# QUANTIFICATION AND ANALYSIS OF THE INFLUENCE OF SELECTED TECHNOLOGICAL PARAMETERS ON THE ANGLE OF WATER JET ANGLE DIGRESSION ON THE SURFACE OF THE AREA MACHINED BY AWJ TECHNOLOGY.

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**Abstract:** The paper briefly presents one of the options of quantification and analysis of the influence of three selected technological parameters on the parameter of machined surface quality – water jet angle digression. It presents an example of numerically and graphically determined concrete relation, new information following it and following conclusions and recommendations.

**Key words:** quantification, influence, technological parameter, parameter of quality of machined surface, water jet angle digression, surface, machined surface, AWJ technology

## 1. INTRODUCTION

Besides the importance of the influence of technological parameters on surface quality, it is important to know also numerical and graphical relations enabling to quantify the influence of technological parameters on the quality of surface cut by AWJ technology when looking for optimal values of technological parameters to reach the required surface quality machined by AWJ technology and cutting effectiveness. Surface quality is quantified by the water jet angle digression.

## 2. OBSERVED PARAMETERS AND THEIR MARKING

Technological parameters: $m_A$ – abrasive weight jet; $p$ – hydroabrasive water

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jet pressure; $v$ – technological head locomotion speed.

Qualitative parameters: machined surface quality parameter; Ø – water jet angle digression

### 3. EXPERIMENT PLAN

It is determined by the method of experiment planning based on experiment theory. The number of combinations of observed values of selected technological parameters is determined according to the formula:

$$y^x = k$$

where is: $y$ = 3 - number of levels of technological parameters; $x$ = 3 - number of factors – technological parameters; $k$ = 27 - resulting number of combinations of technological parameters values.

$$k = 3^3 = 27.$$

There is three-level fully three-factor experiment with total number of combination of technological parameters 27.

### 4. SAMPLES FABRICATION

The samples have been made by a production system by AWJ technology at TU VŠB Institute of Fluid Ray in Ostrava, Czech Republic. The samples of abrasion - resistant steel HARDOX 500 have been machined in the shape of equilateral triangle according to the experiment plan.

#### 4.1. Sample marking

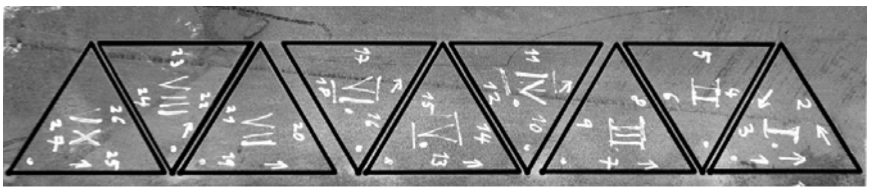

**Fig. 1.** Sample marking method:
I - IX - sample numbers; 1 - 27 - sample sides numbers (number of cut area on the sample)

### 5. MEASURED DATA

Measured numeric values of parameter Ø – water jet angle digression and relevant values of three technological parameters are shown in Table 1, in which also cutting time is given [3]. The set of measurements contains 27 measurements out of the total number of 135 measurements including repeated measurements.

*Table 1.* **Measured values of abrasive water jet imprint digression Ø and roughness *Ra*, *Rz* on cut areas of samples with 40mm thickness**

| **Sample thickness *h*** | | | | | | **40 mm** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SAMPLE IDENTIFICATION** | | **TECHNOLOGICAL PARAMETERS** | | | | **QUALITATIVE PARAMETER** | | | | | | | |
| Sample No. | Sample cut area No. | $m_A$ [g/min] | $p$ [MPa] | $v$ [mm/min] | t [s] | Repeated measurements 0 n | | | | | 0 [°] | *Ra* | *Rz* |
| | | | | | | 01 | 02 | 03 | 04 | 05 | | | |
| I. | 1 | 170 | 300 | 10 | *2.40* | 17,4 | 18,1 | 17,5 | 18,0 | 17,5 | 17,7 | 3,65 | 20,84 |
| | 2 | 170 | 300 | 15 | | 20,8 | 28,0 | 25,2 | 25,1 | 24,2 | 24,7 | 4,09 | 21,90 |
| | 3 | 170 | 300 | 20 | | 34,9 | 26,8 | 28,5 | 28,0 | 32,1 | 30,1 | 6,95 | 24,96 |
| II. | 4 | 170 | 340 | 10 | | 15,0 | 14,2 | 15,8 | 14,2 | 15,9 | 15,0 | 2,90 | 19,79 |
| | 5 | 170 | 340 | 15 | | 17,5 | 19,0 | 18,2 | 17,5 | 18,6 | 18,2 | 3,92 | 21,00 |
| | 6 | 170 | 340 | 20 | | 22,8 | 25,4 | 30,0 | 29,5 | 23,0 | 26,1 | 5,87 | 23,64 |
| III. | 7 | 170 | 380 | 10 | | 14,0 | 14,8 | 14,6 | 14,8 | 14,4 | 14,5 | 2,83 | 19,11 |
| | 8 | 170 | 380 | 15 | *'* | 17,4 | 16,8 | 17,0 | 17,0 | 17,3 | 17,1 | 3,66 | 20,81 |
| | 9 | 170 | 380 | 20 | *120* | 22,1 | 19,7 | 21,7 | 19,4 | 22,9 | 21,2 | 4,10 | *22,90* |
| IV. | 10 | 220 | 300 | 10 | *240* | 14,1 | 14,2 | 14,5 | 14,3 | 14,3 | 14,3 | *2,75* | *18,67* |
| | 11 | 220 | 300 | 15 | *160* | 16,5 | 17,2 | 17,1 | 16,8 | 17,1 | 16,9 | *3,46* | *20,56* |
| | 12 | 220 | 300 | 20 | *120* | 21,7 | 19,8 | 20,3 | 19,6 | 21,3 | 20,5 | 4,07 | 21,10 |
| V. | 13 | 220 | 340 | 10 | *240* | 14,3 | 13,6 | 13,9 | 13,7 | 13,8 | 13,9 | 2,71 | 17,14 |
| | 14 | 220 | 340 | 15 | *160* | 15,4 | 16,0 | 16,1 | 15,8 | 15,5 | 15,8 | 3,22 | 20,60 |
| | 15 | 220 | 340 | 20 | *120* | 19,0 | 21,1 | 19,3 | 18,8 | 21,0 | 19,8 | 3,65 | 20,93 |
| VI. | 16 | 220 | 380 | 10 | *240* | 14,0 | 13,4 | 13,1 | 14,1 | 13,0 | 13,5 | 2,60 | 16,83 |
| | 17 | 220 | 380 | 15 | *160* | 15,1 | 15,7 | 15,3 | 15,4 | 15,4 | 15,4 | 3,02 | 19,66 |
| | 18 | 220 | 380 | 20 | *120* | 18,1 | 19,6 | 18,6 | 18,8 | 18,7 | 18,8 | 3,46 | 20,69 |
| VII. | 19 | 270 | 300 | 10 | *240* | 13,3 | 13,1 | 12,5 | 12,2 | 13,7 | 13,0 | 2,44 | 16,52 |
| | 20 | 270 | 300 | 15 | *160* | 15,0 | 13,5 | 13,8 | 14,7 | 13,6 | 14,1 | 3,01 | 19,30 |
| | 21 | 270 | 300 | 20 | *120* | 17,6 | 18,2 | 19,1 | 19,0 | 17,8 | 18,3 | 3,33 | 20,10 |
| VIII. | 22 | 270 | 340 | 10 | *240* | 11,7 | 10,7 | 12,1 | 12,2 | 11,0 | 11,5 | 2,28 | 16,25 |
| | 23 | 270 | 340 | 15 | *160* | 12,9 | 12,5 | 12,4 | 12,9 | 12,8 | 12,7 | 2,93 | 18,29 |
| | 24 | 270 | 340 | 20 | *120* | 17,1 | 16,7 | 16,5 | 16,8 | 16,8 | 16,8 | 3,21 | 19,77 |
| IX. | 25 | 270 | 380 | 10 | *240* | 10,2 | 9,4 | 9,3 | 9,1 | 9,8 | 9,6 | 2,27 | 16,02 |
| | 26 | 270 | 380 | 15 | *160* | 10,1 | 10,4 | 11,1 | 10,4 | 10,5 | 10,5 | 2,67 | 16,77 |
| | 27 | 270 | 380 | 20 | *120* | 15,2 | 14,7 | 14,1 | 13,9 | 14,9 | 14,6 | 2,96 | 18,40 |
| **Σ*t* [min]** | | | | | 78 | | | | | | | | |
| **Average values Ø, *Ra*, *Rz*** | | | | | | | | | | | **16,8** | **3,41** | **19,72** |

## 6. EVALUATED DATA AND THEIR ANALYSIS

A sample of a set of two-parameter numerical and graphical functional dependencies.

$$Ø = 26{,}048 - 0{,}048 \cdot p + 0{,}702 \cdot v$$

## 7. NEW INFORMATION FOLLOWING EXPERIMENT EVALUATION

The part which is shown here is a part of a complete set of new information from the research and quantification of the influence of three technological parameters $v$, $p$, $m_A$, which considerably influence qualitative parameter Ø during cutting steel HARDOX 500 with the thickness 40 mm by AWJ technology.

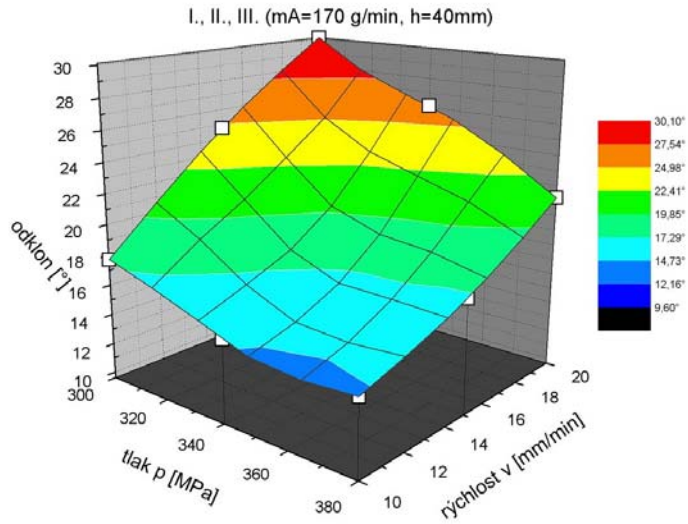


**Fig. 2.** Graphic depiction of 2 – parameter dependencies „0-*p*-*v*" (*h* = 40 mm), „$m_A$" = const. = 170 g/min (odklon=deflection, tlak=pressure, rýchlosť=speed)

$$Ø = 18{,}948 - 0{,}048 \cdot p + 0{,}702 \cdot v$$

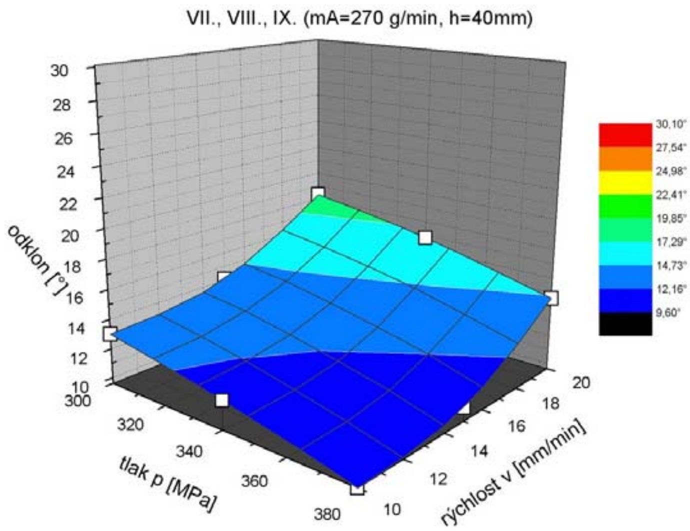


**Fig. 3.** Graphic depiction of 2- parameter dependency „0-*p*-*v*" (*h* = 40 mm) „$m_A$" = const. = 270 g/min (odklon=deflection, tlak=pressure, rýchlosť=speed)

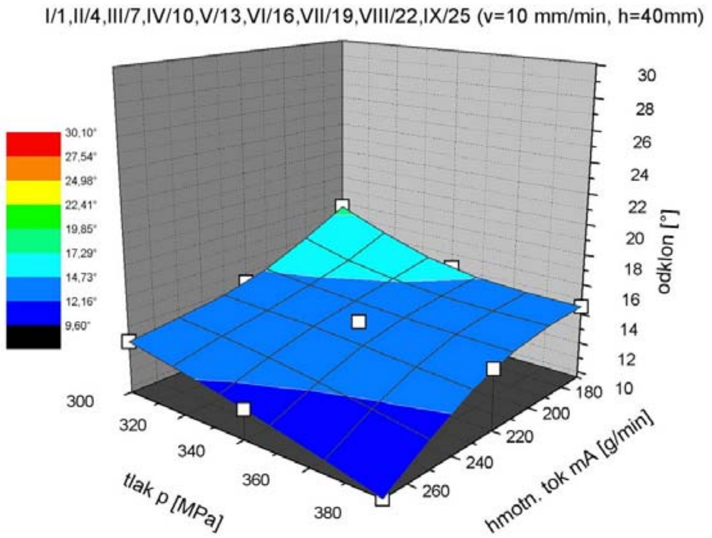


**Fig. 4.** Graphic depiction of 2- parameter dependency „0-*p*-*v*" (*h* = 40 mm) „*v*" = const. = 10 mm/min (odklon=deflection, tlak=pressure, hmotn.tok=mass flow)

New information resulting from Table 1:

✓ Values of technological parameters $m_A$ = 170 g/min, *p* = 300 MPa, *v* = 20 mm/min present a common combination, by which the worst value of qualitative parameter – abrasive water jet imprint digression Ø = 30,1° has been obtained out of total range of measured values <9,6° - 30,1°> on the surface of measured sample with the code 1/3.

✓ Values of technological parameters $m_A$ = 270 g/min, *p* = 380 MPa, *v* = 10 mm/min present a common combination, by which the best values of the jet digression Ø = 9,6° has been reached out of the total range of measured values <9,6° - 30,1°> (which is the improvement in 68% - more than three times more) on the sample with the code (IX/25).

✓ By the decrease of cutting speed (from 20 to 15 and 10 mm/min) the jet digression decreases:

- in the most distinctive way in the combination with technological parameters ($m_A$ = 170 g/min, *p* = 300 MPa and $m_A$ = 170 g/min, *p* = 340 MPa), i.e. minimal weight jet in combination with minimal and medium pressure from the used ranges, where the jet digression for $m_A$ = 170 g/min, *p* = 300 MPa and *v* = 20 mm/min (sample code 1/3) has improved in as much as 41,1% (from 30,1° to 17,7°) by the change of technological parameter to v = 10 mm/min (I/1). And for $m_A$ = 170 g/min, *p* = 340 MPa and *v* = 20 mm/min (cut area II/6) the jet digression has increased in as much as 42,5% (from 26,1° to 15°) by the change to *v* = 10 mm/min (U/4);
- in the least distinctive way by the changes from 8,2% to 9,1% at the combination of values of technological parameters $m_A$ = 270 g/min, *p* = 300 MPa, *v* = 10 mm/min ( VII/19), $m_A$ = 270 g/min, *p* = 340 MPa, *v* = 10 mm/min

(VIII/22)., *mA* = 270 g/min, *p* = 380 MPa, *v* = 10 mm/min (IX/25);

- in the medium distinctive way by the change in the range 12% to 31%, at other combinations of values of technological parameters ($m_A$, *p*, *v*) from the observed ranges.

✓ By increasing the weight jet of the abrasive (from 170 to 220 and 270 g/min) the jet digression decreases:

- in the most distinctive way in the combination of values of technological parameters (*p* = 300 MPa, *v* = 15 mm/min a *p* = 300 MPa, *v* = 20 mm/min and *p* = 380 MPa, *v* = 15 mm/min), i.e. minimal pressure in the combination with medium and maximal cutting speed and maximum pressure with medium speed from the used ranges, where the jet digression at $m_A$ = 170 g/min, *p* = 300 MPa and *v* = 15 mm/min $m_A$ (cut area 1/2) has improved in as much as 42,7% (from 24,7° to 14,1°) by the change of „$m_A$“ into 270 g/min (cut area VII/20). At $m_A$ = 170 g/min, *p* = 300 MPa and *v* = 20 mm/min (cut area 1/3) the jet digression has improved in 39% (from 30,1° to 18,3°) by the change of „$m_A$“ to 270 g/min (cut area VII/21). And for $m_A$ =170 g/min, *p* = 380 MPa and *v* = 15 mm/min (area III/8) the jet digression has improved in 38,6% (from 17,1° to 10,5°) by the change of „$m_A$" to 270 g/min (cut area IX/26);
- in the least distinctive way from 6,9% to 9,2% at $m_A$ = 170 g/min, *p* = 380 MPa, *v* = 10 mm/min (cut area III/7), $m_A$ =170 g/min, *p* = 340 MPa, *v* = 10 mm/min (cut area II/4), $m_A$ = 220 g/min, *p* = 300 MPa, *v* = 10 mm/min (cut area IV/10);
- in the medium distinctive way, by the changes of range 10% to 35%, at other combinations of values of technological parameters ($m_A$, *p*, *v*) from the observed ranges.

✓ By the increase of pump pressure (from 300 to 340 and 380 MPa) the jet digression decreases:

- in the most distinctive way at the combination of values of technological parameters ($m_A$ = 170MPa, *v* = 15 mm/min and $m_A$ = 170 MPa, *v* = 20 mm/min), so at the minimal weight jet of abrasive in the combination with medium and maximal speed from the ranges during the experiment, where the jet digression at $m_A$ = 170 g/min, *p* = 300 MPa and *v* = 15 mm/min (I/2) has improved in 30,7% (from 24,7° to 17,1°) by the change of „*p*” to 380 MPa (III/8). At $m_A$ = 170 g/min, *p* = 300 MPa and *v* = 20 mm/min (I/3) the jet digression has improved in 29,6% (from 30,1° to 21,2°) by the change of „*p*” to 380 MPa (III/9);
- in the least distinctive way by changes from 2,4% to 9,2% at the combination of values of technological parameters $m_A$ = 220 g/min, *p* = 300 MPa, *v* = 10, 15, 20 mm/min (sample IV, cut areas 10, 11, 12), at the combination $m_A$ = 220 g/min, *p* = 340 MPa, *v* = 10, 15, 20 mm/min (sample V/cut areas 13, 14, 15) and at the combination $m_A$ = 220 g/min, *p* = 380 MPa, *v* = 10, 15, 20 mm/min (sample VI/cut areas 16, 17, 18), at the combination $m_A$ = 170 g/min, *p* = 340 MPa, *v* = 10, 15 mm/min (sample II, cut areas 4, 5) and at the combination $m_A$ = 270 g/min, *p* = 300 MPa, *v* = 20 mm/min (cut area VII/21);

- in the medium distinctive way by the changes in range 10% to 26%, at other combinations of the values of technological parameters ($m_A$, $p$, $v$) from the observed range.

✓ By the comparison of measured values of jet digressions with their average value 16,8° it is possible to say that it is possible to reach almost the same jet digression with the dispersion of only 1,9° by several combinations of technological parameters:

$$m_{A\min} - p_{\min} - v_{\min} \sim m_{A\min} - p_{\max} - v_{str} \sim m_{Astr} - p_{\min} - v_{str} \sim m_{Astr} - p_{str} - v_{str} \sim m_{A\max} - p_{\max} - v_{\max}$$

Table 2 shows it more clearly with concrete values of parameters and measured values of jet digression.

*Table 2.* **Example of combination of values of technological parameters from the observed ranges for obtaining approximately same abrasive water jet digression imprint Ø = 16,8° at cut areas of metal plates with thickness 40 mm**

| Parameter combination | Range min | Range mean | Range max | Values | Units | Recorded jet digresion | sample No./cut area No. | Cut course/hour [m] |
|---|---|---|---|---|---|---|---|---|
| 1. | $m_{A\min}$ | | | 170 | g/min | 17,7° | I/1 | 0,6 |
| | $p_{\min}$ | | | 300 | MPa | | | |
| | $v_{\min}$ | | | 10 | mm/min | | | |
| 2. | $m_{A\min}$ | | | 170 | g/min | 17,1° | III/8 | 0,9 |
| | | | $p_{\max}$ | 380 | MPa | | | |
| | | $v_{str}$ | | 15 | mm/min | | | |
| 3. | | $m_{Astr}$ | | 220 | g/min | 16,9° | IV/11 | 0,9 |
| | $p_{\min}$ | | | 300 | MPa | | | |
| | | $v_{str}$ | | 15 | mm/min | | | |
| 4. | | $m_{Astr}$ | | 220 | g/min | 15,8° | V/14 | 0,9 |
| | | $p_{str}$ | | 340 | MPa | | | |
| | | $v_{str}$ | | 15 | mm/min | | | |
| 5. | | | $m_{A\max}$ | 270 | g/min | 16,8° | VIII/24 | 1,2 |
| | | | $p_{\max}$ | 380 | MPa | | | |
| | | | $v_{\max}$ | 20 | mm/min | | | |
| Dispersion | | | | | | 1,9° | | |

It is possible to conclude on the base of Table 2:

- The increase of „$m_A$" from 170 to 270 g/min at the simultaneous increase of „$p$" from 300 to 380 MPa enables to use two-times higher cutting speed and by this it will enable to cut off two times more material at almost the same value of abrasive water jet imprint digression;
- At the constant speed $v$ = 10 mm/min and simultaneous influence of other two technological parameters ($m_A$, $p$) as well as at their independent influ-

ence, the changes in jet digression has shown in a less distinctive way than at constant speeds 15 and 20 mm/min, while at the speed 20 mm/min the changes in the jet digression has been the most distinctive;

- At the smallest speed 10 mm/min out of the observed range these phenomena has been recorded in considerably smaller range and the changes in the amount of abrasive from its minimum into maximal values for different values of the pump pressure they have shown in a less negative way in jet digression (Fig. 4).

✓ By the increase of the amount of abrasive from the value 170 to 220 and 270 g/min at constant pressures as well as constant cutting speeds, the jet digression imprints decrease considerably in the whole range of this qualitative parameter.

✓ By the increase of the pressure from 300 to 340 and 380 MPa at constant weight jets of the abrasive and cutting speeds the jet digression decreases, but less considerably in the whole range.

✓ By the increase of the speed of cutting head from 10 to 15 and 20 mm/min at constant weight jets and pressures the jet digression increases very considerably.

✓ By the common influence of higher values from the used intervals for the weight flow of the abrasive ($m_A$ = 220, 270 g/min) and the pump pressure ($p$ = 340, 380 MPa) at lower values of speeds ($v$ = 10, 15 mm/min) from the used interval, smaller jet digression in the range 9,6° to 15,8 ° has been obtained.

✓ By the common influence of lower values from the used intervals for weight flow ($m_A$ = 170, 220 g/min) and the pump pressure ($p$ = 300, 340 MPa) at higher values from the used interval for speed ($v$ = 15, 20 mm/min), greater jet digression in the range 15,8° to 30,1° has been obtained.

## 8. RECOMMENDATIONS FOLLOWING THE NEW INFORMATION

At cutting steel HARDOX 500 with the thickness 40 mm by AWJ technology we recommend:

- To obtain positive surface quality expressed by the abrasive water jet digression (e.g. Ø = 9,6°) it is suitable to adjust technological parameters into values $m_A$ = 270 g/min, $p$ = 380 MPa, $v$ = 10 mm/min, which however results in prolonging the cutting time to 240 s. If surface quality is the priority, prolonging cutting time does not matter, i.e. at required small cutting range (m);
- It is possible to obtain required less positive surface quality of machined surface, e.g. Ø= 16,8° also by the adjustment of technological parameters into values $m_A$ = 270 g/min, $p$ = 380 MPa, $v$ = 20 mm/min, by which cutting time shortens into 120 s. This combination of the values of technological parameters is suitable to obtain positive ratio of cut surface quality and cutting time, especially at required wide range of cutting (m);
- We do not recommend to adjust the combination of values of technological parameters e.g. $m_A$ = 170 g/min, $p$ = 300 MPa, $v$ = 20 mm/min by which

very negative machined area quality Ø = 30,1° is obtained, although the cutting time is short.

## 9. CONCLUSION

The paper contains original numerical and graphical functional dependencies of the influence of three selected technological parameters – abrasive weight flow, pressure of hydroabrasive water jet, speed of technological head locomotion on the parameter of machined surface quality – water jet angle digression, samples with the thickness 40 mm cut off the steel HARDOX 500 by the production system by AWJ technology. From the evaluation and analysis of experiments presented in the paper but also the data shown in the complete set of numerical and graphical functional dependencies [3], new scientific knowledge has been formed clearly into 20 points and three recommendations for the companies operating production systems with AWJ technology in form of concrete combinations of values of technological parameters to obtain recommended above-average quality of the surface and recommended average quality of the surface obtained at considerably shorter cutting time.

The knowledge introduced in the contribution create the partial part of the grant scientific project VEGA no. 1/0544/08 and Institutional project 5/2010 solution.

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