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THE RESEARCH INTO THE QUALITY OF ROCK SURFACES OBTAINED BY ABRASIVE WATER JET CUTTING

BADANIE JAKOŚCI POWIERZCHNI SKAŁ OTRZYMANYCH W WYNIKU CIĘCIA ABRAZYJNYM STRUMIENIEM WODY

In recent years, water jet cutting technology has been being used more and more often, in various domains of human activity. Its numerous applications include cutting different materials – among them, rock materials. The present paper discusses the results of the research that aimed at determining – in a quantitative manner – the way in which the water jet cutting parameters (such as the traverse speed of the head, and the distance between the high-pressure inlet of the water jet and the cut material) influence the quality of the processed surface. Additionally, the impact of these parameters on the surface of various materials was investigated. The materials used were three granites differing with respect to the size of grains. In the course of the research, the standard parameters defined by the ISO norms were analyzed. It was also proposed that variograms be used to analyze the quality of the cut surface.

Keywords: water jet, rock cutting, surface quality, roughness, variogram

Technologia cięcia strumieniem wodnym staje się w ostatnich latach coraz intensywniej wykorzystywana w różnych dziedzinach działalności człowieka. Jest ona wykorzystywana do obróbki różnorodnych materiałów, również materiałów skalnych. W ramach badań analizowano trzy granity różniące się m.in. wielkościami ziarn, które były przecinane przy różnych prędkościach przesuwu głowicy z wlotem strumienia wodnego. Analizowano standardowe parametry zdefiniowane w normach ISO jak również zaproponowano wykorzystanie wariogramów do analizy jakości wyciętej powierzchni. W pracy opisano w sposób ilościowy zmiany jakości powierzchni skał ciętych strumieniem wodnym ze ścierniwem w zależności od prędkości przesuwu głowicy, jak również w zależności od odległości przecinanego fragmentu powierzchni od wlotu strumienia wodnego do materiału. Wyniki uzyskane w pomiarach wskazują też na wpływ wielkości uziarnienia skały na jakość otrzymanej powierzchni. Jest to szczególnie widoczne dla najmniej optymalnych parametrów cięcia strumieniem wodnym, czyli dla dużych prędkości cięcia i dla fragmentów powierzchni znacznie oddalonych od brzegu próbki. W badaniach wykazano, że przy

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optymalnie dobranych parametrach obróbki wpływ wielkości ziarn na jakość powierzchni jest niewielki, a niekiedy nawet pomijalny.

W pracy opisano również możliwość zastosowania funkcji madogramu do analizy jakości obrabianej powierzchni. Przy wykorzystaniu tej funkcji można nie tylko potwierdzić rezultaty otrzymane na bazie parametrów zdefiniowanych w ISO, ale otrzymuje się bardziej dogłębny obraz ukształtowania badanej powierzchni.

Słowa kluczowe: cięcie strugą wodną, cięcie skał, jakość powierzchni, chropowatość, wariogram

1. Introduction

The demand for natural stones has been increasing, as they are commonly used as urban and interior decorations, as well as in product design. Due to that, there is a need for technological improvement in the field of stone exploitation and processing, so that the higher demand for stones of better quality can be satisfied. However, the traditional methods of stone quarrying and processing are often not sufficient. For instance, the granite sector is still characterized by the extensive use of explosive splitting, flame slotting and wedge shearing, which leads to considerable inaccuracy of block faces and damages the integrity of a stone to a significant depth (Foldyna et al., 2004). Therefore, it is necessary to develop new technological processes and methods of stone quarrying, as well as of the final processing of stone products, in order to combine technological advantages with economic profits and, finally, to satisfy stricter requirements concerning the minimization of the impact of this technology on the natural environment.

As far as cutting of decorative stones is concerned, one very important aspect is the quality of their surfaces (Carrino et al., 2000; Özçelik et al., 2011). Linear cutting of blocks and slabs of decorative stones does not cause any problems and, at a sufficient rate, it can be performed with various types of saws equipped with diamond segments (disks, chains, belts, etc.), or with different types of gangsaw machines. The technology of the abrasive water jet is a progressive one, as it makes it possible to cut shapes and ornaments in rocks without any thermal or mechanical impact on the material in the area of the cut. With appropriate settings of technological parameters (water pressure, the diameter of the water nozzle, cutting rate, the number and type of abrasives, the size of grains of the abrasives, etc.), this technology can produce cut surfaces of a very high quality (e.g. Agus et al., 1995, Özçelik et al., 2013).

The focus of the paper is how the parameters applied in water jet cutting influence the quality of the obtained rock surface. The research material encompassed three granite types, differing with respect to the size of grains. The rocks in question were cut with a water jet, with seven different traverse speeds of the head. Subsequently, on the cut surfaces, seven profiles placed at various distances from the sample edges were reproduced. This was done with an optical profilometer. This data constituted a basis for the research proper. The latter involved the analysis of the standard parameters defined by the ISO norms. It was also proposed that variograms be used to analyze the quality of the cut surface.

2. Processing stones with the high-speed water jet

Over the past few years, the technology of the high-speed water jet has increased in popularity. In particular, it has been used for cutting various materials and for surface cleaning. It has also been applied to remove damaged surface layers of concretes during repairs of building structures (Nilsson, 2009), as well as in excavating rock blocks (Hood, 1993) and processes involving milling materials to obtain micron-sized and submicron-sized fractions (Sitek et al., 2011). Applications of water jets have been thoroughly researched in medical science (Shekarriz et al., 1999), as well as in many other disciplines.

The principle of material disintegration with the high-speed water jet is based on the transmission of large amounts of energy from the jet onto an extremely small area of the material being cut. The material is disintegrated when the jet sprays the material, which brings about some complex physical processes, such as erosion, shearing, failure under rapidly changing localized stress fields, or micromashining effects – depending on the specific properties of the material being disintegrated (see e.g. Hood et al., 1990; Kim & Labus, 1995; Hashish, 1995; Momber 2005). Momber (2001) stated that the removal of a brittle, tension-softening material by a high-speed water jet is predominantly a mechanical fracture process. He noted that this had been verified for rocks and cement-based composites.

At present, there are numerous commercial high-pressure systems available on the market. Some of them generate pressures up to 700 MPa, others deliver up to hundreds of liters of water per minute. Some basic types of water jets are shown in Figure 1. Plain water jets (Fig. 1a) are generated by changing the pressure energy of the water into kinetic energy. This is caused by the acceleration of the water flow within the nozzle.

The cutting capability of continuous water jets can be intensified when using the so-called abrasive water jet (i.e. the continuous water jet + an abrasive). There are two basic types of jets with abrasives: (i) abrasive water jets (AWJ) and (ii) abrasive slurry jets (ASJ). In the case of AWJ (Fig. 1b), abrasive particles are added into the jet downstream of the water nozzle orifice in the mixing chamber, and are subsequently focused and accelerated in the focusing tube. Pressures up to 420 MPa are commonly used to generate AWJ. In the case of ASJ (Fig. 1c), abrasive particles are mixed with water in the pressure vessel, and the abrasive jet is generated when the suspended matter exits the specially designed nozzle. ASJ is generated by pressures up to 250 MPa. Almandine garnet or olivine concentrates with the grain size of about 0.2 mm are commonly used as abrasive materials (Martinec et al., 2002). Abrasive water jet can be successfully applied to cut, drill, turn, mill, etc. difficult-to-machine materials, such as composites, structural ceramics, high-strength alloys, glass and rocks. At the moment, no material exists which cannot be cut by the abrasive water jet.

Abrasive jets have a very good potential - both for creating precise contour cuts in slabs of natural stones and for machining of ornamental stones. It has been proved that cutting of rock materials with the abrasive water jet does not influence their properties, contrary to the traditional technologies of cutting with diamond saw (see, for example, Konečný & Sitek, 1998). Similarly, Carrino et al. (2000, 2001, 2002) studied marble production (starting from slabs) by means of two alternative technologies: diamond milling and AWJ. They found that AWJ technology makes it possible to overcome the main limits of traditional mechanical process, e.g. machining of small areas (such as the product edges or small thickness slabs), by moving along curvilinear paths characterized by both a very small radius and width, and thus reproducing the designed profile more accurately than by means of the traditional technology. Moreover, they observed a decrease in machining costs by more than 50% when using AWJ.

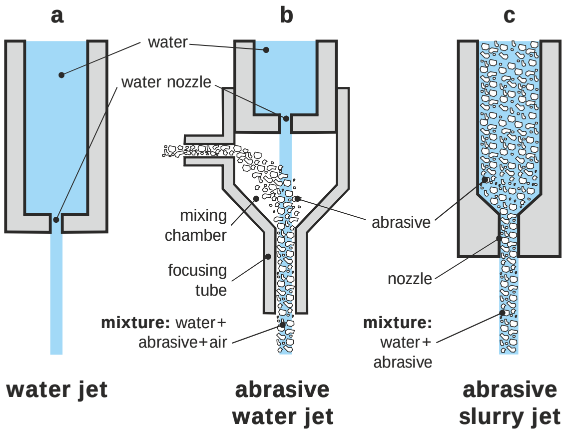


Fig. 1. Basic specification of high-speed water jets according to presence of abrasive

3. Research into the quality of the cut surface

The quality of the surface of the materials being cut by high speed abrasive water jets can be influenced by the parameters involved, which can be set up in different ways. However, some of these parameters are more important than others (these include water pressure, cutting rate, and abrasive flow rate). The mechanical and physical parameters of a cutting material, especially with regard to its inner structure, affect the surface of a cut, too. It is well-known that all beams break up or diffract when moving from one environment to another. The same behaviour can be observed in the case of AWJ when the jet is operating on non-homogenous materials: it can diffract, break up, or, potentially, get reflected. A more compact texture of the cut surface can be expected in the case of more homogenous materials.

Only a few authors have been systematically studying the effects of inner structures of rock materials and material homogeneity on the quality of surfaces which were cut by AWJ. One of them are Miranda et al. (1993), who cut some pieces of the Portuguese marble using AWJ in order to check to what extent the roughness and porosity of the stone influenced the cut surface.

4. The material

In our paper, we attempted to prove that abrasive water jet influences the quality of surfaces of granites with different sizes of grains. The granites used in the research were chosen specifically for their large variety of structures and composition, as well as for their frequent use in civil engineering. Three granites with different sizes of grains from various locations in the Czech Republic were selected:

- **Krásno granite** (Fig. 2a) [Krušné hory pluton – Krásno quarry, aplitic granite, fine-grained, feldspars altered, directionless structure, porosity 5.53%].
- **Žulová granite** (Fig. 2b) [Žulová pluton – Nový Lom quarry; biotite granite, medium-grained with xenomorphic grains with the exception of biotite (hypidiomorphic), directionless structure, porosity 2.78%],

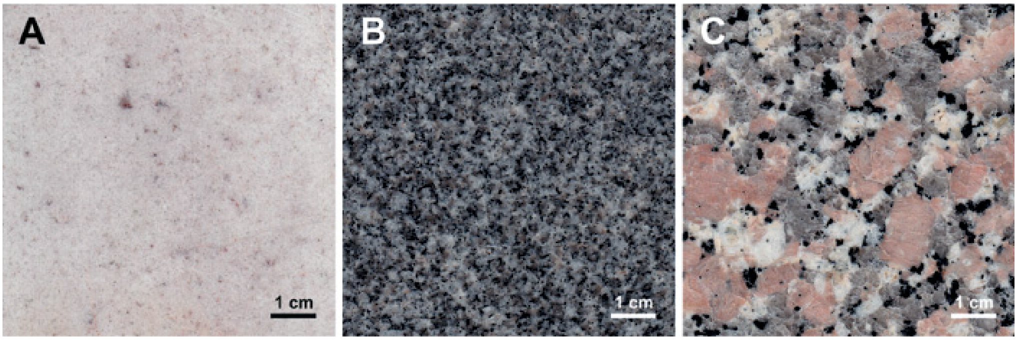


Fig. 2. Examples of rocks used in research (a) the fine-grained granite from Krásno, (b) the medium-grained granite from Žulová, (c) the coarse-grained granite from Liberec

- **Liberec granite** (Fig. 2c) [Krkonoše – Jizera pluton – Ruprechtice quarry; porphyric biotite granite, coarse-grained with the occurrence of feldspar phenocrysts up to 3 cm in size, directionless structure, porosity 3.25%].

Petrographic analysis and classification of the tested samples were determined according to Dudek et al. (1962), Hejtman (1977), Krist et al. (1985), and Kožušníková and Konečný (2011).

5. The experimental facility

The experimental laboratory equipment consisted of a high-pressure water supply system and an XY-table which enables the water nozzle to traverse over test samples (Fig. 3). Granite slabs, approximately 32 mm thick, were prepared for subsequent cutting by abrasive water jet

Fig. 3. The water jet equipment used in the study

(Fig. 4). The samples were cut under constant cutting conditions. The only parameter which varied during individual cuts was the cutting speed. It was increased gradually to 100, 200, 300, 400, 500, 600, and 700 mm·min^{-1}. The parameters of the abrasive water jet were as follows: nozzle diameter - 0.33 mm; water pressure in front of the nozzle – 400 MPa; stand-off distance measured from the exit of the focusing tube to the surface of the target material – 4 mm; diameter of the focusing tube – 1.02 mm; length of the focusing tube – 76.2 mm; angle of jet impingement into the material – 90°. The Australian garnet sand of the grain size of 80 MESH was used as an abrasive, and the abrasive mass flow rate was set constant at the value of 400 g·min^{-1}.

After cutting, all cutting surfaces were scanned with the MicroProf FRT optical profilometer. The profiles of surfaces in 7 distances were measured from the top edge of the jet impingement into the material. The distances were: 0, 5, 10, 15, 20, 25, and 30 mm. For each profile, 10,000 measurement points spaced 4 μm apart were measured.

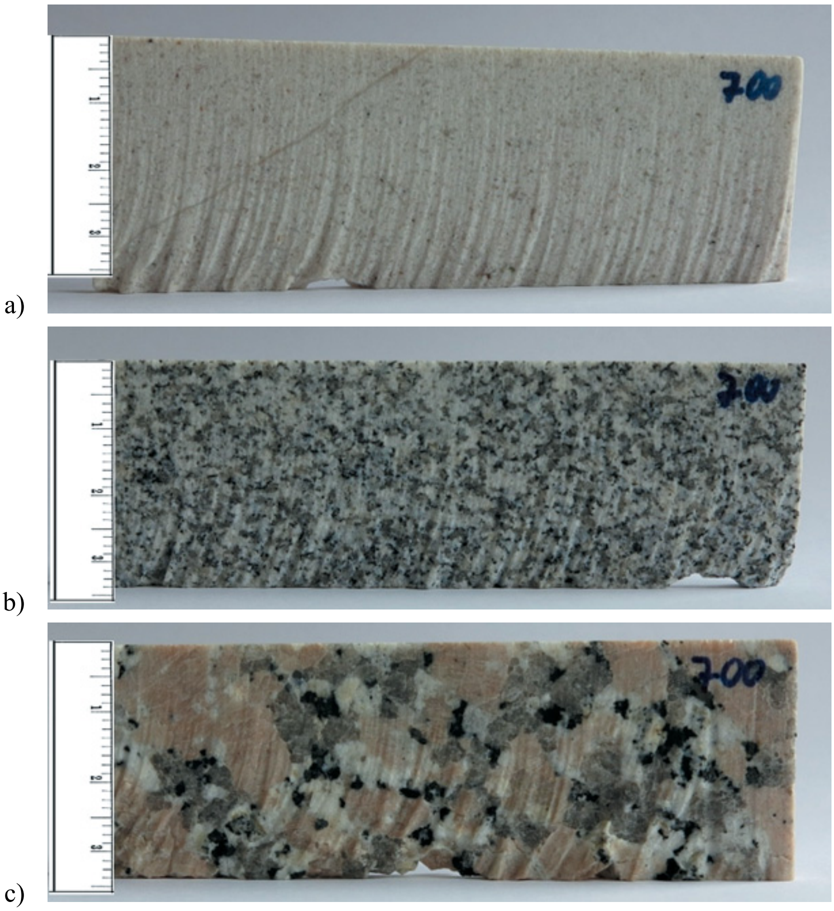


Fig. 4. Examples of surface samples cut at a speed of 700 mm·min^{-1}. (a) the fine-grained granite from Krásno, (b) the medium-grained granite from Žulová, (c) the coarse-grained granite from Liberec. The height of the samples = c.a. 32 mm

6. Results and discussion

6.1. Standard ISO parameters

The standard approach to the analysis of the surface shape – such as the one specified in the ISO 4287 – is based on a quantitative description of profiles measured on this surface. When analyzing profiles, we need to take into account the fact that they are merely a digitized representation of the actual shape of a fracture. Thus, they depend on the measuring instrument that was used, as well as on the adopted measurement parameters. What is more, with standard profilometers, it is not possible to represent these fragments of the actual profile that are "concealed" by its other parts. An example of a normative parameter for surface description (and, in fact, the one that is most commonly used) is Pa – i.e., the arithmetic mean of the ordinates of profile Z determined upon sampling length l.

$$Pa = \frac{1}{l}\int_0^l |Z(x)|\,dx \tag{1}$$

In the ISO 4287, the Pa parameter is defined by means of integration performed along sampling length l. In practice, however, this integration is usually replaced by summation over a given number of measuring points.

The ISO 4287 differentiates between three definition types: one for the parameters calculated on the basis of the original profile (e.g. P_a), one for the parameters calculated on the basis of the roughness profile (e.g. R_a), and one for the parameters calculated on the basis of the waviness profile (e.g. W_a).

The definitions are identical; they differ only with respect to the type of the input data. The norm defines three types of filters that single out short-wave and long-wave components of the surface profile: l_s – the profile filter that delineates the transition from roughness to components of even smaller lengths of waves occurring on the surface; l_c – the profile filter that delineates the transition from roughness to waviness; and l_f – the profile filter that delineates the transition from waviness to components of even larger lengths of waves occurring on the surface.

One of the most common problems encountered by the authors of papers on the issue of roughness is providing a proper definition of filter l_c – i.e., the profile filter that delineates the transition from roughness to waviness. Gurau et al. (2006) analyzed the impact that the scale of filtration has on the basic roughness parameters defined by ISO. Various authors propose various types of such filtration – e.g. using the Fourier transform (Hocheng & Hsieh, 2004), the wavelet method (Chen et al., 1999), or morphological filters (Młynarczuk, 2010). The measurements discussed in this chapter were carried out according to the guidelines specified in the ISO 11562, and with a 2.5 mm Gaussian filter.

The data obtained with a profilometer served as a basis for carrying out an analysis which, in turn, was based on the R_a and W_a parameters. Table 1 presents these parameters, which were calculated on the basis of measurements performed on 147 profiles measured on samples of three granites cut with an abrasive water jet – AWJ. In order to demonstrate the differences in the quality of the surface cut with AWJ – which occurred as the distance from the sample edge (i.e. from inlet of the water jet) was changing – two curves depicting the changes in parameters R_a and W_a for three investigated rocks and three cutting speeds were presented in Table 2. For the sake of clarity, the curves show just the extreme speed values (100 and 700 mm·min^{-1}) and the median speed value (400 mm·min^{-1}).

TABLE 1

List of R_a and W_a calculated on the basis of measurements made by optical profilometer

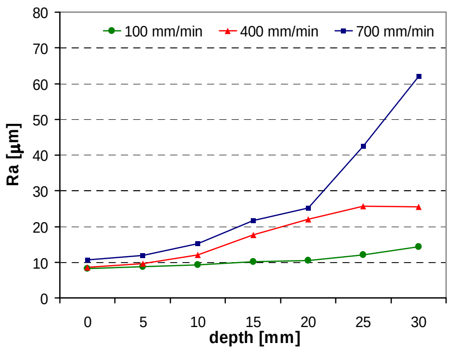
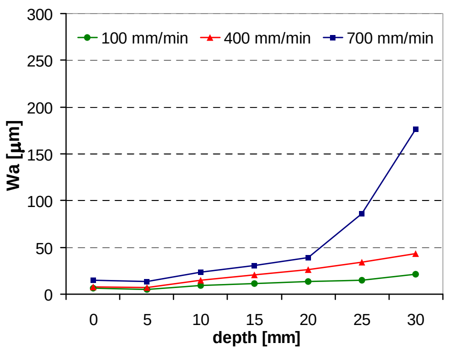
Cutting speed [mm·min^{-1}]	Depth [mm]	Krásno		Žulová		Liberec	
		R_a [µm]	W_a [µm]	R_a [µm]	W_a [µm]	R_a [µm]	W_a [µm]
1	2	3	4	5	6	7	8
100	0	8,15	6,14	18,25	14,13	13,01	7
	5	8,70	5,04	9,75	8,25	10,77	15,83
	10	9,22	9,03	8,88	9,69	12,39	15,18
	15	10,07	11,68	10,74	11,79	15,43	29,74
	20	10,50	13,81	11,96	11,89	17,58	40,21
	25	12,00	14,70	11,44	13,48	19,88	49,80
	30	14,33	21,53	13,49	14,28	21,94	66,25
200	0	7,64	5,80	18,12	16,26	14,98	30,44
	5	9,09	6,68	9,18	6,91	9,99	33,15
	10	10,01	8,81	10,68	9,63	13,00	33,12
	15	11,24	10,09	13,01	14,37	16,54	42,91
	20	14,12	14,82	15,79	17,93	19,06	49,07
	25	14,92	22,15	16,87	20,32	21,66	58,02
	30	18,57	28,67	18,39	24,28	25,56	67,34
300	0	8,14	6,39	14,56	13,14	14,31	18,18
	5	10,18	7,08	10,99	10,25	11,87	14,38
	10	11,28	8,55	11,59	13,76	16,32	37,76
	15	13,59	10,25	14,73	15,22	24,03	59,73
	20	19,24	16,19	17,00	27,34	28,40	88,45
	25	21,97	29,09	22,14	36,59	34,10	92,00
	30	24,56	30,61	27,98	42,58	34,11	115,56
400	0	8,64	7,52	17,05	13,86	14,17	29,02
	5	9,64	7,25	10,71	9,72	12,70	15,10
	10	12,09	14,61	12,84	12,28	17,18	32,70
	15	17,57	20,34	15,40	20,09	24,07	43,43
	20	22,02	26,56	18,66	28,30	37,98	57,44
	25	25,61	34,17	23,97	41,38	41,43	100,95
	30	25,50	43,66	27,82	59,25	43,85	109,64
500	0	9,61	6,52	16,26	13,14	13,24	21,88
	5	10,16	7,31	11,11	9,88	9,35	29,89
	10	12,75	12,58	12,34	15,59	13,76	41,25
	15	18,49	20,54	19,04	20,71	20,66	59,62
	20	20,80	27,72	21,22	28,95	21,87	82,90
	25	23,61	44,81	24,84	45,79	44,22	100,94
	30	30,44	71,45	31,27	64,03	63,47	177,53
600	0	10,34	12,65	19,01	14,41	14,38	21,75
	5	10,87	13,81	12,76	16,10	13,51	22,73
	10	14,32	15,98	14,26	22,51	18,03	40,62
	15	19,50	19,85	17,60	26,37	23,73	56,71
	20	26,92	34,76	22,14	38,75	35,09	106,24
	25	43,13	54,08	27,60	53,81	46,25	174,02
	30	52,97	73,12	42,50	100,47	68,02	242,60

1	2	3	4	5	6	7	8
700	0	10,64	15,01	15,29	24,71	17,99	24,77
	5	11,89	13,75	11,98	23,48	12,09	33,80
	10	15,19	23,60	18,52	28,76	19,37	44,29
	15	21,74	30,35	26,02	43,50	28,19	56,54
	20	25,12	39,23	29,99	58,05	37,31	152,17
	25	42,43	85,92	48,25	77,84	50,69	180,76
	30	62,05	176,51	57,17	117,11	75,97	269,29

The analysis of the curves and Table 1 shows that both the roughness parameter (R_a) and the waviness parameter (W_a) increase as the distance from the sample edge grows. This happens in the majority of cases, and proves that the surface which is further from the edge is of a much worse quality (in relation to the surface right next to the edge, i.e. right next to the inlet of the water jet). It should also be noticed that the observed increase in roughness and waviness is slight for low speed values, but for the highest analyzed speed value both parameters rise the most: 583% (R_a) and 1176% (W_a).

TABLE 2

Changes of the R_a and W_a for 3 studied rocks and for 3 water jet cutting speed

<table>
<tr><td></td><td>R_a</td><td>W_a</td></tr>
<tr><td></td><td>1</td><td>2</td></tr>
<tr><td>Krásno</td><td>
</td><td>
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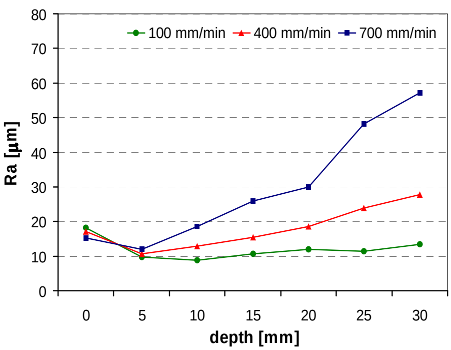
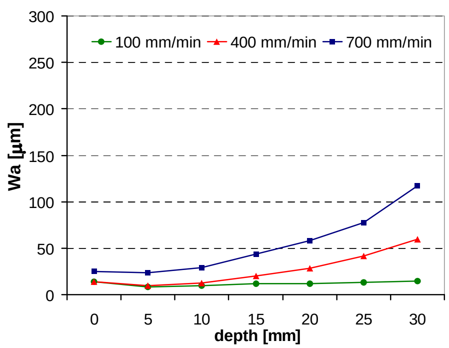
<tr><td>Žulová</td><td>
</td><td>
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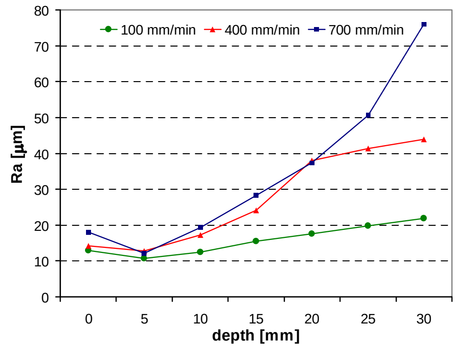
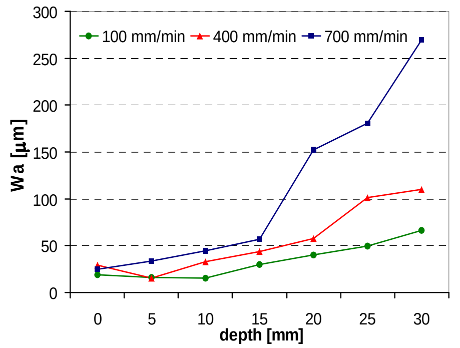
	1	2
Liberec		

The results also show that the investigated rocks react differently. The relatively lowest quality of the cut surface concerns the Liberec granite. It is a coarse-grained rock (contrary to the medium-grained and fine-grained granites). This indicates that large rock grains yield much worse surface parameters, which is probably due to the fact that, far from the sample edge and with higher cutting speed values, these grains are „ripped away" by a water jet rather than cut.

This is well illustrated by the diagrams from Figures 5 and 6, which show that, for a small distance from the sample edge, parameter R_a is stable for each of the investigated rocks, regardless of the cutting speed. For the largest investigated distance from the sample edge (i.e. 30 mm), the quality of the surface worsens considerably together with an increase in the cutting speed. It should also be observed that for the lowest cutting speed (100 mm · min^{-1}) the quality of the surface 30 mm away from the sample edge does not differ from the quality of the surface right next to the edge.

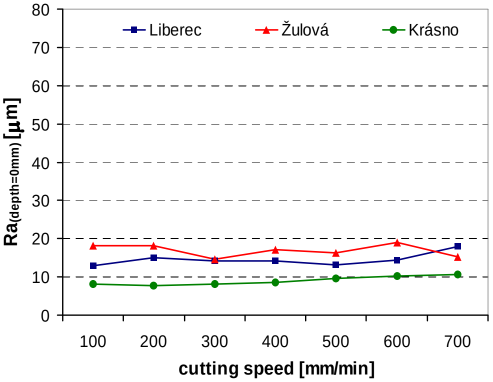


Fig. 5. R_a determined at a depth of 0 mm

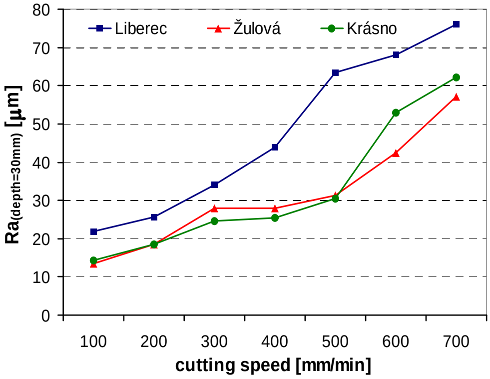


Fig. 6. R_a determined at a depth of 30 mm

Figure 7 presents the relation between the mean value of parameter R_a (calculated for the whole surface as a mean of R_a determined at seven various depths) and the traverse speed. Figure 8 presents the standard deviation of the R_a parameter (understood as the standard deviation of 7 R_a parameters determined at seven various depths) for each of the analyzed speed values.

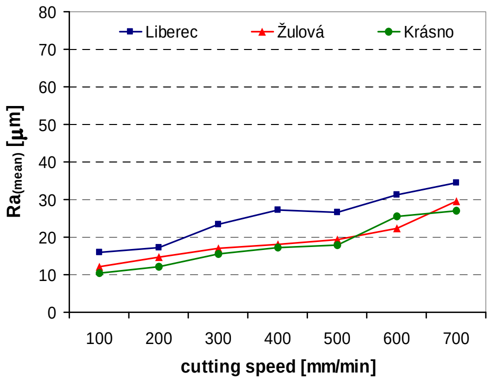


Fig. 7. Average R_a determined for whole areas

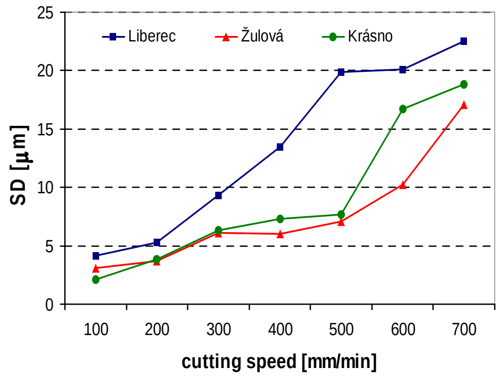


Fig. 8. The standard deviation of the mean R_a for the whole areas

In particular, the second diagram shows the surface quality dispersion across the sample, which is the result of a constant increase in the speed of cutting with a water jet. For the speed value 100 mm·min^{-1}, the whole analyzed surface reveals generally the same quality (regardless of the rock). As the cutting speed increases, the surface quality depends more and more on its position in relation to the inlet of the water jet. Such diversification depends on the processed rock, and is the poorest for coarse-grained granite (the Liberec granite).

The discussed conclusions were based on the analysis of normative parameters R_a and W_a. Similar conclusions can be reached when analyzing some other parameters specified by the ISO 4287 (e.g. R_q and W_q). However, it should be taken into account that these parameters are among the most elementary ones. They do provide an insight into the surface quality, but it is far from comprehensive. Thus, the researchers often use other parameters to investigate and describe the surface quality. One such parameter could be a madogram, which was discussed below.

6.2. Variogram and madogram

The idea of a semivariogram $\gamma(h, a)$ was introduced in 1955 by Matheron. For the sake of practical applications, a variogram is calculated on the basis of the following formula:

$$2\gamma(h,\alpha) = \frac{1}{N}\sum_{i=1}^{N}(Z(x_i) - Z(x_i + h))^2 \qquad (2)$$

where h is the distance – in direction a – between two points: $Z(x)$ and $Z(x + h)$ and N is a number of points. There are three characteristic parameters describing a semivariogram: nugget, sill, and range. When a semivariogram is a function that increases from a value different than 0, this value is called the nugget effect. The sill is the limit reached by a semivariogram, for which no further increase of the function is observed. The range is the distance between 0 and the value where the semivariogram reaches the sill. For the sake of the research discussed in this paper, a specific type of a variogram, called madogram, was adopted. A madogram is a function defined in a similar way – except that the square of the difference $(Z(x_i) - Z(x_i + h))$ is replaced with the module:

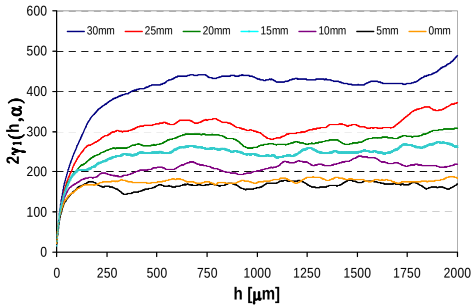
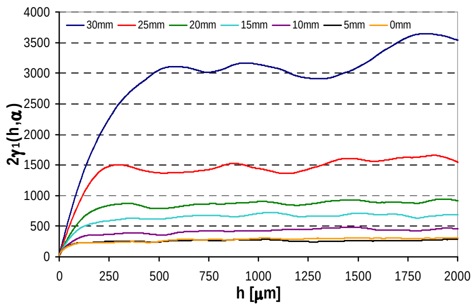
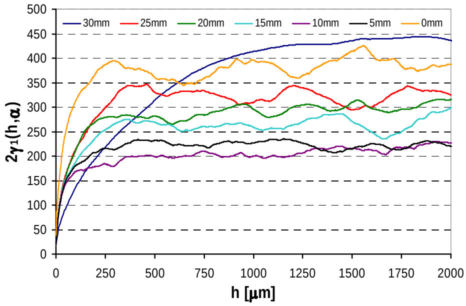
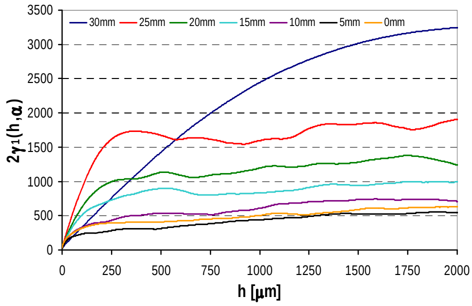
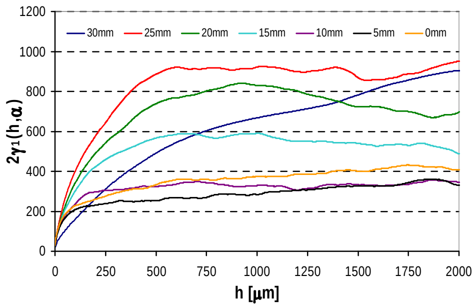
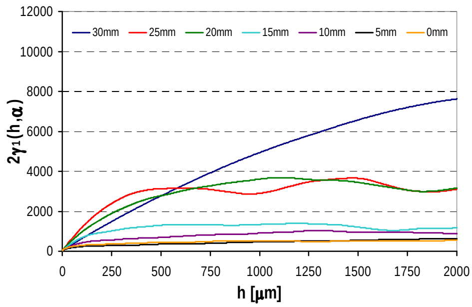
$$2\gamma_1(h,\alpha) = \frac{1}{N}\sum_{i=1}^{N}\left|Z(x_i) - Z(x_i + h)\right| \tag{3}$$

Madograms are less sensitive to extreme values than variograms. They can be useful in the process of concluding about the anisotropy of data sets revealing outliers which are hard to interpret by means of variograms. The usefulness of madograms in analyzing data obtained from profilometers has been discussed, among others, in the papers by Młynarczuk (2004) and Młynarczuk & Wierzbicki (2009).

Table 3 presents madograms for the profiles of original surfaces, obtained at two extreme cutting speed values. When analyzing the results, it is worth noticing that the madogram for the

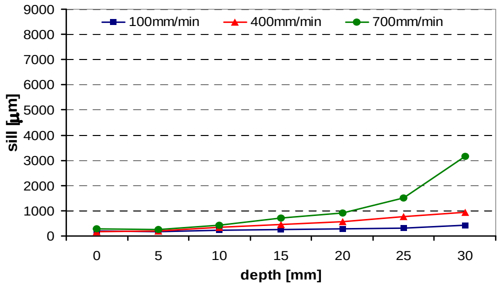
TABLE 3

Madograms determined for surface profiles, obtained using two extreme cutting speeds

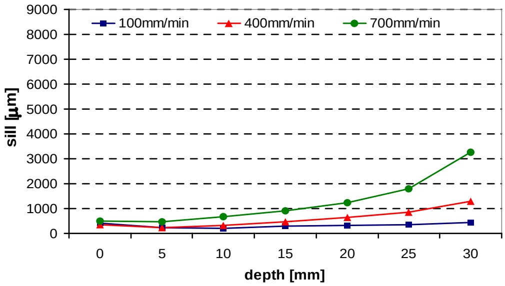
	100 mm/min	700 mm/min
Krásno		
Žulová		
Liberec		

profile which is 30 mm away from the sample edge displays different qualitative behavior from madograms determined for other profiles. This concerns diagrams for the coarse-grained granite from Liberec and the Žulové granite, cut at the speed of 700 mm · min^{-1}. This testifies to the qualitative change of the surface shape in this location (which may be caused by „ripping the grains away" rather than cutting them).This observation was borne out by the inspection of samples subjected to the process of cutting with a water jet. It needs to be stated that such conclusions, drawn on the basis of the analysis of the diagrams from Table 3, prove that using a madogram is more useful than relying upon the parameters defined by ISO norms.

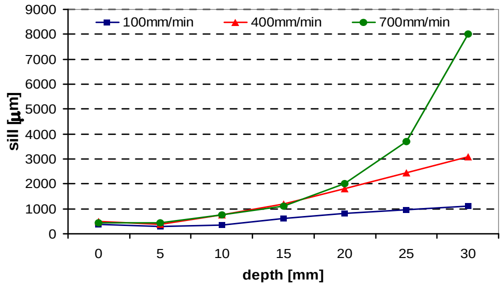
On analyzing Table 3, one can observe that – in the majority of cases – the sills of madograms increase as the distance from the sample edge grows. This testifies to the worsening of the surface quality, and confirms the observations made in the previous chapter. The observed changes are relatively minor for samples cut at the speed of 100 mm/min, but in the case of the samples cut at the speed of 700 mm·min^{-1} the quality of the surface deteriorates considerably. Also, the impact of the processed granite on the increase in the sill value is visible. It is definitely the highest for the coarse-grained granite (consider various ranges of axis Y for the results presented in Table 4). All these relationships were presented in Figure 9, where the changes in madogram sills for particular rocks cut with three various speeds of the head movement were marked.



a)



b)



c)

Fig. 9. The dependence between madogram sill and the distance from the edge of the sample calculated for different cutting speeds. (a) Krásno granite, (b) Žulová granite, (c) Liberec granite

7. Repeatability of measurements

Measurements were carried out in order to verify the repeatability of the quality of the obtained rock surfaces. To this end, from a block of medium-coarsed granite, 5 samples were cut, each time with the same head traverse speed (300 mm·min^{-1}). Each of the samples was scanned with an optical profilometer, according to the procedure adopted during the essential measurements. For the obtained results, the analysis of madograms was performed. The sill values were presented in Table 4. The variability coefficient (CV – defined as the ratio of the standard deviation to the average value, multiplied by 100%) calculated on their basis testifies to small variability of the obtained data. Therefore, it can be concluded that the differences in the quality of the surface are the result of the material's response to specific parameters of the rock processing.

TABLE 4

Results of repeatability analysis. Madogram sills obtained for 7 depths and for 5 surfaces cut with the same parameters

Depth	Madogram sill (μm)					CV
	Surface 1	Surface 2	Surface 3	Surface 4	Surface 5	
0 mm	240	210	200	230	255	9,8%
5 mm	250	230	260	270	220	8,4%
10 mm	300	340	400	320	350	11,0%
15 mm	470	450	550	450	580	12,2%
20 mm	600	650	680	620	700	6,3%
25 mm	800	900	700	710	920	12,8%
30 mm	1120	1090	1000	1050	1100	4,4%

8. Conclusion

The aim of the research was to describe – in a quantitative manner – changes in the quality of a rock surface cut with an abrasive water jet, in relation to the traverse speed of the head, as well as the distance between the surface fragment being cut and the inlet of the water jet. It was demonstrated that the impact of the latter on the surface quality can be minimized by lowering the traverse speed of the head. The results obtained in the course of measurements also show that the size of rock grains influences the surface quality. This is particularly visible for the least advantageous parameters of a water jet cutting process – namely, for high speed values and the surface fragments that are located considerably far (or the furthest) from the sample edge. For the optimal paramaters, the influence of the grain size on the surface quality is minor, and sometimes even negligible.

In addition, the Authors demonstrated the usefulness of madogram in the analysis of the quality of the processed surface. With this tool, it is possible not only to confirm the results obtained on the basis of the ISO parameters, but also procure a more detailed description of the shape of the processed surface.

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