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# INFLUENCE OF THE JET TILT ANGLE ON GEOMETRICAL CHARACTERISTICS OF THE MILLED POCKET ON ALUMINUM ALLOY Al6065

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**Abstract.** The abrasive water jet (AWJ) is a non-traditional process that can be employed to machine a variety of materials that are significantly difficult to machine using conventional machining processes. This paper presents an experimental investigation conducted to evaluate the influence of the jet tilt angle, a kinematic process parameter, on the characteristics of the milled pocket as milling aluminium alloy 6065. The influences of this parameter are assessed by measuring differences in the depth of the milled pocket, the width, and the slope of the pocket wall. It is found that as the jet tilt angle decreases, it has a significant influence on characteristics of the milled pocket due to changing the material removal mechanism during the erosion process. Insight the influence of the jet tilt angle, this work paves a good fundamental for developing strategies for controlled 3D AWJ machining of complex shapes and improving the quality of the milled surfaces.

**Keywords:** Abrasive water jet machining (AWJM), Aluminum 6065, Jet tilt angle, pocket milled.

## 1. INTRODUCTION

In the context of industry 4.0, manufacturers have paid more attention to the environmental and ecological aspects of production in addition to the productivity and quality of components.

For sustainable manufacturing, impacting the environment involves energy efficiency, reduced electricity consumption, and carbon emissions which are serious issues. The growing global alarm and its adverse effects have forced manufacturers to adopt sustainable manufacturing methods to produce quality products economically and environmentally. Sustainability in production has become a necessity rather than a choice. Therefore, the task of researchers is necessary to find new and more friendly solutions to gradually replace processing methods that have an adverse impact on environments.

Abrasive water jet (AWJ) machining is considered as a promising non-conventional technology enabling processing any material regardless to its properties. An AWJ machining system employs a high-pressure water jet forced through a small orifice (0.1-0.3 mm). This orifice allows to entrain and accelerate abrasive particles to a significant high velocity. When the high-velocity jet plume impacts a workpiece, the material is removed by the erosive mechanism. Owing to the erosion by fine abrasive particles, mechanical loads impacting on the target is negligible [1]. Hence, this process does not generate heat-affected zones [2]. AWJ technology has been fully developed for through cutting. However, when the jet plume is used as a milling tool to shape the outcomes from the literature is at a green stage with many challenges, especially to control accuracy of the depth milled surface and the development of freeform surface. Many studies have shown that there is a wide variety of process parameters in the AWJ process [3-5]. Thus, it is difficult to control the amount of the removal material mass. A small variation in the characteristic of the jet plume causes a fluctuation of eroded material mass along the trajectory of the jet plume. This raises a significant issue for controlled-depth milling in AWJ machining. For those reasons, controlling the jet footprint geometry plays the most important role in generating desirable surface geometries.

The AWJ milling process is undertaken by numerous parameters which in turn take control the material removal rate as well as the characteristics of milled surface. Amongst these process parameters, the jet angle onto the workpiece is a kinematic factor has a strong influence on the outcome of the process. The definition of the jet angle has been indicated in Fig. 1. The effect of the attack angle of the jet has been carried out [6-9]. In the literature, these angles have different definitions. Thus, to be more convenient, it should be noted that the inclination angle is also called by tilt angle, firing angle (Fig. 1a) while the impingement angle is called impact angle or lead angle (Fig. 1b).

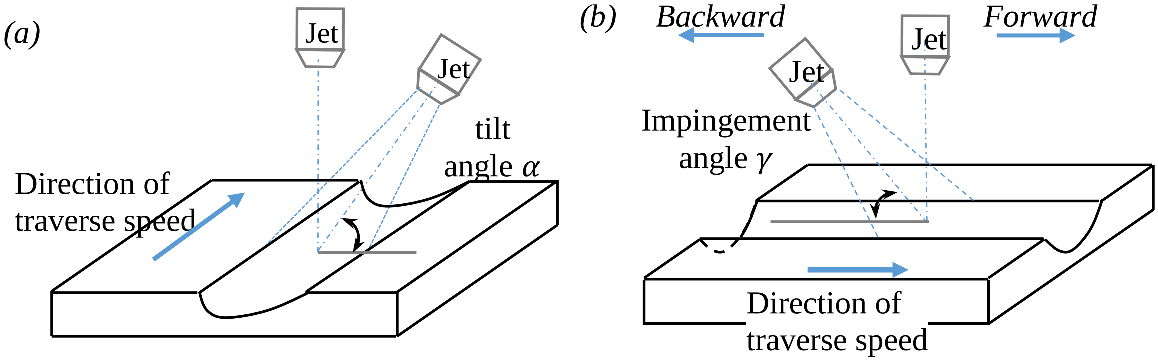


Figure 1. Definition of attack angle of abrasive water jet.

M. Hashish investigated the influence of jet attack angle in abrasive machining for several kinds of materials and noted that it is possible to obtain the maximum mass of the material removal rate corresponding to an optimal attack angle [7]. Consider the influence of the jet impingement angle on material removal mechanism during process [10,11] and the quality of milled surface [12-14], several studies demonstrated that reduction in the jet impingement angle results in a decrease of surface roughness and waviness. It can be seen that at higher impingement angles of the jet, the irregularity of surface machined is illustrated obviously and this irregularity reduce significantly at the lower impingement angles. It indicates that the relative contributions of wear modes (cutting-wear or deformation-wear) vary as the jet angle varies [7]. In a study [10], K. M.C Ojmertz reported that milling at $90^o$ of the jet impingement angle, a mixed morphology of craters due to deformation wear and scratch which are similar to grooves due to cutting wear. Recently, G. Fowler et al. showed that grooved morphologies occur with milling at low impingement angles and an appearance of cratered morphology revealed with increasing in the impact angle [12]. No evidence of grooving is presented when the jet tilt is higher than $75^o$. The evolution of surface milled depending on the jet impingement angles is explained by the effect of a secondary erosion phenomenon [14-16]. This phenomenon occurs due to a slurry including abrasive particle, metallic powder, and water flows beyond the primary footprint of the impinging jet especially for low traverse speed.

In this paper, an attempt is made to mill aluminum alloy Al6065 using AWJM process by varying at five levels of the jet tilt angle. The influence of these parameters is evaluated based on measuring differences in the depth of the milled pocket, the width, and the slope of the pocket wall. Moreover, a discussion related to the importance of the kinematic operating parameter *(α)* on the generation of geometry and dimensional characteristic of open pockets milled by AWJ machining will be presented.

## 2. MATERIAL AND METHODS

Aluminium alloy Al6065 a kind of an alloy containing aluminium (Al) of 95.8 – 98.6 wt% and Magei (Mg) of 0.8 – 1.2 wt%, and other chemical composition listed in Table 1 will be used as a workpiece material for all experiments. This alloy has some outstanding material properties such as minimum tensile strength of 290 Mpa; a minimum yield strength 240Mpa; the relative elongation in the range from 8 to 10%.

Table 1. Al6065 alloy composition by mass.

| **Chemical composition** | **wt (%)** | **Chemical composition** | **wt (%)** | **Chemical composition** | **wt (%)** |
|---|---|---|---|---|---|
| Al | 95.8 - 98.6 | Mg | 0.8 - 1.2 | Si | 0.4 - 0.8 |
| Cr | 0.04 - 0.35 | Mn | Max 0.15 | Ti | Max 0.15 |
| Cu | 0.15 - 0.4 | Other, each | Max 0.05 | Zn | Max 0.25 |
| Fe | Max 0.7 | Other, total | Max 0.15 | | |

The experimental tests were conducted on an abrasive water jet machining (AWJM) system (YF WATERJET) placed at the factory of THU DO GLASS GLASS COMPANY LIMITED, add: Cu Da - Ha Dong – Hanoi (Fig. 2).

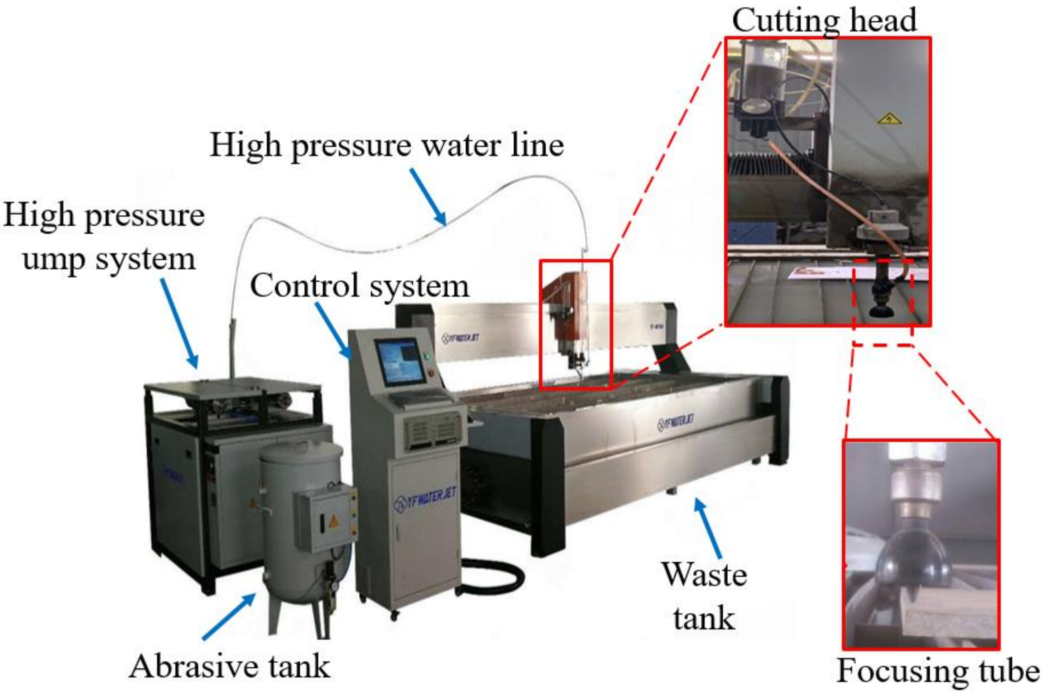


Figure 2. Abrasive water jet machining (AWJM) system - YF WATERJET.

This machine uses an ultra high-pressure pump which provides a maximum pressure of 370 Mpa and is equipped with a PASER4 cutting head with the diameter of 0.33 mm of a water orifice, a focusing tube diameter of 1.01 mm and 101.6 mm length. The kinematic of this AWJM gives a maximum acceleration on each axis at 0.5 m/s2 while the jet feed rate can be varied in the range of 0-20000 mm/min. In this study, the type of abrasive particle employed is garnet in 80 mesh size with average ($\emptyset 177\ \mu$m – GMA Garnet) and aluminum Al6065 specimens with dimensions 20x200x6 mm are used for all tests of the milling operation.

Table 2. A given machine configuration.

| | | | |
|---|---|---|---|
| Pressure (MPa) | 100 | Diameter of focusing nozzle (mm) | 1.01 |
| Washer diameter (mm) | 6 | Abrasive size (mesh) | 80 |
| Orifice diameter (mm) | 0.33 | Standoff distance (mm) | 80 |
| Traverse speed(mm/min) | 1000 | Jet tilt angle ($^o$) | 50, 60, 70, 80, 90 |
| | | Pitch (mm) | 0.7, 1.1 |

The experimental setup for milling pocket with the trajectory of the jet is described in Fig. 3 and the process parameters are given in Table 2.

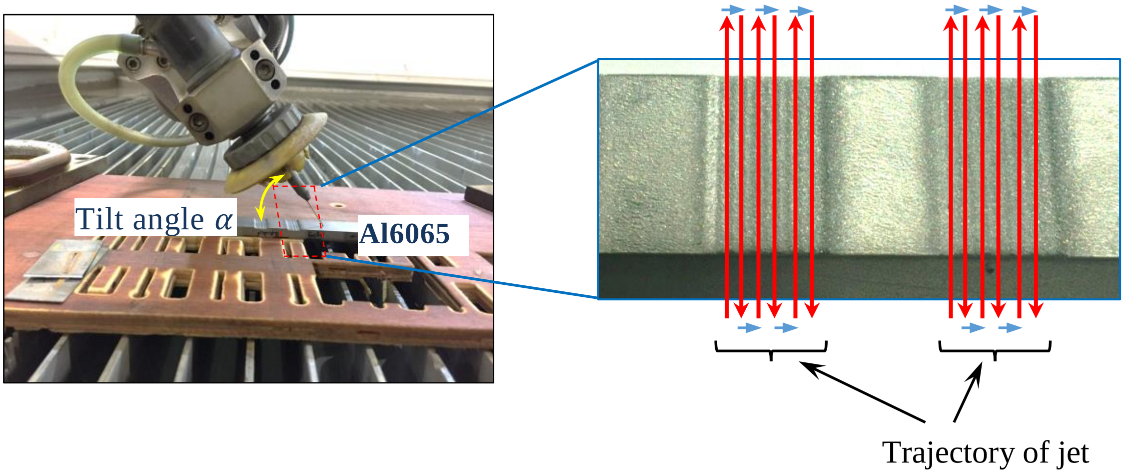


Figure 3. Experimental setup employed for AWJ machining of Al6065.

As mentioned in the previous work [15], the characteristic of a single kerf machined is influenced by a vast of process parameters. In order to gain a jet with a constant energy value, it is necessary to be careful in selecting the values of these process parameters in relation to the material to be machined. To be more convenient, Table 2 presents the selected input parameters which play the role of the setting parameters in a given machine configuration of this study. In addition, in case of controlled parameter, results from previous works [15-17] has demonstrated the efficiency of the model to predict the geometrical characteristics of the kerf profile of both the single kerf and pocket milled for various values of traverse speed. In such a manner, in this present work only consider the influence of the jet tilt angle on the milling process. Experimental tests were implemented at a specific value of the traverse speed *(Vf)* = 1000 mm/min with different jet tilt angles from $50^o$ to $90^o$ in step of $10^o$ (Fig. 3). This selection allows narrowing the number of the experiment but still assuring the reliability thanks to the inheritance of the previous studies.

To study the influence of jet tilt angle on the pocket milled surface, two values of the pitch were used 0.7 mm and 1.1 mm. This selection is based on the results reported in [15] where it demonstrated that to obtain a flat pocket the pitch must belong in an interval of $[0.6 \times B(Vf) - 0.9 \times B(Vf)]$ with *B(Vf)* represented the width factor of the single kerf. Hence, analysis is conducted in order to identify dimensional characteristics of the pocket such as the depth, the width, and the slope of the pocket trailing wall. To enable this analysis, the profile of milled pocket is extracted from the outcome of measuring on the digital microscope VHX-7000 (Fig. 4). This apparatus is able to obtain images of the surfaces milled with high resolution. It also allows measuring and processing results with different functions such as surface roughness, surface morphology and so on. The profiles of milled pockets are a mean value of measuring 1000 curves distributed regularly over 2 mm, using an intersection between the measured surface and 1000 planes perpendicular to the direction of the traverse speed (Fig. 4).

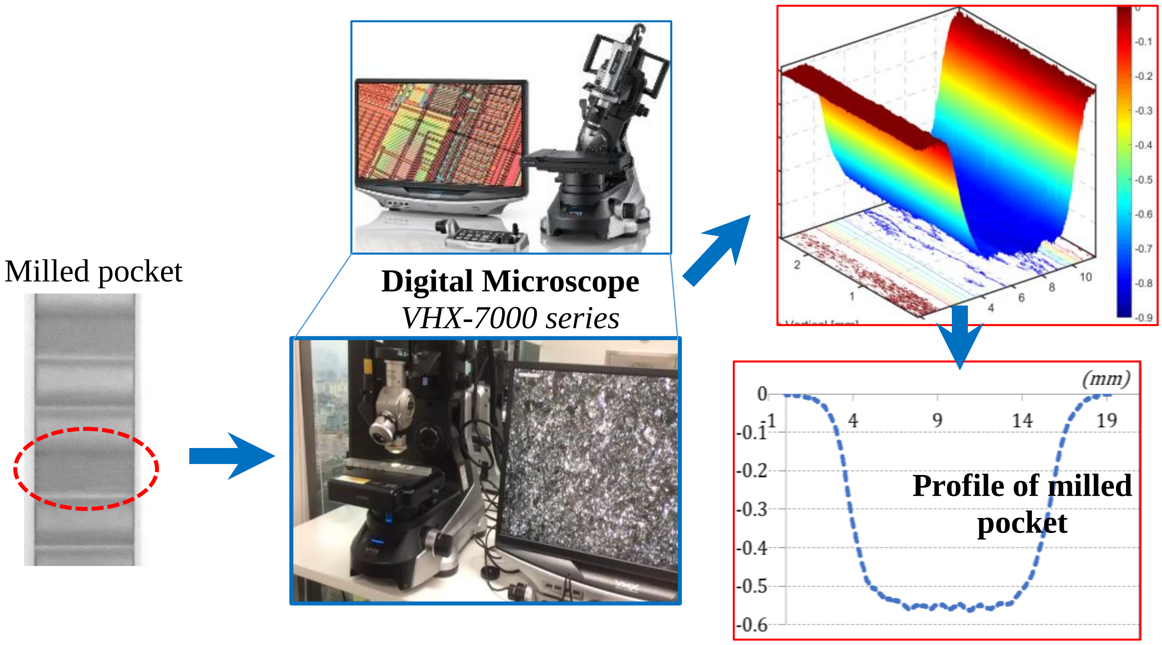


Figure 4. Measurement on the digital microscope VHX-7000 series.

## 3. RESULT AND DISCUSSION

### 3.1. Influence on the depth

The influence of the titl angle of the jet on the depth milled is shown in Fig. 5.

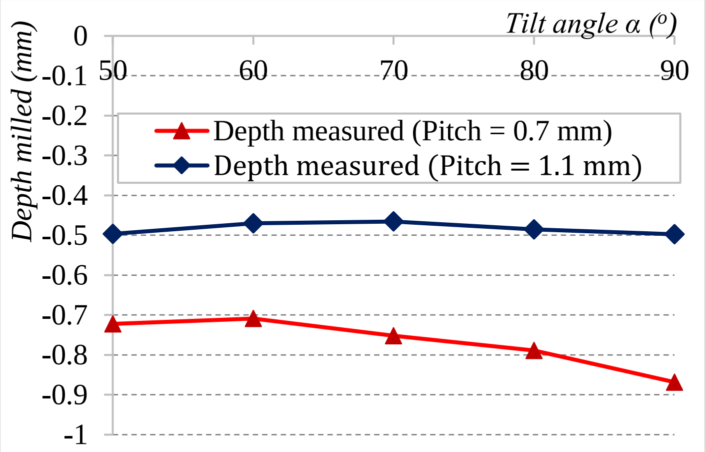


Figure 5. Variation in the depth of pocket with two cases of the pitch.

It can be observed that the pocket reaches the highest value at $90^o$, and then reduces as the jet tilt decreases (Fig .6 and Fig. 5). This trend will stop at $60^o$ with pitch = 0.7 mm and at $70^o$ with pitch = 1.1 mm. For both values of the pitch, the magnitude of the depth depends on the pitch distance. This observation reveals a slight difference from the case of milling elementary pass at which the maximum depth achieved around $60^o - 70^o$ [16].

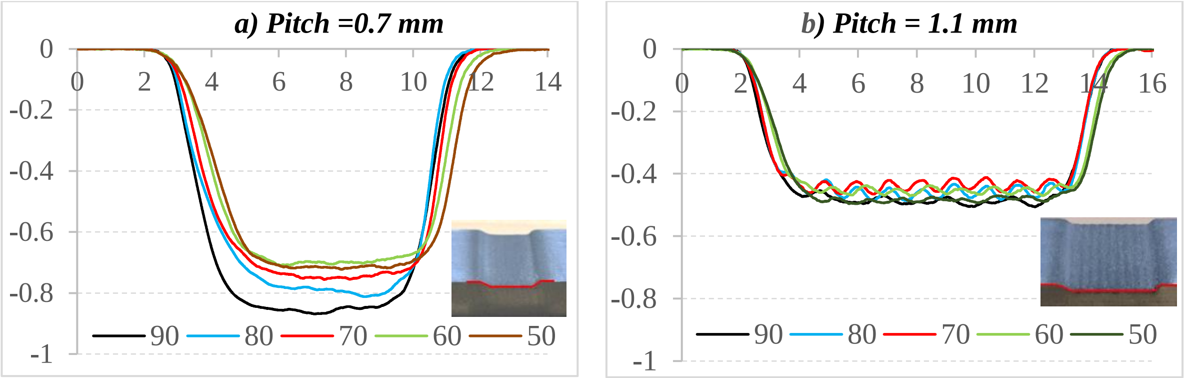
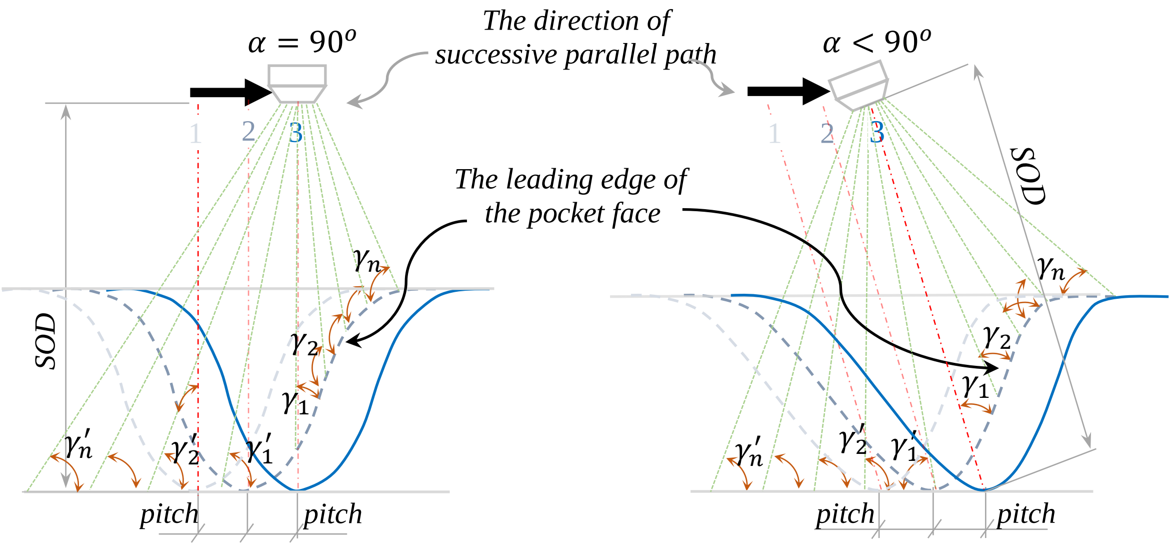


Figure 6. Influence of tilt angles on the profile of depth milled:
a) pitch = 0.7mm; b) pitch = 1.1 mm.

The milling process on ductile material (Al6065) by abrasive water jet is considered as a process which is controlled by erosion mechanism at large particle attack angles. The material erosion mechanism will be varying when the jet tilt angle changes. In order to mill a pocket by AWJ, it is necessary to use the method of superposition of several elementary passes. Fig. 7 presents a schematic illustrating of the pocket generation at different jet tilt angles: $\alpha = 90^o$ (Fig. 7a) and $\alpha < 90^o$ (Fig. 7b) with three elementary passes over the workpiece surface.



*a)*

*b)*

Figure 7. Explanation of different erosion rate from tilt angles of the jet.

At higher impingement angles of the jet, material is mainly removed by plastic deformation due to most of abrasive particles own the normal component of velocity vector greater than the tangential component. Oppositely, when the jet tilt angle decreases, material removal mechanism will be changed from deformation erosion to cutting erosion [18,19]. The material erosion mechanism occurs at the first elementary pass has been mentioned in [16]. For the second elementary pass, the attack of the jet occurs totally difference with the previous one due to the presence of the wall slope (the leading edge of the pocket) – Fig. 7b. Indeed, abrasive particles will attack the leading edge of the pocket ($\gamma_n$- on the left side of the jet axis) at lower tilt angles resulting in removing material by cutting erosion mode while the tilt angles of abrasive particles attacking on the bottom of pocket ($\gamma_n'$- on the right side of the jet axis) is higher and results in removing material by deformation erosion mode. Depending on the effective attack angle of abrasive particles flow, either cutting wear mode or plastic deformation mode will dominate other.

Additionally, it can be seen that milling pocket by AWJ technology raises a problem of *secondary erosion* [4,12,14] which is created by the abrasive water flow beyond the primary footprint of the impinging jet. This problem becomes more important since the surface topography shifted after machining the first elementary pass. It leads to change the erosion mechanism in removing material of the jet. When the slope of the kerf-leading wall is changed after the first elementary pass, the local angle impacts of abrasive particles also vary strongly. As the jet varies the tilt angle ($\alpha$), at lower values, the slope of the kerf-leading wall would be more vertical than that at higher impact angles. From the second to the last elementary pass, the material removal rate has been changed significantly because of variation in the local impact angle of abrasive particles (Fig. 7). However, if the impact angle of the jet further decreases, the divergence of the jet absolutely increases. It leads that jet energy and cutting ability of particles are reduced obviously. Thereby when the jet tilt angle changes, divergence of the jet also results in spreading directions of abrasive particles. The impacting particles forms more unpredictable erosion patterns. In these cases, the erosion capability of the abrasive particles is less and reduces the material removal mass. Overall, the erosion factor which introduced in [15] when milling pocket at $90^o$is also changed.

### 3.2. Influence on the width

It can be observed that for a given machine configuration, the width of the cross-sectional geometry of pocket profile increases when the jet tilt angle decrease. The maximum value is observed at at $50^o$ of the jet tilt angle. This variation is less than 5% in both pitch cases (Fig. 8). This trend is similar to the trend observed as milling elementary passes by varying the jet tilt angles.

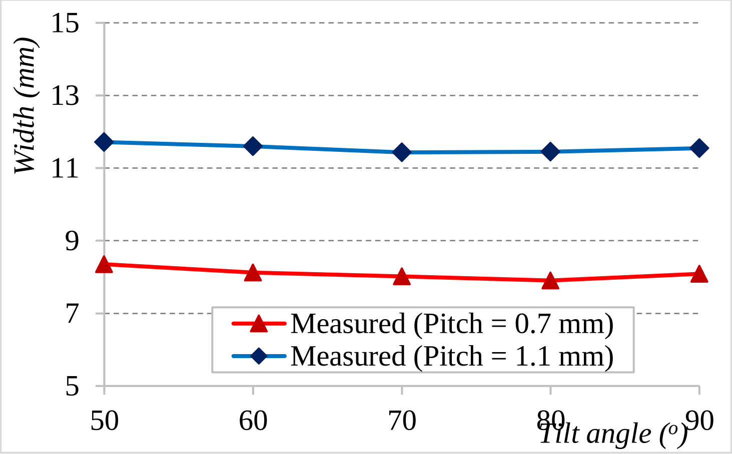


Figure 8. Variation in the width of pocket with two pitch cases.

It could be explained by the divergence of the jet at lower impingement angles and it leads to a greater diameter of the ellipse of jet footprint on machined surface [11,20]. However, consider the characteristic of the jet plume, it could be divided in two concentric zones where the kinetic energy of abrasive particles are different [21]. Hence, the erosive capability of the unstable outer part of the jet plume along its edges is less than that at the inner part of the jet. At lower jet angles, the abrasive particles belong to the boundary of the jet with low erosion capability as interact with the material and do not enhance the erosion which results in a slight increase in kerf width.

### 3.3. Influence on the slope of pocket walls

The pocket wall slope is characterized by a $\beta$ angle that is computed by the slope of a straight line through two points 1 and 2 with a definition of these points presented in Fig. 9. It should be noted that in the scope of this work, the slope is computed on the right side of the milled pocket related to the direction of successive parallel path (Fig. 7). For the slope of the other, it can be done by applying the five axis jet.

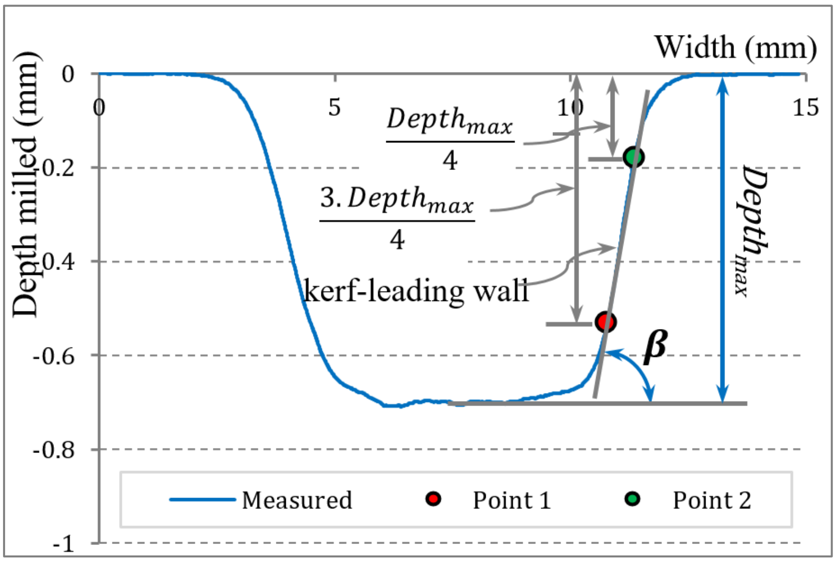


Figure 9. Definition of the slope of pocket kerf wall.

Based on this definition, the slope angle of the pocket wall (Fig. 10) varies from $39^o$ (pitch = 0.7 mm and $\alpha = 80^o$) to $22.5^o$(pitch = 1.1 mm and $\alpha = 90^o$). It is interesting to note that the maximum values of sidewall slope observed occurs at $80^o$ of jet firing angle. The slope angle variation for small pitch is greater than that for large ones. These observations can be attributed to: *(i)* the effective impact angle of abrasive particles on the sidewall slope which depends on the jet tilt angle and *(ii)* the effect of the stepover distance (*Pitch*) between two adjacent elementary passes.

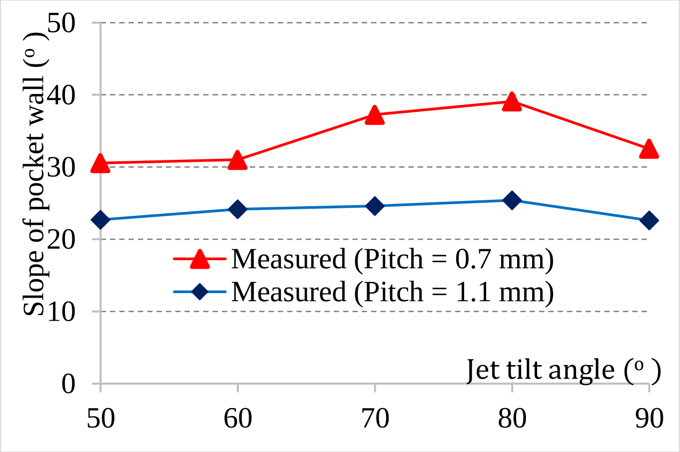


Figure 10. Variation of slope of kerf wall depending on jet tilt angle.

In order to master not only the depth but also the pocket wall of the milled pocket, it is important to investigate whether this slope could be improved and controlled by using the jet tilt angle during the process operation. An initial experiment to mill steeper pocket sidewalls is performed using one orientation of the jet. In this case, pocket is machined with a jet tilt angle at $50^o$ and $80^o$ with two times repeated trajectory (Fig. 3b) over the same milled pocket. The results are shown in Fig. 11. It was observed that the slope of the pocket sidewalls increases from $28.5^o$ to $62.1^o$and $85.2^o$ at jet tilt angle of $50^o$while in case of $80^o$ jet angle, the slope will be $39^o$ to $59.4^o$and $71^o$respectively. Besides, the geometrical characteristics of these pockets were changed due to a significant increase of the milled depth while the width slightly increases less than 8%. Hence, it could be confirmed that once applying the method of the jet orientation, it's possible to obtain pocket milled by abrasive water jet technology with a more vertical angle of the sidewalls. Further works will be performed to have good predictions of these characteristics.

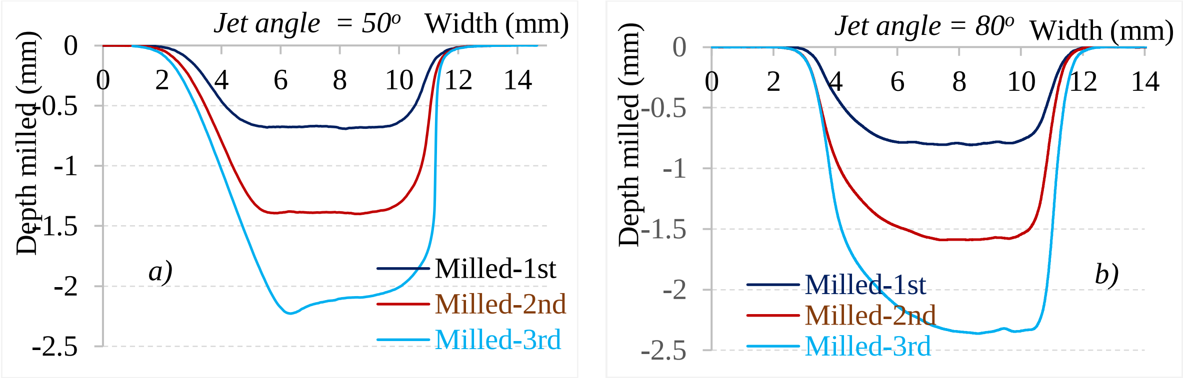


Figure 11. Slope of kerf wall increased as repeating the trajectory over the same pocket milled:
a) Jet angle = $\mathbf{50^o}$; b) Jet angle = $\mathbf{80^o}$.

## 4. CONCLUSION

In this work, the influence of jet tilt angle on the milled pocket is investigated by considering the 2D cross-section profile milling by AWJ applications. It has been assessed for milling open pockets using aluminium alloy (Al6065). The main contribution of this work can be summarized as follows.

- The kerf profile of pocket machined is analysed to get control for the depth of the pocket by varying a jet tilt angles from $50^o$ to $90^o$. It was found that the geometry of the kerf profile of the pocket milled significantly depends on the jet tilt angle $(\alpha)$. The jet tilt angle contributes to local impact angles accounted across the jet footprint, which governs the formation of geometry characteristics of milled pocket such as the depth, the width, and slopes of pocket walls.
- The variation in the depth and width of milled pockets depends on the jet tilt angle. A decrease in the jet tilt angle influences the material removal capability of abrasive particles impacting, which leads a decrease in depth but results in a slightly increase in the width of pockets machined. The maximum depth was obtained at $90^o$ while the maximum width was observed at $50^o$. Additionally, the variation in the impact angle induces a varying in the erosion mechanism behaviour along with the secondary erosion. On milling operation, the erosion mechanism switches between cutting wear and deformation wear according to the local attack angle of abrasive particles on the workpiece surface. It results in

differences of the slope of pocket wall at each level of the jet tilt angle. It is observed that the maximum slope of slopes of pocket walls obtained at $80^o$of the jet tilt angle for both pitch cases (pitch = 0.7 mm and pitch = 1.1 mm).

A part from observing the dependence on the kinematic parameter i.e., the jet tilt angle with the geometrical and dimensional characteristics of the pocket milled, this study desires to present to the machining community the technical task which needs to be solved when posing machining strategies for milling complex geometry using AWJM.

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