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EVALUATION OF ABRASIVE WATERJET PRODUCED TITAN SURFACES TOPOGRAPHY BY SPECTRAL ANALYSIS TECHNIQUES

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Experimental study of a titan grade 2 surface topography prepared by abrasive waterjet cutting is performed using methods of the spectral analysis. Topographic data are acquired by means of the optical profilometr MicroProf®FRT. Estimation of the areal power spectral density of the studied surface is carried out using the periodogram method combined with the Welch´s method. Attention is paid to a structure of the areal power spectral density, which is characterized by means of the angular power spectral density. This structure of the areal spectral density is linked to the fine texture of the surface studied.

Key words: Abrasive waterjet cutting, Surface topography, Spectral analysis

Analiza topografije površina titanove legure nakon rezanja vodenim mlazom pomoću spektralne analize. Eksperimentalna studija površine titana klase 2 dobivene abrazivnim rezanjem vodenim mlazom je provedena korištenjem metode spektralne analize. Topografski su podaci prikupljeni pomoću optičkog profilometra MicroProf®FRT. Procjena površinske snage spektralne gustoće je provedena periodogram metodom u kombinaciji sa Welch metodom. Pozornost je posvećena površinskoj snazi spektralne gustoće koja je karakterizirana pomoću kutnih spektara gustoće snage. Struktura površinskog spektra gustoće je povezana sa istraživanom finom teksturom površine.

Ključne riječi: Rezanje abrazivnim vodenim mlazom, površinska topografija, spektralna analiza

INTRODUCTION

Over the last decades, research and engineering practice have been characterized by the development of non-traditional methods of material machining. Various machining technologies of high-speed cutting by using of liquid jets can be included in this category. Whereas, the technology of high-speed jet machining itself is well defined, the studies of abrasive waterjet (AWJ) quality parameters in the depth of produced cuts are still desirable. The attempt to define the depth of zone where the AWJ - produced surface is yet satisfactory for usual machinery practice has been done e.g. by Hashish [1,2]. Guo suggested the classification of cutting zones by means of the surface roughness spectral analysis and the same problem has been solved also by a wavelet-based topography analysis [3,4]. Surface irregularities in the form of striation were studied in [5–7], where also the quantitative surface roughness data were presented. The most widespread tool used in practice for a surface roughness measurement is a stylus profilometer. Its main drawbacks are an ability of only 2-D assessment of a surface topography and a contact with the surface, which can cause a destruction of certain surfaces and misinterpretation of data measured. Aforementioned drawbacks of the 2-D assessment of a surfaces quality lead to needs of a new generation of instruments enabling a non-contact 3-D assessment of a surface quality (it is along a selected area of the surface). Such an instrument is the optical profilometer MicroProf ® FRT (Fries Research & Technology GmbH).

We shall focus our attention to the spectral analysis of surface 3D topographic data obtained by means of the optical profilometer MicroProf ® FRT from titan surfaces generated by abrasive waterjet.

AREAL POWER SPECTRAL DENSITY OF A RANDOM FUNCTION

It is interesting to apply spectral analysis of a surface topography to surfaces generated by AWJ cutting. These surfaces are of a random character. It is possible to select individual zones of the surface in which the surface function can be considered as a stationary (i.e. there is not any change of the surface character within the whole individual zone) and ergodic (i.e. we can evaluate features of the whole surface topography within the individual zone from an individual sufficiently large realization of the surface within the zone) 2D random function. We shall confine our attention only to the so called transition zone. The reason is that the surface quality within this zone is changing from sufficient to deficient from the viewpoint of engineering production

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requirements. Considering the surface under study as a random function we have to describe the surface by means of mean quantities derived from amplitude Fourier spectra of its realizations or, as usually, from squares of these spectra in the frequency domain (so called energy or power spectra of the surface realizations). We shall describe 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*, where *z* is the height of the surface with respect to the plane *x, y* in the point [*x, y*]. Hence, the function $z=z\,(x, y)$ is the realization of a stationary and ergodic random function $z_r \equiv \{z(x, y)\}$ selected by a process of a measurement. The function $z=z\,(x, y)$ is defined along the whole plane *x, y*. But we acquire information on the function $z=z\,(x, y)$ only from a finite region *X, Y* of the plane *x, y* by the measurement. So we deal with the function $z_{X,Y}=z_{X,Y}(x, y)$defined as follows:

$$\begin{aligned} &z_{X,Y}(x,y)=z(x,y) \quad \mathit{for} \quad |x|\le X \wedge |y|\le Y \\ &z_{X,Y}(x,y)=0 \quad \mathit{otherwise} \end{aligned} \tag{1}$$

This function has the Fourier integral

$$Z_{X,Y}(f_x, f_y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} z_{X,Y}(x,y)\exp[-i2\pi(f_x\,x+f_y\,y)]dx\,dy \tag{2}$$

Then it is possible to define the areal power spectral density (APSD) of the function $z=z\,(x, y)$ as follows

$$P(f_x, f_y)=\lim_{\substack{X\to\infty\\ Y\to\infty}}\left[\frac{|Z_{X,Y}|^2}{XY}\right] \tag{3}$$

APSD of the whole random function z_r is defined as:

$$P_{zr}(f_x, f_y)=\lim_{\substack{X\to\infty\\ Y\to\infty}}\left[\frac{\left\langle |Z_{X,Y}|^2\right\rangle}{XY}\right] \tag{4}$$

where the symbol 〈 〉 denotes the mean of the surface realizations population. The quantity $P_{zr}(f_x, f_y)$ indicates in what way the mean power of the studied surface is distributed within the frequency domain. We shall use it for the characterization of surfaces generated by AWJ. The characterization of the surface topography within the transition zone along an individual surface profile can be also performed by means of amplitude – frequency analysis (2D surface evaluation) [8-10]. More advanced approach is the surface topography characterization by means of the discrete fast Fourier transform (DFFT) [11-13] of 2D data (maps of surface heights) within the zone. According to our best knowledge the application of the areal data spectral analysis has not been used for a topography characterization of surfaces generated by the AWJ cutting yet.

ANGULAR POWER SPECTRAL DENSITY

It is possible to characterize the shape of APSD by means of the angular power spectral density (AnPSD) of the function [11]. To define this quantity it is necessary to transform APSD (see Equation 4) into polar coordinates within the frequency domain.

$$P_{zr}(f_x, f_y)\to P_{zr}(f_r, \theta),$$

where

$$f_x=f_r\cos(\theta),\quad f_y=f_r\sin(\theta),\quad f_r=\sqrt{f_x^{\,2}+f_y^{\,2}},\quad \theta=\mathrm{arctg}\left(\frac{f_y}{f_x}\right)$$

Then AnPSD is defined as follows [11]:

$$P_\theta(\theta)=\int_0^{f_{r\max}(\theta)} P(f_r,\theta)\,df_r, \tag{5}$$

where $0 \le \theta \prec \pi$ and $f_{r\max}$ (θ) is a maximum spatial frequency contained in the section of APSD given by the angle θ. We can describe a distribution of the power of the studied random function along individual directions within the frequency plane by this quantity.

PERIODOGRAM ANGULAR POWER SPECTRAL DENSITY ESTIMATION

We cannot analyze infinite number of possible realizations of the infinite function z_r. It leads to the fact that our result must be only the estimation of APSD from Equation (4) as

$$\left\langle |Z_{X,Y,q}|^2\right\rangle \cong \frac{1}{Q}\sum_{q=1}^{Q}|Z_{X,Y,q}|^2 \tag{6}$$

where Q is the number of realizations available. Hence, we can approximately express Equation (4) as follows:

$$P_{zr}\left(\frac{k}{M\Delta x},\frac{l}{N\Delta y}\right)\cong\frac{1}{Q}\sum_{q=1}^{Q}\left[\left|\frac{Z_{X,Y,q}\;\frac{k}{M\Delta x},\frac{l}{N\Delta y}}{MN\Delta x\Delta y}\right|^2\right], \tag{7}$$

where $0 \le k \le M-1$; $0 \le l \le M-1$.

Using the relation (7) we employ so called periodogram method of the determination of the ASPD estimation of the random function z_r.

WELCH'S METHOD

Calculation of the right side of Equation (7) can be carried out in several ways. We selected the Welch's method. Within the framework of this method we resolve the measured domain of the given realization into a sufficient number of mutually overlapping sub-domains $Z_{X',Y}\,(x_{m'}, y_m)$. Then we carry out weighting the surface function in each sub-domain by a chosen weighting function $w(x_{m'}, y_m)$. Thereafter we determine the following expression for each the weighted sub-domain denoted by the indices *q'*:

$$\frac{\left|Z_{w,X',Y',q'}\left(\frac{k}{M'\,\Delta x},\frac{l}{N'\,\Delta y}\right)\right|^2}{M'\,N'\,\Delta x\,\Delta y} \tag{8}$$

for $0 \le k \le M'-1$; $0 \le l \le N'-1$, $M' \prec M$, $N' \prec N$

The symbol $Z_{w,X',Y',q'}\left(\frac{k}{M'\Delta x},\frac{l}{N'\Delta y}\right)$ in Eq. (8)

denotes the Fourier transform of the surface function weighted by the function $w(m'\Delta, n'\Delta y)$ within the selected q'^{th} domain X', Y'. In conclusion we calculate the arithmetic average of Q' spectra of weighted surface function within all sub-domains

$$\overline{P}_W = \frac{1}{Q'}\sum_{q'=1}^{Q'} \frac{\left| Z_{w,X',Y',q'}\left(\frac{k}{M'\,\Delta x},\frac{l}{N'\,\Delta y}\right)\right|^2}{M'\,N'\,\Delta x\,\Delta y} \tag{9}$$

Considering the assumption of the function z_r ergodicity the term (9) is equivalent to the arithmetic average of the given number of finite realizations of z_r. The term (9) is the resulting statistical estimate of the APSD defined by Equation (4).

$$P_{zr}\left(\frac{k}{M'\,\Delta x},\frac{l}{N'\,\Delta y}\right) \cong \overline{P}_W\left(\frac{k}{M'\,\Delta x},\frac{l}{N'\,\Delta y}\right) = \tag{10}$$

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

As regards to the discrete form of the term (5) for AnPSD we used an appropriate numerical algorithm for their calculation.

RESULTS

The 3D matrix of surface heights measured by the optical profilometer MicroProf ® FRT on a typical titan grade 2 surface prepared by AWJ cutting under conditions listed in Tab.1 is presented in Figure 1.

The evaluation of the surface topography has been done within the transition zone marked by the white rectangle. The estimate of the APSD obtained by mentioned procedure is presented in Figure 2. This figure shows contours of the APSD for the sake of clearness. Two lines in the figure represent the directions in which AnPSD is reaching its maximum for low (the solid line) and high spatial frequencies (the dashed line). The heading angles of both the lines equal the angular coordinates θ of the normalized AnPSD maximum for low and high spatial frequencies. Values of those maxima AnPSD angular coordinates are as follows:

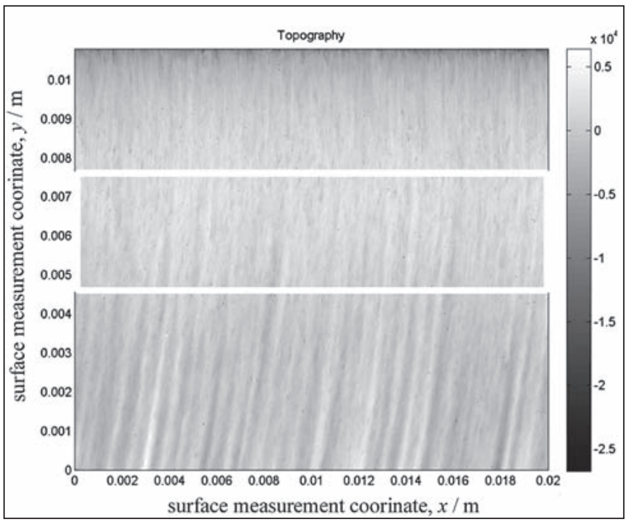

Figure 1 Digital map of the typical titan grade 2 surface topography produced by AWJ cutting (Optical profilometer MicroProf ® FRT)

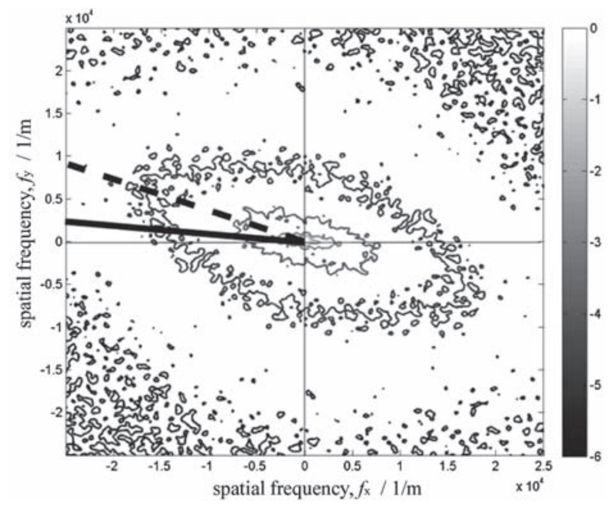

Figure 2 Contours of the APSD of the surface from Figure 1 within the transition zone (semilogarithmic scale). Solid line –direction of surface striation, dashed line – direction of the fine surface texture.

$$\theta_{ml} = (174{,}9\pm0{,}3)^\circ,\ \theta_{mh} = (158{,}6\pm0{,}2)^\circ$$

These values were obtained from 10 independent procedures of the parameters evaluation; their random uncertainties are of 95 % confidence level.

DISCUSSION

We can interpret the difference between θ_{ml} and θ_{mh} in the following way. The topography of the surface studied shows typical striation (see Figure 1). With regard to dimensions of this striation they contribute to the APSD within the low spatial frequencies region (the smallest contour in Figure 2) In accordance with the theorem of similarity, which is valid for the Fourier transform [10], we can state that the main orientation of this striation is perpendicular to the solid line in Figure 2. For the same reasons we can also state that there is a fine texture corresponding to high spatial frequencies in the surface topography, the main orientation of which is slightly rotated with respect to the direction of the surface striation. In the case presented the difference between these directions is $\Delta\theta = \theta_{ml} - \theta_{mh} = (16{,}3\pm0{,}3)^\circ$. It can be explained by a supposed mechanism of the surface generation. The abrasive water jet creates surface striation as the main feature of the surface topography in transition and so called rough zones. Inside an individual groove the turbulent flow of the abrasive water jet originates a fine texture in the surface topography with a prevailing direction different from the prevailing direction of the surface striation. This proposed mechanism is supported by the detailed study of the surface topography by means of optical microscopy which has been carried out too.

CONCLUSION

In this paper we studied a titan grade 2 surface topography prepared by abrasive waterjet cutting. Topographic data were acquired by optical profilometer MicroProf ® FRT. We focused our attention to the transition surface zone. Using APSD and AnPSD we found that an abrasive water jet creates besides striation also a fine texture inside individual grooves. These two components of the surface topography show different prevailing directions which were determined by means of the angular coordinate of the maximum of the normalized AnPSD. We explained this fact by the proposed mechanism of AWJ surface generation, i. e. by a turbulent flow of the abrasive water jet inside an individual surface groove. We can conclude that the spectral analysis of surfaces generated by AWJ provide results useful for topography characterization of such surfaces. These results can be used for an optimization of the AWJ machining process.

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REFERENCES

[1] Hashish, M.: Modeling Study of Metal Cutting with Abrasive Waterjets. Trans. of the ASME, Journal of Eng. Mat&Tech, 106(1984)1

[2] Hashish, M.: Pressure Effect in Abrasive – Waterjet (AWJ) Machining. Trans. of the ASME, Journal of Eng. Mat&Tech., 106(1984)7

[3] Guo, N. S.: Schneidprozess und Schnittqualität beim Wasserabrasiusstrahl – schneiden. VDI Verlag, 1994

[4] Raja, J. et al. Recent advances in separation of roughness, Waviness and Form, Precision Engineering: Journal of the International Societies for Precision Engineering and Nanotechnology 26 (2002) 222–235.

[5] Chen, F., L. et al. Improving the cut surface qualities using different controlled nozzle oscillation techniques, International Journal of Machine Tools and Manufacture 42 (2002) 717–722.

[6] Lemma, E. Optimising the AWJ cutting process of ductile materials using nozzle oscillation technique, International Journal of Machine Tools and Manufacture 42 (2002) 781–789.

[7] Hloch S et al. Experimental study of surface topography created by abrasive waterjet cutting. In: Strojarstvo. 49(2008)4, 303-309

[8] Valíček J, Hloch S. Optical measurement of surface and topographical parameters investigation created by abrasive waterjet. In: International Journal of Surface Science and Engineering. 3(2009)4, 360-373

[9] Valíček J, Hloch S. Using the acoustic sound pressure level for quality prediction of surfaces created by abrasive waterjet. In: The International Journal of Advanced Manufacturing Technology. 48(2010)1-4, 193-203

[10] Valíček J, Hloch S, Kozak D. Surface geometric parameters proposal for the advanced control of abrasive waterjet technology. In: The International Journal of Advanced Manufacturing Technology. 41(2009)3-4, 323-328

[11] Brigham, E., O. The Fast Fourier Transform and its application, Prentice-Hall, Upper Saddle River, 1988.

[12] Bracewell, R.N. The Fourier Transform and its Applications, 3rd ed., McGraw-Hill Companies, Boston, 2000

[13] Mainsah, E. et al. Metrology and Properties of Engineering Surfaces, Kluwert Academic Publishers, Dordrecht, 2001

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