FACTA UNIVERSITATIS
Series: **Architecture and Civil Engineering** Vol. 17, N° 4, 2019, pp. 417-428
https://doi.org/10.2298/FUACE190710026J

APPLICATIONS OF THE ABRASIVE WATER JET TECHNIQUE IN CIVIL ENGINEERING

UDC 621.924.93

Predrag Janković[1], Tomislav Igić[2], Miroslav Radovanović[1], Dragana Turnić[2], Srđan Živković[2]

[1]University of Niš, Faculty of Mechanical Engineering, Niš, Serbia
[2]University of Niš, Faculty of Civil Engineering and Architecture, Niš, Serbia

Abstract. *Water jet processing techniques can be successfully applied in many fields of civil engineering, such as: structural engineering, structural reconstruction, renovation, demolition and recycling. The problem of cutting difficult-to-machine materials led to the development and application of today the most attractive method for contour cutting - Abrasive Water Jet Cutting (AWJC). It is a high-tech technique that provides unique capabilities compared to conventional machining processes. This paper, along the theoretical derivations, provides a study on use of water jet in construction and civil engineering. The particular part of this paper deals with the results of the original experimental research on granite and aluminum cutting.*

Key words: *Abrasive water jet cutting, civil engineering, damage mechanics, granite specimen test, aluminum specimen test.*

1. INTRODUCTION

In the 1960's, an American aerospace company faced the challenge of cutting fiber-reinforced, honeycombed, and sandwich materials. Conventional cutting processes destroyed the material's structure and could not be used. It was, therefore, imperative that a new cutting method is found so that the industry could go forward. The solution was found in pressurizing water to ultra-high pressures and focusing it into a high velocity stream. The first abrasive water jet machine was introduced in 1982. Since then, the technology has grown with the increased use of sophisticated materials and the need for complex shapes.

Abrasive water jet (AWJ) cutting is a non-conventional machining process that uses high velocity water with abrasives for cutting a variety of materials. It is the most suitable process for very thick, highly reflective or highly thermal-conductive materials, as well as hard

Received July 10, 2019 / Accepted November 13, 2019
Corresponding author: Dragana Turnić
University of Niš, Faculty of Civil Engineering and Architecture, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: dragana.turnic@gaf.ni.ac.rs

materials. Abrasive water jets can cut a wide range of thicknesses. Typical thicknesses are 100 mm for stainless steel, 120 mm for aluminium, 140 mm for stone, 100 mm for glass, but not limited to that.

Abrasive water jet machining is appropriate and cost effective for a number of procedures and materials and is applied in nearly all areas of modern industry. Table 1 gives a review about industrial applications of the water jet technique [1].

Table 1 Industrial applications of water jet technique

Industrial area	Application
Manufacturing operations	Metal cutting with abrasive water jet
	Conventional machining with water-jet assistance
	Piercing and drilling by abrasive water jets
Civil engineering	Concrete hydro demolition
	Cutting of concrete sections
	Concrete surface preparation
	Surface cleaning
	Architectural profiles
Chemical process engineering	Pipeline cleaning and decoating
	Vessel, container and autoclave cleaning
Maintenance and corrosion prevention	Coating removal
	Emission-free surface preparation
Automotive engineering	Lacquer stripping
	Engine reconditioning
	Deburring
Environmental Engineering	Material recycling
	Emission-free decontamination

2. ABRASIVE WATER JET CUTTING PROCESS

An abrasive water jet is a jet of water which contains abrasive particles. Solid particles – the “abrasive” – join the water jet in a mixing chamber (Fig. 1) and are focused by the abrasive nozzle. High pressure water enters the upper portion of the nozzle assembly and passes through a small-diameter (d_0 = 0.08 - 0.4 mm) water nozzle to form a narrow jet. The water jet then passes through a small chamber where a Venturi effect creates a slight vacuum that pulls abrasive material and air into this area through a feed tube. The abrasive particles are accelerated by the moving stream of water, and together they pass into a long, hollow cylindrical nozzle. The abrasive and

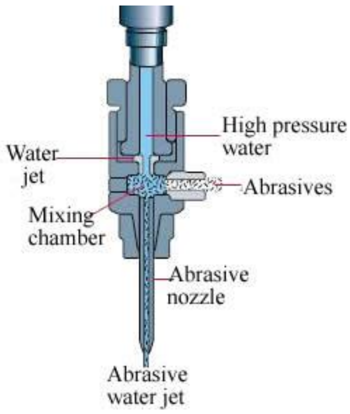


Fig. 1 Abrasive water jet cutting head

water mixture exits the abrasive nozzle as a coherent abrasive water jet and cuts the material.

In the process of abrasive water jet cutting the high pressure pump produces the required pressure up to p = 400 MPa. When the pressurized water comes out from the orifice, a water jet is created. The result is a very thin, extremely high velocity (approx. 900 m/s) water jet. Velocity of the water jet can be calculated on behalf of Bernoulli's law, and is expressed as:

$$v_{wj} = \sqrt{\frac{2p}{\rho_w}} \tag{1}$$

Leakage velocity of water jet from a nozzle is crucial because its role is to accelerate the abrasive particles. Due to the extra weight, abrasive particles, however, cannot achieve the velocity of water jet but only a part of that velocity [2].

The volume flow rate of water may be expressed as:

$$q_w = A_{orifice} v_{wj} \tag{2}$$

$$\text{for } v_{wj} = \sqrt{\frac{2p}{\rho_w}} \text{ and } A_{orifice} = \frac{\pi}{4} d_0^2$$

$$q_w = \frac{\pi}{4} d_0^2 \sqrt{\frac{2p}{\rho_w}} \tag{3}$$

The law of conservation of momentum says that the total momentum of any closed system, i.e., the vector sum of the momentum vectors of all the things in the system, is a constant. The momentum of air before and after mixing will be neglected due to very low density. Further, it is assumed that after mixing both water and abrasive phases attain the same velocity of abrasive water jet. Moreover, when the abrasive particles are fed into the water jet through the port of the mixing chamber, their velocity is also very low and their momentum can be neglected, and the general equation leads to:

$$q_w v_{wj} + q v_a = (q_w + q) v_{awj} \tag{4}$$

$$v_{awj} = \frac{q_v}{q_w + q} v_{wj}$$

$$v_{awj} = \frac{v_{wj}}{1 + \frac{q}{q_w}} . \tag{5}$$

As during the mixing process the momentum loss occurs as the abrasives collide with the water jet and at the inner wall of the abrasive nozzle multiple times before being entrained, the velocity of abrasive water jet is given as,

$$v_{awj} = \eta \frac{v_{wj}}{1 + \frac{q}{q_w}} \tag{6}$$

where η- momentum loss factor, whose values lies around 0.65-0.85 [3].

Then, solid abrasive particles are added and mixed with the water jet. The resulting abrasive water jet is focused to the material through the abrasive nozzle. The impact of solid particles is the main mechanism in the process of removing material by the abrasive water jet [4].

Hashish [5] proposed a general model for the material removal mechanism, in which a stable cutting process takes place to a certain depth of penetration of the abrasive water jet, followed by the formation of steps on the surface of the cut. Below the critical depth, the processing is unstable resulting in the creation of striated or wavy surface of the cut (Fig. 2).

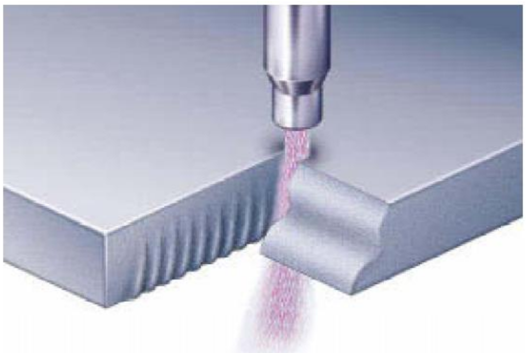


Fig. 2 Development of the cut surface by abrasive water jet cutting

With increasing depth and creating steps, the removal mechanism is changing from cutting to the separating material by plastic deformation. The above-described mechanism, cyclic repeating, resulting in different types of material damage, which is the subject of the study of damage mechanic.

The cut surfaces produced by the abrasive water jet cutting typically exhibit a smooth upper zone followed by a lower striated zone (Fig 3).

These phenomena can be related to the jet loss of energy during the cutting process, e.g. deformation of the sharp edges of the abrasive particles as illustrated in Fig. 4 [6].

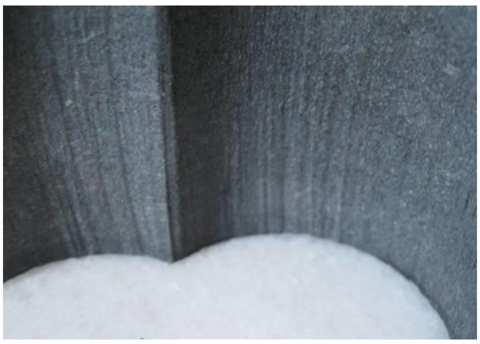


Fig. 3 Cut surface generated by abrasive water jet cutting of granite

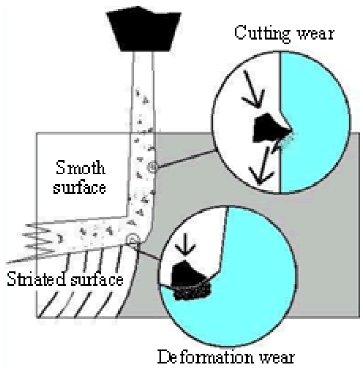
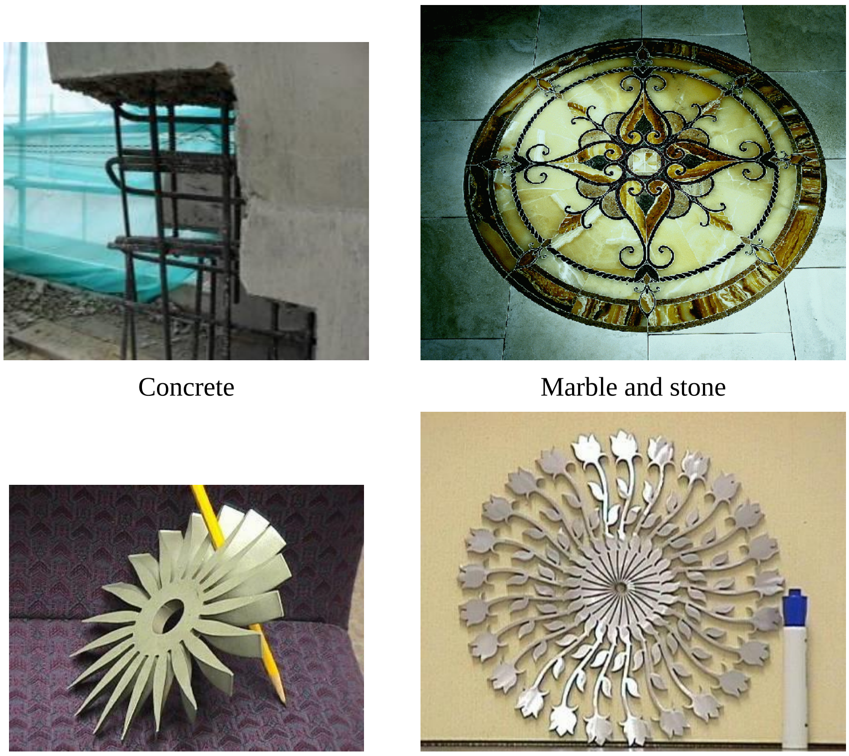


Fig. 4 Formation of different regions in abrasive water jet cutting

Application of cutting by abrasive water jet lie in the field of: non-metallic materials (glass, ceramics, marble, granite, concrete, polymers, composite materials, tool ceramics) and metallic materials (medium and high strength alloy steels, tool steels and stainless steels, abrasion resistant steel, cast iron, aluminum, copper, titanium, tungsten, manganese, hard alloy). Modern abrasive water jet cutting is gaining popularity because of the ability of processing almost any material of significant thickness (Fig. 5). Materials that are reflective, with a high heat transfer coefficient or sensitive to heat treatment, are suitable for cutting with abrasive water jet. As the thickness of the material increases the abrasive water jet cutting is becoming more convenient method of machining, especially when it is necessary to maintain accuracy.



Concrete | Marble and stone | Ceramic | Steel

Fig. 5 The possibility of cutting different materials by abrasive water jet

3. Possible Applications of Abrasive Water Jet Technique in Civil Engineering and Construction

The water jet is a promising tool not only for manufacturing industries but also for the civil engineering field due to its distinctive features of low vibration, little dust, and low impact or disturbance to areas adjacent to the operation. This makes the water jet an environmentally-friendly technique over conventional cutting and dismantling methods such as the use of drilling and blasting, a hydraulic jackhammer, and a diamond saw cutter. Where there is concrete to be removed or prepared for reapplication water jetting is the cost effective solution.

Following are some examples where the water jet has already been used or has been tested and found to be suitable for the application [7].

Concrete hydrodemolition

Hydrodemolition is the process of removing concrete with minimal or no vibration with a water jet (Fig. 6). Hydrodemolition is used for various procedures where deteriorated or damaged concrete has to be removed, but leaving the reinforcing steel washed clean, intact and undamaged. The remaining concrete surface has a rough washed clean finish, with great bonding properties, to allow superior repairs.

Fig. 6 Selective removal of deteriorated concrete

Hydrodemolition is widely used in the construction industry for bridge repairs/ strengthening. The benefits are: no vibration (does not cause stress fractures sometimes called micro cracks), no dust (because you are cutting the concrete with water the area remains dust free and is washed clean at the same time), no damage to steel reinforcing (the steel reinforcing gets cleaned during the jetting process and remains undamaged), thus enabling a fast and cost effective repair.

Concrete Surface Preparation

Surface preparation is used for preparing a surface ready for inspection; repair or maintenance, another form of surface preparation is coating removal. Surface preparation of concrete also known as scabbling or scarifying, it is often done by ultra high pressure water with rotary nozzles. This nozzle has 4 to 6 jets which reduces the impact of water jet and has a larger coverage compared to a standard single nozzle (Fig. 7).

Fig. 7 Surface preparation

Surface Preparation and coating removal with Ultra high pressure water is a technique that has many advantages over sand/grit blasting. When removing coatings from steel surfaces, the water jet only removes the coating and leaves the steel undamaged and clean (Fig. 8). Water jetting does not create dust and reduces the cost of cleanup and disposal of spent abrasive.

Fig. 8 Decoating of reinforced concrete with hand-held high-pressure water jet equipment

Cutting of concrete sections

In the construction industry, the abrasive water jet will most likely be used for cutting steel beams and concrete sections (Fig. 9). For steel, the cutting rates are slower with the water jet than for other tools, such as plasma arcs. However, often the cost is offset by the time saved by reducing or eliminating finishing steps. This is because there is no heat affected zone with the water jet. The water jet has also been able to cut through thick slabs of concrete. This will save in the cost of buying diamond tipped saws and sharpening them [8].

Fig. 9 Cutting of heavily reinforced concrete ceilings

Architectural Profiles

Abrasive water jet cutting has revolutionized the decorative fabrication industry. Many shops experience benefits using this new wave of technology. From simple block letters to complex and intricate designs, abrasive water jet cutting bring ideas of architects and designers from concept to completion within a short time [9]. Extraordinary results and superior edge finishes can be achieved with the state-of-the-art abrasive water jet equipment in cutting diverse materials from marble to glass and brass to wood. Typical applications are ranging from cutting of marble and granite floor inlays to cutting of small labels for name plates (Fig. 10). The variety of shapes and designs in which the signages can be crafted is endless.

Fig. 10 Custom flooring from stone

For use of abrasive water jets in civil and constructive engineering it is specific that equipment often is not located in shops, but these systems can be supplied for mobile operation at construction sites (Fig. 11).

Fig. 11 Mobile equipment and concrete removal with hand-held water jet tools

4. EXPERIMENTAL WORK

A series of water jet cutting experiments were conducted in order to determine linear cutting speed at which a complete cut still happens, i.e. to just barely cut through material. In this way a boundary line that separates the area in which the cut is complete, and the one where we have only a partial cut (Fig. 12) is defined.

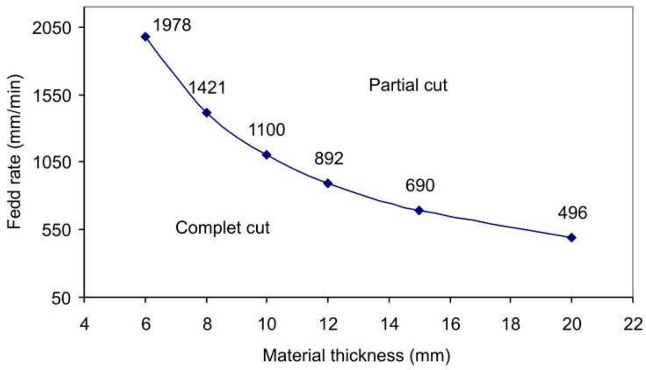


Fig. 12 Cut-through speed boundary line

Work piece material, aluminium alloy AA-ASTM 6060 (Al MgSi) and granite was used. These materials are chosen as a work piece material because they are very attractive and can provide significant value for the end user. Also, aluminium and its alloys are characterized by high reflectivity and thermal conductivity. This makes them relatively difficult to cut with lasers. Abrasive water jet cutting, which does not create an observable heat affected zone, is much more useful for cutting aluminum for modern applications. Granite is a widely used material in construction industry. A high efficiency and high quality cutting method for granite cutting is always demanded by industry. The AWJ cutting may also be used for other rock cutting [10].

The survey was conducted on prepared specimens with thickness of: s = 6, 8, 10, 12, 15 and 20 mm. Other parameter values of the process were:

- workpiece material: granite and aluminium alloy,
- water pressure: p = 400 MPa,
- water nozzle diameter: d_0 = 0,30 mm,
- abrasive nozzle diameter: d_A = 1,02 mm,
- abrasive flow rate q = 300 and 400 g/min and
- distance of the cutting head to workpiece z = 2 mm.

Feed rate (v) is, for each cut, gradually increased, until there was no cut in which the sample is not completely cut through, as shown in Fig. 13.

Fig. 13 Incomplete cut

The value of the cutting speed at which there is a complete separation of material through its whole thickness is influenced by many factors, among which the most important are: the type of material, its thickness, and abrasive flow rate and water pressure [11]. With consideration that, in practice, for cutting we always use the maximum pressure that the machine can achieve, the influence of water pressure, even though it has a major impact on the ability of AWJ cutting has not varied, but the maximum value of water pressure of p = 400 MPa was used.

Diagram showing the influence of the type of material, thickness of the work piece and the abrasive flow rate on cut-through cutting speed (feed rate) is presented in Fig. 14.

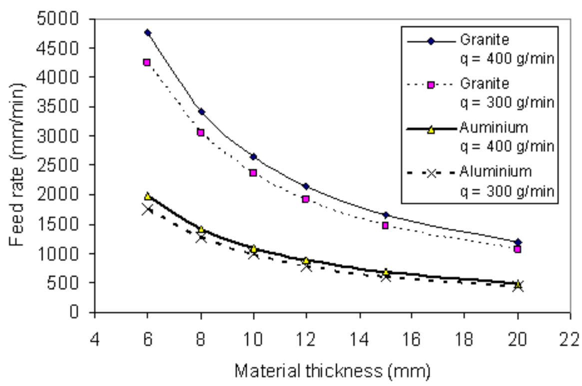


Fig. 14 Effect of process parameters on separation speed

Experimental studies, presented in this paper, were carried out in real working conditions, in which the measured parameters are depending on the parameters of the machining. With the increasing use of abrasive water jet cutting, there is a need for quantitative description of the processing operations, and therefore are necessary mathematical models to describe the process parameters [12].

5. Conclusion

Water jet technique could be successfully employed in many areas of civil engineering and construction, such as: structural engineering, foundation engineering, construction repair, renovation, demolition and in recycling.

Abrasive water jet cutting is of great interest for various reasons. Almost any material can be cut, with a wide range of thickness. The abrasive water jet makes it possible to cut random contours, very fine tabs and filigree structures.

Although there are no restrictions on the types of work piece material by the use of AWJ, however there is a limit to the thickness of the workpiece that can be cost-effectively machined, compared to other cutting processes. Therefore, the knowledge of material cutting speed limit and influence of process parameters is step towards ensuring optimum cost of production and meeting the demands of customers.

In this study, the maximum cutting speed of the machined material in terms of process parameters in AWJ-machined aluminium alloy and granite was investigated experimentally. Summarizing the main features of the results, the following conclusions may be drawn:

- The value of process parameters at which the cut is complete, depend primarily on the type of material and thickness of the work piece. During the processing of aluminum, cutting speed is over two times less than processing granite of the same thickness.
- As the feed rate increases, the AWJ cuts narrower kerf. This is because the feed rate of abrasive water jet allows fewer abrasives to strike on the jet target and hence generates a narrower slot.

Acknowledgement: *Paper is result of technological projects TR35034 and TR36016 which is supported by Ministry of Education, Science and Technological Development of the Republic of Serbia*

References

1. W. Momber, R. Kovacevic, Principles of Abrasive Water Jet Machining, Springer, London, New York, 1998.
2. P. Janković, T. Igić, D. Nikodijević, Process parameters effect on material removal mechanism and cut quality of abrasive water jet machining, Journal Theoretical and Applied Mechanics, Serbian Society of Mechanics, Vol. 40 (S1), 2012, p. 277-293.
3. S. Zhang, P. Nambiath, Accurate hole drilling using an abrasive water jet in titanium, American Watejet conference, Houston, 2005.
4. Z. Guo, M. Ramulu, M.G. Jenkins, Analysis of the waterjet contact/impact on target material, Optics and Laser in Engineering, No. 33, 2000, p. 121-139.
5. M. Hashish, Wear in abrasive-waterjet cutting systems, *Wear of Materials*, Vol. 2, New York, 1987, p. 769-776.
6. A. Akkurt, Cut front geometry characterizion in cutting applications of brass with abrasive water jet, *Journal of Materials Engineering and Performance*, Volume 19, Issue 4, 2009, p.599-606.
7. http://www.woma.com.au/industrysolutions/

8. L. A. Hitchox, Vote of Confidence for Abrasive Waterjet Cutting, Metal Progress, Vol. 130, 1986, p. 33-34.
9. A. Momčilović-Petronijević, G. Topličić-Ćurčić, A. Ćurčić: “Architecture and ceramic materials, development through time: adobe and brick”, Facta Universitatis, Series Architecture and Civil Engineering, Vol.16, No 3, 2018, University of Niš, Niš, 2018, pp. 387- 400
10. Y. Liu and X. Chen, Key Engineering Materials Vols. 257-258, Trans Tech Publications, 2004, p. 527-534.
11. P. Janković, V. Blagojević, Estimation method for maximum cutting speed by abrasive water jet machining, XI International SAUM Conference, University of Nis, Faculty of Electronic Engineering, Nis, Serbia, 2012, p. 144-147.
12. P. Janković, J. Č. Baralić, V. A. Blagojević, Modeling as Way to Better Understanding of the Influencing Process Factors - AWJ Machining Case Study, XIII International Conference on Systems, Automatic Control and Measurements, XIII International Conference on Systems, Automatic Control and Measurements, Niš, Serbia, 2016, pp. 51-54.

PRIMENA OBRADE ABRAZIVNIM VODENIM MLAZOM U GRAĐEVINARSTVU (GRAĐEVINSKOM INŽENJERSTVU)

Tehnika obrade vodenim mlazom može se uspešno primenjivati u mnogim oblastima građevinskog inženjerstva, kao što su: strukturalno inženjerstvo, rekonstrukcija konstrukcija, renovirenje, rušenje i u potupcima reciklaže. Problem sečenja teško obradivih materijala doveo je do razvoja i primene, danas naj atraktivnije metode za konturno sečenje materijala abrazivnim vodenim mlazom. To je visoko tehnološki postupak koji poseduje jedinstvene karakteristike u odnosu na uobičajene postupke obrade materijala. U ovom radu su, pored teorijskog osvrta, predstavljene mogućnosti primene ove tehnike u građevinskom inženjerstvu, dok su u delu rada predstavljeni rezultata ispitivanja na uzorcima od granita i aluminijuma.

Ključne reči: *Sečenje abrazivnim vodenim mlazom, građevinsko inženjerstvo, mehanika oštećenja, ispitivanje uzorka od granita, ispitivanje uzorka od aluminijuma.*