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MODELING PROFILES AFTER VAPOUR BLASTING

Paweł Pawlus[1], Rafał Reizer[2]

1) Rzeszow University of Technology, Department of Manufacturing Processes and Production Organization, W. Pola 2, 35–959 Rzeszow, Poland (✉ ppawlus@prz.rzeszow.pl, + 48 17 865 1183)

2) University of Rzeszow, Institute of Technology, Rejtana 16A, 35–959 Rzeszow, Poland (rreizer@univ.rzeszow.pl)

Abstract

The irregularity profiles of steel samples after vapour blasting were measured. A correlation analysis of profile parameters was then carried out. As the result, the following parameters were selected: Pq, Pt, PΔq, Pp/Pt and Pku. Surface profiles after vapour blasting were modeled. The modeled surfaces were correctly matched to measured surfaces in 78% of all analyzed cases. The vapour blasting experiment was then carried out using an orthogonal selective research plan. The distance between the nozzle and sample d and the pressure of feed system p were input parameters; selected surface texture coefficients were output parameters. As the result of the experiment, regression equations connecting vapour blasting process parameters p and d with selected profile parameters were obtained. Finally, 2D profiles of steel samples were forecasted for various values of vapour blasting parameters. Proper matching accuracy of modeled to measured profiles was assured in 75% of analyzed cases.

Keywords: surface topography, simulation, forecasting.

1. Introduction

The tribological behaviour of engineering surfaces, such as hydrodynamic and elastohydrodynamic lubrication, wear or contact problems can be predicted numerically. The solution of these problems involves input of surface data, which can be obtained either from digital output from a profilometer or from numerical simulation of the rough surfaces. Randomly generating surface roughness by numerical means is simpler and offers some advantages. The hardware and software requirements can be eliminated. The simulation of surface forming during manufacturing and operating processes ensures a decrease of cost and time of experimental investigation.

The numerical characterization of stylus-measured data is based on the recording of 2D profiles. The surfaces of the big participation of the random components do not have in their spectra dominating components. Most engineering surfaces have height distributions which are approximately Gaussian. Many investigators accepted the random process description of engineering surfaces, so it was possible to generate a rough surface by a random simulator. The time series model of a rough surface [1, 2] was applied to one-dimensional Gaussian profile generation by the authors of [3]. Recently, the fractal approach of profile description was introduced. The authors of the papers [4, 5] simulated fractal rough surface profiles.

It was found that surface topography exists in three, not in two dimensions. There was a need of measuring and modeling surface microgeometry in 3 dimensions. The Fast Fourier Transform (FFT) is popular in generating surfaces [6, 7, 8]. Newland in 1984 used it. He applied a circular autocorrelation function [6]. In 1992, Hu and Tonder used a finite impulse response filter. The procedure of generation of Gaussian surfaces having a specified autocorrelation function was described in Reference [7]. Wu in 2000 [8] developed a

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numerical procedure of three-dimensional surface modeling. This method was based on FFT. It can simulate surfaces with given spectral density or autocorrelation function.

In initial investigations of the present authors [9] AR and FFT models were used to simulate the 2D profiles of normal ordinate distribution. Methods presented in the papers [6, 7, 8] were modified in order to simulate surface profiles. It was found that only the features near the origin of autocorrelation function were simulated well by AR models. From FFT procedures, the method developed by Wu [8] was the best. Therefore, only this FFT method for generating 3D surface topographies was used in the present work.

2. Materials and methods

Steel plates from S235JR material were taken as samples. A vapour blasting experiment was carried out using the KIS-900 special equipment. Aloxite 95A-60-J was used as an abrasive material. Entrance angle was 40^o, diameter of nozzle was 5 mm. There were the following variables in the vapour blasting process:

- feed system pressure **p**,
- distance between nozzle and samples **d**.

Firstly, a lot of samples (about 20) were subjected to the vapour blasting process. Then a three-dimensional measurement of surface topography was conducted, using a Surtronic 3+ profilometer. The assessment length was 4 mm and the sampling interval was 0.5 µm. The nominal radius of the stylus tip was 5 µm. The measurement was done using the skid. After measurement, profiles were leveled. No digital filtration was used.

Then, correlation and regression analysis was used in order to eliminate highly-correlated surface topography parameters. The following parameters were analyzed: Pa, Pq, Pt, Pz, Pp, Ppm, Pv, Pvm, Psk, Pku, PΔq, Pp/Pt, Pk, Pvk, Ppk, Pmr1 and Pmr2. As the result of correlation analysis, a set of parameters describing the surface topography of steel samples was selected. Then the 2D irregularity profiles were simulated. It was assumed that the modeling accuracy was good when the parameters of the modeled surface were within confidence intervals for average parameters of measured surfaces.

Secondly, the vapour blasting experiment was carried out using an orthogonal selective research plan. The distance between the nozzle and sample **d** (in the range: 6–14 cm) and the pressure of the feed system **p** (0.4–0.6 MPa) were input parameters. The experiment was carried out in other research points than those resulting from the plan, too. As the result of the experiment, the regression equations connecting vapour blasting process parameters **p** and **d** with selected surface texture parameters were obtained. Finally, 3D surface topographies were forecasted for various values of vapour blasting parameters.

3. Results and discussion

It was assumed that parameters were strongly correlated when the absolute value of the linear correlation coefficient r was greater than 0.7. In this case the determination coefficient (square of the linear correlation coefficient) was larger than 0.5. The analyzed variables are then correlated for substantiality level $\alpha = 0.05$. Table 1 presents the values of the linear correlation coefficients between parameters of surface profiles.

Table 1. Correlation coefficients for 2D profiles.

	Pa	Pq	Pt	Pp	Ppm	Pv	Pvm	Psk	Pku	Pp/Pt
Pa	**1**	0.991	0.718	0.466	0.466	0.682	0.682	-0.035	-0.154	-0.159
Pq	-	**1**	0.771	0.524	0.524	0.709	0.709	-0.009	-0.040	-0.132
Pt	-	-	**1**	0.801	0.801	0.797	0.797	0.108	0.454	0.042
Pp	-	-	-	**1**	**1**	0.277	0.277	0.562	0.478	0.627
Ppm	-	-	-	-	**1**	0.277	0.277	0.562	0.478	0.627
Pv	-	-	-	-	-	**1**	**1**	-0.395	0.247	-0.566
Pvm	-	-	-	-	-	-	**1**	-0.395	0.247	-0.566
Psk	-	-	-	-	-	-	-	**1**	0.227	0.801
Pku	-	-	-	-	-	-	-	-	**1**	0.207
Pp/Pt	-	-	-	-	-	-	-	-	-	**1**

Table 1. (continued).

	PΔq	PSm	Pk	Ppk	Pvk	Pmr1	Pmr2
Pa	0.682	0.807	0.926	0.525	0.721	0.047	0.077
Pq	0.697	0.788	0.880	0.604	0.737	0.104	0.016
Pt	0.662	0.552	0.584	0.672	0.675	0.018	-0.116
Pp	0.418	0.393	0.316	0.764	0.243	0.147	-0.088
Ppm	0.418	0.393	0.316	0.764	0.243	0.147	-0.088
Pv	0.641	0.490	0.618	0.307	0.758	-0.119	-0.096
Pvm	0.641	0.490	0.618	0.307	0.758	-0.119	-0.096
Psk	-0.075	0.033	-0.089	0.603	-0.463	0.364	0.300
Pku	0.023	-0.143	-0.311	0.483	0.298	0.082	-0.283
Pp/Pt	-0.144	-0.061	-0.235	0.402	-0.417	0.233	0.006
PΔq	**1**	0.565	0.630	0.411	0.540	0.095	0.023
PSm	-	**1**	0.790	0.420	0.427	-0.025	0.186
Pk	-	-	**1**	0.328	0.451	-0.204	0.317
Ppk	-	-	-	**1**	0.320	0.328	-0.023
Pvk	-	-	-	-	**1**	0.036	-0.309
Pmr1	-	-	-	-	-	**1**	0.028
Pmr2	-	-	-	-	-	-	**1**

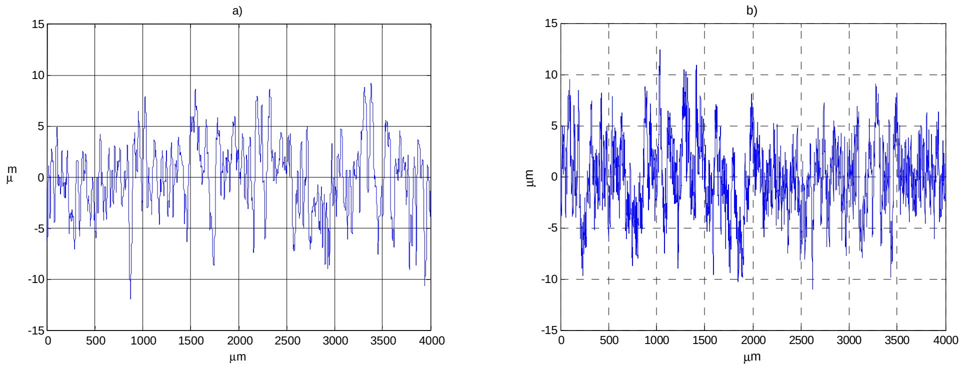
The Pa and Pq parameters are strongly interrelated. The linear correlation coefficients **r** between them and the following parameters: Pt, Pv, Pvm, PSm, Pk and Pvk are greater than 0.7. Proportionality between statistical amplitude parameters and spacing parameter PSm is substantial ($r \approx 0.8$). However parameters describing the peak surface part: Pp, Ppm and Ppk are connected with parameters characterizing the maximum surface height, like Pt. Therefore, the Pq and Pt amplitude parameters were selected for profile description. The correlation coefficients among the rms slope and height parameters were not greater than 0.7. Therefore, the PΔq parameter was selected for the description of the profile after vapour blasting. Parameters describing the shape of the ordinate distribution Psk and Pp/Pt are statistically connected (r=0.8). The emptiness coefficient Pp/Pt was selected with respect to its interpretation. The statistically independent kurtosis Pku was also included. The Pmr1 and Pmr2 parameters are also statistically independent. As it was not possible to find connections with the functional properties of the machined elements, they were not recommended for profile description.

As a result of this analysis the authors decided to select the following set of parameters describing the analyzed profiles: Pq, Pt, PΔq, Pp/Pt and Pku.

The condition of proper matching of parameters of modeled to measured profiles is that the parameters of the simulated profile should lie within confidence intervals of measured parameters. Standard deviations of parameters were obtained for the number of repetitions 6.

We obtained the following values of confidence intervals: for Pq $\pm$ 0.206 μm, Pt $\pm$ 1.39 μm, PΔq $\pm 0.65^{o}$, Pku $\pm$ 0.32 and Pp/Pt $\pm$ 0.057. The parameter Pq of modeled surface topography was correctly matched in 94%, Pp/Pt in 94%, Pku in 88%, PΔq in 94%, Pt in 88% of analyzed cases. The joint matching condition of all selected parameters was fulfilled in 78% of cases. Average relative errors of Pq parameter determination were 4.4%, Pt 5.83%, Pp/Pt 8.1, Pku 7.9% and PΔq 2.6%. The relative errors of determination of other parameters were: for Pp 15.7%, Pv 13.6%, PSm 18.5%, Pk 9.2%, Ppk 26.1%, Pvk 26.3%, Pmr1 31% and Pmr2 5.11%.

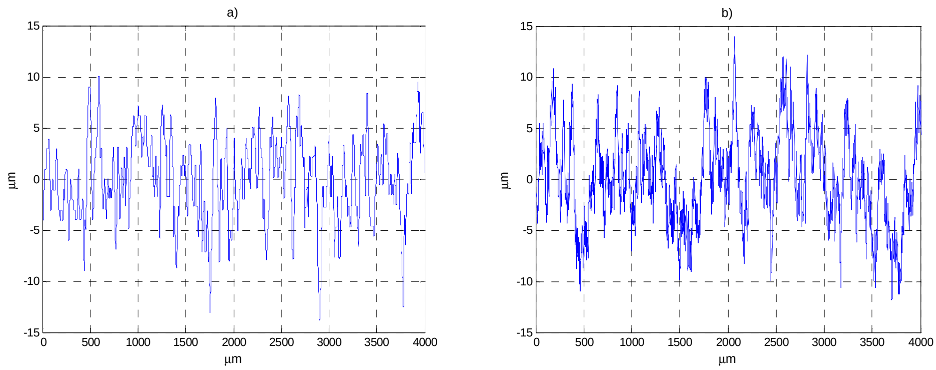
Figs 1 and 2 present examples of measured and modeled profiles.



Pa = 2.73 µm, Pq = 3.44 µm, Pt = 21.86 µm,
Pp = 9.75 µm, Ppm = 9.64 µm,
Pv = 12.11 µm, Pvm = 12.08 µm, Psk = -0.102,
Pku = 3.11, Pp/Pt = 0.45, PΔq = 19.14°

Pa = 2.93 µm, Pq = 3.69 µm, Pt = 20.25 µm,
Pp = 9.49 µm, Ppm = 9.47 µm,
Pv = 11.96 µm, Pvm = 11.96 µm, Psk = 0.36,
Pku = 2.98, Pp/Pt = 0.46, PΔq = 19.07°

Fig. 1. Measured a) and modeled b) profiles of steel surface topographies after vapour blasting.



Pa = 3.18 µm, Pq = 3.94 µm, Pt = 23.12 µm,
Pp = 9.88 µm, Ppm = 9.87 µm,
Pv = 13.23 µm, Pvm = 13.23 µm, Psk = -0.19,
Pku = 3.071, Pp/Pt = 0.43, PΔq = 18.63°

Pa = 3.4 µm, Pq = 4.01 µm, Pt = 21.09 µm,
Pp = 9.76 µm, Ppm = 9.77 µm,
Pv = 12.13 µm, Pvm = 12.14 µm, Psk = 0.32,
Pku = 2.71, Pp/Pt = 0.46, PΔq = 18.4°

Fig. 2. Measured a) and modeled b) profiles of steel surface topographies after vapour blasting.

The vapour blasting experiment was then carried out using an orthogonal selective research plan. The distance between the nozzle and sample **d** and the pressure of the feed system **p** were input parameters, however selected surface texture coefficients were output parameters (see Table 2). In addition, the experiment was carried out in other research points than those resulting from the plan.

Table 2. The effect of vapour blasting parameters on profile parameters.

p [0.1 MPa]	4	4	4	5	5	5	6	6	6	σ
d [cm]	6	10	14	6	10	14	6	10	14	
Pq [μm]	3.407	3.292	3.707	3.255	3.526	3.670	3.747	4.386	4.117	0.179
Pt [μm]	20.492	19.713	24.417	21.388	22.575	21.585	23.623	25.364	26.466	1.211
Pku	2.796	2.946	3.525	3.284	3.273	3.008	3.133	2.909	3.234	0.281
Pp/Pt	0.451	0.502	0.529	0.475	0.473	0.485	0.474	0.494	0.445	0.049
PΔq [°]	18.319	17.091	18.285	18.477	18.124	18.624	19.962	20.942	20.679	0.564

Standard deviations of parameters σ, obtained from 6 repetitions are also presented in Table 2. After removal of unsubstantial coefficients the following regression equations were obtained:

$$Pq = 1.54 + 0.31\,\mathbf{p} + 0.045\,\mathbf{d}$$

$$Pt = 9.59 + 1.81\,\mathbf{p} + 0.29\,\mathbf{d}$$

$$Pku = 3.02$$

$$Pp/Pt = 0.49$$

$$P\Delta q = 11.59 + 1.317\,\mathbf{d}$$

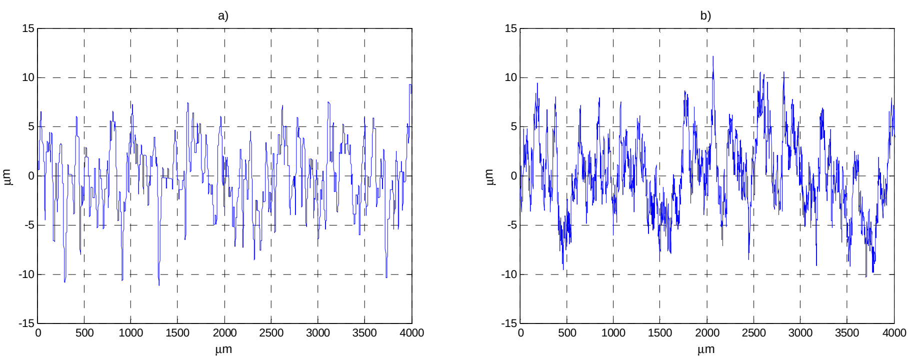
Increasing pressure **p** and increasing distance **d** increases height parameters Pq and Pt. rms slope is proportional to **d**. However the values of parameters Pku and Pp/Pt are approximately constant.

For different machined parameters, the surface topography parameters should obtain the following values:

– for **p** = 0.45 MPa, **d** = 80 mm: Pq = 3.295 μm, Pt = 10.14 μm, PΔq = 19.14^{o};
– for **p** = 0.45 MPa, **d** = 120 mm: Pq = 3.48 μm, Pt = 22.903 μm, PΔq = 19.66^{o};
– for **p** = 0.55 MPa, **d** = 80 mm: Pq = 3.605 μm, Pt = 20.61 μm, PΔq = 19.36^{o};
– for **p** = 0.55 MPa, **d** = 120 mm: Pq = 3.46 μm, Pt = 21,0 μm, PΔq = 19.072^{o}.

Surface profiles characterized by these parameters were modeled. The authors compared the results of simulation with parameters of measured surface profiles for vapour blasting process parameters mentioned above. Matching accuracy of modeled to measured profiles was fulfilled in 75% of cases.

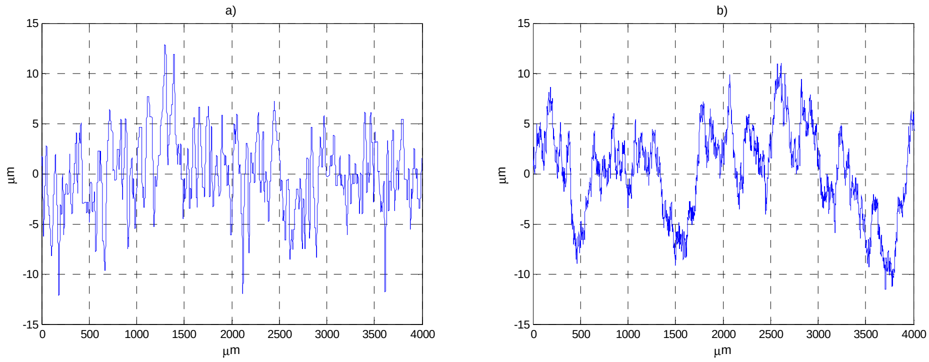
Figs 3, 4, 5 and 6 present examples of measured and forecasted profiles from steel surface topographies for various vapour blasting process parameters.



Pq = 3.47 μm, Pt = 20.13 μm,
PΔq = 19.13^{o}, Pku = 3.1, Pp/Pt = 0.45

Pq = 3,295 μm, Pt = 20.14 μm,
PΔq = 19.14^{o}, Pku = 3.02 , Pp/Pt = 0.49

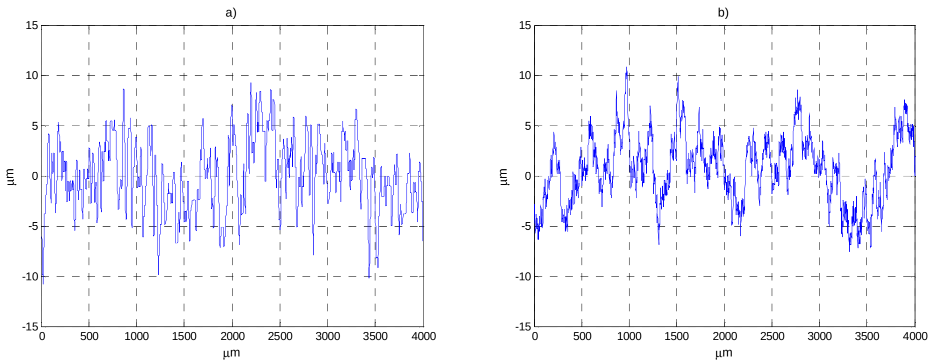
Fig. 3. Measured a) and anticipated b) profiles for the following vapour blasting parameters: **p** = 0.45 MPa, **d** = 80 mm.



Pq = 3.52 μm, Pt = 23.9 μm,
PΔq = 19.66°, Pku = 3.21, Pp/Pt = 0.47

Pq = 3.48 μm, Pt = 22.903 μm,
PΔq = 19.66°, Pku = 3.02, Pp/Pt = 0.49

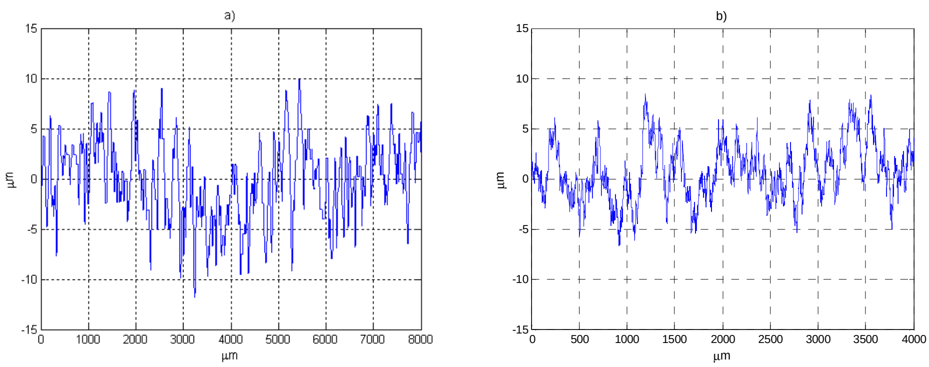
Fig. 4. Measured a) and anticipated b) profiles for the following vapour blasting parameters: **p** = 0.45 MPa, **d** = 120 mm.



Pq = 3.4 μm, Pt = 20.61 μm,
PΔq = 19.25°, Pku = 2.94 , Pp/Pt = 0.46

Pq = 3.605 μm, Pt = 20.61 μm,
PΔq = 19.36°, Pku = 3.02 , Pp/Pt = 0.49

Fig. 5. Measured a) and anticipated b) profiles for the following vapour blasting parameters: **p** = 0.55 MPa, **d** = 80 mm.



Pq = 3.6 μm, Pt = 21.4 μm,
PΔq = 19.08°, Pku = 3.06, Pp/Pt = 0.5

Pq = 3.46 μm, Pt = 21,0 μm,
PΔq = 19.072 °, Pku = 3.02, Pp/Pt = 0.49

Fig. 6. Measured a) and anticipated b) profiles for the following vapour blasting parameters: **p** = 0.55 Mpa, **d** = 120 mm.

4. Conclusions

The following parameters were included for the description of steel sample surface topography after vapour blasting: Pq, Pt, PΔq, Pp/Pt and Pku. Correlation analysis was helpful in their selection. The modeled profiles were correctly matched to measured profiles in 78% of all analyzed cases. The pressure of the feed system and the distance between the nozzle and sample are very important parameters of great influence on surface topography. It is possible to forecast 2D profiles after vapour blasting when machining parameters are known. Matching accuracy of anticipated to measured profiles was fulfilled in 75% of all analyzed cases.

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