SIMULATION OF THE EFFECT OF STYLUS TIP RADIUS ON THE RESULTS OF SURFACE TOPOGRAPHY MEASUREMENT

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Abstract: *This paper presents the results of application of numerical methods for surface topography analysis. Surface profiles after one and two-processes were computer generated. The effect of various tip radii on distortion of surface topography measurement results was analysed.*

Keywords: *surface topography; roughness; stylus measurement; tip radius*

ACM Classification Keywords: J.2 *Physical Sciences And Engineering;* ***G.1.2*** *Approximation;* ***G.1.3*** *Numerical Linear Algebra;*

Introduction

Despite a great development of optical and other techniques a stylus profilometer is still the most common roughness measuring device in mechanical industry. The principle of a contact measurement and methods of its making was not changed for years. However development of the microelectronics and the computer technique create occasion to increase the range and the resolution of devices and to introduce facilities for operators to reduce their chances to make mistakes. It seems that it will be the trend in development of a stylus surface measurement in the next years [Mathia, (in press)].

The probe tip is characterized by its radius and flank angle. The sizes of stylus tip decide about instrument transmission characteristics. Te behaviour of tip depends of not penetrating narrow valleys or irregularities of smaller sizes than tip size. Poon and Bhushan [Poon, 1995] found that spherical tip caused profile distortion by increase of correlation length (the distance, in which autocorrelation function slowly decayed to a defined value – usually 0.1) or other similar spacing parameters and decrease of standard deviation of Gaussian profile height. Whitehouse [Whitehouse, 1974] found that after application of 10 micrometers tip radius the surface height of elements after typical machining processes decrease up to 15%. Usually the tip of smaller radius should be used to measurement of very smooth surfaces, which is connected with the fact that the main wavelengths of them is usually very small.

Some authors [Whitehouse, 1974; Chetwynd, 1979; Mendeleyev, 1997; Wu, 1999; O'Donell, 1993] tried to simulate the co-action between tip and the surface. But these effects were mainly concentrated on random surfaces after one processes. However the role of two-process surfaces still increases. The surface topography of two-process surfaces is functionally important in tribology, but it is notoriously difficult to characterize. Plateau honed cylinder surface is the typical example of two-process surfaces. It consists of smooth wear-resistant and load-bearing plateaux with intersecting deep valleys working as oil reservoirs and debris trap. Cylinder surface topography affects running-in duration, oil consumption, exhaust gases emission and engine performance. Manufacturing cylinder liner is difficult because the demands on good sealing and on optimal lubrication are antagonistic.

The measurements based on a stylus profilometers in 3D surface topography of the surface are time consuming, what is significant limitation of them. A possibility of overcoming this inconvenience is a spiral sampling [Wieczorowski, 2001]. Irrespective of the contact devices the constructions based on the optical phenomena are being developed [Mathia, (in press)].

Methods of profiles modeling and simulation of stylus tip effect on measurement results

Method of profile modeling

Cylinder profiles of Gaussian ordinate distribution were computer generated using procedure proposed by Wu [Wu, 2000]. The other similar procedures [Hu, 1992; Newland, 1984] were also taken into consideration but Wu method was found to be the best. Gaussian profiles of exponential shape of autocorrelation function were simulated. There were the following input values: correlation length CL and standard deviation of profile height Pq.

The parameters describing surface after 2 processes can be calculated from the probability plot of material ratio curve, according to ISO 13565-3 standard. The slope of each presented straight lines gives the Pq roughness of the corresponding process. Also the transition characteristic, called plateau depth Pd from one to another process can be estimated. In standard ISO 13565-3 the Pd parameter is not calculated. Instead of it Pmq is computed. But there is a connection between Ppq, Pvq, Pmq and Pd:

$$Pd = Pmq\,(Ppq - Pvq) \tag{1}$$

The following procedure should be done in order to simulate two-process profile [Pawlus, 2008; Pawlus, 2006]:

1. Creation two Gaussian profiles PP (plateau) and PV (valley) with correlation lengths and variances as parameters describing them.
2. The choice of the distance (Pd) between the mean lines of the profiles (the centre of the Gaussian distributions).
3. For all the points "i" of two distributions (profiles): If PP(i) > PV(i) then RP (i) (resulting profile after two processes) = PV(i), else RP (i) = PP(i).

Figure 1 presents example of modelling of 2-process profile [Pawlus, 2006].

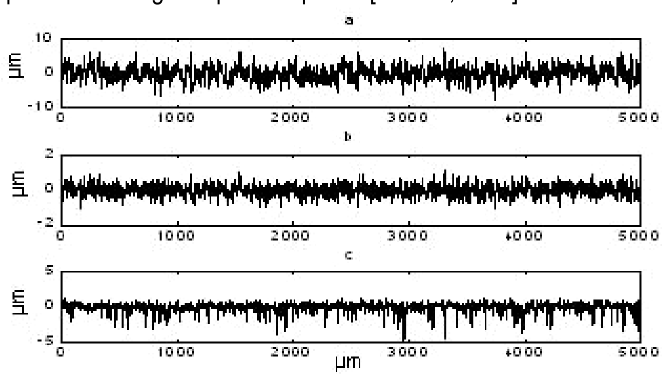

Figure 1. Computer generated profile after 2 processes: (a) valley profile, (b) plateau profile, (c) resulting profile

The special software in C language was generated to random profile after one and two-processes modeling. It was found that the Pq and CL parameters of Gaussian profiles were very cose to assumptions (input values).

Method stylus tip effect simulation on measurement results

The method presented in papers [Mendeleyev, 1997; Wu, 1999] was applied to simulate the effect of circular tip on measurement results. Figure 2 presents the idea of this method (after) [Wu, 1999].

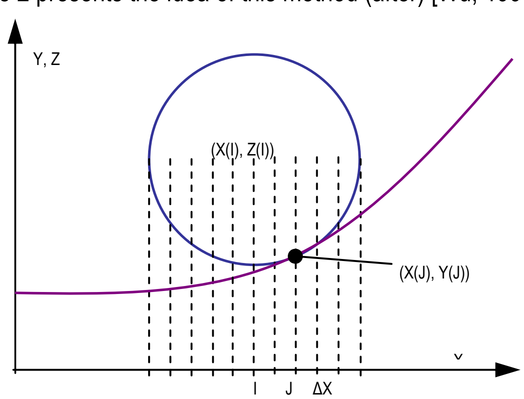

Figure 2. Method of rounded profile tip mechanical filtration simulation

It was assumed that probe tip radius was r and that plastic deformation don't occur.

Contact point has coordinates X(J) and Y(J), but middle point of tip: X(i) and Y(I). Index J of contact point is the result of discrete points searching in order to find maximum of function:

$$H(J)+Z(J)=Z(I)=\max_k(H(k)+Y(k)) \tag{2}$$

where:

$$H(k)=\sqrt{r^2-(k-I)^2(\Delta x)^2} \tag{3}$$

There is the following range of k index: from I – (r/Δx) to I + (r/Δx).

The problem of so-called edge effect on other profile details exists. It was solved by assumption that profile near finishing profile points is flat.

The special software in C language simulating the effect of radius of spherical tip on profile distortion was developed in C language. The results were very similar with those obtained using Villarubia's software [ftp.nist.gov/pub/spm_morph].

Results and discussion

Profiles of normal ordinate distribution

The analysis of 2D profile filtration is simplification. It can be used for highly anisotropic rough surfaces analysis. Rounded stylus tips had diameter of 2, 5 and 10 micrometers. Gaussian profiles were characterized by the Pq parameter in ranges: 0.2-10 µm, and correlation length CL in ranges 2-100 µm. Sampling interval was 1 µm. The changes of commonly used surface topography parameters [Pawlus, 2006]] caused by mechanical filtration by stylus tip were used. In addition, peak and valleys curvatures (pc and vc, respectively) and correlation lengths were also studied. Tables 1-2 show relative changes of absolute values of Pq, PSm (spatial parameter), PΔq (rms. slope), pc and vc parameters caused by stylus tip mechanical filtration of radii 5 and 10 micrometers. Only PSm values increased, other parameters decreased as the result of mechanical filtration by stylus tip. Changes of the parameters seem to be too high because some profiles look unrealistic (it is difficult to find profiles with correlation length of 20 and especially 2 micrometers, especially for high roughness height). Usually when height is higher, spacing parameters (like PSm) are larger. However the main intention of authors was only to find tendency of parameter changes. Please take into mind that the possibility of create surfaces with different profile shapes recently increased. Usually the parameters after mechanical filtration are compared with the result obtained with those of profile measured with the smallest tip radius (always 2 micrometers). In this case the parameters relative changes would be higher. Wu [Wu, 1999] proposed application of minimum sampling interval depending on parameters of measured surface and on radius tip. The correctness of Wu's calculation was confirmed by our investigations. When this sampling interval was used, changes of horizontal parameter were smaller (maximum relative changes of PSm was 10%). Changes of parameters connected with height and spacing (like slope and peak radius) were then similar to changes in the Pq parameter, not depending on sampling interval. Similar tendency of parameter changes were obtained after analysis of profiles measured with tip of 2 µm radius.

Table 1. Relative absolute changes of the Pq parameters as the result of mechanical filtration by stylus tips of radii 5 µm and 10 µm

CL, µm	r=5 µm Pq= 0.2 µm	r=5 µm Pq=1 µm	r=5 µm Pq=5 µm	r=10 µm Pq=0.2 µm	r=10 µm Pq=1 µm	r=10 µm Pq=5 µm
2	20.46%	31.07%	37.35%	25.67%	35.82%	42.56%
20	2.79%	6.69%	11.09%	4.43%	9.56%	16.33%
100	0.15%	1.06%	2.18%	0.53%	1.56%	3.37%

Table 2. Relative absolute changes of the PSm parameter as the result of mechanical filtration by stylus tips of radii 5 µm and 10 µm

CL, µm	r=5 µm Pq= 0.2 µm	r=5 µm Pq=1 µm	r=5 µm Pq=5 µm	r=10 µm Pq=0.2 µm	r=10 µm Pq=1 µm	r=10 µm Pq=5 µm
2	59.09%	184.14%	400.57%	102.16%	291.39%	663.80%
20	22.78%	101.65%	202.47%	53.67%	143.85%	322.41%
100	3.16%	52.33%	157.02%	23.01%	94.70%	229.21%

Table 3. Relative absolute changes of the PΔq parameter as the result of mechanical filtration by stylus tips of radii 5 µm and 10 µm

CL, µm	r=5 µm Pq= 0.2 µm	r=5 µm Pq=1 µm	r=5 µm Pq=5 µm	r=10 µm Pq=0.2 µm	r=10 µm Pq=1 µm	r=10 µm Pq=5 µm
2	40.24%	67.73%	79.01%	54.30%	78.02%	88.55%
20	18.64%	45.23%	60.63%	30.72%	57.88%	73.94%
100	2.95%	31.07%	52.31%	16.55%	43.01%	64.25%

Table 4. Relative absolute changes of the pc parameter as the result of mechanical filtration by stylus tips of radii 5 µm and 10 µm

CL, µm	r=5 µm Pq= 0.2 µm	r=5 µm Pq=1 µm	r=5 µm Pq=5 µm	r=10 µm Pq=0.2 µm	r=10 µm Pq=1 µm	r=10 µm Pq=5 µm
2	61.21%	91.10%	98.08%	79.19%	95.45%	98.95%
20	28.15%	80.37%	95.67%	56.29%	89.83%	97.70%
100	3.22%	60.84%	90.94%	25.32%	78.95%	95.31%

Table 5. Relative absolute changes of the vc parameter as the result of mechanical filtration by stylus tips of radii 5 µm and 10 µm

CL, µm	r=5 µm Pq= 0.2 µm	r=5 µm Pq=1 µm	r=5 µm Pq=5 µm	r=10 µm Pq=0.2 µm	r=10 µm Pq=1 µm	r=10 µm Pq=5 µm
2	164.17%	76.12%	84.04%	146.87%	84.00%	91.71%
20	28.72%	82.33%	70.38%	45.04%	86.51%	81.24%
100	4.49%	46.42%	67.50%	25.92%	57.93%	76.33%

Mechanical filtration by stylus tip causes decrease in amplitude parameters. Changes of maximum parameters are a little bigger than those of average parameters like Pa and Pq. Profile slope also decreases, its changes is bigger than of height parameters. Horizontal parameters, like PSm and correlation length increase. Changes are greater for initial smaller parameter values. Standard deviation of peak height decreases, peak density and curvature also decrease. Changes of valleys parameter are similar to those of peak; however valleys height decrease is smaller than peak amplitude change. Height of peaks and valleys usually decrease as the result of mechanical filtration.

After mechanical filtration profile became more asymmetric; the parameters Psk and Pku increase. The emptiness coefficient Pp/Pt also increases.

Generally relative changes of parameters of the same height are larger for smaller initial value of spacing parameters like PSm and CL. However the changes of profiles with the same correlation length are higher for larger initial height. It seems that initial values of spacing parameters are more important.

The tendency was found that parameter changes were higher for bigger sizes of stylus tip. The application of tip with radius of 2 µm caused small changes of profile parameters of initial value of Pq parameter 0.2 µm and correlation length of 100 µm.

Figures 3 and 4 present profiles details before and after mechanical filtration by spherical probes.

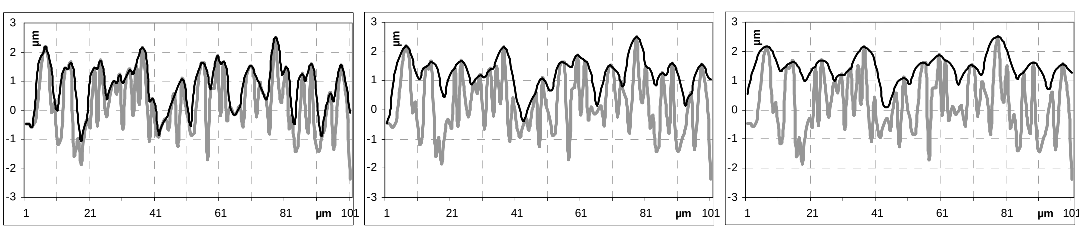

Figure 3. Detail of profile (Pq = 1 µm, CL = 2 µm) – grey line and profile after mechanical filtration by spherical tip - black line. The tip radius r = 2 µm (a), 5 µm (b) and 10 µm (c)

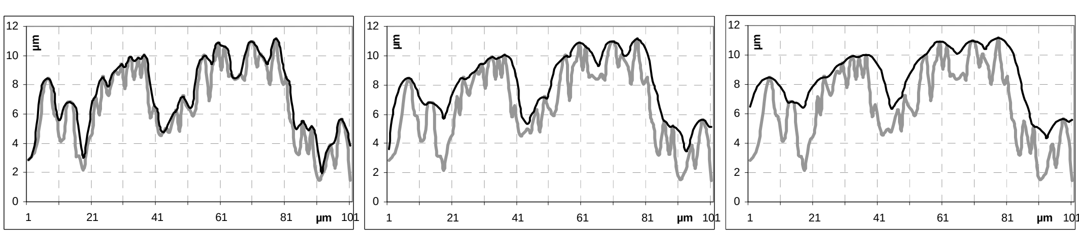

Figure 4. Detail of profile (Pq = 5 µm, CL = 100 µm) – grey line and profile after mechanical filtration by spherical tip - black line. The tip radius r = 2 µm (a), 5 µm (b) and 10 µm (c)

Two-process profiles

Profiles after 2 processes were simulated using described above procedure. The correlation length of plateau (peak) part was called CLp and of valley part CLv. Two cases were analysed: when CLp was not bigger than CLv (first case characteristic for plateau honed surfaces) and when CLp was bigger than CLv (second case characteristic for surface after a low wear process). Pmq parameter was higher than 50%. In first case horizontal parameters, like CL and PSm were larger. Table 6 presents selected parameters of 6 analysed profiles. Table 7 shows parameters of these profiles after mechanical filtration by spherical tip of radius 2 μm, Table 8 - 5 μm, but Table 9 – 10 μm.

Table 6. Parameters of two-process profiles

Parameter / Profie	Ppq μm	Pvq μm	Pmq %	PSk -	CLp μm	CLv μm	CL μm	Pq μm	PSm μm	PΔq -	pc 1/ μm	vc 1/ μm
B1	1.14	4.95	50.1	-2.127	40	300	229.59	2.80	35.31	0.49	0.91	0.92
B2	0.96	4.96	50.2	-2.142	300	40	34.27	2.74	18.33	1.12	1.62	1.81
B3	0.20	5.02	49.8	-2.251	2	20	14.95	2.84	12.55	1.54	2.14	2.51
B4	0.11	5.05	50.3	-2.266	20	2	1.29	2.87	5.04	2.93	4.75	6.44
B5	0.12	5.02	83.2	-3.461	40	300	177.01	1.13	103.70	0.25	0.24	0.25
B6	0.115	4.9	84.6	-4.081	300	40	15.96	1.14	26.77	0.63	0.52	0.66

Table 7. Parameters of two-process profiles after mechanical filtration by spherical stylus tip of radius 2 μm

Parameter / Profile	Ppq μm	Pvq μm	Pmq %	PSk -	CL μm	Pq μm	PSm μm	PΔq -	pc 1/ μm	vc 1/ μm
B1	1.10	4.16	66.8	-2.148	229.38	2.72	52.51	0.36	0.42	0.55
B2	0.71	3.99	62.3	-2.263	34.39	2.20	32.13	0.63	0.34	0.69
B3	0.16	4.17	65.0	-2.738	14.24	1.93	25.92	0.74	0.33	0.78
B4	0.09	2.5	65.2	-3.487	3.70	0.68	10.78	0.55	0.34	0.79
B5	0.10	3.41	82.1	-3.551	170.96	1.02	157.54	0.18	0.11	0.15
B6	0.08	3.40	88.8	-5.014	14.10	0.73	30.45	0.32	0.09	0.22

Table 8. Parameters of two-process profiles after mechanical filtration by spherical stylus tip of radius 5 μm

Parameter / Profile	Ppq μm	Pvq μm	Pmq %	PSk -	CL μm	Pq μm	PSm μm	PΔq -	pc 1/ μm	vc 1/ μm
B1	1.06	4.06	65.5	-2.159	230.09	2.64	70.62	0.27	0.18	0.37
B2	0.73	3.60	70.4	-2.284	35.60	1.82	41.80	0.40	0.16	0.38
B3	0.13	3.55	73.7	-3.196	13.98	1.35	33.44	0.43	0.16	0.39
B4	0.085	0.45	75.8	-4.079	4.74	0.28	9.15	0.18	0.14	0.27
B5	0.10	3.16	82.9	-3.634	167.79	0.92	199.80	0.13	0.08	0.10
B6	0.08	2.67	92.1	-5.867	13.39	0.47	32.90	0.17	0.05	0.10

Table 9. Parameters of two-process profiles after mechanical filtration by spherical stylus tip of radius 10 μm

Parameter / Profile	Ppq μm	Pvq μm	Pmq %	PSk -	CL μm	Pq μm	PSm μm	PΔq -	pc 1/ μm	vc 1/ μm
B1	1.03	4.01	66.1	-2.176	230.35	2.58	87.15	0.21	0.10	0.28
B2	0.72	3.00	74.4	-2.120	41.58	1.52	44.52	0.26	0.09	0.26
B3	0.12	2.75	78.6	-3.505	15.46	0.92	35.31	0.24	0.09	0.23
B4	0.075	0.45	89.4	-3.155	7.08	0.17	10.81	0.09	0.08	0.15
B5	0.10	2.88	83.0	-3.722	165.49	0.84	182.04	0.10	0.06	0.08
B6	0.07	2.16	83.0	-6.461	13.96	0.33	31.63	0.10	0.03	0.06

The tendencies of parameters changes caused by mechanical filtration of two-process profiles were similar to those of profiles of normal ordinate distribution. Height parameters decreased; the changes were higher for profiles from second case. Changes in maximum height parameters were smaller than those of statistical parameters. As example, in first case, the maximum change of Pq parameter was 56%, but of Pt parameter 36%, when stylus tip of radius 2 μm was used. In the second case the changes were larger.

Changes of most of horizontal and hybrid parameters were higher for the second case than in the first case and those of profiles of normal ordinate distribution. Horizontal parameters increased as the result of mechanical filtration. Increases of the PSm parameter were higher those of CL parameter; maximum change of PSm was 160%, but CL 15% for stylus tip of 5 µm radius and the first cases. For the second case, these changes were higher. Surface slope decreased; these changes were higher than those of height parameters. It is the result of the fact that slope depends on spacing and height profile features. Maximum slope decrease was 45% when stylus tip of 2 µm radius was applied (first case) and 81% (second case). Peak and valleys curvatures decreased; the changes of peak curvatures were bigger. Peak height decreased; similarly to other parameters changes were larger for the second case.

Parameters describing the shape of the profile ordinate distribution usually decreased (maximum change of Pp/Pt was 21%, but of Pku 56 for the highest analysed tip radius) for the first case. The values of the Pku parameter increased (maximum change was 90%). In the second case the possibility of Psk and Pp/Pt increase and of Pku decrease occurred. It can be explained by difficulty of stylus tip penetration to the bottoms of valleys of small width.

The changes of parameters from the standards ISO 13565-2 and ISO 13565-3 were also studied. These parameter are commonly used for two-process surface topography description. Similarly to other analysed parameters the biggest changes of profiles belonging to the second case occurred. The decrease of parameters Pvq and Pvk took place. Decrease of the Pk parameter was smaller. Usually Ppq parameter values also decreased. However parameters Pmq, Pmr1 and Pmr2 increased for most of the profiles. Similar character of changed of profiles belonging to the first group took place.

The described analysis was carried out for sampling interval equal to 1 µm. Tendency of changes in parameters describing profile height was the same for higher sampling interval used. However dependencies of frequency-dependent parameters could be changed. For example increase of the sampling interval caused similar changes of radii of peaks and valleys. Some of the tested profiles were unrealistic. However the intention of the present authors was to find the tendency of profile distortion caused by tip radius increase.

Figures 5 and 6 present details of two-process profiles belonging to the first and second cases, respectively, before and after mechanical filtration by spherical probes.

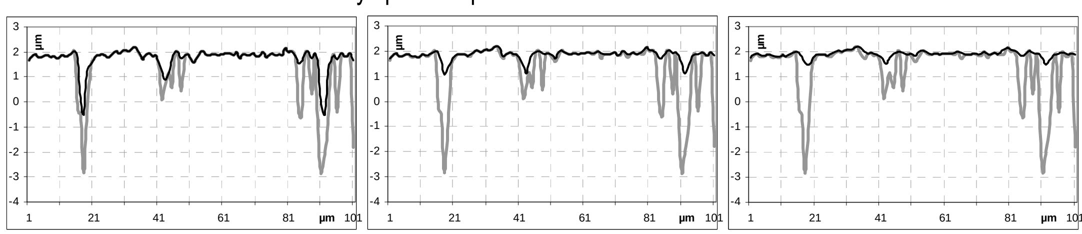

Figure 5. Detail of profile B3 – grey line and profile after mechanical filtration by spherical tip – black line. The tip radius r = 2 µm (a), 5 µm (b) and 10 µm (c)

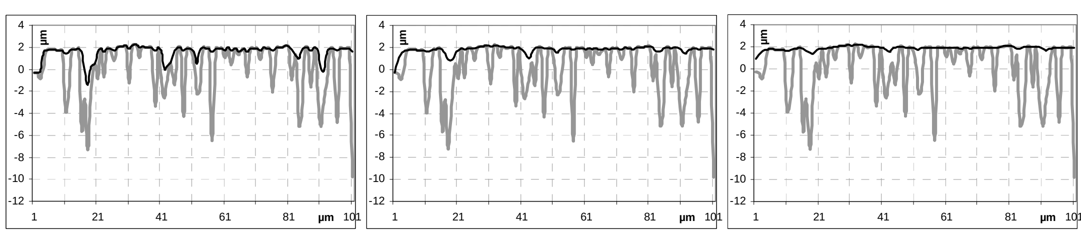

Figure 6. Detail of profile B4 – grey line and profile after mechanical filtration by spherical tip – black line. The tip radius r = 2 µm (a), 5 µm (b) and 10 µm (c)

Conclusions

Today reference data are needed to check accuracy of the algorithms and output parameters from the software. The mechanical filtration by the stylus tip can be predicted numerically. Input of surface data can be obtained either from digital input from 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. It also removes the need to filter out the unwanted wavelengths from the measured surface. Furthermore, surface modeling and simulation of the effect of stylus tip radius on the results of surface topography measurement ensure decrease of cost and time of experimental investigation.

Measurement of surface profiles by stylus tip of spherical radius causes changes in profile parameters. Profile height, slope and peak density decrease, main wavelength and peak radius increase. Changes of parameters are higher for higher radius of the probe tip.

Distortion of one-process profile of normal ordinate distribution depends on ratios between profile height and correlation length and between profile height and tip radius. Changes in profile shape are the highest for the highest profile height and the smallest correlation length.

Character of profile after two processes distortion is more complicated than that of one-process profile of Gaussian ordinate distribution. Changes of profile shape caused by mechanical filtration by stylus tip can be large when the main wavelength of plateau part is higher than that of valley part.

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