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Investigation on surface roughness and kerf analysis in abrasive water jet machining of silicon carbide

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ABSTRACT

Purpose: Machining silicon carbide (SiC) is challenging due to its brittle and maximum tensile nature. Lapping or laser beam are done with a high cost of manufacturing and low material removal rates. Water abrasive jet cutting is a promising candidate since the machining temperatures and processing force of ceramics are extremely low. Investigation into the abrasive water jet machining of silicon carbide is carried out in the present work.

Design/methodology/approach: The variations in traverse speed while abrasive water jet cutting of silicon carbide and its effect on the surface roughness and kerf characteristics are studied. Silicon Carbide abrasive material is used as garnet consisting of 80 mesh. The surface roughness was calculated along with the depth of the cut made during the processing.

Findings: The outcomes demonstrated that the traverse speed is more effective upon the surface roughness and is an important factor that damages the top kerf width and the kerf taper angle.

Research limitations/implications: Based on the hardness and thickness of the SiC plate, the taper angle is high, and for a feed rate of 10 mm/min, the surface roughness is low. Less thickness of the SiC plate could have a lower taper angle than with high thickness. The erosive force is provided by abrasive material along with the jet stream.

Practical implications: Water abrasive fine jet could effectively machinate silicon carbide ceramic material with a better surface finish accurately. Suitable surface roughness with higher productivity can be attained with medium traverse speed.

Originality/value: The effect of process parameters on kerf taper angle and top kerf width in the abrasive water jet machining of silicon carbide is explored, considering surface roughness as an important output parameter.

Keywords: Ceramic, Cutting, Abrasive water jet machining

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Silicon carbide is an important reinforcement in metal matrix composites that brings appreciable enhancements to the composites. The traditional method of cutting silicon carbide was a difficult process as it is time-consuming, leads to material wastage, and creates dust and noise. All these concerns lead to exploring suitable cutting solutions. Untraditional machining processes like abrasive water jet machining (AWJM), ultrasonic machining, water jet machining (WJM), laser beam machining (LBM), etc., have provided cutting solutions. In general, the ultrasonic machining method is applicable for both nonconductive and brittle materials, but the main drawbacks are time consumption, low speed, and high tool wear rate [1]. LBM can be used, but the major drawback is the height of the workpiece [2]. Thus, research has been conducted to find suitable problem-solving solutions for machining silicon carbide and abrasive water jet machining evolved as potential cutting solutions. This was primarily established in 1974 for cleaning the metal.

The inclusion of abrasives into the water jet improved the removal rate of the material and the speed range of cutting lies between 51 to 460 mm/min. Usually, in AWJM, composite materials are cut ten times faster than the other conventional machining methods. The cutting power is gained via hydrostatic energy (400 MPa) conversion into a jet with the necessary amount of kinetic energy (almost 1000 m/s) for breakdown. For this conversion, the energy is attained by forcing water to ultrahigh-pressure, and the extreme cutting stream is formed in high-speed water within a small orifice. The AWJ cutting is built on the principle of the erosive nature of the material by the influence of jets which contains two parts, i.e., the water and abrasive material. The erosive force is provided by abrasive material within the jet stream. Still, the water jet with increased abrasive substance is preferred to increase the speed to achieve a superior impact on materials-changes in momentum help to perform its function [3]. Every hard abrasive particle appears to be a unique tool for point cutting. The abrasive particle-laden water jet invades against the surface were the workpiece and the substance are detached by the method, namely the erosion process. The "abrasive water jet (AWJ)" machining gained more advantages over other cutting machines due to the presence of minimal cutting forces, more versatility in terms of applications, the absence of thermal distortion on the workpiece, and maximum flexibility to cut in all directions [4]. It is a safe and non-hazardous procedure where the abrasive water jet cutting is a heat and radiation emission-free process. Almost all the airborne dust is eradicated. Likewise, the noise level (ranging from 85 to 95 dB) is acceptable.

Previously, the AWJM method was applicable to cut materials with vast amounts extending from conventional steels to ceramic substances. The process- efficiency and intensity depend on several parameters such as angle of impact, stand-off distance, traverse rate, etc. [5]. Numerous experiments were carried out on the cutting performance measures to ensure the accurate effects in this process variables like surface roughness, kerf taper, and width. The kerf geometry typically shows more interest in the method of abrasive waterjet cutting. As mentioned in Figure 1, the AWJ usually opens a slot that is tapered with top kerf (W_t), which is wide compared to the bottom kerf (W_b), kerf taper, or kerf taper angle (Θ) and also other nomenclature are represented.

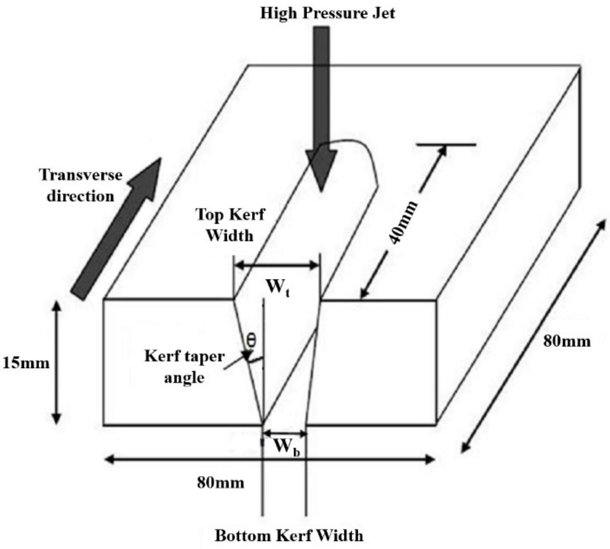

Fig. 1. Kerf geometry of specimen

2. Literature review

In metal matrix composites, silicon carbide plays an important role which brings significant changes [6-11]. Many scholars have examined the impact of AWJM diverse materials. Some works have stated that when the kerf taper angle decreases upon the rise in water pressure [12-14]. Wang and Jun observed while cutting of polymer matrix composite, which showed a reverse tendency of kerf taper angle concerning the water pressure as the outer rim of the diverged jet has tolerable energy to break the soft material. Some reviews reveal that the kerf taper angle increases with an increase in the focusing tube transverse speed [12,13]. Wang and Jun stated that there is a decrease in kerf taper angle with a gradual increase of focusing tube transverse speed; this is achieved by using speed ranges selected, different pressure, types of materials chosen and diverse ratios of jet energy to cut material. The kerf taper angle increases by increasing in standoff distance (i.e., distance between the focusing tube tip and the work surface) [12,13,15]. The investigational report on ceramic material, specified abrasive mass flow rate wouldn't sign on the kerf taper angle, as the abrasive mass flow rate disturbs significantly and also the lowest kerf width in an analogous magnitude or scale [16]. Correspondingly, Shanmugam and Masood detected that with a rise in the abrasive mass flow rate, there is a decline in the kerf taper angle insignificantly [12]. Water pressure, transverse speed, and standoff distance have a supplementary modification on kerf taper angle other than abrasive flow rate. To generate the parallel kerf, a mixture of low transverse speed, high-water pressure, and small standoff distance are required. The problem is that a gradual increase in water pressure led to an increase in top kerf width (W_t in Fig. 1) [12, 16-18]. Some research works reveal that more amount of water pressure yields a broader slot as kinetic energy in the form of the jet is enforced into the target material. Although Kantha and Krishnaiah Chetty say that there is no relation between top kerf width and water pressure [19]. Hascalik et al. assumed that transverse speed at the focusing tube is inversely proportional to top kerf width since they permit slowly and there is more impact on the abrasive particle to target and open a wider slot [20]. It varies for different reinforcements [21,22]. Chen et al. initiated that focusing tube transverse speed resulted in small changes in top kerf width while cutting the brittle material [17]. Hlavac et al. expressed through research that deformation is possible in copper while machining with AWJM due to the jet delay inside the kerf. A mathematical model also developed for compensating the taper [23]. An exclusive equation has to be incorporated into the mathematical model to express the jet delay compensation [24,25].

Overall, the literature reveals that the AWJM can be applied to a wide range of materials, but marble cutting remains unknown. Although there are diverse results came for parametric factors of AWJM on kerf characteristics for various materials, potential research scope is there owing to diverse compositions and properties of the material. Effects of process parameters of AWJM on silicon carbide have to be studied and explored as they are commonly used. The current paper focuses on the influence of traverse speed on kerf angle and surface roughness in the AWJM process.

3. Experimentation

The samples are machined using DWJ1313-FB water jet cutter prepared with a DIPS6-2230 ultrahigh-pressure pump. The size distribution of silicon carbide specimen is 80 mm × 80 mm × 15 mm. Table 1 specifies the vital application of silicon carbide (a material chosen for experimentation).

Table 1.
Mechanical and physical properties of silicon carbide

Property	Hardness	Density	Compressive strength
Value	9 on Mohr's Scale	3200 Kg/m^3	3900 MPa

As pre the literature review, numerous variables are associated with AWJM, and these variables influence the cutting results. Among these variables, the influence of traverse speed against kerf angle and surface roughness are examined in the current work. Now, all other parameters are kept constant except the focusing tube's traverse speed which is given in Table 2.

Table 2.
Constant parameters and their values

Constant parameters	OD	FTD/MTD	FTL	Abrasive type and size (grit no)	(SOD)
Value	0.35 mm	0.76 mm	101.65 mm	Garnet and mesh size - 80	1 mm

SOD – standoff distance, OD – orifice diameter, FTD – focusing tube diameter, MTD – mixing tube diameter, FTL – focusing tube length

To accomplish a systematic cut, the mixtures of the variables in the process must give enough energy to the jet to penetrate completely into the specimens. The least value of water pressure is 200 MPa and the abrasive flow rate is 200 g/min during the process of cutting. Experimentations were shown by varying the traverse speed as 10 mm/min, 20 mm/min and 30 mm/min.

In cut surface, the surface roughness was observed by the average roughness (R_a) measurements of surface roughness are made at various zones.

The value of kerf taper, depth of cut and top kerf width are taken at the end of the kerf before segregating the sample for measuring the smooth surface depth of the cut. As in the jet tailback effect, the AWJ contouring the walls of two kerf doesn't looks symmetrical. Therefore, the kerf taper and smooth depth of cut were found at both the kerf walls.

The kerf taper calibrates the inclination of kerf wall ($W_t - W_b$) as of the top kerf edge as shown in Figure 1. The taper angle is measured by the given equation. Table 3 represents data observed.

$$\theta = tan^{-1}\,(W_t - W_b)/2\,t \qquad (1)$$

where the top kerf width is W_t, the bottom kerf width is W_b and thickness of the workpiece is 't'.

Table 3.
Experimental data on kerf characteristics

Experiment No.	Focusing tube traverse speed, mm/min	Surface roughness, R_a, µm
1	10	8.6
2	20	19.3
3	30	25.7

4. Results and discussions

Silicon carbide is an important reinforcement in metal matrix composites that brings appreciable enhancements. Various constrains are associated with traditional method of cutting the silicon carbide such as time consumption, material wastages, tool wear, etc. AWJM possesses potential qualities for machining silicon carbide. Analysis of the effect traverse speed against kerf angle and surface roughness are discussed in this section.

4.1. The effect of traverse speed on surface roughness

In Figure 2, the AWJ cutting, thickness of silicon carbide is measured as 15 mm which contributes to develop the study on effect of traverse speed in surface roughness. Abrasive mass flow rate is kept as constant value of m = 320 g/min and trials are performed. One of the evaluation profiles taken with the combination of Surface roughness tester (Surftest SJ-210) and Surftest communication software is given in the Figure 3. The average of three surface roughness values for each traverse speed are given in Table 3 and same are plotted against traverse speed (Fig. 2). It is explored that as the traverse speed rises, the surface roughness also rises. Now the roughness R_a changes to some extent at the depth of the surface cut.

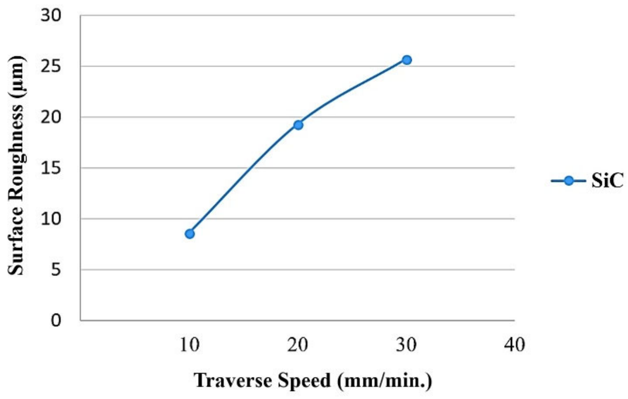

Fig. 2. Effect of traverse speed on surface roughness

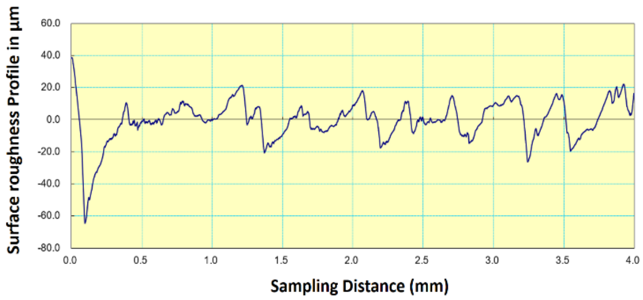

Fig. 3. Evaluation profile of the 8.972 µm surface roughness value for the Traverse Speed of 10 mm/min

4.2. The effect of traverse speed on kerf characteristics

In AWJ cutting of silicon carbide plate, the thickness of the surface roughness throughout the plate is 15 mm the abrasive mass flow rate was kept constant as 320 g/min.

It is identified that as the traverse speed rises, the kerf angle also rises (Fig. 4). The results reveal the impact of travers speed on kerf angle.

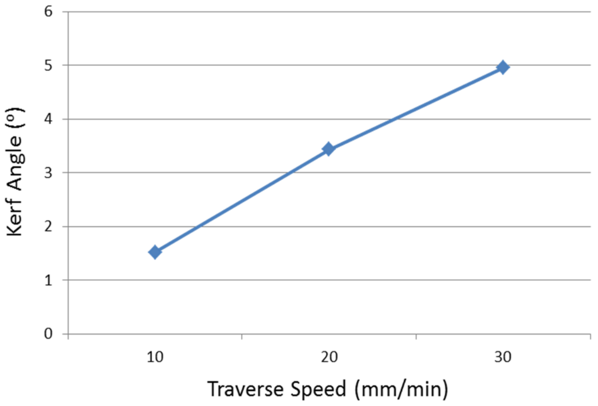

Fig. 4. Effect of traverse speed on kerf angle

5. Conclusions

Two types of surface texture were characterized based on the cutting of surface by the abrasive water jet. The first texture was cut at the beginning and categorized as the smooth surface and the second texture was cut at the bottom and categorized as rough surface. Suitable surface roughness with higher productivity can be attained in medium traverse speed with high quality in the optimal solution. Based on the hardness and thickness of the SiC plate the taper angle is high and for a feed rate of 10 mm/min, the surface roughness is low. Less thickness of the SiC plate could have a lower taper angle than with high thickness. Consequently, the lesser thickness of work piece-low traverse speed will produce a high precision cut surface with low taper whereas high traverse speed may lead to high taper.

Additional information

The work presented in this paper was presented in “Two Days Virtual National Meet on Nano Interface Science (NIS-2021)”, Chettinad Academy of Research & Education, Chennai, India, 2021.

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