POSSIBILITIES OF 3D MACHINING OF MATERIALS BY ABRASIVE WATER JETS

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ABSTRACT

Machining of materials through classical way, i.e. using conventional tools for turning, drilling, milling, grinding and polishing, has some limits that can be overcome applying an abrasive water jet (AWJ). Therefore, some possibilities of 3D machining by AWJ placed on 6 axes robot have been tested. Programming of traverse speeds and tilting angles of cutting head was based on Hlaváč's theoretical model. Low pressure pump has been used for tests. Because of very low pumping pressure, a self-designed and manufactured special mixing chamber was used in the experiments. The article deals with preliminary results and points at the direction of further research.

Keywords: abrasive water jet, composite, cutting, trailback, taper

NOMENCLATURE

α_e	Experimentally determined coefficient of abrasive water jet velocity loss in interaction with material…[-]
θ	Angle measured in the plane containing vector of traverse speed and stating the deviation of the jet axis in depth *h* and the perpendicular in the point where the jet axis penetrates surface of material – the declination angle…[rad]
$\theta_{\lim}$	Limit value of the declination angle…[rad]
ξ_j	Attenuation coefficient of abrasive jet in the environment between the focusing tube outlet and the material surface…[m^{-1}]
ρ_j	Density of abrasive jet (conversion to homogeneous liquid)…[kg.m^{-3}]
ρ_m	Density of material being machined…[kg.m^{-3}]
σ	Trailback…[m]
σ_m	Strength of material being machined (compressive, tensile or shear)…[Pa]
φ	Angle measured in the plane perpendicular to the vector of traverse speed and stating the deviation of the tangent to the plane section with kerf wall and the perpendicular in the point where the jet axis penetrates surface of material – the inclination angle…[rad]
$\varphi_{\lim}$	Limit value of the inclination angle…[rad]
a_n	Average mean size of the abrasive particles after the mixing process…[m]
C_A	Coefficient modifying abrasive water jet performance in relation to the changing content of abrasive below so-called saturation level (above this level, the jet performance increases no more and $C_A = 1$)[-]
D_{bc}	Bottom diameter of the circular part of cutting trajectory…[m]
d_o	Water nozzle (orifice) diameter…[m]
d_a	Focusing tube diameter…[m]
h	Depth of material disintegration (actual depth of cut)…[m]

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p. 18 – 23, ISSN 1802-5420
DOI 10.35180/gse-2019-0008

$h_{\lim}$	Maximum depth of liquid jet penetration into material for selected conditions…[m]
H	Material thickness…[m]
L	Stand-off distance of the material surface or the investigated plane perpendicular to the liquid jet axis from the nozzle or focusing tube outlet…[m]
p_j	Pressure calculated from Bernoulli's equation for *liquid* with density and velocity of *abrasive jet*…[Pa]
q	Constant characterizing ductility and brittleness of material…[rad]
R	Set radius of cutting trajectory…[m]
S_P	Ratio between the quantity of non-damaged grains (i.e. not containing defects) and the total quantity of grains in the supplied abrasive material…[-]
v_P	Traverse speed of the jet trace on the material surface…[m.s^{-1}]
$v_{P\min}$	Minimum traverse speed of cutting – correction for the zero traverse speed (the value should be equal to the average mean size of the abrasive particles after the mixing process per minute, i.e. $v_{Pmin} = a_n/60$)…[m.s^{-1}]
$v_{P\lim}$	Limit traverse speed of jet trace on the material surface for the thickness H…[m.s^{-1}]

1 INTRODUCTION

Abrasive water jet (AWJ) machining has been known for over 40 years. It was introduced, described and presented by Hashish [1]. It is often used to cut either semi-finished products or even final products, namely from plan-parallel plates of material. Nevertheless, applications of abrasive water jets for milling [2], turning [3], grinding [4] or polishing [5] are tested more and more often, because they bring some benefits regarding classical machining processes. Utilization of abrasive water jet as a machining tool for composite materials and rocks is getting broader [6-8]. One of the important benefits of AWJ utilization is low probability of damage of this tool due to sudden material strength changes. This fact can be a big advantage in cases, when various materials are to be machined, e.g. for decorative purposes or small-scale production. Therefore, job-shops have arisen besides big firms applying AWJ for their large-series production of rarely variable semi-finished or final products. The job-shops machine semi-final or final products from materials demanded by customer, therefore, need to cover a whole scale of material strengths' changes. The tested machining system is based on a low pressure pump with approximately three times higher flow rate regarding commonly used high pressure pumps and six axes robot. The first experience, experimental results and further research plans are presented in this article.

2 THEORETICAL BACKGROUND

The theoretical base for AWJ machining control has been published few years ago by Hlaváč [9] and Hlaváč et al. [10, 11]. It is focused on the two important parameters closely related to the jet penetration through material – limit penetration depth and limit traverse speed. The limit penetration depth is the maximum average one (for selected traverse speed, material type and jet parameters) that can be reached in material by AWJ (Eq. 1).

$$h_{\lim} = \frac{C_A\, S_p\, \pi\, d_o \sqrt{2\rho_j p_j^3\, e^{-5\xi_j L}}\, \left(1-\alpha_e^2\right)}{8\left(v_P + v_{P\min}\right)^{1.5} \left(\rho_m p_j \alpha_e^2\, e^{-2\xi_j L} + \rho_j \sigma_m\right)} \tag{1}$$

Similarly, the limit traverse speed is the maximum average one (for selected material type, thickness and jet parameters) that enables to provide dividing cut (Eq. 2).

$$v_{P\lim} = \left[\frac{C_A S_P \pi d_0 \sqrt{2\rho_j p_j^3 e^{-5\xi_j L}}\;\; 1-\alpha_e^2}{8H\;\; \rho_m p_j \alpha_e^2 e^{-2\xi_j L} + \rho_j \sigma}\right]^{\frac{2}{3}} - v_{P\min} \tag{2}$$

Volume LXV (2019), No. 2
p. 18 – 23, ISSN 1802-5420
DOI 10.35180/gse-2019-0008

Both these factors are closely connected with the two main problems limiting AWJ machining accuracy: the trailback and the taper. The typical simplistic description of jet penetration through material is replacement of the real trajectory by simple curves, namely of a parabolic shape. The respective equations describing the trailback and the taper are presented in articles published by Hlaváč et al. [10, 11]. Equation (3) describes the trailback

$$\sigma = \frac{2}{5} H \operatorname{tg}\left[\theta_{\lim}\left(\frac{v_P}{v_{P\lim}}\right)^{\frac{3}{2}}\right] \tag{3}$$

and Eq. (4) describes the inclination angle closely related to the taper.

$$\varphi = \varphi_{\lim}\left(\frac{h}{h_{\lim}}\right)^{\frac{2}{5}} + q \tag{4}$$

The resulting theoretical equation combining influence of the trailback and the taper has been presented in Hlaváč et al. [12] and it enables calculation of the bottom diameter in the curved parts of trajectories:

$$D_{bc} = 2\left[\sqrt{\left(\frac{2}{5} H \tan\theta\right)^2 + R^2} + \frac{2}{5} H \tan\varphi\right] + d_a \tag{5}$$

It is evident that compensation of influence of the diameter of an abrasive focussing tube, the trailback and the taper shift can be suppressed by jet tilting and correction of the trajectory radius. Therefore, these corrections were tested in the experimental part of the research work.

3 EXPERIMENTAL SET-UP

Experiments were performed with a special injection abrasive water jet head for low pressure and high flow rate. The deformation of column samples and reduction of difference between the top and the bottom diameters was tested. The photo of the robot used for sample preparation with various tilting of cutting head is presented in Fig. 1. The experimental conditions used in all presented tests are summarized in Table 1. Results of column cutting with cutting head without and with tilting are presented in Fig. 2. This figure also shows the typical striations on the samples' walls. It is evident that non-tilted jet makes more noticeable striations and the sample is rather truncated cone shaped then a "column" shaped. By contrast to it, the tilted jet produces rather barrel shaped samples with striations better visible even in the bottom part. It can also be noticed by the naked eye that diameter of the top base of the sample produced by a non-tilted jet is smaller than that of the tilted jet and some slight increase of the diameter of the bottom base can be also noticeable.

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p. 18 – 23, ISSN 1802-5420
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Figure 1. Device for the AWJ cutting – robot with special mixing head

Table 1. Parameters used in experiments

Pressure in pump	23 MPa
Water jet diameter	1.2 mm
Focusing tube diameter	3 mm
Focusing tube length	152 mm
Abrasive mass flow rate	500 g/min
Mean abrasive grain size[a]	0.375 mm (50 mesh)[b]
Abrasive type	Australian garnet (almandine)
Traverse speed	20 mm/min
Stand-off distance	2 mm

[a] Mean grain size is determined on the commercial particles size analyzer.

[b] The "mesh" specification is commercial indication provided by suppliers.

Several columns were cut: one half of them with jet axis perpendicular to the surface of the plan-parallel sheet of composite plate, the second half with tilting of the cutting head compensating deformation caused by trailback. Both sets of samples were measured on the top and bottom to compare their diameters with each other.

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DOI 10.35180/gse-2019-0008

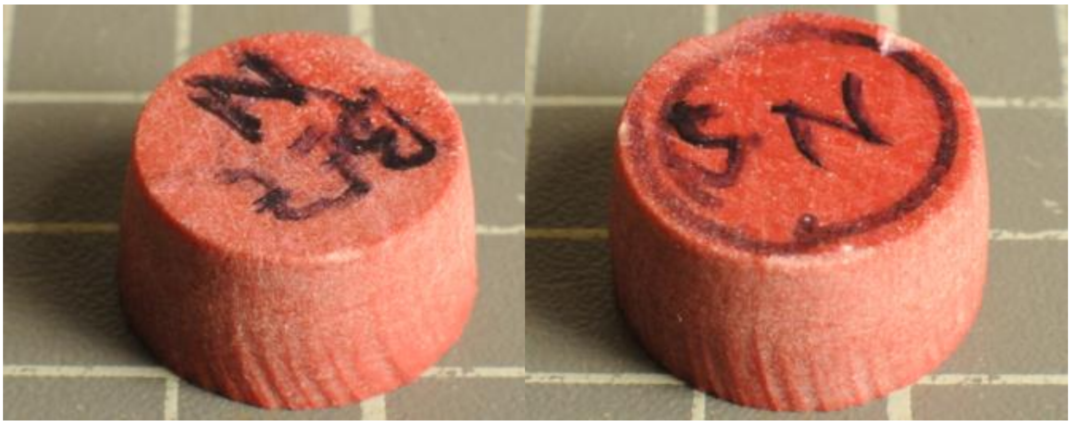

Figure 2. Column cut without AWJ head tilting (left) and with tilting (right)

The respective average diameters for a non-tilted jet are 16.47 mm at the top and 18.59 mm at the bottom. The respective values for tilted jet are 18.30 mm (top) and 19.34 mm (bottom). The set-up diameter was 20 mm for all experimental tests. The increase of top and bottom diameters for tilted regarding the non-tilted jets correlates with findings presented by Hlaváč et al. (2018). All results have proved that the quality of samples prepared with compensation (cutting head tilting) is very good and difference in shape dimensions is negligible.

4 DISCUSSION

Preliminary results aimed at column sample distortion proved that tilting of the cutting head is a proper way for reduction of trailback and the taper. The difference between diameters of column bases on the inlet side and the outlet one has been reduced by 204 % eliminating the trailback. Elimination of the taper causes additional 50 % of reduction. The resulting average diameters after tilting in both directions (compensation of trailback and taper) are 18.48 mm on the top and 18.58 mm on the bottom, i.e. the diameter difference is only 0.1 which means 0.52 % of real top diameter (0.48 % for the set-up diameter). Difference between the set-up and the real diameter is caused by leaving out the jet radius being about 1.5 mm. For real object diameter 20 mm the set-up diameter should be approximately 21.5 mm. The experiments have also proved that even a low pressure AWJ can efficiently cut composite materials. Therefore, the costs of cutting can be reduced, because pump pressure can be lowered and it means much lower capital costs and also operational costs (pump maintenance). The benefit of the AWJ composite cutting is negligible production of air pollution, namely composite material dust and toxic fumes.

Provided that a robot is used for manipulation with cutting head, the possibilities of 3D machining will increase substantially. Unfortunately, programming of cutting of the 3D objects by abrasive water jet is quite difficult, because it is necessary to take into account that residual energy of the AWJ is still efficient in material damage. Therefore, the programming process needs to calculate with anticipated directions of residual jet deflection. For well-prepared 3D AWJ machining some operations can be less time consuming and more precise. However, the proper programming is not possible without deep and exact knowledge of deflected jet behaviour. To obtain all necessary information the further research of AWJ, both theoretical and experimental, is inevitable.

5 CONCLUSIONS

The preliminary experiments aimed at AWJ machining of composite materials proved that such machining is possible with a relatively high precision. The accuracy of the machining is limited by precision of used machines and respective operation software. Nevertheless, the first tests show that product distortion and/or difference from entered contour can be substantially decreased, by more than 200 %. The resulting distortion comparing with ideal shape was below 1 %, even without any optimization. This result indicates that proper optimization process can improve the production of final products by AWJ to be competitive with classical machining tool production, and simultaneously, much lower amount of health hazardous and risky by-products like dust and fumes. Therefore, further research and development aimed at improving AWJ machining for composite materials is strongly recommended.

ACKNOWLEDGEMENTS

Presented research was supported by project CZ.01.1.02/0.0/0.0/15_018/0004857 of the Ministry of Industry and Trade of the Czech Republic.

REFERENCES

[1] HASHISH, M. A Modelling Study of Metal Cutting with Abrasive-Waterjets. *Journal of Engineering Materials and Technology – Transactions of the ASME*. 1984, 106(1), 1984, pp. 88-100. Available from: doi: 10.1115/1.3225682

[2] RABANI, A., J. MADARIAGA, C. BOUVIER, and D. AXINTE. An approach for using iterative learning for controlling the jet penetration depth in abrasive waterjet milling. *Journal of Manufacturing Processes*. 2016, 22, pp. 99-107. Available from: doi: 10.1016/j.jmapro.2016.01.014

[3] ZOHOURKARI, I., M. ZOHOOR and M. ANNONI. Investigation of the Effects of Machining Parameters on Material Removal Rate in Abrasive Waterjet Turning. *Advances in Mechanical Engineering*. 2014, Article Number 624203. Available from: doi: 10.1155/2014/624203

[4] LIANG, Z., B. XIE, S. LIAO and J. ZHOU. Concentration degree prediction of AWJ grinding effectiveness based on turbulence characteristics and the improved ANFIS. *International Journal of Advanced Manufacturing Technology*. 2015, 80(5-8), pp. 887-905. Available from: doi: 10.1007/s00170-015-7027-0

[5] CHE, C.L., C.Z. HUANG, J. WANG, H.T. ZHU and Q.L. LI. Theoretical model of surface roughness for polishing super hard materials with Abrasive Waterjet. *Advances in Machining and Manufacturing Technology IX, Key Engineering Materials*. 2008, 375-376, pp. 465-469. Available from: doi: 10.4028/www.scientific.net/KEM.375-376.465

[6] MING, I.W.M., A.L. AZMI, L.C. CHUAN and A.F. MANSOR. Experimental study and empirical analyses of abrasive waterjet machining for hybrid carbon/glass fiber – reinforced composites for improved surface quality. *International Journal of Advanced Manufacturing Technology*. 2018, 95, pp. 3809-3822. Available from: doi: 10.1007/s00170-017-1465-9

[7] WONG, M.M.I., A.L. AZMI, C.C. LEE and A.F. MANSOR. Kerf taper and delamination damage minimization of FRP hybrid composites under abrasive water-jet machining. *International Journal of Advanced Manufacturing Technology*. 2018, 94, pp. 1727-1744. Available from: doi: 10.1007/s00170-016-9669-y

[8] RUIZ-GARCIA, R., P.F.M. ARES, J.M. VAZQUEZ-MARTINEZ and J.S. GOMEZ. Influence of Abrasive Waterjet Parameters on the Cutting and Drilling of CFRP/UNS A97075 and UNS A97075/CFRP Stacks. *Materials*. 2019, 12, pp. 1-18. Available from: doi: 10.3390/ma12010107

[9] HLAVÁČ, L.M. Investigation of the Abrasive Water Jet Trajectory Curvature inside the Kerf. *Journal of Materials Processing Technology*. 2009, 209(8), pp. 4154-4161. Available from: doi:10.1016/j.jmatprotec.2008.10. 009

[10] HLAVÁČ, L.M., B. STRNADEL, J. KALIČINSKÝ and L. GEMBALOVÁ. The model of product distortion in AWJ cutting. *International Journal of Advanced Manufacturing Technology*. 2012, 62(1-4), pp. 157-166. Available from: doi:10.1007/s00170-011-3788-2

[11] HLAVÁČ, L.M., I.M. HLAVÁČOVÁ, V. GERYK and Š. PLANČÁR. Investigation of the taper of kerfs cut in steels by AWJ. *International Journal of Advanced Manufacturing Technology*. 2015, 77(9-12), pp. 1811-1818. Available from: doi:10.1007/s00170-014-6578-9

[12] HLAVÁČ, L.M., I.M. HLAVÁČOVÁ, Š. PLANČÁR, T. KRENICKÝ and V. GERYK. Deformation of products cut on AWJ x-y tables and its suppression. *IOP Conference Series: Materials Science and Engineering*. 2018, 307(1), Article number 0120152017. Available from: doi:10.1088/1757-899X/307/1/012015