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EFFECT OF MACHINING PARAMETERS ON JET LAGGING IN ABRASIVE WATER JET CUTTING

Vlatko Marušić, Jelena Baralić, Bogdan Nedić, Željko Rosandić

Preliminary notes
The main characteristics of the surface machined with the abrasive water jet are the differences in surface roughness at the top and bottom of the cut and the appearance of curved lines-striations, which are characteristic for all machining processes with the concentrated stream of high energy. The curvature of these lines is the consequence of jet lagging. Jet lagging is the cause of errors in cutting of radius and sharp corners. The machining parameters have a great influence on this phenomenon. Therefore, it is necessary to know and to define the influence of machining parameters on this phenomenon. The aim of this paper is to investigate the effect of machining parameters on the jet lagging, i.e. cut front geometry. The specimens of AISI 304 were machined by the abrasive water jet under varying traverse speeds, operating pressures and abrasive mass flow rates. The jet lagging was measured at ten monitoring points by the depth of cut. Based on these results, the relationship between the jet lagging and machining parameters has been formed.

Keywords: *abrasive water jet, jet lagging, machining parameters*

Utjecaj parametara obrade na zaostajanje mlaza kod rezanja abrazivnim mlazom vode

Prethodno priopćenje
Glavne karakteristike površine obrađene abrazivnim mlazom vode su razlike u hrapavosti površine na vrhu i na dnu reza i pojava zakrivljenih linija-brazgotina koje su karakteristične za sve procese obrade s koncentriranim tokom velike energije. Zakrivljenost ovih linija je posljedica zaostajanja mlaza. Zaostajanje mlaza je uzrok grešaka pri rezanju radijusa i oštrih kutova. Parametri obrade imaju značajan utjecaj na ovu pojavu. Iz tog razloga nužno je poznavati i definirati utjecaj parametara obrade na ovu pojavu. Cilj ovog rada je istražiti utjecaj parametara obrade na zaostajanje mlaza, odnosno geometriju reza. Uzorci od AISI 304 obrađeni su abrazivnim mlazom vode različitim posmičnim brzinama, radnim tlakovima i protocima abraziva. Zaostajanje mlaza mjereno je na 10 mjernih mjesta preko dubine reza. Na temelju tih rezultata, formiran je odnos između zaostajanja mlaza i parametara obrade.

Ključne riječi: *abrazivni mlaz vode, parametri obrade, zaostajanje mlaza*

1 Introduction

When all you have is a hammer, everything looks like a nail [1]. This saying best explains our traditional view of the machining, where the cutting tools are made of hard material and must have at least one cutting edge. Over fifty years ago, a new machining procedure appeared, and the tool was quite different from the conventional understanding. In the early seventies, the first machine for this machining was produced. This procedure was the water jet machining and the tool was a clean water jet. In the eighties, this method was enhanced by adding the abrasive material into the water jet and thus a new procedure for machining (abrasive water jet machining) was created. The abrasive water jet proved to be ideal for processing of very hard and brittle materials, and easy to handle with fragile materials. It is very convenient for the design of different types of materials [2]. It is also good for machining of parts that have limitations in terms of clamping force. The abrasive water jet machining is an economic and environmentally friendly (green) process. This method is a cold processing method, and no heat affected zones or mechanical stresses are left on a water jet cut surface [3]. These are the main advantages of abrasive water jet machining compared to other non-conventional treatment processes [4].

In the abrasive water jet cutting, the tool is the abrasive water jet. The abrasive water jet is a narrow, high-speed water jet stream, formed by highlighting the small diameter water orifice. Downstream from the orifice, in the mixing chamber, abrasive particles are added in the high speed water jet. They are accelerated by momentum exchange with the high speed water jet in an abrasive nozzle. The abrasive water jet is collimated in the abrasive nozzle. From there, the abrasive water jet is directed to the work piece, Fig. 1. In the process of cutting, the abrasive water jet moves along the work piece at a definite feed rate.

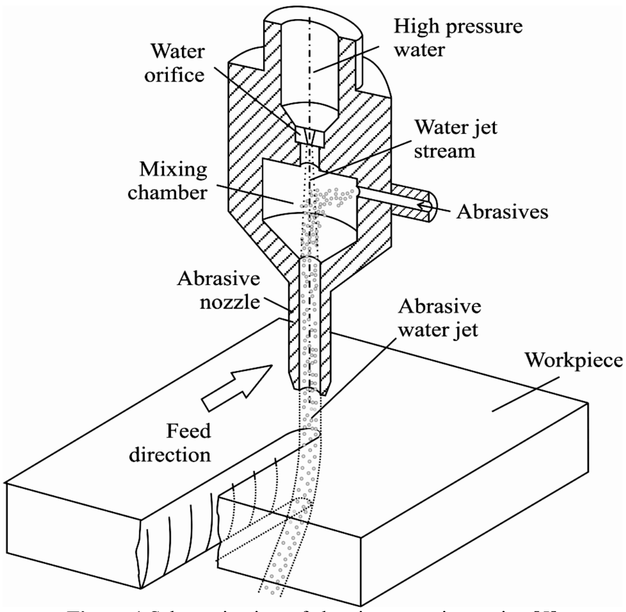


Figure 1 Schematic view of abrasive water jet cutting [5]

The cut geometry is a very complex phenomenon. It is determined by the following: machined surface roughness, taper of the cut, waviness of machined surface and appearance of the curved lines. The appearance of the curved lines is caused by the abrasive water jet lagging.

3D visualization of the cut geometry in the abrasive water jet applications is shown in Fig. 2 [6].

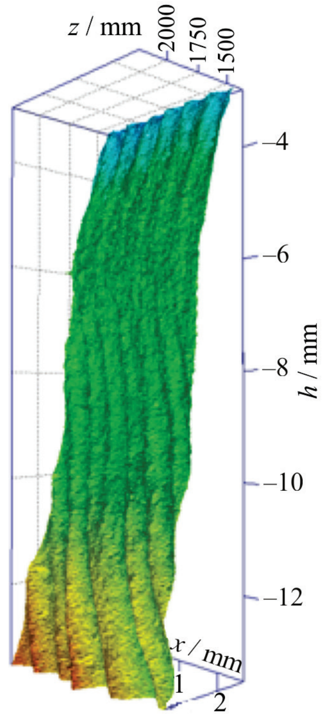


Figure 2 3D visualization of the cut geometry in abrasive water jet applications [6]

The curved lines present the trajectory of the abrasive water jet through the work piece. This trajectory is actually the cut front geometry, and it shows the abrasive water jet lagging. The cut front geometry of the work piece machined by the abrasive water jet is influenced by machining parameters such as traverse speed, operating pressure, abrasive flow rate, standoff distance, depth of cut and angle of cutting [7, 8]. The level of influence of individual parameters is different. The most influential are traverse speed, operating pressure and abrasive flow rate.

The dimensions and shape of the cut define the quality and accuracy of the work piece. The most frequent errors at parts machined with the abrasive water jet, Fig. 3, are [9]:

- Deviation of the machined surfaces in governmentality
- Cut beginning and end errors
- Radius errors and corner errors.

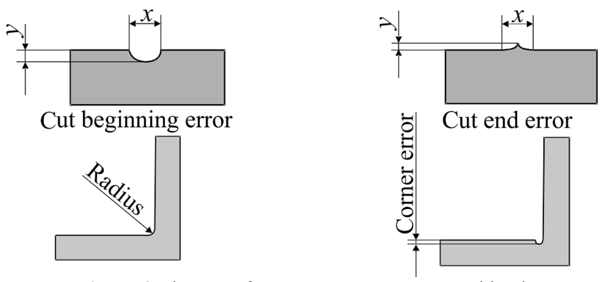


Figure 3 The most frequent errors at parts machined with abrasive water jet

The jet lagging results in diversion on the exit edge, which causes geometry errors, especially on corners and radii, Fig. 3. Because of the diameter of the abrasive water jet and traverse speed, there are restrictions on the minimum radius that can be produced with the abrasive water jet. The minimum radius is between 0,25 and 0,8 mm [9].

The corner error is especially influenced by the traverse speed; the greater the traverse speed, the greater the corner error [9].

The corner error is generally between 0,05 and 3 mm.

There are several papers dealing with the formation of cut front geometry and the factors that influence its final appearance. Some authors claim that the cut front geometry is caused by the formation stage [10], Fig. 4.

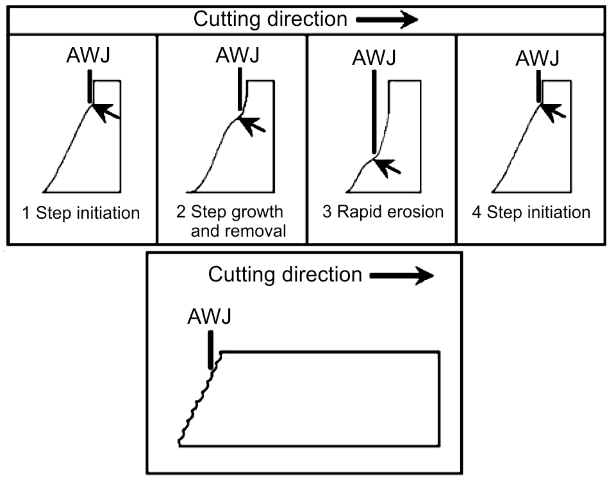


Figure 4 Formation stage [10]

Raju and Ramulu [11] found that the main cause of changes in the quality of machined surface, surface roughness and striation formation is the change of the amount of energy of abrasive water jet. Momber and Kovačević [8] explained the deviation of the cut front geometry from ideal as a consequence of energy loss during the cutting process, Fig. 5.

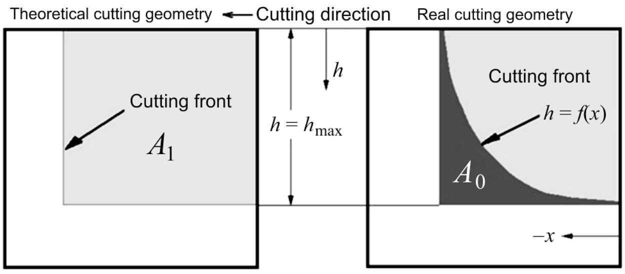


Figure 5 Deviation of the cut front geometry from ideal [8]

The line that defines the lagging of abrasive water jet is usually described as a parabola, Fig. 6, which is given in the equation (1):

$$h(x) = a\cdot(x - b)^2 + c \tag{1}$$

A. Akkurt [12] approximated the line that describes the cut front geometry, with the second order polynomial. In this polynomial, the coefficients are independent of the machining parameters and characteristics of the material to be machined, and can be applied only to the precisely defined cases. A. Lebar and M. Junkar [13] described the cut front geometry with the unit event. The unit event is when one abrasive particle strikes the material. This unit event is a feature which is repeated a large number of times. Based on the angle at which the abrasive particles strike the material and reflect from it, they were able to model the appearance of the surface machined by the abrasive water jet. H. Orbanic and M. Junkar [14] used the new two-dimensional cellular automata (CA) model for the simulation of the abrasive water jet cutting process. L. Hlavač [15] and B. Strnadel, L. Hlavač and L. Gembalova [16] investigated the influence of the mechanical characteristics of machined material and depth of cut on the angle of a tangent to the cut front line.

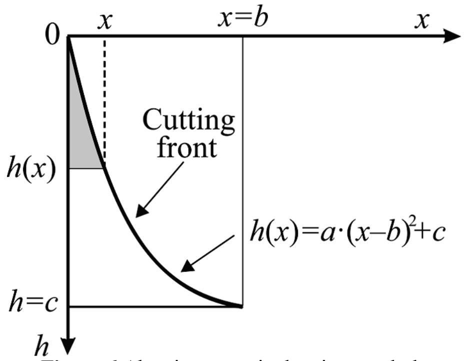


Figure 6 Abrasive water jet lagging parabola

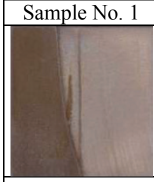
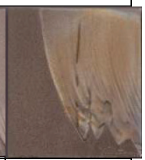
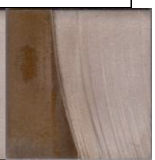
All these models are mostly based on the measurement of jet lagging for different depths of cut, and the changes of jet lagging, depending only on the depth of cut, were observed. The effects of various machining parameters on the size of jet lagging were not observed. The aim of this paper is to determine the influence of abrasive water jet machining parameters, such as operating pressure, abrasive mass flow rate and traverse speed on the jet lagging.

2 Experimental work

In this paper, the effect of traverse speed, operating pressure and abrasive mass flow rate on the jet lagging has been analyzed. The AWJ cutting experiments were performed using PTV-3.8/60 machine. It is equipped with multiplier H2O-JET, type 60K, with the maximum operating pressure of 413 MPa. The diameter of the water orifice is 0,254 mm, the diameter of the abrasive nozzle (focusing tube) is 1,02 mm (ROCTEC 100), standoff distance is 2 mm. In all experiments, the Australian garnet was used, mesh size 80, average grain size approximately 0,27 mm. The material that was used for the specimens in the experiment was stainless steel AISI 304, 30 mm thick. The material was cut in the appropriate mode to a length of 20 mm. Then the flow of abrasives was stopped and then the machine was stopped. After that, the specimens were cut to the end with Wire Electric Discharge Machining. Cutting with Wire Electric Discharge Machining was done to avoid damaging the cut front line and that it could be possible to measure the jet lagging. In this way, 17 samples were made. Seven samples (1 ÷ 7) were cut with different values of traverse speed: 10, 20, 30, 40, 50, 60 and 70 mm/min respectively, while the other machining parameters were kept constant. The next five samples (8-12) were cut with different values of operating pressure: 413, 335, 290, 245 and 205 MPa, while the next five samples (13 ÷ 17) were cut with different values of mass flow rate: 350, 300, 250, 200 and 150 g/min. Other values of machining parameters were kept constant.

The obtained samples are shown in Tab. 1. Because of the limitations on the machine, operating pressure, traverse speed and abrasive mass flow rate can be adjusted only to certain values; it is not possible to work with any of values of the machining parameters in the cutting regime.

Table 1 Cut samples after testing

				
v_1=10 mm/min	v_2=20 mm/min	v_3=30 mm/min	v_4=40 mm/min	
Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	
				
v_5=50 mm/min	v_6=60 mm/min	v_7=70 mm/min		
Sample No. 5	Sample No. 6	Sample No. 7		
Water jet pressure p = 413 MPa. Abrasive mass flow rate m_a = 400 g/min. Abrasive type – garnet, MESH#80.				
				
p_1=413 MPa	p_2=335 MPa	p_3=290 MPa	p_4=245 MPa	p_5=205 MPa
Sample No. 8	Sample No. 9	Sample No. 10	Sample No. 11	Sample No. 12
Traverse speed v = 35 mm/min. Abrasive mass flow rate m_a = 400 g/min. Abrasive type – garnet, MESH#80.				
				
m_{a1}=350 g/min	m_{a2}=300 g/min	m_{a3}=250 g/min	m_{a4}=200 g/min	m_{a5}=150 g/min
Sample No. 13	Sample No. 14	Sample No. 15	Sample No. 16	Sample No. 17
Water jet pressure p = 413 MPa. Traverse speed v = 35 mm/min. Abrasive type – garnet, MESH#80.				

In order to define the curvature of the cut front-jet lagging, the samples were examined under the optical microscope, and the deviation of the jet lagging from the ideal cut front geometry was measured at certain depths of cut, as shown in Fig. 7.

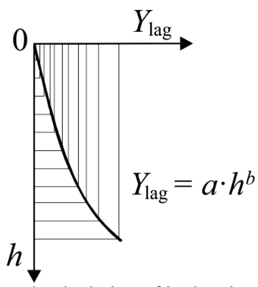


Figure 7 Determining the deviation of jet lagging from ideal cut front geometry

3 Results and discussion

After measuring on the optical microscope, the observed values of the jet lagging are presented in Tabs. 2, 3 and 4.

Table 2 Measured values of jet lagging for different values of traverse speed

Sample No.		1	2	3	4	5	6	7
v / mm/min		10	20	30	40	50	60	70
h / mm	0	0	0	0	0	0	0	0
	3	0,056	0,100	0,104	0,093	0,248	0,271	0,277
	6	0,120	0,206	0,221	0,282	0,409	0,496	0,507
	9	0,208	0,334	0,346	0,523	0,667	0,806	0,845
	12	0,314	0,487	0,543	0,808	1	1,253	1,269
	15	0,462	0,643	0,768	1,104	1,412	1,776	1,801
	18	0,514	0,888	1,005	1,551	1,878	2,308	2,416
	21	0,625	1,151	1,316	2,1	2,510	2,957	3,169
	24	0,799	1,431	1,620	2,622	3,308	3,677	4,152
	27	0,971	1,749	2,009	3,17	4,193	4,492	5,104
	30	1,228	2,060	2,253	3,725	4,898	5,27	5,987

Table 3 Measured values of jet lagging for different values of operating pressure

Sample No.		8	9	10	11	12
p / MPa		413	335	290	245	205
h / mm	0	0	0	0	0	0
	3	0,127	0,122	0,145	0,188	0,248
	6	0,253	0,313	0,413	0,478	0,538
	9	0,422	0,547	0,67	0,789	0,918
	12	0,640	0,825	1,026	1,177	1,672
	15	0,818	1,210	1,547	1,672	2,647
	18	1,046	1,643	2,196	2,331	3,973
	21	1,340	2,230	2,949	3,413	5,268
	24	1,662	2,965	3,656	4,477	7,01
	27	1,984	3,624	4,269	5,409	×
	30	2,345	4,464	4,972	6,420	×

Table 4 Measured values of jet lagging for different values of abrasive mass flow rate

Sample No.		13	14	15	16	17
m_a / g/min		350	300	250	200	150
h / mm	0	0	0	0	0	0
	3	0,138	0,217	0,209	0,222	0,221
	6	0,324	0,435	0,488	0,525	0,524
	9	0,501	0,721	0,782	0,788	0,796
	12	0,845	1,035	1,129	1,194	1,189
	15	1,145	1,508	1,510	1,768	1,73
	18	1,589	1,92	2,095	2,309	2,417
	21	2,033	2,635	2,669	3,060	3,135
	24	2,611	3,320	3,381	3,795	3,933
	27	3,301	4,093	4,296	4,612	4,829
	30	3,926	4,960	5,289	5,618	5,614

The diagrams of machining parameters influence on the jet lagging, Figs. 8, 9 and 10, were created using the measured values in Tabs. 2, 3 and 4. The mathematical model that describes the impact of the corresponding machining parameters on the jet lagging was given together with each diagram.

$$Y_{\text{lag}} = 0{,}463 \times 10^{-3} \cdot v^{0{,}90057} \cdot h^{1{,}66356}, \text{ mm.} \quad (2)$$

The coefficient of determination (R^2) for this model is 0,99076113, R = 0,99536984.

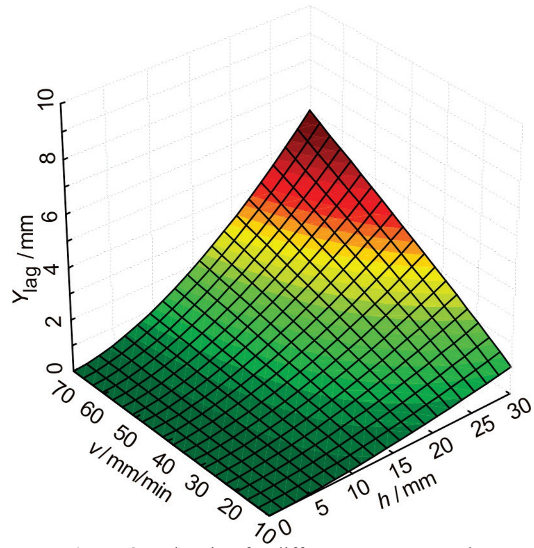


Figure 8 Jet lagging for different traverse speeds

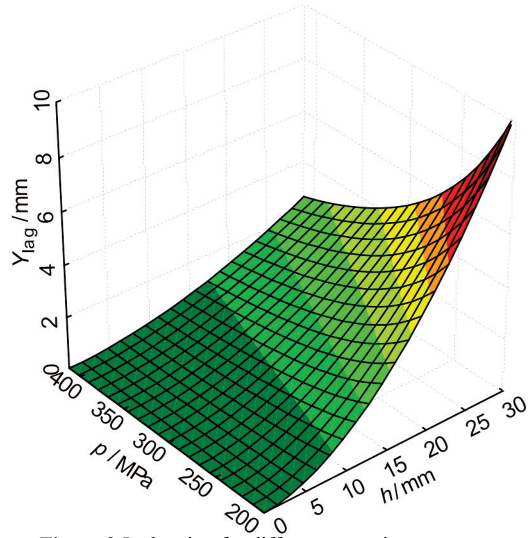


Figure 9 Jet lagging for different operating pressures

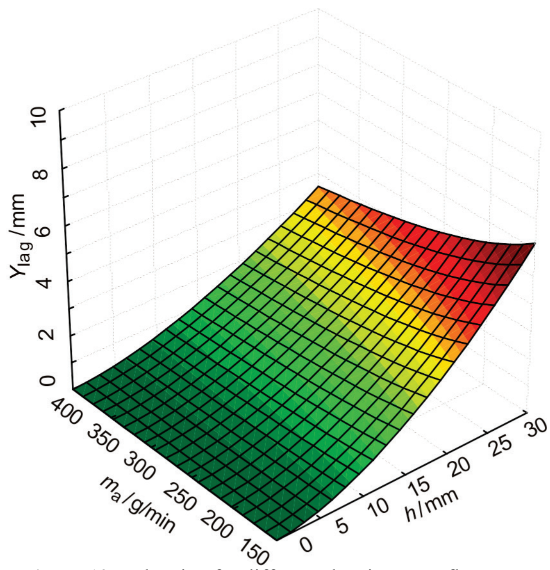


Figure 10 Jet lagging for different abrasive mass flow rates

$$Y_{\text{lag}} = 476{,}752 \cdot p^{-1{,}8898} \cdot h^{1{,}81888}, \text{ mm.} \quad (3)$$

The coefficient of determination (R^2) for this model is 0,98749811, R = 0,99372939.

$$Y_{\text{lag}} = 0{,}372139 \cdot m_a^{-0{,}57433} \cdot h^{1{,}67259}, \text{ mm.} \quad (4)$$

The coefficient of determination (R^2) for this model is 0,95804442, R = 0,97879744.

Based on the measured values in Tabs. 2, 3 and 4, the relationship between the jet lagging and traverse speed, operating pressure, abrasive mass flow rate and depth of cut, is formed. This relationship is represented by a mathematical model described in Eq. (5).

$$Y_{\text{lag}} = 132{,}3607 \cdot \frac{v^{0{,}9274} \cdot h^{1{,}687}}{p^{1{,}4297} \cdot m_a^{0{,}691}}, \text{ mm.} \quad (5)$$

Fig. 11 shows the observed values of the jet lagging versus the values of the jet lagging predicted by the model presented in Eq. (5).

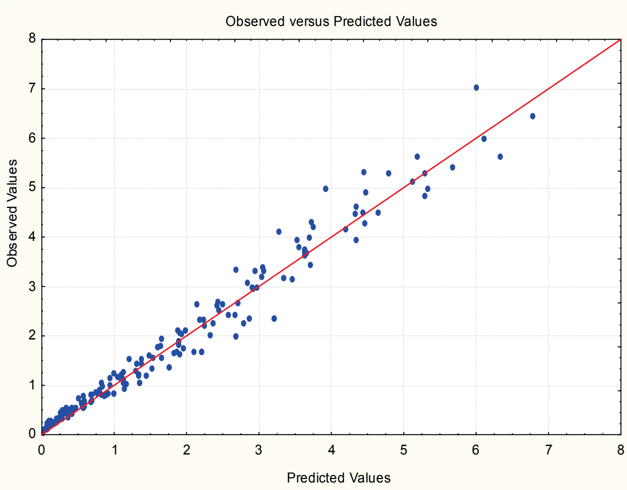


Figure 11 Observed versus predicted values of the jet lagging

The coefficient of determination (R^2) for this model is 0,97276116, R = 0,98628655.

From the Eq. 5, we can conclude that an increase of the depth of cut and traverse speed leads to an increase of the jet lagging, which was already known. The influence of operating pressure and abrasive mass flow rate has not been investigated so far. From the Eq. 5, we can see that an increase of operating pressure and abrasive mass flow rate causes a decrease of the jet lagging.

4 Conclusion

The paper presents the results of the research concerning the machining parameters influence on the change of the water jet lagging. In Figs. 8, 9 and 10, the change of the jet lagging as the function of traverse speed, operating pressure and abrasive flow rate can be noted. With the increase of the traverse speed, there is an increase of the jet lagging. Furthermore, it can be observed that the increase of operating pressure and abrasive flow rate causes the decrease of the water jet lagging. This clearly suggests a firm correlation between the water jet lagging and the referred machining parameters. The influence of the depth of cut on the jet lagging is also significant. With the increasing depth of cut, the jet lagging also increases.

All these influences are described in the summary model given in Eq. (5). On the diagram 11, the measured values of the jet lagging, and the values obtained from the model, Eq. (5), are compared and quite good matching of the values can be observed. The maximum deviation is observed in the samples that were machined with extreme values of the machining parameters.

It is interesting that the exponent associated with the depth of cut, in all Equations (2, 3, 4 and 5), has a value of about 1,7, whereas in all previous models, the value of the exponent was 2.

Based on the model in Eq. (5), it can be concluded that with the proper selection of the machining parameters, the desired values of the jet lagging can be achieved. The entire length of the cut does not need to be machined with such selected machining parameters, but only the parts of the path that make the radius or angle, because major mistakes occur there.

The experiments were carried out on only one material, AISI 304, so that the obtained models are only valid for this material. It is necessary to carry out the experiments in several different materials to determine the effects of the mechanical properties of materials on the jet lagging.

It would also be interesting to carry out the experiments on the same material with different thickness. In this way, it will be determined whether the jet lagging phenomenon is independent of the thickness of the material which is machined.

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Authors' addresses

dr. sc. Vlatko Marušić, red. prof.
J. J. Strossmayer University of Osijek
Mechanical Engineering Faculty in Slavonski Brod,
Trg Ivane Brlić-Mažuranić 2
35000 Slavonski Brod, Croatia
vlatko.marusic@sfsb.hr
+38535493420

Jelena Baralić
Faculty of Technical Sciences Čačak
University of Kragujevac
65, Svetog Save St.
32000 Čačak, Serbia
jelena.baralic@ftn.kg.ac.rs
+38132302736

dr Bogdan Nedić, red. prof.
Faculty of Engineering in Kragujevac
University of Kragujevac
6, Sestre Janjic Str.
34000 Kragujevac, Serbia
nedic@kg.ac.rs
+38134335990

Željko Rosandić
J. J. Strossmayer University of Osijek
Mechanical Engineering Faculty in Slavonski Brod,
Trg Ivane Brlić-Mažuranić 2
35000 Slavonski Brod, Croatia
zeljko.rosandic@sfsb.hr
+38535493421