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# Characterization of Abrasion and Erosion Mechanisms during Abrasive Waterjet Machining of Hard Metals

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**Abstract.** Abrasive water jet machining is a process that removes material using sand and water. This versatile process uses a high-pressure water jet loaded with abrasive particles of mineral origin. It allows the machining of all materials and is particularly suitable for machining or stripping applications on hard metal sheets. Due to a local action, the abrasive water jet limits heating and deformation. During machining, the removal of material occurs abrasion and erosion [1]. The identification of the respective importance of this abrasion and this erosion conditions the precision of the modeling of the machined depth. In this study, these mechanisms are presented and characterized for machining on 6mm thickness TiAl6V titanium alloys sheets with or without inclination of the jet. It is possible to model an elementary passage and it allows predicting the pocket bottom profile obtained after a succession of passages. During machining, two mechanisms appear. Abrasion occurs when machining an elementary pass. Erosion will characterize the effect of repetition of passages. The analysis of the machined profiles makes it possible to characterize the influence of the abrasion mechanism and abrasion mechanism. The variation of the coefficients associated with these mechanisms can be characterized as a function of the angle of inclination of the jet.

## 1. Introduction

Abrasive water jet machining involves projecting a jet of water loaded with abrasive particles onto a workpiece (Fig 1). The water jet is obtained by a pump integrated into the machine (Fig. 1-b). It is then conveyed to the cutting head (Fig. 1-c) where it incorporates abrasive particles from mineral origin (Fig. 1-a), most of the time it is garnet because of its hardness, density and sharpness but it can also be aluminum oxide or silicon carbide. In the cutting head potential pressure energy is transformed to kinetic energy, which is finally transferred to the abrasive particles in the mixing chamber. The action of the particles, due to their kinetic energy produces a material removal on the part which allows parts to be machined (Fig. 1-d).

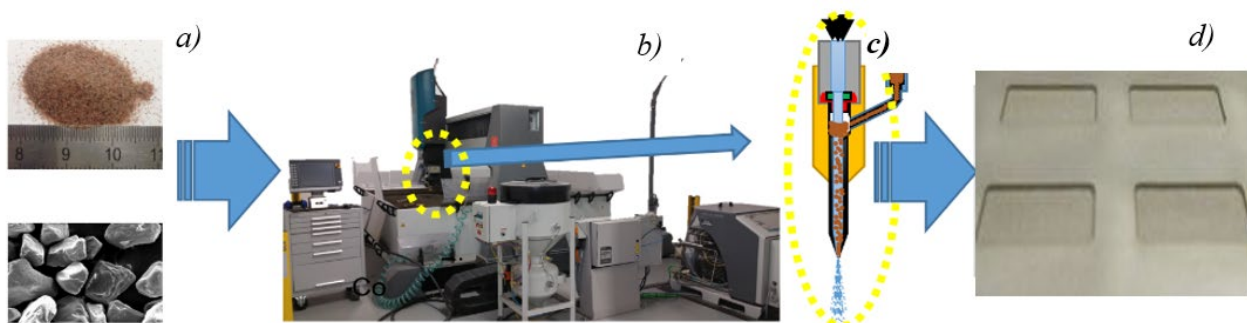


Fig. 1. Abrasive water jet machining

Abrasive water jet machining can machine all types of materials and it can be considered as an eco-process using eco materials because indeed it only requires sand and water. The abrasive is a sand obtained by sieving and crushing natural mineral (garnet) but it can also be synthesized in laboratory (aluminum oxide). Its characteristics influence the way of the material is detached from the part.

The material removal is produced by the combined action of two mechanisms, the impact and the micro incision [1, 2]. The mechanism of impact is due to an abrasive particle trajectory close to perpendicular to the surface (high angle of impact). The micro incision mechanism corresponds to a trajectory of the abrasive particles close to the tangent to the surface, which means with a low impact angle. Material's nature and particle's geometry (Fig. 2) will determine the relative importance of these two mechanisms. By observing the particles, it is possible to estimate if the abrasive contains more or less principal abrasive material like garnet, it may contain some other material like zirconium, quartz, titanium oxide, etc. The principal abrasive material is most present in the abrasive, 90/95% most of the time. This is the hardest mineral present in the abrasives, and the particles observation allow to shows that some have more or less sharp shapes (Fig. 2). A study in progress will subsequently present a method for comparing the cutting power of different abrasives.

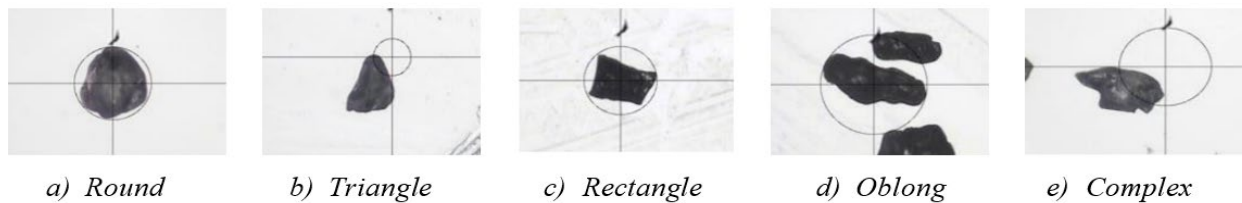


Fig. 2. Abrasive particles

To model the profile of the machined surface, it is possible to first model an elementary profile obtained during a single pass over the part and to apply a summation principle. This approach was employed to deal with the case where the jet is perpendicular to the surface [3] and the case where it is inclined [4]. In both cases, it is necessary to take into account complementary mechanisms due to the orientation of the particle's trajectory relative to the machined surface (Fig. 3). The jet's inclination is characterized in Figure 3c by the angle ( $\alpha$ ).

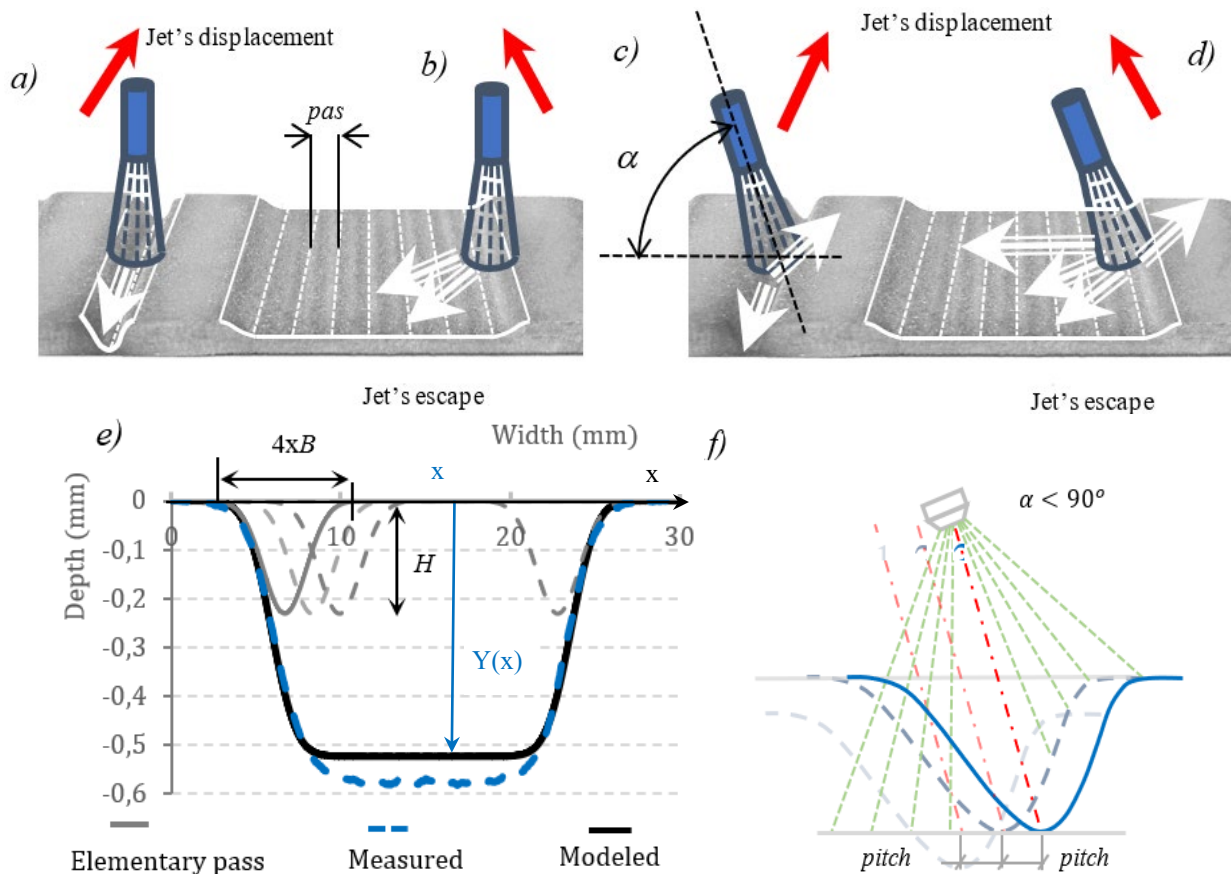


Fig. 3. Machining of open pockets with abrasive water jet.

## 2. Erosion and Abrasion

### 2.1. Characterization of abrasion and erosion

In this study, abrasion is the manifestation of the micro incision mechanism that occurs when machining an elementary pass (Fig. 3a and 3c). This term is chosen by similarity to a grinding tool making a pass. Unlike erosion will characterize the effect of the micro incision during machining by repeated passes and especially the additional action of the particles during a specific pass on the already machined surface (Fig. 3b and 3d).

### 2.2. Modeling of an elementary profile and a pocket bottom profile

It is possible to model the depth profile:  $Y(x)$  for an elementary pass perpendicular to the surface (Fig. 3a) using the equation (Eq. 1) as proposed by A. Alberdi [5]:

$$Y(x) = H \times e^{\left(-\frac{x^2}{B^2}\right)}. \quad (1)$$

In this expression,  $H$  is the total depth of an elementary pass (Fig. 3e) and  $B$  is a width factor. The width of a pass is  $4xB$  (Fig. 3e).

Because abrasive water jet machining depends on a large number of parameters, Bui [3] make a distinction between machine setting parameters and control parameters. The setting parameters are those that cannot be modified during machining: pressure, type of abrasive and abrasive flow rate. The control parameters are those that can be controlled by the machining program: standoff distance, abrasive feed rate, transvers speed and the pitch offset. Bui [3] propose a notion of given machine configuration which gather a given material, a given pressure, a defined abrasive type and flow of abrasive and a constant standoff distance. It lock all setting parameters and the standoff distance which is a control parameter but standoff distance characterize the elementary pass with it two geometric parameters  $H$  and  $B$ . Finally, in this configuration,  $H$  and  $B$  parameters are only dependent on the traverse speed.

By applying a summation, it is possible to model the depth of a succession of perpendicular passes, a pocket bottom (Fig. 3b-3e), using the equation (Eq. 2):

$$Y(x) = Ke \times \sum_{i=0}^n \left[ H \times e^{\left( -\frac{(x-i \times \text{pitch})^2}{B^2} \right)} \right]. \quad (2)$$

In the previous expression, *pitch* is the distance between two consecutive passes and the coefficient *Ke* characterizes the erosion due to repeated passes. A geometric approach, using the  $\cot(\alpha) \times x$  term, also makes it possible to consider an angle of inclination of the jet  $\alpha$  relative to the surface and to establish the equation of the profile of an elementary pass (Fig. 3d) using the equation (Eq. 3):

$$Y(x) = Ka(\alpha) \times H \times e^{-\left(\frac{x}{B}\right)^2} + \cot(\alpha) \times x. \quad (3)$$

The angle  $\alpha$  participates to characterize the inclination of the jet relative to the surface, but it also affects the jet's escape. The corresponding abrasion mechanism is considered using the coefficient *Ka*. Finally, the summation makes it possible to model the profile obtained using a succession of passes of an inclined jet (Fig. 3c):

$$Y(x) = Ke(\alpha) \times \sum_{i=0}^n \left[ Ka(\alpha) \times H \times e^{\left( -\frac{(x-i \times \text{pitch})^2}{B^2} \right)} + \cot(\alpha) \times x \right]. \quad (4)$$

In this expression, the coefficient *Ka* considers the influence of the angle of inclination of the jet on an elementary pass and the coefficient *Ke* considers the erosion due to the repeated action of the passes on the surface.

The model does not consider micro phenomena, it only presents what happens at macro scale. The local angle varies in every point on the elementary pass but *Ka* and *Ke* parameters are only considered for macro scale. But a future study on these micro scale phenomena starts soon but it will be presumably based on numerical tools.

### 3. Experimental Data and Discussion

#### 3.1. Experimental data

Experiments were carried out by machining TiAl6V titanium sheets with a nominal thickness of 6 mm. The machine used was a FLOW MACH4C (Fig. 1b) equipped with a PASER4 cutting head. The nozzle was of diameter 0.33 mm and the focus mechanism 1.02 mm in diameter and 101.6 mm in length. The pressure was generated using a Hyplex-Prime pump with a maximum of 400 MPa. Control machine was ensured by two software packages (Flowpath and Flowcut) provided by FLOW. The abrasive used was garnet particles Opta Minerals 120 mesh and water jet pressure was 100 MPa.

The work of Bui [3] recommends a ratio between the factor *H* and the width *B* of an elementary pass (Eq. 1) close to 0.9 and its results show that this leads to a constant coefficient  $Ke = 1.3$  regardless of pressure, forward speed and standoff distance. In another study, Bui [4] presents for the same machined material coefficients of abrasion and erosion (Eq. 3-4) established for machining with use of an inclined jet. Bui [6] also shows that *Ka* only depends of the inclination angle.

#### 3.2. Discussion

The definition and characteristics of abrasion and erosion phenomena during abrasive water jet machining can be shown in Figure 4.

The abrasion concerns the elementary pass (Fig. 4a-4b) and can be analyzed as follows:

- The graphic on Fig. 4c was built from results on of large experimentation campaign, measuring the depth of elementary passes with different jet's inclination angle. Standoff distance was 30, 60 and 90 mm, forward speed was 300, 450 and 600 mm/min. Results shows that *Ka* coefficient does not

depend of pressure, forward speed and standoff distance, but only of jet's inclination angle, as shows by Bui [6].

- The abrasion from the micro-incision for an elementary pass *without* inclination of the jet (Fig. 4a) is constant. It comes from the response of the material to the action of the jet and could be characterized by a constant coefficient  $Ka = 1$  in the equation (Eq. 1). It would be a basic abrasion, a kind of reference.

- The abrasion resulting from the micro-incision for an elementary pass *with* inclination of the jet (Fig. 4b) results from the response of the material to the action of the jet and depends on the inclination ( $\alpha$ ). This abrasion is characterized by a  $Ka$  coefficient in equation (Eq. 3). With a correlation coefficient  $R^2 = 0.976$  it confirms that  $Ka$  coefficient has the property of evolving in an almost linear trend (Fig. 4c). It also reaches the value  $Ka(90) = 1$  for  $\alpha = 90^\circ$  which corresponds to the reference situation which means with a non-inclined jet. These properties of the  $Ka$  coefficient allow to determine it for a new configuration with a single elementary pass with  $\alpha \neq 90^\circ$ .

- The Fig. 4c shows that more the jet moves away from the reference angle of  $90^\circ$  more  $Ka$  increase which means that the machined depth of the pocket decrease because the material is less removed because of the inclination there is an increase of particle bounce.

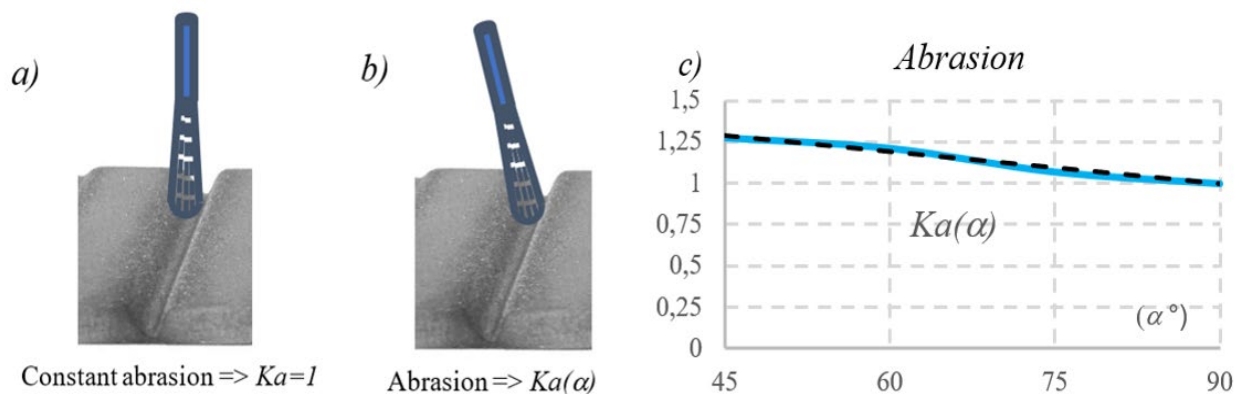


Fig. 4: Abrasion situation

Erosion concerns repeated pass (Fig. 5a-5b). The action of an  $n^{\text{th}}$  pass on the previous ones depends on the value of the pitch (Fig. 3b) and the greater it is, the less the influence on the previous passages will be. This erosion can be interpreted as follows:

- The graphic on Fig. 5c was built from results on of large experimentation campaign, measuring the depth of elementary passes with different jet's inclination angle. Standoff distance was 30, 60 and 90 mm, forward speed was 300, 450 and 600 mm/min, pitch was 0.7 and 1.1 mm. Results shows that  $Ke$  coefficient does not depend of pitch, pressure, forward speed and standoff distance, but only of jet's inclination angle, as shows by Bui [4].

- The erosion which appears for repeated pass without inclination of the jet is a stationary phenomenon. It is characterized by the coefficient  $Ke$  in the equation (Eq. 2). This coefficient is a constant which depends only on the pitch.

- The erosion which occurs during repeated pass of an inclined jet is also a stationary phenomenon characterized in equation (Eq. 4) by a coefficient  $Ke$  which depends on the inclination of the jet. This coefficient changes linearly (Fig. 5c) as a function of the inclination ( $\alpha$ ) with a 0.98 correlation coefficient. So, it is possible to determine  $Ke$  for new conditions with only two experiments with just a variation of the inclination angle.



- The Fig. 5c shows that more the jet moves away from the reference angle of  $90^\circ$  more  $Ke$  decrease which means that the total machined depth of the pocket decrease because of the inclination angle which make the erosion mechanism less effective so the material is less removed.

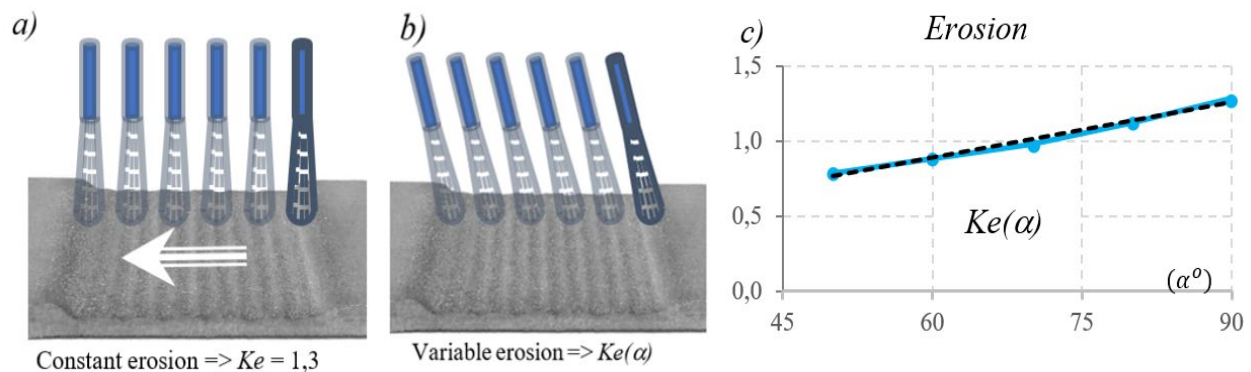


Fig. 5: Erosion situation

#### 4. Conclusion

The study presented the impact and the micro incision which are the material removal mechanisms present during abrasive water jet machining. The micro incision mechanism generates abrasion on elementary passes and erosion on a succession of repeated passes. These phenomena are related to the sweep pitch and the inclination angle of the jet.

This study proposes a model which consider these mechanisms and their combined effects. These two mechanisms are related to linear coefficients which are easy to find with only one experimentation for  $Ka$  and two for  $Ke$ . The model presented in this work as a good precision for a specific inclination angle domain which is  $90^\circ$  to  $45^\circ$ . For a jet with an inclination angle lower than  $45^\circ$  the model loses its precision because of a bounce phenomenon between particles and the material surface.

A subsequent experimental study will show the importance of the geometry and the nature of the abrasive particles on these mechanisms.

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