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The Influence of Silicon Carbide Abrasive on Machining of Ti-6Al-4V by AWJ †

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Abstract: During Abrasive Waterjet (AWJ) machining of hard-to-cut materials, apart from other important process parameters, the properties of the abrasive material can also considerably influence its outcome. In this research, the efficiency of silicon carbide as an abrasive on the geometrical characteristics of the kerf is investigated. Slots were machined on a Ti-6Al-4V workpiece under various conditions and Taguchi method was used to design the experiment. The findings indicate that SiC abrasives are effective for machining titanium alloys and the appropriate regulation of process parameters can affect considerably both geometric characteristics of the kerf and productivity.

Keywords: hard-to-cut materials; silicon carbide abrasive; Taguchi method; Abrasive Waterjet Machining; Ti-6Al-4V

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1. Introduction

AWJ (Abrasive Water Jet) method is a well-known manufacturing technique that enables cutting the majority of materials including soft, hard [1,2], brittle, or ductile objects [3,4]. The development of AWJ is key to achieving better surface quality, efficiency, the possibility to cut more complex geometries, and widening the spectrum of its applications while maintaining method advantages. One of the key subjects regarding AWJ milling is the efficient control of geometrical characteristics of the produced features. For example, it would be very beneficial to look closer into the AWJM (AWJ Machining) method, especially research regarding the depth of the cut (DOC) control, as this strategy opens the possibilities for creating difficult-to-manufacture geometries in hard-to-machine materials with the benefits of the AWJ method.

V. K. Pal and P. Tandon [5] conducted experiments in which the effects of the DOC and material characteristics on machining time were investigated. Pockets made at a particular depth of alumimum, brass, titanium and steel workpieces were milled and results showed that milling time and surface roughness depend on the machinability index and mechanical properties of the samples. V. H. Bui et al. [6] combined the depth of cut model with a rapid calibration method to achieve the best MRR (material removal rate). A model based on an experiment in which rectangular pockets were machined in titanium alloy sample was obtained and the suitable stand-off distance, pressure and type of abrasive were verified with accuracy equal to 5%. R. Pahuja and M. Ramulu [7] studied the characteristics of machined stacked two-layer Ti6Al4V and CFRP workpiece. A new model for predicting the DOC was created and evaluated to improve the results in comparison to the multivariate regression model. A different model for predicting the DOC was proposed by Y. Ozcan et al. [8]. The model relies on momentum and conservation of energy, and the assumption that material removal is related to the machinability number of the workpiece material. The new approach eliminated the need for conducting calibration tests. In another study, Y. Hu [9] used the wet abrasive jet machining process (wet AJM) method to machine micro-features on Reaction Bonded-SiC (Silicon Carbide) workpiece avoiding the formation of surface defects. The conclusion was that for machining cracks-free complex geometries in RB-SiC, it is necessary to adjust the mask thickness, nozzle feed rate, and abrasive size.

Silicon Carbide is extensively used for making cutting tools, and parts for nuclear fuel, automotive, and electrical systems. Thanks to its mechanical properties, especially high hardness and geometrical aspects, it can be used as an abrasive for sandblasting and the AWJ method. The abrasive size, shape, and mechanical properties have a huge influence on the erosion process, and thus surface integrity, and machined geometry [10–12]. G. Aydin, S. Kaya, I. Karakurt [13] examined the influence of the type of abrasive on kerf characteristics obtained after cutting marble workpiece. Garnet, white fused alumina, brown fused alumina, silicon carbide, glass beads and emery powder were used for cutting the material with constant process parameters. Results confirm that the hardness and density of the abrasive particles strongly affect AWJ performance. It was also revealed that for the silicon carbide and fused alumina, higher cutting performances in terms of the DOC and kerf angle were noted. R. Shibin et al. [14] investigated the feasibility of machining Aluminium alloy AA2014 workpiece using SiC as an abrasive. Parameters used for achieving the biggest DOC were 100 mm/min traverse feed rate, 1.5 mm SOD, 350 MPa jet pressure, and 9 g/s mass flow rate. K. Saravanan et al. [15] conducted experiments involving cutting the titanium alloy sample using SiC particle added to garnet abrasive to optimize the MRR and surface roughness of the workpiece. SiC volume, SiC size and the abrasive flow rate were considered significant variables. The conclusion of the study revealed that the particle size had the biggest influence on MRR and surface roughness, whereas adding SiC to garnet improves the removal rate.

Due to the fact that the literature on AWJ machining of hard-to-cut materials with SiC abrasives is rather limited compared to the considerable amount of the works conducted using garnet abrasive, in the current work, the efficiency of using SiC abrasives during AWJ machining of titanium alloy workpieces was evaluated under various process conditions. The basic kerf characteristics, such as depth, width and taper angle were measured and the influence of process conditions on them, as well as on material removal rate in each case was analyzed and discussed

2. Materials and Methods

The abrasive waterjet machine used for the study was H. G. RIDDER Automatisierungs-GmbH model HWE-P 1520. In the experiments, hard-to-machine titanium alloy Ti-6Al-4V cuboid sample was used as a workpiece and grooves were machined on it. The values of process parameters, namely traverse feed rate (vt), abrasive mass flow rate (ma) and stand-off distance (h) were chosen using the Taguchi method, especially L9 orthogonal array, which allowed reduction of the number of required experiments. Other parameters influencing the outcome were kept constant, such as jet pressure set on 150 MPa, the 1 mm nozzle diameter, and silicon carbide abrasive mesh size F-60 (250–300 μm). The process parameters were varied to achieve the total depth penetration not exceeding the total thickness of the workpiece. Geometric characteristics such as depth, width and taper angle were measured using the digital microscope. For the results analysis the ANOVA method was carried out.

3. Results and Discussion

The results of the experiment are presented in Table 1. The outcome values obtained after measuring geometrical characteristics were: penetration depth, groove top kerf and kerf taper angle. Moreover, MRR was estimated in each case based on geometric features and kinematic parameters.

Table 1. Experimental results.

Traverse Feed Rate [mm/min]	Abrasive Mass Flow Rate [g/s]	Stand-Off Distance [mm]	Depth [μm]	Top Kerf Width [μm]	Kerf Taper Angle [deg.]	MRR [mm³/min]
500	2	1	877.480	1146.492	10.22	433.603
500	5	3	1726.720	1277.933	11.81	791.605
500	8	5	1994.743	1472.832	10.77	1090.523
700	2	3	558.177	1269.773	27.72	381.532
700	5	5	1278.603	1429.195	14.73	978.298
700	8	1	1639.627	1199.443	8.03	1111.164
900	2	5	478.093	1468.102	38.00	470.978
900	5	1	909.307	1199.140	10.62	841.814
900	8	3	1331.270	1363.540	15.96	1177.547

The aforementioned results were obtained by measuring particular dimensions repeatedly and calculating arithmetic means. The implemented technique assures a credible outcome. To visualize parameter impact on geometric characteristics, ANOVA method was used. ANOVA allows testing the significance of differences between means. In Figure 1a,b the plot contains expected mean squares of depth, top kerf width and kerf taper angle of the machined grooves, as well as MRR, in respect to traverse feed rate.

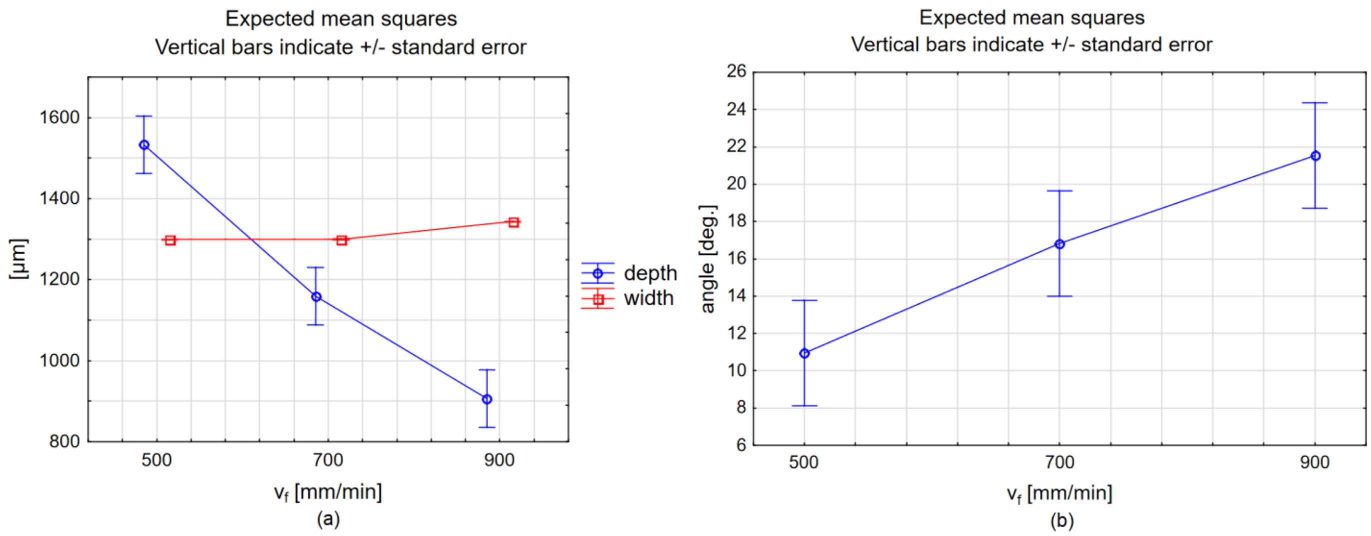

Figure 1. (**a**) Relation between traverse feed rate and grooves depth and top kerf width. (**b**) relation between traverse feed rate and kerf taper angle.

Slower head movement causes more abrasive particles to hit the machined surface in a unit of time, which strongly impacts how deep the jet can penetrate the material. Due to the increasing depth of the grooves, a correlated decrease in the wall inclination angle can also be noticed. Feed rate is shown not to have a significant influence on top kerf width and possible minor deviations might be caused by the water stream deflection phenomenon. The grooves' depth decreased by around 24.5% after increasing the traverse speed from 500 mm/min to 700 mm/min, and similarly by 21% after changing the parameter to 900 mm/min. Moreover, kerf taper angle changes almost linearly and varies by 49% between extreme feed rate values. Finally, based on ANOVA results, MRR is shown to increase slightly with feed rate.

In Figure 2, based on the expected mean squares plot it was deduced that depth was strongly affected by the mass flow rate. The reason behind the noticeable increase in depth is the increase of the number of abrasive particles per unit volume of water, which causes more silicon carbide particles to hit the surface and intensifies the erosion process. After changing the mass flow rate from 2 to 5 g/s we can observe penetration depth increase by over 50% and respectively after setting the value to 8 g/s by over 21%. Increasing the discussed parameter does not cause a linear increase in the depth of the groove because the abrasive particles hit a limited surface of the sample. The erosion process intensifies when SiC particles do not reduce each other's energy, what might happen when setting the machining parameter too high. However, grooves' top kerf width is shown not to be strongly affected by the mass flow rate. Finally, along with increasing depth, a decreasing wall inclination angle was observed at higher mass flow rate values, something that can be deduced by observing the relationship between the depth and kerf taper angle diagram. The more intense the growth causes the more intense the decline of kerf taper angle becomes, as it is at first changed by 51% and then sharply decreased to 6.5%. Finally, based on ANOVA results, abrasive mass flow rate is a significant parameter for MRR which is observed to increase considerably at higher abrasive mass flow rate, almost three times between extreme values.

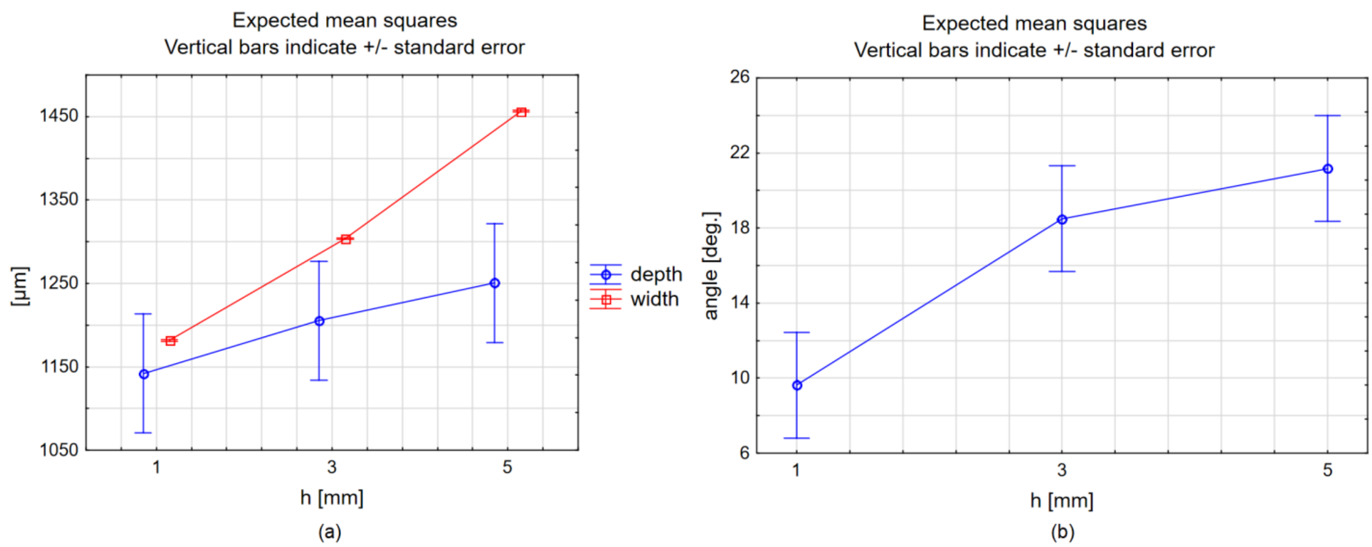

Figure 2. (**a**) Relation between abrasive mass flow rate and grooves' depth and top kerf width. (**b**) relation between abrasive mass flow rate and kerf taper angle.

The influence of stand-off distance on geometric characteristics can be read in Figure 3. This parameter has the biggest influence on grooves top kerf width, which is caused by the water jet expansion phenomenon. The increase in the width after setting the distance between the workpiece material and the nozzle to 3 mm changes by almost 10% and then after another increase by 11%. The depth increase is almost linear and between 1 and 5 mm changes by 8.8%. ANOVA results confirm that stand-off distance is a less significant parameter than previously discussed ones. The slight increase of depth might be caused by the higher kinematic energy of the abrasive particles and the wider area in which the erosion process appears due to the expansion of the beam. The same phenomenon affects the increase in kerf taper angle. SiC particles hit the walls of the groove at a greater angle, which causes detachment of the titanium alloy particles closer to the upper surface of the sample and eventually, increase in kerf taper angle, which gets up to around 53% between the minimum and the maximum stand-off distance levels. Finally, ANOVA results indicate that MRR exhibits a slight increase between the extreme stand-off distance values, but this parameter is not significantly important for MRR.

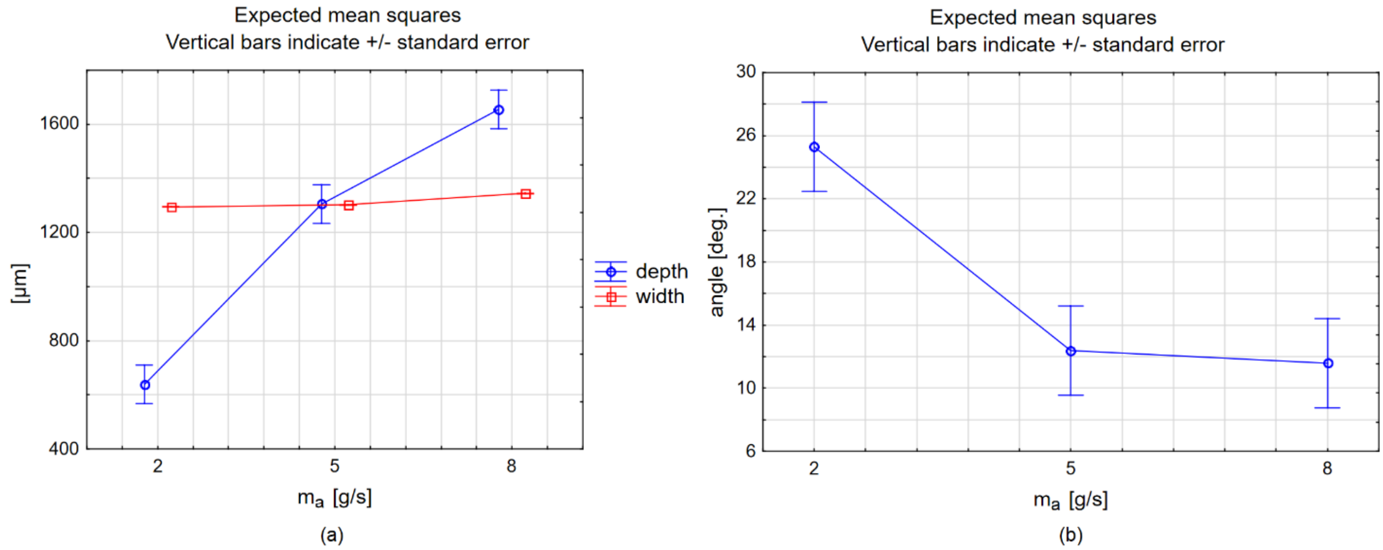

Figure 3. (**a**) Relation between stand-off distance and grooves' depth and top kerf width, (**b**) relation between stand-off distance and kerf taper angle.

4. Conclusions

The current study investigated the geometrical characteristics in AWJ groove cutting of Ti6Al4V workpiece material by SiC abrasives. The experiment was designed using the Taguchi method, including three input parameters: traverse feed rate, stand-off distance and abrasive mass flow rate and dependent variables were the maximum depth and width of the slot, kerf taper angle and material removal rate. Based on the experiments and ANOVA results, the following conclusions were drawn:

- Silicon carbide as an abrasive can be used in the abrasive waterjet machining process, but its hardness should be taken into account when choosing a nozzle.
- The most significant parameters to control the penetration depth are abrasive mass flow rate which allows obtaining deeper geometries when it is increased (~70%), and traverse feed rate, which causes intensive deepening of grooves when it is decreased (~45%).
- The accurate input parameter to control the top kerf width of the slots is stand-off distance, which caused grooves to widen by around 20% when increased to the maximum value.
- Parameters which have a significant influence on the depth of the grooves also cause changes in the kerf taper angle. The deeper the grooves are, the sharper the angle becomes. Moreover, with an increase in the stand-off distance, the kerf taper angle increases by 53%.
- Productivity of the machining process, expressed by MRR, is shown to be mostly affected by abrasive mass flow rate, whereas traverse flow rate and stand-off distance were found to be less significant within the selected parameter range.

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