ANALYSIS AND MODELING OF THE EFFECTS OF PROCESS PARAMETERS ON SPECIFIC CUTTING ENERGY IN ABRASIVE WATER JET CUTTING

by

Predrag Lj. JANKOVIĆ *, ***Miloš J. MADIĆ, Dušan Lj. PETKOVIĆ, and Miroslav R. RADOVANOVIĆ***

Faculty of Mechanical Engineering, University of Nis, Nis, Serbia

Original scientific paper
https://doi.org/10.2298/TSCI18S5459J

The problem of cutting difficult-to-machine materials used in the aerospace industry, aircraft industry, and automobile industry, led to the development and application one of today's most attractive technology for contour cutting – abrasive water jet cutting. For the efficient use of abrasive water jet cutting, it is of great importance to analyze the impact of process parameters on performance indicators, such as cutting quality, productivity, and costs. But also, from the energy utilization point of view, it is very important to analyze the impact of these parameters on the specific cutting energy which represents the amount of energy spent on the removal of material in the unit time. Having this in mind, this study presents the experimental results of abrasive water jet cutting of aluminum alloy with the aim of creating a mathematical model for estimating specific cutting energy as an important indicator of the degree of utilization of the available energy in the cutting process. The mathematical model of the specific cutting energy is explicitly represented as a non-linear function of the process parameters, obtained by the artificial neural network.

Key words: *specific cutting energy, abrasive water jet cutting, modeling, artificial neural networks, aluminum alloy*

Introduction

The last decades witnessed an increasing industrial use of contemporary materials with improved properties [1]. The growing need for machining complex and precise shapes of these materials, has resulted in the advancements of a number of new machining processes, commonly known as non-conventional machining processes (NCMP) [2]. Appearance of new, primarily fibrous and layered composites in aviation and aerospace industry demanded the development of NCMP that would be able to process these materials sensitive to heat and pressure. The solution was found in adapting of water jet technology that has already been used for decades in mining. Improvements in the process and adding abrasives to high-speed water jet, resulted in the development of the tool able to cut virtually any material. The first machine for abrasive water jet (AWJ) cutting of automotive glass was sold in 1983. New cutting technology was first adopted in the automotive and aerospace industry, which has been used for the processing of materials such as stainless steel, titanium, and carbon fiber rein-

* Corresponding author, e-mail: p.jankovic@masfak.ni.ac.rs

forced composites. Later, this technology extended to the other industries, such as metal processing, construction, shipbuilding, *etc.*

The AWJ processing is superior to similar processing operations when it comes to making parts that have complex 2-D shape. This advantage is even more apparent when it comes to processing thin sheets and foil, and that with this procedure materials can be cut, regardless of whether they are brittle and tough materials. The great advantage of this technology is the fact that in the processing zone there is no significant increase in temperature and that the cutting forces are very small [3].

In the last few years, the AWJ technology has shown a rapid development due to its remarkable advantages and its capability to extend to new fields of application; it is able to cut any kind of material, cut complex profiles, prevent thermal and mechanical damages on the target material, reduce the burr formation, and the delamination phenomena. The most common operations that can be performed with AWJ processing are: cutting, surface polishing, surface cleaning, *etc.* In all cases, the processing mechanism is based on erosion, where AWJ jet is the cutting tool. The cutting process is most similar to the grinding. The difference is that the abrasive particles are moved through the material by water rather than by a solid wheel.

As a consequence of the aforemantioned development, the demand for an increased finish and working precision has increased. In many cutting operations there is a set of conditions at which one of the performance indicators of the cutting results at its maximum. Increasing or decreasing the value of one of the parameters will decrease the value of the considered performance indicator. For example, increase of cutting speed will increase amount of removed material from the workpiece, and, on other hand their decrease will increase the workpiece quality. Therefore, finding the balance between the cutting speed, which has a direct relation with the machining cost, and the required quality has to be found in AWJ cutting [4].

The AWJ is a complex machining process for contour cutting which has been continuously developed and researched. In past years, a number of experimental studies were conducted so as to analyze the effects of process parameters on performance indicators such as quality, productivity, cost and some specific process performance indicators. Xu and Wang [5] investigated the effects of process parameters on surface roughness, depth of cut and kerf taper in AWJ cutting of alumina ceramics with controlled nozzle oscillation. Karakurt *et al.* [6] investigated the effects of process parameters on kerf taper angle in AWJ cutting of the granite. The design philosophy of Taguchi was followed to conduct experiments while analysis of variance was used to determine the major significant process parameters. Barcik *et al.* [7] analyzed the AWJ cutting of medium density fireboards and studied the effects of process parameters on kerf width. Vundavilli *et al.* [8] developed fuzzy logic-based expert system for prediction of depth of cut. The training data was generated artificially (at random) with the help of response equations obtained through the regression analysis. Ushasta *et al.* [9] studied variation of the depth of cut with respect to changes in water pressure, abrasive flow rate, traverse speed and standoff distance. Optimum condition of control parameter setting was also searched through particle swarm optimization. Hlavac *et al.* [10] conducted an experimental research aimed at investigation of the taper formation. The experiments were performed on three sets of steel plates with thicknesses of 30 mm. Kumar *et al.* [11] studied the topography as well as the roughness of the surfaces in friction stir welded joints, machined by AWJ. It has been observed that the surface topography of AWJ-cut surface is not affected by the rotational speed of the tool. An experimental analysis of surface roughness, striation zone and striation angle in AWJ cutting of Al/SiC/Al_2O_3 composite was performed by Santhanakumar *et al.* [12]. The water pressure, traverse speed, abrasive flow rate and stand-off distance were considered as input parameters. Determination of optimal conditions was based on the use of grey theory based response surface methodology. Yuvaraj and Kumar [13] investigated 3-D surface topography and 2-D roughness profiles, and micrographs in AWJ cutting of AISI D2 steel by varying water jet pressures and jet impact angles. The results indicated that the jet impact angle of 70° maintained better surface integrity of D2 steel than normal jet impact angle of 90°. Recently, Wang *et al.* [14] proposed kerf profile characterization by a mathematical model instead of a taper angle. The experimental investigation revealed that the kerf profile can be fitted well with a real parabolic curve. Energy transfer efficiency analysis of the AWJ cutting was studied by Paul *et al.* [15] and Hoogstrate *et al.* [16]. Paul *et al.* [15] determined analytical mathematical models for stress wave energy associated with a single impact by an abrasive particle (non-spherical with sharp cutting edges) at any angle of impact in relation to the AWJ cutting of brittle materials. In the case of high pressure (over 400 MPa) AWJ cutting, Hoogstrate *et al.* [16] observed that there exists an optimum abrasive load ratio, is independent of the water pressure, above which the cutting ability of the jet decreases due to the less efficient power transfer from water jet to the abrasives.

From the review of recent experimental studies, it could be observed that the recent experimental researches applied different methodologies for establishing relationships between AWJ process parameters and performance indicators, particularly geometrical characteristics of the cut such as kerf width and kerf taper, quality characteristics of the cut such as surface roughness, and specific process performance indicators such as depth of cut. However, there is a lack of research regarding the analysis of the effects of process parameters on other process performance indicators such as the specific cutting energy which shows the amount of energy required to remove volume of material in unit time. In this regard the present study aimed at experimental investigation of the AWJ cutting of Al alloy and development of a mathematical model for the estimation of specific cutting energy as a function of different process parameters.

Experimental details and applied methods

Process optimization, as a background of its successful application, is provided by correct choice of influencing process parameters. First step toward to this goal is identification and understanding of process influencing parameters. Effectiveness, accuracy, and quality of the cutting process depend on a wide range of parameters and technological effects of these parameters. These parameters can be classified according to fig. 1.

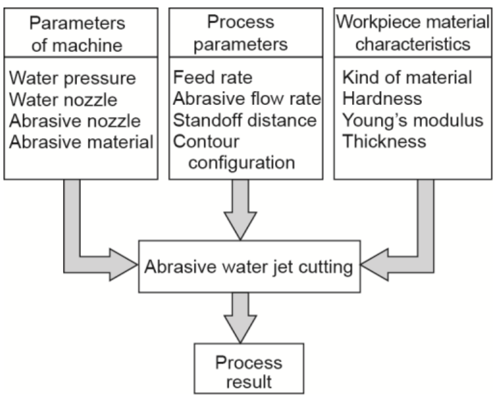


Figure 1. Parameters of AWJ cutting process

Although AWJ cutting involves a large number of parameters and virtually all these variables affect the cutting results (geometry and surface quality of cuts, material removal rate, separation cutting speed, productivity, costs), only few major and easy-to-adjust dynamic variables were considered in the present study. Those are: feed rate, material thickness, and abrasive flow rate. The other process parameters were kept constant using the standard machine configuration. Feed rate (cutting speed) is the speed of the relative movement of the cutting head relative to the workpiece. The feed rate is an important parameter of this technology because it affects the quality of the cut and amount of removed material. Also, it depends on the type and thickness of material being cut, and the desired cut quality.

The abrasive flow rate is the amount of abrasive material per unit of time, which is added to water jet, for mixing and forming AWJ. In the newer machines abrasive flow can be regulated during operation, specified by the program. Higher flow rates lead to higher productivity and better quality of the cut, but with the increased processing costs. Depending on the desired productivity and quality of cut, in practice, abrasive flow rate takes values between Q = 300 g per minute and Q = 400 g per minute.

Experimental set-up and data collection

A series of water jet cutting experiments were conducted using a Byjet 4022 AWJ cutting machine (manufacturer Bystronic AG, Switzerland). It is equipped with a dual intensifier high output pump with power of 37 kW and a five axis positioning system. The machine was used to cut 40 mm long slots on 700 × 50 mm test speciments with thickness of 6 mm, 8 mm, and 10 mm. The major characteristics of the water jet cutting machine are listed in tab. 1.

Table 1. Experimental set-up

Byjet 4022 AWJ cutting machine characteristics			
Working area for sheet processing	x = 3000 mm, y = 1500 mm, z = 230 mm	Machine tolerance	± 0.08 mm
Number of cutting heads	1 to 4	Abrasive flow rate	0 to 600 g per minute
Maximum operating pressure	413 MPa	Water supply volume	0 – 5 L per minute
Main process parameters			
Constant factors	Values	Variable factors	Values
Water pressure, p	380 MPa	Material thickness, s	6, 8, and 10 mm
Water orifice diameter, d_0	0.30 mm		
Abrasive nozzle diameter, d_A	1.02 mm	Abrasive flow rate, Q	300, 350, and 400 g per minute
Stand-off distance, z	2 mm		
Impact angle, α	90°	Feed rate, v 200, 300, 400, 500, 800 and 1000 mm per minute	
Abrasive material	GMA Australian garnet mesh #80		
Workpiece material: aluminum alloy AA 6060 (EN AW-6060; ISO Al MgSi)			
Nominal chemical composition: Si 0.30-0.60%, Fe 0.10-0.30%, Cu max. 0.10%, Mn max. 0.10 %, Mg 0.35-0.60 %, Zn max. 0.15%, Ti max. 0.10%, Cr max. 0.05% Mechanical properties: ultimate tensile strength, R_m = 205 MPa, yield strength R_p = 170 MPa, percent elongation A = 12%, Hardness 60 HB			

As workpiece material, aluminum alloy AA-ASTM 6060 (EN AW-6060; ISO AlMgSi) was used. Alloy 6060 is one of the most popular of the 6XXX series alloys. Typical uses include architectural sections, sections fit for forming processes, automotive parts, and sports equipment. It offers good finishing characteristics and responds well to anodizing. The aluminum alloy was chosen as a workpiece material because the material is very attractive, possesses resistance to corrosion and can provide significant value for the end user. Also, aluminum and its alloys are characterized by high reflectivity and thermal conductivity. This makes them relatively difficult to cut with lasers. The AWJ cutting, which does not create an observable heat affected zone, is much more useful for cutting aluminum for modern applications. The chemical composition and mechanical properties of AWJ-machined aluminum alloy is listed in tab. 1.

As a result of interaction of AWJ and workpiece material a through cut is generated. The geometry of this kerf is a characteristic of major interest in AWJ cutting process, in terms of the cut quality and quantity of the material being taken away from the workpiece [17]. A top and bottom kerf widths were measured from the optical microscope images with 40 times magnification, equipped with a CMOS camera and USB connection to a PC, fig. 2. Camera sensor size is 1/2 inch, a resolution of 1280 × 1024 dots and wide field of view of 5.4 mm.

The top kerf is commonly wider than the bottom due to the decrease in AWJ power (energy) as a unique feature of AWJ technology. As a result of this, a taper is produced. The large kerf taper ratio worsens the perpendicularity of the straightness of the cutting cross-section, resulting in an inaccurate dimensional quality.

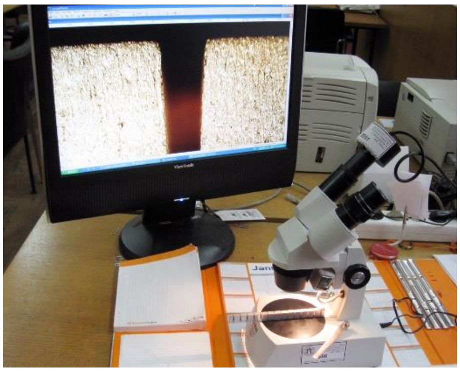


Figure 2. Optical microscope with CMOS camera

Specific cutting energy

The AWJ cutting process can be divided into subsequent steps.

- Transformation of the potential energy of water under high pressure into kinetic energy of a water jet.
- Transfer of a part of the kinetic energy of the high-speed water jet to abrasive particles by accelerating them and focusing the resulting AWJ.
- Use of the kinetic energy of the abrasive particles and water jet to remove small chips of the work material.

In the AWJ cutting process the energy required for cutting materials is obtained by pressurizing water to high pressures (usually up to 600 MPa) and then forming a high-intensity stream of water by focusing through a small orifice [18].

When the pressurized water comes out from the orifice, a water jet is created. The result is a very thin, extremely high velocity water jet. The speed of this water jet can be determined using the Bernoulli's formula. Bernoulli's equation is the law of conservation of energy applied to an ideal fluid:

$$p+\frac{\rho_\mathrm{w}v_\mathrm{w}}{2}+\rho_\mathrm{w}\mathrm{g}h=\mathrm{const.} \tag{1}$$

where p is the water pressure, v_w – the velocity of water, ρ_w – the density of water, g – the acceleration due to gravity, and h – the height of the observed points above the reference plane.

By observing the leakage of high pressure water jets in the air and using eq. (1), one can determine the leakage velocity of water jet from a nozzle based on water pressure. If one ignores the difference in altitude (several millimeters) and assuming that the speed of the water on nozzle entrance is negligible compared to the speed of the jet at the nozzle exit (several hundred times), and the atmospheric pressure is much smaller than the water pressure at the entrance to the nozzle (400 MPa), one gets the equation for calculating the velocity of the water jet after exiting the water nozzle:

$$v_{wj} = \sqrt{\frac{2p}{\rho_{\mathrm{w}}}} \tag{2}$$

Speed of water jet is critical because the water jet serves primarily as an energy transmission medium for accelerating the particle of abrasive material. By adding small particles of very hard abrasive materials in the pure water jet, AWJ is formed. The AWJ has enough energy to get through the solid material. Insertion of the abrasive particles into the water flow is carried into the mixing chamber, a part of cutting head. Predetermined quantities of abrasive particles are introduced into the mixing chamber. During mixing process, the abrasive particles are gradually accelerated due to transfer of momentum from the water phase to abrasive phase and when the jet finally leaves the cutting head, phases, water and abrasive, are assumed to be at same velocity. The higher the speed with which the solid particles hit against the material to be cut, the higher the removal rate is.

The law of conservation of momentum shows that the total momentum of any closed system, *i. e.*, the vector sum of the momentum vectors of all the constitutive factors 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 AWJ. 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:

$$Q_{\mathrm{w}} v_{\mathrm{wj}} + Q v_{\mathrm{a}} = (Q_{\mathrm{w}} + Q) v_{\mathrm{awj}} \Rightarrow v_{\mathrm{awj}} = \frac{Q_{\mathrm{w}}}{Q_{\mathrm{w}} + Q} v_{\mathrm{wj}} \tag{3}$$

$$v_{\mathrm{awj}} = \frac{v_{\mathrm{wj}}}{1 + \dfrac{Q}{Q_{\mathrm{w}}}} \tag{4}$$

where Q_{w} [g per minute] is the water flow rate, Q [g per minute] – the abrasive flow rate, v_{wj} [mm per minute] – the speed of pure water jet, v_{a} [mm per minute] – the speed of abrasive particles, and v_{awj} [mm per minute] – the speed of AWJ.

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

$$v_{\mathrm{awj}} = \eta \frac{v_{\mathrm{wj}}}{1 + \dfrac{Q}{Q_{\mathrm{w}}}} \tag{5}$$

where η is the momentum loss factor, whose values lies around 0.65-0.85 [19].

The abrasive flow rate determines the number of impacting abrasive particles as well as their kinetic energies. The power of the AWj, E_{awj}, can then be expressed:

$$E_{\mathrm{awj}} = \frac{1}{2} Q v_{\mathrm{awj}}^2 = \frac{1}{2} Q^{\eta^2} \frac{v_{\mathrm{wj}}^2}{\left(1 + \dfrac{Q}{Q_{\mathrm{w}}}\right)^2} \tag{6}$$

Combination of eqs. (2) and (6) gives power of AWJ, needed to overcome the fracture energy of the material in order to damage (cut) workpiece material:

$$E_{\mathrm{awj}} = \frac{1}{2} Q \eta^2 \frac{2p}{\rho_{\mathrm{w}}} \frac{Q_{\mathrm{wj}}^2}{(Q_{\mathrm{wj}} + Q)^2} \tag{7}$$

In a machining process, most of the environmental impact stems from the energy consumed [20]. Therefore, the specific cutting energy is frequently used as a quantitative measure of the environmental affinity of the machining process. In this study, the goal is to calculate energy and determine the influence of process parameters on its value.

Specific cutting energy, e_c, [Jmm^{-3}] values are determined by dividing the energy of the jet by the volume of the material removed from workpiece material in unit time:

$$e_{\mathrm{c}} = \frac{E_{\mathrm{awj}}}{V'} \tag{8}$$

where V' represents volume of the material removed from workpiece material in unit time, alalso called as material removal rate, [mm^{3}s^{-1}].

In the volume calculation, kerf geometry is considered based on the measurement of the width of the cut at its top, W_{t}, and its bottom, W_{b}, side of the workpiece material, fig. 3.

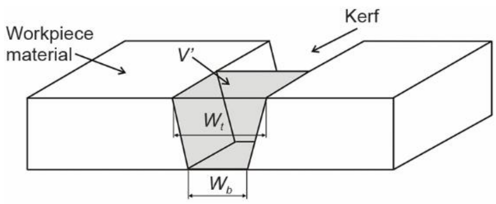


Figure 3. Volume of the material removed in unit of time, V' [mm^{3}s^{-1}]

Mathematical model for estimation of specific cutting energy

In order to calculate specific cutting energy for different sets of AWJ cutting parameters, an accurate mathematical model is needed. Considering that artificial neural networks (ANN) provide a better estimation of the parameters for the AWJ cutting process in comparison to linear and non-linear regression models [21], the specific cutting energy model was developed using ANN. The entire set of experimental results (30 trials with different combinations of feed rate and abrasive flow rate for various material thicknesses, *s*) was divided in two sets, one for ANN training (containing about 80% of the available data) and one set for testing the validity of the developed model. In order to develop the specific cutting energy model by means of ANN software package MATLAB was used.

To establish a mathematical relationship between specific cutting energy and the process parameters a standard three-layered ANN model was developed having hyperbolic tangent sigmoid and linear transfer functions in hidden-layer and output-layer, respectively. This combination of transfer functions was used since it was assumed that there exists a certain level of non-linearity in the relationship between the process parameters and the specific cutting energy [22]. Initialization of ANN hidden- and output-layer's connection weights and biases was performed according to Nguyen-Widrow initialization algorithm with random element. The Levenberg-Marquardt algorithm was used for connection weights and biases determination considering mean square error (MSE) as the optimization criterion. It was found that the 3-4-1 ANN model (model having 4 hidden neurons) provides the best data fitting capability after reaching 195 training epochs and MSE value of 0.00017.

For statistical assessment of the specific cutting energy model, absolute percentage error (APE), as one of the most stringent criteria, was used:

$$\mathrm{APE} = \left| \frac{\text{Experimental value} - \text{Predicted value}}{\text{Experimental value}} \right| \cdot 100\% \tag{9}$$

The average APE for the training and testing data were found to be 1.56% and 1.45%, respectively. These results, particularly results on validation trials, tab. 2, clearly indicate the validity and accuracy of the developed mathematical model.

Table 2. Experimental trials used for ANN model validation

s [mm]	Q [g per minute]	v [mm per minute]	e_c [Jmm^{-3}]	ANN prediction of e_c [Jmm^{-3}]	APE [%]
6	300	300	36.09	35.99	0.28
6	400	300	43.12	43.49	0.85
8	350	600	16.81	17.71	5.36
10	300	200	30.49	30.65	0.52
10	400	500	17.36	17.32	0.25

Results and discussion

The validity of the developed ANN model enabled the use of the model for the analysis of the effects of the process parameters on the specific cutting energy. Initially, the main effects of the process parameters on the specific cutting energy were analyzed by changing one parameter at a time, while keeping the other two parameters constant at center level (8 mm for material thickness, 350 g per minute for abrasive flow rate, and 600 mm per minute for cutting speed, fig. 4).

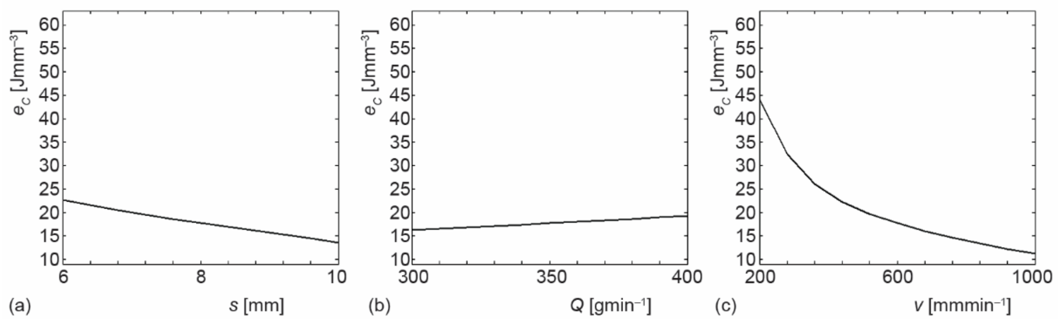
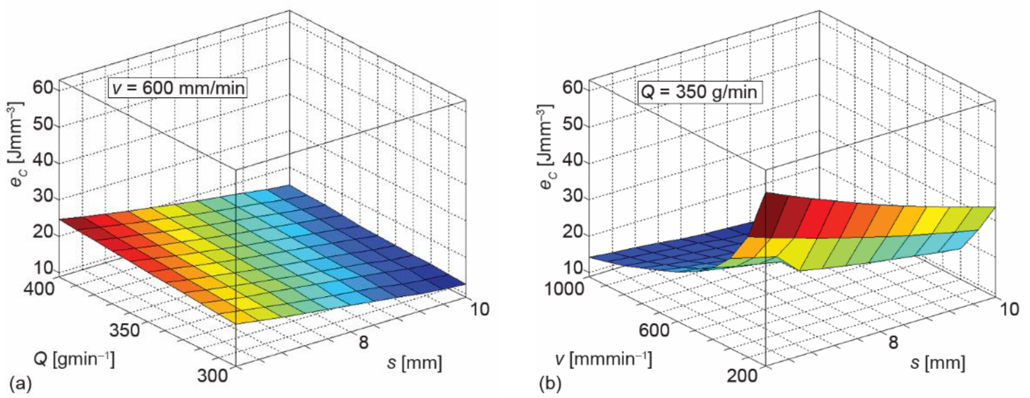


Figure 4. Effects of the process parameters on the specific cutting energy

From fig. 4 it could be observed that the most significant parameter affecting specific cutting energy is the cutting speed (feed rate), followed by material thickness and abrasive flow rate. From figs. 4(a) and 4(b) it is seen that there exists a linear relationship between specific cutting energy and material thickness and abrasive mass-flow. On the other hand, strong non-linear relationship is evident in the case of the effects of cutting speed on the change in specific cutting energy, fig. 4(c).

From fig. 4(a) it can be seen that the increase in material thickness results in decrease in the specific cutting energy as a consequence of higher volumetric materials removal rates. From fig. 4(b) it can be seen that the ductile materials are sensitive on number of abrasive particles that hit workpiece surface. By increase of abrasive flow rate the larger number of abrasive particles is involved in the cutting process, which results in increase of the specific cutting energy. The increase in cutting speed significantly affects specific cutting energy due to significant effect on the volume of the removed material. Cutting speed has a negative effect on both the top and bottom kerf widths, because a faster passing of AWJ allows fewer abrasives to strike on the workpiece material and hence generates a narrower slot.

In order to analyze interaction effects of the process parameters on the specific cutting energy, three 3-D surface plots were generated considering two parameters at a time, while the third parameter was kept constant at center level, fig. 5.



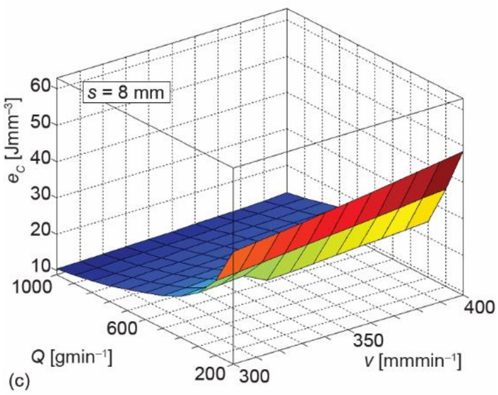


Figure 5. Interaction effects of the process parameters on the specific cutting energy (*for color image see journal web site*)

It could be observed from fig. 5(a), that, in accordance with the already observed individual effects of material thickness and abrasive flow rate, and their interaction effect also does not lead to significant changes in the specific cutting energy. It should be noted that the application of the AWJ cutting is applicable or suitable for processing and considerably larger thicknesses than those investigated and the impact of the thickness of the workpiece would be more significant. The small change obtained in the specific cutting energy is due to the relatively small material thickness relative to the one that this technology can process, but in accordance with the already adopted principle of testing on the samples most commonly encountered in the production practice, these thickness values are selected.

As shown in fig. 5(b), the effect of the cutting speed on the specific cutting energy is variable and is dependable on the material thickness. Generally, an increase in the cutting speed reduces the specific cutting energy. However, in the case of smaller material thicknesses, the increase in the cutting speed results in greater decrease in the specific cutting speed, which is due to the fact that one has at disposal a greater amount of energy than the one needed to achieve a complete cut. Since the material thickness is smaller, the value of the critical specific energy is great, and this allows cutting using higher speeds where very small values of the specific cutting energy are obtained (around 10 J/mm^3).

In order to select the cutting rates to be considered in the analysis and modeling of AWJ cutting, previous studies were carried out to determine the cut-through speed at which the separation of the machining material is still going along the entire length of the processing – creating a complete cut. The cutting speed (feed rate) was gradually increased until the value at which did not produce a cut along the entire thickness of the workpiece material. These feed rates (1200 mm per minute for a workpiece material thickness of 10 mm, and 2100 mm per minute for a workpiece material thickness of 6 mm) correspond to a specific cutting energy less than 10 J/mm^3). Although, from the energy side of the viewpoint, processing at these cutting speeds is most effective, there are other requirements as well, such as cut geometry or surface roughness.

In the abrasive mass-flow and the cutting speed interaction plot, fig. 5(c), it can be seen that increase in the cutting speed consistently decreases the specific cutting energy, whereas the effect of the abrasive mass-flow on the specific cutting energy is negligible and this may be due to narrow change interval of this parameter.

Conclusion

In the last decade, AWJ cutting technology shows rapid development, due to its many advantages over traditional processing methods and the possibility of extending to new fields of application. In addition, this technology can be described as *ecological* or *clean*, because the main materials used in the machining process (water and sand) are inert and environmentally harmless, as well as due to absence of airborne dust particles, smoke, and gases. In a machining process, many of the environmental impact stems from the energy consumed. Therefore, the specific cutting energy is frequently used as a quantitative measure of the environmental affinity of the machining process.

In this study, the cutting ability, kerf geometries of the machined surfaces and amount of energy used in terms of process parameters in AWJ cutting of aluminum alloy were investigated experimentally. From the analysis of main results, in the covered experimental hyperspace, the following concussions may be drawn.

- The cutting speed is the most significant process parameter, and an increase of the cutting speed results in the non-linear decrease of the specific cutting energy, whereby this decrease is more pronounced in the case of lower material thicknesses.

- The specific cutting energy is less sensitive to the changes in abrasive mass-flow and material thickness and this may be due to narrower changer intervals of these parameters.
- Different cutting regimes, in which full trough cut was achieved, have drastically different specific cutting energy values which indicates that certain changes in main process parameter values significantly affect the energy utilization degree in AWJ cutting.
- The ANN model trained with Levenberg-Marquardt algorithm proved to be successful for modeling the relationships between process parameters and specific cutting energy in the AWJ cutting.

The efficient and effective application of the AWJ cutting technology implies, in a wider context, consideration of a number of performance indicators such as quality criteria, both surface roughness and dimensional, productivity, cutting time, cutting cost, and also energy consumption for the realization of the given cutting process. An increase or decrease in the process parameter values will differently affect process indicators which necessitates of making balance between process indicators through process modeling and optimization. In this regards, the developed mathematical model for estimation of the specific cutting energy can be used as objective function in the formulation of different optimization problems with the ultimate aim at ensuring efficient energy used as well as satisfaction of other important performance indicators.

Acknowledgment

This work was carried out within the project TR 35034, financially supported by the Ministry of Science and Technological Development of the Republic of Serbia.

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Paper submitted: March 14, 2018
Paper revised: July 24, 2018
Paper accepted: July 26, 2018