Deformation of products cut on AWJ x-y tables and its suppression

L M Hlaváč\textsuperscript{1,4}, I M Hlaváčová\textsuperscript{1}, Š Plančár\textsuperscript{2}, T Krenický\textsuperscript{3}, V Geryk\textsuperscript{1}

\textsuperscript{1}VŠB - Technical University of Ostrava, Department of Physics, 17.listopadu 15/2172, 70833 Ostrava – Poruba, Czech Republic
\textsuperscript{2}Watting, s.r.o., Budovateľská 38, 080 01 Prešov, Slovak Republic
\textsuperscript{3}Technical University of Košice, Faculty of Manufacturing Technologies, Štúrova 31, 080 01 Prešov, Slovak Republic

libor.hlavac@vsb.cz

Abstract. The aim of this study is namely investigation of the abrasive water jet (AWJ) cutting of column pieces on commercial x-y cutting machines with AWJ. The shape deformation in curved and/or stepped parts of cutting trajectories caused by both the trailback (declination angle) and the taper (inclination of cut walls) can be calculated from submitted analytical model. Some of the results were compared with data measured on samples cut on two types of commercial tables. The main motivation of this investigation is determination of the percentage difference between predicted and real distortion of cutting product, i.e. accuracy of prepared analytical model. Subsequently, the possibility of reduction of the distortion can be studied through implementation of the theoretical model into the control systems of the cutting machines with the system for cutting head tilting. Despite some limitations of the used AWJ machines the comparison of calculated dimensions with the real ones shows very good correlation of model and experimental data lying within the range of measurement uncertainty. Results on special device demonstrated that the shape deformation in curved parts of the cutting trajectory can be substantially reduced through tilting of the cutting head.

Nomenclature

\begin{itemize}
  \item \textit{a_m} average size of material structural units [m]
  \item \textit{C_A} coefficient for adjusting jet power with respect to variations in abrasive content below and above the saturation level [-]
  \item \textit{C_Q} coefficient enabling calculation of the traverse speed ensuring achievement of desired cut wall quality [-]
  \item \textit{d_o} water nozzle diameter [m]
  \item \textit{D_{le}} experimentally determined inlet diameter of the column sample cut by AWJ [mm]
  \item \textit{D_{lt}} theoretically determined inlet diameter of the column sample cut by AWJ [mm]
  \item \textit{D_{oe}} experimentally determined outlet diameter of the column sample cut by AWJ [mm]
  \item \textit{D_{ot}} theoretically determined outlet diameter of the column sample cut by AWJ [mm]
  \item \textit{h} actual cut depth [m]
  \item \textit{h_{lim}} limit cut depth at a given traverse speed [m]
  \item \textit{h_Q} cut depth at which the desired wall quality is achieved [m]
  \item \textit{H} material thickness [m]
\end{itemize}
1. Introduction

Abrasive water jets (AWJ) can be used for machining of a broad range of materials, provided that suitable parameters are set for respective processes. Today, AWJ is tested as a tool in many machining processes assigned to the rigid tools in past: turning, milling, grinding and polishing. Nevertheless, the most frequent application remains the cutting of shapes from plate-type materials, mainly metals, rocks, glass and plastics. Actually, this method can achieve very good standards of quality selecting lower traverse speeds. The process could be more economical with higher traverse speeds, but the product distortion increases over the acceptable tolerances. Compensation techniques implemented into modern machines act automatically without necessity to set and control them by operator. Nevertheless, some operations cannot be performed. This contribution is aimed at potential improvement of quality through implementation of the controllable device for tilting of the cutting head based on presented cutting model.

The quality of cutting, with a particular focus on the role of material parameters and AWJ parameters, has been studied in past. Some basic models were prepared by Hashish [1], Zeng and Kim [2], Kovacevic and Yong [3, 4], Paul et al. [5, 6], and many other researchers [7-10]. A specific approach to the explanation of several phenomena occurring during AWJ material cutting was presented by Hlaváč [11]. This model is based on the laws of conservation of energy and momentum and on the geometric analysis [12] of phenomena caused by AWJ on cut walls, namely the declination angle and the respective product distortion [13]. Further studies of AWJ cutting phenomena focus on the kerf taper [14] or surface roughness [15]. Nevertheless, the declination angle seems to be a sensitive parameter reflecting the setting of parameters for AWJ processes and material properties (even more sensitive than roughness or the taper). Therefore, this study focuses primarily on comparing the predicted results calculated from theory presented in more detail in [13] and data measured on steel “column” samples cut from plates of various thickness using commercial AWJ machines. Steels were selected due to requirement of relatively homogeneous structure of tested
material, because laminar and honeycomb structures or significantly non-homogeneous materials destroy the penetrating jet. Therefore, the samples are destroyed rather randomly than deterministically.

2. Theoretical background
The theoretical results were calculated from the model presented in [13] and derived for limit cutting parameters defined in previous publications [13, 14]. One of these significant limit parameters is the limit traverse speed. It is the maximum attainable traverse speed for the given thickness and type of material at which neither non-cut-through parts are more frequent than once per 50 mm, nor the lengths of them are greater than 25% of the cut width. The modified Eq. (1) is used for calculation of the limit traverse speed \( v_{\text{Plim}} \) belonging to a given material thickness \( H \), i.e. the maximum traverse speed with a minimum quality at the bottom edge (with even some small uncut parts, according to the definition reminded above). The coefficient \( \alpha \) is defined by Eq. (2) derived from the law of momentum conservation on the micro-level (grain of abrasive – grain of material) [16]. It determines the effectiveness of the disintegration process regarding selected material properties and several characteristics of the liquid jet. Due to a very difficult getting of all necessary variables in practice (\( K, t, a_m \) and \( \sigma_s \)), the combination of them present in Eq. (2) is often substituted by material parameter \( k_m \) characterizing resistance of material to AWJ penetration. This material characteristic can be calculated from an experimental cut performed on specimen of tested material. Subsequently, the parameter \( k_m \) is used for calculation of the coefficient \( \alpha \) (substituting the respective combination of variables \( K, t, a_m \) and \( \sigma_s \) for \( k_m \)) – Eq. (3).

\[
v_{\text{Plim}} = \frac{C_P S_P \pi d_o \left(2 \rho \rho_i \alpha e^{-3a \alpha} (1 - \alpha^2)^{-\frac{3}{2}} - v_{\text{Pmin}}\right)}{8H (p_i \rho_i \alpha e^{-3a \alpha} + \sigma_P^{\frac{1}{2}})}
\]

\[
\alpha = 1 - \frac{\sqrt{2p_j} K_t}{8 \sqrt{\rho_i a_m \sigma_s}}
\]

\[
\alpha = 1 - \frac{\sqrt{2p_j} k_m}{8 \sqrt{\rho_i}}
\]

For the purpose of determining speed \( v_{\text{PQ}} \), which ensures the achievement of the desired quality of the cut walls, the basic relation for determining the limit traverse speed was complemented by the coefficient \( C_Q \) (see [11]) – the speed \( v_{\text{PQ}} \) is determined by Eq. (4). It is also possible to determine the value \( C_Q \) from the normalized average angle of striations at the bottom of the cut material (then the Eq. (5) is to be respected).

\[
v_{\text{PQ}} = C_Q v_{\text{Plim}}
\]

Speed \( v_{\text{Plim}} \) (or \( v_{\text{PQ}} \)) and the dependency of the declination angle on the material thickness [11] can be used to determine the jet delay, which causes deformations of the work-piece (see line segment BC in figure 1). The declination angle is calculated at a selected traverse speed from the Eq. (5) being derived from equation for traverse speed presented in [11]:

\[
\theta = C_{\text{lim}} \left( \frac{v_p}{v_{\text{Plim}}} \right)^2
\]

Plane \( \lambda \) in figure 1 is determined by points ABC; A is the intersection of the jet axis with the inlet surface of material, B is the intersection of the jet entry axis with the outlet surface of material, and C is the intersection of the momentary axis of the curved cutting jet with the outlet surface of material. The red line is the centerline of the trajectory of the jet penetrating the material and lying in plane \( \lambda \).
The blue dashed line indicates the cross-section of the jet flowing out of cut material with the bottom plane of the plane-parallel material plate. The dotted line marks the resulting cut shape of the sample (product of the column cutting without use of the compensating tilting). It is necessary to realize that plane $\lambda$ is “rolling” along the column surface drawn by impinging jet axis.

The taper, studied in [14], can add some deformation described by Eq. (6). The total deformation of the column shape on its bottom can be then calculated from the Eq. (7).

$$\varphi = \varphi_{\text{lin}} \left( \frac{h}{h_{\text{lin}}} \right)^{\frac{2}{5}} + q \quad (6)$$

$$D_{\text{he}} = 2 \left[ \sqrt{\frac{2}{5} H \tan \vartheta} + R^2 + \frac{2}{5} H \tan \varphi \right] + d_a \quad (7)$$

Compensation of the “column” deformation can be accomplished by jet tilting (see figure 2). The attention has been focused namely on the first part of the deformation component in this study, i.e. on the deformation caused by declination angle (retardation of jet in cut). Some calculations of the taper are also presented.

3. Experimental set-up
The preparation and evaluation of the experiments are based on these two assumptions:
- the actual jet axis inside kerf is parallel with the tangent to the front line of the curved cutting edge (see drawing in figure 3),
- the character of the curves of striations produced on the cut walls is identical to the character of the kerf cutting edge front line (shape of the front wall of the channel formed by penetrating jet).

The following process was applied in experiment: The respective traverse speed $v_{PQ}$ was calculated for each tested material and selected declination angle from Eq. (4). Subsequently, cuts were performed at this speed along a circular trajectory in a plane-parallel metal plate using non-tilted jets (perpendicular to the inlet surface of material).

The experiments were carried out at the machines located in the Laboratory of Liquid Jet at the VŠB-Technical University of Ostrava (Czech Republic) and in the company Watting s.r.o. in Prešov (Slovak Republic). The equipment in each case consisted of a pump (enabling working pressure and
flow to be set within a certain range) and a CNC table. The table is without controlled tilting in Ostrava and with an automated tilting that can be switched off in Prešov. The selected parameters at the individual workplaces were identical except type of the abrasive and respective mean grain size of the inlet particles, determined by laser analyzer of particles Mastersizer 2000. The conditions are summarized in Table 1.

![Diagram showing kerf cutting parameters](image)

**Figure 3.** Kerf cutting: 1 – jet axis, 2 – kerf width axis on the top, 3 – kerf width axis in the depth \( h \), 4 – kerf cutting edge front line, 5 – tangent to the front line in the depth \( h \), 6 - actual jet “axis” parallel to the tangent of the front line in the depth \( h \), 7L, 7R – left and right kerf wall striations with shapes copying the shape of the kerf cutting edge front line.

| Table 1. Constant parameters used for experiments and calculations |
|---------------------------------------------------------------|
| **Factor** | **Constant cutting parameters on testing workplaces** |
|-------------|--------------------------------------------------|
| Pressure in pump | Ostrava | Prešov |
| Water jet diameter | 380 MPa | 380 MPa |
| Focusing tube diameter | 0.254 mm | 0.254 mm |
| Focusing tube length | 1.02 mm | 1.02 mm |
| Abrasive mass flow rate | 76 mm | 76 mm |
| Abrasive type | 250 g/min | 250 g/min |
| Mean abrasive grain size | Australian garnet (almandine) | Indian garnet (almandine) |
| Stand-off distance | 0.275 mm (80 mesh) | 0.225 mm (80 mesh) |
| Abrasive type | 22 mm | 2 mm |

*Mean grain size is determined on the commercial particles size analyzer.

*The “mesh” specification is commercial indication provided by suppliers.
Several kinds of steel samples with thickness 10 mm were used in experiments. One type of steel – WNR 1.0038 (RSt 37-2) – was tested with three thicknesses: 10, 15 and 20 mm. All the cut shapes were the cylindrical “columns” with the diameter 10 mm drawn by the intersection of the jet axis with the selected material surface. The angle was 0° (between jet axis and normal to the material surface), i.e. the perpendicular impact of the jet on the surface. The traverse speeds were calculated for the expected declination of the cutting jet at the exit from material 20°. So, the declination angle 20° is expected to be measured as declination of the striation at the bottom edge of the cut wall. Selected angle (20°) corresponds with the medium cutting quality, which is considered to be the best economical solution for most applications. However, the jet delay causes visible deformations of the sample at these traverse speeds, overcuts and undercuts in stepped parts of jet trajectories and, therefore, improvement is needed. The declination angle 30° has been also tested, as it corresponds with quality sufficient for cutting of products prepared for subsequent finishing processes. The traverse speeds necessary to achieve the selected declination angles were also calculated in the first series of experiments for each material separately.

4. Experimental results

The results of calculations and experiments are presented in tables 2 – 4. Table 2 summarizes results of the preparation phase of investigation – calculation of limit traverse speed and respective traverse speeds for expected declination angles 20° and 30° and calculation of the inlet and outlet diameters of column samples cut in steel plates.

| Material type | H  | v_{\text{Plim}} | v_{\text{P20}} | v_{\text{P30}} | D_{\text{I20t}} | D_{\text{O20t}} |
|---------------|----|----------------|---------------|---------------|----------------|----------------|
| WNR norm (DIN norm) | mm | mm/min | mm/min | mm/min | mm | mm |
| 1.057 (St 52-3) | 10 | 250 | 146 | 191 | 8.96 | 9.40 |
| 1.0503 (C 45) | 10 | 200 | 116 | 153 | 8.96 | 9.40 |
| 1.7131 (16 MnCr 5) | 10 | 220 | 128 | 168 | 8.96 | 9.40 |
| 1.7225 (42 CrMo 4) | 10 | 180 | 105 | 137 | 8.96 | 9.40 |
| 1.4541 (X6 CrNiTi 18 10) | 10 | 200 | 116 | 153 | 8.96 | 9.40 |
| 1.2436 (X210 CrW 12) | 10 | 160 | 93 | 122 | 8.96 | 9.40 |
| 1.0038 (RSt 37-2) | 10 | 300 | 175 | 229 | 8.96 | 9.40 |
| 1.0038 (RSt 37-2) | 15 | 200 | 116 | 153 | 8.96 | 9.88 |
| 1.0038 (RSt 37-2) | 20 | 140 | 82 | 107 | 8.96 | 10.58 |

Table 3 contains comparison of calculated and measured results for technological equipment without tilting (in Ostrava) and evaluation of the respective relative uncertainties. The equipment in company Watting s.r.o. in Prešov, unfortunately, prevented operators to switch off functions of automated compensation of the jet diameter and the taper. This fact influenced comparison of results from Ostrava and Prešov (although the conditions were set identical except the abrasive material type and respective grain size). Results calculated for samples with compensating functions switched on and respective data measured on samples are summarized in table 4. All results presented in tables indicate that differences between values calculated from the model and the ones determined from experiment are small for both the input and the output diameters of “column” samples prepared on both commercial machines. The results from Prešov proved that input of corrections into the theoretical model during calculations yields results differing from the experimental ones within the uncertainty of measurement (see table 4, columns with theoretical and experimental diameters).
Table 3. Comparison of calculated and experimentally determined inlet ($D_{li}$, $D_{le}$) and outlet ($D_{lo}$, $D_{oe}$) diameters of “column” samples cut from 10 mm thick steel plates by a non-tilted jet with traverse speeds $v_{P20}$ including differences $\Delta D_{li}$ and $\Delta D_{lo}$ of the diameters.

| Material type          | $v_{P20}$ (mm/min) | $D_{li}$ (mm) | $D_{le}$ (mm) | $D_{lo}$ (mm) | $D_{oe}$ (mm) | $\Delta D_{li}$ (%) | $\Delta D_{lo}$ (%) |
|------------------------|--------------------|---------------|---------------|---------------|---------------|---------------------|---------------------|
| WNR norm (DIN norm)    |                    |               |               |               |               |                     |                     |
| 1.057 (St 52-3)        | 146                | 8.96          | 8.96          | 9.40          | 9.53          | 0.22                | 1.36                |
| 1.0503 (C 45)          | 116                | 8.96          | 9.00          | 9.40          | 9.52          | 0.44                | 1.37                |
| 1.7131 (16 MnCr 5)     | 128                | 8.96          | 8.92          | 9.40          | 9.54          | 0.45                | 1.57                |
| 1.7225 (42 CrMo 4)     | 105                | 8.96          | 8.97          | 9.40          | 9.55          | 0.11                | 1.57                |
| 1.4541 (X6 CrNiTi 18 10) | 116              | 8.96          | 8.98          | 9.40          | 9.53          | 0.22                | 1.47                |
| 1.2436 (X210 CrW 12)   | 93                 | 8.96          | 8.92          | 9.40          | 9.61          | 0.22                | 2.29                |

*a Theoretical inlet diameter is determined from the circle diameter set on the cutting machine and the diameter of the abrasive water jet (regarding the stand-off distance).

Table 4. Measurement in Prešov – comparison of theoretical ($D_{li}$, $D_{lo}$) and experimental ($D_{le}$, $D_{oe}$) inlet and outlet diameters of “column” samples for traverse speed $v_{P20}$ (from table 1) with non-tilted jet and respective percentage differences $\Delta D_{li}$ and $\Delta D_{lo}$ of these diameters. The samples were prepared with automatically implemented compensation of jet diameter.

| Material type          | $H$ (mm) | $D_{li}$ (mm) | $D_{le}$ (mm) | $D_{lo}$ (mm) | $D_{oe}$ (mm) | $\Delta D_{li}$ (%) | $\Delta D_{lo}$ (%) |
|------------------------|---------|---------------|---------------|---------------|---------------|---------------------|---------------------|
| WNR norm (DIN norm)    |         |               |               |               |               |                     |                     |
| 1.057 (St 52-3)        | 10      | 10.01         | 10.03         | 10.41         | 10.44         | 0.20                | 0.19                |
| 1.0503 (C 45)          | 10      | 10.01         | 10.03         | 10.41         | 10.33         | 0.20                | 0.77                |
| 1.7131 (16 MnCr 5)     | 10      | 10.01         | 10.04         | 10.41         | 10.48         | 0.30                | 0.67                |
| 1.7225 (42 CrMo 4)     | 10      | 10.01         | 10.02         | 10.41         | 10.26         | 0.10                | 1.56                |
| 1.4541 (X6 CrNiTi 18 10) | 10     | 10.01         | 10.03         | 10.41         | 10.34         | 0.20                | 0.68                |
| 1.2436 (X210 CrW 12)   | 10      | 10.01         | 10.04         | 10.41         | 10.44         | 0.30                | 0.29                |
| 1.0038 (RSt 37-2)      | 10      | 10.01         | 10.05         | 10.41         | 10.55         | 0.40                | 1.42                |
| 1.0038 (RSt 37-2)      | 15      | 10.01         | 10.04         | 10.91         | 11.08         | 0.30                | 1.53                |
| 1.0038 (RSt 37-2)      | 20      | 10.01         | 10.06         | 11.57         | 11.46         | 0.50                | 0.96                |

All measurements of samples were carried out using a digital Vernier caliper. Micrometer measurements and evaluation of diameter from the surface of “bases” transformed into circles with the same area were also tested and detectable differences were in the scope of the uncertainties for each method. Therefore, the most simple and quick method was selected. An average combined expanded uncertainty of 0.4 mm was determined for all measurements. It represents a relative uncertainty about 4% that is usual for this type of experiment. Nevertheless, individual values determined for differences between inlet and outlet bases of cut column samples are usually lower, as it is evident from the results summarized in tables. Therefore, presented results lay in the scope of the overall measurement accuracy.

Table 5 summarizes results calculated for expected declination angle 30° and data measured on cut “column” samples. This declination angle corresponds to the most common traverse speeds used in practice for rough semi-finished products preparation. Therefore, it was necessary to investigate, whether the model yields sufficiently exact results also for these traverse speeds.
Table 5. Measurement in Prešov – comparison of theoretical (D_{It}, D_{Ot}) and experimental (D_{Ie}, D_{Oe}) inlet and outlet diameters of “column” samples for traverse speed \( v_{P30} \) (from table 1) with non-tilted jet and respective percentage differences \( \Delta D_{I30} \) and \( \Delta D_{O30} \) of these diameters. The samples were prepared with automatically implemented compensation of jet diameter.

| Material type | WNR norm (DIN norm) | \( v_{P30} \) | \( H \) | \( D_{It} \) | \( D_{Ie} \) | \( D_{Ot} \) | \( D_{Oe} \) | \( \Delta D_{I30} \) | \( \Delta D_{O30} \) |
|---------------|---------------------|-------------|-----|---------|---------|---------|---------|----------|----------|
| 1.057 (St 52-3) | 10 | 10.01 | 10.04 | 10.78 | 10.72 | 0.30 | 0.65 |
| 1.0503 (C 45) | 10 | 10.01 | 10.03 | 10.78 | 10.58 | 0.20 | 1.89 |
| 1.7131 (16 MnCr 5) | 10 | 10.01 | 10.08 | 10.78 | 10.62 | 0.70 | 1.51 |
| 1.7225 (42 CrMo 4) | 10 | 10.01 | 10.06 | 10.78 | 10.55 | 0.50 | 2.27 |
| 1.4541 (X6 CrNiTi 18 10) | 10 | 10.01 | 10.04 | 10.78 | 10.54 | 0.30 | 2.28 |
| 1.2436 (X210 CrW 12) | 10 | 10.01 | 10.04 | 10.78 | 10.57 | 0.30 | 1.99 |
| 1.0038 (RSt 37-2) | 10 | 10.01 | 10.05 | 10.78 | 10.68 | 0.40 | 0.84 |
| 1.0038 (RSt 37-2) | 15 | 10.01 | 10.08 | 11.47 | 11.72 | 0.70 | 2.13 |
| 1.0038 (RSt 37-2) | 20 | 10.01 | 10.04 | 12.32 | 11.80 | 0.30 | 4.41 |

The last group of experiments was intended for verification of benefits yield by tilted-jet cutting according to proposals published in [13]. This experiment, however, requires compliance with the proper geometry of cutting around the whole column circumference like it is shown in figure 2.

This geometry is not easily feasible on classical x-y tables with integrated software automatically tilting the cutting head regarding internal procedures reflecting projected cutting trajectory and set traverse speeds. Therefore, it was necessary to design and construct a special device (figure 4) facilitating the desired geometry sketched in figure 2.

Figure 4. Special device for sample rotation.

This device has been used for carrying out the experiments most exactly complying requirements stated for compensation of distortion caused by the declination angle on column samples (without compensation of the taper). The device is used on x-y table with stable cutting head tilted to the
selected angle and it rotates with the cut material. Therefore, the tilted jet is properly situated in the plane tangential to the column surface around the whole column circumference and this configuration makes possible to study compensation of the declination angle very precisely and independently to the taper. Measured results are summarized in Table 6.

Table 6. Ostrava – experiments with rotating cut material 10 mm thick and stable jet: inlet $D_I$ and outlet $D_O$ diameters of “columns” are reported. Speed $v_{P20}$ was applied for expected declination angle of 20° for non-tilted jet and tilting 10° was applied for expected elimination of distortion effects caused by trailback. The percentage differences between the theoretical and experimental results at the inlet and the outlet column bases are compared ($\Delta D_I$ for inlet, $\Delta D_O$ for outlet). All results are rounded to two decimal places.

| Material type                  | $v_{P20}$ (mm/min) | $D_I$ (mm) | $D_O$ (mm) | $D_{le}$ (mm) | $D_{ae}$ (mm) | $\Delta D_I$ (%) | $\Delta D_O$ (%) |
|-------------------------------|-------------------|------------|------------|---------------|---------------|-----------------|-----------------|
| WNR norm (DIN norm)           |                   |            |            |               |               |                 |                 |
| 1.057 (St 52-3)               | 146               | 9.33       | 9.68       | 9.33          | 9.73          | 0.01            | 0.48            |
| 1.0503 (C 45)                 | 116               | 9.30       | 9.66       | 9.33          | 9.66          | 0.28            | 0.06            |
| 1.7131 (16 MnCr 5)            | 128               | 9.29       | 9.65       | 9.32          | 9.73          | 0.36            | 0.84            |
| 1.7225 (42 CrMo 4)            | 105               | 9.30       | 9.66       | 9.32          | 9.63          | 0.22            | 0.24            |
| 1.4541 (X6 CrNiTi 18 10)      | 116               | 9.28       | 9.64       | 9.31          | 9.62          | 0.32            | 0.25            |
| 1.2436 (X210 CrW 12)          | 93                | 9.31       | 9.67       | 9.34          | 9.66          | 0.29            | 0.03            |

The relative impact of declination angle and the taper on the cut part shape depends on the radius of cutting trajectory – the smaller the radius the major relative deformation. Detailed explanation of this fact was presented in [13]. In view of the uncertainties mentioned above and the measurement uncertainties, it was not possible to determine clearly the amount of deformation caused by the convergence or divergence of the cut walls (the taper), as described in [14]. This issue will be examined in subsequent studies of jet – material investigations. It is also necessary to evaluate influence of other phenomena affecting the process, as documented in [16, 17, 18], i.e. material refining and heat treatment, vibrations of the cutting system or quality of abrasive material and non-homogeneity of its feeding rate. In certain systems, it can be also problem with pulsing of the water due to stopping and starting of the system, like described in [19]. Quality of cutting on certain materials, namely aluminium alloys, can be influenced also by size of abrasive grains [20]. Therefore, further research will be focused also on these factors. Nevertheless, contemporary results show a very good agreement of predicted product dimensions with the real ones measured after cutting.

5. Discussion

This contribution is aimed at proof of predictions derived from the own theoretical models on the real machines for water jetting used in practice. The predicted results were fully confirmed as it can be seen not only from results presented in Tabs 3 – 5, but namely from results presented in Tab 6, where the taper calculated for respective traverse speeds has been incorporated. It can be seen, that respective relative differences can be caused by some defects in tested material, operation of manipulating technique, abrasive feed rate etc. Further investigations will be focused also on the extent of these factors and their impact on product shape and accuracy to make the tool abrasive water jet even more precise.

6. Conclusions

Presented investigations were focused on distortion of “column”-shaped samples during abrasive water jet cutting on equipment in commercial firms. The expected results were calculated from
presented model and compared with results measured on produces samples. Two machines were used for this investigation. A special device constructed so that it can eliminate limitations introduced by manufacturers into software controlling movement of cutting machines was produced. The device rotates with material under stable jet (either non-tilted or tilted). Therefore, no machine software is used during experiment. Results of this investigation reliably proved that theoretical model is powerful tool for calculations of the predicted product shapes both for non-tilted and tilted jets. The results also proved that tilting of the cutting head (and thus AWJ) can substantially suppress an undesirable shape damage caused by AWJ trailback and taper.

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