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Shape distortion reduction method for abrasive water jet (AWJ) cutting☆

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ABSTRACT

The aim of this study is to test a theoretical model for calculating abrasive water jet (AWJ) cutting parameters in order to reduce the shape deformation in curved cutting trajectories. Experimental results were produced using commercial AWJ machines. Despite the limitations of these commercial AWJ machines in terms of both software and hardware, the comparison of calculated and experimental results showed a sufficient correspondence between the theoretical and experimental data sets, with the difference lying within the range of measurement uncertainty. The difference between theoretical and experimental results is up to 2.5 %, similarly to the combined measurement uncertainty. The maximum deviations of the measured values from the calculated averages are up to 0.2 mm and the measuring device uncertainty is up to 0.1 mm. A method aimed at reducing the shape distortion caused by AWJ in curved geometric features is suggested and tested. It was unambiguously demonstrated that the jet markedly reduces the shape deformation in curved geometric features when it is tilted according to the proposed method. Such an error compensation procedure can be already applied on commercial machines.

1. Introduction

Abrasive water jets (AWJ) can cut materials with high accuracy and quality, provided that suitable parameters are set for the process. AWJ can also be applied for milling [1–3], turning [4–6], grinding [7], polishing [8] and complex machining [9]. However, cutting of shapes from plate-type materials remains the most frequent application up to now. Although this method can achieve very good standards of quality, there is still space for improvement. The study presented in this paper can be used to improve the AWJ cutting quality, thus generating economic benefits.

Cutting of materials by AWJ has been studied by Hashish [10], Zeng and Kim [11], Paul et al. [12,13], who prepared first models for calculation of the depth of cut in material. Later on many other researchers [14–23] studied various aspects of the cutting process both analytically and experimentally. Hlaváč prepared theoretical model based on physical laws of conservation [14], Momber explained stress-strain phenomena during erosion process of the AWJ [15], Vikram and Babu [16], Chen et al. [17], Deam et al. [18] and Orbanic and Junkar [19] prepared models for prediction of the surface topography, namely formation of striations during cutting process. Caydas and Hascalik [20] studied the surface roughness, Srinivasu et al. [21] focused their research on machining of the silicon carbide ceramics, Srinivas and Babu [22] prepared an analytical model for AWJ cutting of ductile materials and Thomas [23] studied the formation of cavities on surfaces cut by AWJ. One of the specific approaches to the explanation of several phenomena occurring during AWJ cutting of materials was taken by Hlaváč [24]. His theory is based on the laws of conservation of energy and momentum [14] and on a geometric analysis of phenomena caused by AWJ on cut walls [25]. The theoretical description of the depth of AWJ penetration into material is the topic of the paper [14]. The extension of this model by description of the declination angle dependence on either depth of AWJ penetration to material or on the limit traverse speed for selected material thickness were presented namely in [24]. Hlaváč et al. [25] introduced the theoretical description of product distortion caused by AWJ trailback and method of application of this model.

The deflected jet shape when passing through the material has been

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Nomenclature

a_m	Average size of material structural units [m]
C_A	Coefficient for adjusting jet power with respect to variations in abrasive content below and above the saturation level [-]
C_Q	Coefficient enabling calculation of the traverse speed ensuring achievement of desired cut wall quality (based on limit traverse speed) [-]
d_O	Water jet diameter [m]
d_a	Abrasive water jet diameter [m]
D_I	Inlet diameter of the column sample cut by AWJ [mm]
D_O	Outlet diameter of the column sample cut by AWJ [mm]
D_{OB}	Basic outlet diameter of the column sample cut by AWJ (deformation caused only by trailback) [mm]
D_{Ie}	Experimentally determined inlet diameter of the column sample cut by AWJ [mm]
D_{It}	Inlet diameter of the column sample cut by AWJ calculated from theory [mm]
D_{Oe}	Experimentally determined outlet diameter of the column sample cut by AWJ [mm]
D_{Ot}	Outlet diameter of the column sample cut by AWJ calculated from theory [mm]
ΔD_N	Percentage difference of the average inlet and outlet diameters of the column sample cut by non-tilted AWJ (ΔD_{N20} for outlet declination angle 20°) [%]
ΔD_T	Percentage difference of the average inlet and outlet diameters of the column sample cut by tilted AWJ (ΔD_{T20} for compensated declination angle 20°) [%]
H	Material thickness [m]
K	Material resistance to abrasive (e.g. hardness) [-]
L	Stand-off distance [m]
p_j	Pressure determined from density and speed of abrasive jet [Pa]
S_P	Coefficient of particle integrity (ratio of number of intact particles to total number of particles) [-]
t	Interaction time [s]
v_P	Traverse speed [m s^{-1}]
v_{P20}	Traverse speed calculated for outlet declination angle 20° [m s^{-1}]
v_{Plim}	Limit traverse speed calculated for cutting material of thickness H [m s^{-1}]
v_{Pmin}	Minimum traverse speed – correction for stopped movement – it is determined from average abrasive particle size [m s^{-1}]
v_{PQ}	Traverse speed ensuring achievement of desired cut wall quality throughout the thickness H of the material [m s^{-1}]
α_e	Coefficient of jet speed loss in the interaction process with the material [—]
θ	Positive value of angle determined at the depth h between the tangent to the striation curve and the jet axis at the point of impact [°]
θ_{lim}	Absolute value of angle determined at the depth h_{lim} between the tangent to the striation curve and the jet axis at the point of impact [°]
ξ_j	Coefficient of attenuation of abrasive jet between focusing tube outlet and material surface [m^{-1}]
ρ_j	Density of abrasive jet (conversion to homogeneous liquid) [kg m^{-3}]
ρ_m	Density of machined material [kg m^{-3}]
σ	Tensile strength (or compressive strength) of processed material [Pa]

studied also by several other authors [17–19,21,22]. Their conclusions can be combined with the findings described in [24], especially the equations for calculating the jet delay and the related declination angle. Most of the published studies focus on the characteristic traces left by the AWJ process on the material surface, namely striations and roughness (see e.g. [16,19,20,23,26]). Nevertheless, Hlaváč considers the declination angle being the one of the sensitive output variables reflecting the AWJ parameters setting and the material properties [24]. His method for determining the declination angle and examining its dependency on the cutting head traverse speed is described mainly in publications [24,25]. He correlated his results also with material properties [27] and found the equations for calculation of taper dependence on the traverse speed [28,29], because the model presented in [30] was specific for ceramics. The present paper focuses primarily on comparing the results of his previously presented theoretical equations used to predict the shape variance in an AWJ-cut sample with

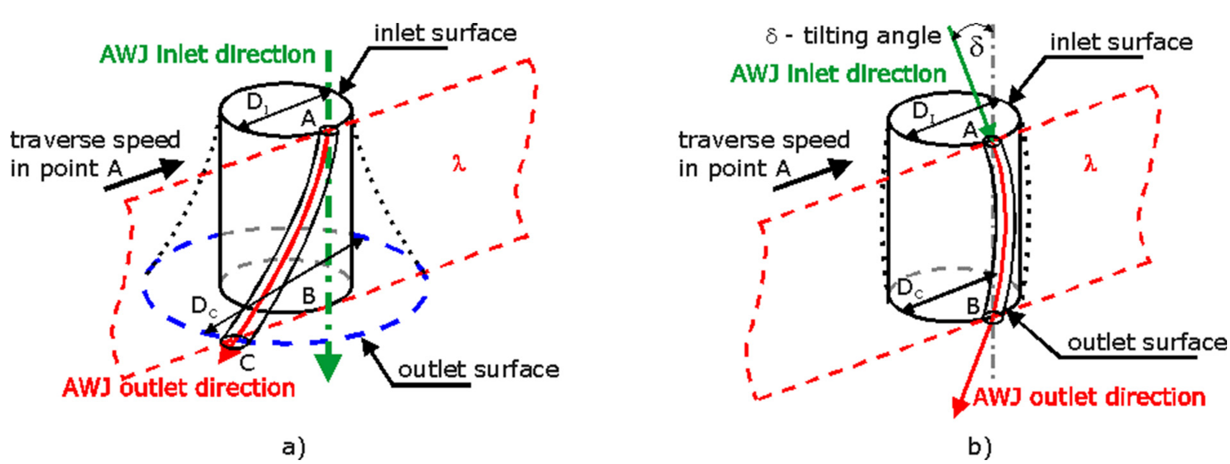

Fig. 1. **a**) Column sample distortion: Plane λ is determined by points ABC; A is the intersection of the jet axis with the inlet surface, B is the intersection of the jet entry axis with the outlet surface, and C is the intersection of the momentary axis of the curved cutting jet with the outlet surface (the solid red line marks the trajectory of the jet penetrating the material and lying in plane λ, the dotted line marks the resulting sample shape), D_I and D_O are the diameters of "column" product on the inlet and outlet side of plate material. **b**) Compensation of column sample distortion: Plane λ is determined by the jet axis (the green arrow) and the perpendicular to the workpiece surface at the point of impact, and it is tangential to the side surface of the cut column sample. The red line marks the trajectory of the jet penetrating the material and lying in plane λ. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)