SPECTRAL ANALYSIS OF METALLIC SURFACES TOPOGRAPHY GENERATED BY ABRASIVE WATERJET

Kateřina Brillová, Miloslav Ohlídal, Jan Valiček, Dražan Kozak, Sergej Hloch, Michal Zeleňák, Marta Harničárová, Petr Hlaváček

A basic study of a surface topography generated by an abrasive waterjet cutting is performed by means of the spectral analysis of these surfaces. The initial data were acquired by using an optical profilometer MicroProf FRT in the form of 2D maps of the surfaces' heights. The basic notions of the spectral analysis applied to the surface topography are presented. Limitations of the measurement procedure are considered. Distortions of the areal power spectral density are discussed. An estimation of the areal power spectral density is carried out using a periodogram method combined with the Welch’s method. A comparison of surfaces prepared by the abrasive waterjet cutting with different values of the cutting technological parameters is performed. It has been demonstrated that the areal spectral analysis of the aforementioned surfaces offers new possibilities of their topography characterization.

Keywords: abrasive waterjet cutting, spectral analysis, surface topography

Introduction

Development and applications of new materials in mechanical engineering practice bring a lot of questions concerning their technological treatment. Nowadays classical machining of these materials is complemented by new technologies. The machining of materials by an abrasive waterjet (AWJ) represents one of such relatively new and progressive methods. AWJ offers a versatile flexible tool to allow machining of all natural and artificial materials which may get in contact with water. A wide range of such materials brings a lot of unanswered problems concerning their mutual interaction with the AWJ. The first pioneering works in this field were accomplished by Hashish [6] who studied the influence of technological parameters on the depth of cutting profile. He also proposed a mathematical model for the prediction of the maximum depth of the cut. A great deal of attention was paid to a study of the surface topography of cutting walls generated by AWJ. A study of the surface topography is important for AWJ modelling and prediction. A mechanism of the AWJ stock removal is still a poorly studied field of the AWJ technology. A disintegration of materials by means of AWJ involves a mechanism of cutting, plastic deformation, fatigue and fracture of those materials. Due to the investigation of the surface topography generated by the AWJ machining process it is possible to gain a better understanding of this process; to specify its theory and to quantify correctly the AWJ stock removal mechanism [7–10]. Surfaces generated by means of AWJ machining show a characteristic topography. The picture of a surface (see Fig. 1) includes specific zones, namely the initiation zone, smooth zone, transition zone and rough zone. The surface has four topographical different zones with different values of surface parameters Ra, Rq, Rz [1–5].

Experiments

Investigated surfaces generated by AWJ cutting were prepared from 10-mm thick steel plates (material AISI 304) of size 300×50×10 mm³. The schematic diagram of the cutting AWJ head used in experiment is presented in Fig. 2. Ultra high - pressure water goes through the water nozzle into the inlet chamber where it is mixed together with the garnet abrasive. The abrasive waterjet is formed in the cutting nozzle and interacts with the upper surface of sample, which is perpendicular to the abrasive waterjet. The constant parameters of the AWJ cutting were: Jet diameter = 0,1 mm, focusing tube diameter = 1 mm, abrasive grain size 80 MESH, nozzle–surface distance = 3 mm.

Several AWJ cutting technological parameters of the surface preparation were selected to observe their influence on the surface topography. These parameters were the following: the pressure of water on the input of the cutting AWJ head, the traverse speed of the AWJ head and the abrasive flow rate.

The values of the AWJ cutting technological parameters being changed are presented in Tab. 1.
Topography measurement

The aforementioned surfaces were measured by using an optical profilometer (Fig. 3). This profilometer MicroProf FRT enabled us to obtain a map of the surface heights with regard to a reference plane. It is useful for 3D surface topography assessment. The principle of the optical profilometer operation is based on utilization of chromatic aberration of the positive lens of the optical sensor CHR 150 N (Fig. 4). White light from a halogen bulb goes through the positive lens with high chromatic aberration. Different light monochromatic components are focused in different heights from the reference plane at the output of the optical fibre. The same optical fibre collects scattered light from the surface under study. This light is analysed by means of a spectrometer. The light is best captured when focused on the surface. It means that the spectral intensity distribution of the light being processed by the spectrometer has a maximum at a wavelength of a monochromatic component exactly focused on the surface. The height of the surface irregularities is deduced by means of a calibration table from the wavelength of the spectral distribution of maximum intensity. The optical sensor is non-movable, the sample under study lies on a scanning table.

The same optical fibre collects scattered light from the surface under study. This light is analysed by means of the spectrometer. The results of the measurement have the form of a vector and/or the matrix of heights of the surface under study. Study. This light is analysed by means of a spectrometer. The light is best captured when focused on the surface. It means that the spectral intensity distribution of the light being processed by the spectrometer has a maximum at a wavelength of a monochromatic component exactly focused on the surface. The height of the surface irregularities is deduced by means of a calibration table from the wavelength of the spectral distribution of maximum intensity. The optical sensor is non-movable, the sample under study lies on a scanning table.

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Spectral analysis of surface topography

Spectral analysis of a surface topography provides a special view of the surface topography characterization. Analysis of the topography in the frequency domain makes it possible to accentuate some surface topography features which are noticeable worse within the spatial domain. It is interesting to apply the spectral analysis to surfaces generated by AWJ cutting. These surfaces are of a random character (the detailed specification can be found in [13]). The process of their topography measurement provides individual realization of a 2D random function which represents the surface under study (so called surface function). This function is non-stationary within its complete extent. As already mentioned in the introduction, it is possible to select the individual zones of the surface in which the surface function can be considered as a stationary function (i.e. there is not any change of the surface character within the whole individual zone) and ergodic (i.e. it is possible to evaluate the features of the whole surface topography within the individual zone from an individual sufficiently large surface realization within the zone) 2D random function. Considering the surface under study as the random function it is necessary to describe the surface by means of the mean quantities derived from an amplitude of Fourier's spectrum realization or, as usually, from the squares of these spectra in the frequency domain. These squares of Fourier spectra are called the energy or power spectra of surface realization. The expected value (mean) of Fourier transforms of individual surface realizations usually tends to zero function identically due to the
distribution of their phases. Thus, the mean of these Fourier transforms does not provide any information.

A non-limited (i.e. defined along the whole plane \(x, y\)) realization of the random surface under study by the surface function \(z = z(x, y)\) in the coordinate system \(Oxyz\) will be described, whereas \(z\) is the surface height with respect to the plane \(x, y\) at the point \([x, y]\). Hence, the function \(z = z(x, y)\) is the realization of a stationary and ergodic random function \(z_{xy} = z(x, y)\) selected by a process of measurement. The function \(z = z(x, y)\) is defined along the whole plane \(x, y\). But information on the function of \(z = z(x, y)\) is acquired only from a finite region \(X, Y\) of the plane \(x, y\) by the MicroProf FRT profilometer measurement. So, it is necessary to deal with the function \(z_{xy} = Z_{xy}(x, y)\) defined as follows:

\[
Z_{X,Y}(x, y) = z(x, y) \quad \text{for} \quad |x| \leq X \land |y| \leq Y
\]

\[
z_{X,Y}(x, y) = 0 \quad \text{otherwise.}
\]

This function has the Fourier integral

\[
Z_{X,Y}(f_x, f_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} z(x, y) \exp[-2\pi i(f_{x}x + f_{y}y)] dx dy.
\]

Then it is possible to define the areal power spectral density (APSD) of the function \(z = z(x, y)\) as follows (Remark: The expression areal power spectrum is used for this quantity in literature alternatively):

\[
P_{\varphi}(f_x, f_y) = \lim_{X \to \infty, Y \to \infty} \frac{\int_{-X}^{X} \int_{-Y}^{Y} \left| Z_{X,Y} \right|^2}{XY}.
\]

APSD of the whole random function \(z\) is defined as:

\[
P_{\varphi}(f_x, f_y) = \lim_{X \to \infty, Y \to \infty} \frac{\left< \left| Z_{X,Y} \right|^2 \right>}{XY}.
\]

where the symbol \(<\) denotes the mean of the surface realizations population. The quantity \(P_{\varphi}(f_x, f_y)\) indicates in what way the mean power of the studied surface is distributed within the frequency domain. This quantity will be used for the characterization of surfaces generated by AWJ. The characterization of the surface topography within these zones along an individual surface profile can be performed by means of a frequency-amplitude analysis (2D surface evaluation) [12]. A more advanced approach is the surface topography characterization by means of the discrete fast Fourier transform (DFFT) [11, 12] of 2D data (maps of surface heights) within these zones (in accordance with the technical practice so called 3D evaluation of surfaces is performed). Of course it is possible to base the spectral analyses on other transforms. The aim of the work presented is to find the characteristic features of the surface within the individual zones by means of this technique, to link them to the technological parameters of the surface preparation and to obtain their relationship to the mechanism of the surface generation during the cutting of materials by AWJ. According to our best knowledge the application of the areal data spectral analysis has not been used yet for the topography characterization of the surfaces generated by the AWJ cutting. More detailed quantitative description of a random function within the frequency domain is allowed by the following quantities derived from APSD of the function. These are angular power spectral density (AnPSD) and radial power spectral density (RPSD) of the function. It is possible to characterize the shape of APSD, i.e. the distribution of the random function power within the frequency plane by means of both [13]. To define these quantities it is necessary to transform the APSD (see Eq. 4) into polar coordinates within the frequency domain

\[
P_{\varphi}(f_x, f_y) \to P_{\varphi}(f_r, \theta),
\]

where

\[
f_x = f_r \cos \theta, \quad f_y = f_r \sin \theta, \quad f_r = \sqrt{f_x^2 + f_y^2}, \quad \theta = \arctan\left(\frac{f_y}{f_x}\right).
\]

Then AnPSD is defined as follows [13]:

\[
P_{\varphi}(\theta) = \frac{1}{2\pi} \int_{0}^{2\pi} P(f_r, \theta) df_r.
\]

4.1 Limitations of measuring procedure

The measurement of the studied surface heights by the optical profilometer MicroProf FRT provides a discrete form of the function \(Z_{x,y}(x_m, y_n)\), i.e. the sampled function \(Z_{x,y}(x_m, y_n)\), where \(m = 0...M - 1\), \(n = 0...N - 1\), \(m, n\) are integers. The surface of the sample in the squared grid of equidistant points, i.e. \(M = N\), is usually measured. It is obvious that the integral Fourier transform \(Z_{xy}(f_x, f_y)\) of the continuous function \(Z_{x,y}(x_m, y_n)\) must be replaced by the discrete Fourier transform \(\tilde{Z}_{xy}(f_x, f_y)\) of the sampled function \(Z_{x,y}(x_m, y_n)\). It is defined as follows:

\[
\tilde{Z}_{X,Y} = \frac{k}{M \Delta x \cdot N \Delta y} \int = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} z_{X,Y}(m \Delta x, n \Delta y) \exp\left[-i2\pi \left(\frac{k}{M} m + \frac{l}{N} n\right)\right]
\]

where \(0 \leq k \leq M - 1\); \(0 \leq l \leq N - 1\), \(\Delta x\) is the sampling interval along the \(x\) axis, \(\Delta y\) is the sampling interval along the \(y\) axis, \(k/(M \Delta x)\) is the \(k\)th value of the spatial frequency along the \(f_x\) axis, \(l/(N \Delta y)\) is the \(l\)th value of the spatial frequency along the \(f_y\) axis. The function \(\tilde{Z}_{xy}\) is used to determine \(P(f_x, f_y)\) in...
Eq. (3). Nevertheless a distortion in this procedure is necessarily committed, the cause of which is as follows:

- The limit transition in Eq. (3) supposes a possibility to enlarge the \( X, Y \) region (where the topography of the surface is measured) without any stilt. But the surface topography can be measured only from a limited region \( X, Y \) of the surface.
- The sampled discrete function is used.

\[
z_{X,Y}(x_n,y_n) = z_{X,Y}(x,y) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \delta(x-m\Delta x) \delta(y-n\Delta y)
\]

instead of the continuous function \( Z_{xy}(x,y) \) from Eq. (2).

Meaning of symbols in Eq. (8) is as follows:

- \( \sum_{m=-\infty}^{\infty} \) is the sequence of the Dirac distributions displaced with a step \( \Delta x \) along the \( x \) axis,
- \( \sum_{n=-\infty}^{\infty} \) is the sequence of the Dirac distributions displaced with a step \( \Delta y \) along the \( y \) axis.

4.2 Discussion of APSD distortions

Let us discuss these distortions. The surface topography is measured within the finite region described by Eq. (1). The surface function can be written within this region as follows:

\[
z_{X,Y}(x,y) = z(x,y) \text{rect} \left( \frac{x}{X} \right) \text{rect} \left( \frac{y}{Y} \right)
\]

where the truncation function

\[
\text{rect} \left( \frac{x}{X} \right) \text{rect} \left( \frac{y}{Y} \right)
\]

is defined in the following way:

\[
\text{rect} \left( \frac{x}{X} \right) \text{rect} \left( \frac{y}{Y} \right) = 1 \text{ } \left| x \right| < X \land \left| y \right| < Y
\]

\[
\text{rect} \left( \frac{x}{X} \right) \text{rect} \left( \frac{y}{Y} \right) = \frac{1}{2} \text{ } \left| x \right| = X \lor \left| y \right| = Y
\]

\[
\text{rect} \left( \frac{x}{X} \right) \text{rect} \left( \frac{y}{Y} \right) = 0 \text{ } \text{otherwise}.
\]

Product in Eq. (9) leads to a convolution of the Fourier transform of the function \( z(x,y) \) (this Fourier transform exists in a generalized sense of the Fourier transform within the limit) and also the Fourier transform of the function \( \text{rect}(x/X)\text{rect}(y/Y) \), i.e. the function \( \text{rect}(x/X)\text{rect}(y/Y) \).

Because of the finite extent of the definition domain of the function \( \text{rect}(x/X)\text{rect}(y/Y) \) this convolution leads to a distortion of the Fourier transform of the function \( z(x,y) \) being sought. This distortion gives rise to nonzero components of the spectrum in new frequencies. It is so called the leakage spectrum in these new incorrect frequencies. This phenomenon can be suppressed by a selection of the largest possible domain of definition \( X, Y \) of the function \( \text{rect}(x/X)\text{rect}(y/Y) \), i.e. the region of the surface topography measurement. Another possibility suppressing the leakage of the spectrum is to use another more appropriate function – so called weighting function \( w(x,y) \) (e.g. Hann function – see below) instead of the function \( \text{rect}(x/X)\text{rect}(y/Y) \) in Eq. (9). Then so called weighting the function \( z(x,y) \) by the data-weighting function \( w(x,y) \) is carried out. Further consequence of the aforementioned convolution is a smearing or blurring of the Fourier transform of the function \( z(x,y) \). Of course, the less frequency smear, the better the frequency-resolving power is possible. It is possible to decrease the frequency smear by the selection of a wider truncation function. In that case the function \( \text{rect}(x/X)\text{rect}(y/Y) \) is the data-weighting function \( w(x,y) \) which is carried out. Further consequence of the aforementioned convolution is a smearing or blurring of the Fourier transform of the function \( z(x,y) \). Of course, the less frequency smear, the better the frequency-resolving power is possible. It is possible to decrease the frequency smear by the selection of a wider truncation function. In that case the function \( \text{rect}(x/X)\text{rect}(y/Y) \) is the data-weighting function \( w(x,y) \).
plane $x, y$. It is not also possible to find $\langle |z_{x,y}|^2 \rangle$ because it is not possible to analyse an infinite number of possible realizations of the function $z$. These two reasons lead to the fact that the result must be only an estimate of the APSD from the Eq. (4). The mean value $\langle |z_{x,y}|^2 \rangle$ can be estimated in the Eq. (4) from a finite number of realizations of the random function $z$ as the arithmetic average

$$
\frac{1}{Q} \sum_{q=1}^{Q} |Z_{x,y,q}|^2,
$$

i.e. the following approximation is used:

$$
\langle |Z_{x,y,q}|^2 \rangle \approx \frac{1}{Q} \sum_{q=1}^{Q} |Z_{x,y,q}|^2.
$$

(11)

Hence, it is possible to express approximately the Eq. (4) as follows:

$$
P_w \left( \frac{k}{M \Delta x}, \frac{l}{N \Delta y} \right) \approx \frac{1}{Q} \sum_{q=1}^{Q} \left| \frac{Z_{w,x',y,q}}{Q} \left( \frac{k}{M' \Delta x}, \frac{l}{N' \Delta y} \right) \right|^2
$$

(12)

where $0 \leq k \leq M-1; 0 \leq l \leq N-1$. Using the relation (12) so called periodogram method of the determination of the APSD estimation of the random function $z$ is employed.

### 4.4 Welch's method

The calculation on the right side of the Eq. (12) can be carried out in several ways. The Welch’s method has been selected because only one finite discrete realization $z_{x,y}(x_m,y_n)$ of the random function $z$ is available. This method is based on the assumption that the relevant function $z$ is ergodic, i.e. the measured realization $z_{x,y}(x_m,y_n)$ provides representative information about the whole random function $z$. Within the framework of this method the measured domain of the given realisation is resolved into a sufficient number of the mutually overlapping sub-domains $z_{x,y}(x_m,y_n)$. As the next step of the Welch’s method weighting the surface function in each sub-domain by a chosen weighting function $w(x_m,y_n)$ was carried out. The following expression for each weighted sub-domain denoted by the indices $q$ was determined:

$$
Z_{w,x',y',q} = \frac{1}{Q} \sum_{q=1}^{Q} \left| \frac{Z_{w,x',y',q}}{Q} \left( \frac{k}{M' \Delta x}, \frac{l}{N' \Delta y} \right) \right|^2
$$

(13)

for $0 \leq k \leq M'-1; 0 \leq l \leq N'-1$. The symbol $Z_{w,x',y',q}$ in the expression

(13) denotes the Fourier transform of the surface function weighted by the function $w(x_m \Delta x, y_n \Delta y)$ within the selected sub-domain $x', y'$. The resolution within the frequency domain is again decreased by the selection of $M' \Delta x, N' \Delta y$ in the Eq. (13) and simultaneously an undesired smoothing of the APSD estimations from the individual sub-domains accompanied by the improved leakage of the adequate spectra is performed. In conclusion the arithmetic average of the $Q'$ spectra of the weighted surface function within the all sub-domains was calculated:

$$
\bar{P}_w = \frac{1}{Q} \sum_{q=1}^{Q} \left| \frac{Z_{w,x',y',q}}{Q} \left( \frac{k}{M' \Delta x}, \frac{l}{N' \Delta y} \right) \right|^2
$$

(14)

Considering the assumption of the function $z$, ergodicity the term (14) is equivalent to the arithmetic average of the given number of finite realizations of $z$. The term (14) is the resulting statistical estimate of the APSD defined by the Eq. (4). Hence

$$
P_w \left( \frac{k}{M' \Delta x}, \frac{l}{N' \Delta y} \right) \approx \bar{P}_w \left( \frac{k}{M' \Delta x}, \frac{l}{N' \Delta y} \right)
$$

(15)

It is obvious that the dispersion of the resulting estimate $P_w$ of the APSD was decreased by increasing the number of sub-domains used in averaging on the one hand, but simultaneously the resolution within the frequency domain was decreased by reducing the sub-domains size on the other hand. Thus the information about the details of the averaged APSD shape was lost. The choice of the domains size and the number of them is a question of a compromise.

The estimate $\bar{P}_w$ of the APSD of the surface under study gives an interesting view about the typical features of this surface (see below). As regards the discrete form of terms (5) and (6) for the APSD and RPSD an appropriate numerical algorithm for their calculation was used.

### 5 Results and discussion

The surface topography was measured within the one-piece region of $6 \times 2 \text{ mm}^2$ inside the individual zones. 18 overlapping sub-domains (with a 50 % overlap) with a size of $0.6 \times 0.6 \text{ mm}^2$ ($M'=N'=300$ were used for estimation of

$$
P_w \left( \frac{k}{M' \Delta x}, \frac{l}{N' \Delta y} \right)
$$

of the APSD of the surface under study. The Hann weighting function (16) was used

$$
w(x_m,y_n) = \cos^2 \left( \frac{\pi m' \Delta x}{M'} \right) \cos^2 \left( \frac{\pi n' \Delta y}{N'} \right)
$$

(16)

for each sub-domain to suppress the leakage of its spectrum. The minimum sampling interval of the surfaces measured by the optical profilometer MicroProf FRT is $\Delta x = \Delta y = 2 \mu m$. Hence, it is not possible to distinguish the surface details corresponding to the spatial frequencies $f_x \geq 1/2M'$ ($1/\mu m$), $f_y \geq 1/2N'$ ($1/\mu m$). So, the upper frequency limit of surface topography measurements is $1.7 \times 10^{-3} \text{ (1/m)}$ for

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both frequencies $f_s, f_r$. These limitations should be considered when the results are interpreted.

5.1 Influence of water pressure variation

First the results for two selected values of the water pressure (for the constant values $m_w = 500$ g/min, $v_w = 70$ mm/min) are compared (see Fig. 5 - Fig. 12). A half-width of the main peak of the normalized RPSD within the individual surface zones is studied to find a quantitative parameter characterizing the variations in the APSD of the surface under study. Values found are presented in Tab. 2. It is obvious from Tab. 2 that the half-width of the normalized RPSD peak does not significantly change with the water pressure variations within the smooth zone. The half-width of the normalized RPSD peak is wider for higher water pressures. Another way to characterize the variations in APSD of the studied surface can be the AnPSD utilization. The angular coordinate $\theta$ of a maximum of the normalized AnPSD is monitored within the individual surface zones. Values found are presented in Tab. 3. It should be noted that the maxima of the normalized AnPSD are relatively flat, i.e. the significant fluctuations in their values can be observed.

<table>
<thead>
<tr>
<th>Zones</th>
<th>Smooth</th>
<th>Rough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-width of the peak, 1/m</td>
<td>289.4</td>
<td>287.5</td>
</tr>
<tr>
<td>Relative difference, %</td>
<td>0.0</td>
<td>20.2</td>
</tr>
</tbody>
</table>

It can be seen from Tab. 3 that no changes of the angular coordinate $\theta$ of the normalized AnPSD maximum occur with the water pressure change within the smooth zone. However the displacement of the maximum angular coordinate of normalized AnPSD is significant in the case of the rough zone. It can be seen from values of $\theta$ in Tab. 3 that the curvature of waterjet surface striation within the rough zone is higher for the lower water pressure.

5.2 Influence of abrasive mass flow rate

Now the results for two selected values of the abrasive flow rate (for constant values $p_a = 200$ MPa, $v_a = 70$ mm/min) will be compared. For further explanation the presentation of digital maps of the studied surfaces and images of their APSD, normalized RPSD and normalized AnPSD will be omitted. The half-width of the normalized RPSD peaks and the angular coordinate $\theta$ of the normalized AnPSD maxima of surfaces under study will be determined likewise in the case of the water pressure variation. It can be seen from Tab. 4 that the half-width of the normalized RPSD peak does not change significantly with the variation of the abrasive flow rate within the smooth and rough zone.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Half-width of the peak, 1/m</td>
<td>293.4</td>
<td>289.4</td>
</tr>
<tr>
<td>Relative difference, %</td>
<td>1.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

It is observed within the rough zone that the coordinate $\theta$ of the normalized AnPSD maximum is lower for the higher abrasive flow rate. It means that the curvature of the surface striation is higher within the rough zone at the lower abrasive flow rate.

<table>
<thead>
<tr>
<th>Zones</th>
<th>Smooth</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Coordinate $\theta$ of the maximum, °</td>
<td>48.0</td>
<td>48.0</td>
</tr>
<tr>
<td>Relative difference, %</td>
<td>0.0</td>
<td>27.0</td>
</tr>
</tbody>
</table>

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<th>Rough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate $\theta$ of the maximum, °</td>
<td>40.8</td>
<td>35.5</td>
</tr>
</tbody>
</table>
5.3 Influence of abrasive mass flow rate

Here the results for two selected values of the AWJ traverse speed (for constant values $p = 200$ MPa, $m_i = 500$ g/min) will be compared. The values of the half-width of the normalized RPSD peak are almost the same within the smooth zone in this case (Tab. 6). The significant difference between the half-width of the peak occurs within the rough zone case. The half-width of the normalized RPSD peak is wider at the lower traverse speed of the cutting head.

<table>
<thead>
<tr>
<th>Zones</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$v$ (mm/min)</td>
<td>70</td>
<td>120</td>
</tr>
<tr>
<td>Half-width of the peak, 1/m</td>
<td>287,5</td>
<td>289,2</td>
</tr>
<tr>
<td>Relative difference, %</td>
<td>0,6</td>
<td>49,0</td>
</tr>
</tbody>
</table>

As evidenced by Tab. 7, the angular position of the normalized AnPSD maximum is the same for both values of the traverse speed selected within the smooth zone. Within the rough zone the coordinate $\theta$ of the normalized AnPSD maximum is higher when the higher AWJ head velocity is utilized. It means that the curvature of the surface striation within the rough zone is greater at the higher traverse speed of the cutting head.

<table>
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</thead>
<tbody>
<tr>
<td>$v$ (mm/min)</td>
<td>70</td>
<td>120</td>
</tr>
<tr>
<td>Coordinate $\theta$ of the maximum, °</td>
<td>48,0</td>
<td>48,3</td>
</tr>
<tr>
<td>Relative difference, %</td>
<td>0,6</td>
<td>53,3</td>
</tr>
</tbody>
</table>
The angular coordinate of the maximum of the normalized AnPSD decreases very significantly with the increase of the water pressure at the input of the AWJ cutting head. Greater curvature of the surface striation within the rough zone is obtained by using lower water pressure. This result indicates that the higher the water pressure, the more easily the water jet cuts the samples. This conclusion must be proved by a more detailed research with an even higher number of samples.

The angular coordinate of the maximum of the normalized AnPSD significantly increases with the increase of the abrasive flow rate. Alike in the previous case the curvature of the surface striation within the rough zone is greater by using the lower abrasive flow rate. It could be interpreted in the way that the water jet loses its kinetic energy markedly within the upper part of the cutting wall at the higher traverse speed of the cutting head.

The angular coordinate of the maximum of the normalized AnPSD significantly increases with the increase of the traverse speed of the AWJ cutting head. The angular coordinate of the maximum of the normalized AnPSD increases with the increase of the traverse speed of the AWJ cutting head. It is possible to conclude that the spectral analysis of surfaces generated by AWJ can provide the results useful for the surface topography characterization. The main advantage of this technique with respect to topography parameters usually utilized in that case consists in a different view of the surface topography characterization. Particularly it allows quantitative evaluating directions of surface irregularities orientation within individual zones of the surfaces.

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