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EXPERIMENTAL RESEARCH POSSIBILITIES OF MONITORING THE AWJ CUTTING PROCESS USING A STRAIN SENSOR

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Abstract: As part of comprehensive research on the impact of vibration on the AWJ (abrasive waterjet) cutting process, the article deals with the topic of process monitoring using sensory systems available in industrial machines for collision detection. As part of the study, an assessment of the impact of force interactions on the indications of the strain sensor previously used in the collision detection machine was made. Correlations between the impacts on the abrasive nozzle tip and the sensor indications were carried out using the FEM numerical model, followed by experimental verification of this correlation. Finally, basic research was conducted on the effectiveness of this approach during the cutting process. The result of the research is the possibility of implementing the concept of the cutting process with determined cutting parameters depending on the actual cutting conditions by real-time measurement of the strain measured on the cutter head. It is important, among others when cutting contours of a complex shape, where it is important to constantly change the value of the feed speed to obtain an effective cut. This is a condition for obtaining constant parameters of the surface topography.

Key words: abrasive waterjet machining, strain sensor, cutter head, measusing system, FEA model.

1. INTRODUCTION

The selection of parameters of the water-abrasive cutting process is a relatively complicated issue, due to the fact that it is associated not only with the effectiveness of this process, but also with the dimensional and shape quality obtained in the cutting process.

The surface topography obtained is also important here, and the selected parameters of abrasive water jet cutting mainly depend on the type of material and the thickness of the workpiece. These parameters are usually selected before the start of the cutting process, and rarely modified during the treatment. Sometimes it turns out that after the cutting process, the quality parameters of the cut surface are unsatisfactory or the cutting process itself due to too high parameters (feed speed) prove to be inefficient. This results in the emerging bridges of the uncut material of the object being cut out. Improving this condition may not be possible or less profitable. That is why solutions are being sought to monitor the cutting process in real time. The acquired information is to be used to control the parameters of the abrasive water jet cutting in order to improve the surface quality after cutting.

There are many studies that prove that, among others, vibrations that occur duri ng the process and their proper interpretation regarding the generated frequencies and forms can very reliably identify the process conditions in real time.

These studies show promise that there is a very close correlation between the course of the process and the impact of this process on the vibrations of selected machine components, including e.g. cutting head, machine table or to vibrations of the workpiece itself.

The current state of knowledge often tries to de-termine the impact of occurring vibrations of individual components of the abrasive water jet machine on the quality of cutting. In the research presented in article [1] (Kmec et al., 2012) it was observed that the change in pump operating conditions significantly affects the quality of the edges cut, so control over unwanted vibrations affects the lifespan of the hydraulic system. Further studies presented in the article [2] (Hreha P. et al., 2015) show that the vibration frequencies significantly depend on the set values of the abrasive flux intensity. This was found on the basis of recording vibrations using sensors placed on the surface of the object.

In the research presented in the article [3] (Monno and Ravasio, 2005) vibrations measurements during clean water jet cutting were carried out for various cutting conditions, in which it was assumed that all irregularities on the surface result from the instability of the jet. To achieve that, head vibration was measured, and the direct effect of vibration on surface quality was proven, particularly in relation to surface topography. In particular, the authors noticed that the feed speed has an impact on the increase in the frequency of vibrations, but also on the increase in

the amplitude of surface waviness. After the above tests, it can be concluded that the form of postmachining traces (transitions on the cutting stream - the effect of striation) results mainly from the frequency of vibrations during the process. Such a relationship between the occurrence of vibrations and surface quality was also indicated in the studies described in article [4] (Hreha et al., 2014) for materials such as stainless steel or copper alloys.
As a continuation of the abovementioned studies, similar conclusions were presented regarding the impact of vibration on the obtained surface quality in articles [5] (Perzel V. et al., 2012) and [6] (Hreha and Hloch, 2013), where vibration measurements were made by accelerometers placed directly on the cut object observing the magnitude of the vibration amplitude depending on changes in such parameters as abrasive jet intensity and feed speed. Research presented in article [7] (Lissek et al., 2016) showed similar correlations between changes in vibration processing parameters based on measurements of acoustic emission signals and sensors mounted on the object.
There are many surface quality tests after cutting that attempt to identify a cut quality model based on selected water jet abrasive machining parameters. The article [8] (Gylienė et al., 2014) indicates that the feed rate is important from the point of view of the depth of the first cutting zone characterized by a smooth surface as the most preferred one. The authors pointed out that it is this zone that ensures uniform, even surface quality and can be taken into account in assembly applications.
This article focuses primarily on the measurement of the cutter head deformation, on the basis of which an attempt was made to identify the reaction forces during the cutting process. They refer to the first cutting zone called smooth surface. There are a number of studies that confirm that the increase in feed rate parameter is also associated with an increase in the amplitude of vibrations affecting the deformation of the cutter head. This article is a continuation of research initiated, among others, in [9] (Wala and Lis, 2017).
Furthermore, during the experimental tests, the deformation of the cutter head structure is measured for a stabilized cutting process. As it has been pointed out in the article [10] (Zhonghua Huang and Ya Xie, 2011) the piercing process has a strong influence on the increase of forces, deformations and vibration amplitudes and decreases only at the moment of initiating the first crack of eroded material.

2. THE CONCEPT OF THE MEASURING SYSTEM

The AWJ machines are characterized by a low load on the cutting system due to the forces resulting from the cutting process. Studies carried out i.a. in [9] prove that they do not exceed 30N even during piercing. The design of both the machine itself and the support element of the cutter head is optimized in terms of the conditions occurring during the operation of the machine. Therefore, the support element of the cutting head does not have to have greater rigidity than neccessary. A simplified view of the supporting element and the design of the five axis AWJ machine and cutter head itself on the example of the HWM-P1520/1-3D Ridder manufacturer machine is shown in Figure 1.

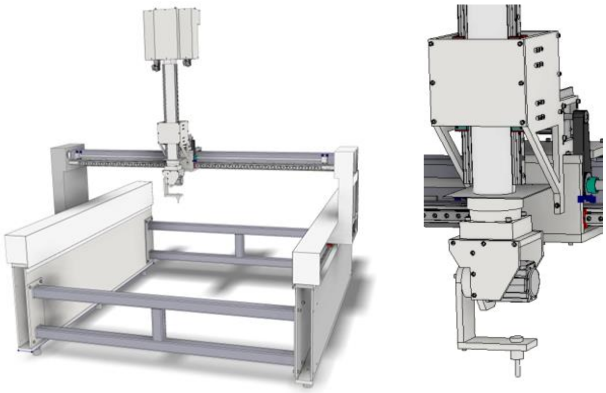


Fig. 1. Model of the machine's tool support HWM-P1520/1-3D

It is a Waterjet Waricut HWM-P1520/1-3D machine from Ridder. Due to the abovementioned features of this type of machines, it is relatively easy to implement a collision detection system based on measuring the deformation of the cutter head support structure.
This system has relatively high sensitivity. An example of such a system is shown in Figure 2.

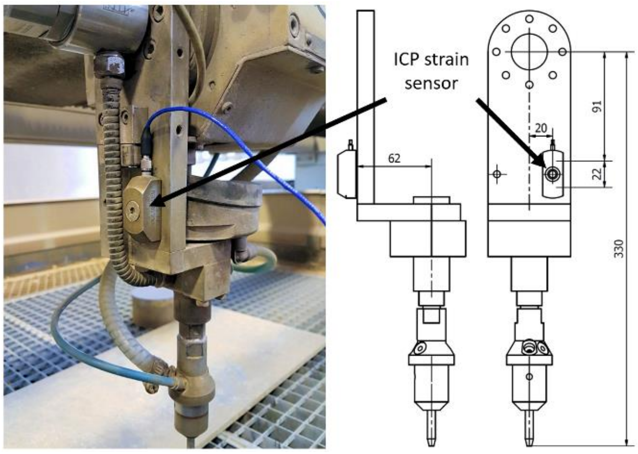
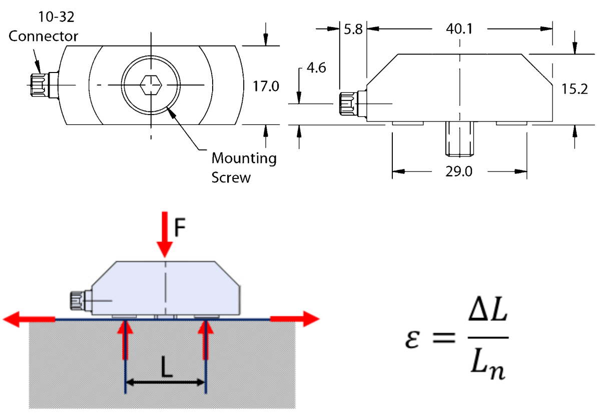


Fig. 2. The way of mounting the deformation of cutter head sensor in the supporting structure of the AWJ machine

The operation of the collision detection system is based on the detecting when the threshold value of the sensor is exceeded. This value is set in the machine's service parameters but it is also available to the operator. To monitor the load on the cutter

head by the reaction forces arising during the cutting process, the concept of using such a sensor was developed. The sensor used is ICP industrial strain sensors - model M240 PCB manufacturer with the followings parameters: sensitivity of 50mV/με, amplitude range 100 με, low frequency response 0.004Hz, amplitude linearity ±2%, excitation voltage 20-30V, constant current excitation 2 to 20mA, discharge time constant >150s (Figure 3).
The sensor has a high resolution of 0.0002με in the range from 1 to 10kHz and a high overload capacity up to 100με.



$$\varepsilon = \frac{\Delta L}{L_n}$$

Fig. 3 The dimension of the PCB ICP sensor used - M240A03 model [11]

3. MODEL AND EXPERIMENTAL RESEARCH

The FEM model identification was made in order to identify the features of the measuring system used for the abovementioned supporting structure. The approach aims to determine with what sensitivity the presented measuring system reacts to individual component forces occurring in the cutting process. The terminology for the designation of component forces used in other sources [9] (Wala and Lis, 2017) was adopted (Figure 4) where F_f is the feed force, F_b force perpendicular to the feed direction, and F_h is the axial force.

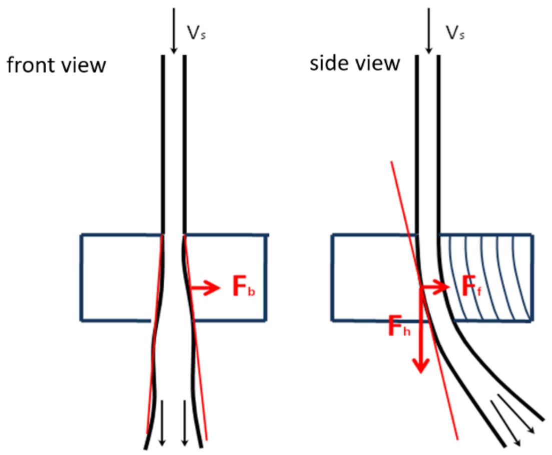


Fig. 4. Distribution of accepted components of forces F_f, F_h, F_b [9]

The identification was carried out using FEM, and the analyses carried out in turns covered components of forces F_f, F_h, F_b. A reference test force of 10N was used, and steady state linear analysis was set to obtain the deformation results shown in Figure 5.

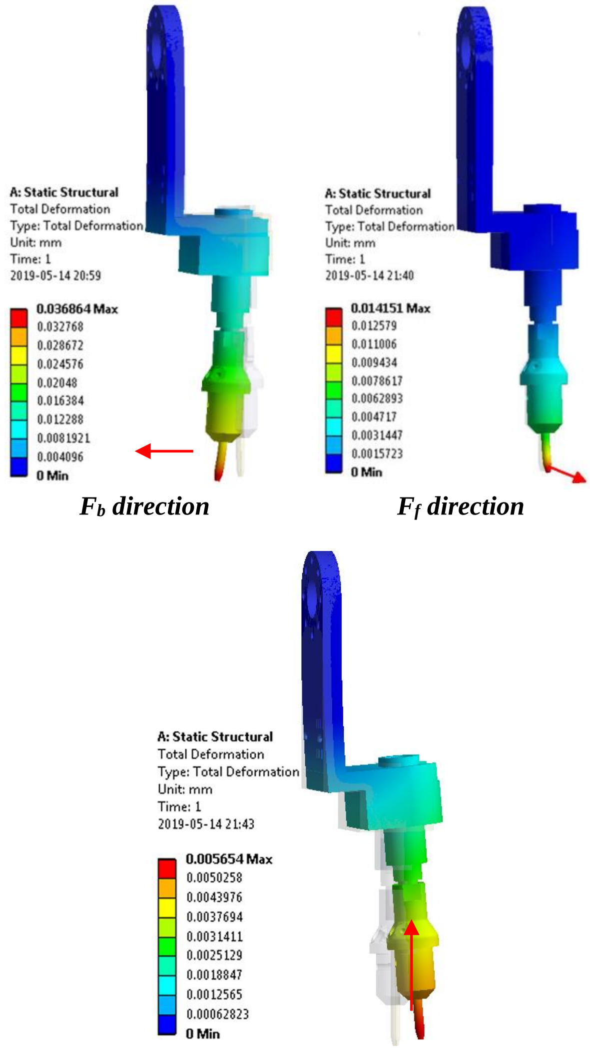


Fig. 5. Results of cutter head deformation tests

The obtained deformation results were analyzed in the context of their impact on the sensor at the place where it was mounted. Table 1 presents the results of the sensor constant relative to individual components and approximate directional rigidity of the structure. To verify the results obtained, experiments were performed. The research was carried out in accordance with the plan implemented in the model part, i.e. the superposition of individual components. The scheme of the test stand is presented in Figure 6.
The tests were carried out in a static manner exerting force on the abrasive nozzle tip for individual components.
Table 1 shows the results of the sensor constant related to individual components obtained from the experiment. The results of the experiment differ from the results of model tests.

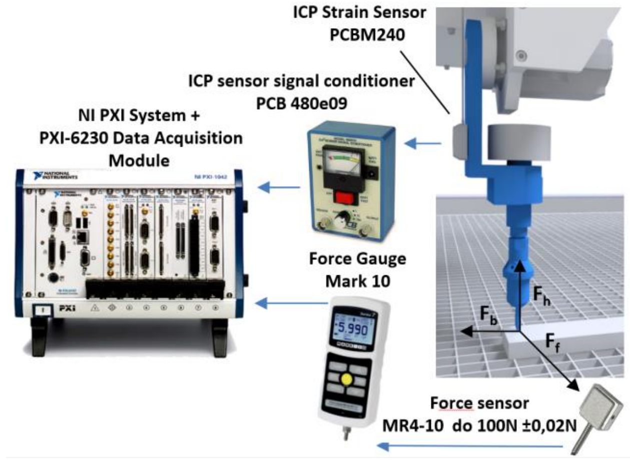


Fig. 6 Measuring station scheme and view of the axis distribution of the cutter head

Table 1. The results of the determined parameters of the measuring system and the supporting structure of the cutter head.

	F_b direction	F_f direction	F_h direction
Directional constant FEM results [με/N]	4.99	0.24	1.04
Directional stiffness [N/μm]	0.28	0.7	2
Directional constant Results of the experiment [με/N]	1.11	0.066	0.25
Scale error: FEM - experiment	4.7	4.3	3.4

However, when considering the proportions relating to individual components, the differences are small. Assuming that the ratio of sensitivity components obtained from experimental and model tests for F_b is equal to 0, the analogous ratio for the F_h component differs by 7% while the feed component F_f differs by 23%. At the same time, on the chart (Figure 7) it can be seen that for this component the indications are the smallest and the correlation is the lowest (the least sensitivity is in this direction).

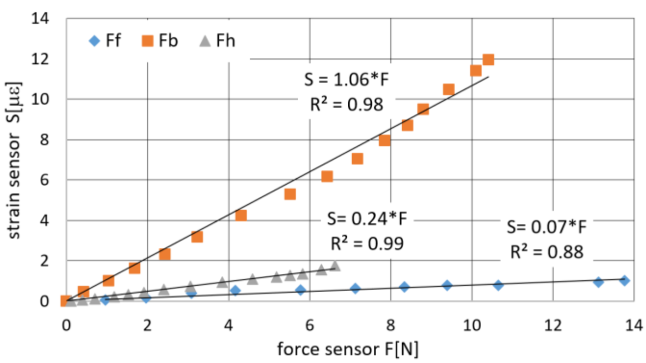


Fig. 7 The relationship of sensor indications as a function of force acting on the nozzle tip in the direction of F_b, F_f, F_h

It can be observed that the strain sensor readings are smaller than the expected model results. The sensor is mounted to a structure with relatively low stiffness, so since it is mounted locally, it stiffens it strongly at the point of mounting. It is important that the proportions between the individual components are kept and the sensor indications can be proportionally converted to actual cutting nozzle loads. In this case, you can use the dependence on the sensor indication:

$$S=1.1 \cdot F_b+0.25 \cdot F_h+0.07 \cdot F_f \qquad (1)$$

It can also try to reflect the indications of the stress sensor in the deformation of the head in particular directions. The obtained values result from force interactions and directional stiffness:

$$S=0.31 \cdot b+0.5 \cdot h+0.046 \cdot f \qquad (2)$$

where: b, h, f - directional deformations of the head in relation to its restraint expressed in [μm].

However, this relationship does not take into account the deformations of other system components.
The given course obtained from testing the forces of impacts on the nozzle in the cutting process, whose methodology is described in more detail in [9] (Wala and Lis, 2017) is presented in Figure 8. It shows that the force F_f occurring during the process is definitely the largest. The relationship (1) shows that its impact on the strain sensor readings is one order of magnitude smaller.

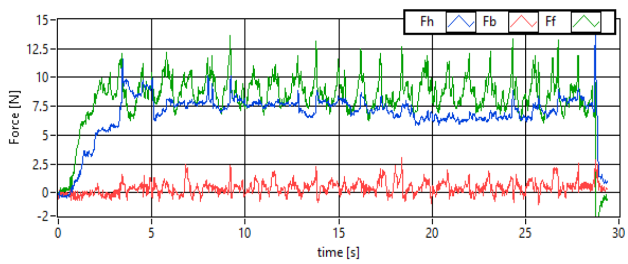


Fig. 8 Dependence of sensor indications as a function of force acting on the nozzle tip in the direction of F_b, F_f, F_h. Parameters: S235RJ material, abrasive flow feed: m_a = 340 g/min, pressure: 330 MPa, feed speed: f = 90 mm/min

The relationship (1) is correct when the configuration from the point of view of the axis distribution of the cutter head coordinate system during the cutting is as shown in Figure 6.
In this case the indications depend mainly on the force F_b, which is very small.
It should be noted that the F_b force should theoretically be a force close to valuze zero with the correct cutting process, because its influence results from the response perpendicular to the feed direction and the direction of plunging (F_b component shown in Figure 4). Its non-zero values may result from the

jet turbulence during the deflection of the cutting jet at the exit from the lower cutting zone of workpiece. It can also be assumed that the value of the force F_b may inform about the occurring taper of the gap.

During the 2D cutting, manipulation of the C axis (rotation around the axis of the abrasive nozzle) on a 5-axis machine, so that the rotation of the head follows the cutting direction, allows constant measurement of F_b and F_f components in constant proportions. It is also possible to rotate the head by 90° in relation to the cutting direction, enabling the position exchange of F_b and F_f sensing the head to the feed component instead of the side component.

Studies show that the values of these forces can provide important diagnostic information, e.g. from the point of view of the jet deflection during cutting.

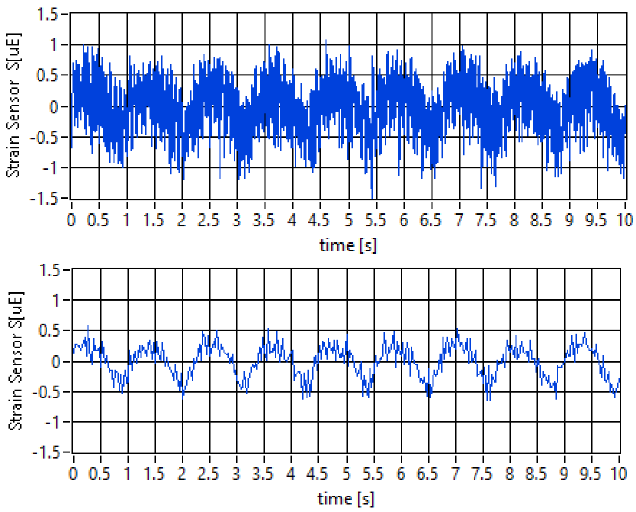


Fig. 9 An example of the strain sensor readings during the cutting process.

Above raw signal (8kHz sampling), bottom after low-pass filter flow = 30Hz). Similar cstting parameters were used as for the Figure 7.

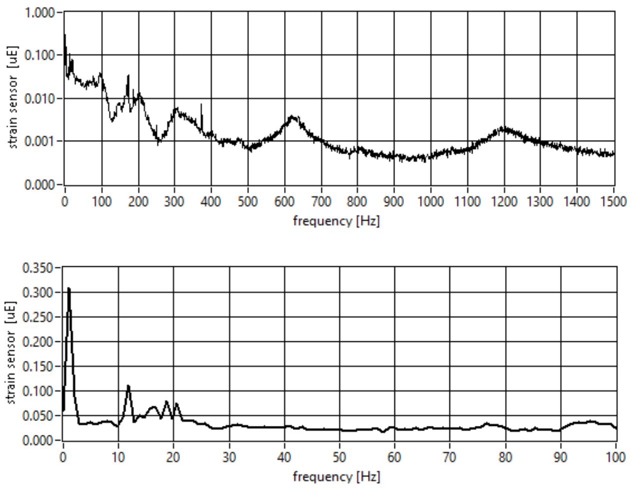


Fig. 10 An example of Fourier transform of the strain sensor readings during the cutting process.

Above 0 - 4kHz frequency range and logarithmic uniform amplitude scale axis, bottom 0 – 100Hz frequency range and linear uniform amplitude scale axis (similar cutting parameters were used as for the Figure 7).

In the example signal (Figure 9) you can see the 0.87 Hz component corresponding to the high pressure pump duty cycle. This frequency is also visible on the spectra of these signals (Figure 10). They are associated with slight pressure fluctuations while supplying the head with high pressure water. Referring to work [9] (Wala and Lis, 2017) such values were also observed in other studies Figure 11. The graph shows the results obtained as a result of the cutter head vibrations tests using accelerometers.

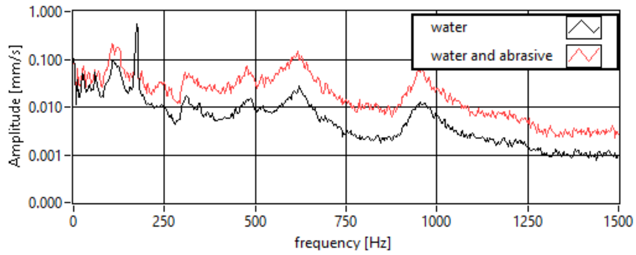


Fig. 11. Cutting head vibration frequency determined based on Fourier transform for the pure waterjet and the abrasive waterjet – measuring by using accelerometer

Comparing the spectra obtained during Strain Sensor measurements (Figure 12) and the accelerometer, one can see corresponding other frequencies as well. There is a peak corresponding to the speed of the high pressure pump motor (about 173Hz). When interpreting the vibrations occurring at the frequency of 174Hz, it should be noted that the motor driving the hydraulic pump is an asynchronous motor with two pairs of poles, and its nominal speed is 1480 rpm, which corresponds to 24.(6) rps. At the same time, it is known that the hydraulic pump that pumps the oil to the multiplier is a piston pump with seven pistons, which when multiplied by the number of engine revolutions per second gives a frequency of about 172Hz.

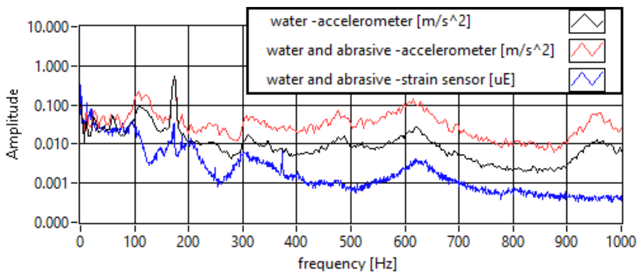


Fig. 12. Comparation FFT obtained during measuring two methods: strain sensor and accelenometer placed in cutting head.

It should be noted that the compared spectra (Figure 12) refer to amplitudes representing different units:

for the accelerometer these are the head vibration accelerations and the strain sensor indications are proportional to the cutter head movements. The analysis shows that the accelerometer highlights indications for high frequencies and the Strain Sensor better reflects low frequencies.

4. CONCLUSIONS

As seens on the Figure 8 the value of the feed speed has a significant impact on the value of the feed force F_f. It has been shown that higher feed speed causes an increase in the value of this force. In the scope of the research carried out, the change of the feed force F_f in relation to the change of the feed speed shows a linear relationship.

During the experimental tests, a slight increase in forces was also observed in the lateral direction F_b perpendicular to the cutting direction (to the feed force F_f). This increase is noticeable for thinner samples, regardless of the type of material being cut. There is no such relationship for thicker samples.

The value of the reaction force F_h is characterized by high irregularity in various ranges of the feed value. This force, like the feed force, is characterized by significantly higher values in relation to the lateral force. Its increase was observed with an increase in the feed speed, which results from the increasing resistance during the penetration of the abrasive water jet into the object.

The concept of process monitoring and its implementation presented above is an attempt to use a specific sensor which is a piezoelectric strain sensor to assess loads and deformations of the cutter head, and thus the abrasive nozzle during the cutting process in industrial conditions. Further research may focus on the location of the sensor so that the indications mainly concern the components of the head load that are of our interest.

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