577. Estimation of surface roughness using high frequency vibrations

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Abstract. Surface roughness is an important parameter for evaluating the quality of material surfaces. It affects the tribological and optical properties of the materials. The paper proposes a new method for estimation of surface roughness, which is based on measurement of high frequency vibrations that are generated when air flow interacts with the surface of a solid body. It was determined that intensity of high frequency vibrations depends on surface roughness. Sandpapers with different magnitudes of surface roughness were used for the experimental study.

Keywords: Surface roughness, high frequency vibrations

Introduction

Surface roughness is an important parameter for evaluating the quality of material surface. This parameter affects the tribological and optical properties of the materials [1]. Methods that are currently in use can be divided into two major groups: contact and non-contact [2]. Contact methods are based on the interaction between probe and surface. The methods of stylus profiling, atomic force microscope and others are classified as contact methods. Optical, microscope, interferometry, pneumatic, capacitance and others are non-contact measurement methods [2–5]. Methods can also be classified into three categories: profiling, area-profiling and area-averaging [2].

Profiling techniques provide quantitative assessment of surface peaks and valleys through point-by-point measurement with a high-resolution probe.

Three-dimensional representations of the surface roughness can be produced by using a procedure known as area-profiling. Area-profiling gives a much more complete representation of the surface roughness than profiling.

The area-averaging technique probes the surface over a finite area all at once to produce a measured property that represents a statistical average of peaks and valleys. Area-averaging techniques offer the potential for high speed inspection, but most of them have limited effectiveness.

Many methods mentioned above have disadvantages and therefore are not appropriate for practical applications.

Relevance of the presented work is to demonstrate possibility of application of high frequency vibrations (HFV) as a measurement method for estimation of surface roughness. This method can be attributed to the area-averaging category. The purpose of the presented work is to investigate possibility of the application of HFV measurement method for estimation of the surface roughness.

Evaluation of surface roughness

Surface roughness is a measure of topography of the surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth.

There are many parameters of the surface roughness that can be used to analyze the surface [2, 6]. The most common parameter used in industry is the average roughness. The average roughness can be calculated as:

$$R_a = \frac{1}{l}\int_0^l |y(x)|dx = \frac{1}{n}\sum_{i=1}^{n}|Y_i|, \tag{1}$$

where n is the number of sample points; Y_i or $y(x)$ is the value of the profile deviation from the mean line; l is the basic length.

The geometrical interpretation of surface roughness is presented in Fig. 1.

Other common parameters of the surface roughness are R_q, R_t, R_z, R_v, R_p, R_{sk} and R_{ku} [6]. Some of them are used only in certain industries or within certain countries. R_q is root mean square roughness. It is the root mean square of the measured value deviations taken within the evaluation length and measured from the mean line. It can be calculated:

$$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n}Y_i^2}\ . \tag{2}$$

R_t defines maximum peak-to-peak-valley height. It is the absolute value between the highest and lowest peaks and can be evaluated as:

$$R_t = \left|\min_{1\le i\le n} Y_i\right| + \left|\max_{1\le i\le n} Y_i\right|. \tag{3}$$

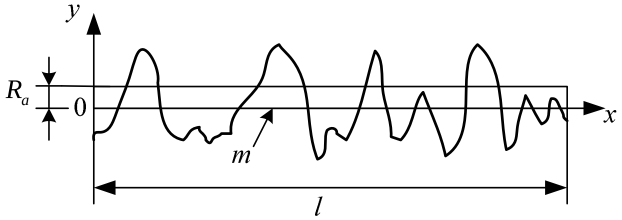

Fig. 1. Geometrical interpretation of the surface roughness: R_a – average roughness; m – mean line; l – basic length

R_z is the average absolute value of the five highest peaks and the five lowest valleys over the evaluation length. R_v is the depth of the deepest valley in the roughness profile over the evaluation length. R_p is the height of the highest peak in the roughness profile over the evaluation length.

R_{sk} and R_{ku} are skewness and kurtosis respectively. Both of them describe the shape of the amplitude distribution function of surface roughness. Skewness measures the symmetry of the variation of a profile about its mean line. Kurtosis relates to the spikiness of the profile.

Application of HFV measurement method for estimation of surface roughness

Acoustical HFV measurement method may be used for estimation of the surface roughness. This estimation is based on the measurement of high frequency vibrations. The measurement transducer in the frequency band of 30…200 kHz is used. The formation of HFV is based on the interaction between the air flow and the surface of a solid body. It was estimated that intensity of HFV depends on the roughness of the surface of a solid body. The principle of the formation of the HFV is based on the assumption that the air flow moves along the surface and forms the air whirls. The theoretical investigation of the formation of HFV is complicated. Therefore experimental investigation is performed here. The block diagram of the measurement system is presented in Fig. 2.

Air from the compressor is applied to a nozzle, where the air pressure is measured. Air flow from the nozzle interacts with the surface of a solid body. This interaction results is the formation of HFV around. The HFV are measured by transducer. Afterwards measured signals are amplified and stored in the oscilloscope. Finally, the signals are transferred to the computer, where Matlab programme is used for data processing.

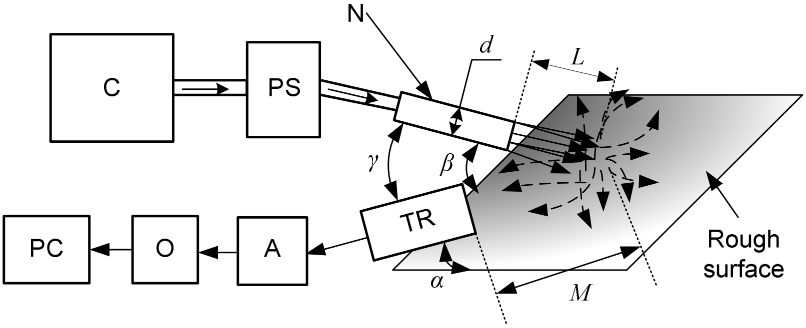

Fig. 2. Experimental measurement system: C – air compressor; PS – pressure sensor; N – nozzle with air flow; TR – HFV transducer; A – amplifier; O – oscilloscope; PC – computer; L – distance between nozzle and surface; M – distance between surface and HFV transducer; d – diameter of the nozzle; α – angle between the HFV transducer and rough plate; β – angle between the nozzle and rough plate; γ – angle between the HFV transducer and the nozzle

Experimental results and discussion

The experiments were performed with the plates of different roughness. Sandpapers with various grit sizes were used for this purpose. Grit size refers to the size of the particles of abrading materials embedded in the sandpaper. The parameters and examples of the investigated surfaces are presented in Table 1 and Fig. 3. The average roughness R_a decreases when the sandpaper grit number (size) increases.

a) b)

c) d) e)

Fig. 3. Examples of the investigated roughness of the surface: a) sandpaper with grit size 20; b) sandpaper with grit size 50; c) sandpaper with grit size 100; d) sandpaper with grit size 240; e) sandpaper with grit size 400

Table 1. The parameters of the investigated surfaces.

Sandpaper grit size, No	20	36	50	60	80	100	120	150	180	240	280	360	400
Average particle diameter, μm *	1000	538	336	269	201	162	125	100	82	59	52	41	35
Average roughness, μm *	-	123	91	67	54	32	23	17,4	16.9	-	13	9	8.9

* “Nanovea” test results [7] and measurements by TR 200 [8].

It can be stated that the signals measured by HFV transducer are noise type signals. The example of the measured signal is shown in Fig. 4.

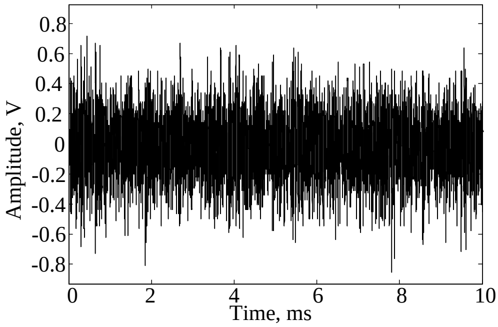

Fig. 4. Representative example of the measured signal

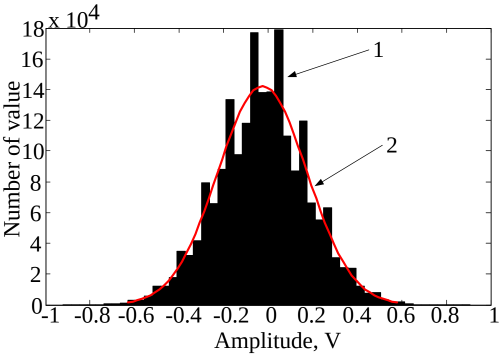

Fig. 5. Distribution of the measured signal – 1; Gaussian distribution – 2 (results are obtained for stable air flow)

The distribution of the measured signal (Fig. 4) can be approximated by Gaussian distribution (Fig. 5). The root mean square (RMS) value and the average of the RMS value can be used for the evaluation of intensity of HFV signal [9]. The RMS value of the HFV signal is calculated according to the following equation:

$$RMS = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N} U_T^2(n)}\,, \tag{4}$$

where $U_T(n)$ is the digitized time signal; N is a number of points.

The average of the RMS values (RMS_{AVE}) is calculated as follows:

$$RMS_{AVE} = \frac{1}{K}\sum_{k=1}^{K} RMS(k), \tag{5}$$

where K is the number of the RMS values.

Signal characteristics in the frequency domain are also important. The example of the spectrum of the measured signal is presented in Fig. 6.

In order to evaluate the maximum speed of the measurement, it is necessary to establish the minimum measurement duration [9], which ensures statistically reliable and non-correlated measurement result.

The minimum measurement duration $\tau_{\min}$ is evaluated according to the following equation [9]:

$$\tau_{\min} = \int_{0}^{\infty} \rho^2(\tau) d\tau, \tag{6}$$

where $\rho(\tau) = \frac{R(\tau)}{R(0)}$ is the standard autocorrelation function. In our case $\tau_{\min} \approx 2 \cdot 10^{-5}$ s. It can be noted that signals, obtained by dividing the measured signal into time intervals of a length $\tau_{\min}$, do not correlate with each other [9]. The standard autocorrelation function of the stochastic transducer signal is presented in Fig. 7.

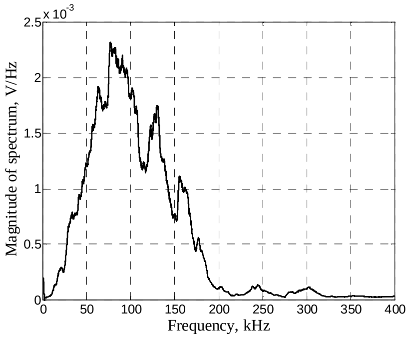

Fig. 6. Spectrum of the measured signal

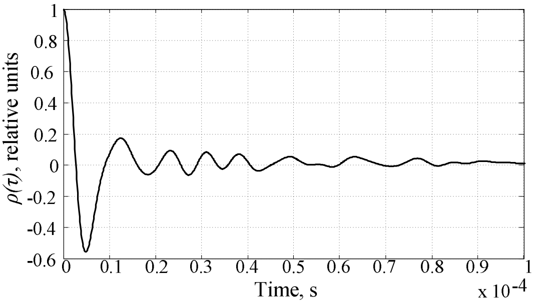

Fig. 7. Standard autocorrelation function of the measured signal

The calibration curve showing the dependence between the output signal RMS of the HFV transducer and sandpaper grit size was obtained. Air pressure (in the nozzle) is constant during this experiment. The relationship between measured RMS values of the HFV transducer signals and sandpaper grit size is presented in Fig. 8. The RMS values are measured 100 times at the each point of the calibration curve. The measurement duration for each RMS value is 2 ms. The averages of the RMS values (RMS_{AVE}) are used for the calibration curve (Fig. 8). Sandpaper roughness can be assessed by another parameter – the average roughness. Then a linear relationship between measured RMS values of the output signals of the HFV transducer and average roughness was obtained (Fig. 9).

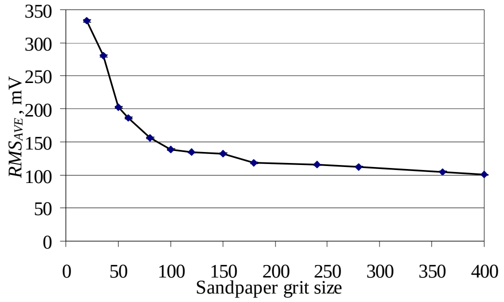

Fig. 8. Relationship between measured RMS values of the output signals of the HFV transducer and sandpaper grit size

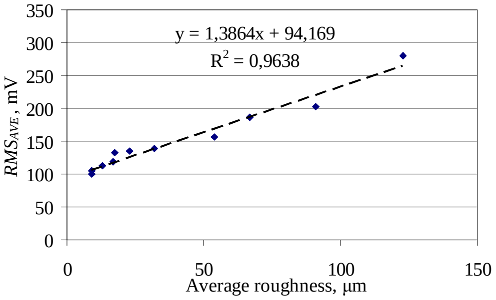

Fig. 9. Relationship between measured RMS values of the output signals of the HFV transducer and average roughness (the parameters of the sandpaper are presented in Table 1)

The relationship between the intensity of HFV signals and nozzle diameter was investigated. When diameter of the nozzle increases (air flow increases too) RMS value of HFV signals also increases. Air pressure and the plate of roughness are constant during this experiment. The relationship between RMS value of HFV signals and nozzle diameter is presented in Fig. 10.

The relationship between the intensity of HFV signals and air pressure was investigated. When air pressure increases (air flow increases too) RMS value of HFV signals also increases. The nozzle diameter and the plate roughness are constant during this experiment. The relationship between RMS value of HFV signals and air pressure is presented in Fig. 11.

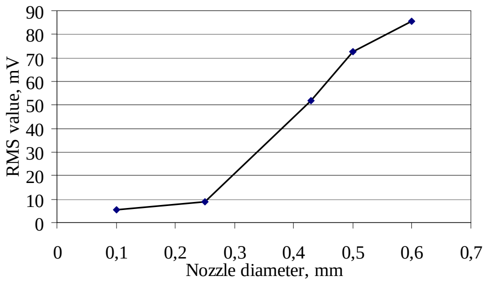

Fig. 10. Relationship between RMS value of HFV signals and nozzle diameter

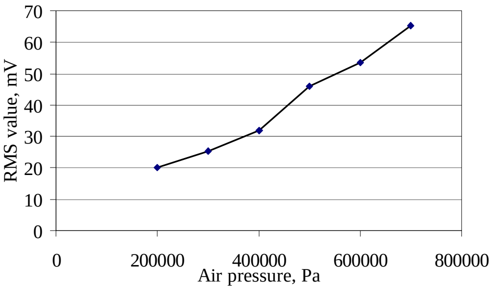

Fig. 11. Relationship between RMS value of HFV signals and air pressure

The relationship between the calculated power spectrum density of measured HFV signals and sandpaper grit size is presented in Fig. 12. It is demonstrated that the positions of the frequency band resonances do not depend upon sandpaper grit size.

According to Fig. 2 the optimum nozzle and transducer positions were investigated. Optimality is associated with a higher intensity of HFV. The angle γ=90°, the surface roughness, air pressure and nozzle diameter are constant during the experiment. In this case angle β (between the nozzle and rough plate) was constant while the angle α (between the HFV transducer and rough plate) was varied. The experimental results are presented in Fig. 13. HFV intensity is normalized with respect to the maximum value. Fig. 13 indicates that the most appropriate angle β is equal to 90° or 25°. When β is equal to 90°, α should be equal to 50 degrees. When β is equal to 25°, α should be equal to 30 – 50°.

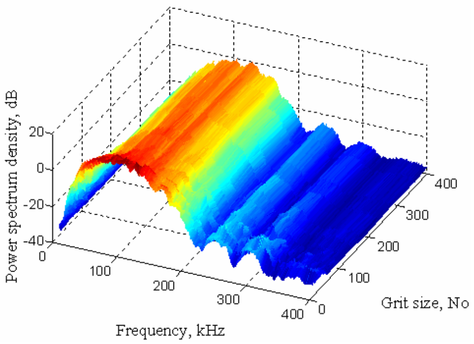

Fig. 12. Relationship between power spectrum density of the measured signals and sandpaper grit size

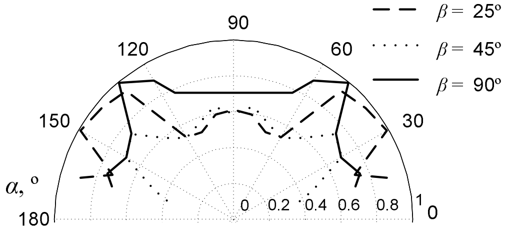

Fig. 13. Directional diagram of HFV: β is angle between nozzle and rough plate; α is angle between the HFV transducer and rough plate (notations are used according Fig. 2)

Concluding remarks

New method for the measurement of surface roughness is proposed in the paper. It is based on the application of high frequency vibrations and can be used for practical purposes. The presented method is based on measurement of intensity of HFV, which are formed as a result of interaction between air flow and surface of a solid body.

The proposed method enables contactless measurement and evaluates average roughness of solid body in the range of ca. 10–120 μm. Experimental results demonstrate that generated HFV signals are noise-type signals. The basic measured parameters of HFV signals are RMS value, average RMS value and power spectrum.

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