

# CONTRIBUTIONS TO THE ABRASIVE WATERJET MACHINING OF PARTS

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**ABSTRACT:** The requirement for increasing the efficiency of waterjet machining processes such as to improve surface quality and dimensional precision has led to research with major global contributions. Abrasive waterjets are increasingly used in modern industry, despite the challenge of explaining the extremely complicated phenomena underlying the machining process. The paper presents a series of aspects concerning the mechanics of cutting in abrasive waterjet machining. Based on the imposed conical model of the abrasive grain a methodology is put forward for the computation of the necessary work pressures in the case of waterjet boring and cutting.

**KEYWORDS:** abrasive waterjet, abrasive boring, abrasive cutting, work pressure

## 1. INTRODUCTION

Abrasive waterjet machining entails destroying the integrity of the part surface and removing the tooling allowance by means of erosion agents materialised as solid particles (abrasive grains) [1]. In the case of the machining process under discussion the abrasive grains are driven by a low viscosity fluid, typically water.

By its flexibility and simple deployment waterjet machining has proved its importance. The advantages that place waterjet machining among the top special technologies include the diversity of machinable materials, the low machining costs, reduced impact on the environment, high flexibility, easy programming, rapid machining, and conserving the material's properties due to the low machining temperatures [2]. In order to benefit from these advantages in-depth research is called for in order to solve the problems of waterjet erosion, namely relatively low precision and the occurrence of certain surface defects (striations, mini-craters, high roughness).

Waterjet machining pertains to the category of abrasive erosion machining processes that are generally used for the finishing of parts such as to ensure the dimensional, form and position precision of the surfaces. Also important in such procedures is the surface quality, considering that in certain cases roughness values of  $10^{-10}$  m are obtained. Further of interest is the structure of the processed material layers or of those in the immediate vicinity of the work area, as this is little or not at all affected by the deployed erosive agent.

One of the methods of abrasive erosion of parts is waterjet machining or waterjet cutting, where

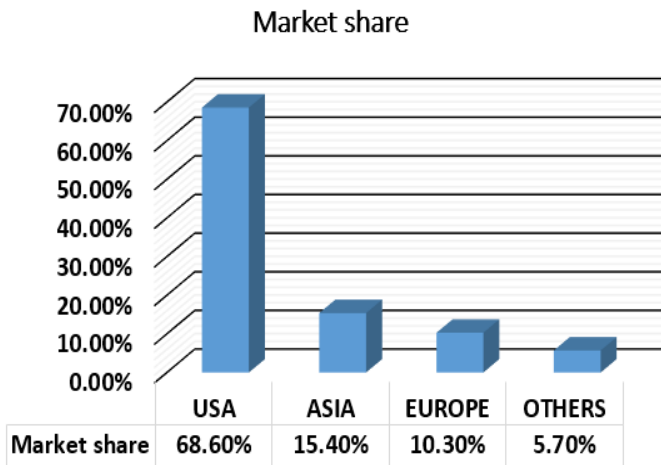
erosion is initiated by the kinetic energy of a moving fluid. Waterjet as an erosive agent (without added abrasive) dates back as far as the 1900, when it was used in mining for cutting coals at pressure not exceeding 100 MPa.

The abrasive jet machining technology entails introducing a certain quantity of abrasive grains into the waterjet, thus improving its coherence, amplifying its mechanical effect and increasing cutting speed by about 30%. In waterjet machining erosion is activated by the kinetic energy of a fluid in motion.

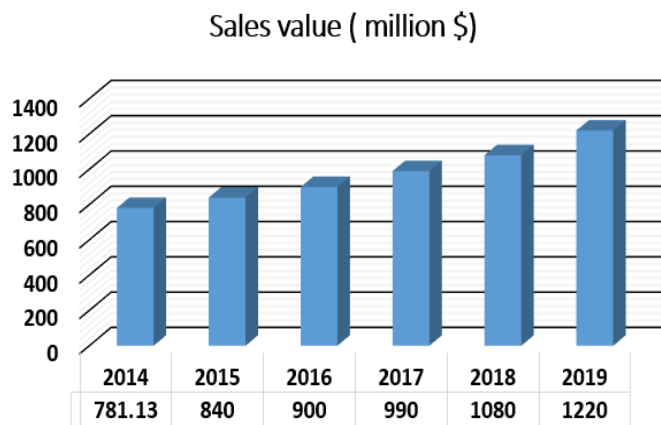
Waterjet machining has become possible in the 1970s with the launching of dedicated pumps [3], [4]. The first cutting installations were developed allowing increased performance of machining. Further milestones in the evolution of this technology are the abrasive mixing tubes made by ROCTEC, a ceramic composite of tungsten carbides (1980), the fluid motion control systems (1990), the tilting system of the cutting head (2000) and the CNC software implemented on waterjet cutting machines in the first decade of the 21<sup>st</sup> century [5].

Due to their benefits, waterjet machining procedures are continuously expanding. The Global Waterjet Machine Market report for 2015-2019 highlights the waterjet machining technology sales forecast for the American market [6]. Thus, starting from sales of USD 781.16 million in 2014, an increase up to USD 1221.12 million is envisaged until 2019. The main beneficiaries are the aerospace, the automotive and the rock and ore extractive industries.

Figure 1 shows the current market shares of the most important manufacturers of waterjet machines as established in the mentioned report [6].



**Figure 1.** Current market shares of the top waterjet machine manufacturers



**Figure 2.** Annual sales values of waterjet machines

The mentioned report also estimates a number of about 20,000 waterjet machines deployed worldwide in 2014 and an increasing trend of 5-6% yearly.

The same report presents the increase of the market due to the benefits of the technology and forecasts sales exceeding a billion dollars starting 2018 (Figure 2).

Due to its numerous advantages, in many industrial countries this process has been employed intensively. Thus, for example in Germany abrasive jets were employed for the cutting of aluminium (41%), steel (29%), glass (22%), granite, marble and rock (21%), non-ferrous metals (7%), wood (7%), rubber (5%), titanium (5%), etc. Abrasive jet cutting devices currently hold about 35% of the total cutting machines worldwide, what proves once again the efficiency and advantages of this processing method.

Pressure waterjet machining yields a number of significant benefits, including [7]:

- special quality of the edges resulted upon cutting, eliminating the need for subsequent deburring;

- the cut contour can have complex shapes; zig-zag lines can be machined, as well as narrow bridges and interior contours;
- depending on the diameter of the jet, a very narrow cutting slot is generated in the part, thus achieving important material savings;
- tool sharpening and re-sharpening operations are eliminated;
- no preliminary contour drawing on the surface of the part is necessary;
- the machining process lends itself to automation;
- high productivity of cutting;
- minimum processing expenditure, given the reduced cost of water, abrasives, etc.

A comparison between waterjet cutting and cutting with welding equipment, with plasma, laser, abrasive stones or a mechanical saw highlights the benefits of the former, as cutting occurs at normal, even low temperatures and no alteration of the material structure are caused by melting or internal stress. The relatively low price and minimum impact on the environment render waterjet cutting a technology of the future. Emerged and developed over the last years waterjet micromachining has improved precision to 0.02 mm and allows optimisation of surface roughness by configuring the process input factors by robust design.

Abrasive waterjet machining is not an actual “cutting”, but chip removal, similar to sawing. An analysis of the material removed by the jet reveals chips of sizes up to 5 μm, comparable to those generated in diamond disk cutting [8].

Considering the complexity of the phenomena occurring in the contact area of the pressure jet with the machined part, this paper discusses certain key aspects of the mechanics of chip removal in waterjet machining.

## 2. MODELLING THE EROSION PROCESS IN ABRASIVE WATERJET MACHINING

Modelling the chip removal process in waterjet machining is definitely challenging. The complexity of the problem is given, *inter alia*, by the very varied shapes and sizes of the grains and by the modifications of these two characteristics during contact with the machined part.

The above listed causes generate errors in the extrapolation of the results obtained by analysing a single abrasive grain, hence the requirement of in-depth research.

The abrasive powders used in waterjet machining are the actual cutting tool. The abrasive grain, in

direct contact with the machined part is the effector element that removes the material. The configuration of an abrasive grain is extremely complex, consisting of several basic geometric shapes positioned randomly in relation to a symmetry centre. For the simplicity of analysis literature offers several models of geometric shapes used for explaining chip removal by waterjet machining. Thus the known models work with grains that are conical, biconical, pyramid, sphere, prism or Cassini oval shaped [9], [10]

The shape of the abrasive grains used in waterjet machining is decisive. The recommended grain shape should be as close as possible to spherical, as shown in Figure 3 [7].

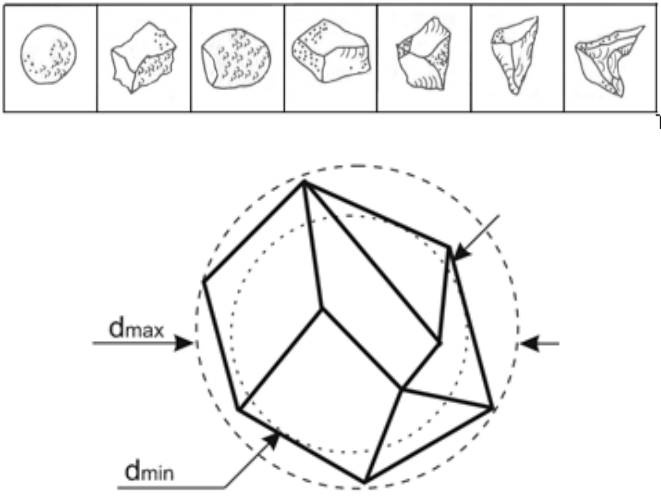


Figure 3. Recommended shapes of abrasive grains

The abrasive grains used in waterjet machining are selected by a form factor calculated by equation:

$$F_f = \frac{d_{min}}{d_{max}} \quad (1)$$

where  $d_{min}$  is the largest diameter of a circle that can be inscribed in the abrasive grain, while  $d_{max}$  is the smallest diameter of a circle circumscribed to the grain. The usual values of the form factor range between 0.64 and 0.70.

The modelling of the waterjet erosion process discussed further on considers conical grains with a  $2\theta$  apex angle. Two situations will be analysed, namely the boring and cutting of a part, respectively.

### 2.1 The case of boring a part

Figure 4 shows the work model adopted for determining the pressure to be supplied by the waterjet machine, namely the biconical model, where the abrasive grain is considered a body consisting of two cones joined base-to-base.

The pressure supplied by the equipment can be determined by the Rabinowicz model, where the

abrasive grain is assumed a conical penetrator. The contact surface between the grain and the material of the part, as shown in Figure 5, can be calculated by the following relationship:

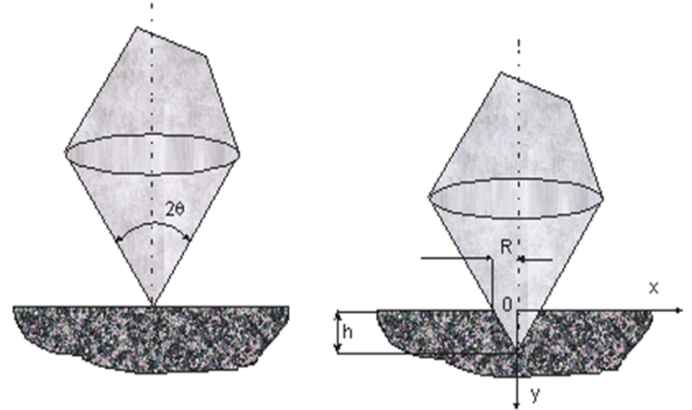


Figure 4. Model of a grain with conical vertices

$$A_c(y) = \frac{\pi \cdot R}{h \cdot \cos \theta} \cdot y^2 \quad (2)$$

where  $h$  is the maximum penetration depth of the abrasive grain.

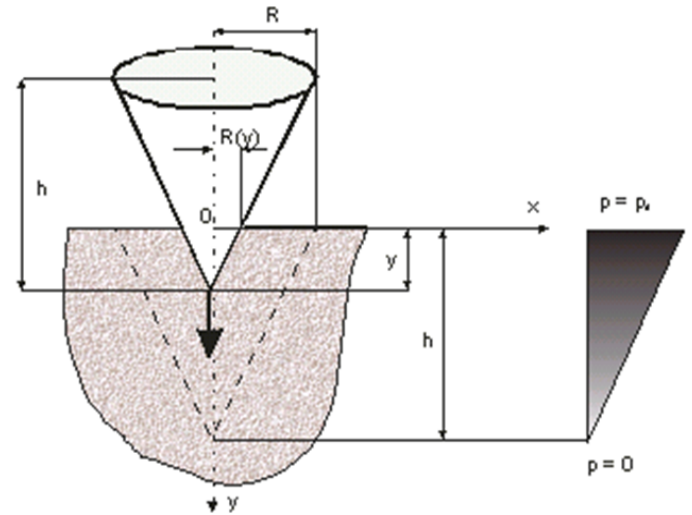


Figure 5. Penetration of the grain into the machined part

Using the adopted model further on it is assumed that the pressure exerted by the grain on the machined part decreases linearly, from a maximum value  $p_s$  (system pressure) to zero, as described by equation (3):

$$p(y) = p_s \cdot \left(1 - \frac{y}{h}\right) \quad (3)$$

The pressure force exerted by one abrasive grain on the machined part is calculated with equation (4):

$$F(y) = p(y) \cdot A_c(y) = p_s \cdot \left(1 - \frac{y}{h}\right) \cdot \frac{\pi \cdot R}{h \cdot \cos \theta} \cdot \frac{y^2}{h} \quad (4)$$

The work completed by the abrasive grain is determined with equation (5):

$$L = \int_0^h F(y) dy = \frac{\pi}{12} \cdot p_s \cdot \frac{R \cdot h^2}{\cos \theta} \quad (5)$$

According to the law of energy conservation, the work completed by one grain is transformed into deformation energy and transmitted to the machined part, as described by equation (6).

$$L = \delta_S \cdot V \quad (6)$$

The specific processing energy is computed by equation (7) [11].

$$\delta_S = \frac{\tau_t^2}{2 \cdot G} \quad (7)$$

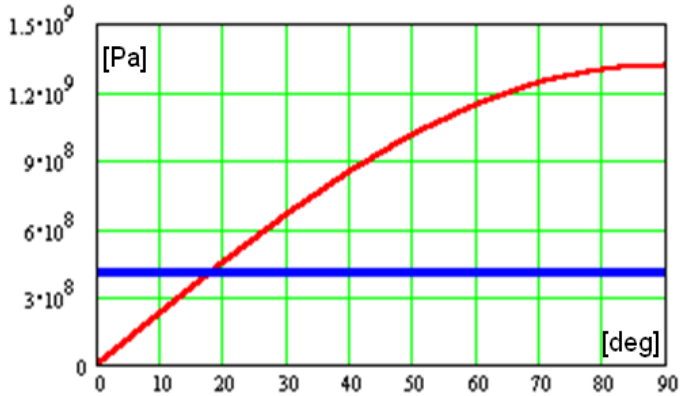
where  $\tau_t$  [Pa] is the theoretical shear strength and  $G$  [Pa] the transversal elasticity modulus of the machined material.

The volume of the chip removed by one grain is computed by equation (8):

$$V = \frac{\pi \cdot R^2 \cdot h}{3} \quad (8)$$

Following substitutions, equation (9) describes the dependence of the pressure to be supplied by the system on the nature of the processed material and the geometry of the abrasive grain (angle  $\theta$ ):

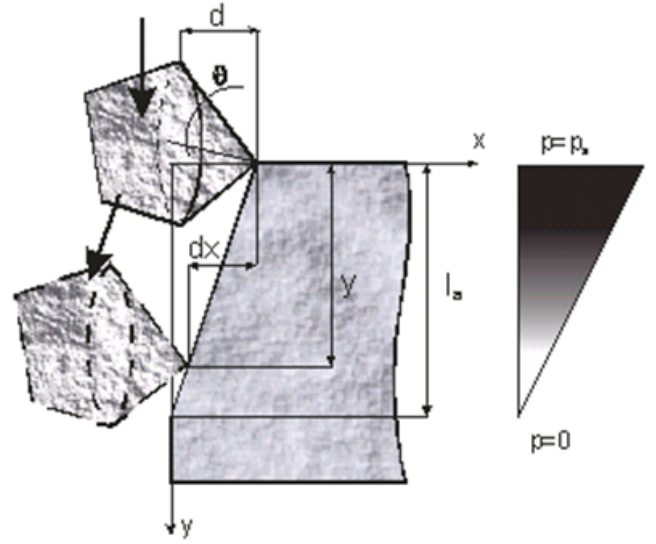
$$p_S = 4 \cdot \delta_S \cdot \sin \theta \quad (9)$$



**Figure 6.** Necessary pressure of the abrasive jet versus the half angle of the abrasive grain cone

## 2.2 The case of cutting a part

In this case the path of the abrasive grains is tilted, consequently to the gradual decrease of their initial kinetic energy (Figure 7).



**Figure 7.** The path of the abrasive grains

In this case too, the necessary pressure to be supplied by the equipment is computed based on the Rabinowicz model, where the abrasive grain is considered a conical penetrator. The initial contact surface between the grain and the material of the part is merely half of the lateral surface area of a cone and is computed by equation (10):

$$A_C = \frac{1}{2} \cdot \pi \cdot d^2 \cdot \tan \theta \cdot \sqrt{1 + (\tan \theta)^2} \quad (10)$$

According to the adopted model the following conditions are imposed:

- The trajectory of the abrasive grain tip is linear;
- The pressure exerted by the abrasive grain on the machined part decreases linearly, from a maximum value  $p_S$  (the system pressure) to zero, according to equation (11):

$$p(y) = p_S \cdot \left(1 - \frac{y}{l_a}\right) \quad (11)$$

where  $l_a$  is the length of the chip removed by one abrasive grain.

Considering these conditions the evolution of the contact surface area as the abrasive grain penetrates the part can be computed by equation (12):

$$A_C(y) = \frac{1}{2} \cdot \pi \cdot (d - dx)^2 \cdot \tan \theta \cdot \sqrt{1 + (\tan \theta)^2} \quad (12)$$

As:

$$dx = d \cdot \frac{y}{l_a} \quad (13)$$

it can be written that:

$$A_C(y) = \frac{1}{2} \cdot \pi \cdot d^2 \left(1 - \frac{y}{l_a}\right)^2 \cdot \tan \theta \cdot \sqrt{1 + (\tan \theta)^2} \quad (14)$$

The force developed at the contact between the abrasive grain and the part is computed with equation (15):

$$F(y) = p(y) \cdot A_c(y) = \frac{1}{2} \cdot \pi \cdot d^2 \cdot p_s \cdot \left(1 - \frac{y}{l_a}\right)^3 \cdot \tan \theta \cdot \sqrt{1 + (\tan \theta)^2} \quad (15)$$

or:

$$F(y) = F_{max} \cdot \left(1 - \frac{y}{l_a}\right)^3 \quad (16)$$

The work completed by the abrasive grain is computed with equation (17):

$$L = \int_0^{l_a} F(y) dy = F_{max} \cdot \int_0^{l_a} \left(1 - \frac{y}{l_a}\right)^3 \cdot dy = \frac{F_{max} \cdot l_a}{4} \quad (17)$$

or:

$$L = \frac{\pi \cdot d^2}{8} \cdot p_s \cdot l_a \cdot \tan \theta \cdot \sqrt{1 + \tan \theta)^2} \quad (18)$$

Knowing equation (7) for  $\delta_s$  - the marginal shearing energy density of the part material and equation (6) for the work completed by one abrasive grain, eventually an equation can be obtained that describes the dependency of the pressure supplied by the system on the type of machined material and the geometry of the abrasive grain. For this, starting from the notations of Figure 8, first the volume of the chip removed by one abrasive grain is computed with equation (19):

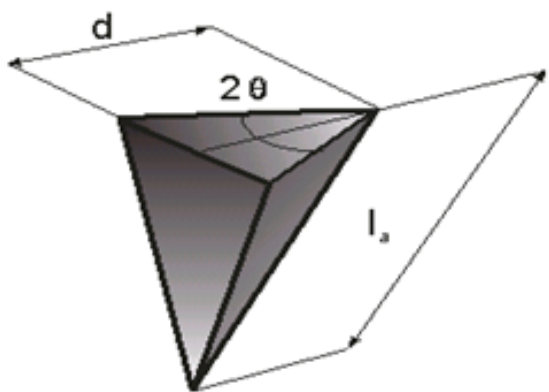


Figure 8. Chip generated by waterjet erosion

$$V = \frac{1}{3} \cdot d^2 \cdot l_a \cdot \tan \theta \quad (19)$$

In this case the work pressure will be computed by equation (20):

$$p_s = 0.849 \cdot \frac{\delta_s}{\sqrt{1 + (\tan \theta)^2}} \quad (20)$$

Figure 9 presents the concrete case of machining an aluminium part. The graph reveals that as the half

angle of the cone is greater, that is the grain tends to become “rounder”, the pressure to be supplied by the installation can be smaller.

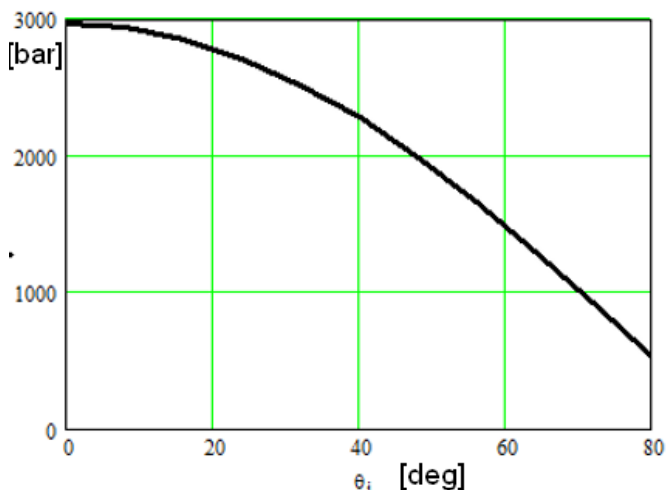


Figure 9. Necessary pressure of the abrasive waterjet versus the half angle of the abrasive grain cone

### 3. CONCLUSION

Given the complexity of the phenomena occurring in the contact area of the fluid jet with the machined part, the paper proposes several methods for computing the pressures to be supplied by the machine. In the case of aluminium parts work pressures were found as being dependent on the geometry of the used grains, the smaller the work pressures can be.

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