Connection Between the Dynamic Character of the Cutting Force and Machined Surface in Abrasive Waterjet Machining

Jelena Baralić[1] ✉ – Suzana Petrović Savić[2] – Branko Koprivica[1] – Stefan Đurić[2]

1 University of Kragujevac, Faculty of Technical Sciences Čačak, Serbia

2 University of Kragujevac, Faculty of Engineering, Serbia

✉ jelena.baralic@ftn.kg.ac.rs

Abstract *This paper presents the results of research on the effect of traverse speed on cutting forces and machined surface in abrasive water jet machining. The results indicated that there is a significant connection between the dynamic character of the cutting force in abrasive waterjet machining, namely, peaks in the cutting force signal, with the appearance of irregularities and uncut parts in the machined surface. Also, the research showed that the increase of the traverse speed produces an increase in the mean value of the static component of the cutting force. In experiments, the vertical component of the cutting force has been measured for an Aluminium AlMg3 12 mm thick rod cut at traverse speeds from 900 mm/min to 1100 mm/min. Cutting with higher traverse speeds yields more irregularities, which are connected with the appearance of peaks in the measured cutting force.*

Keywords *abrasive water jet, cutting force, traverse speed, machined surface*

Highlights:

- *Developed experimental setup for measuring AWJ cutting force.*
- *Proposed a new method for calculating AWJ cutting force.*
- *Analysed the effect of cutting force on machined surface.*
- *Analysed the effect of traverse speed on cutting force.*

1 INTRODUCTION

With the development of new materials such as ceramics, reinforced and composite materials and heat-sensitive alloys, the problem of their machining has arisen. For machining of some new materials, high cutting forces or low clamping forces are required. Some materials must be machined so that high temperatures do not occur in the cutting zone. Hence, there has been an increasing use of an abrasive water jet (AWJ) in the machining of new materials. Almost all types of materials can be cut with AWJ [1]. It is widely used in the contour cutting of materials and the machining of materials that are difficult to process [2]. A great advantage of this machining procedure is that contour cutting becomes very easy, no matter how complex the contour [3].

The AWJ machining process consists of several complex processes (formation of pressurised water, mixing of pressurised water and abrasive, erosion of machined material and others). A short overview of this AWJ cutting technology, with emphasis on the cutting forces, will be given.

AWJ machining is an unconventional process of recent date, which has been the subject of much research during the last two decades. The output of the AWJ machining process is a machined surface. In order to ensure the good quality of the machined surface and detect errors, it is necessary to monitor and control the AWJ process. That is why numerous experimental studies on process monitoring, such as monitoring of cutting forces [4] and [5], monitoring through acoustic and vibration signals [6] and [7] are currently being carried out. An overview of these monitoring methods will also be given. When cutting with an AWJ at high traverse speeds, there is an increase in the value of the roughness parameters of the cut surface, especially in the zone where the AWJ exits the machined material. Increasing the traverse speed results in decreasing the depth of the cut [8]. Depending on the traverse speed, occasionally the material is not completely cut. However, this important subject has not yet been thoroughly investigated.

Previous research of cutting forces in AWJ machining have dealt with the development of a universal system for measuring the cutting force [4] and [9], using the cutting force to determine some parameters of the kerf geometry (mainly the maximum depth of cut) [10]. However, there are very few works on this subject regarding the modelling.

In this paper, a simple mathematical model for the calculation of the cutting force is proposed. The equation for calculating the cutting force in conventional cutting is applied to AWJ machining and the abrasive water jet itself is represented as a cutting tool. When there is an incomplete cut of the material, the cutting force increases, because then the jet acts on the material of the workpiece with its entire surface, that is, the cross-sectional area of the chip is a maximum.

For the purpose of investigation of the variation of the cutting force with the traverse speed also at higher traverse speeds, a specific system for measuring the cutting force has been developed. Thus, this paper presents the experimental setup for force measurement based on a personal computer (PC), the measurement results, along with their discussion and important observations.

In their research, many authors have used the vertical component of the cutting force as the main parameter for monitoring and evaluating the AWJ cutting process. Kovačević [11] measured the vertical force component when cutting with the AWJ. A three-component dynamometer was used to measure the vertical component force. The vertical component of the cutting force was

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measured for different values of the AWJ machining parameters. The aim of the research was to control the depth of cut based on the signal of the vertical force component. A precisely controlled depth of cut is very important when milling with the AWJ, i.e. engraving contours in the material. Measurements showed that the vertical component of the cutting force increases with increasing water pressure, nozzle diameter and abrasive mass flow rate. Also, it was found that it decreases with increasing standoff distance. Large oscillations in the values of the vertical force component indicated wear of the nozzle and that the maximum depth of cut had been reached.

In further research, Kovačević et al. [9] used the same principle for measuring the vertical cutting force component as in the previous work, with the aim of investigating the possibility of connecting the dynamic characteristics of the cutting force with the profile of the machined surface. Various parameters of the AWJ machining process were varied: water pressure, traverse speed, abrasive flow rate and standoff distance, in order to determine their effect on the cutting force and profile of the machined surface. It was found that both the abrasive flow rate and traverse speed have a slight effect on the vertical component of the cutting force. The influence of the AWJ machining parameters on the cutting force was analysed using stochastic modelling of the force data. Autoregressive moving average (ARMA) models are suitable for processing the results of measuring the vertical component of the cutting force for different values of the machining parameters. It was observed that the spectral density of the dynamic force ARMA model behaves in the same way as the measured profile of the machined surface. Based on this, they concluded that the signal of the vertical component of the cutting force can be considered as a potential parameter for the monitoring of the surface profile at the deformation wear zone.

Hassan et al. [10] proposed a model for monitoring the depth of cut during abrasive waterjet machining based on acoustic emission (AE) monitoring. The aim was to establish the dependence between these two parameters, so that the depth of the cut could be predicted based on the AE. Carbon steel AISI 1018 was used as a workpiece. The cut length of the samples was 38 mm to ensure a steady-state of cutting. During cutting, the working pressure values were varied from 100 MPa to 350 MPa. The vertical component of the cutting force was measured for all values of the working pressure, and the AE was also monitored. For all cuts, the mean value of the cutting force and the root mean square of the acoustic emission energy (AErms) for steady-state of cutting were calculated. It was observed that AErms increases linearly with an increase in the depth of cut and could be used for its on-line monitoring [10]. Hlavač et al. [4] constructed a special device for cutting force measurements during machining with AWJ. They monitored the signal of the cutting force in the normal and tangential directions before the start of cutting and during the cutting of the material. The workpieces were made of different materials, such as steels, duralumin, copper, and brass. The cutting of the workpiece was done in different modes. Also, the cutting was performed both with and without rotation of the cutting head. The tangential-to-normal force ratio (TNR) was taken as the most appropriate indicator for monitoring the cutting force and the quality of the machined surface. It was observed that the TNR reaches its maximum value at approximately 50 % of the maximum value of the traverse speed. Hlavač et al. [5] used the same measuring device as in [4], only the obtained signal of the vertical component of the cutting force was used for the detection of irregularities during cutting with AWJ, i.e. for the detection of incomplete cutting of the material.

Orbanić et al. [12] measured the diameter of the AWJ. A hard metal insert was the workpiece. During machining, the cutting force signal was monitored. Three characteristic areas can be observed on the obtained diagram of the cutting force: The first one was where the cutting force is equal to zero - the contact of the jet and the insert has not yet occurred. The second one is where the force increases - the jet comes into contact with the insert and the contact surface increases. The third one is where the force has stabilised - the whole jet is on the insert. The Vishay Transducers 1022 load cell was used to measure the vertical force component. Based on the change in the value of the vertical component of the force and the traverse speed, the diameter of the jet was calculated.

Momber [13] analysed the efficiency of the energy transformation using measurements of the vertical component of the cutting force. A Kistler dynamometer, model 9273, was used to measure the vertical component of the force. It was shown that the forces exerted by the high-speed jet on the workpiece can be successfully used to analyse the energy dissipation process during the formation of high-speed water-jets and during the mixing and acceleration of solid particles and air by high-speed waterjet (during the formation of the AWJ).

Baralić and Nedić [14] measured the cutting force using a three-component dynamometer for turning, KISTLER Type 9265A1, for samples of X5CrNi 18-10 with various thicknesses. The aim was to investigate the influence of the AWJ machining parameters (traverse speed, operating pressure, abrasive mass flow and material thickness) on the cutting force. It was found that an increase in the operating pressure leads to an increase of the cutting force. The effect of the abrasive mass flow on the cutting force is almost negligible, while an increase of the traverse speed, as well as an increase of the thickness of the material being machined, leads to an increase of the cutting force.

In the literature, there is no simple model for expressing the relation of the cutting force, as the significant output parameter of the system that can be measured, and the traverse speed as the input parameter that is set before the cutting of the material. Furthermore, the relation between these two quantities has not yet been thoroughly investigated for higher traverse speeds, when irregular cuts appear, as well as peaks in the cutting force. The present paper focuses on these shortcomings, with the goal of establishing a simplified $F_v(v_c)$ model, measure accurately the cutting force at higher traverse speeds, analyse the peaks in the cutting force in relation to the roughness of the surface, and validate the $F_v(v_c)$ model for the peak values of the cutting force. This paper contributes to the state of the art in the field by introducing a new $F_v(v_c)$ model and its experimental validation.

2 METHODS & MATERIALS

The main goal in today's production is to make as many products as possible in the shortest possible time and with as little investment as possible. In order to make this possible when machining with an AWJ, it is necessary to perform the machining with the highest possible traverse speeds. Machining with a high traverse speed results in an increase in the roughness parameters of the machined surface. This phenomenon is significantly expressed in the rough zone of the machined surface, that is, at the exit of the AWJ from the workpiece [15]. When the maximum traverse speed with which it is possible to completely cut materials of a certain thickness, is reached, the process of cutting with the AWJ becomes unstable and the material is, occasionally, not completely cut. The assumption is that in places where the material has not been completely cut, there is a sudden increase in the vertical component of the cutting force.

In the case that material is not completely cut, in practice the traverse speed is most often changed (reduced). The abrasive mass flow rate is rarely changed, and the operating pressure is almost never changed. Therefore, the influence of traverse speed on cutting force was analysed, even though the process of machining itself is influenced by numerous factors.

2.1 Proposed Model for Calculation of Cutting Force in AWJ Machining

During its movement through the machined material, the AWJ acts on the material with some force. This force has the same direction as the speed of the AWJ, that is, it is tangent to the path of the AWJ cutting front line, Fig. 1.

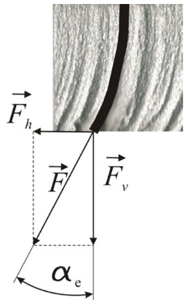

Fig. 1. Cutting force while machining with AWJ

The cutting force with which the AWJ acts on the workpiece can be divided into two components, vertical and horizontal:

$$\vec{F} = \vec{F}_v + \vec{F}_h. \tag{1}$$

In general, the diagram of the change of the vertical component of the cutting force F_v with time has the form as shown in Fig. 2. This diagram shows that the force F_v has its dynamic and static components. Due to the dynamic character of the AWJ machining process, the cutting force has a distinctly dynamic character. During a complete cut, the dynamic character of the cutting force is a consequence of oscillations in the values of the working pressure and the number of abrasive particles that are in contact with the object of processing. Also, a peak in the value of the cutting force can occur due to inclusions in the material of the workpiece. From Fig. 2, it can be seen that the value of the vertical cutting force component F_v increases when the AWJ starts cutting the sample.

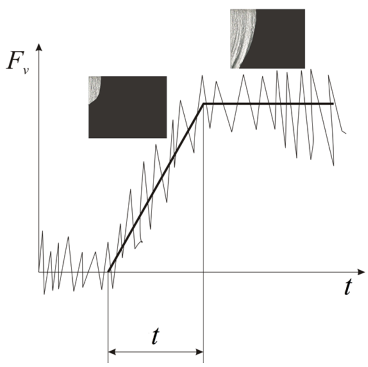

Fig. 2. Diagram of the vertical component of the cutting force, F_v

This value increases until the AWJ begins to cut completely through the entire thickness of the material. After that moment, there is no further increase in the value of the vertical cutting force component.

Abrasive particles in AWJ can be approximated by the cutting edge of a multi-cutting tool moving at a speed v_{awj} through the material being machined. At the same time, the cutting head moves at the traverse speed v_c, Fig. 3.

In a case of conventional cutting, the work W of the mechanical force F done along path L can be calculated in a simplified form as:

$$W = F L, \tag{2}$$

for a constant force along a straight path and when the force has the direction of the path. This work, during the cutting with the AWJ, can be equated with the cutting energy of the water jet, E_{awj}. Thus, the force can be determined by this energy,

$$F = \frac{E_{awj}}{L} = \frac{E_c V}{L}, \tag{3}$$

where E_c is the specific cutting energy of AWJ machining, V is the volume of removed material, and L is the length of the arc of the cutting front line. It is the length over which the cutting force acts (chip length).

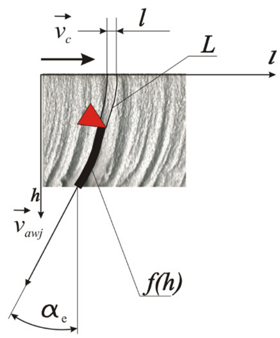

Fig. 3. Approximation of the abrasive water jet machining process

The volume of removed material can be calculated using Eq. (4).

$$V = L\,l\,w_m. \tag{4}$$

The mean width of the cut w_m is the mean value of w_{en} and w_{ex}, the width of cut at the entry of the AWJ into the material being machined and the width of the cut at the exit of the AWJ from the material, respectively:

$$w_m = \frac{w_{en} + w_{ex}}{2}. \tag{5}$$

The path of the cutting head, while the AWJ removes the material along a single striation (cut the forehead through the whole material thickness) is l, according to Fig. 3 it is equal to:

$$l = v_c t, \quad t = \frac{L}{v_{awj}}. \tag{6}$$

According to Eqs. (4) to (6), it follows that the volume of removed material V is:

$$V = L^2 w_m \frac{v_c}{v_{awj}}. \tag{7}$$

By substituting the equations for calculating the volume of removed material into Eq. (3), the equation for calculating the cutting force can be written in the form:

$$F = E_c L w_m \frac{v_c}{v_{awj}}. \tag{8}$$

In Eq. (8), the most influential factor is the traverse speed v_c. The dependence of the cutting force on the traverse speed can be approximately represented as linear. It can be concluded that with an increase in the traverse speed, there is an increase in the value of the cutting force, i.e. the vertical component of the cutting force. The biggest peak in the cutting force occurs when the material of the workpiece is not completely cut, because then the AWJ acts with its entire surface of the machined material.

According to Fig. 1 and Eq. (1), the vertical component of the cutting force, F_v, can be calculated by:

$$F_v = F \cos\alpha_e = E_c L w_m \frac{v_c}{v_{awj}} \cos\alpha_e. \tag{9}$$

where α_e is the angle of the tangent of the cut front line.

2.2 Experimental Setup for Cutting Force Measurement

The phenomenon that when the cutting with an abrasive water jet does not completely cut through the material, there occur extreme values in the cutting force signal (peaks) and pronounced roughness of the obtained cut surface imposes the need for specific research.

Accordingly, the research presented in this paper has focused on the connection between the dynamic character of cutting forces, peaks in the cutting force, and the appearance of irregularities and uncut parts on the machined surface while machining at high traverse speeds. The experimental measurements of the cutting force were carried out for the PTV-3.8/60 abrasive water jet machine with a KMT cutting head. The cutting was done over the water. The cutting force has been measured at traverse speeds around 1000 mm/min (much higher than usual). The maximum value of traverse speed at which a complete cut can be obtained (based on the KMT calculator) is 900 mm/min. Traverse speeds were chosen so to obtain a regular cut and a combination of regular and irregular cuts, but not complete uncut piece. Prior to the force measurement, a set of cuts was made with the same sample at different traverse speeds, from lower to higher, to determine the range of speeds that suits the purpose of the planned research. Thereafter, relevant set of cuts and cutting force measurement were done in the range of traverse speeds of interest. Other parameters of the machining process were constant during AWJ cutting of the samples: the operating pressure was 4130 bar, abrasive mass flow rate 350 g/min, standoff distance x_o was 3 mm and the abrasive was garnet mesh size 80. The water nozzle (orifice) diameter was 0.3 mm and focusing tube diameter was 1.02 mm.

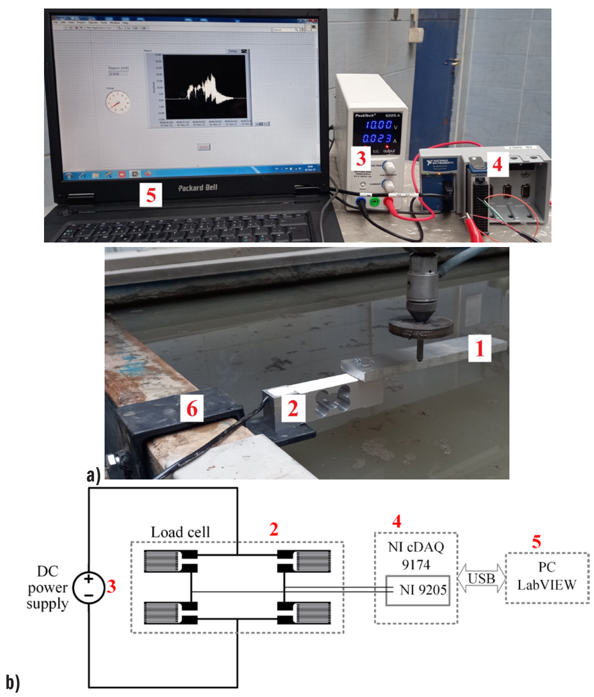

Fig. 4. Experimental setup for cutting force measurement: a) photograph of the components, b) block scheme of connections

The experimental setup for measurement of cutting force is based on a PC. It consists of the following equipment: 1) the test sample, fixedly mounted to 2) the load cell CZL623B (for 10 kg, up to approximately 100 N), 3) the direct current (DC) power supply for the load cell, 4) the data acquisition card NI 9205 (placed in the chassis NI cDAQ 9174) and 5) a PC with LabVIEW software. The load cell is fixed to 6) the steel carrier profiled so it fits well one side of the waterjet cutting machine. Fixed mounting of the carrier to the machine has been made with three large screws. A photograph of the equipment used is shown in Fig. 4a, and a block scheme of the connections is given in Fig. 4b.

The test sample is a 12 mm thick aluminium rod, 50 mm wide and 300 mm long. Aluminium is of ENAW-5754 (AlMg3) quality, the main alloying element is magnesium. Tensile strength of AlMg3 is in the range of 80 MPa to 280 MPa and Brinell Hardness (HB) from 52 to 88. It has been screwed to the load cell at one end by two screws and the other end was free. The material has been selected because of its often used in practice. The dimensions were chosen so to have a significantly long cutting path, and the thickness of the sample so as to obtain irregular cuts at higher speeds.

The load cell contains four strain gauges connected in full bridge (Fig. 4b). Its sensitivity is rated by the manufacturer at 2 mV/V for the mass of 10 kg, or in other terms it is 2mV/kg for 10 V supplied by the DC power supply. Thus, the output voltage would be 10 mV for 10 V of input voltage and 5 kilograms of the load. The data acquisition (DAQ) card NI 9205 is an analogue voltage input module of 16 bits resolution and 250 kS/s maximum sample rate (in samples per second). Its lowest input range is 200 mV. Thus, it is suitable for the measurement of low voltages from the load cell and is fast enough to observe transients. During the measurements, the DAQ card acquired 1200 S/s. This card has been inserted into a chassis NI cDAQ 9174 which provides the power supply for the card and a connection with a PC over the USB cable.

A standard DC laboratory supply of a stable DC voltage was used as the power supply for the load cell. The laptop computer was running LabVIEW 2014. A simple program for acquisition of the voltage generated at the output of the load cell has been created for the planned measurements. The program was set to continuous sample acquisition and writing the data to the computer memory.

Prior the measurements of the force of the abrasive water jet machine, the load cell was calibrated in the laboratory using precision weights and by measurement of the output voltage. The calibration has been performed using the measurement setup presented in Fig. 4b. The test sample 1, load cell 2 and steel carrier 6 were fixedly mounted to the laboratory table (similarly to Fig. 4a). Supplied DC voltage was set to 10 V. Laboratory weights of different masses, from 50 g to total 5000 g (about 49 N), were positioned on the test sample and the output voltage was recorded using the LabVIEW application. The measurement results obtained are graphically presented in Fig. 5, together with the linear fit of these data.

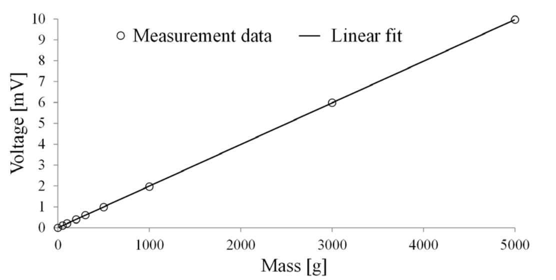

Fig. 5. Measurement data and linear fit obtained during the calibration of load cell

The slope of the linear fit is 2.001 mV/kg, which confirms the rated sensitivity of the load cell given by the manufacturer, which is 2 mV/kg.

The manufacturer also stated the accuracy of the load cell 2 % as 0.02 % of the full scale (10 kg), which is equal to 2 g of the absolute error in the whole measurement range. This corresponds to an absolute error of 4 µV at the maximal load cell output voltage (20 mV). The manufacturer of the DAQ NI 9205 stated the absolute error of 175 µV in the range of ±0.2 V.

The force F has been determined from the measured load cell output voltage u_{LC} as:

$$F = g\frac{u_{LC}}{S_{LC}} = 9.80665\frac{u_{LC}}{S_{LC}}, \tag{10}$$

where S_{LC} is the load cell sensitivity. The combined uncertainty $u_c(F)$ of force F measurement is defined according to the sensitivity coefficients, which are calculated as partial derivatives of F, and the absolute uncertainties of each independent variable, as in [16]:

$$u_c(F) = \sqrt{\left(\frac{\partial F}{\partial u_{LC}}\right)^2 u_{B,u_{LC}}^2 + \left(\frac{\partial F}{\partial S_{LC}}\right)^2 u_{B,S_{LC}}^2}, \tag{11}$$

where $u_X = |\partial F / \partial X| u_{B,X}$, $X \in \{u_{LC}, S_{LC}\}$ and $u_{B,u_{LC}}$, $u_{B,S_{LC}}$ are Type B standard uncertainty calculated by dividing corresponding absolute errors with $\sqrt{3}$, for a rectangular distribution with the confidence level of 95 %. Sensitivity coefficients are calculated for maximal voltage $u_{LC_{\max}}$ and previously calculated S_{LC}. All calculated values are given in Table 1.

Table 1. Type B uncertainty for load cell calibration at 49 N (5 kg)

Variable	$u_{LC_{\max}}$	S_{LC}
Value	9.968 mV	2 mV/kg
Absolute error	175 μV	0.4 μV/kg
Sensitivity coefficient	4903.3 N/V	−244382 kg/V
Absolute standard uncertainty u_X [N]	0.495	0. 056
Relative uncertainty [%]	1.014	0.115

The combined uncertainty value is 0.499 N and its relative value is 1.02 %. A correction factor k = 2 can be used for calculating the expanded uncertainty. In such a case, the confidence level is around 95 % and expanded uncertainty is 1.00 N or 2.04 %. The calculations need to be repeated to obtain the uncertainty for other values of the force (mass).

It should be noted that the measured values of the force are not the real ones because the cutting force is not developing coaxially to the load cell. However, this issue was not considered significant, as the bending of the steel carrier, load cell or sample was negligible, due to their robustness.

3 RESULTS AND DISCUSSION

The measurements of the cutting force have been performed at higher traverse speed to examine the relation between irregularities in the machined surface and the cutting force applied to the test sample made by the AWJ. Cuts have been performed in the longitudinal direction of the sample. The cuts were 100 mm long. One transversal cut has been made prior to all other cuts at lower speed (600 mm/min) as a trial case. Other cuts have been performed at four traverse speeds, namely: 900 mm/min, 950 mm/min, 1000 mm/min and 1100 mm/min.

A comparison of the forces obtained for 600 mm/min and 900 mm/min is presented in Fig. 6. Both traverse speeds are low enough that the cutting through the material is regular.

The light grey line in Fig. 6 represents the original measured data, whereas the blue and orange lines represent the smoothed measured data (obtained using the built-in function Smooth of OriginLab software). The force has the same level of 5 N before and after the cutting and it increases up to 15 N for the transversal cut and up to 18 N for the longitudinal cut. Thus, both directions can be used for observing the cutting force and the quality of cutting. The longitudinal cutting contains more pronounced oscillations in the force and even significant peaks in the range from 30 N to 40 N. All that is a consequence of the higher traverse speed.

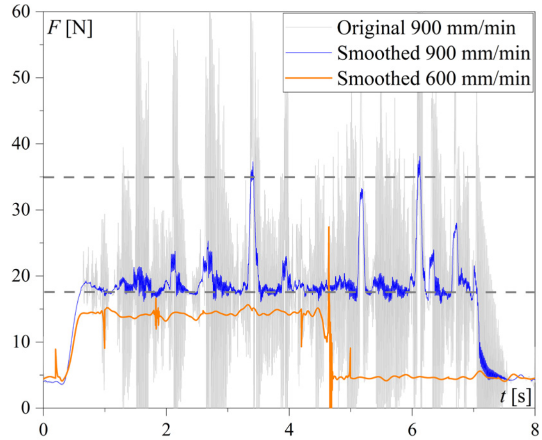

Fig. 6. Comparison of cutting force measured at lower (600 mm/min) and higher (900 mm/min) traverse speeds

Further analysis of the results will be focused on higher traverse speeds. The force profile for each of four cuts made will be discussed in detail. Photographs of the bottom and side view for each cut will be shown along with the force profile and their relation will also be discussed.

A profile of the cutting force for a traverse speed of 900 mm/min is presented in Fig. 7. The grey dashed lines represent the lower (17.5 N) and upper (35 N) cutting force limits chosen so that most of the measured data is within those limits when the cutting is correct. In Fig. 7, below the cutting force signal, there are photographs of the cut surfaces (orange box and black arrows) and a view from the underside of the cut sample (magenta box and black arrow). Green arrows and circles indicate cutting force peaks that are within (or slightly above) the upper and lower limits, which correspond to normal cutting or with irregularities of negligible size. In this case, the bottom view shows no irregularities in the cutting. Small irregularities can be seen in the side view, where the AWJ has created several cavities of small sizes. Their position corresponds to the position of the force peaks.

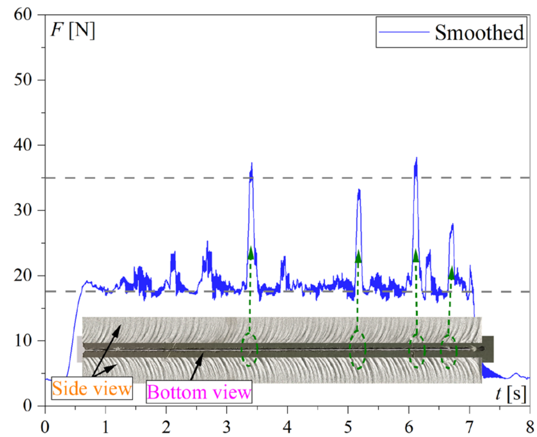

Fig. 7. Profile of cutting force for traverse speed of 900 mm/min, along with photographs of the cut

The profile of the cutting force for the next traverse speed of 950 mm/min is presented in Fig. 8. This slight increase in the traverse speed results in an increase in the number of peaks in the force profile. Still, the cutting is regular, as can be seen from the bottom view, but the number of cavities is evidently larger, and again it corresponds well to the number of peaks. Also, the size of the cavities is larger than for the lower traverse speed.

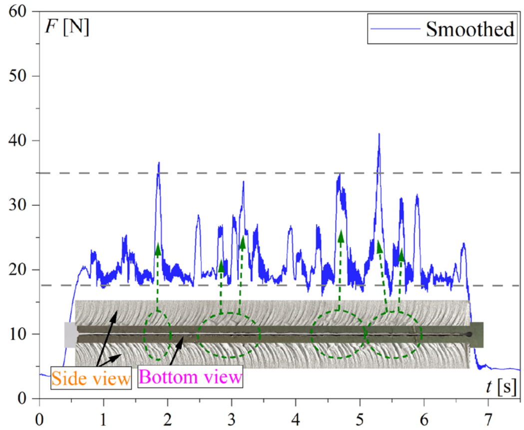

Fig. 8. Profile of cutting force for traverse speed of 950 mm/min, along with photographs of the cut

The profile of the cutting force for the third traverse speed of 1000 mm/min is presented in Fig. 9.

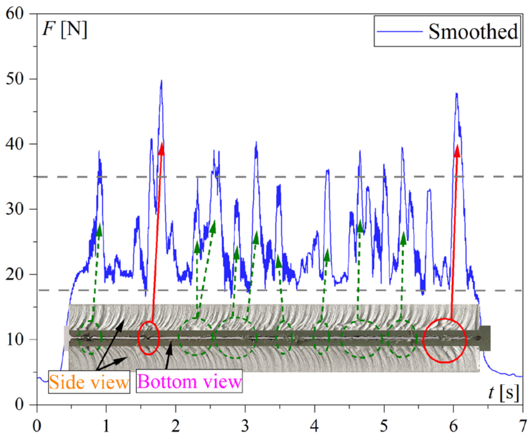

Fig. 9. Profile of cutting force for traverse speed of 1000 mm/min, along with photographs of the cut

The bottom view shows that the cutting is occasionally irregular, as there are several smaller uncut regions and regions with material remaining. Almost the whole cut is covered with cavities, as can be seen in the side view. Many smaller peaks appear in the force profile, as well as two larger peaks (marked with red arrows and circles). These two peaks appear in the places where the material remained uncut. The force reaches almost 50 N in those two cases. The number of smaller peaks above 35 N has increased from 2 in the previous two cases to 8 in this case.

Fig. 10 shows cavities on the machined surface for a traverse speed of 1000 mm/min. Small uncut triangles can also be observed. Cavities are formed when the material is not completely cut, so the AWJ reflects from the uncut material. AWJ, part of whose energy has been spent, turns into solid material, where due to insufficient energy, swirling of the AWJ and creation of cavities occurs. Jerman at al. [17] noticed this phenomenon in their study of the development of the cutting front in AWJ machining. This is due to the jet's redirection at the bottom of the cut and not a reduction in the intensity of the AWJ.

The profile of the cutting force for the last traverse speed of 1100 mm/min is presented in Fig. 11.

In this most extreme case, the cutting is mostly irregular (clearly visible in the bottom view). Some smaller or larger uncut regions exist, as well as regions with contiguous uncut parts. Two individual uncut parts in the left half have produced two individual peaks, while multiple uncut parts have produced multiple peaks (in the right side). The duration of the peak is proportional to the length of the uncut triangle. The force profile is such that the force is significantly higher than the lower limit during the whole cut. Again, force peaks reach 50 N and more for the uncut regions. Furthermore, multiple cavities can be observed in the side view of the region with multiple uncut parts. Some of the cavities are quite large and moved from the surface to the inside of the material (for up to one quarter of the thickness).

Fig. 10. Cavities on machined surface for traverse speed of 1000 mm/min

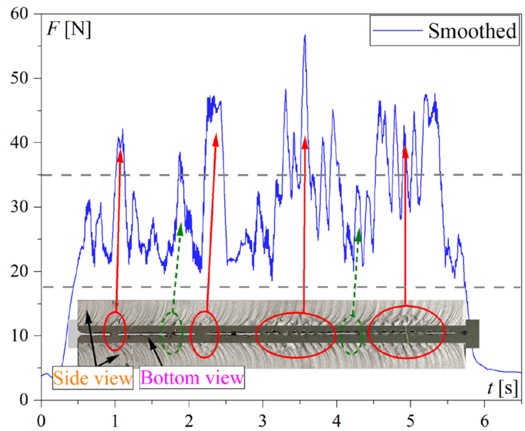

Fig. 11. Profile of a cutting force for traverse speed of 1100 mm/min, along with the photographs of the cut

A summary of the characteristic data related to all four traverse speeds is given in Table 2. It contains the following data: the traverse speed v_c, the cutting time t_c, the number of smaller peaks N_{ps}, the number of larger peaks N_{pl}, the number of uncut parts N_u and the maximum of the vertical force F_{vm} for the whole cut.

Table 2. Characteristic data for four cuts

v_c [mm/min]	t_c [s]	N_{ps}	N_{pl}	N_u	F_{vm} [N]
900	6.66	8	0	0	38.37
950	6.32	15	0	0	41.10
1000	6.00	18	3	2	49.78
1100	5.45	14	12	18	56.84

The results for the number of peaks and cuts and maximal force are related to the smoothed data. They depend slightly on the smoothing parameters, but without any significant changes in the nature of the overall force profile.

Previous research has shown that the cutting force increases with increase of the traverse speed in the range up to 100 mm/min [18], and up to 300 mm/min [19]. Also, in [5], it was shown, using the results of experiments on several different metals, that there is a connection between peaks in the value of the cutting force and uncut parts of the material.

Taking the data for traverse speed and peak of cutting force given in Table 2 and taking into account that the peak of the cutting force amounted to around 15 N for the speed of 600 mm/min (see Fig. 6), a variation of the cutting force with the traverse speed has been presented graphically in Fig. 12. All values of the force are reduced by the force made by the test sample (around 4.5 N), which exists before and after the cutting (Figs. 6 to 11).

The measured data (black dots) have been fitted with a linear function, and the result obtained is presented by a dashed blue line, along with the data. The result in Fig. 12 confirms linear relationship given by Eq. (8), when considering the cutting force peak and the traverse speed. The linear dependence of the cutting force on the cutting depth and feed also exists in conventional cutting machining [20]. When machining with AWJ, cutting depth and feed depend on traverse speed.

This simplified model could be useful for application in the practice. However, such a linear relation should be investigated experimentally also for other materials and parameters of AWJ process. Also, the relationship of the cutting force and other input parameters needs to be investigated to improve overall knowledge about AWJ process and obtain other useful calculation tools. This was out of the scope of this paper and might be a subject of a future research in this field.

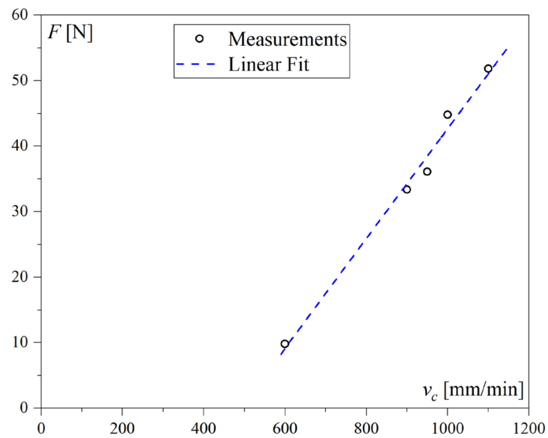

Fig. 12. Variation of cutting force with traverse speed

4 CONCLUSIONS

This paper presents the results obtained by experimental measurement of the vertical component of the cutting force, showing that measuring the vertical component of the cutting force makes it possible to observe a period when the machined material is not completely cut. Also, online measurements of the cutting force can be used for the evaluation of the quality of the machined surface.

The experimental results allow concluding that an increase of the traverse speed, above a certain limit, results in the appearance of irregularities in the cut and in an increase of the vertical component of the cutting force. Even when the cut is regular, such as for speeds of 900 mm/min and 950 mm/min, the maximum values of the vertical component of the cutting force can be more than two times larger than the lower limit. In the case of higher traverse speeds, when irregular cuts appear, the maximum values of the vertical component of the cutting force can be more than three times larger than the lower limit.

Beside the appearance of the uncut parts, smaller or larger cavities are produced in the material during cutting at high traverse speeds. These cavities significantly increase the roughness of the machined surface. Such unwanted side effects would require additional treatment of the machined surface after cutting. It can influence the quality of the final product.

The results of the conducted experiment can also be used for a better understanding of the material cutting process performed with the AWJ. There can be established a relation between the duration of the cutting force peak and the length of the uncut part, as well as their frequency. Also, based on the appearance of peaks in the profile of the vertical component of the cutting force, the beginning of cutting with an unsatisfactory quality of the machined surface can be determined.

In conventional cutting, increasing the auxiliary speed (feed) causes an increase in the cross-sectional area of the chip, and therefore the volume of the removed material, which further leads to an increase in the value of the cutting force. In this paper, machining with abrasive water jet is viewed as a classic cutting process. The abrasive water jet is represented as a cutting tool, while the cross-sectional area of material removed per unit of time is represented as a cross-sectional area of the chip. By applying the formulas valid for conventional cutting procedures, a new model was obtained for the calculation of the cutting force during machining with an abrasive water jet. This model is much simpler than the models presented in previous research by other authors. In AWJ machining, traverse speed is most often varied in practice, while operating pressure and abrasive mass flow rate are less frequently changed. In these conditions, the model presented in the paper shows that there is a linear relation between the traverse speed and cutting force. With the increase of traverse speed, there is an increase in the cross-sectional area of the chip, and therefore the volume of the removed material. This further leads to an increase in the value of the cutting force. Measurements have shown that with an increase in the traverse speed, there is an increase in the value of the cutting force, which confirmed these assumptions. To determine the cutting force for a given material and machining parameters, it is necessary to determine the specific cutting energy, which can be the subject of further research. Also, future research can deal with the influence of the operating pressure and mass flow rate on the values of the cutting force.

AWJ requires a much larger number of input parameters than considered in the conducted research. However, the focus was given to the traverse speed as input parameter and the cutting force as the output parameter to validate the model under specific conditions. It was of a particular importance to investigate if the direct proportionality of the simplified model still remains valid at higher speeds.

To apply the conclusions presented in this paper to the current manufacturing of parts using abrasive water jet technology, it is essential to develop specialized cutting tables. These tables should facilitate online monitoring of cutting force values, which could also be a subject for further research.

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Povezava med dinamičnim značajem rezalne sile in obdelano površino pri obdelavi z abrazivnim vodnim curkom

Povzetek V članku so predstavljeni rezultati raziskave o vplivu hitrosti premikanja na rezalne sile in obdelano površino pri obdelavi z abrazivnim vodnim curkom. Rezultati so pokazali, da obstaja pomembna povezava med dinamičnim značajem rezalne sile pri obdelavi z abrazivnim vodnim curkom, natančneje med vrhovi v signalu rezalne sile, ter pojavom nepravilnosti in nerazrezanih delov na obdelani površini. Prav tako je raziskava pokazala, da povečanje hitrosti pomikanja povzroči povečanje srednje vrednosti statične komponente rezalne sile. V eksperimentih je bila izmerjena navpična komponenta rezalne sile za 12 mm debelo palico iz aluminija AlMg3, rezano s hitrostmi premikanja od 900 mm/min do 1100 mm/min. Pri rezanju z večjimi hitrostmi se pojavijo večje nepravilnosti, ki so povezane s pojavom vrhov v izmerjeni rezalni sili.

Ključne besede abrazivni vodni curek, rezalna sila, prečna hitrost, obdelana površina