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[1.] LIBOR M. HLAVÁČ, [2.] JIRÍ KALIČINSKÝ, [3.] LUCIE GEMBALOVÁ
[4.] VILÉM MÁDR, [5.] IRENA M. HLAVÁČOVÁ, [6.] EVA JANUROVÁ

INFLUENCE OF IMPACT ANGLE ON ABRASIVE WATER JET CUTTING QUALITY

Abstract:
The analytical model has been derived for description of the abrasive water jet cutting efficiency. Several material parameters are included in the model and the investigation of their influence on both the qualitative and quantitative cutting results is the topic of the contribution. The theoretical equation has been prepared for description of the dependence of the angle between the tangent to the striation curve and the impinging jet axis, called the declination angle, on the depth of jet into material penetration. Tilting of the cutting head reducing negative phenomena can be evaluated from this theory. The levels describing depth-dependent surface quality of cutting walls has been introduced and the experimental methods for quality evaluation were prepared. The so-called "geometrical model" describing the negative consequences of water jet delay inside the cutting kerf was prepared. Comparison of the theoretical investigation and experimental data is discussed.

Keywords:
abrasive water jet; cutting; declination angle; striations; surface quality

INTRODUCTION

The abrasive water jet has been investigated since the end of seventies of the twentieth century. Many researchers are dealing with this topic all over the world. A small group of researchers has been dealing with the problem also in our country since the middle of eighties. The theoretical approach based on the law of conservation of energy and the law of conservation of momentum was presented in the beginning of nineties. Thenceforth, the model has been continually improved and updated. The efforts of the improvement of the CNC cutting machines started the new stage of a deeper interest in theoretical and experimental investigation of the process. Some recent approaches and results are presented in the paper.

PRESENT STATE-OF-THE-ART

One of the earliest models and experiments in the branch were performed in the beginning of eighties of the last century. They were improved many times and many new elements were introduced into them extending their use and validity range (e.g. Hashish 1989, Zeng and Kim 1996). Further investigations were aimed at 3D abrasive water jet machining (Kovacevic and Yong 1996a, b) or the cutting quantity (Hlaváč 2001, Chen et al. 2003, Henning and Westkämper

2006, Monno et al 2006). The most often situation is, however, that the own theoretical bases not easily interchangeable or addible are developed. Published experimental data are non-comparable for some important information being omitted many times.

The theoretical approach of Hlaváč has been used in this work, especially his description of the abrasive water jet interaction with material (Hlaváč 2001). His model was enhanced implementing the declination angle relationship on the cutting depth (Hlaváč 2009).

THEORETICAL APPROACH

Theoretical description of the cutting process is based on the energy conservation law (Hlaváč 1998). The resulting set of equations enables to calculate the limit depth of penetration of the abrasive water jet into the material with known parameters for implicit cutting parameters. The modification of the traverse speed from the limit value to the one assuring the selected quality even on the worse part of the cutting wall was derived from the five-step kerf evolution process fully described in 2009 (Hlaváč 2009). The declination angle of the jet axis in the cut is in a direct relationship with the respective wall quality in a certain depth. Declination angle Θ is measured between the tangent to the striation curve in the depth h and the impinging jet axis. It is determined by equation

$$\theta = arctg\left(\frac{df(h)}{dh}\right) : h^{1.5} \qquad (1)$$

The basic equations used in a subsequent experimental work were derived and presented by Hlaváč (2009). They enable calculation of the declination angle respective to certain depth in material or respective to the traverse rate. Inverse calculation of the appropriate traverse rate v_P for selected declination angle Θ is possible from Eq. 2

$$v_P = v_{P\,lim}\left(\frac{\theta}{\theta_{lim}}\right)^{\frac{2}{3}} \qquad (2)$$

v_{Plim} is the limit traverse rate and Θ_{lim} is the respective limit declination angle for given material thickness H.

EXPERIMENTAL PROCEDURE

The experiments were performed with the following invariable parameters:

Pressure inside the pumping system	400 MPa
Water orifice diameter	0.25 mm
Stand-off distance	2 mm
Focusing tube diameter	1.02 mm
Focusing tube length	76 mm
Abrasive mass flow rate	225 g/min
Abrasive material average grain size	0.275 mm
Abrasive material type	Australian garnet
Basic angle of impact	0 rad

Firstly the linear cuts were performed and later on the circular cuts were done. The differences in the radii on the top and on the bottom of the kerf were analyzed. Several steals and copper were investigated to prove the supposed relationships between the individual material parameters and respective declination angles measured according to Hlaváč et al. (2009). These relationships are inherently included in the theoretical base (Hlaváč 1998, 2001).

The Eq. 2 was used for calculation of the traverse speeds for the appropriate declination angles by the exit of the jet from material. Some results are presented in Tab. 1. The variable H is the material sample thickness, V_{Pt20} is the traverse speed determined from the theory for the declination angle 20°. Similarly, the quantity V_{Pe20} is the experimentally determined traverse speed for the declination angle 20°. Tilting of the cutting head should improve the quality of the walls in kerf (especially delay of the jet) as it is demonstrated in Fig. 1 for tilting 10°.

Tab. 1. Some experimental results and their comparison with presented model

steels	H	V_P	Θ	V_{Pt20}	V_{Pe20}
CSN EN	mm	mm/min	(°)	mm/min	mm/min
11523	10	100	11.4	146	140
12050	10	100	16.5	116	115
14220	10	100	13.7	128	125
15142	10	100	17.9	105	105
17246	10	100	16.6	116	110
19437	10	100	23.6	93	90

Fig. 1. Plate from Hardox™ 500 15 mm thick cut with tilted cutting head (angle 10°, traverse rate calculated from Eq. 2)

The radii of the curves on the inlet surface and on the outlet surface are different for curved trajectories when all material and jet parameters are constant. It is supposed that this difference is caused by a geometrical variable directly chained with the radius of the trajectory curvature called the trailback, demonstrated in Fig. 2.

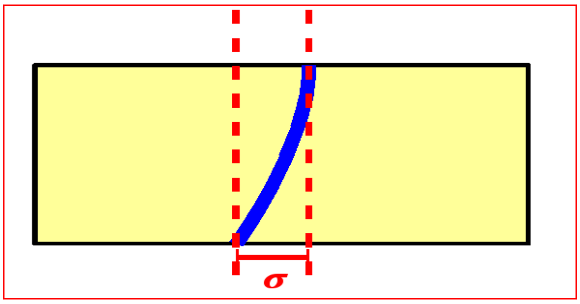

Fig. 2. Trailback σ the blue line demonstrates striation line being the trace of the jet penetrating through material

In the case of curved trajectory the jet delays inside the cut in the plane given by the jet axis and tangent to the jet trace trajectory on the material surface. This situation is graphically outlined in Fig. 3.

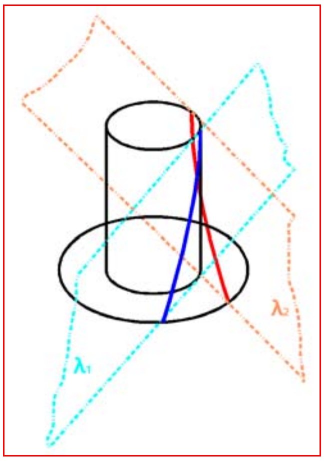

Fig. 3. An example of planes λ_1, λ_2 determined by jet axis and respective tangents to the required cutting curve

It is evident from the Fig. 4 that knowledge of the trailback σ for given material and depth is fully sufficient for determination of the relationship between the radii R_1 and R_2 of the conically disturbed column shape. It is evident that the maximum deviation Δ_σ from the required curve radius is determined from the equation 3.

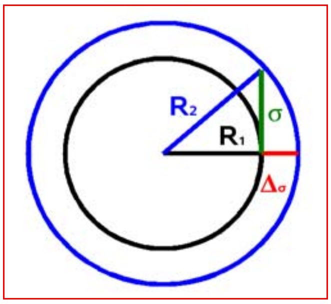

Fig. 4. Deviation Δ_σ from the required curve radius R_1

$$\Delta_\sigma = \sqrt{R_1^2 + \sigma^2} - R_1 \qquad (3)$$

R_1 is a required radius of the cutting trajectory and σ is the trailback. Equation 3 describes the influence of the cutting curvature radius on deviation from the required dimension for a constant trailback σ that includes material and cutting parameters. The trailback enables to determine the deviations Δ_σ of the radii of curves during the cutting process. The model can be generalized using Eq. 2. Trajectory of the jet can be described as a function of jet and material parameters included in a previously derived theoretical base (Hlaváč 2001). Introducing the knowledge from Eq. 2 into Eq. 3 the maximum deviation from the required shape is expressed as Eq. 4

$$\Delta_\sigma = \sqrt{R_1^2 + \left[\frac{2}{5} H \, tg\left[\vartheta_{lim}\left(\frac{v_P}{v_{P\,lim}}\right)^{\frac{3}{2}}\right]\right]^2} - R_1 \qquad (4)$$

Equation 4 is a function of important variables like the sample thickness H, traverse rate v_P and the cut curvature radius R_1. Information about liquid pressure, abrasive mass flow rate, the stand-off distance and material parameters is included in the limit traverse rate v_{Plim} and the limit declination angle Θ_{lim}. The submitted model was compared with data obtained from measurement of the radii of experimental rings with various diameters (an example of rings is presented in Fig. 5). The graph in Fig. 6 shows the *typical comparison of results calculated from the model and the ones measured on rings.*

Fig. 5. An example of rings cut in steel plate

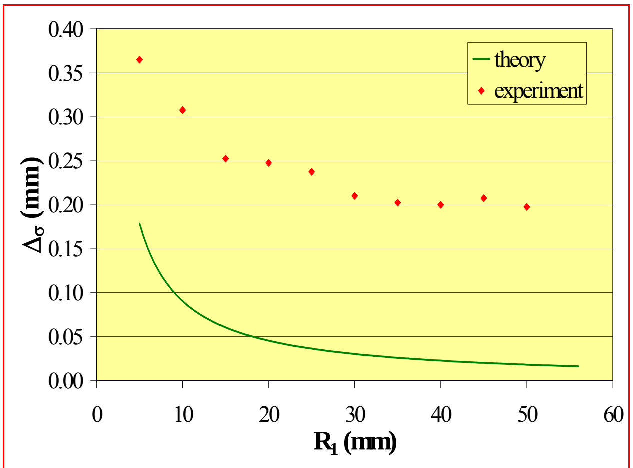

Fig. 6. An example of rings cut in steel plate

It is evident that some shift is needed for a theoretical model to correlate it with experimental results. Therefore, it can be supposed that the model should consist of two independent parts – the one related to the radius of cutting curvature R_1 and the one independent on the curvature. It is supposed that this second part is closely related to the jet divergence or convergence inside the cutting kerf (see the scheme in Fig. 7).

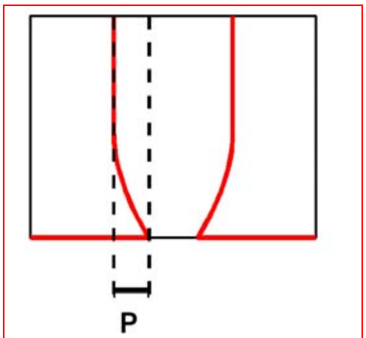

Fig. 7. Finding of the constant parameter P

As the shift is to be independent on curvature radius, it can be found out from the linear cut similarly to the parameter σ. The cross profile of the cut enables to determine the shift (Hlaváčová et al. 2008), because for the traverse rate higher than the optimum one the bottom part of the sample is not cut in the same width as the upper part like at the scheme in Fig. 7. The taper of the cut P is identical for both linear and curved cuts. The deviation from the normal projection of the upper edge of the cut to the output sample surface characterizes the convergence of the cut and it is the parameter P being searched for.

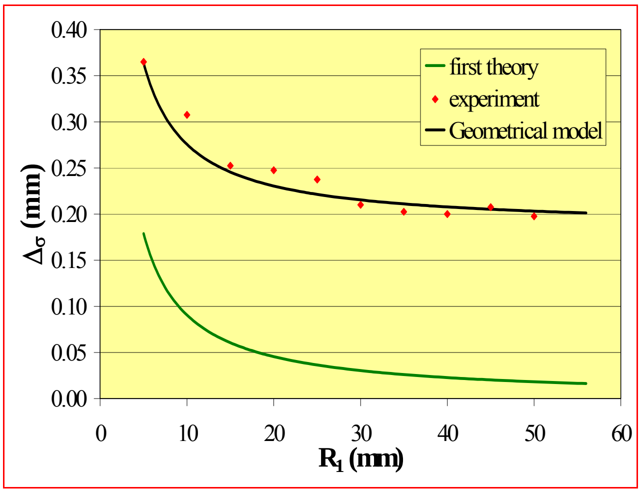

Fig. 8. Comparison of the Geometrical model with experiments

The theoretical model improved by implementation of the parameter P is named the Geometrical model. It is in a good correlation with experimental data (Fig. 8). This model is fully applicable and describes the relationship of the deviation of the real dimension of the work-piece from the required one when cutting in curvature. Application of this model in practice is possible through this equation

$$\Delta_\sigma = \sqrt{R_1^2 + \left[\frac{2}{5} H \; tg\left(\theta_{lim}\left(\frac{v_P}{v_{P\,lim}}\right)^{\frac{3}{2}}\right)\right]^2} - R_1 + P \qquad (5)$$

Δ_σ is the deviation of the cut shape, R_1 is the curvature radius, H is the sample thickness, v_P is the traverse rate, v_{Plim} is the limit traverse rate and Θ_{lim} is the limit declination angle.

DISCUSSION

The theoretical model was used for calculation of the respective traverse speeds for declination angle 20° and several materials. Subsequently, the experiments were performed verifying the hypothesis that tilting of the cutting head into the half value of the declination angle should result in such a deformation of the striation lines that the jet penetrating the material exits it approximately along the normal to the material surface created at the point of jet axis entry. The tilting of the cutting head to the half value of the respective declination angle should minimize the typical defects caused by the abrasive water jet deflection when the cut starts, ends, changes direction in the corners and curved parts of trajectories.

The presented theory and experimental data imply that the changes of the impact angle through the tilting of the cutting head can be used for modification of the cutting surface quality.

CONCLUSION

The declination angle between the tangent to the striation and the impinging abrasive water jet axis can be used for calculation of the required traverse speed or the tilting angle of the cutting head. Tilting of the cutting head can be utilized for reduction of the shape deviation in the case of curved cuts. It is demonstrated that the theoretical model can be used for prediction of cutting variables. The power of the model is demonstrated in comparison with experimental results and it is proved that it is usable for calculation of the cutting head tilting respective to the traverse speeds and their changes.

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AUTHORS & AFFILIATION

[1.] LIBOR M. HLAVÁČ,
[2.] JIRÍ KALIČINSKÝ,
[3.] LUCIE GEMBALOVÁ
[4.] VILÉM MÁDR,
[5.] IRENA M. HLAVÁČOVÁ,
[6.] EVA JANUROVÁ

[1., 2., 3.,4.,5.] INSTITUTE OF PHYSICS, FACULTY OF MINING AND GEOLOGY, VŠB - TECHNICAL UNIVERSITY OF OSTRAVA, CZECH REPUBLIC