UNIVERZITET CRNE GORE
MAŠINSKI FAKULTET
PODGORICA

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Broj: 2293
Podgorica, 30.09.2021. godine

Na osnovu člana 64. Statuta Univerziteta Crne Gore (Bilten UCG br. 337 – posebno izdanje od 13. Februara 2015.godine), i člana 33, stav 2 Pravila doktorskih studija Univerziteta Crne Gore, Vijeće Mašinskog fakulteta u Podgorici, na sjednici održanoj elektronskim putem, dana 30.09.2020. godine, usvojilo je prijedlog

ODLUKE
o prihvatanju godišnjih izvještaja mentora o napredovanju doktoranada

I Prihvataju se godišnji izvještaji mentora o napredovanju doktoranata za sledeće kandidate:

1. Ramiza Kurbegovića,
2. Vuka Kovijanića,
3. Borisa Hrnčića,
4. Marka Mumovića.

II Prihvaćeni godišnji izvještaji mentora o napredovanju doktoranada (IM obrasci) su sastavni dio ove Odluke.

III Izvještaji se dostavljaju Odboru za doktorske studije na saglasnost.

DEKAN,
Prof. dr Igor Vušanović

DODSTAVLJENO:
- Odboru za doktorske studije
- Stuentskoj službi
- Sekretaru
- a/a

GODIŠNJI IZVJEŠTAJ MENTORA O NAPREDOVANJU DOKTORANDA

Akademska godina za koju se podnosi izvještaj	2020/2021				
OPŠTI PODACI O DOKTORANDU					
Titula, ime, ime roditelja, prezime	mr Ramiz Mirsad Kurbegović				
Fakultet	Mašinski Fakultet				
Studijski program	Mašinstvo				
Broj indeksa	06/18				
MENTOR/MENTORI					
Prvi mentor	Prof. Dr Mileta Janjić	Mašinski fakultet, Crna Gora	Proizvodno mašinstvo		
EVALUACIJA DOKTORANDA*					
Koliko ste zadovoljni kvalitetom održanih susreta sa doktorandom?	☐1	☐2	☐3	☒4	☐5
(Ako je prethodni odgovor „1" ili „2" dati obrazloženje i prijedloge za poboljšanje)					
Da li je definisan plan rada sa doktorandom?	☒DA	☐NE			
Da li je doktorand ostvario napredak prema predviđenom planu rada?	☐DA	☒NE			
(Ako je prethodni odgovor „ne" dati obrazloženje i prijedloge za poboljšanje) Kandidat nije u potpunosti odradio eksperimentalna istraživanja, zbog nepostojanja mogućnosti u zemlji i okruženju za specifičnom termičkom obradom materijala za ispitivasnje. Iz tog razloga se pristupilo nabavci opreme - peći za termičku obradu koje mogu da odgovore zahtjevima.					
Kvalitet napretka doktorandovog istraživačkog rada u periodu između dva izvještaja je:	☐1	☐2	☒3	☐4	☐5
(Ako je prethodni odgovor „1" ili „2" dati obrazloženje i prijedloge za poboljšanje)					
Dati ocjenu doktorandove spremnosti za konsultacije.	☐1	☐2	☐3	☒4	☐5
Dati ocjenu planiranja i izvršavanja godišnjih istraživačkih aktivnosti i stručnog usavršavanja doktoranda.	☐1	☒2	☐3	☐4	☐5
Dati ocjenu napretka u savladavanju metodologije naučno-istraživačkog rada.	☐1	☐2	☐3	☒4	☐5
ISPUNJENOST USLOVA DOKTORANDA					
Spisak radova doktoranda iz oblasti doktorskih studija koje je publikovao doktorand					
1. Kurbegović, R., Janjić, M. i Vukčević, M. (2019) Engineering economic analysis of water,					

*Ocjene su: 1 – nedovoljan, 2 – dovoljan, 3 – dobar, 4 – vrlo dobar, 5 – odličan

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2. Kurbegović, R., Janjić, M., Vukčević, M. i Đurović, D. (2020) Uticaj Parametara Obrade Abrazivnim Vodenim Mlazom na Odstupanje Prednje Linije Reza. 42. JUPITER Konferencijaa. Beograd, Srbija. pp. 3.81-3.87,
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5. Kurbegović, R. and Janjić M. (2021) Jet Lagging in Abrasive Water Jet Cutting of Tool Steel. 14th International Scientific MMA 2021 - Flexible Technologies. Novi Sad, Srbija. Accepted.

Obrazloženje mentora o korišćenju sprovedenih istraživanja u publikovanim radovima

Doktorand, mr Ramiz Kurbegović je položio sve ispite u skladu sa nastavnim planom doktorskih studija. Aktivnosti vezane za odbranu polaznih istraživanja, pripremu uzoraka za glavna istraživanja i publikovanje rezultata su vremenski pomjerene. Ovo je nastupilo dijelom uslijed COVID-19 situacije.

Javna odbrana polaznih istraživanja organizovana je 09.07.2020. godine na Mašinskom fakultetu Univerziteta Crne Gore. Kandidat je vrlo uspješno obrazložio izabranu temu „Istraživanje parametara obrade abrazivnim vodenim mlazom" i zaključke do kojih je došao nakon realizovanih polaznih istraživanja. Nakon uvida u dostavljeni materijal, javne odbrane polaznih istraživanja i odgovora kandidata na postavljena pitanja, Komisija je mišljenja da je tema doktorske disertacije aktuelna i disertabilna i jednoglasno predložila Vijeću Mašinskog fakulteta i Senatu Univerziteta Crne Gore da prihvati temu ove doktorske disertacije i kandidata.

Doktorska disertacija kandidata mr Ramiza Kurbegovića zahtjeva specifičnu termičku pripremu uzoraka za glavna istraživanja. Kako se nije mogao naći adekvatan način za pripremu uzoraka u Crnoj Gori i okruženju, nabavljena je odgovarajuća oprema kako bi se prevazišlo ovo ograničenje i nastavilo sa daljim radom na doktorskoj disertaciji.

Pripremljeni su programi za analizu rezultata mjerenja koji će se dobiti tokom glavnih istraživanja i na taj način ubrzati analiza i obrada podataka istraživanja.

Dati ocjenu o aktivnostima sprovedenim na pisanju i objavljivanju naučnih radova.	☐1	☐2	☒3	☐4	☐5
Dati ocjenu doktorandovog generalnog odnosa prema studijama.	☐1	☐2	☒3	☐4	☐5
Dati ocjenu ukupnog kvaliteta doktorandovog rada.	☐1	☐2	☒3	☐4	☐5
(Ako je prethodni odgovor „1" ili „2" dati obrazloženje i prijedloge za poboljšanje)					

SAGLASNOST ZA NASTAVAK STUDIJA

Može li doktorand nastaviti studije?	☐Da ☒Da, uz određene uslove

	☐ Ne
(Ako je prethodno dat odgovor pod „b)" ili „c)" dati obrazloženje i prijedloge za poboljšanje) Uslov je da Kandidat intenzivira rad na završetku eksperimentalnih istraživanja, obradi rezultate, dođe do zaključaka koji će potvrditi hipoteze Disertascije, a sve to objavi u radovima koji će biti publikovani u časopisima na SCI/SCIE listi.	
Napomene	
U Podgorici, 10.09.2021. godine Mentor, Prof. dr Mileta Janjić	

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UCG Podgorica 10. 09. 2021

1st International Conference on New Research and Development in Technical and Natural Science,

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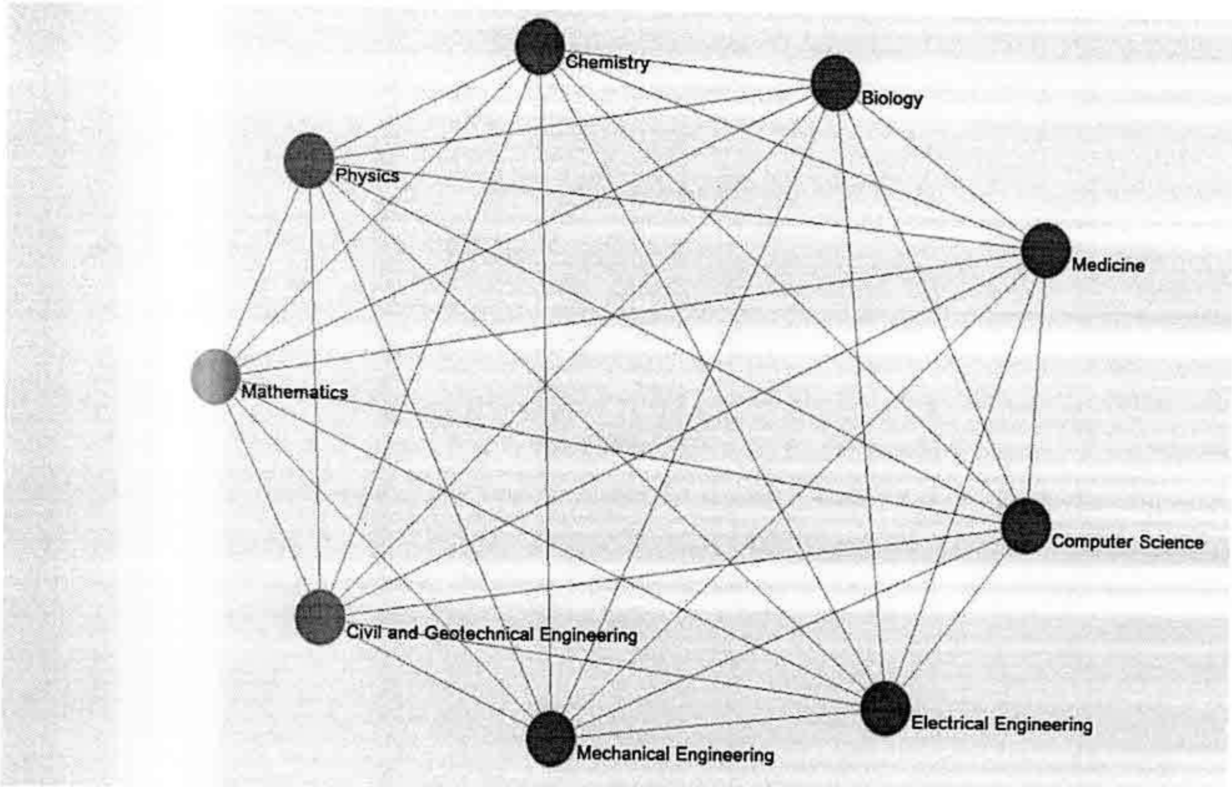

Radenci, Slovenia, 18.- 20. September 2019

The organizers of the 1st International Conference on New Research and Development in Technical and Natural Science, ICNRDTNS are expecting you, our dear participants and guests at another traditional gathering of all of those who are interested in the use of Mathematics, Physics, Chemistry, Biology, Medicine, Computer Science, Electrical Engineering, Mechanical Engineering, Civil and Geotechnical Engineering and all related high technologies in the felds of Engineering and Science.

During the whole week from 18th until 20th of September 2019 in Radenci, Slovenia, the 1st convention ICNRDTNS offers you a number of interesting events. The first bioclimate health resort in Slovenia, featuring springs of mineral and thermal Radenska water, invites relaxation that will boost your health and well-being. Numerous regular guests are loyal to this health resort with a big heart. The conference venue is the hotel Radin. Radenci Spa is located in the northeastern Slovenia, 5 kilometers from Gornja Radgona at the Austrian border and 12 kilometers from Murska Subota. Legends say that the path for the mineral water in the Radenci Spa is paved by the diligent elves. Karl Henn was listening to the underground ripples in 1833, when he visited Radenci for the first time. After detailed water analysis, he came back to Radenci as an acknowledged doctor and filled a first bottle with Radenska mineral water in 1869. It was later delivered to the imperial court in Vienna and to the pope in Rome. First guests visited Radenci almost 130 years ago, or in the year of 1882 to be more exact. Radenci Spa is known worldwide for its mineralized water. Mineral water Radenska is sodium-calcium-hydrogen-carbonate mineral water and its CO2 concentration make it one of the most abundant mineral waters in Europe. It has multiple therapeutic and beneficial effects on our body: stabilizes blood pressure, precipitates digestion, neutralizes excessive gastric acid, lowers the uric acid values, increases urine excretion and strengthens the body and well being in general. Mineral water helps with different heart and blood vessel diseases: arterial hypertension, stable angina pectoris, conditions after suffering a heart attack, conditions after heart and blood vessels surgeries, obstructed peripheral arterial and vein circulation. Mineral water is used in water-intake therapies and mineral baths. The temperature of the mineral bath is 30-33 degrees Celsius, it lasts from 5 to 20 minutes, depending on the individual. A significant therapeutic factor in Radenci spa is also the sweet water mud. Peloid compress has a soothing effect, alleviates the pain and has a positive effect on chronic inflammations. As one of the rare true health resort towns, Radenci boasts as many as four natural healing factors: natural mineral water, thermal water, healing mud (peloid) and beneficial climate with 250 sunny days per year. Radenci is know as oldest marathon. This is the oldest marathon, not only in Slovenia but in all of south-eastern Europe. All tracks are officially measured by AIMS/IAAF. They are run on flat terrain between fields and villages along the river Mura. As a participant describes the event: "One of the last running events with heart and soul" Three Hearts Marathon (Slovene: Maraton treh src) is a marathon, organised in Radenci in Slovenia. It has been taking place since 1981 and attracts several thousand people each year. In addition to the marathon, a half marathon (21 km), recreative running (10 km) and a course for juniors and teenagers are organised. The event was the Slovenian national championships race from 1992 to 1998 and has hosted the national race in even-numbered years since then, now sharing the honour with the Ljubljana Marathon.

The programme of ICNRDTNS includes plenary sessions, core dialogues, debates, discovery demos, knowledge exchange sessions, knowledge factories, networking meet-ups, panel talks and poster presentations on specific topics and informal networking opportunities in which practitioners share their experiences, ideas, new information and perspectives.

On behalf of the International Program Committee we express our sincere gratitude to our sponsors.

Come to magical, ancient and sunny Radin, participate in ICNRDTNS 2019 and be part of the ICNRDTNS events from September 18 – 20, 2019.

Dr. Matej Babič, Ph.D.

International Program Committee General Chair

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ENGINEERING ECONOMIC ANALYSIS OF WATER, ELECTRICITY AND ABRASIVES COSTS AND THEIR EFFECT ON THE PRICE OF ABRASIVE WATER JET MACHINING

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Abstract

Abrasive water jet machining is one of the non-conventional production technologies, and for its many advantages over other cutting technologies, it is often used in the industry. However, to find a wider application and improve its performance, it is necessary to perceive a number of input and output parameters and their impact on the machining process.
The aim of this paper is to investigate the effect of water, electricity and abrasives costs, as most dominant operating costs, on the price of abrasive waterjet machining and to find the economically acceptable variance of process parameters. Major significant process factors affecting the price of abrasive waterjet machining were determined. Relationship between the cost of abrasive waterjet machining and the costs of water, electricity, and abrasives has been formed.

Keywords: Abrasive Water Jet, Engineering economic analysis, Water jet lagging

1. Introduction

The principles on which the abrasive water jet machining process is based on is erosion. Some authors explain the process of erosion as a kind of abrasive wear, at which abrasive particles and water jet repeatedly impact the surface, resulting in flushing of the material from that surface [1,2].
The cutting front geometry of the workpiece 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 [1,3].
Defining the geometry of the cutting front, is in fact, the determination of the deviation - lagging, Ylag, of the abrasive water jet from the vertical line. The line that defines the lagging of abrasive water jet is described by Zeng et al. [4] as a parabola.
Analyzing and comparing costs represents the basic aspects of engineering practice [5]. Since there are a large number of costs that affect the final price of the abrasive water jet machining, the analysis of the most dominant operating costs will provide insight into the justification of the variation of certain process parameters. The cost of water, electricity, and abrasive, represent the most dominant exploitation costs.

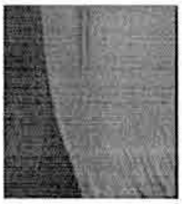
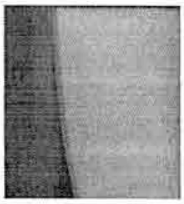
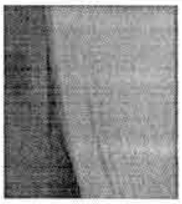
2. Experimental details

Experimental research was realized to define the influence of water, electricity and abrasives costs on the price of abrasive water jet machining and to achieve better machining performance.
Samples presented by Marušić et al. [6], concerning the influence of the water pressure (p), traverse speed (v_g) and abrasive flow ($\dot{m}_a$) on the abrasive water jet lagging, were used for creating experimental variants for this work. Machining parameters are shown in table 1.
The system used for machining the samples, is the product of PTV JETS, model 3,8/60 Classic, Czech Republic. Orifice inner diameter was 0.254 mm. Inner diameter of the focusing tube was 1.02 mm with a length of 76 mm. Jet impact angle

[1] - name of the presenter

was 90°. Abrasive material was Garnet mesh 80. Work piece material was stainless steel X5CrNi 18–10, thickness of 30 mm. Distance between focusing tube and material was 2 mm.
Maximum installed power of the system is $P_{max} = 49{,}4\ kW$. 3-phase asynchronous motor on the pump has a nominal power of 37 kW. Other consumers, with an installed power of $P_{OC} = 12{,}4\ kW$, are air compression machine, water treatment system, abrasive supply system, oil cooling system and CNC (Computer Numerical Control) workstation with automation. Maximum water flow of the system is 3,8 l/min (Q_A).

Table 1. Samples and its parameters [6]

Sample 4	Sample 5	Sample 10	Sample 11	Sample 13	Sample 17
					
$v_4 = 40\ \frac{mm}{min}$ $p = 413\ MPa$ $\dot{m}_a = 400\ \frac{g}{min}$	$v_5 = 50\ \frac{mm}{min}$ $p = 413\ MPa$ $\dot{m}_a = 400\ \frac{g}{min}$	$v = 35\ \frac{mm}{min}$ $p_3 = 290\ MPa$ $\dot{m}_a = 400\ \frac{g}{min}$	$v = 35\ \frac{mm}{min}$ $p_4 = 245\ MPa$ $\dot{m}_a = 400\ \frac{g}{min}$	$v = 35\ \frac{mm}{min}$ $p = 413\ MPa$ $\dot{m}_{a,1} = 350\ \frac{g}{min}$	$v = 35\ \frac{mm}{min}$ $p = 413\ MPa$ $\dot{m}_{a,5} = 150\ \frac{g}{min}$

Measurements for determining water jet lagging were performed in ten places (at the same distance) along with the sample thickness using optical microscope.
For the description of the operation of centrifugal pumps the affinity laws given by Equations (1), (2) and (3) can be used. They are useful for quick and precise enough analysis.

$$\frac{Q_A}{Q_B} = \frac{n_A}{n_B} \tag{1}$$

$$\frac{p_A}{p_B} = \left(\frac{n_A}{n_B}\right)^2 \tag{2}$$

$$\frac{P_A}{P_B} = \left(\frac{n_A}{n_B}\right)^3 \tag{3}$$

where: Q – flow, p – pressure, P – power of the motor and n – speed of pump impeller.
Needed Strength of the pump (and motor) is described with equation (4).

$$P = \frac{p \cdot Q}{\eta_U} \tag{4}$$

2.1. Experimental Procedure

Variant A of this work will be sample 17 from table 1. For getting almost identical values of water jet lagging, as in sample 17, linear interpolation was used on water pressure parameter on samples 10 and 11. Calculated value of water pressure is $p_x = 265\ MPa$ and that will be the Variant B of this work. Both variants and its parameters are presented in table 2.

Table 2. Variants for the analysis

Variant A	Variant B
$v = 35\ \frac{mm}{min}$ $p = 413\ MPa$ $\dot{m}_{a,5} = 150\ \frac{g}{min}$	$v = 35\ \frac{mm}{min}$ $p_x = 265\ MPa$ $\dot{m}_a = 400\ \frac{g}{min}$

Costs will be analyzed for a year of machining, with a straight line machining of 30 m/day, 20 working days/month. Water price will be $UP_W = 1\ €/m^3$ and price of abrasive Garnet # 80 will be $UP_A = 400\ 1\ €/t$. Electricity price will be calculated in accordance with the Price List of Elekroprivreda Crne Gore A.D. Niksic [7] for a basic model consumer with a single tariff meter connected to a 10 kV line, measuring the average 15-minute load, active and reactive power.

3. Results

According to the given length of machining (l_{DM}) and the speed of cutting head (v) we can get daily machining time $t_{DM} = 857{,}14\ min/day$, which is same for both variants.

Using the t_{DM}, number of working days (N_{WD}), abrasive mass flow for variants A ($\dot{m}_{a,5}$) and B ($\dot{m}_a$) and price of abrasive (UP_A), we can calculate abrasive grand total for A (PA_A) i B (PA_B):

$$PA_A = t_{DM} \cdot N_{WD} \cdot \dot{m}_{a,5} \cdot UP_A \cdot 10^{-6} \cong 12.342{,}82\ €/year \quad (5)$$

$$PA_B = t_{DM} \cdot N_{WD} \cdot \dot{m}_a \cdot UP_A \cdot 10^{-6} \cong 32.914{,}18\ €/year \quad (6)$$

Conditions for electricity cost calculation: $\eta_{P,A} = \eta_{P,B} = \eta_P = 80\ \%$, $\eta_{EM,A} = \eta_{EM,B} = \eta_{EM} = 93\ \%$, $\eta_{PN,A} = \eta_{PN,B} = \eta_{PN} = 98\ \%$, $\eta_{I,A} = \eta_{I,B} = \eta_I = 90\ \%$, $cos\varphi_A = cos\varphi_B = cos\varphi = 1$, and $n_A = 1480\ rpm$, where: η_P, η_{EM}, η_{PN}, η_I – efficiency of pump, motor, pipe network and intensifier, $cos\varphi$ – power factor, and n_A – rotation speed of motor. Total system efficiency (η_T) is 65,621 %.

Using affinity laws (1), (2), (3), and equation (4), we can calculate pump impeller speed ($n_B = 1186 rpm$) and flow for variant B ($Q_B = 3{,}05\ l/min$), required power for electric motor for variant A ($P_A = 23{,}92\ kW$) and B ($P_B = 12{,}28\ kW$). Total required power of A ($P_{T,A} = 30{,}12\ kW$) and B ($P_{T,B} = 18{,}48\ kW$) variant will be a sum of required powers of electric motors with a half of installed power of other consumers (P_{OC}). Price of the electricity, for variants A and B, are shown in tabs 3, 4 and 5.

Table 3. Monthly price of the electricity for a variant A

Name	Unit of measure	Unity price [€c/kWh]	Consumption [kWh]	Price [€]
Active electricity	kWh	4,4932	8605,69	386,67
Reactive electricity	kVArh	0,8986	0,00	0,00
Engaging transmission capacity	kW	9,3632	30,12	282,02
Losses in the distribution system	kWh	0,1113	8605,69	9,58
Compensation to the market operator	monthly	0,0175	8605,69	150,60
			Price w/o VAT (21%)	828,87

Tabela 4. Monthly price of the electricity for a variant B

Name	Unit of measure	Unity price [€c/kWh]	Consumption [kWh]	Price [€]
Active electricity	kWh	4,4932	5279,98	237,24
Reactive electricity	kVArh	0,8986	0,00	0,00
Engaging transmission capacity	kW	9,3632	18,48	173,03

Losses in the distribution system	kWh	0,1113	5279,98	5,88
Compensation to the market operator	monthly	0,0175	5279,98	92,40
			Price w/o VAT (21%)	508,55

Table 5. Price of the electricity

Name	Price [€/year]
Price of the electricity for variant A (PE_A)	9.946,44
Price of the electricity for variant B (PE_B)	6.102,60

Total price of water consumption (PW_A) and (PW_B) is calculated using equations 7 and 8.

$$PW_A = UP_W \cdot Q_A \cdot 60 \cdot t_{DM} \cdot N_{WD} \cong 781{,}95\ €/year \quad (7)$$

$$PW_B = UP_W \cdot Q_B \cdot 60 \cdot t_{DM} \cdot N_{WD} \cong 627{,}62\ €/year \quad (8)$$

Total price of the machining for A (MP_A) and B (MP_B) is calculated using equations 9 and 10.

$$MP_A = PE_A + PA_A + PW_A = 23.071{,}21\ €/year \quad (9)$$

$$MP_B = PE_B + PA_B + PW_B = 39.644{,}40\ €/year \quad (10)$$

Relationship between total price of the machining for A and B is shown in equation 11.

$$\frac{CK_B}{CK_A} = 1{,}7183 \quad (11)$$

Calculating the price difference, we can improve productivity of the variant A for the given difference. Improvement in abrasive flow of the variant A (I_A) will be:

$$I_A = \frac{(MP_B - MP_A)}{UP_A \cdot N_{WD} \cdot t_{DM}} \cong 201\ g/min$$

Sample 13 have similar machining parameters for economically identical and improved variant A. To get the productivity improvement, linear interpolation was carried on samples 4 and 5 (shown in table 1) to get traverse speed value. That value is $v_I = 41{,}7\ mm/min$.

Improvement in productivity of the abrasive water jet system will be:

$$\frac{v_I}{v} = 1{,}1914 \quad (12)$$

4. Conclusions

Total price of the machining, using parameters from variant B, is 71,83% higher than a total price of the machining using parameters from variant A, with a same productivity and quality if the machining.

Prices of water and electricity influences less on a total price of the machining than a price of abrasive. From this we can conclude that the variance of abrasive flow, as most dominant cost, represents an economically sound approach, while variance of pressure – lowering working pressure, represents an economically wrong approach.

Machining speed of variant A could be improved to 41,7 mm/min, for the same quality and price as in variant B, and improve productivity of the system by 19,14%.

Acknowledgment

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42. JUPITER KONFERENCIJA

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Kurbegović, R., Janjić, M., Vukčević, M., Đurović, D. [1)]

UTICAJ PARAMETARA OBRADE ABRAZIVNIM VODENIM MLAZOM NA ODSTUPANJE PREDNJE LINIJE REZA [2)]

Rezime

Obrada abrazivnim vodenim mlazom je jedna od nekonvencionalnih proizvodnih tehnologija koja se sve više koristi u industriji. Međutim, da bi se unaprijedile njene performanse, neophodno je bolje razumijevanje brojnih ulaznih i izlaznih parametara ove obrade i njihova međusobna zavisnost. Cilj ovog istraživanja je određivanje uticaja ulaznih parametara obrade (radnog pritiska, brzine kretanja rezne glave, protoka abraziva i rastojanja rezne glave od predmeta obrade) na odstupanje prednje linije reza od svoje upravne linije. Sva saznanja do kojih se došlo ukazuju da primjenjeni parametri obrade utiču na odsupanje prednje linije reza od svoje idealne upravne linije.

Ključne reči: Obrada abrazivnim vodenim mlazom, Obrada materijala, Odstupanje prednje linije reza

1. UVOD

Mehanizam na kom se zasniva postupak obrade abrazivnim vodenim mlazom je erozija. Neki autori objašnjavaju proces erozije kao vrstu abrazivnog habanja, pri kojem abrazivne čestice i vodeni mlaz uzastopno vrše udare na površinu, što rezultira ispiranjem materijala sa te površine [1,2].

Postoji nekoliko radova koji se bave geometrijom reza i faktorima koji utiču na njegov konačan izgled. Uglavnom na geometriju reza koji je obrađen abrazivnim vodenim mlazom utiču parametri obrade kao što su radni pritisak, brzina kretanja rezne glave, protok abraziva i rastojanja rezne glave od predmeta obrade [1,3].

Definisanje geometrije reza je zapravo utvrđivanje odstupanja - zaostajanja, Y_{lag}, abrazivnog vodenog mlaza od svoje vertikalne linije. Linija koja opisuje zaostajanje abrazivnog vodenog mlaza, Zeng i ostali [4] su definisali kao parabolu.

Cilj ovog rada je odrediti uticaj parametara obrade abrazivnim vodenim mlazom, kao što su radni pritisak, p, rastojanje rezne glave od predmeta obrade, x, brzina kretanja, v_c i protok abraziva, m_a, na zaostajanje abrazivnog vodenog mlaza.

2. EKSPERIMENTALNA ISTRAŽIVANJA

Analiziran je uticaj radnog pritiska, brzine kretanja rezne glave, protoka abraziva i rastojanja rezne glave od predmeta obrade na zaostajanje abrazivnog vodenog mlaza. Istraživanje je obavljeno na mašini za obradu abrazivnim vodenim mlazom proizvođača WJS, Švedska, model NCX 4020. Korišteni prečnik vodene mlaznice je 0,254 mm, a abrazivne (fokusirajuće cijevi) 0,768 mm (ROCTEC 100). U svim eksperimentima korišten je garnet # 80.

Kao materijal na kom je vršeno istraživanje je brzorezni alatni čelik EN HS6-5-2 (JUS č.7680, AISI M2), proizveden EPT (Elektro pretapanje pod slojem troske) metodom u kalupu okruglog oblika, normalizvan, mašinski rezan na ploče debljine 42 mm, zatim mašinski obrađen na mjeru 40±0,05 mm. Iz diskova su abrazivnim vodenim mlazom dobijeni uzorci dimenzija 40x40x110 ± 0,05 mm. Strana koja je obrađena abrazivnim vodenim mlazom mašinski je obrađena na 38 ± 0,1 mm za potrebe razlikovanja.

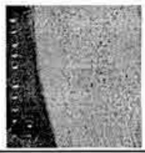
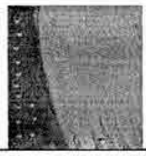
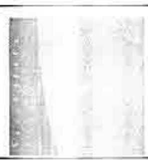
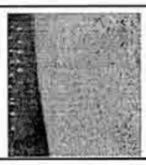
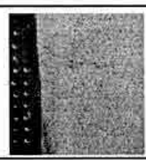
Uzorci su rasijecani do dužine od 30 mm. Na toj dužini reza zaustavljan je dotok abraziva, a odmah zatim

[1)] mr Ramiz Kurbegović, Univerzitet Crne Gore, Mašinski fakultet, (rkurbeg@gmail.com), prof. dr Mileta Janjić, Univerzitet Crne Gore, Mašinski fakultet, (mileta@ucg.ac.me), prof. dr Milan Vukčević, Univerzitet Crne Gore, Mašinski fakultet, (milanvu@ucg.ac.me), Dušan Đurović, AD Mehanizacija i programat, (admip@t-com.me)

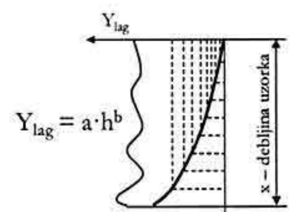
[2)] U okviru ovog rada saopštavaju se rezultati istraživanja koja se sprovode na projektu doktorskog istraživanja „Istraživanje parametara obrade abrazivnim vodenim mlazom" koji finansijski podržava Ministarstvo nauke Crne Gore

i mašina. Na taj način je ocrtana linija koja pokazuje putanju po kojoj se kretao abrazivni vodeni mlaz. Nakon toga, uzorci su do kraja rasijecani erozimatom. Napravljeno je sedamnaest uzoraka. Dobijeni uzorci i korišteni parametri obrade prikazani su u tabeli 1.

Tabela 1. Uzorci rezanja i korišteni parametri

I					
	$p_1 = 199,9$ MPa	$p_2 = 251,7$ MPa	$p_3 = 299,9$ MPa	$p_4 = 351,6$ MPa	$p_5 = 413,7$ MPa
	Rastojanje rezne glave od obradnog materijala x = 2 mm Brzina kretanja rezne glave v_c = 20 mm/min Protok abraziva m_a = 395 g/min				
II					
	$x_1 = 3$ mm	$x_2 = 4$ mm	$x_3 = 6$ mm		
	Radni pritisak p = 413,7 MPa Brzina kretanja rezne glave v_c = 20 mm/min Protok abraziva m_a = 395 g/min				
III					
	$v_{c1} = 5$ mm/min	$v_{c2} = 10$ mm/min	$v_{c3} = 30$ mm/min	$v_{c4} = 40$ mm/min	$v_{c5} = 60$ mm/min
	Radni pritisak p = 413,7 Mpa Rastojanje rezne glave od obradnog materijala x = 2 mm Protok abraziva m_a = 395 g/min				
IV					
	m_{a1}=166,5g/min	m_{a2}=229g/min	m_{a3}=274,5g/min	m_{a4}=331,5g/min	
	Radni pritisak p = 413,7 MPa Rastojanje rezne glave od obradnog materijala x = 2 mm Brzina kretanja rezne glave v_c = 20 mm/min				

Kako bi se odredila linija reza, uzorci su istraženi uz pomoć optičkog mikroskopa, a odstupanje mjereno na dvadeset mjesta po dubini reza. Princip mjerenja odstupanja abrazivnog vodenog mlaza je prikazan na slici 1.



Slika 1. Mjerenje odstupanja abrazivnog vodenog mlaza [5]

3. REZULTATI EKSPERIMENTALNIH ISTRAŽIVANJA

U tabelama 2, 3, 4 i 5 su date izmjerene vrijednosti odstupanja prednje linije reza od svoje idealne upravne linije, a u zavisnosti od promjene parametara procesa obrade (radnog pritiska, **p**, brzine kretanja rezne glave, v_C, protoka abraziva, m_a i rastojanja rezne glave od obradnog materijala, **x**).

Tabela 2. Izmjerene vrijednosti Y_{lag} u zavisnosti od p

	Uzorak				
	1	**2**	**3**	**4**	**5**
p, MPa	**199,9**	**251,7**	**299,9**	**351,6**	**413,7**
h, mm	**Y_{lag}, mm**				
0	0	0	0	0	0
2	0,0978	0,0774	0,0693	0,0590	0,0453
4	0,1473	0,1294	0,1277	0,0804	0,0906
6	0,1554	0,1534	0,1661	0,1531	0,1359
8	0,2108	0,2133	0,2104	0,1865	0,1811
10	0,3152	0,2726	0,2436	0,2198	0,2264
12	0,4381	0,3314	0,2608	0,2537	0,2717
14	0,5450	0,4058	0,3066	0,3042	0,3170
16	0,6765	0,5350	0,4178	0,4162	0,3623
18	0,8117	0,6642	0,5569	0,5385	0,4076
20	1,0111	0,7969	0,6451	0,6536	0,4786
22	1,2282	0,9297	0,8191	0,7461	0,5329
24	1,4628	1,1341	0,9932	0,8241	0,6382
26	1,7640	1,3384	1,1247	0,9159	0,7434
28	2,0834	1,5427	1,2561	1,0661	0,8487
30	2,5039	1,8170	1,3876	1,2163	0,9539
32	-	2,0914	1,6424	1,4484	1,1120
34	-	2,4332	1,8973	1,6805	1,2701
36	-	2,8380	2,1376	1,9127	1,4282
38	-	3,2731	2,4666	2,1448	1,5863
40	-	3,8638	2,7958	2,3769	1,7445

Tabela 3. Izmjerene vrijednosti Y_{lag} u zavisnosti od v_C

	Uzorak					
	9	**10**	**5**	**11**	**12**	**13**
v_C, mm/min	**5**	**10**	**20**	**30**	**40**	**60**
h, mm	**Y_{lag}, mm**					
0	0	0	0	0	0	0
2	0	0	0,0453	0,0926	0,0926	0,0926
4	0	0	0,0906	0,1852	0,1852	0,1852
6	0	0	0,1359	0,2777	0,2777	0,2777
8	0	0	0,1811	0,3703	0,3703	0,3703
10	0	0,0329	0,2264	0,4351	0,4351	0,5809
12	0	0,0658	0,2717	0,5232	0,6626	0,7997
14	0	0,1023	0,3170	0,6245	0,8925	1,1137
16	0,0393	0,1389	0,3623	0,8342	1,1718	1,4497
18	0,0786	0,2365	0,4076	1,0439	1,4512	1,7856
20	0,1179	0,3342	0,4786	1,3387	1,8412	2,3621
22	0,1572	0,4319	0,5329	1,6336	2,2312	2,9387
24	0,1965	0,5532	0,6382	1,9633	2,6259	3,4368
26	0,2359	0,6744	0,7434	2,2930	3,0207	4,0273
28	0,2752	0,7631	0,8487	2,7636	3,5046	4,6854
30	0,3289	0,9202	0,9539	3,2342	3,9984	5,3470
32	0,3826	1,0672	1,1120	3,7047	4,4723	6,0086
34	0,4363	1,2141	1,2701	4,1753	4,9562	6,6703
36	0,5485	1,3298	1,4282	4,6183	5,4635	7,5399
38	0,6608	1,5612	1,5863	5,0612	5,9708	8,4366
40	0,7730	1,6769	1,7445	5,5042	6,4779	9,3471

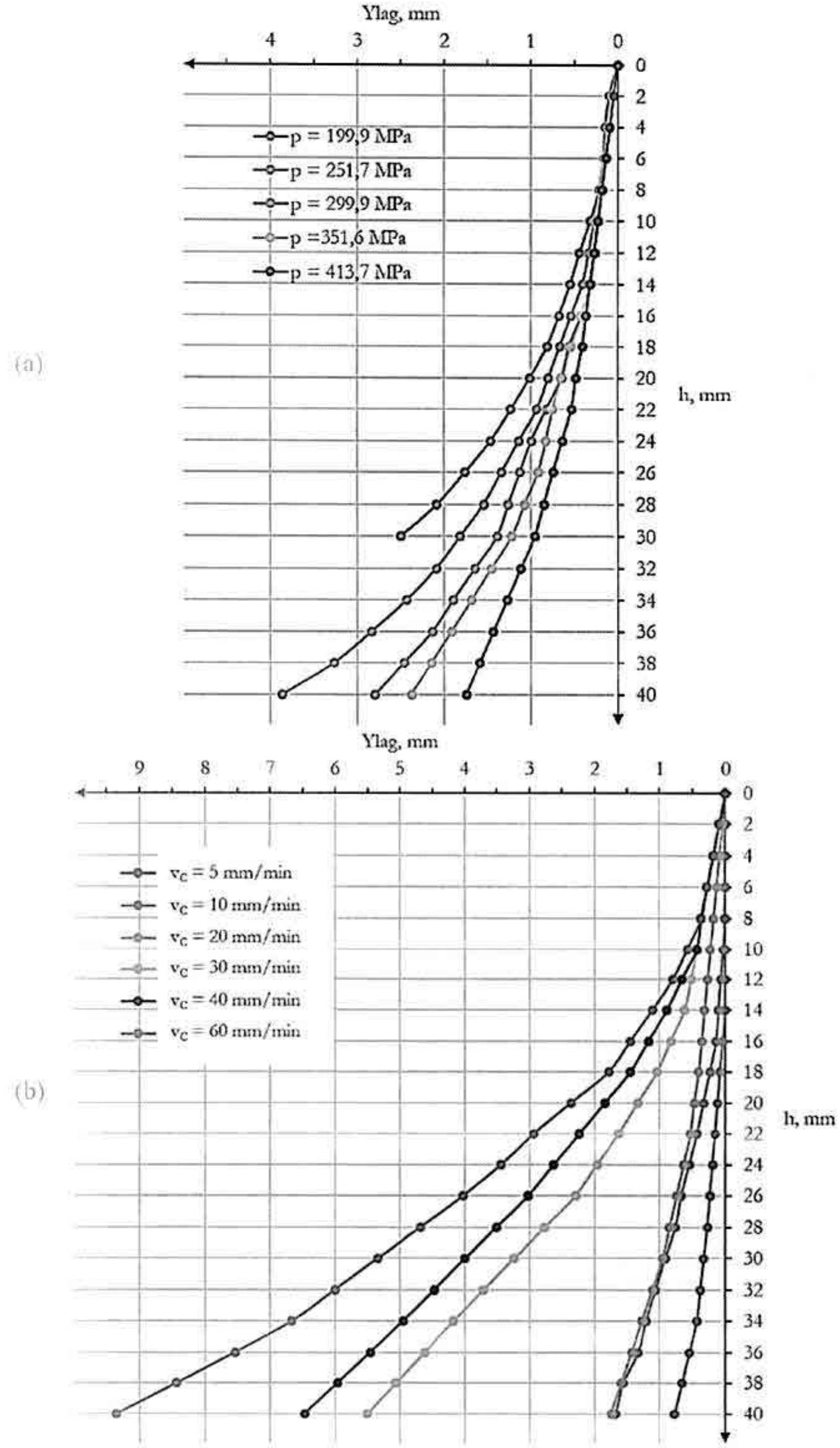
Tabela 4. Izmjerene vrijednosti Y_{lag} u zavisnosti od m_a

	Uzorak				
	14	**15**	**16**	**17**	**5**
m_a, g/min	**166,5**	**229**	**274,5**	**331,5**	**395**
h, mm	**Y_{lag}, mm**				
0	0	0	0	0	0
2	0,0926	0,0926	0,0834	0,0410	0,0453
4	0,1852	0,1852	0,1668	0,0820	0,0906
6	0,2777	0,2777	0,2503	0,1229	0,1359
8	0,3703	0,3703	0,3439	0,1639	0,1811
10	0,4715	0,4715	0,4175	0,2962	0,2264
12	0,6278	0,6278	0,4691	0,4284	0,2717
14	0,8224	0,7458	0,5187	0,5606	0,3170
16	1,0830	0,9277	0,7437	0,6928	0,3623
18	1,4235	1,0865	0,9907	0,8251	0,4076
20	1,7762	1,3359	1,2030	0,9999	0,4786
22	2,1288	1,5853	1,4153	1,1748	0,5329
24	2,5145	1,8378	1,7352	1,3876	0,6382
26	2,8689	2,0485	2,0485	1,7095	0,7434
28	3,2476	2,3667	2,3667	2,0332	0,8487
30	3,6263	2,6848	2,6848	2,3569	0,9539
32	4,0051	3,0029	3,0029	2,6806	1,1120
34	4,3838	3,321	3,3210	3,0043	1,2701
36	4,9571	3,8172	3,6890	3,3133	1,4282
38	5,5929	4,3531	3,9815	3,6340	1,5863
40	6,1071	4,8004	4,1935	3,9440	1,7445

Tabela 5. Izmjerene vrijednosti Y_{lag} u zavisnosti od x

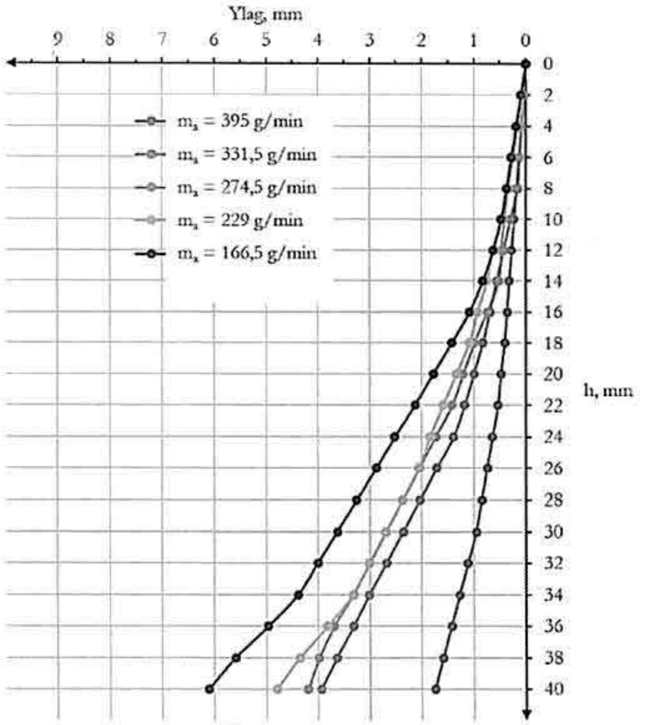
	Uzorak			
	5	**6**	**7**	**8**
x, mm	**2**	**3**	**4**	**6**
h, mm	**Y_{lag}, mm**			
0	0	0	0	0
2	0,0453	0,0651	0,0709	0,0703
4	0,0906	0,1303	0,1418	0,1407
6	0,1359	0,1954	0,2126	0,2110
8	0,1811	0,2309	0,2571	0,2813
10	0,2264	0,2754	0,3016	0,3517
12	0,2717	0,3198	0,3329	0,4220
14	0,3170	0,3643	0,3708	0,4923
16	0,3623	0,4087	0,4087	0,5627
18	0,4076	0,4624	0,5130	0,6330
20	0,4786	0,5160	0,6173	0,7033
22	0,5329	0,6443	0,7217	0,8407
24	0,6382	0,7726	0,8260	0,9782
26	0,7434	0,9107	0,9803	1,1337
28	0,8487	1,0489	1,1346	1,2892
30	0,9539	1,1871	1,2890	1,4448
32	1,1120	1,3642	1,5121	1,6671
34	1,2701	1,5414	1,7351	1,8894
36	1,4282	1,7185	1,9582	2,1116
38	1,5863	1,8957	2,1813	2,3339
40	1,7445	2,0729	2,4045	2,5563

Na osnovu ovih rezultata su nacrtani dijagrami koji pokazuju na slici 2. uticaj promjene režima rezanja i dubine rezanja na odstupanje prednje linije reza od svoje idealne linije, odnosno realan izgled prednje linije reza.

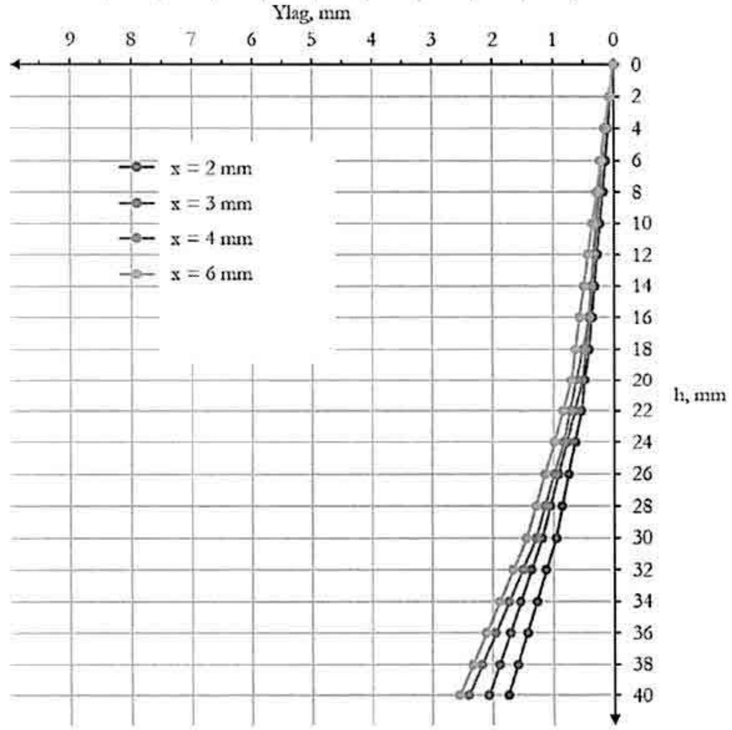


Slika 2 . Uticaj parametara procesa obrade abrazivnim vodenim mlazom na odstupanje prednje linije reza od svoje idealne upravne linije: (a) **p**, (b) $\mathbf{v_C}$, (c) $\mathbf{m_a}$ i (d) **x**.

(c)



(d)



Slika 2 (nastavak). Uticaj parametara procesa obrade abrazivnim vodenim mlazom na odstupanje prednje linije reza od svoje idealne upravne linije: (a) **p**, (b) $\mathbf{v_C}$, (c) $\mathbf{m_a}$ i (d) **x**.

4. ZAKLJUČAK

Sa dijagrama se uočava da sa porastom dubine rezanja raste i odstupanje prednje linije reza od svoje idealne linije. Takođe, porast brzine kretanja rezne glave i rastojanja rezne glave od obradnog materijala ima za poslijedicu povećanje odstupanja prednje linije reza od idealne. Sa povećanjem vrijednosti parametara obrade protoka abraziva i radnog pritiska, odstupanje prednje linije reza od idealne se smanjuje.

Ovim se jasno dokazuje jaka korelacija između odstupanje prednje linije reza od svoje idealne linije i primjenjenih parametara obrade.

Eksperimenti su izvršeni samo za jedan materijal, brzorezni alatni čelik EN HS6-5-2 (JUS č.7680, AISI M2), tako da je potrebno odraditi dodatna istraživanja na drugim materijalima kako bi se odredio uticaj mehaničkih karakteristika materijala na odstupanje prednje linije reza u odnosu na svoju idealnu liniju.

Takođe, istraživanje ovog odstupanja na materijalima sa različitim debljinama i drugim mehaničkim karakteristikama (modul elastičnosti, tvrdoća) može se istražiti ovaj fenomen i njegove zavisnosti od parametara obrade abrazivnim vodenim mlazom.

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Kurbegović, R., Janjić, M., Vukčević, M., Đurović, D.

EFFECT OF ABRASIVE WATER JET MACHINING PROCESS PARAMETERS ON JET LAGGING

Abstract: *Abrasive water jet processing is one of the unconventional production technologies that is increasingly used in the industry. However, in order to improve its performance, it is necessary to better understand the numerous input and output parameters of this process and their interdependence. The aim of this paper is to determine the influence of input processing parameters (working pressure, traverse speed, abrasive flow rate, and stand-off distance) on jet lag, or the deviation of the cutting front line from its ideal, perpendicular line. All the findings indicate that the applied machining parameters affect the jet lagging.*

Key words: *Abrasive Water Jet Machining, Material Processing, Jet lagging*

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Engineering Economic Analysis of Abrasive Water Jet Machining Quantitative Characteristics

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Abstract— **Abrasive waterjet machining (AWJM) is one of the unconventional manufacturing technologies of recent date. To find a wider application in the industry and to improve its performance, it is necessary to understand the numerous input and output machining parameters and their interaction on the machining. This paper aims to investigate the effect of process parameters such as traverse speed and abrasive flow rate, on the abrasive water jet machining quantitative characteristics – productivity and price. All findings obtained during the investigation indicate that process parameters of the machining influence its quantitative characteristics.**

Keywords— **Abrasive Water Jet, Engineering economic analysis, Water jet lagging, Quantitative characteristics, Material machining**

I. INTRODUCTION

The principles on which the abrasive water jet machining process is based on is erosion. Some authors explain the process of erosion as a kind of abrasive wear, at which abrasive particles and water jet repeatedly impact the surface, resulting in flushing of the material from that surface [1,2].

Several papers are dealing with the formation of cut front geometry and the factors that influence its final appearance. Mostly, the cutting front geometry of the workpiece machined by the abrasive water jet is influenced by machining parameters such as operating pressure, stand-off distance, traverse speed, abrasive flow rate [1,3].

Defining the geometry of the cutting front, is in fact, the determination of the deviation - lagging, Ylag, of the abrasive water jet from the vertical line. The line that defines the lagging of abrasive water jet is described by Zeng, Heines and Kim [4] as a parabola.

The aim of this paper is to analyse the influence of abrasive water jet machining parameters, such as traverse speed, vc, and abrasive mass flow rate, ma, on the quantitative characteristics of the machining – productivity and price. From our previous work [5], we concluded that the variation of operating pressure represents an economically wrong approach.

Analysing and comparing costs represents the basic aspects of engineering practice [6]. Since there are a large number of costs that affect the final price of the abrasive water jet machining, the analysis of the most dominant operating costs like water, electricity, and abrasive material, will be used.

II. EXPERIMENTAL WORK

To achieve better machining quantitative characteristics, productivity and price, influence of machining parameters such as traverse speed and abrasive flow rate were analysed.

Samples presented by Kurbegovic, Janjic, Vukcevic and Durovic [7], concerning the influence of the water pressure (p), traverse speed (vc), abrasive flow rate (ma) and stand-off distance (x) on the abrasive water jet lagging, were used for creating experimental variants for this work. Samples and its machining parameters are shown in tab. I.

The system used for machining the samples is the product of WJS, model NCX 4020, Sweden. The diameter of the water orifice was 0,254 mm and the abrasive nozzle (focusing tube) diameter was 0,768 mm (ROCTEC 100). The abrasive material was Garnet mesh 80.

The material used for the experiment is high-speed tool steel EN HS6-5-2 (JUS c.7680, AISI M2), produced with the Electro Slag Remelting (ESR) method in a round-shaped ingot, normalized, bandsawed to 42 mm thick discs and lathe cut to 40±0,05 mm. Material is then water jet machined to a 40x40x110±0,05 mm specimens. The side which is water jet machined is milled and flatten to 38±0,05 mm for distinction purposes. The material was cut to a length of 30 mm. Then the flow of abrasives was stopped and then the machine was stopped. After that, the specimens were cut till 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.

Measurements for determining water jet lagging were performed in twenty places (at the same distance) along the sample thickness using an optical microscope.

Measured values of jet lagging for samples shown in table I, are shown in Table II.

TABLE I SAMPLES AND ITS PARAMETERS [7]

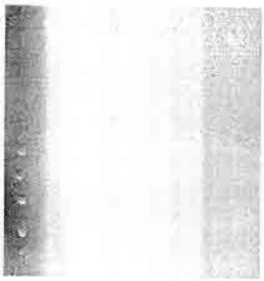
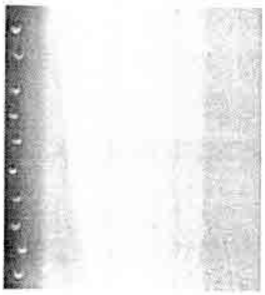
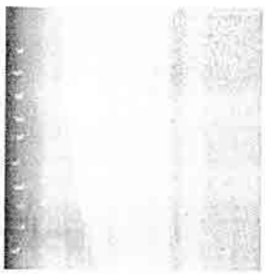
Sample 5	
	m_{a1} = 395 g/min p = 413,7 MPa x = 2 mm v_c = 20 mm/min
Sample 11	
	m_a = 395 g/min p = 413,7 MPa x = 2 mm v_{c3} = 30 mm/min
Sample 12	
	m_a = 395 g/min p = 413,7 MPa x = 2 mm v_{c4} = 40 mm/min
Sample 14	
	m_{a1} = 166,5 g/min p = 413,7 MPa x = 2 mm v_c = 20 mm/min
Sample 15	
	m_{a2} = 229 g/min p = 413,7 MPa x = 2 mm v_c = 20 mm/min

TABLE III MEASURED VALUES OF JET LAGGING

h	5	11	12	14	Calc.	15
0	0.000	0.000	0.000	0.000	0.000	0.000
2	0.045	0.093	0.093	0.093	0.093	0.093
4	0.091	0.185	0.185	0.185	0.185	0.185
6	0.136	0.278	0.278	0.278	0.278	0.278
8	0.181	0.370	0.370	0.370	0.370	0.370
10	0.226	0.435	0.435	0.472	0.472	0.472
12	0.272	0.523	0.663	0.628	0.628	0.628
14	0.317	0.625	0.893	0.822	0.766	0.746
16	0.362	0.834	1.172	1.083	0.969	0.928
18	0.408	1.044	1.451	1.424	1.175	1.087
20	0.479	1.339	1.841	1.776	1.452	1.336
22	0.533	1.634	2.231	2.129	1.729	1.585
24	0.638	1.963	2.626	2.515	2.016	1.838
26	0.743	2.293	3.021	2.869	2.265	2.049
28	0.849	2.764	3.505	3.248	2.599	2.367
30	0.954	3.234	3.998	3.626	2.933	2.685
32	1.112	3.705	4.472	4.005	3.267	3.003
34	1.270	4.175	4.956	4.384	3.602	3.321
36	1.428	4.618	5.464	4.957	4.118	3.817
38	1.586	5.061	5.971	5.593	4.680	4.353
40	1.745	5.504	6.478	6.107	5.145	4.800

The maximum installed power of the system was Pmax = 49,4 kW. Oil pump is driven by asynchronous motor with a nominal power of 37 kW. Other consumers, with an installed power of POP = 12,4 kW, are: air compressor, water treatment system, abrasive supply system, oil cooling system and CNC (Computer Numerical Control) workstation with automation. The maximum water flow of the system is 3,8 l/min (QA).

Conditions for electricity cost calculation are:

- η_P = 90 % - efficiency of the pump,
- η_{EM} = 93 % - efficiency of the electric motor,
- η_{CM} = 98 % - efficiency of the pipe network,
- η_{MP} = 90 % - efficiency of the intensifier,
- cos φ = 1 - power factor, and
- k = 0,5 - other consumers simultaneity coefficient.

Variant A of this work will be sample 14 from table 1. For getting almost identical values of water jet lagging, as in sample 14, linear interpolation was used on traverse speeds on samples 11 and 12. The calculated value of traverse speed is vcx = 36,61 mm/min and that will be the Variant B of this work. Both variants and its parameters are presented in Table III.

TABLE IIII VARIANTS FOR THE ANALYSIS

Variant A	Variant B
m_{a1} = 166.5 g/min	m_a = 395 g/min
p = 413,7 MPa	p = 413,7 MPa
x = 2 mm	x = 2 mm
v_c = 20 mm/min	v_{cx} = 36,61 mm/min

Costs will be analysed for a year of machining, with straight-line machining of 18 m/day, 20 working days/month. Water price will be JCV = 1 €/m3 and the price of abrasive Garnet # 80 will be JCA = 400 € /t. Electricity price will be calculated in accordance with the Price List of Elekroprivreda Crne Gore A.D. Niksic [8] for a basic model consumer with a two tariff meter connected to a 10 kV line, measuring the average 15-minute load, active and reactive power. The usage of electricity is divided evenly for both tariffs.

The needed Power for the pump (and motor) is described with equation (1).

$$P_P = \frac{p \cdot Q_A}{\eta_U} \qquad (1)$$

III. RESULTS AND DISCUSSION

According to the given length of machining (lD) and the traverse speeds (vc) we can get daily machining time (tO) for both variants (tO,A and tO,B).

$$t_{O,A} = \frac{l_D}{v_c} = 900 \ \frac{min}{day} \qquad (2)$$

$$t_{O,B} = \frac{l_D}{v_{cx}} = 491,67 \ \frac{min}{day} \qquad (3)$$

Using the tO, number of working days (NRD), abrasive mass flow rates for variants A (ma1) and B (ma) and unity price of abrasive (JCA), we can calculate abrasive grand total for A (CKAA) i B (CKAB):

$$CK_{AA} = t_{O,A} \cdot N_{RD} \cdot m_{a1} \cdot JC_A \cdot 10^{-6} \cong 14385,60 \ \frac{€}{year} \qquad (4)$$

$$CK_{AB} = t_{O,B} \cdot N_{RD} \cdot m_a \cdot JC_A \cdot 10^{-6} \cong 18644,13 \ \frac{€}{year} \qquad (5)$$

Total price of water consumption for A (CKVA) and B (CKVB) is:

$$CK_{VA} = JC_V \cdot Q_A \cdot t_O \cdot N_{RD} \cdot 10^{-3} \cong 820,80 \ \frac{€}{god} \qquad (6)$$

$$CK_{VB} = JC_V \cdot Q_A \cdot t_O \cdot N_{RD} \cdot 10^{-3} \cong 448,40 \ \frac{€}{god} \qquad (7)$$

From the given conditions for electricity cost calculation, total system efficiency (η_U) is 73,823 %.

The power needed by the abrasive water jet system, for both variants, is:

$$P_U = P_P + k \cdot P_{OP} = 27,49 \ kW \qquad (8)$$

The price of the electricity, for variants A and B, are shown in tabs IV, V and VI.

TABLE IVV MONTHLY PRICE OF THE ELECTRICITY FOR A VARIANT A

Name	Unit	Unity price [€c/kWh]	Consum. [kWh]	Price [€]
Active High	kWh	5.5340	4124	228.22
Active Low	kWh	2.7670	4124	114.11
Engaging	kW	7.3224	27.49	201.29
Losses High	kWh	0.5645	4124	23.28
Losses Low	kWh	0.2822	4124	11.64
Enc.Sus.En.	kWh	0.9439	8248	77.85
			Price w/o VAT (21%)	656.39

TABLE V MONTHLY PRICE OF THE ELECTRICITY FOR A VARIANT B

Name	Unit	Unity price [€c/kWh]	Consum. [kWh]	Price [€]
Active High	kWh	5.5340	2253	124.68
Active Low	kWh	2.7670	2253	62.34
Engaging	kW	7.3224	27.49	201.29
Losses High	kWh	0.5645	2253	12.72
Losses Low	kWh	0.2822	2253	6.36
Enc.Sus.En.	kWh	0.9439	4506	42.53
			Price w/o VAT (21%)	449.92

TABLE V PRICE OF THE ELECTRICITY

Name	Price [€/year]
Price of the electricity for variant A (CK_{EEA})	7876,68
Price of the electricity for variant B (CK_{EEB})	5399,04

The total price of the machining for variants A (CKA) and B (CKB) is:

$$CK_A = CK_{AA} + CK_{EEA} + CK_{VA} = 23083,08 \ \frac{€}{god} \qquad (9)$$

$$CK_B = CK_{AB} + CK_{EEB} + CK_{VB} = 24491,57 \ \frac{€}{god} \qquad (10)$$

The relationship between the total price of the machining for variants A and B is shown in equation 11.

$$\frac{CK_B}{CK_A} = 1{,}061 \qquad (11)$$

Calculating the price difference, we can improve the productivity of the variant A for the given difference. Improvement in the abrasive flow of the variant A (ma1') will be:

$$m'_{a1} = \frac{(CK_B - CK_A)}{[illegible]} \cdot 10^6 + m_{a1} \cong 183 \text{ g/min} \qquad (12)$$

For getting almost identical values of water jet lagging for newly abrasive flow rate, linear interpolation was used on samples 14 and 15. Calculated values of Ylag are shown in tab. II.

To get the productivity improvement, linear interpolation was carried on samples 5 and 11 (shown in tab. II) to get traverse speed value. Calculated value of traverse speed is vcy = 28,8 mm/min.

Improvement in productivity of the abrasive water jet system will be:

$$\frac{v_{cy}}{v_c} = 1{,}44 \qquad (13)$$

IV. CONCLUSIONS

The total price of the machining, using parameters from variant B, is 6,1% higher than the total price of the machining using parameters from variant A, with a same jet lagging and quality of the machining.

Machining speed of variant A could be improved to 28,8 mm/min, for the same jet lagging and quality of the machining and the price as in variant B. Improved productivity of the system will be 44%.

ACKNOWLEDGMENT

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Jet Lagging in Abrasive Water Jet Cutting of High-Speed Tool Steel

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Abrasive water jet machining is a very efficient unconventional method for contour cutting of different types of materials. Is one of the main characteristics of the quality of surfaces machined with this method is curved lines that appear during machining. These lines are a consequence of the deviation of the abrasive water jet from its ideal vertical line, jet lagging, which are the cause of machining errors.

The aim of this work is to investigate the influence of machining parameters on jet lagging. The samples of high-speed steel EN HS6-5-2 (JUS č.7680) were machined with an abrasive water jet under varying working pressure, traverse speed, abrasive mass flow rate, and stand-off distance. The jet lagging was measured at twenty places along with the depth of cut, and based on these results, the relationship between the jet lagging and machining parameters has been formed.

In order to correctly select the process parameters, an empirical model for the prediction of jet lagging in abrasive waterjet cutting of high-speed steel EN HS6-5-2 was developed using regression analysis. This developed model has been verified with the experimental results that reveal high applicability of the model within the experimental range used.

Keywords: Jet lagging, Abrasive waterjet, Empirical model, High speed tool steel, Regression analysis

1. INTRODUCTION

Abrasive Waterjet Cutting [AWJC] has various distinct advantages over the other non-conventional cutting technologies, such as no thermal distortion, high machining versatility, minimum stresses on the work piece, high flexibility and small cutting forces and has been proven to be an effective technology for processing various engineering materials [1]. It is superior to many other cutting techniques in processing variety of materials and has found extensive applications in industry [2]. However, AWJC has some drawbacks and limitations. It creates tapered edges on the kerf, especially when cutting at high traverse rates [3,4], generate loud noise and a messy working environment.

In the abrasive water jet cutting, the tool is the abrasive waterjet, Figure 1.

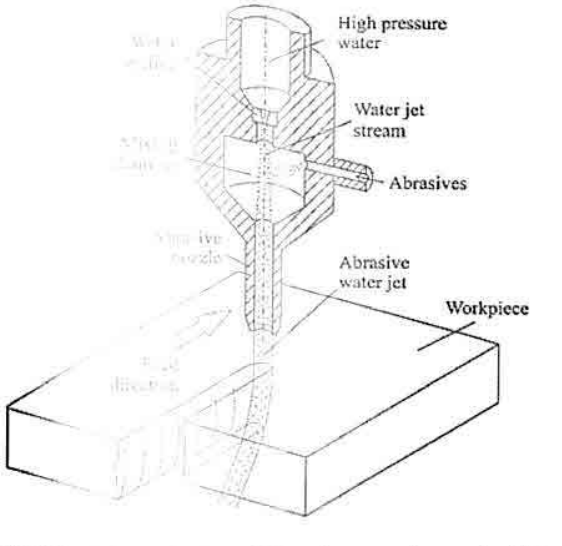

Figure 1: Machining view of abrasive water jet cutting [5]

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. From there, the abrasive water jet is directed to the work piece.

The principles on which the abrasive water jet machining process is based on is erosion. Some authors explain the process of erosion as a kind of abrasive wear, at which abrasive particles and water jet repeatedly impact the surface, resulting in flushing of the material from that surface [2,6].

There are several papers dealing with the formation of cut front geometry and the factors that influence its final appearance. Mostly, the cutting front geometry of the workpiece machined by the abrasive water jet is influenced by machining parameters such as operating pressure, stand-off distance, traverse speed, abrasive flow rate [2,7].

Defining the geometry of the cutting front, is in fact, the determination of the deviation - lagging, $\mathbf{Y_{lag}}$, of the abrasive water jet from the vertical line. Momber and Kovačević [2] explained the deviation of the cut front geometry from ideal as a consequence of energy loss during the cutting process, Figure 2.

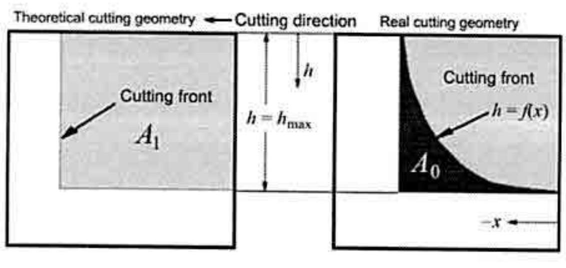

Figure 2: Deviation of the cut front geometry from ideal [2]

The line that defines the lagging of abrasive water jet is described by Zeng, Heines and Kim [8] as a parabola.

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The aim of this work is to investigate the influence of machining parameters, such as operating pressure, p, standoff distance, Sd, traverse speed, U, and abrasive mass flow rate, Ma, on jet lagging and to make an empirical model for the prediction of jet lagging in abrasive waterjet cutting of high-speed steel EN HS6-5-2.

M. Chithirai Pon Selvan i N. Mohana Sundara Raju [9] observed the maximum cutting depth, h_{max}, as a main parameter for evaluating the applicability of the abrasive water jet machining process for a particular material. They found that water pressure has the most effect on the depth of cut and surface roughness. An increase in water pressure is associated with an increase in depth of cut but a decrease in surface roughness. Depth of cut constantly increases and surface roughness decreases as mass flow rate increases. As nozzle traverse speed increase, surface roughness increases but depth of cut decreases. This means that low traverse speed should be used to have more depth of cut and surface smoothness but is at the cost of sacrificing productivity. This experimental study has resulted that standoff distance has no apparent effect on depth of cut. Nevertheless, surface smoothness increases as stand-off distance decreases. Using regression analysis, they developed a model for predicting the depth of cut of stainless steel. During the development of the model, various parameters of the abrasive water jet machining process were taken into account. Their model is represented by a formula:

$$h_{max} = 675 \cdot \frac{p^{0,130} \cdot Ma^{0,107} \cdot d_a^{1,795} \cdot \rho_a^{0,878}}{E^{0,24} \cdot U^{0,137} \cdot Sd^{0,009} \cdot \rho_w \cdot d_j} \quad (1)$$

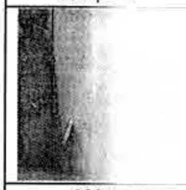
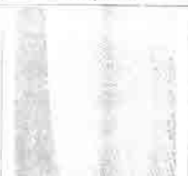
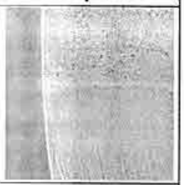
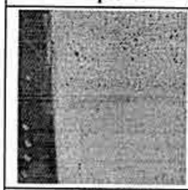
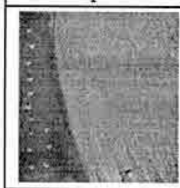
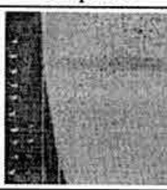
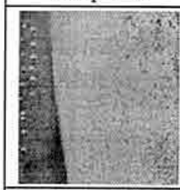
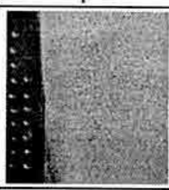
where p is the working pressure, **Ma** is the abrasive mass flow rate, d_a is the mean value of the abrasive particle diameter, ρ_a is the density of the abrasive particles, **E** is the material modulus of elasticity, **U** is the traverse speed, **Sd** is the stand-off distance of the cutting head from the workpiece, ρ_w is the density of the water and d_j is the diameter of the water jet.

This model showed a good corelation with the experimentally obtained results and will be used as a basis for experimental analysis of the influence of the machining process parameters on the jet lagging.

2. EXPERIMENTAL WORK

Samples examined by Kurbegovic, Janjic, Vukcevic and Durovic [10], Table 1, concerning the influence of the water pressure (p), traverse speed (U), abrasive flow rate (Ma) and stand-off distance (Sd) on the abrasive water jet lagging, were used for creating relationships and adopting a mathematical model of influence of the machining process parameters on the jet lagging.

Table 1: Samples and its machining parameters [10]

Sample 1	Sample 2	Sample 3
		
p_1 = 199,9 MPa U = 20 mm/min Ma = 395 g/min Sd = 2 mm	p_2 = 251,7 MPa U = 20 mm/min Ma = 395 g/min Sd = 2 mm	p_3 = 299,9 MPa U = 20 mm/min Ma = 395 g/min Sd = 2 mm
Sample 4	Sample 5	Sample 6
		
p_4 = 351,6 MPa U = 20 mm/min Ma = 395 g/min Sd = 2 mm	p_5 = 413,7 MPa U = 20 mm/min Ma = 395 g/min Sd = 2 mm	p = 413,7 MPa U = 20 mm/min Ma = 395 g/min Sd_1 = 3 mm
Sample 7	Sample 8	Sample 9
		
p = 413,7 MPa U = 20 mm/min Ma = 395 g/min Sd_2 = 4 mm	p = 413,7 MPa U = 20 mm/min Ma = 395 g/min Sd_3 = 6 mm	p = 413,7 MPa U = 5 mm/min Ma = 395 g/min Sd = 2 mm
Sample 10	Sample 11	Sample 12
		
p = 413,7 MPa U_2 = 10 mm/min Ma = 395 g/min Sd = 2 mm	p = 413,7 MPa U_3 = 30 mm/min Ma = 395 g/min Sd = 2 mm	p = 413,7 MPa U_4 = 40 mm/min Ma = 395 g/min Sd = 2 mm
Sample 13	Sample 14	Sample 15
		
p = 413,7 MPa U_5 = 60 mm/min Ma = 395 g/min Sd = 2 mm	p = 413,7 MPa U = 20 mm/min M_{a1} = 166,5 g/min x = 2 mm	p = 413,7 MPa U = 20 mm/min M_{a2} = 229 g/min Sd = 2 mm
Sample 16	Sample 17	
		
p = 413,7 MPa U = 20 mm/min M_{a3} = 274,5 g/min Sd = 2 mm	p = 413,7 MPa U = 20 mm/min M_{a4} = 331,5 g/min Sd = 2 mm	

The system used for machining the samples is the product of WJS, model NCX 4020, Sweden. The diameter of the water orifice was 0,254 mm and the abrasive nozzle (focusing tube) diameter was 0,768 mm (ROCTEC 100). The abrasive material was Garnet mesh 80.

The material used for the experiment is high-speed tool steel EN HS6-5-2 (JUS c.7680, AISI M2), produced with the Electro Slag Remelting (ESR) method in a round-shaped ingot, normalized, bandsawed to 42 mm thick discs and lathe cut to 40±0,05 mm. Material is then water jet machined to a 40x40x110±0,05 mm specimens. The side which is water jet machined is milled and flatten to 38±0,05 mm for distinction purposes. The material was cut to a length of 30 mm. Then the flow of abrasives was stopped and then the machine was stopped. After that, the specimens were cut till the end with Wire Electric Discharge Machining (WEDM). Cutting with WEDM was done to avoid damaging the cut front line and that it could be possible to measure the jet lagging.

Measurements for determining water jet lagging were performed in twenty places (at the same distance) along the sample thickness using an optical microscope. Measurement principle of jet lagging is shown on Figure 3.

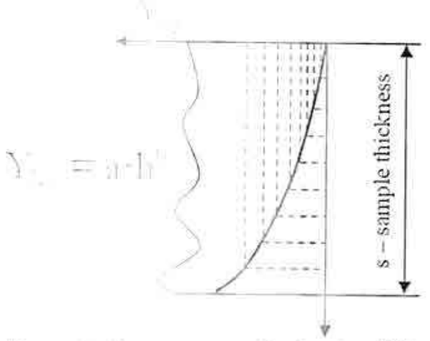


Figure 3: Measurement of jet lagging [11]

Measured values of jet lagging for samples shown in Table 1 are shown in Table 2.

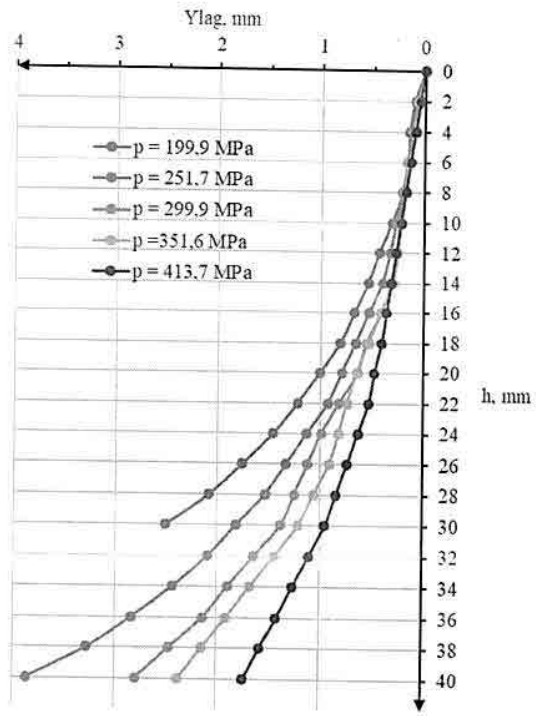
Table 2: Measured values of jet lagging [10]

	Sample 1	Sample 2	Sample 3	Sample 4
h, mm	Y_{lag}, mm			
0	0	0	0	0
2	0,0978	0,0774	0,0693	0,0590
4	0,1473	0,1294	0,1277	0,0804
6	0,1554	0,1534	0,1661	0,1531
8	0,2108	0,2133	0,2104	0,1865
10	0,3152	0,2726	0,2436	0,2198
12	0,4381	0,3314	0,2608	0,2537
14	0,5450	0,4058	0,3066	0,3042
16	0,6765	0,5350	0,4178	0,4162
18	0,8117	0,6642	0,5569	0,5385
20	1,0110	0,7969	0,6451	0,6536
22	1,2282	0,9297	0,8191	0,7461
24	1,4628	1,1341	0,9932	0,8241
26	1,7640	1,3384	1,1247	0,9159
28	2,0834	1,5427	1,2561	1,0661
30	2,5034	1,8170	1,3876	1,2163
32	-	2,0914	1,6424	1,4484
34	-	2,4332	1,8973	1,6805
36	-	2,8380	2,1376	1,9127
38	-	3,2731	2,4666	2,1448
40	-	3,8638	2,7958	2,3769
	Sample 5	**Sample 6**	**Sample 7**	**Sample 8**
h, mm	**Y_{lag}, mm**			
0	0	0	0	0
2	0,0453	0,0651	0,0709	0,0703
4	0,0906	0,1303	0,1418	0,1407
6	0,1359	0,1954	0,2126	0,2110
8	0,1811	0,2309	0,2571	0,2813
10	0,2264	0,2754	0,3016	0,3517
12	0,2717	0,3198	0,3329	0,4220
14	0,3170	0,3643	0,3708	0,4923
16	0,3623	0,4087	0,4087	0,5627
18	0,4076	0,4624	0,5130	0,6330
20	0,4786	0,5160	0,6173	0,7033
22	0,5329	0,6443	0,7217	0,8407
24	0,6382	0,7726	0,8260	0,9782
26	0,7434	0,9107	0,9803	1,1337
28	0,8487	1,0489	1,1346	1,2892
30	0,9539	1,1871	1,2890	1,4448
32	1,1120	1,3642	1,5121	1,6671
34	1,2701	1,5414	1,7351	1,8894
36	1,4282	1,7185	1,9582	2,1116
38	1,5863	1,8957	2,1813	2,3339
40	1,7445	2,0729	2,4045	2,5563
	Sample 9	Sample 10	Sample 11	Sample 12
h, mm	**Y_{lag}, mm**			
0	0	0	0	0
2	0	0	0,0926	0,0926
4	0	0	0,1852	0,1852
6	0	0	0,2777	0,2777
8	0	0	0,3703	0,3703
10	0	0,0329	0,4351	0,4351
12	0	0,0658	0,5232	0,6626
14	0	0,1023	0,6245	0,8925
16	0,0393	0,1389	0,8342	1,1718
18	0,0786	0,2365	1,0439	1,4512
20	0,1179	0,3342	1,3387	1,8412
22	0,1572	0,4319	1,6336	2,2312
24	0,1965	0,5532	1,9633	2,6259
26	0,2359	0,6744	2,2930	3,0207
28	0,2752	0,7631	2,7636	3,5046
30	0,3289	0,9202	3,2342	3,9984
32	0,3826	1,0672	3,7047	4,4723
34	0,4363	1,2141	4,1753	4,9562
36	0,5485	1,3298	4,6183	5,4635
38	0,6608	1,5612	5,0612	5,9708
40	0,7730	1,6769	5,5042	6,4779
	Sample 13	Sample 14	Sample 15	Sample 16
h, mm	**Y_{lag}, mm**			
0	0	0	0	0
2	0,0926	0,0926	0,0926	0,0834
4	0,1852	0,1852	0,1852	0,1668
6	0,2777	0,2777	0,2777	0,2503
8	0,3703	0,3703	0,3703	0,3439
10	0,5809	0,4715	0,4715	0,4175
12	0,7997	0,6278	0,6278	0,4691

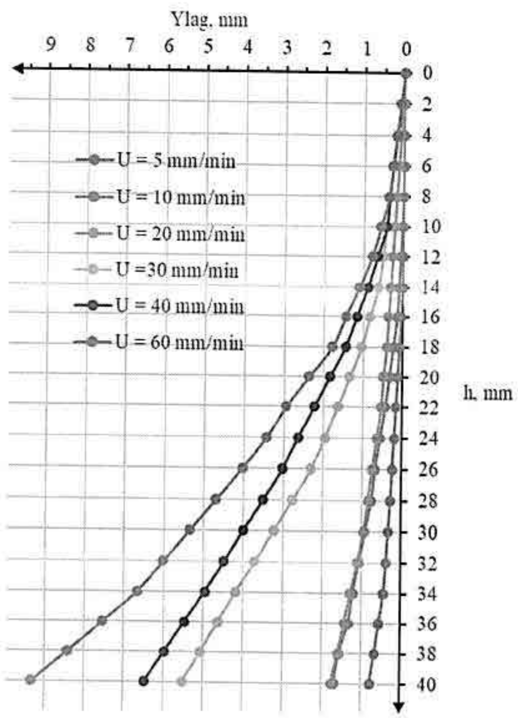
14	[illegible]	[illegible]	0,7458	0,5187
16	[illegible]	1,0830	0,9277	0,7437
18	1,7856	1,4255	1,0865	0,9907
20	2,3621	1,7762	1,3359	1,2030
22	2,9387	2,1288	1,5853	1,4153
24	3,4368	2,5145	1,8378	1,7352
26	4,0273	2,8689	2,0485	2,0485
28	4,6854	3,2476	2,3667	2,3667
30	[illegible]	3,6263	2,6848	2,6848
32	6,0086	4,0051	3,0029	3,0029
34	[illegible]	4,3838	3,321	3,3210
36	[illegible]	4,9571	3,8172	3,6890
38	8,4360	5,5929	4,3531	3,9815
40	9,3471	6,1071	4,8004	4,1935

	Sample [illegible]
h, mm	Y_{lag}, mm
0	0
2	[illegible]
4	[illegible]
6	[illegible]
8	0,1639
10	0,2962
12	[illegible]
14	0,5606
16	[illegible]
18	[illegible]
20	[illegible]
22	[illegible]
24	[illegible]
26	[illegible]
28	2,0552
30	2,3569
32	2,6806
34	[illegible]
36	[illegible]
38	[illegible]
40	[illegible]

It was concluded in [10] and shown on figure 2 that as the cutting depth increases, the deviation of the front cutting line from its ideal line, jet lagging, also increases. The increase in traverse speed and the distance of the cutting head from the machining material, stand-off distance, results in an increase of the jet lagging. As the values of the abrasive flow and working pressure processing parameters increase, the jet lagging decreases. This clearly demonstrates the strong correlation between the jet lagging and the applied machining parameters.



(a)



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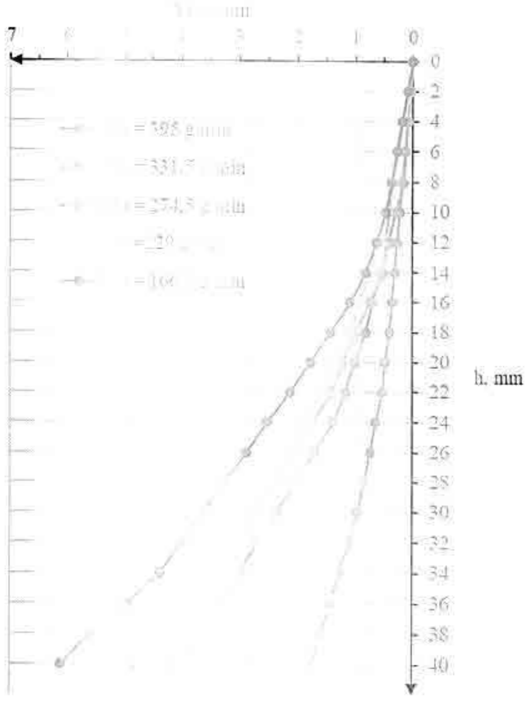
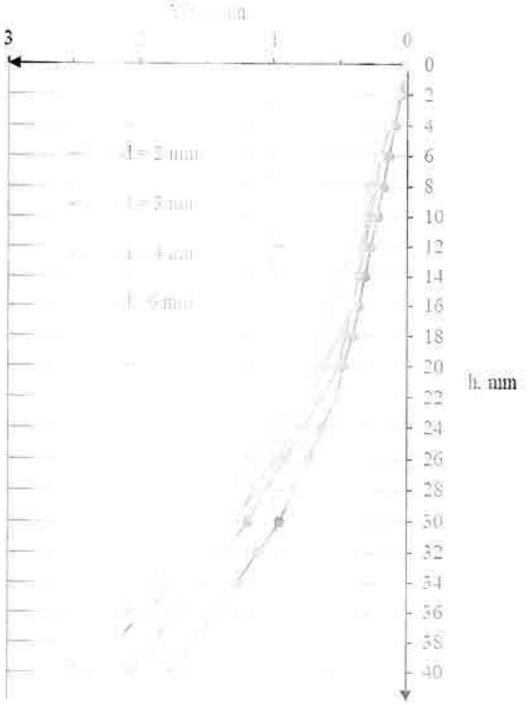


(c)



(d)

Figure 4: Influence of (a) operating pressure, (b) traverse speed, (c) abrasive mass flow rate and (d) stand-off distance on jet lagging [10]

3. PREDICTIVE MODEL FOR JET LAGGING

AWJC process involves a large number of variables that affect the cutting performance. Dimensional analysis is a powerful analytical technique in describing the relationship between physical engineering quantities (such as jet lagging) and independent variables. This technique is used to develop mathematical model for the jet lagging based on the experimental data for high-speed tool steel. The constants in the models were obtained by the regression analysis technique. These constants were statistically determined at minimum 95 % confidence level. This model relates the jet lagging to four process variables, namely water pressure, nozzle traverse speed, abrasive mass flow rate and nozzle stand-off distance.

Mathematical model adopted for this research work will be as follows:

$$Y_{lag}=a \cdot h^{b} \cdot p^{c} \cdot U^{d} \cdot Ma^{e} \cdot Sd^{f} \quad (2)$$

where **a, b, c, d, e, f** are regression analysis coefficients.

The above model is valid for the operating parameters in the following range for practical purposes and machine limitations:

- Water pressure: 199,9 MPa < p < 413,7 MPa,
- Traverse speed: 5 mm/min < U < 60 mm/min,
- Abrasive mass flow rate: 166,5 g/min < ma < 395 g/min and
- Stand-off distance: 2 mm < Sd < 6 mm.

The mathematical model that describes the impact of the corresponding machining parameters on the jet lagging was given for each diagram.

$$Y_{lag}=1.347 \cdot h^{2.132} \cdot p^{-1.251} \quad (3)$$

Standard deviation of (3) is R = 0.9948869.

$$Y_{lag}=0.0001017 \cdot h^{1.945} \cdot U^{1.046} \quad (4)$$

Standard deviation of (4) is R = 0.986002.

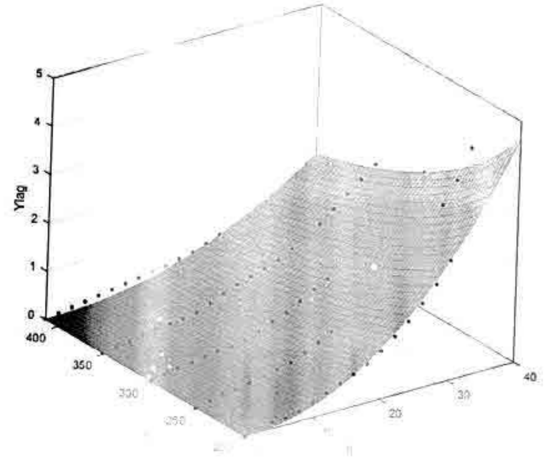
$$Y_{lag}=1.022 \cdot h^{1.821} \cdot Ma^{-0.9575} \quad (5)$$

Standard deviation of (5) is R = 0.9948869.

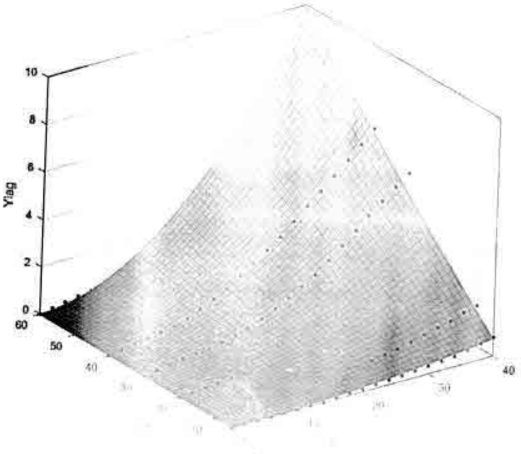
$$Y_{lag}=0.001864 \cdot h^{1.789} \cdot Sd^{0.352} \quad (6)$$

Standard deviation of (6) is R = 0.9943339.

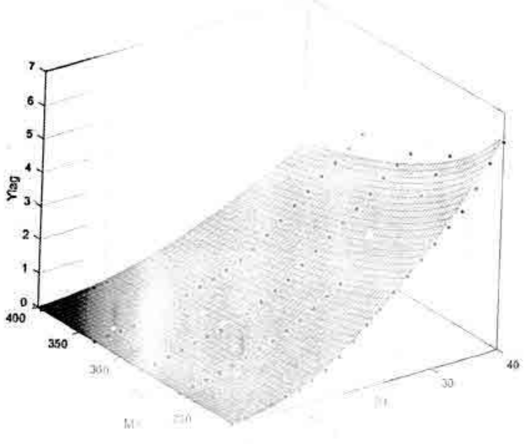
It is shown that the model predictions are in good agreement with the experimental data with the deviations less than 3 %. Also, using the MATLab software package, multiple regression analysis was performed on the measured values of jet lagging, Ylag, and given in a 3D representations in figure 5, within the experimental range.



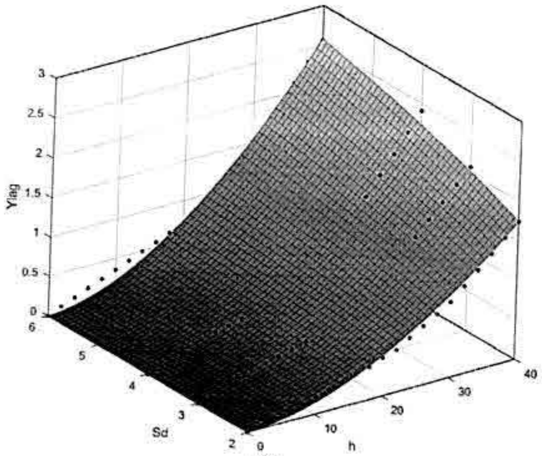
(a)



(b)



(c)



(d)

Figure 5: Influence of (a) operating pressure, (b) traverse speed, (c) abrasive mass flow rate and (d) stand-off distance on jet lagging

Based on the measured values in Table 2, the relationship between the jet lagging and operating pressure, stand-off distance, traverse speed, abrasive mass flow rate and depth of cut, is formed. This relationship is represented by a mathematical model described in (2).

$$Y_{lag}=3.4656\cdot\frac{h^{1.4008}\cdot Sd^{0.1086}\cdot U^{1.1424}}{p^{0.4053}\cdot Ma^{1.1316}} \qquad (7)$$

Standard deviation of (7) is R = 0.9702062.

Figure 6 shows the observed values of the jet lagging versus the values of the jet lagging predicted by the model presented in (7).

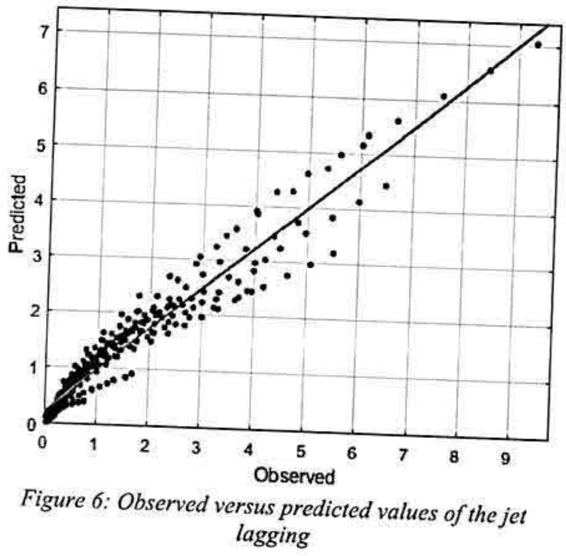


Figure 6: Observed versus predicted values of the jet lagging

4. CONCLUSIONS

Experimental investigations have been carried for the jet lagging in abrasive waterjet cutting of high-speed tool steel. The effects of different operational parameters such as: pressure, abrasive mass flow rate, traverse speed and nozzle stand-off distance on jet lagging have been investigated.

The change of the jet lagging as the function of operating pressure, stand-off distance, traverse speed, and abrasive mass flow rate can be noted. With the increase of the traverse speed, there is an increase in 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.

It is interesting that the exponent associated with the depth of cut in all Equations (3, 4, 5 and 6), has a value of about 2.

As a result of this study, it is observed that these operational parameters have a direct effect on jet lagging. It has been found that traverse speed has the most effect on jet lagging. An increase in traverse speed is associated with an increase in jet lagging. These findings indicate that the use of low traverse speed is preferred to obtain overall good cutting performance but at the cost of productivity. Jet lagging constantly decreases as the mass flow rate increases. It is recommended to use a more mass flow rate to decrease jet lagging. Among the process parameters considered in this study traverse speed and abrasive mass flow rate have a similar effect on jet lagging, but one opposite from another. Stand-off distance has no apparent effect on jet lagging but to achieve an overall cutting performance, low stand-off distance should be selected.

From the experimental results, an empirical model for the prediction of jet lagging in the AWJC process of high-speed tool steel has been developed using regression analysis. Also verification of the developed model for using it as a practical guideline for selecting the parameters has been found to agree with the experiments. Therefore, the need for extensive experimental work in order to select the magnitudes of the most influential abrasive waterjet cutting parameters on jet lagging of high-speed tool steel can be eliminated.

Based on the model from (7), 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 curve, because major mistakes occur there.

From the (7), we can conclude that an increase of the depth of cut, stand-off distance and traverse speed leads to an increase of the jet lagging, and with an increase of operating pressure and abrasive mass flow rate jet lagging decreases.

The experiments were carried out on only one material, EN HS6-5-2 so that the obtained models are only valid for this material. It is necessary to carry out the experiments on different materials or the same material with different heat treatments to determine the effects of the mechanical properties of materials on the jet lagging.

It would also be interesting to carry out the experiments of the same material with different thicknesses and other mechanical properties, and to investigate this phenomenon and its dependencies.

NOMENCLATURE

d_a	Mean diameter of abrasive particles
d_j	Diameter of water jet
h	Depth of cut
Ma	Abrasive mass flow rate
p	Working pressure
U	Traverse speed
Sd	Stand-off distance
E	Materials Young´s modulus
Y_{lag}	Jet lagging
ρ_a	Abrasives density
ρ_w	Density of water
s	Sample thickness
a, b, c, d, e f	Coefficients of regresion analysis

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MMA 2021 Flexible Tehnologies <mma2021@uns.ac.rs> — Wed, Aug 25, 2021 at 4:47 PM

To: Ramiz Kurbegović <rkurbeg@gmail.com>, Mileta Janjić <mileta@ucg.ac.me>

Dear colleagues,

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Mašinski fakultet
Komisija za doktorske studije
Podgorica, 24.09.2021.

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Predlažemo Vijeću Mašinskog fakulteta da usvoji izvještaje i da se isti, uz mišljenje dostave Odboru za doktorske studije UCG na dalje postupanje.

Srdačno,

Za Komisiju za doktorske studije

Prof. dr Aleksandar Vujović