

Article

Assessment of the Influence of Selected Technological Parameters on the Morphology Parameters of the Cutting Surfaces of the Hardox 500 Material Cut by Abrasive Water Jet Technology

Tibor Krenicky ^{1,*} , Stefania Olejarova ¹ and Milos Servatka ²

¹ Department of Technical Systems Design and Monitoring, Faculty of Manufacturing Technologies with a Seat in Presov, Technical University of Kosice, Sturova 31, 08001 Presov, Slovakia; stefania.olejarova@tuke.sk

² IMSLOV, P. Horova 19, 08001 Presov, Slovakia; ms@imslov.sk

* Correspondence: tiber.krenicky@tuke.sk

Abstract: This article deals with the evaluation of selected aspects of abrasive water jet technology (AWJ) in the cutting of abrasion-resistant steel (HARDOX 500) with a thickness of 40 mm. The high abrasion resistance as a typical significant property of this steel ranks it among the special materials that are increasingly used. As the AWJ is a multiparametric technology, selected levels of feed rate, abrasive mass flow and pump working pressure were used in the experiments from the spectrum of technological parameters. For the purposes of evaluation, the examined cut surfaces were documented by a modified photographic method of displaying the cut surface by means of side lighting on the untreated cutting surface. The experimental part evaluates the dependences of selected cutting surface quality parameters (surface roughness and abrasive water jet deflection) on selected important technological parameters of the production system with AWJ technology (abrasive mass flow, technological head feed rate and pump working pressure). Based on the evaluation of the experiments, regression models were created to interpolate and extrapolate data to compare or supplement existing solutions in the field of research and as a basis for optimizing operating costs and increasing the efficiency of production systems with abrasive water jet technology.

Keywords: abrasive water jet; material cutting; surface quality; cut profile; regression model; Hardox; technological head feed rate; mass flow of abrasive



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1. Introduction

Abrasive water jet technology (AWJ) is a progressive tool used to machine a wide range of materials. Profiting from its several unique features, such as cold machining of hard-to-machine materials without their deformation, separation of inhomogeneous materials and a small amount of waste material, AWJ has a significant potential to replace other machining techniques in several applications [1]. The pioneer scientists dealing with the topic were Hashish [2] and Zeng and Kim [3]. Later, numerous investigations aimed at the machining process appeared, e.g., by Kovacevic and Yong [4,5]. The current state of research of abrasive water jet technology revealed that one of the most important problems is the quantification and modeling of the influence of technological parameters on surface quality parameters, particularly at hard-to-machine materials sheets by Savkovic [6]. Abrasive water-jet cutting is a multiparametric process where the quality of the output characteristics relies on the inputs. This has been proven by various experiments and theoretical analyses. Evaluation of cutting quantity and quality has been continuously studied by various groups [7–10]. Sutowska et al. [11] studied the influence of cutting parameters on kerf quality in detail. Some of the recent experiments were performed on HardoxTM 400, 450 and 500 steel sheets by Filip et al. [12,13]. Yet there are numerous attempts at creating the

models that characterize the cut area quality under specific conditions regarding material type and thickness, technological head feed rate, the abrasive mass flow rate, grain size and many others. Evaluation of the cutting quality is related to the quality of the cut walls. Although there is a constantly growing set of developed solutions to the problem, including methodologies and evaluations of experiments valid for specific measurement conditions, the current solutions still do not cover several variations.

Models of machining materials using AWJ technology describe the action of a concentrated water jet, the efficiency of which is often increased by doping with solid abrasive particles such as garnet [14]. The model proposed by Monno and Ravasio [15] is based on the assessment of the striation formation that depends mainly on the jet instability caused by vibrations during the cutting process. Similar to other high-energy beam technologies, the AWJ jet generates visible striations on the machined surface [16–20]. The quality of the cutting process is the result of the tool's operation as part of the overall effect on the overall quality of the product, conditioned by three types of accuracy: shape, dimensional and surface measure, characterized mainly by roughness parameters [21]. The roughness of the machined surface using AWJ deteriorates from the point of entry into the material to the point of exit. The striating is generated at a certain depth below the surface and gradually deepens, causing a negative effect on the quality of the machined surfaces as well as on the shape accuracy of the products. The machined surface is thus divided into a smooth zone and a rough–striated zone. This behavior arises from the fact that since the jet penetrates the material, it gradually loses its kinetic energy and deflects. The relatively smooth area in the upper part of the cut is identified as the zone of cutting wear of the material, while the second striated area in the lower part of the cut arises as a consequence of deformation wear during cutting by AWJ technology [22,23].

The most common characteristics used for the evaluation of the surface roughness are R_a , the mean arithmetic deviation of the profile, and R_z , the height of the profile unevenness. These two quantities can be measured by contact profilometers or by non-contact profilometers [24–26]. Nevertheless, the values depend not only on cut material or depth in the kerf but also on abrasive material quality and grain size [27]. Hlaváč's group had presented a different approach to the determination of the cutting wall quality than the use of the R_a and R_z values, proposing a direct relationship between the declination angle (measured between the tangent to the striation curve in the definite depth h and the impinging jet axis) and respective cutting wall quality [28,29]. Understanding the influence of machining conditions on the quality of the obtained cuts enhances the quality and effectiveness of cutting. The basic process parameters characterizing the machining of materials using AWJ include the pumping pressure; feed rate of the technological head; abrasive mass flow; diameter of the nozzle and focusing tube and distance of the technological head from the material surface [30]. The microscopic models describing the mechanism of material cutting were prepared as well as the macroscopic model of cutting front behavior [31,32].

The recent research is focused on complementing existing models and preparing some new ones that would be simple enough to be applicable in industrial conditions to help predict and control the production quality. The results presented in this paper can be used for the regression models helping predict the surface quality relationship with the cutting factors, such as water pressure, feed rate and abrasive mass flow rate. In our opinion, the study of parameters in presented combination and range are unique. Thus, the novelty of the present manuscript is based on a unique combination of the thick durable material and varied operational parameters. Our work is aimed to complement data for models present in some other research works as some readers maybe appreciate such kind of information. Authors hope that data can be useful from research as well as practical points of view.

2. Materials and Methods

The experimental cutting of test specimens was performed in the Liquid Jet Laboratory, Institute of Physics, Faculty of Mining and Geology, University of Mining—Technical University of Ostrava using a production system with AWJ technology. The system includes a Flow HSQ 5X high-pressure pump and an X-Y WJ1020-1Z-EKO workbench together with an X-Y CNC control system with a PaserIIITM cutting head.

All samples were cut from HardoxTM 500 abrasion-resistant plates with a nominal hardness of 500 HBW developed for applications with high demands on abrasion resistance. Material properties were obtained by a combination of quenching and tempering performed by manufacturer SSAB Oxelösund AB, Sweden. A sheet thickness of 40 mm was used for the individual sets of experiments.

The samples were cut from sheet metal at combinations of feed rate v (10; 15 and 20 mm/min), abrasive mass flow m_A (170; 220 and 270 g/min) and pump working pressure p (300; 340 and 380 MPa). The plate was placed on the grid of the X-Y workbench, the mutually perpendicular sides of the plate being parallel to the working axes X and Y of the table. The distance of the nozzle of the cutting head from the material surface at all cuts was 2 mm. The process of cutting itself consisted of 2 parts—the production of the hole in the material from which the water jet began to cut, and consequently, cutting the samples in the form of an equilateral triangle (Figure 1a). All holes were made before cutting, while the cutting head held on its body a protective sheet metal element in the shape of a cylinder closed on the top that was designed to prevent spraying the reflected jet into the space and thus polluting the laboratory with droplets of water and abrasive (Figure 1b).

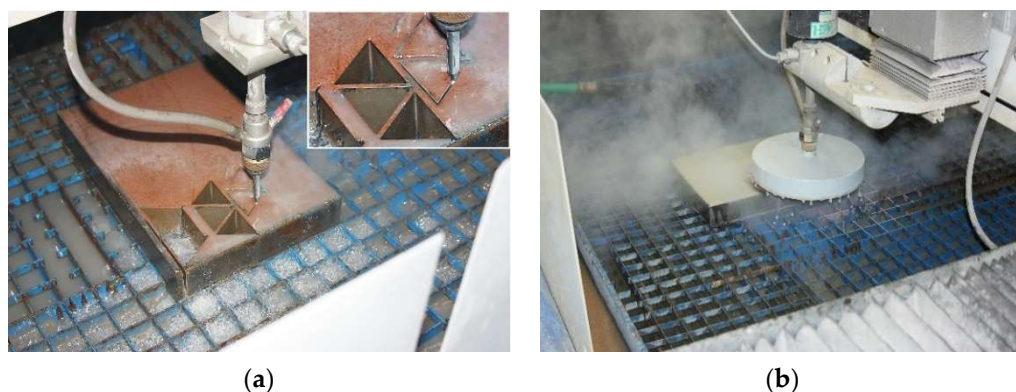


Figure 1. (a) Cutting 40 mm thick Hardox 500 sheet metal; (b) usage of protective cylinder.

Cutting parameters were as following:

Water orifice diameter d_o —0.25 mm

Stand-off distance L —2 mm

Focusing tube diameter d_a —1.02 mm

Focusing tube length l_a —76 mm

Abrasive material average grain size a_o —0.275 mm (MESH 80)

Abrasive material—Australian garnet GMA

A total of 9 pieces of samples were cut. The total number of various cutting parameter combinations was 27 (3 areas on each sample). All the samples cut by abrasive water jet were marked for accurate evaluation to avoid confusion. The marking was performed immediately after cutting the set of samples and drying them on their upper surfaces (closer to the upper cutting edges). The beginning of the cut was marked with a dot on each upper surface of the sample. The arrow indicated the cutting direction and procedure. The method of labeling the samples for evaluation can be seen in Figure 2.

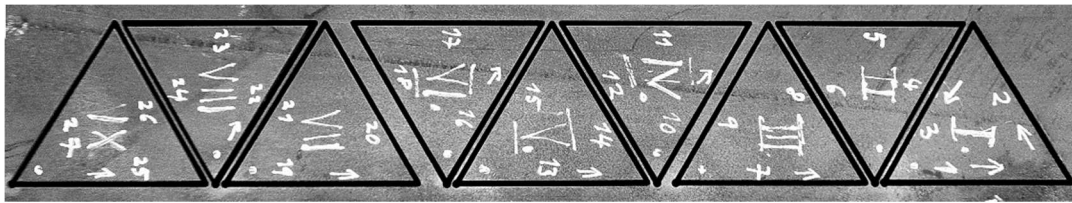


Figure 2. Example of sample marking.

The roughness parameters R_a and R_z were measured in the middle height of the sample, i.e., at half the cut material's thickness. The roughness parameters R_{a4} and R_{z4} were measured on the cut surfaces of samples at a distance of 4 mm from the upper cutting edge (from the surface of the sheet where the jet enters the material) using the Mitutoyo SurfTest SJ-301 roughness tester—see Figure 3. Repeated control measurements were performed for the reliability of all measured sets of values. The control measurements' total errors for the roughness R_a , R_z , R_{a4} , and R_{z4} are in the range $\langle 3.06; 5.09 \rangle$ percent [15].

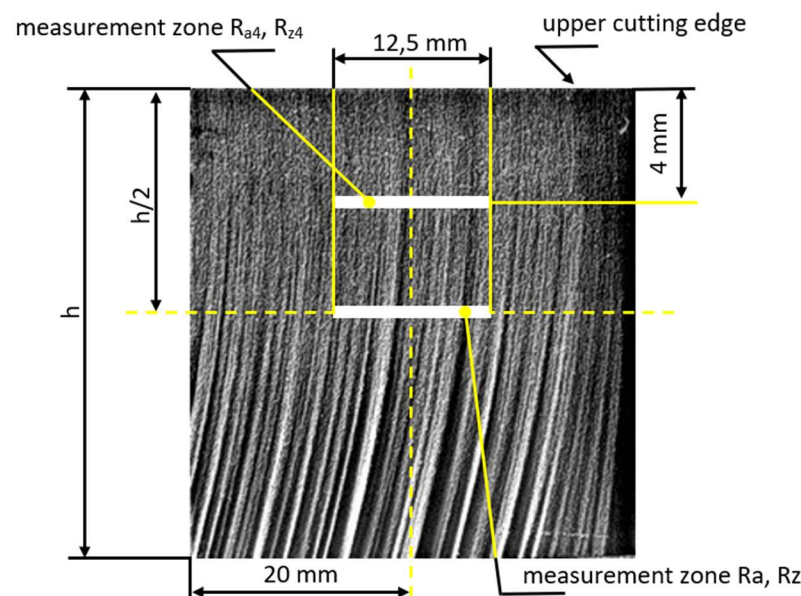


Figure 3. Roughness measuring zones for the parameters R_a , R_z , R_{a4} , and R_{z4} on the cut surfaces of the samples.

The deflection of the abrasive water jet \varnothing was measured at 5 locations on each cut surface, steadily at 5 mm distance from the previous measurement in the cutting direction according to Figure 4.

2.1. Description of Measuring Equipment

Roughness measurements of the cut surfaces of the samples were performed using the Mitutoyo SurfTest SJ-301 roughness tester. The device was used to measure the surface roughness of the cut surfaces (R_a , R_z , R_{a4} and R_{z4}) of the samples. The device contains a contact probe, which measures the surface profile using a differential induction detection method and evaluates the surface quality calculating parameters according to the standards. The length of the measuring needle path in the roughness measuring device was 12.5 mm. The detail of the measuring device when measuring the roughness of the cut surface of the sample is illustrated in Figure 5.

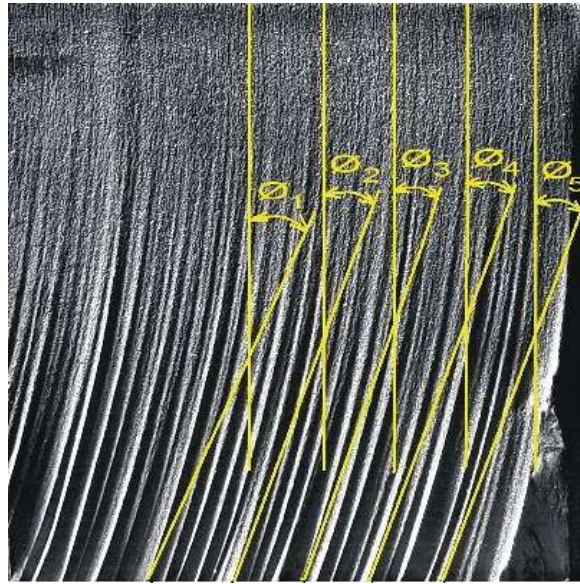


Figure 4. Localization of the measurement of the deflection of the abrasive water jet trace on the cut surface.



Figure 5. SurfTest SJ-301 device measuring the roughness of the cut surface.

2.2. Analysis and Evaluation of the Surface

The analysis of the results of the experimental studies was structured into the following blocks:

- Measured values of roughness Ra , Rz , Ra_4 and Rz_4 and deflection of the jet \emptyset ;
- Roughness measured in the middle of the cut areas of the samples;
- Roughness measured 4 mm from the upper cutting edges on the samples' cut surfaces;
- Deflection of the abrasive water jet;
- Evaluation based on photographic pictures of cut surfaces.

3. Results

3.1. Measured Values of Roughness Ra , Rz , Ra_4 and Rz_4 and Deflection of the Abrasive Water Jet \emptyset

Table 1 presents a set of measured values of the deflection of the abrasive water jet \emptyset and the surface roughness parameters Ra and Rz measured in the centers of the cut areas of the samples according to locations depicted in Figures 3 and 4, varying with change in the selected technological parameters—feed rate of the technological head, abrasive mass flow and pumping pressure.

Table 1. Values of the deflection of the abrasive water jet track \emptyset and the roughness parameters Ra and Rz as measured on the cut surfaces of the samples.

| Sample Identification | | Technological Parameters | | | Qualitative Parameters | | | | | | | |
|--|----------------|--------------------------|-----------|--------------|--|---------------|---------------|---------------|---------------|-----------------|------|-------|
| Sample No. | Sample Cut No. | m_A [g/min] | p [MPa] | v [mm/min] | Repeated Measurements for Evaluation \emptyset [°] | | | | | \emptyset [°] | Ra | Rz |
| | | | | | \emptyset_1 | \emptyset_2 | \emptyset_3 | \emptyset_4 | \emptyset_5 | | | |
| I | 1 | 170 | 300 | 10 | 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 | 22.1 | 19.7 | 21.7 | 19.4 | 22.9 | 21.2 | 4.10 | 22.90 |
| IV | 10 | 220 | 300 | 10 | 14.1 | 14.2 | 14.5 | 14.3 | 14.3 | 14.3 | 2.75 | 18.67 |
| | 11 | 220 | 300 | 15 | 16.5 | 17.2 | 17.1 | 16.8 | 17.1 | 16.9 | 3.46 | 20.56 |
| | 12 | 220 | 300 | 20 | 21.7 | 19.8 | 20.3 | 19.6 | 21.3 | 20.5 | 4.07 | 21.10 |
| V | 13 | 220 | 340 | 10 | 14.3 | 13.6 | 13.9 | 13.7 | 13.8 | 13.9 | 2.71 | 17.14 |
| | 14 | 220 | 340 | 15 | 15.4 | 16.0 | 16.1 | 15.8 | 15.5 | 15.8 | 3.22 | 20.60 |
| | 15 | 220 | 340 | 20 | 19.0 | 21.1 | 19.3 | 18.8 | 21.0 | 19.8 | 3.65 | 20.93 |
| VI | 16 | 220 | 380 | 10 | 14.0 | 13.4 | 13.1 | 14.1 | 13.0 | 13.5 | 2.60 | 16.83 |
| | 17 | 220 | 380 | 15 | 15.1 | 15.7 | 15.3 | 15.4 | 15.4 | 15.4 | 3.02 | 19.66 |
| | 18 | 220 | 380 | 20 | 18.1 | 19.6 | 18.6 | 18.8 | 18.7 | 18.8 | 3.46 | 20.69 |
| VII | 19 | 270 | 300 | 10 | 13.3 | 13.1 | 12.5 | 12.2 | 13.7 | 13.0 | 2.44 | 16.52 |
| | 20 | 270 | 300 | 15 | 15.0 | 13.5 | 13.8 | 14.7 | 13.6 | 14.1 | 3.01 | 19.30 |
| | 21 | 270 | 300 | 20 | 17.6 | 18.2 | 19.1 | 19.0 | 17.8 | 18.3 | 3.33 | 20.10 |
| VIII | 22 | 270 | 340 | 10 | 11.7 | 10.7 | 12.1 | 12.2 | 11.0 | 11.5 | 2.28 | 16.25 |
| | 23 | 270 | 340 | 15 | 12.9 | 12.5 | 12.4 | 12.9 | 12.8 | 12.7 | 2.93 | 18.29 |
| | 24 | 270 | 340 | 20 | 17.1 | 16.7 | 16.5 | 16.8 | 16.8 | 16.8 | 3.21 | 19.77 |
| IX | 25 | 270 | 380 | 10 | 10.2 | 9.4 | 9.3 | 9.1 | 9.8 | 9.6 | 2.27 | 16.02 |
| | 26 | 270 | 380 | 15 | 10.1 | 10.4 | 11.1 | 10.4 | 10.5 | 10.5 | 2.67 | 16.77 |
| | 27 | 270 | 380 | 20 | 15.2 | 14.7 | 14.1 | 13.9 | 14.9 | 14.6 | 2.96 | 18.40 |
| Average values of \emptyset , Ra and Rz , respectively | | | | | | | | | | 16.8 | 3.41 | 19.72 |

Table 2 presents a set of measured values of roughness parameters Ra_4 and Rz_4 of cut surfaces measured at a distance of 4 mm from the upper cutting edge according to Figure 3.

Table 2. Values of the roughness parameters Ra_4 and Rz_4 as measured on the cut surfaces of the samples at a distance of 4 mm.

| Sample Identification | | Technological Parameters | | | Qualitative Parameters | |
|-----------------------|----------------|--------------------------|-----------|--------------|------------------------|--------|
| Sample No. | Sample Cut No. | m_A [g/min] | p [MPa] | v [mm/min] | Ra_4 | Rz_4 |
| I | 1 | 170 | 300 | 10 | 3.03 | 18.87 |
| | 2 | 170 | 300 | 15 | 3.10 | 19.37 |
| | 3 | 170 | 300 | 20 | 3.36 | 21.69 |
| II | 4 | 170 | 340 | 10 | 2.81 | 18.44 |
| | 5 | 170 | 340 | 15 | 2.93 | 19.17 |
| | 6 | 170 | 340 | 20 | 3.10 | 21.39 |
| III | 7 | 170 | 380 | 10 | 2.47 | 18.01 |
| | 8 | 170 | 380 | 15 | 2.83 | 19.01 |
| | 9 | 170 | 380 | 20 | 3.02 | 19.99 |

Table 2. Cont.

| Sample Identification | | Technological Parameters | | | Qualitative Parameters | |
|--|----------------|--------------------------|-----------|--------------|------------------------|--------------|
| Sample No. | Sample Cut No. | m_A [g/min] | p [MPa] | v [mm/min] | Ra_4 | Rz_4 |
| IV | 10 | 220 | 300 | 10 | 2.36 | 17.86 |
| | 11 | 220 | 300 | 15 | 2.56 | 18.72 |
| | 12 | 220 | 300 | 20 | 2.99 | 19.95 |
| V | 13 | 220 | 340 | 10 | 2.26 | 17.23 |
| | 14 | 220 | 340 | 15 | 2.49 | 18.61 |
| | 15 | 220 | 340 | 20 | 2.78 | 19.67 |
| VI | 16 | 220 | 380 | 10 | 2.16 | 16.90 |
| | 17 | 220 | 380 | 15 | 2.44 | 18.09 |
| | 18 | 220 | 380 | 20 | 2.71 | 19.53 |
| VII | 19 | 270 | 300 | 10 | 2.11 | 16.81 |
| | 20 | 270 | 300 | 15 | 2.29 | 17.92 |
| | 21 | 270 | 300 | 20 | 2.68 | 18.96 |
| VIII | 22 | 270 | 340 | 10 | 2.07 | 16.64 |
| | 23 | 270 | 340 | 15 | 2.24 | 17.54 |
| | 24 | 270 | 340 | 20 | 2.53 | 18.92 |
| IX | 25 | 270 | 380 | 10 | 2.02 | 16.19 |
| | 26 | 270 | 380 | 15 | 2.22 | 17.23 |
| | 27 | 270 | 380 | 20 | 2.50 | 18.78 |
| Average values of Ra_4 and Rz_4 | | | | | 3.15 | 20.95 |

The values are varying with change in the selected technological parameters—feed rate of the technological head, abrasive mass flow and pumping pressure.

3.2. Roughness Measured in the Centers of the Cut Areas of the Samples

The graphs in Figure 6 present a graphical evaluation of 1-parametric dependencies of $Ra = f(v)$. These dependencies are presented in the form of conjugated graphs for cases of constant abrasive mass flow (in each graph, three dependencies are plotted for the three different values of pressures of 300, 340 and 380 MPa).

The graphs in Figure 7 present a graphical evaluation of 1-parametric dependencies of $Rz = f(v)$. These dependencies are shown in the form of conjugated graphs for cases of constant abrasive mass flow (in each graph, three dependencies are plotted for the three different values of pressures 300, 340 and 380 MPa).

3.3. Roughness Measured 4 mm from the Upper Cutting Edges of the Cut Areas of the Samples

Graphical evaluation of the 1-parametric dependence in Figure 8 shows the dependence of the technological parameter v on the quality parameters of the cut surface Ra_4 at a constant distance of the roughness measuring point from the upper cutting edge as presented in Figure 3. The mass flow of the abrasive is constant. In each graph, three dependencies are plotted for the three different values of pressures 300, 340 and 380 MPa.

The graphs in Figure 9 show a graphical evaluation of the 1-parametric dependencies of $Rz_4 = f(v)$ at a constant distance of the roughness measuring point from the upper cutting edge (Figure 3). These dependencies are presented in the form of conjugated graphs for cases of the constant abrasive mass flow (in each graph, three dependencies are plotted for three different values of pressures of 300, 340 and 380 MPa).

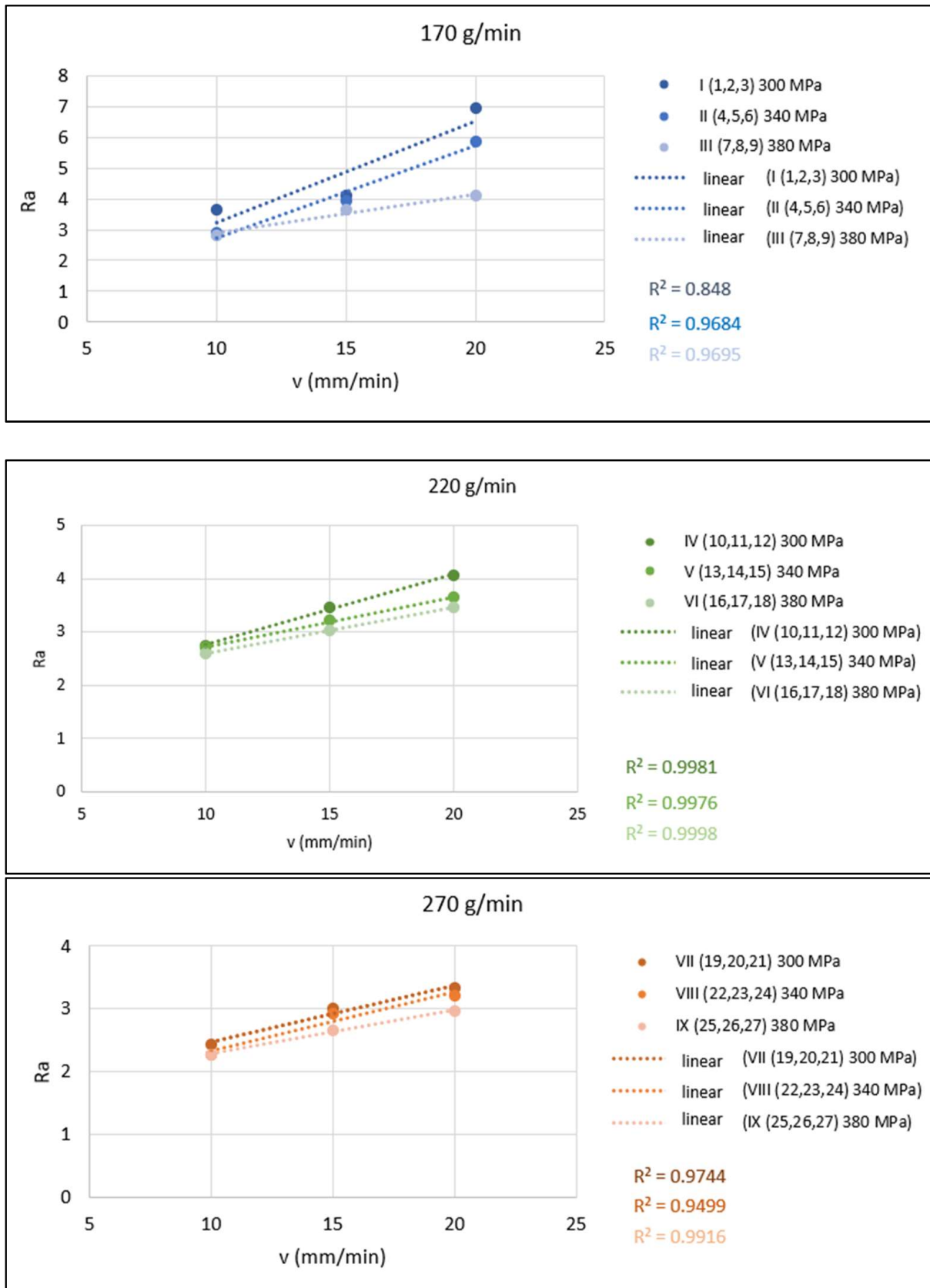


Figure 6. Graphical evaluation of 1-parametric dependences of $Ra = f(v)$ for $m_A = 170, 220$ and 270 g/min.

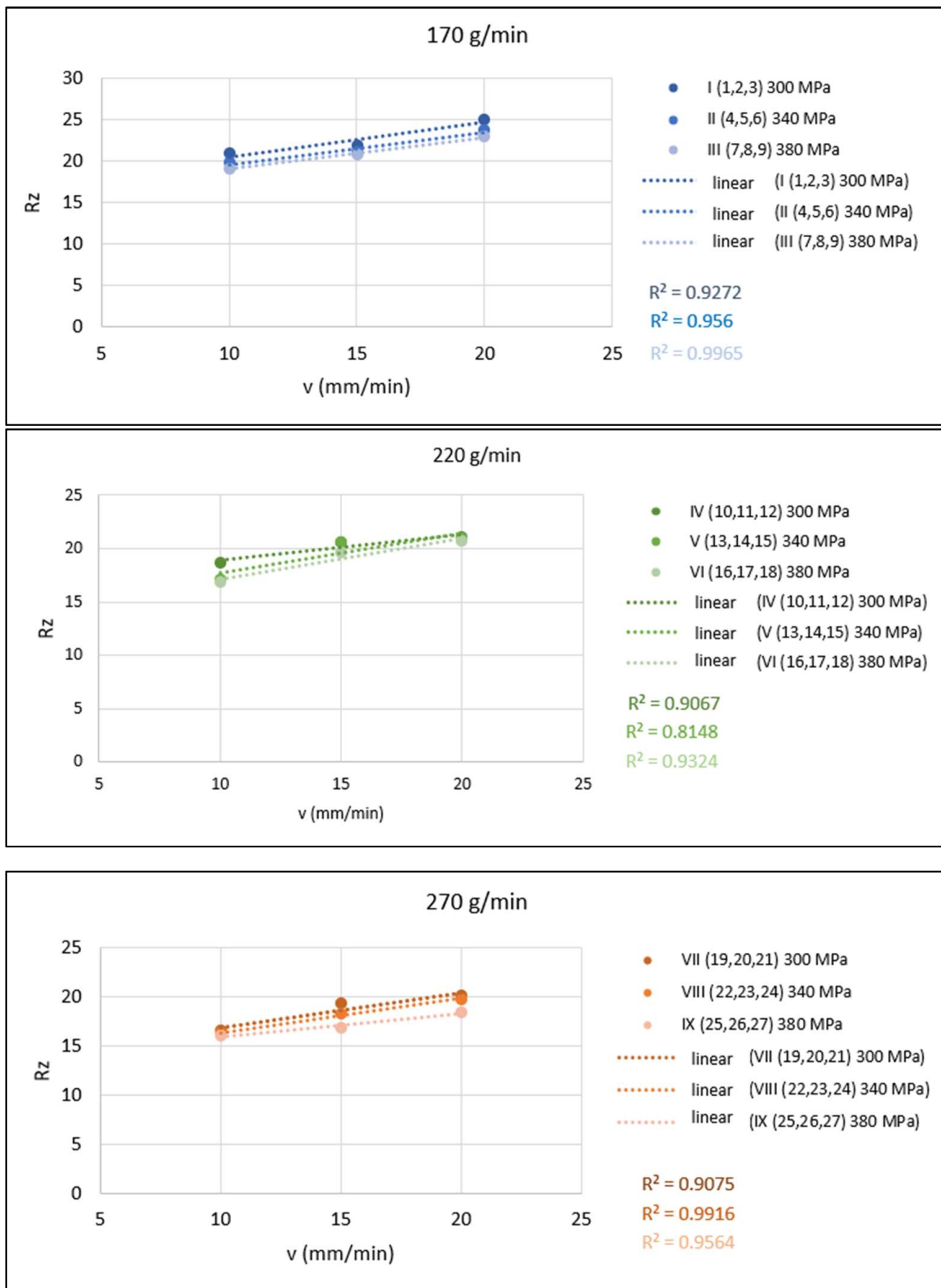


Figure 7. Graphical evaluation of 1-parametric dependencies of $Rz = f(v)$ for $m_A = 170, 220$ and 270 g/min.

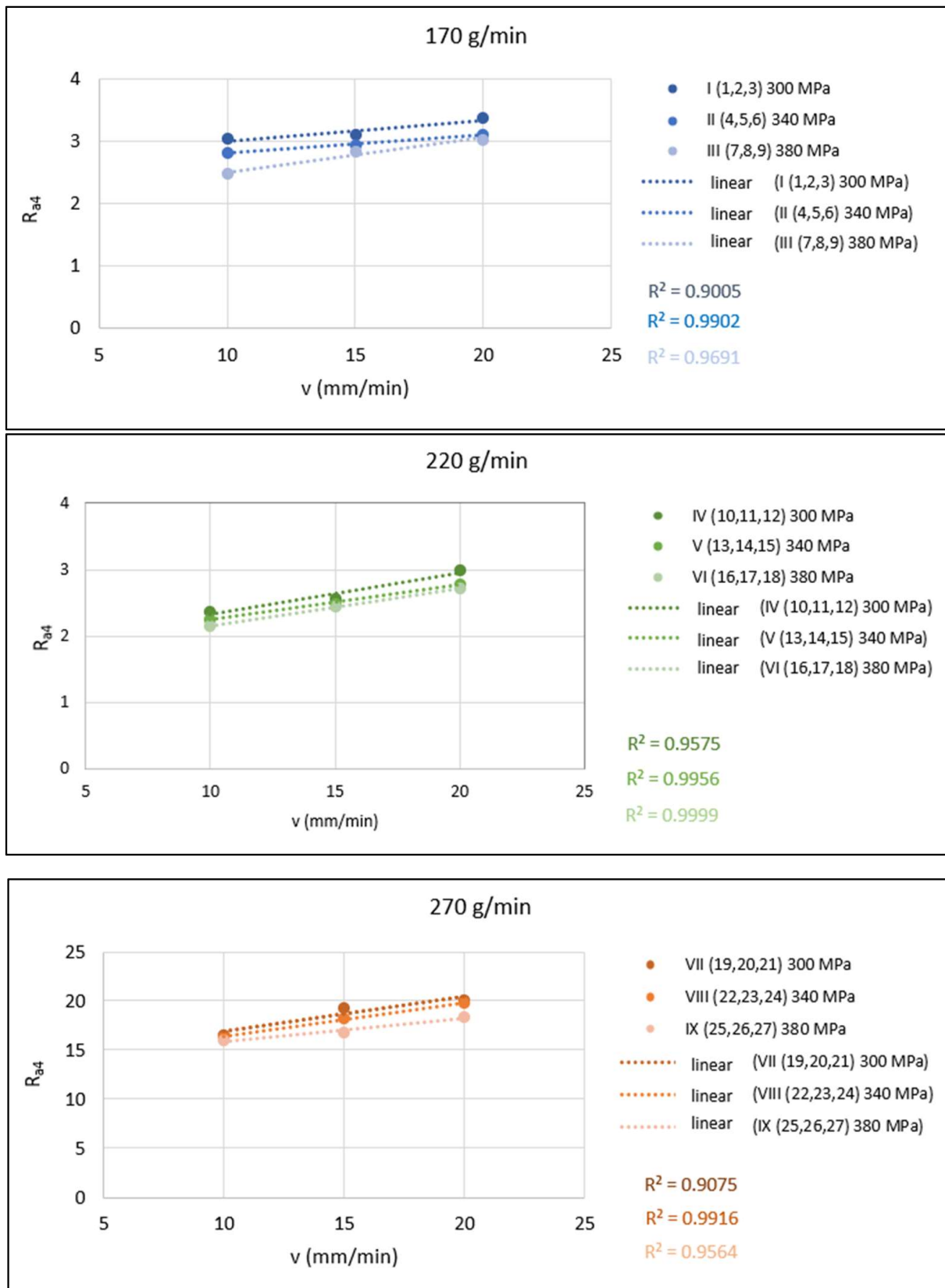


Figure 8. Graphical evaluation of 1-parametric dependencies of $Ra_4 = f(v)$ for $m_A = 170, 220$ and 270 g/min.

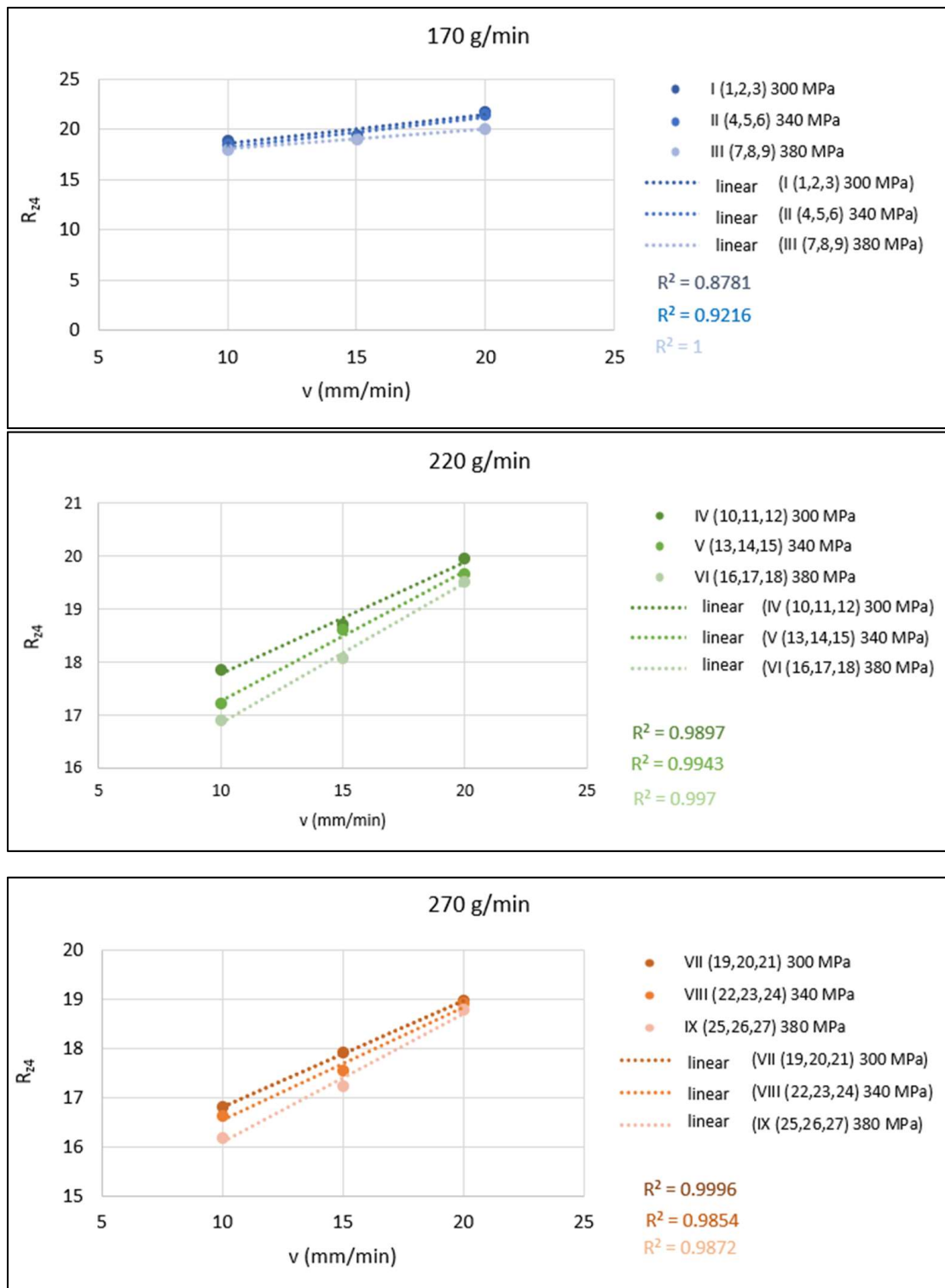


Figure 9. Graphical evaluation of 1-parametric dependencies of $Rz_4 = f(v)$ for $m_A = 170, 220$ and 270 g/min.

3.4. Evaluation Based on Photographic Images of Cut Surfaces

The acquisition of a set of digital images from the cut areas of the examined samples was provided by a specific photographing method using side lighting to illuminate the untreated cut area, enabling jet deflection measurements. Figure 10 provides an example of four selected images of the cut surfaces taken by the above-mentioned method.

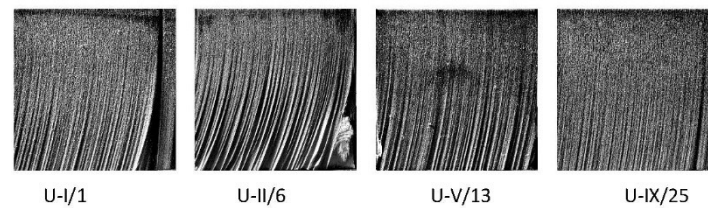


Figure 10. Photographic images of cut surfaces.

The observations made using the photographic pictures complement the previous information gained from experimental data evaluation and enable obtaining a more complete and clearer view of the specific technological parameters effect. Observing the lower parts of the cut surfaces of selected samples presented in Figure 10 (at the values of technological parameters m_A and p from their lower ranges and v from the upper range), a markedly rough surface is visible, characterized by large bended striations caused by significant deflection (lagging) of the water jet and significant depth difference between the peaks and valleys of the striations.

All cut areas of the sample set show a significantly lower roughness in their upper part (closer to the cutting edge on the jet entering side) as compared with the lower part. Striations are visible on the cut surfaces of all samples. With more favorable values of technological parameters (lower v , higher p and higher m_A) from the experimental set, it is possible to observe a gradual straightening of striations and simultaneously a reduction in the deflection of the abrasive water jet. The beginnings of striations are transferred with more favorable values of technological parameters from the upper part of the cut area to the lower part, as illustrated in Figure 10 U-I/1, U-V/13 and U-IX/25.

3.5. Deflection of the Abrasive Water Jet

The qualitative parameter deflection of the abrasive water jet \varnothing on the surface of the cut surface as a dependence $\varnothing = f(v)$ is shown in Figure 11. These dependencies are presented in the form of conjugated graphs for the cases where the mass flow of the abrasive is constant (in one graph, three dependencies are plotted for three different values of pressures 300, 340 and 380 MPa).

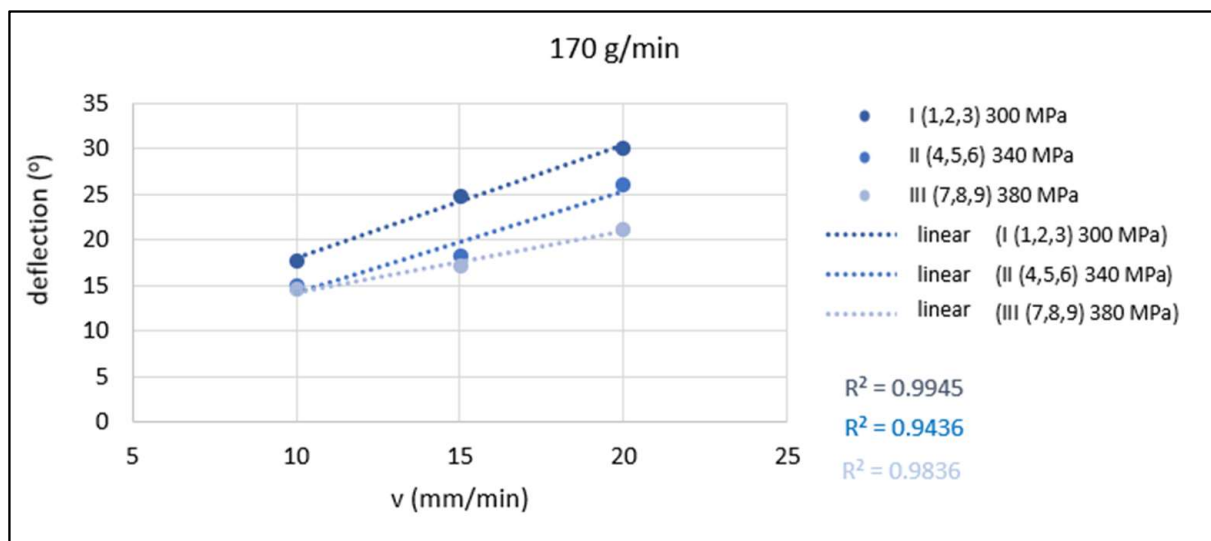


Figure 11. Cont.

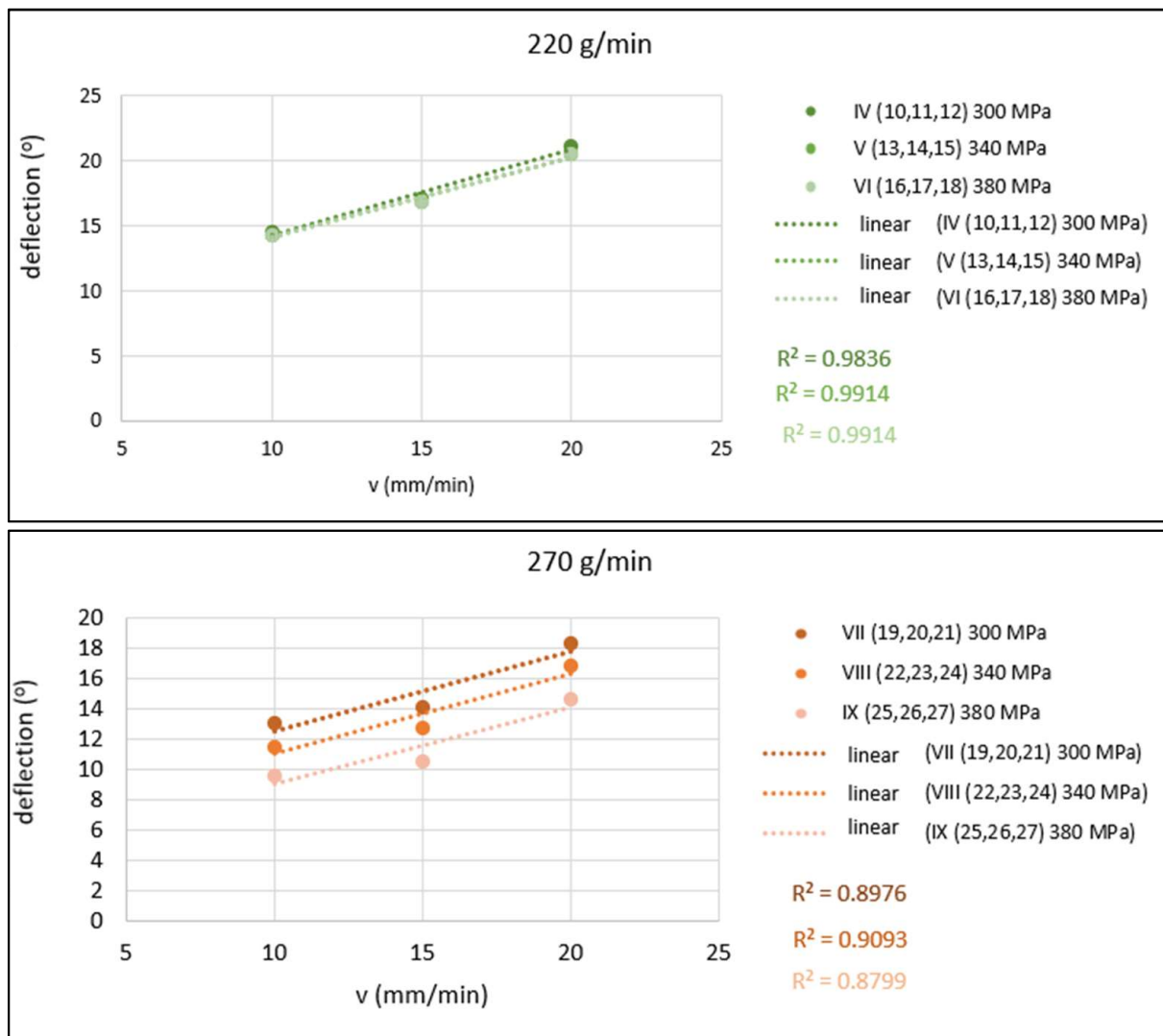


Figure 11. Graphical evaluation of 1-parametric dependencies of $\varnothing = f(v)$ for $m_A = 170, 220$ and 270 g/min.

4. Discussion

Specifically, the values of technological parameters $m_A = 170$ g/min, $p = 300$ MPa and $v = 20$ mm/min (cut I/3) represent the combination for the highest values of the roughness parameters measured ($Ra = 6.95$ and $Rz = 24.96$), whereas Ra values range from 2.27 to 6.95 and Rz range from 16.02 to 24.96. The possibility to reduce the Ra value from 6.95 to 2.27 represents an improvement in roughness of almost 68% (approximately one third of the highest value reached).

On the other side, the values of technological parameters $m_A = 270$ g/min, $p = 380$ MPa and $v = 10$ mm/min (cut IX/25) represent the combination for the lowest roughness parameters measured ($Ra = 2.27$ and $Rz = 16.02$). The reduction in the Rz value from 24.96 to 16.02 represents an improvement in roughness of almost 36%.

Mathematical models describing the functional dependence of selected technological parameters m_A (x_1), p (x_2) and v (x_3) on the quality parameters Ra (y) and Rz (y) are presented below. Figure 12 graphically indicates the significance of individual parameters. The indices of determination indicate a close approximation of the curve given by the functional dependence of the curve constructed from the evaluation of the measured values.

$$Ra \ y = 7.288 - 0.014 \ x_1 - 0.009 \ x_2 + 0.146 \ x_3 \quad R^2_u = 0.733 \quad (1)$$

$$Rz\ y = 28.725 - 0.037\ x_1 - 0.018\ x_2 + 0.348\ x_3 \quad R^2_u = 0.942 \quad (2)$$



Figure 12. Graph of significance of mathematical model parameters for Ra and Rz roughness parameters.

According to the significance graphs in Figure 12, it can be stated that the greatest influence of the monitored technological parameters on the roughness parameters Ra and Rz has almost the same share as the cutting feed rate v and the abrasive mass flow mA. On the other side, the smaller influence has the pump pressure p. By comparing the measured values of roughness with their average values Ra = 3.41 and Rz = 19.72, it can be stated that about the same roughness Ra and Rz with deviations of 0.13 can be achieved by several combinations of technological parameters, according to Table 3. By increasing the mA from 220 to 270 g/min at a constant pressure of 300 MPa, it is possible to cut a third more material with almost the same roughness value Ra of the cut surface. By increasing the mA from 170 to 270 g/min at a constant p = 340 MPa, it is possible to cut twice the amount of material with almost the same roughness value Rz of the cut surface.

Table 3. Example of combinations of values of technological parameters for achieving approximately equal (average) roughness Ra = 3.41; Rz = 19.72.

| Combination of Parameters | Technological Parameter | Value | Ra | Cutting Surface Identification | Rz | Cutting Identification |
|---------------------------|-------------------------|-----------------------------------|------|--------------------------------|-------|------------------------|
| 1 | m_A p v | 220 g/min 300 MPa 15 mm/min | 3.46 | IV/11 | 19.79 | II/4 |
| 2 | m_A p v | 220 g/min 380 MPa 20 mm/min | 3.46 | VI/18 | 19.66 | VI/17 |
| 3 | m_A p v | 270 g/min 300 MPa 20 mm/min | 3.33 | VII/21 | 19.77 | VIII/24 |

The values of technological parameters $m_A = 170$ g/min, $p = 300$ MPa and $v = 20$ mm/min represent the combination for which the highest values of roughness were achieved for $Ra_4 = 3.36$ and $Rz_4 = 21.69$ for Ra_4 ranging from 2.02 to 3.36 and Rz_4 ranging from 16.19 to 21.69 (cut I/3).

On the other side, the values of technological parameters $m_A = 270$ g/min, $p = 380$ MP and $v = 10$ mm/min represent the combination for which the lowest values of roughness were achieved, that is $Ra_4 = 2.02$ and $Rz_4 = 16.19$ from the range of $Ra_4 <2.02;3.36>$ and $Rz_4 <16.19;21.69>$ of the cut (I/3). It can also be stated that as the abrasive mass flow increases (from 170 to 220 and 270 g/min), the roughness decreases. Similarly, the roughness also decreases with increasing pump operating pressure (from 300 to 340 and 380 MPa). By reducing the feed rate (from 20 to 15 to 10 mm/min), the roughness also decreases.

Mathematical models for expressing the functional dependence of selected technological parameters m_A (x_1); p (x_2) and v (x_3) on the quality parameters Ra_4 (y) and Rz_4 (y) are

given below. Figure 13 shows a graphical representation of the significance of individual parameters. These indices of determination indicate an approximation of the curve given by the functional dependence to the curve constructed from the measured values.

$$Ra_4 y = 5.037 - 0.007 x_1 - 0.003 x_2 + 0.014 x_3 \quad R^2_u = 0.943 \quad (3)$$

$$Rz_4 y = 27.982 - 0.026 x_1 - 0.013 x_2 + 0.057 x_3 \quad R^2_u = 0.918 \quad (4)$$



Figure 13. Graph of significance of mathematical model parameters for Ra_4 and Rz_4 roughness parameters.

According to the significance graphs in Figure 13, it can be stated that the greatest influence on the change in roughness values Ra_4 and Rz_4 has a change in the feed rate of the technological head (observed at constant abrasive mass flow and pump pressure), where the interval of variations respective to lower roughness values of Ra_4 range from 1.6% to 44.8% and of Rz_4 from 1% to 32.8%. The second greatest effect on roughness has the value of abrasive mass flow (observed at constant pump pressure and cutting head feed rate), with an interval for the improved values ranging for Ra_4 from 2.9% to 30.4% and for Rz_4 from 2.3% to 19%. The pump pressure (observed at constant abrasive mass flow and cutting head feed rate) has the least effect on roughness from the selected parameters, with an interval of varying values ranging for Ra_4 from 0% to 18.5% and for Rz_4 from 1.1% to 14.1%.

By comparing the measured values of roughness with their average values of $Ra_4 = 3.15$ and $Rz_4 = 20.95$, it can be stated that about the same roughness Ra_4 (with a variance of 0.07) and Rz_4 (with a variance of 0.2) can be achieved by several combinations of technological parameters, according to Table 4.

Table 4. Example of combinations of values of technological parameters for achieving approximately equal (average) roughness $Ra_4 = 3.15$; $Rz_4 = 20.95$.

| Combination of Parameters | Technological Parameter | Value | Ra_4 | Cutting Surface Identification | Technological Parameter | Value | Rz_4 | Cutting Identification |
|---------------------------|-------------------------|-----------|--------|--------------------------------|-------------------------|-----------|--------|------------------------|
| 1 | m_A | 170 g/min | 3.10 | I/2 | m_A | 170 g/min | 19.99 | III/9 |
| | p | 300 MPa | | | p | 380 MPa | | |
| | v | 15 mm/min | | | v | 20 mm/min | | |
| 2 | m_A | 170 g/min | 3.10 | II/6 | m_A | 170 g/min | 21.39 | II/6 |
| | p | 340 MPa | | | p | 340 MPa | | |
| | v | 20 mm/min | | | v | 20 mm/min | | |
| 3 | m_A | 170 g/min | 3.03 | I/1 | m_A | 220 g/min | 19.95 | IV/12 |
| | p | 300 MPa | | | p | 300 MPa | | |
| | v | 10 mm/min | | | v | 20 mm/min | | |

The values of technological parameters $m_A = 170$ g/min, $p = 300$ MPa and $v = 20$ mm/min represent a combination for which the worst qualitative parameter value was achieved, whereas the deflection of the abrasive water jet was observed at $\varnothing = 30.1^\circ$, ranging from 9.6° to 30.1° (cut I/3). The values of technological parameters $m_A = 270$ g/min, $p = 380$ MPa and $v = 10$ mm/min represent the combination for which the best value of the jet deflection of $\varnothing = 9.6^\circ$ was observed, ranging from 9.6° to 30.1° (which means an improvement of

68%) for the cut (IX/25). It can also be stated that as the cutting head feed rate decreases (from 20 to 15 and further to 10 mm/min), the jet deflection decreases. As the abrasive mass flow increases (from 170 to 220 up to 270 g/min), the jet deflection decreases. As the pump pressure increases (from 300 to 340 and 380 MPa), the jet deflection decreases.

The mathematical model for expressing the functional dependence of the selected technological parameters m_A (x_1), p (x_2) and v (x_3) on the quality parameter represented by deflection of the abrasive water jet \emptyset (y) is given below. Figure 14 provides a graphical representation of the significance of individual parameters. These indices of determination indicate an approximation of the curve given by the functional dependence to the curve constructed from the measured values.

$$\emptyset y = 38.118 - 0.071 x_1 - 0.048 x_2 + 0.702 x_3 \quad R^2_u = 0.873 \quad (5)$$

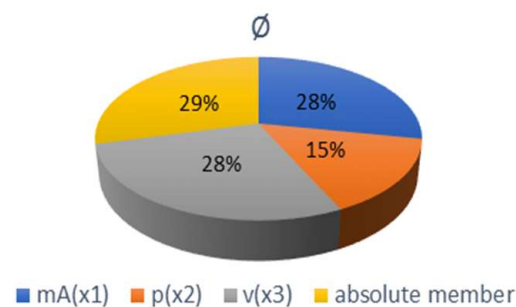


Figure 14. Graph of significance of mathematical model parameters for deflection \emptyset .

Based on the differences of the specific measured values of the jet deflection at the mutual concurrent influence of the monitored technological parameters (m_A , p and v), and according to the graph of significance in Figure 14, it can be stated that the greatest influence on the variations of jet deflection values is the change of the cutting head feed rate (observed at constant m_A and p), where the interval of changes towards the lower jet deflection values was from 8.2% to 42.5%. The second largest, which had almost the same effect on the jet deflection as the feed rate of the cutting head, has a change of the abrasive mass flow (observed at constant p and v) with the change's interval towards better values, from 6.9% to 42.7%. The pump pressure (observed at constant m_A and v) has a smaller effect on the jet deflection with a variation interval of 2.4% to 30.7%.

When comparing the measured values of jet deflections with their average value of 16.8° , it can be stated that almost the same jet deflection with a scattering of only 1.9° can be achieved by several combinations of technological parameters $m_{Amin} - p_{min} - v_{min} \sim m_{Amin} - p_{max} - v_{med} \sim m_{Amed} - p_{min} - v_{med} \sim m_{Amed} - p_{med} - v_{med} \sim m_{Amax} - p_{max} - v_{max}$ (*med* denotes medium value). Table 5 summarizes this more clearly with specific parameter values and measured jet deflection values.

4.1. Recommendations for Values of Roughness R_a , R_z and Deflection of Abrasive Water Jet \emptyset

The recommended values of technological parameters for achieving the minimum and maximum experimentally measured values of roughness R_a , R_z and \emptyset are clearly summarized in Table 6. The significance of the monitored technological parameters influencing the quality of the cut surfaces is given in Table 7.

Table 5. Combinations of technological parameter values selected from the evaluated ranges that have a similar effect to achieving approximately the same deflection of the abrasive water jet \emptyset (16.8°).

| Combination of Parameters | Min | Medium | Max | Technological Parameter Value | Jet Deflection | Cutting Identification |
|---------------------------|--------------------------------------|--------------------------------------|--------------------------------------|-----------------------------------|----------------|------------------------|
| 1 | m_{Amin} p_{min} v_{min} | | | 170 g/min 300 MPa 10 mm/min | 17.7° | I/1 |
| 2 | m_{Amin} | v_{med} | p_{max} | 170 g/min 380 MPa 15 mm/min | 17.1° | III/8 |
| 3 | p_{min} | m_{Amed} v_{med} | | 220 g/min 300 MPa 15 mm/min | 16.9° | IV/11 |
| 4 | | m_{Amed} p_{med} v_{med} | | 220 g/min 340 MPa 15 mm/min | 15.8° | V/14 |
| 5 | | | m_{Amax} p_{max} v_{max} | 270 g/min 380 MPa 20 mm/min | 16.8° | VIII/24 |

Table 6. Recommended values of technological parameters for achieving minimum and maximum experimentally measured values of parameters Ra , Rz and \emptyset .

| | Technological Parameter | | | Qualitative Parameter | | | |
|-----------------------------|-------------------------|---------|-----------|-----------------------|-------|-------------|--|
| | m_A | p | v | Ra | Rz | \emptyset | Quality (Surface Roughness), Application |
| for minimum measured values | 270 g/min | 380 MPa | 10 mm/min | 2.27 | 16.02 | 9.6° | low roughness, without/easy further processing |
| for maximum measured values | 170 g/min | 300 MPa | 20 mm/min | 6.95 | 24.96 | 30.1° | very high roughness, material cutting |

Table 7. Significance of technological parameters influencing the quality of the cut surface.

| Technological Parameter | Significance of the Technological Parameter | Technological Conditions | | |
|-------------------------|---|--------------------------|---------------|--------------|
| | | m_A [g/min] | p [MPa] | v [mm/min] |
| m_A | High | 170; 220; 270 | 300; 340; 380 | 10; 15; 20 |
| p | Low | | | |
| v | High | | | |

4.2. Recommendations for Roughness Values Ra_4 and Rz_4

For 40 mm thick sheets, in order to achieve low roughness (Ra_4 about 2 and Rz_4 about 16) on the cut surface at a distance of 4 mm from the upper cutting edge (Figure 3), and to achieve a small deflection of the abrasive water jet (\emptyset below 10°), it is recommended to use values of technological parameters $m_A = 270$ g/min, $p = 380$ MPa and $v = 10$ mm/min. High roughness values (Ra_4 about 3.4 and Rz_4 about 21.7) at a distance of 4 mm from the upper cutting edges is achieved at technological parameters $m_A = 170$ g/min, $p = 300$ MPa and $v = 20$ mm/min. The most influential (most important) parameter for the change of roughness is the feed rate of the cutting head, followed by the mass flow of the abrasive, and the least influential parameter is the pump pressure.

5. Conclusions

The article is aimed at the study of the influence of three selected technological parameters (abrasive mass flow, pump pressure and cutting/technological head feed rate on selected quality parameters of cut surfaces (surface roughness Ra , Rz , Ra_4 , Rz_4 and jet deflection \emptyset)) after cutting 40 mm thick Hardox 500 steel sheet samples using the AWJ technological system. The presented results apply to the specific conditions of the experiments as described in the article. The obtained results of measurements and analyses allow to formulate the following conclusions:

- The most significant improvements regarding the roughness of the cut surfaces of 40 mm thick Hardox sheets are achieved by reducing the feed rate of the cutting head and increasing the mass flow of the abrasive. The same applies to the deflection of the abrasive water jet. Pump pressure parameter is less effective to change the roughness as well as the deflection of the abrasive water jet;
- Lower roughness values of Ra , Rz , Ra_4 and Rz_4 in the samples were caused by lower cutting feed rate, but at the same time, the highest used value of the feed rate $v = 20$ mm/min can be considered as the limit if it acts in combination with the lowest values of the other two technological parameters m_A and p . If this limit value is exceeded, it may not be possible to perform a complete cut of the sheet;
- The feed rate of the cutting head has the greatest influence on the deflection of the jet because half the rate can compensate for the simultaneous change of mass flow and pressure from the maximum (Table 5, combination of parameters No. 5) to the level of their medium value (No. 4), as well as reduction in the feed rate from maximum (No. 3) to mean value (No. 5) compensates for the reduction in pressure from maximum to minimum and at the same time the mass flow from maximum to medium value (No. 3), as well as only the change of mass abrasive flow from maximum to minimum (No. 2). Similarly, reducing the feed rate from maximum to minimum compensates for the change in mass flow and pressure maxima (No. 5) to their minimums (No. 1). The pump pressure parameter has the least effect on the jet deflection;
- The surface quality of the upper zone of the cutting material is better than the quality of the lower zone.
- The evaluation of experiments presented in this article does not elaborate all related issues of the problems of examining the influence of selected technological parameters in terms of surface quality. It is therefore necessary to continue in this important research, especially in the context of AWJ process optimization for industrial applications. The directions of future research within the topic may comprise, for example, expanding the set of experiments for other sheet thicknesses of Hardox 500 steel or other types of Hardox steel (400, 450, 550, 600, Extreme, HiTuf or other hard-to-machine material). An alternative way is to investigate the dependence of other types of abrasive on the quality parameters of the cut surface. Finally, it could also be widening to research the influence of selected technological (m_A , p , v , ...) and quality parameters (Ra , Rz , \emptyset , ...) at wider intervals of their values.

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