Nano World Journal

https://doi.org/10.17756/nwj.2023-s4-008

Research Article

Open Access

Experimental Investigation of Kerf Angle and Drilling Rate in AWJM Deep Hole Drilling on SSAISI 316L

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Received: September 15, 2023
Accepted: November 20, 2023
Published: November 23, 2023

Citation: Jeyaprakash BC, Nagarajan L, Rathinasuriyan C, Sethuraman B. 2023. Experimental Investigation of Kerf Angle and Drilling Rate in AWJM Deep Hole Drilling on SSAISI 316L. *NanoWorld J* 9(S4): S43-S48.

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Abstract

The need for mechanical deep hole drilling is gaining attention for small diameter applications in automobile, aerospace, and medical industries, etc. This leads to the manufacturing industry looking for an advanced method to produce such holes. In recent trends, the use of abrasive waterjet drilling is increasing tremendously owing to its exceptional drilling capability of almost all types of materials with good dimensional stability. However, this method of manufacturing incurs higher initial investment, as well as higher maintenance and running costs. As a result, the identification of drilling process parameters is critical for the economical, efficient, and successful use of this method. The focus of this investigation is to find the appropriate range of water pressure and standoff distance in the abrasive waterjet drilling process and their impact on kerf angle (KA) and drilling rate during the making of deep holes on stainless steel AISI 316L with a high aspect ratio (1:45). According to the outcomes of this experimental work, water pressure is the most influential parameter for improving drilling rate and minimizing KA. However, with the specified range of drilling process parameters, the standoff distance reduces the drilling rate and increases the KA.

Keywords

SS 316L, Deep hole drilling, Abrasive waterjet machining, Kerf angle, Drilling rate

Introduction

Abrasive waterjet machining (AWJM) is the most adaptable modern manufacturing process. It's used to drill holes in ceramics and glass stone with no/less heat affected zone [1]. AWJM is the most adaptable modern manufacturing method. AWJM removes material by impinging abrasive particles with a great-velocity water jet. Cutting and deformation wear modes are used during ductile erosion [2]. An abrasive waterjet is a form of cold machining that is utilized in the production of precision components for usage in industries such as the aerospace industry, the automobile industry, and the marine industry [3]. Drilling holes that have a high aspect ratio (L/D > 10) require the use of a specific machining method known as deep hole drilling [4]. In today's world, the production of such holes typically makes use of a wide variety of non-traditional methods including electrical discharge machining and laser. However, those methods involve several challenges, including heat affected zone, microcracks, thermal stress, recast layer, and poor dimensional stability in the machined surfaces. This has an impact on the machined component's surface integrity (altered layer) [5, 6]. Because this modified layer affects the performance of the components in a wide variety of uses, including fuel injectors of automobiles, engine oil flow, blades of turbines, etc. [7].

Hashish and Whalen. [8] experimental results showed that AWJM can generate more constant high-quality holes with a diameter of above 0.5 mm on ceramic coated materials without affecting the surface irregularities. Akkurt [9] investigated the amount of time required to drill holes in a variety of materials, including stainless steel-AISI 304, aluminum alloy-Al-6061, brass-353, and tool steel-D3. According to the findings of the study, the amount of time it takes to machine a material is significantly influenced by the type of material being machined as well as the mechanical qualities of the material being machined. In addition, the drilled holes surface quality deteriorates through increasing material depth, which leads to a decline in overall quality. Alberdi et al. [10] implemented hole drilling on Ti6Al4V and CFRP stacks. Because of the poor machinability of these materials, the positive and negative KA was noticed on Ti6Al4V and CFRP stacks in nearly all cutting settings. Furthermore, when water pressure increases, the taper angle decreases. Hamatani and Ramulu. [11] investigations revealed that AWJM is capable of providing acceptable surface finishes on high-temperature composites with minimum damage.

Liu and Schubert [12] reviewed the piercing impact generated by piercing pressure on a variety of materials, including aluminum laminates up to 4.6 mm thick, Inconel substrate up to 2.6 mm thick, and epoxy-impregnated fiber glass laminate up to 9 mm thick. The findings of the experiments demonstrated that the surface integrity of drilled holes is diminished when the piercing pressure is greater than the ultimate strength of the materials. Prasad and Chaitanya. [13] examined the surface quality and dimensional stability of 8 mm thick GFRP composites by varying process parameters such as water pressure, standoff distance, mass flow rate, and fiber orientation angle. It was reported that decreasing the standoff distance and fiber orientation angle resulted in a drilled hole with better dimensional consistency and reduced surface roughness with improved water pressure and abrasive mass flow rate. Wakuda et al. [14] examined the effect of alumina ceramic abrasive on surface quality. The silicon carbide abrasive can yield a superior surface finish on alumina ceramics than synthetic diamond and aluminum oxide. Bhavani et al. [15] used Taguchi L_{18} orthogonal array approach to optimize input parameters and deep hole drill brass 353 of thickness 50 mm to evaluate KA, material removal rate (MRR), and surface quality (SR). Water pressure (281 MPa), flow rate (185 g/min), and SOD (3 mm) were determined to produce deep holes with minimal KA, SR, and MRR, respectively.

Preedawiphat et al. [16] utilized AWJM to explore the deep hole features of SS 316 and MS A36. According to the findings of this experimental inquiry, the material thickness, as well as the machinability index, is the most significant factor that determines the amount of time needed for drilling. Rajadurai [17] drilled deep holes in Ti-6Al-4V to investigate the possibility of using an AWJM on a super alloy. The drilled holes of size Ø3 mm and 100 mm thickness were revealed to be tapered at the bottom. Increasing the jet's drilling time produced a constant diameter through the material's thickness. Furthermore, the surface integrity of the holes increases with the depth of the material. Li and Wang [18] experimental findings on Ti-6Al-4V demonstrated that the hole's diameter and depth increase as the water pressure increases. Orbanic and Junkar [19] showed that the aspect ratio of the drilled hole was discovered to increase steadily with the depth of the hole. In addition, neither the type of material nor its mechanical properties have a substantial effect on the geometry of the holes. However, this impacts the drilling duration. Kumaran et al. [20] found that coarse abrasive particles improve MRR and SR. Boud et al. [21] tested the drilling capability of five sorts of abrasive on titanium alloy. The material's waviness affects cutting. The examination showed that cutting efficiency is practically similar for all abrasives except morphology.

Rajamani et al. [22] conducted a series of experimental trials including the utilization of abrasive waterjet cutting techniques on green composites that were reinforced with nano clay particles. Based on the findings of this investigation, it was observed that augmenting the weight percentage of nano clay by 1.15% resulted in the attainment of superior component quality. Furthermore, it was observed that the incorporation of nano clay resulted in improved mechanical and machining properties of the natural fiber composite. The experimental findings of Selvam et al. [23] demonstrated that the incorporation of nano fillers resulted in enhanced fracture stiffness and strength of the resin. Al-Alkawi and Al-Salihi. [24] fabricated a metal matrix composite by including alumina as the nano filler material. The experimental findings demonstrated a significant enhancement in the mechanical characteristics of the metal matrix composite. Venkatesh et al. [25] employed hybrid nanoparticles as a reinforcing agent to augment the mechanical characteristics of the Al6061 aluminum alloy material.

Based on the review of the literature, it has continuously been a significant difficulty to make precise holes with tight tolerance, which is critical in the fields of automobile, aerospace, and biomedical that use difficult-to-cut materials. As a result, industrial sectors are seeking an innovative manufacturing technique for producing such holes while causing the minimum damage to the workpiece. Abrasive waterjet drilling has surpassed all other production techniques in the modern era owing to its superior machining capabilities.

Materials and Method

Because of recent developments in component reduction and miniaturization, deep hole drilling with a high aspect ratio has become increasingly important. This is important in the fabrication of vehicle fuel injector bodies and in the manufacturing of bio-medical devices like bone screws and surgical equipment [26]. Small-diameter deep holes with a large depth-to-diameter ratio are becoming increasingly important in manufacturing. To increase combustion efficiency and injection pressure, for instance, boreholes of this type are used in the design of fuel injectors for the automotive sector. The automotive industry frequently employs stainless steel 316L for the design of fuel injectors due to the material's high hardness and good resistance to chemical corrosion [27]. Stainless steels are alloy steel with exceptional properties such as durability, resistance to heat and corrosion, low maintenance requirements, high hardness, and adaptability in production. Stainless steels are alloy steel with exceptional properties such as

durability, resistance to heat and corrosion, low maintenance requirements, high hardness, and adaptability in production [28].

In this work, deep holes were drilled in AISI 316L stainless steel measuring 100 x 100 x 135 mm. Stainless steels are alloy steels with great rust and heat resistance and high tensile strength at high temperatures. A great deal of study has been conducted to investigate the benefits of employing stainless steel in automotive, biomedical, and other industrial processes [29].

The selection of input parameters and different levels is a very important step to obtain a good quality hole. The parameters and level were fixed based on the literature reviews that had been carried out in the past on stainless steel, graphite/epoxy laminates, brass, and titanium alloy [30, 31]. The process parameter ranges used in this experiment are water pressure (WP) 260 MPa - 360 MPa, abrasive mass flow rate (AMFR) 0.5 kg/min, and standoff distance (SOD) 1.5 - 3.5 mm. The levels of the parameters are given in table 1.

Deep hole drilling was performed on AISI 316L stainless steel using an AWJM (Model G3020, German) with a nozzle diameter of 1.02 mm and an abrasive type 80 mesh garnet as an abrasive type. The typical AWJM experimental setup is depicted in figure 1. The drilling parameters viz; WP, SOD, and AMFR were fixed based on table 1. The 100 x 100 x 135 mm SS 316L material was secured with steel clamps on AWJM's worktable. By adjusting the settings of the drilling operation, six deep holes were drilled into the chosen material. Each hole's drilling time was recorded as it was drilled. Figure 2 shows the AWJM deep holes fabrication process. Each hole was individually marked for easy identification. The diameters at the entry and exit of the drilled deep holes are studied through a video profile projector (ME2020) displayed in figure 3 whose traverse speeds on the X and Y axes are 250 x 150 mm and 300 x 200. The lens used in this device is a high-resolution telecentric zoom lens. The software used for measurements is 3D geometric with programming. The optical accessories of this device are a Renishaw touch probe and a motorized zoom lens. The KA shows a vital role in determining the quality of holes drilled with AWJM. In deep-hole drilling of high-strength materials, the KA is a regular phenomenon. It's measured in degrees and is proportional to the difference between the largest and smallest diameters of the drilled holes. The KA of drilled holes are calculated using equation 1 given below. In the equation θ refers to the KA measured in degrees, D_{entry} and D_{exit} are entry and exit diameters of the deep holes, whereas T refers to the thickness of the selected material in mm. The measurement KA at the various levels is detailed in table 2.

$$\theta = \tan^{-1}\left(D_{entry} - D_{exit}\right)/2T \quad (1)$$

During drilling operations, the quantity of material removed has a significant impact on the processing cost and output rate. As a result, industries are constantly searching for methods to increase drilling rates in order to satisfy demand while minimizing production costs. During the drilling pro-

Table 1: Levels of process parameter.

Level	WP (MPa)	SOD (mm)	AMFR (kg/min)
I	260	1.5	0.5
	310	1.5	
	360	1.5	
II	260	3.5	
	310	3.5	
	360	3.5	

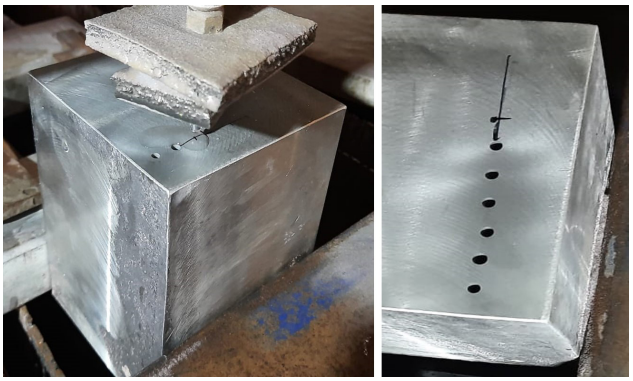


Figure 2: AWJM Deep hole making process.



Figure 1: AWJM experimental system.



Figure 3: Video profile projector.

Table 2: Measurement of entry and exit diameters.

Level	Water pressure (MPa)	AMFR (kg/min)	SOD (mm)	Top hole diameter (mm)	Bottom hole diameter (mm)
1	260	0.5	1.5	3.46	3.09
	310	0.5	1.5	3.44	2.99
	360	0.5	1.5	3.63	3.11
2	260	0.5	3.5	3.36	3.02
	310	0.5	3.5	3.41	2.98
	360	0.5	3.5	3.53	2.55

cedure, the time it takes to drill each hole is recorded using a stopwatch. The drilling rate is calculated using equation 2 presented below. In this equation D_{rate} represents the drilling rate, T_h indicates the time taken for drilling the holes and T represents the thickness of the workpiece material.

$$D_{rate} = \frac{T}{T_h} \quad (2)$$

Results and Discussion

In this investigation, an attempt has been made to explore the possible use of abrasive waterjet machining for making deep holes on AISI 316L stainless steel and also to study the effect of process parameters namely WP and SOD on KA, hole diameters (entry and exit) and drilling rate. The entry and exit diameter of each hole measured against respective parameters by video profile projector is listed in table 2. The image obtained from the video profile projector is also shown in figure 4 and figure 5 for levels 1 and 2. The first hole was drilled on the workpiece using the level 1 process variables of 260 MPa WP, 1.5 mm SOD, and 0.5 kg/min AMFR. According to the depiction in figure 4, the WP is insufficient to make a hole through the entire thickness of the workpiece. This is owing to the water's low kinetic energy to travel through the full thickness. Because some of the material was not removed, the hole-making procedure was incomplete.

The hole manufactured for levels 1 and 2 with WP 310 MPa and SOD of 1.5 and 3.5 mm seen in figure 4 and figure 5 reveals that the WP is sufficient to make a deep hole on the workpiece, although the entry and exit diameters showed lesser variability. The WP of 360 MPa for levels 1 and 2 is more suited for drilling a deep hole in the workpiece with minimum variation in the entry and exit diameters. In the deep hole drilling making, blind holes were drilled by AWJM through the piercing. The KA and drilling rate for different WP and SOD were investigated. Figure 6a shows the kerf angle for the water pressure 260 MPa to 360 MPa with a different SOD between 1.5 mm and 3.5 mm. It was observed from the trend, lower WP resulted in a lower KA irrespective of the SOD. As both the parameter WP and SOD increase the kerf angle also increases. An increase in the WP leads to increases in the waterjet stream, which in turn accelerates the abrasive particles and strikes the selected material with superior velocity to form larger diameter on the top of the specimen. In addition, as the depth of the specimen increases, the KA reduces, which

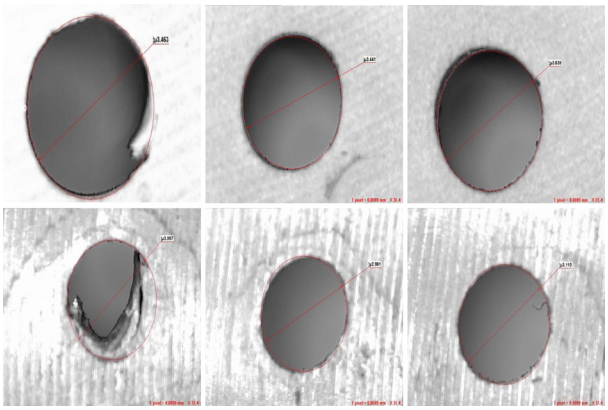


Figure 4: Entry and exit diameter of level 1.

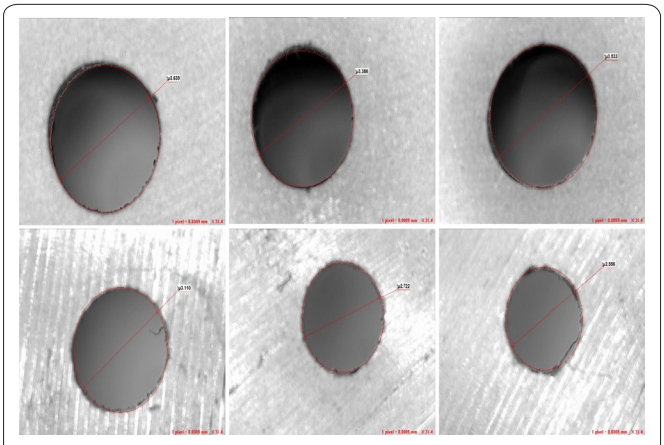


Figure 5: Entry and exit diameter of level 2.

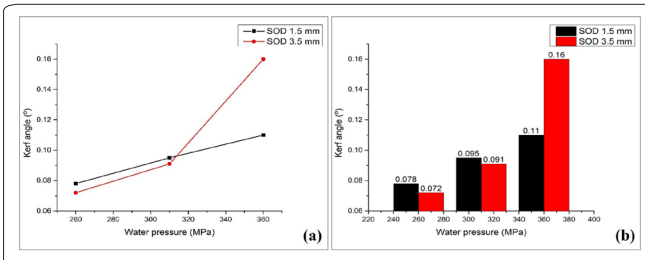


Figure 6: Effect of input parameters on kA.

in turn results in less material erosion. This is because the bottom of the workpiece has a smaller diameter than the rest of the workpiece. A tapered shape is formed on the drilled holes as a result of the difference in diameter between the top and bottom of the holes. It has been discovered that this conical impact is more prevalent for greater WP and SOD. It is recommended to use low WP and SOD for minimum KA. This outcome is similar to the result stated by Sanghani and Korat. [32] conducted abrasive waterjet drilling on AISI 304 to explore the effect of process variables on KA and SR. Less KA was witnessed for the decreased WP.

The KA formation at different WP and SOD combination is illustrated in figure 6b. The percentage of KA rate is increased to 8.33%, 4.3%, and 45.45%, respectively, under the WP of 260 MPa, 310 MPa, and 360 MPa with different SOD 1.5 mm and 3.5 mm. The KA is increased by 41.02% on maximum WP when compared to minimum WP at con-

stant SOD of 1.5 mm. Correspondingly, the percentage of KA is increased by 122.2% on maximum WP when compared to minimum WP at constant SOD of 3.5 mm. The KA percentage is increased to 41.02% on maximum WP and fixed SOD 3.5 mm. It is also seen from figure 6 that there is a noticeable deviation in the percentage of KA for higher and medium WP with SOD 1.5 mm - 3.5 mm are 15.78% and 75.82%, respectively. The WP is found to be the most dominating factor in the formation of KA as compared to SOD which contributes less to KA formation. If both WP and SOD increase, then the KA also increases. It is recommended to set the WP range from 260 MPa to 310 MPa and SOD of 1.5 mm for the hole with minimum KA.

In the deep hole-making process, it is seen from figure 7 that when WP increases drilling rate also increases. Arise in WP increases the kinetic energy of the water stream and hits the workpiece with great impact as a result the workpiece is penetrated through depth in a shorter period. It is also noted from figure 7 that the water pressure is directly proportional to machining time. When WP increases, machining time decreases. Karthik et al. [33] commented that MRR and machining time were strongly influenced by waterjet pressure. The same trend was reported in past studies for various materials with different depths [34-36]. Li and Wang. [18] stated that hole depth and diameters are directly proportional to drilling time, and increased WP is intended to increase the depth and the hole diameters.

The graph is drawn for WP (260 - 360 MPa) and SOD (1.5 - 3.5 mm) to understand the trend of drilling rate that is illustrated in figure 8. The percentage of drilling rate increased to 17.86%, 39.30%, and 41.14%. respectively. under the WP (260 MPa - 360 MPa) with different SOD (1.5 mm - 3.5 mm). The drilling rate is increased by 118.50% on maximum WP when compared to minimum WP at constant SOD of 1.5 mm. Similarly, the drilling rate is increased by 89.9% on maximum WP when compared to minimum WP at constant SOD of 3.5 mm. It is evident from figure 8 there is not much deviation in the percentage of drilling rate for higher and medium WP with SOD 1.5 mm - 3.5 mm are 27.38% and 25.7%, respectively. Keeping higher WP with lower SOD improves the drilling rate.

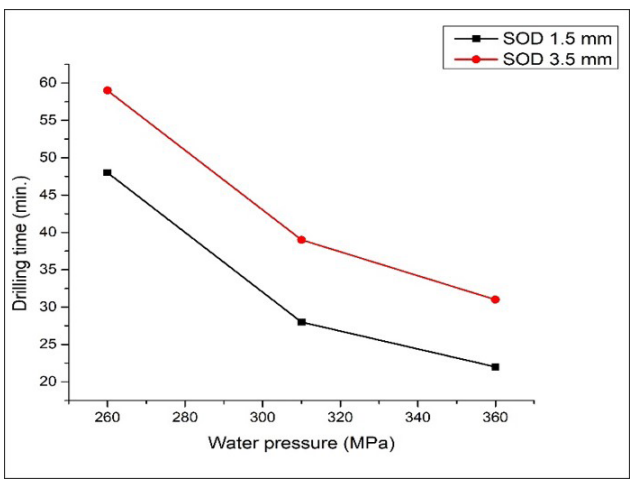


Figure 7: Effect of input parameters on drilling time.

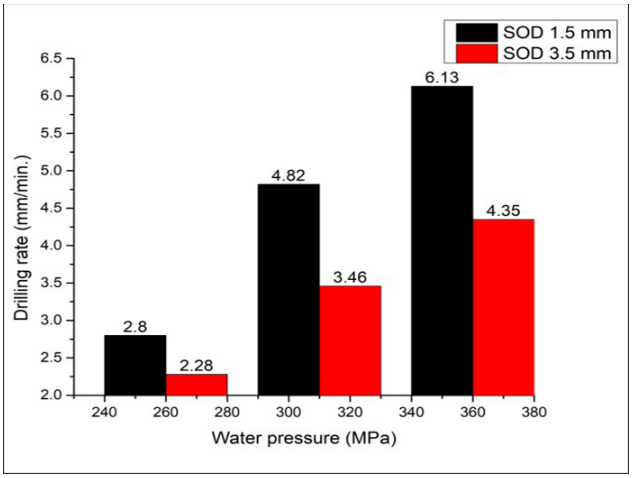


Figure 8: Effect of input parameters on drilling rate.

Conclusion

The experimental investigation on the KA and drilling rate in abrasive waterjet deep hole drilling on stainless steel AISI 316L revealed that both WP and SOD increase so does the KA. The KA was determined to be minimum at a WP of 260 MPa and SOD of 1.5 mm, however, this WP is insufficient to make deep holes in the workpiece. The allowable KA was determined to be between 260 and 310 MPa. This was one of the results of the experiment. Increase in WP accelerates the drilling process. The highest drilling rate was obtained for WP ranging from 310 MPa to 360 MPa with SOD ranging from 1.5 mm to 3.5 mm. When exact hole dimensions are required, it is recommended to set WP between 260 MPa and 310 MPa. In contrast, WP ranging from 310 MPa to 360 MPa helped to a faster drilling rate. This could be especially helpful in applications where drilling time is critical.

Acknowledgements

None.

Conflict of Interest

None.

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