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EXPERIMENTAL INVESTIGATION ON TOOL PATH PATTERNS IN CONTROLLED DEPTH ABRASIVE WATER JET MACHINING

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Abstract

Abrasive waterjet machining (AWJM) is used for machining of difficult-to-cut materials, i.e. very soft or very hard, which may be problematic when conventional milling is used. Unlike potential benefits, AWJM is mostly used for 2D through thickness cutting purposes. Controlled depth milling with AWJ is relatively rare, which can be achieved by adjusting the feed rate. In this paper, tool path patterns, for extended use of AWJ in controlled depth is experimentally studied. It is aimed to identify tool path strategies to achieve even, smooth cut quality in terms of the removed material depth. So that, AWJM can be used in a milling manner for roughing purposes of difficult-to-cut materials.

Keywords:

Abrasive Waterjet Machining; Tool path; 5-axis Machining.

1 INTRODUCTION

In AWJM, the energy of the pressurized water is converted to jet velocity. In order to increase the cutting efficiency, high velocity water jet is mixed with abrasive particles. AWJM while providing a machining environment for hard metals such as Ti and Ni alloys, it stands as an alternative machining method for deep machining of relatively softer materials such as steel and aluminum. AWJM processes are inherently complex in nature and the process parameters nonlinearly affect the process outputs. There are inherent dimensional and geometrical inaccuracies associated with AWJM, which can be mentioned as delamination in composite cutting and tapered geometry behind the cut as mentioned by [Shanmugam, D. K. 2008]. Nonetheless, it is advantageous for reduced thermal stresses, minimized heat affected zones and no short-term tool wear as summarized by [Axinte, D. A. 2014] in a recent CIRP Keynote Paper. Minimized burr, reduced work hardening, higher fatigue life, machining capability for thick and hard materials can be mentioned as other advantages [El-Hofy H. 2005] and [Montesano J. 2017].

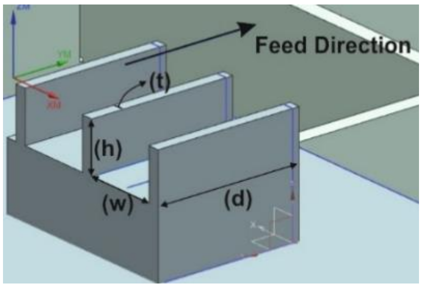
Utilization of AWJM for controlled depth machining is a challenging alternative among the versatile use. Due to the exposure-based nature of the process, the cutting depth depends on the jet feed velocity [Momber, A.W. 2012]. Non-homogenous abrasive size, pressure fluctuation, vibration on nozzle, turbulent flow can be listed as the issues increasing the uncertainty in material removal and hence accuracy. Aerospace parts such as center wing box, wing skins, vertical stabilizer, stiff rotors and turbine blades are the typical application areas for AWJM [Snider, D. 2011].

5-axis AWJM requires in-depth understanding on the effect of process parameters on the kerf profile and erosion mechanism, which is a function of parameters such as mechanical properties of the material, pump pressure, orifice size, mixing tube geometry, abrasive type, abrasive size, abrasive and water flow rate, stand-off distance (SOD), and impact angle. [Hashish M. 1979] proposed that kerf profile could be predicted by varying energy profiles. While the high-energy jet forms a convergent profile as it approaches the center of the jet, the low-energy parts form axially and radially divergent profiles. Low energy profiles also erode material at low speed. [Srinivasu D.S. 2009] observed kinematic parameters of 5-axis AWJM on ceramics. They pointed out that the effect of different feed, SOD, and impact angle form distinct types of kerf profiles and they are key parameters. In addition, they emphasized the effect of extra passes (overlapping) on kerf profile. [Axinte D.A. 2009] studied cut depths for different energy profiles. They showed that divergent profile is formed in low energy conditions (low erosion rate), while in the axially and radially central regions of the jet profile, convergent profiles are visible, because low-energy profiled jet will be scattered without touching the material and will have a wider surface area. The high-energy jet will pass through the material without disintegration and will affect a focused spot. [Billingham J. 2013] modelled kerf profile mathematically by using semi-analytical method for 5-axis AWJM. The importance of the study is the fact that it considers the lead, tilt angles and overlapping for wide variety of cases. In application of AWJEM on titanium machining [Gilles P. 2017] developed new, rapid and effective method to calculate depth of kerf profile with overlapped case. It was a useful method for high feed rate applications.

In industrial applications, abrasive water jet machining is useful for parting purposes. Generally, hard to cut block materials such as metals or composites are cut with AWJM. In the literature, there are several studies on parting strategies, which is more advantageous in terms of cutting time and cost compared to conventional or other non-traditional machining operations such as EBM, ECM etc. [Shanmugam, D. K. 2008], [Axinte, D. A. 2014], [Hocheng, H. 2012]. However, parting is not the only cutting method for AWJM. Since erosion is higher compared to the other high energy proceses, AWJM can be used for controlled depth milling operation [Momber, A. W. 2012]. Other advantageous aspects of AWJM are the ability to use for hard to cut materials like Inconel or Titanium [Momber, A. W. 2012]. Tool life is an important issue in conventional milling. In conventional milling, tool life is material dependent and may decrease to 20 minutes or even less for very hard materials [Sharman, A. R. C. 2008]. However, in AWJM tool life is almost independent from material type. For a typical AWJM system, the nozzle and orifice life are around 40 and 200 hours, respectively [Sharman, A.R.C. 2008]. Considering such aspects, AWJM has potential to be an alternative for controlled depth machining of several industrial parts [Snider, D. 2011]. In a recent study [Popan, A. 2015] achieved successful results in generating slots, profiles and pockets by using AWJM (see Fig. 1a).

In this paper, tool path patterns and cutting parameters are compared in terms of the obtained material removal and shape to achieve controlled depth machining of pockets using AWJM. As it is of great importance to have even material removal in controlled depth of cut, the comparison if performed based on the evenness in material removal both in axial and lateral directions. Mostly, visual observations are provided considering the significant difference in material removal shape among the tool path patterns and parameter sets. Henceforth, the manuscript is organized as follows, Section 2 introduces the test part geometry used in the experiments. This is followed by the parameters in AWJM process together with the design sets of parameters to perform experiments in Section 3. The experimental results are provided in Section 4 and the manuscript is finalized by discussions.

(a) Example part manufactured by AWJM [Popan, A. 2015].



(b) Representative geometry for the test part.

Fig. 1. Application of AWJM in pocket milling.

2 TEST PART GEOMETRY

In order to investigate the potential of AWJM in generating various industrial parts a representative test workpiece geometry is defined, which has rectangular, wide slots (see Fig. 1b). Such a geometry is selected to mimic the application of AWJM in controlled depth milling of turbine blades. In the tests, AL6061-T6 material is used for its low cost and availability. In this section, the geometrical parameters of the test parts are provided.

2.1 Sample geometries used in the tests

In selection of geometrical parameters of the slots, realistic turbine blade pocket area is considered as four pocket geometries are used with different height (h), thickness (t), width (w) and depth (d) as listed in Table 1.

The part thickness is reduced to see the possible minimum wall thickness that can be achieved by AWJM. Slot width is determined according to nozzle outside diameter.

Table 1: Geometric parameters for the samples.

Sample ID	height (mm)	thickness (mm)	width (mm)	depth (mm)
1	11	6	20	37
2	11	6	20	30
3	7	3	20	32
4	7	10	20	25

2.2 Expected AWJM process quality

Abrasive water jet machining is proposed as an alternative technology for rough machining of difficult-to-cut materials, either very soft or very hard. However, the kerf depth control is required to achieve an acceptable post-form after the roughing cycle. As the expectation in roughing is barely achieving a pre-form shape before semi-finish or finishing pass, the expected AWJM process quality is compared to the roughing conditions, where the aim is removing the unwanted volume as quick as possible. Although, in this study, numerical tolerances are not defined to evaluate the performance of different tool path patterns in AWJM roughing, the comparison is performed visually considering that first the aim is identifying the tool path patterns leading to acceptable post-form shapes.

3 PARAMETERS IN AWJM

In controlled depth AWJM, the cut depth is inversely proportional to the jet feed rate, through the exposure time of the material to the jet. The other parameters affecting the depth of cut are water pressure, abrasive size and rate. Therefore, the developed strategies need to be in good correlation with the process parameters as the depth of cut should be known for a given parameter set.

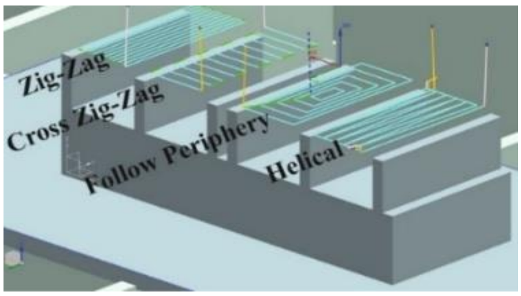


Fig. 2. Alternative tool path strategies.

3.1 Process parameters affecting jet energy

Increased exposure time at low feed rates increases the tendency to material erosion. Water pressure is the energy parameter, where higher the pressure leads to higher impact velocity and hence higher momentum of the abrasive particles. Thus, at high water pressures higher the material removal rate is achieved.

SOD is the axial distance between the nozzle and the workpiece, affecting the energy profile of the jet. As the jet leaves the nozzle, its cross section enlarges. As a result, jet intensity on the exposure surface decreases leading to decreased depth of cut and potentially micro forging effect.

The jet energy is a function of the water and abrasive flow High abrasive-to-water flow ratio would result in higher deformation rate. Jet impingement angle is related to exposure area. While perpendicular impacts create craters, inclined impacts result in smoothed cut area but less material removal. Henceforth, the experimental parameters are explained. Pressure, feed, step over, levelling down and edge region deformation issues are investigated for slot machining by abrasive water jet. The cutting tests are performed under the conditions given in Table 2.

Table 2: Process Parameters.

Sample Number	R2 Pressure (bar)	R2 Feed Rate (mm/min)	R2 Abrasive Flow Rate (g/min)	Approx. Duration (min:sec)
1	3500	1200	220	1:25
2				
3				
4				1:32
5				1:45
6				2:05
7				8:33
8	1500	1500	145	11:12
9				
10				
11				14:33

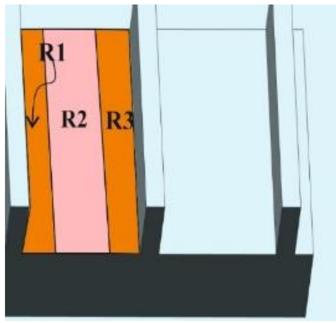
**R1 and R3 pressure is constant at 3500 bar,*
***R1 and R3 feed rate is 1500 mm/min,*
****Abrasive flow rate at R1&R3 is 220 g/min*

3.2 Geometrical parameters

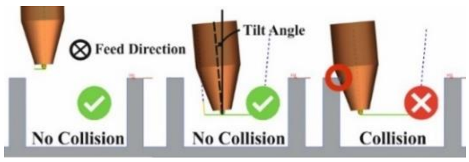
In controlled depth AWJM there are geometrical parameters related to the selected milling strategy such as lead and tilt angle, path strategy (zig-zag, zig, helical, spiral etc.), step over distance. In this study, tilt angle, level down distance, zigzag and helical path strategy, step over distance are used in machining of 11 test parts as listed in Table 2. The slot area is divided into three regions, i.e. R1, R2 and R3, as shown in Fig. 3b, which represents right edge, middle portion, and left edge, respectively.

Tool path strategies shown in Fig. 2 are implemented in machining of the middle region, R2, for levelling down, where in R1 and R3, low jet feed rate is utilized in order to open an initial area to prevent nozzle-workpiece collision (see Fig. 3b). Thus, it is needed implement higher pressure, lower feed and higher abrasive flow rate to achieve deeper cut for clearing off the sides in R1 and R3 before cutting R2.

To achieve even material removal at each pass in the middle region R2, SOD needs to be kept constant. In all samples, SOD is selected equal to the material removal depth. This is important especially in R2 region to avoid collisions along Z direction as shown in Fig. 3b.



(a) Machining regions for strategy development.



(b) Collision avoidance in strategy development.

Fig. 3. Regions in the test parts and collision avoidance.

4 RESULTS

In this section, the cutting results are visually compared in terms of the evenness of the achieved material removal. The first three samples were cut applying three different tool path patterns to determine the suitable tool path pattern for R2 region. The top and front view of the samples after the cut are shown in Fig. 4.

4.1 Single-level controlled depth cutting

In machining of Sample 1, zig-zag tool path was selected. Since step over direction was out of cutting plane, the reduction of feed rate did not cause extra material removal and resulted in almost uniform cutting depth (see Fig. 4). However, as in machining of Sample 2 and Sample 3, ‘follow periphery’ and ‘cross zigzag’ tool path patterns were applied, respectively. Where, the feed rate was reduced during the step over move when the nozzle was still in cut. As the jet did not leave the cut area, R2, it resulted in excessive cuts compared to Sample 1 (see Fig. 4).

Thus, it can be said that implementing zig-zag tool path pattern in R2 region results relatively even material removal compared to ‘cross zig-zag’ and ‘follow periphery’.

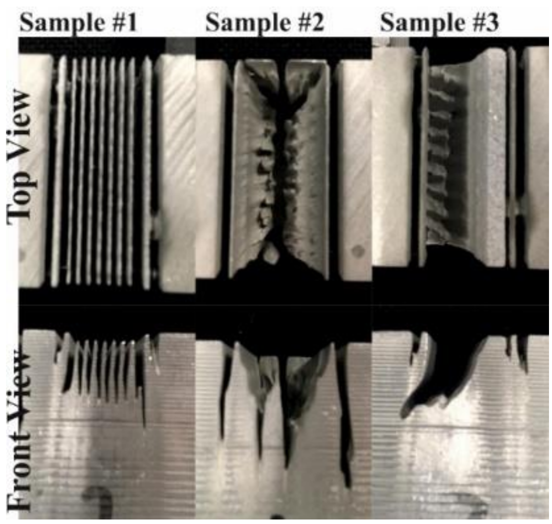


Fig. 4. The samples after cut.

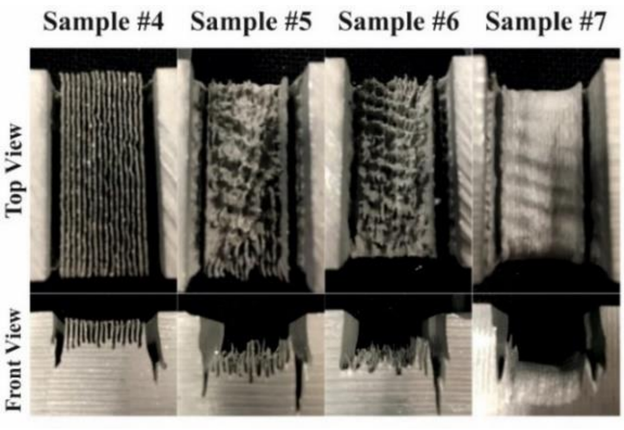


Fig. 5. Test Sample Results (4th to 7th).

Note that, as even and cleared-off material removal couldn't be achieved further levels were not tried in cutting of Samples 1, 2 and 3. Especially in machining of Sample 2, kerf profile was formed in thin fin shape, which occurs at high pressure and abrasive flow, low feed, and long stepover distance. Another challenging issue was removing the fin shapes resulted in between cutting steps of the AWJ.

Even if tilting was applied, the abrasive jet tends to flow towards the low energy regions, which is between two successive fin areas. Under such circumstance, the erosion occurs at the bottom portion rather than the top, which increases the depth of the fin. As a result, undesired thin-features form in the slot area intended to be cut.

4.2 Multi-level controlled depth cutting

At the second phase of experiments, application of multi-level controlled depth cut was investigated for volumetric material removal in the slot area. After determining the suitable tool path strategy for R2 region as zig-zag, the jet is tilted by 2.5 degrees while cutting R1 and R3 regions to compensate the generated taper angle. However, significant improvement was not observed. It is also important to determine the appropriate step over distance to achieve even and cleared-off material removal for the corresponding level, without generating fin-like geometries. As it was mentioned previously, large step over values do not lead to even material removal in the slot area. Thus, the step over value were decreased to 0.6mm when cutting Sample 4 and Sample 6. Then, it was realized that there is a significant improvement in waviness. Therefore, to see the limit of the smoothness on the surface, the step over is decreased to 0.1 mm for the 7th sample. The smoothest surface on R2 region is obtained at 0.1 mm of step over at the expense of cycle time. Another achievement on this sample was successful implementation of the levelling down strategy, where similar uniform depth of cut at every pass was obtained.

Table 3: Kinematic Parameters.

Sample ID	R1,3 Tilt (°)	R2 Tilt(°) (Zig-Zag)	Level Down Distance (mm)	R1 and R3 Step over Distance (mm)	R2 Step over Distance (mm)	R2 Strategy	R1 Strategy	R3 Strategy
1	0	0-0	3	0.35	1.4	Zig-Zag	Zig	Zig
2	0	0-0	3	0.35	1.4	Follow periphery	Zig	Zig
3	0	0-0	3	0.35	1.4	Cross Zig-Zag	Zig	Zig
4	2.5	0-0	3	0.35	1	Zig-Zag	Zig	Zig
5	2.5	0-0	3	0.35	0.8	Zig-Zag	Zig	Zig
6	2.5	0-0	3	0.35	0.6	Zig-Zag	Zig	Zig
7	0	0-0	3	0.35	0.1	Zig-Zag	Zig	Zig
8	0	0-0	2	0.35	0.35	Zig-Zag	Zig-Zag*	Zig-Zag**
9	0	0-0	2	0.35	0.35	Zig-zag	Zig-Zag*	Zig-Zag*
10	0	0-0	2	0.35	0.35	Helical	Zig-Zag*	Zig-Zag**
11	1.5	5-5	2	0.35	0.35	Zig-Zag	Zig-Zag*	Zig-Zag*

*Start at edge, **Start at middle

Even if the surface finish at the 7th sample is comparatively much better than previous samples, cycle time seems to be way longer than acceptable range. Therefore, it can be said that step over is a critical trade-off variable compromising the surface finish and cycle time. In this study, the step over value is rated according to the internal diameter of the nozzle. It is known that the abrasion energy of the jet decreases with the radial distance. Therefore, while machining samples 8 to 11, the step over value of 0.35 mm was selected, which is slightly smaller than half of the nozzle diameter, 0.76 mm.

On the 8th sample without any tilt angle, the zig-zag tool path is applied on all areas (R1, R2 and R3) and no significant difference was observed compared to previous cases. However, since the step over distance is selected as 0.35, in R2 the surface seemed to be significantly more uniform compared to sample 1 to 6, with a reasonable surface waviness and roughness.

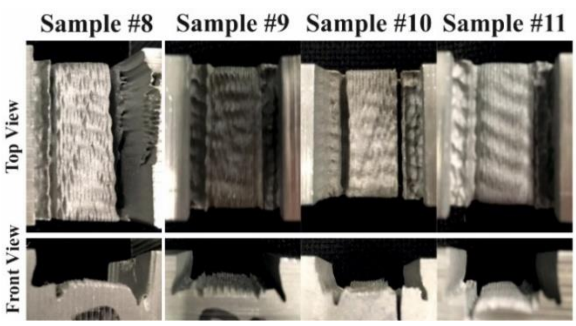


Fig. 6. Test Sample Results (8th to 11th)

In this study, 4 mm and 6 mm of wall thickness values were studied in terms of manufacturability. The thickness of the wall between two successive slots is selected as 6 mm for Samples 1, 2, and 3. This is then decreased to 4 mm for the samples 4, 5, and 6. It was observed that on R1 region of the slot being machined and R3 region of successive slot tends to merge, with the effect of tapered material removal, at the bottom of the part. Although the part was not separated a big gap was observed, which may not be acceptable even for roughing purposes.

Another approach is starting to cut at R3 region from the middle portion (R2 side), which resulted in an undesired surface. While the jet moves along the step over direction, it continues to remove material at the previous regions (previous step over regions). Therefore, compared to the where the cut started from the edge side, starting from the middle portion creates excessive cuts. In order to eliminate this problem, it may be more appropriate to start cutting the edge side first for both R1 and R3 region. This approach is applied on 9th and 11th samples. On 9th sample, it was aimed to solve the excessive cut problem, which occurred on R3 region. For such a purpose, starting point is moved to middle portion (right side of the R2 region) to the edge side (right side of the R3). Zigzag tool path is applied on R1 region. It should be noted that the jet continuously erodes material from previous cutting steps. Since these points were cut as the second time, while machining R2 region, a non-uniform surface was obtained. Therefore, tool path is selected as symmetrical with respect to the slot center. As a result, a more uniform slot surface was obtained in this case. In order to improve the surface roughness and waviness, helical pattern and tilting is applied on the tool path for 10th and 11th, respectively. On the 10th sample, helical tool path gave non-uniform surface profile at R2 region, which was worse than 9th sample. In machining of Sample 11, the inclination angles at edges decreased compared to 9th case as a result of 1.5 degrees tilt angle at R1 and R3 regions. Also 5 degrees is applied in machining of R2 region to obtain smoother surface. However, it resulted in lower erosion rate due to decreased exposure area. Note that from 8th to 11th samples, it was aimed to achieve smoother surface finish in R2 region. To do that feed rate was decreased.

5 CONCLUSIONS

In this study, the effect of tool path patterns in achieving a proper post form geometry after roughing with controlled depth AJWM, was investigated. So that, the use of AWJM can be extended from 2D peripheral cuts to 3D cuts. The results can be considered as an initial step towards roughing twisted blade type geometries using AWJM, which may require layer-by-layer machining. Considering the eliminated tool life constraint in cutting of hard materials compared to conventional milling, it was shown that as long as even material removal can be achieved, AWJM has potential to be used for 3D roughing purposes, where tool life is not an issue in machining of difficult-to-cut metals.

An evolutionary approach was proposed to identify the appropriate tool path patterns to achieve even material removal suitable to remove a pocket volume. The cut area was divided into 3 regions. The material at the left (R1) and right (R3) regions need to be removed beforehand to prevent nozzle-part collisions to enable levelling down in the middle region (R2). For such a purpose, lower feed rate was utilized at region R1 and R3 to achieve deep cut. However, this gave a bad surface finish. Since, the area at R1 and R3 is much smaller compared to R2, this result may be acceptable for rough type cuts.

As high step over results in fin-like geometries in the machined region, the step over was decreased to half of the jet diameter, which resulted in clear material removal in the pocket area leading to a pocket machining like process at the expense of increased cycle time, obviously. However, selection of the step over value still needs to be investigated. Another important observation as a result of this study is the benefit of implementing symmetrical tool path pattern with respect to the middle region. It can be said that applying a symmetrical tool path pattern leads to even material removal.

As the tool patterns are compared, implementing zig-zag tool path leads to even material removal in axial direction. However, cross zig-zag, helical and follow periphery type patterns are more prone to leave undesirable rough volume. As tilting the jet axis increases the exposure area, the result cut becomes smoother and more even. Though, this observation is open to a quantitative comparison by measuring the surface in terms of kerf profile and surface roughness.

In conclusion, the below suggestions are derived for controlled depth AWJM applications;

- Apply zig-zag type tool path pattern, which are along the wall length.
- Select a step over value less than the jet diameter around half of the diameter.
- Apply initial clear cuts at the left and right regions of the pocket to prevent collisions in the lower levels.
- Tilt the jet axis to smoothen the resulting cut.

6 ACKNOWLEDGMENTS

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