ISSN 1330-3651
UDC/UDK 621.7.044.4 : 519.67-7

ANALYSIS OF SIGNALS OBTAINED FROM SURFACES CREATED BY ABRASIVE WATERJET BY MEANS OF AMPLITUDE-FREQUENCY SPECTRA AND AUTOCORRELATION FUNCTION

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Preliminary notes

The paper deals with the description of contemporary methodology of topography evaluation of surfaces created by the abrasive water jet by using the existing standard and non-standard parameters in combination with an autocorrelation function. The grid projection method was used for measurement of samples prepared from stainless steel AISI 309 by abrasive water jet. The optical signals obtained by means of grid projection method of these surfaces were processed by Fourier transform and the norm autocorrelation function in order to get information about height and longitudinal fluctuations. The obtained results are analysed and interpreted.

Keywords: *abrasive waterjet, autocorrelation function, grid projection method*

Analiza signala dobivenih s površina koje su nastale abrazivnim vodenim mlazom pomoću spektra amplituda-frekvencija i funkcije autokorelacije

Prethodno priopćenje

U ovom radu je opisana suvremena metodologija topografske evaluacije površina, koje su nastale abrazivnim vodenim mlazom, korištenjem standardnih i ne-standardnih parametara u kombinaciji s funkcijom autokorelacije. Metoda projekcije mreže je korištena za mjerenje uzoraka pripremljenih od nehrđajućeg čelika AISI 309 pomoću abrazivnog vodenog mlaza. Optički signali dobiveni pomoću metode projekcije mreže ovih površina su obrađeni pomoću Fourier pretvorbe i funkcije autokorelacije norme kako bi se dobile informacije o fluktuacijama visine i duljine. Dobiveni rezultati su analizirani i objašnjeni.

Ključne riječi: *abrazivni vodeni mlaz, funkcija autokorelacije, metoda projekcije mreže*

1 Introduction
Uvod

Any technological method used for the generation of surfaces in technical fields leaves irregularities, which have a fundamental importance for the function of these surfaces. In the cutting plane a new profile is created which provides a fundamental source of information for judgements of surface topography 1, 2. The method of objective evaluation as one of the most important components of surface structure roughness has a long history. At first a sinusoidal model of irregularities was used, when quantity H_{SK} (analogy of the effective value of alternating current) was used as a parameter for evaluation. Later, a parameter R_a (analogy of the mean value of alternating current) was preferred together with some further parameters. In connection with a new conception of a geometrical specification of production (GPS-geometrical product specifications) some more sophisticated systems for the assessment and evaluation of surface topography were created. This is the system which is regulated in the engineering manufacturing by currently valid standards, which do not include specification of metrology surface created by abrasive waterjet technology (AWJ).

2 Related and previous works
Radovi sa istom problematikom

The irregularities on the surface represent a three-dimensional formation which can be solved by reduction into the plane of cut through a plane vertical to the surface (Fig. 1). The surface topography is divided into components according to the pitch of overall irregularities. There are three components in the surface topography: a component with the smallest pitch creating roughness of surface, a component called waviness of surface and a component with the biggest pitch of irregularities, called the basic profile.

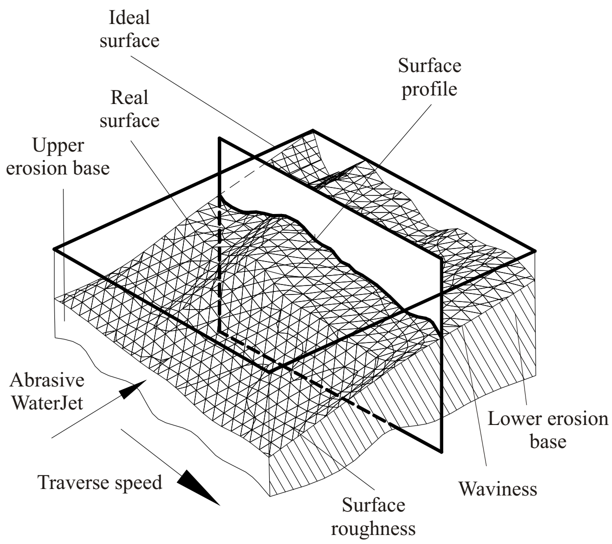

Fig. 1. The profile of surface irregularities
Slika 1. Profil hrapavosti

The surfaces created by AWJ are especially quasi-periodic. The surface and the signals obtained we classify among deterministic signals. Because every surface created by AWJ shows specific type of determinism. However, at the beginning the cut shows stochastic character owing to abrasive elements, which have an impact on a stochastic surface by big part. As we have already mentioned that AWJ surface is quasi-periodic from technical point of view oscillating, discontinuous signals in time (digital signal), then consisting of several sum of series of sines and cosines. We use fast Fourier transform (FFT) to analyse the obtained signals. This contains in its base sines and cosines, and therefore with advantage utilizes those actualities. From the principal point of view we require continuous signals but from the real point of view it is not like this, therefore we try to decrease sampling and so approximate to a connected signal.

A proposal for the technical use of specific properties of autocorrelation has been carried by Peklenik already in the years 1967-68 [3] and next it was applied by Whitehouse [4], Guo [5]. There are typical shapes of autocorrelation coefficients for depth of cut z = 5 mm, 15 mm, 20 mm, 25 mm describing basic types of irregularities on the roughness, slotting, grooving and waviness levels described in this study [5]. The author of this publication does not consider the conversion method for quantifying the parameter *Ra* or the wavelength of irregularities ; therefore the classification methods according to [5] and [6] have the character of a qualitative evaluation without the possibility of more technical use for standardization of quality or automation of its control or for a quantitative method for the decomposition of surface topography into its stochastic and periodic components. To achieve better characterisation it is possible to continue the work of the author [1], which describes the autocorrelation function as follows:

$$r_{yy}(x) \approx Ra^2 \cdot \left(C_{\gamma n}^2 \cdot \gamma_n \cdot e^{-\alpha_p^2 \cdot x^2} + C_{\beta p}^2 \cdot \beta_p \cdot \cos \frac{2\pi}{\lambda_{\beta p}} \cdot x \right), (1)$$

which means that the autocorrelation function represents the sum wave of two correlation functions which do not converge to zero. In an equation this means:

C_γ - coefficient dependent on the amplitude distribution of the stochastic component of the surface profile,

$C_{\beta p}$ - coefficient dependent on the shape of the periodic distribution of surface irregularities,

γ_n - coefficient of randomness of the surface profile,

β_p - coefficient of surface regularity,

α_p - coefficient decline of the correlation function,

$\lambda_{\beta p}$ - the length of the correlation wave, the pitch of periodical irregularities.

By applying this form of the autocorrelation function it is possible to calculate the arithmetic mean deviation of the assessed profile *Ra* and using applications with the evaluated coefficients in tables even its stochastic component *Ra* and the periodic component *Ra*, the length of the correlation wave and its components (stochastic and periodic). In this work we use Gauss distribution of height irregularities. This distribution is the most used one in relation to technically realized surface. It is confirmed by criterion of central limit theorem, which affirms that if the stochastic variable is sum of many independent stochastic variables (with arbitrary distribution), then this variable has Gauss distribution. We exploit similar presumption of valid ergodic hypotheses; therefore we do not need to carry out *n* realization, only to obtain one profile from single realization, which contains *n* realization within. The stochastic process is taken as ergodic, if every statistical characteristic obtained as mean value of the whole set, can be determined as mean value from the realization of relevant length. The condition of ergodicity is, that autocorrelation function r_{yy} decreases to zero for $\Delta x \to \infty$. The ergodicity and stationarity are two different properties of stochastic process. Every ergodic process is stationary; however stationary process does not have to be ergodic. The ergodic stationary processes are useful because there is no need to study big set of realization, but only to observe one realization during the long definition interval. This property of some stochastic processes, similarly to stacionarity, considerably facilitates solution within statistic analyses and metrology.

According to results obtained from measurement by shadow method and contact profilometer HOMMEL TESTER T8000 [7], [8] is this ratio at intervals 1.18-1.22 optical rated funds and at average 1.2 about etalon values from contact profilometer on identical samples.

From the viewpoint of topography the same objection as for the above mentioned parameter *Ra* is analogically valid for parameter *Rq*. The root mean square deviation of profile *Rq* acquires significance, however, if the profilometry of the surface is carried out optically. It is assigned by the fact that the majority of optical signals are based on detection of intensity, which is a quadratic value of its amplitude. Nevertheless, there is much more information about parameter *Ra* in the technical literature and, furthermore, this parameter yields a more definite image of the real heights of irregularities, so our own correlation process is focused on finding out the relationships between the optically acquired signal and parameter *Ra*, above all also because the parameter *Ra* is a value directly specified by the contact profilometer and so it still remains the main standard for all optical measurements.

The autocorrelation function gives us an idea of the periodicity; or rather the casualness of the profile and it is defined by the relationship:

$$R_{yy}(\Delta x) = \frac{1}{N - \Delta x} \cdot \sum_{i=1}^{\frac{N-\Delta x}{\delta x}} \left[y(x_i) - m_y \right] \cdot \left[y(x_i - \Delta x) - m_y \right], \quad (2)$$

where

δx - step of sampling, mm

Δx - distance, mm.

The principle of autocorrelation function is illustrated in Fig. 2. Obtained profile can be fed against the second one by distance Δx so as idea about periodic or stochastic profile can be obtained. Concerning periodic and stochastic profile according to [1], which λ_o is $r_{yy}(x) \leq 0,05$, there is no correlation profile surface. Correlative longitude λ_o defines then elements profile surface and at practical analysis it is evaluated numerically. The relation (2) is written in a discreet form. For continuous function (x) representative topographic function surface pass $\xi(x)=[y(x_i)-m_y]$. In experimental parts derive we benefit from relation (2) divided with dispersion $D_y = \sigma^2$ that is obtained from conditions $\Delta x = 0$. The decrease r_{yy} according to (3) on 1/e we obtain autocorrelation length λ_o, which is a parameter of topography surface related to lateral three - dimensional frequencies existing incidentally at any place on surface of the sample, then related with lateral three - dimensional

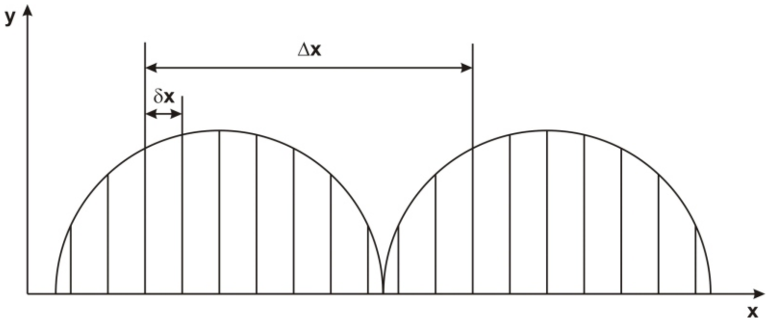

Fig. 2. The principle of autocorrelation function
Slika 2. Princip funkcije autokorelacije

pitch *Sm* of height amplitudes. In such a way we obtain information about pitch or lateral three - dimensional frequencies from obtained spectra. Reciprocal value $1/f$ is wavelength λ_a = f (λ_o, *Sm*). Mutual relationship between lateral three - dimensional frequencies and height fluctuation is very complicated and it depends on character of surface. For surface cut by AWJ very important are spectra of lateral three - dimensional frequencies in level of surface.

The value $R_{yy}(0)$ represents the dispersion $R_{yy}(0)= D_y$. For the evaluation of the proper profile curve of the surface itself, the so-called standard autocorrelation function is used:

$$r_{yy}(x) = \frac{R_{yy}(x)}{D_y} \; . \tag{3}$$

3 Experimental conditions and measurement procedure
Eksperimentalni uvjeti i postupak mjerenja

Test samples of size 20 x 20 x 8 mm (Fig. 3) were prepared at laboratory of the Institute of Physics in Ostrava, from 8 mm thick plates of steel material AISI 309 by the AWJ under the following factor conditions: pressure: p = 300 MPa, jet diameter: d_o = 0,25 mm, focusing tube diameter: d_f = 0,8 mm, focusing tube length: l_f = 76 mm, abrasive mass flow: m_a = 250 g/min, abrasive grain size: 80 MESH, nozzle-surface distance: z = 2 mm. The stainless steel AISI 309 has been chosen as a target material because: material is very attractive, because of its resistance to corrosion; it can provide significant value creation for the end user when considering all of the important attributes and how they help to bring reliability, performance, and safety to industry and the consumer.

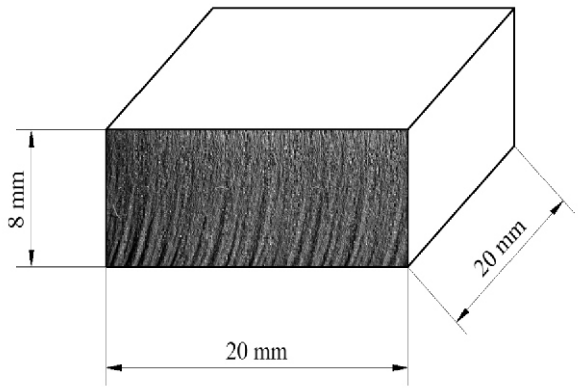

Fig. 3. Topography of surface created under AWJ factor conditions traverse speed v = 200 mm/min, *material AISI 309*
Slika 3. Topografija površine koja je nastala abrazivnim vodenim mlazom AWJ prosječne brzine v = 200 mm/min, *materijal AISI 309*

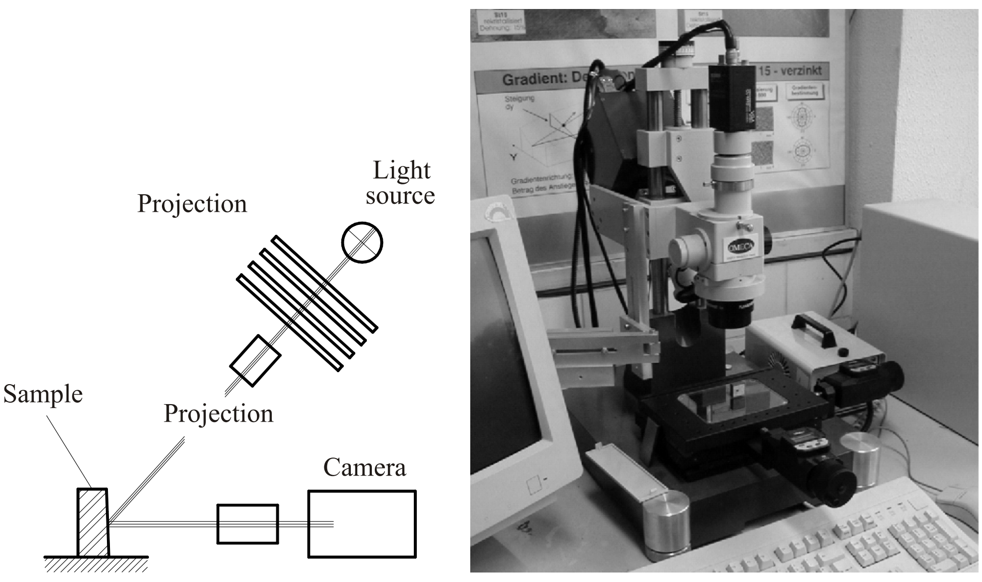

Fig. 4. The principle scheme of the grid projection method and overall view of the device in Wasserstrahl Labor laboratory in Hannover.
Slika 4. Osnovna shema metode za projekciju mreže i prikaz uređaja u laboratoriju u Hannoveru (Wasserstrahl Labor)

Measurements have been provided in laboratory in Hannover (Wasserstrahl Labor) (Fig. 4). To measure the profile geometry of the AWJ-produced surface, the grid projection method was used [9]. The AWJ cutting surface diffusely reflects light with a specific scattering diagram. The projection grid method of projection grid allows us to define a relative elevated position of individual points in the measured field from that one of the image setting of the camera. The principle of the grid projection method is so that if the investigated surface is of a uniformly height built (i. e. the construction planes have regularly spaced distances), then the horizontal or inclined plane projects onto parallel lines, which are colour-distinguished. The unevenness of the surface with a line grid projection creates irregularities of the grid image projected by optics. The detected height 3D-information is transferred into an image of colour picture, which appears on the monitor of the computer. The colour imagination of the 3-D image can be interlaced with by arbitrary profiling cuts for other geometrical analyses or separated into a 2-D profile. The program FRINGE program covers three measuring principles of the treatment of 3-D elevated images, namely the method based on the projection grid, the method of shift in phase and the method of grey code.

4
Analysis of the signals obtained by the grid projection method
Analiza signala dobivenih pomoću metode za projekciju mreže

To specify better and to determine the stochastic and periodic components, in practice the autocorrelation function of the whole topographical profile has been used for the analysis of signals (Fig. 5).

The classification of surface parameters through two components (the stochastic and the periodic ones) is proposed in [6]. The authors [3], [5], [6] are motivated to draw this conclusion by the fact that the short-wave irregularities, especially roughness, is caused by the stochastic character of the disintegration induced by particular abrasive particles of the AWJ. The evaluation of the autocorrelation function provides the tool for mathematical manipulation with the topographic function of the geometrical form of the surface and enables us to find the so-called autocorrelation length and autocorrelation coefficient (Fig. 6).

The results have convinced us that it is possible to detect and quantitatively determine both the stochastic as well as the periodic character of surface topography and thus to quantify the statistics of the height fluctuations.

We can see major differences in the course of autocorrelation functions evaluated from the measured data in the zone A, B, C on the surface created by AWJ. By mutual comparison of the autocorrelation functions of the

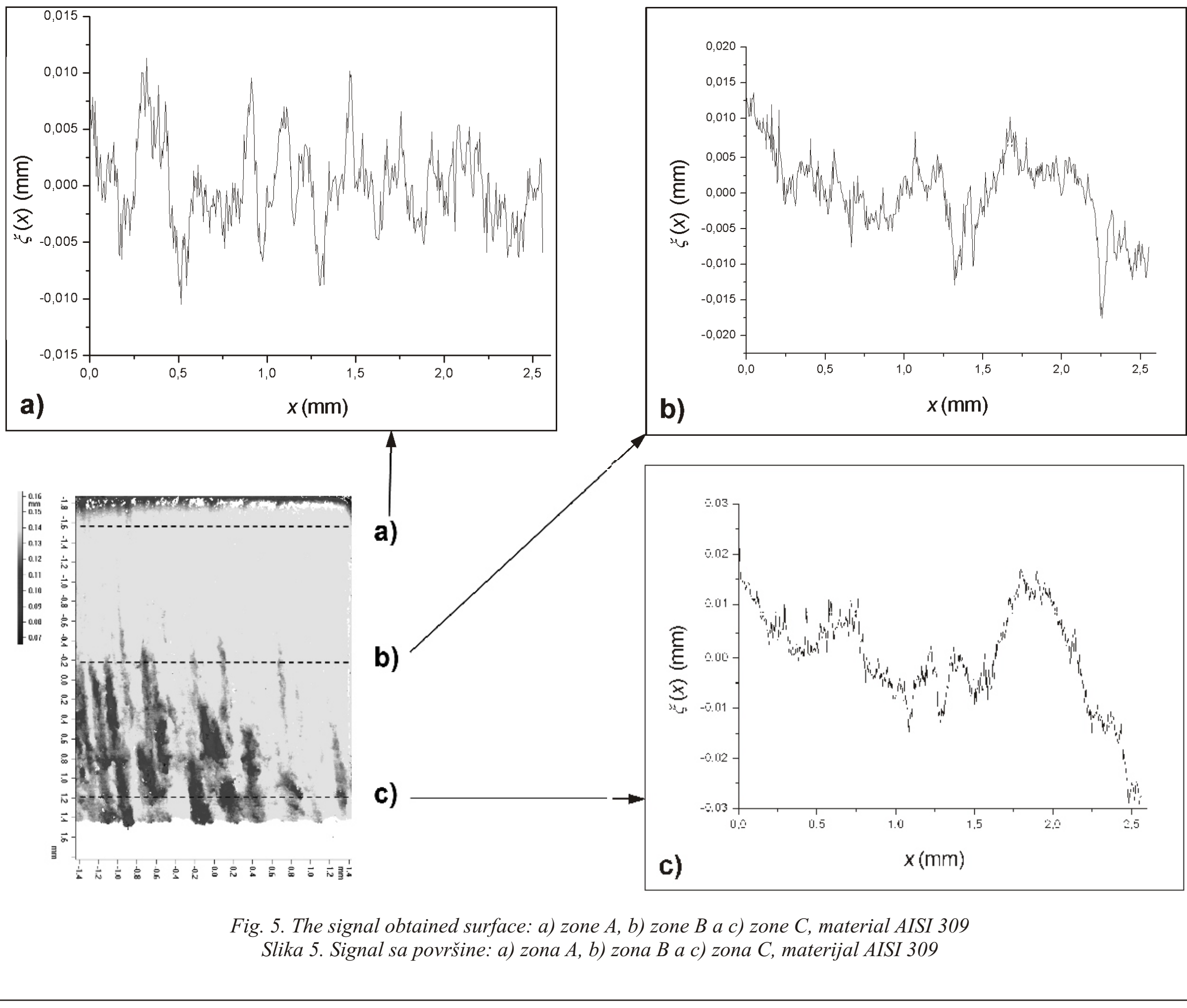

Fig. 5. The signal obtained surface: a) zone A, b) zone B a c) zone C, material AISI 309
Slika 5. Signal sa površine: a) zona A, b) zona B a c) zona C, materijal AISI 309

surface created by AWJ it can be said that the tendency of the autocorrelation functions is getting near to the rough part from the zone A to the zone C. We can see more expressive effect of abrasive particles in Fig. 6 in comparison with the zone C, where in the area to the 2,5 1/mm expressive peak of height amplitude representative highs dominate periodically with recurrent waves, on which with bounds high-frequency component topography of surface, whereas transitional quasi-periodic component is in the zone C already considerably in suppression. The experimental results obtained show that the surface correlation length increases along a trace of the AWJ. The correlation length represents the horizontal property of a surface profile. The stochastic component in the upper part of the cut is much bigger than in the lower part because in those parts they have big effect abrasive element, that have direction to the major depths loses of its force (they are broken down by stream of water and crunches from surrounding walling). The analysis of the autocorrelation function gives information about the autocorrelation length as a function of pitches of surface irregularities (it corresponds to the wavelength of surface topography irregularities).

In Fig. 7 there are represented the types of obtained signals and shapes of standard autocorrelation function which further accommodate with qualitative also quantitative confrontation resulting of values measured by shadow method on samples cut technology by AWJ. Profile of roughness is demonstrated by high frequencies and low amplitude irregularities of surface. In Fig. 7a we can see that there is superposed roughness of the surface.

It demonstrates that the general profile of heights' irregularities of the surface is binary and that total amplitude heights' irregularities A_{cel} is then a sum of partial components of related sinuation A_w and partial components of related roughness A_r.

$$A_{cel} = A_w + A_r \,. \tag{4}$$

Both these components can to be distinguished only by a wavelength λ and three-dimensional frequency *f*. As the views of a quantified definition of parameters λ and *f* have not been yet matched, we therefore suggested the use of working division according to tab. 1, where according to a character signal we define I - waviness, II - grooving-slotting and III - roughness. Similar classification was performed by Guo [5].

Tab. 1. The area of spatial frequency and wavelength divided into spectra Fig. 7.
Tab. 1. Područje prostorne frekvencije i valne duljine podijeljeno u spektre (slika 7.)

Order	f, mm^{-1}	λ, mm
I	$f \le 2{,}5$	$\lambda \ge 0{,}4$
II	$2{,}5 < f \le 20$	$0{,}4 > \lambda \ge 0{,}05$
III	$f > 20$	$\lambda < 0.05$

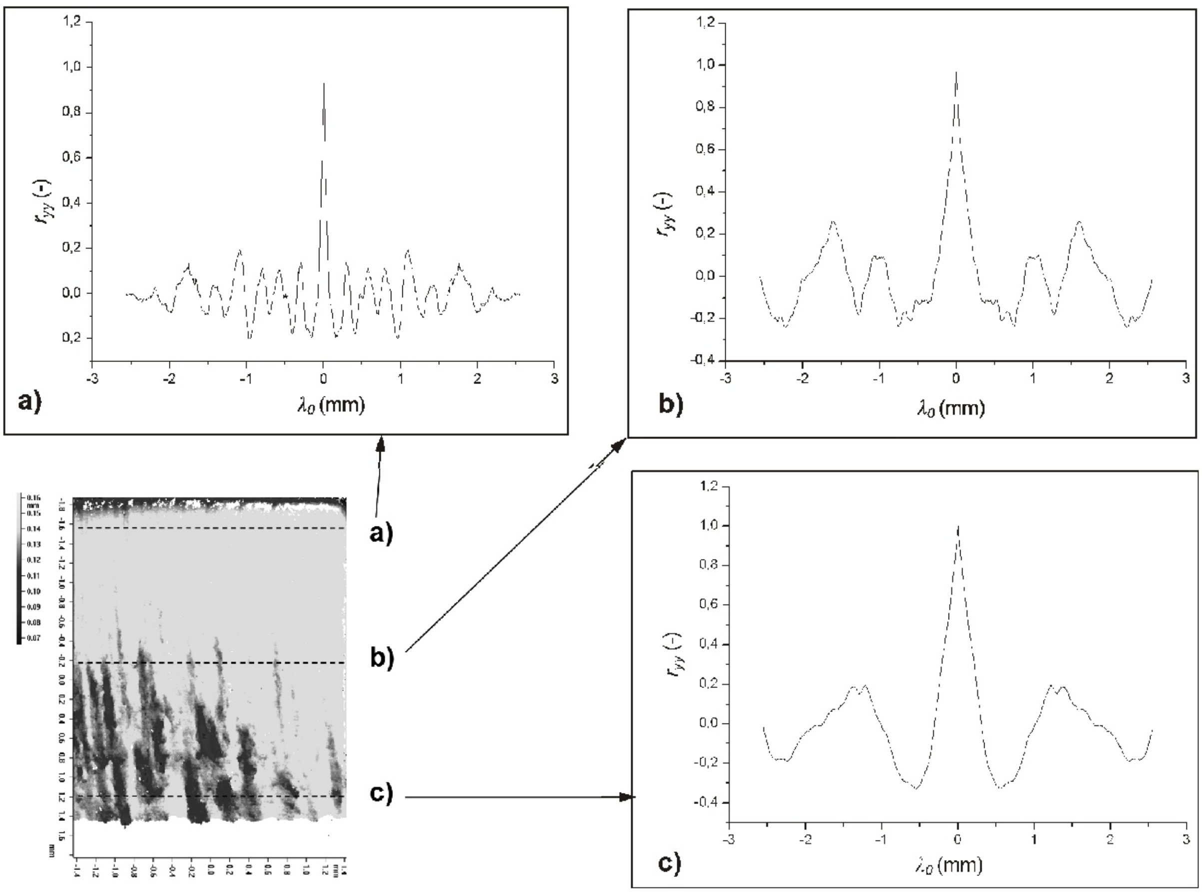

Fig. 6. The standard autocorrelation function: a) zone A, b) zone B a c) zone C, material AISI 309
Slika 6. Standardna funkcija autokorelacije: a) zona A, b) zona B a c) zona C, materijal AISI 309

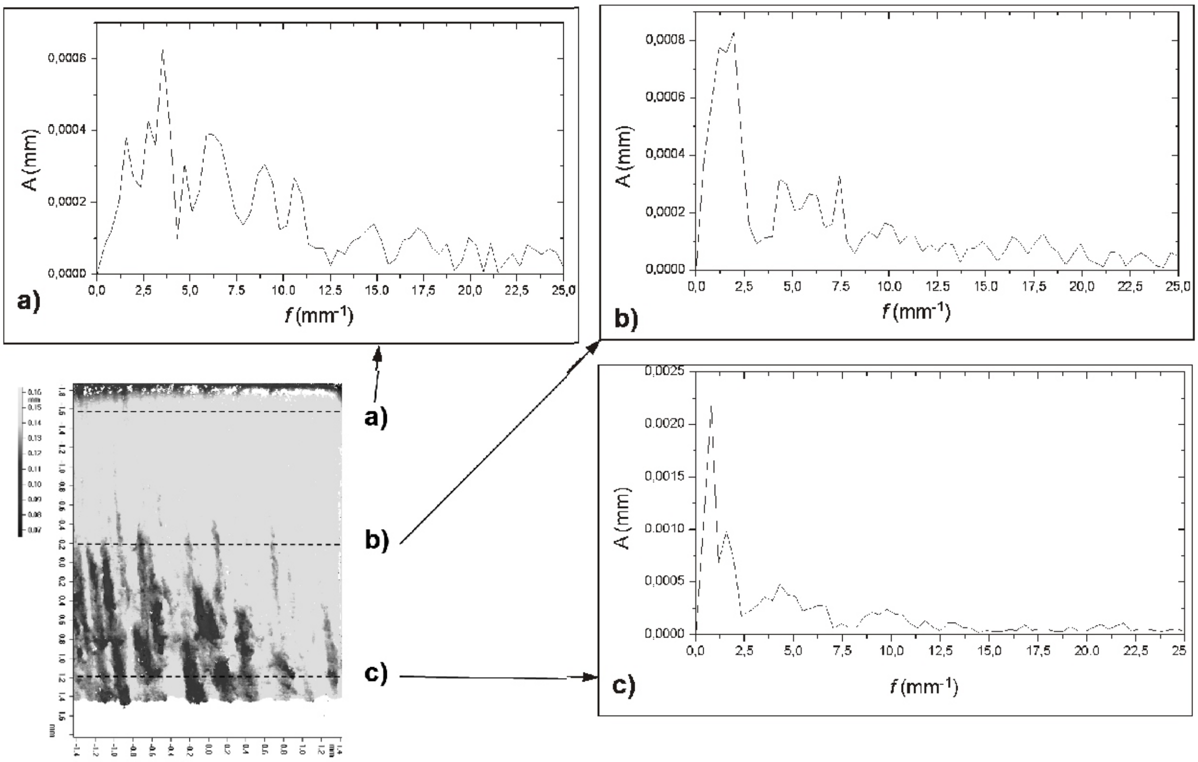

Fig. 7. The amplitude-frequency spectrum of signal: a) zone A, b) zone B a c) zone C, material AISI 309.
Slika 7. Spektar amplituda-frekvencija (za signal): a) zone A, b) zona B a c) zona C, materijal AISI 309.

For profile roughness of surface amplitude-frequency characteristic is mentioned here (see Fig. 7b), where we can see that the basic profile of surface is identical with axis A, waviness detects in the area high three-dimensional frequency and surface roughness detects in the area high three-dimensional frequency. However this is only a model situation, real surfaces have far more complicated amplitude- frequency spectrum. Therefore when evaluating surface there is often provided an amplitude-frequency decomposition on individual spectral levels (see Fig. 8) and submission measuring lines to the specific spectral zones (see Fig. 8). The analyses of AWJ parameters prove that hydraulic parameters (pressure p, diameter of the nozzle outlet d_o) and abrasive parameters (kind of abrasive material, amount of abrasive particles a_o, mass flow rate m_a) have the greatest influence on the process of cutting materials and its effectiveness. Among the mixing parameters, the average d_a and length l_a of the focusing tube have the greatest influence and among the group of cutting parameters for the process of AWJ cutting the traverse speed v has the ultimate influence.

For comparative analysis it is necessary to observe uniform preparation test samples and uniform composition technological parameters changes. Especially at the time, when we have geometric parameters measured with surface derive we can benefit from the study of mechanism hydroabrasive disintegration, or to study influence of mechanical parameters of material on a dividing process and on a surface quality of dividing walls.

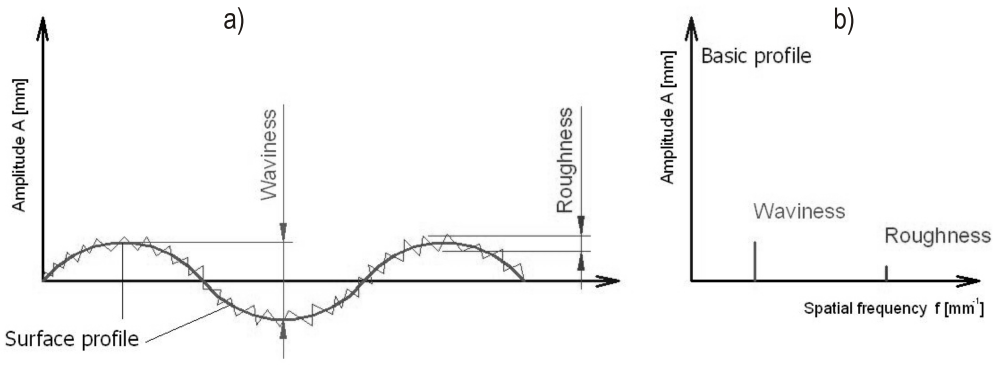

Fig. 8. a) The height fluctuation of surface profile and b) their amplitude-frequency spectra
Slika 8. a) Fluktuacija visine profila površine i b) njihov spektar amplituda-frekvencija

5 Conclusion
Zaključak

In the paper an evaluation of the surfaces created by AWJ is presented as well as interpretation of the obtained results by means of grid projection method. Based on the analysis of amplitude-frequency spectra and standardized autocorrelation functions we have composed tab. 1, which divides the surfaces AWJ and gives first notions, what frequencies we can expect in zone I, II and III according to tab. 1. It is then necessary to approach a more complex classification of AWJ surfaces and height amplitude of irregularities and properly complete with longitudinal, or frequency topographic characteristics, namely e.g. submitted in this way. With more complex evaluation a total surface quality from the point of the view of their prospective functionality and service life in constructions is objectively assessed. Due to an insufficient level of knowledge of physical processes and a mechanism of disintegration of tools such as AWJ there have been many questions raised in theory as well as practice.

In the respective references we can still find lots of disagreements and different solution attitudes. It is considered as a very interesting physical mechanical process, which is complicated due to a character of applied destructive forces and tensile-deformation states. The incidence of interaction forces and their developed tensile and deformation states in final consequence express and display on micro and macrogeometry of dividing wall surface and on a shape of topographic surface function. Generalization of closes requires a range of other comparison measurements by applying of new interpretative elements, as well as new analytical approaches. Wide, intensive and high quality cooperation among particular specialists and special workplaces from theory and practice requires nowadays an elaboration of consistent and standard nomenclature specialized on surface metrology generated by the hydroabrasive jet.

Acknowledgements
Zahvala

The contribution was written thanks to support provided by the IGS-HGF VŠB TUO-2007-2101/516 grant project and the VEGA 1/1075/04, 1/4157/07 and the project MŠMT No. MSM6198910016.

References
Literatura

[1] Bumbálek, B., Odvody, V., Ošťádal, B. Surface roughness. Praha, SNTL 1989. (in Czech)
[2] ISO 4287:1997 Geometrical product specifications (GPS) Surface texture: Profile method Terms, definitions and surface texture parameters.
[3] Peklenik, J. New Development in Surface Characterisation and Measurement by Means of Random. Process Analysis. Proceedings of Mechanical Engineering. Vol. 182, 1967.
[4] Whitehouse, D. Handbook of Surface Metrology. Rank Taylor Hobson Ltd., England, 1994.
[5] Guo, N., S., Schneidprozess und Schnittqualität beim Wasserabrasiusstrahl schneiden, VDI Verlag, 1994, pp. 1-174.
[6] Capelo, E., Monno, M., Semeraro, Q. On the characterisation of surfaces obtained by abrasive water jet machining. In: Proc. 12th Int. Conf. Jet Cutting Technology, ed. N. G. Allen, Mechanical Engineering Publishing, Ltd., London, 1994.
[7] Valíček, J. et al. Experimental analysis of irregularities of metallic surfaces generated by abrasive waterjet. In: International Journal of Machine Tools and Manufacture. vol. 47, no. 11 (2007), pp. 1786-1790.
[8] Valíček, J. et al. An investigation of surfaces generated by abrasive waterjet using optical detection. In. Strojniški vestnik - Journal of Mechanical Engineering. 0039-2480: 53, 2007. pp. 224 - 323. ISSN 0039-2480.
[9] Valíček, J. Characterisation and qualification of cutting edges in the field of water jet cutting. Wassertrahl Labor Hannover, Hannover, 2003 (Report)

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