jet structure is characterized by a high energy resulting due to low turbulence thus resulting in higher material removal rate.

4. Conclusions

In pursuit of achieving deep drilling of high depth-to-diameter ratio holes by abrasive waterjet machining, the experiments were conducted to investigate the effects of pressure, standoff distance, and machining time on various machining responses. From the in-depth analysis, the following main conclusions can be drawn:

In AWJ drilling of aluminum 7075-T6 alloy, the hole diameter increases with an increase in SoD and P but the hole depth increases with the decrease in SoD. However, the depth increases with P as well.

For high aspect ratio holes, a small standoff distance and high pressure are recommended.

To achieve high geometrical accuracy i.e. reduced taper angle, high pressures and smaller standoff distance are recommended. The machining time effect on taper formation is less than 1% when compared to pressure and standoff distance.

A higher machinability index in terms of volumetric material removal rate in deep-hole drilling can be achieved by utilizing smaller standoff distance and higher pressure. However, the machining time should be carefully controlled to achieve anticipated depths.

Conflict of Interest

The authors declare that the submitted work was carried out without a conflict of interest.

Author Contributions

Joseck Nyaporo: Research conceptualization and methodology, preparation, experiment, analysis, discussion, and writing original draft, **Mahmoud A. Ahmed:** Supervision, review, and editing, **Hassan A. El-Hofy**: Supervision, review, and editing. All authors have read and approved the publication of this version of this manuscript.

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