METHODS OF RECONSTRUCTION OF SURFACE PROFILES MEASURED BY STYLUS METHOD

Sławomir Górka, Paweł Pawlus

Abstract: *The paper shows information of distortion of measurement results by stylus method. The review of surface topography reconstruction method is presented. These methods were used by the present authors to reconstruct one-process and two-process modeled and measured profiles. In the final part of the paper, example results of surface profile reconstruction are given.*

Keywords: *Surface topography, stylus method, surface reconstruction, simulation*

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

Introduction

Profile measurement using stylus technique still plays an important role in the assessment of surface topography. There are the following advantages of this method: short measurement time, the ability to provide information about surface topography and low cost of instrument.

As the stylus scans the surface, the pick-up converts the mechanical movement of the stylus to an electrical signal (via transducer) which is transmitted to computer (see Figure 1).

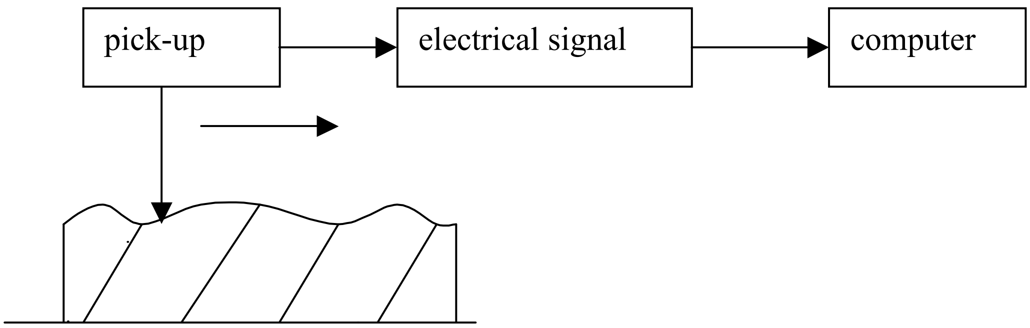

Fig. 1. Schematic diagram of stylus instrument

The pick-up is made from the following elements: the stylus, the transducer and/or the skid. The skidless pick-up is fixed rigidly to a reference plane, which is usually the datum bar inside the traverse unit.

The stylus is not mathematical point, it has finite dimension. According to ISO standards a stylus may have an included angle of 60 or 90 degrees and a tip radius of curvature of 2, 5 or 10 micrometers. But sometimes flat styli are used.

The stylus tip radius is very important in measuring of surface topography. The so-called mechanical filtration is done during the stylus tip movement. The effect of tip radius is larger than the influence of flank angle. This mechanical filtration effect is similar to low-pass digital filtration. As the result of it, the measured surface height decreased, but main wavelength increased. The distortion of surface topography depends on its shape and on dimension of stylus tip. The lower sizes of the stylus tip causes smaller distortions of the results of measurement, but tips of small dimensions are expensive, they are also subjected to wear. Figure 2 presents shapes of new and worn stylus tip.

a b

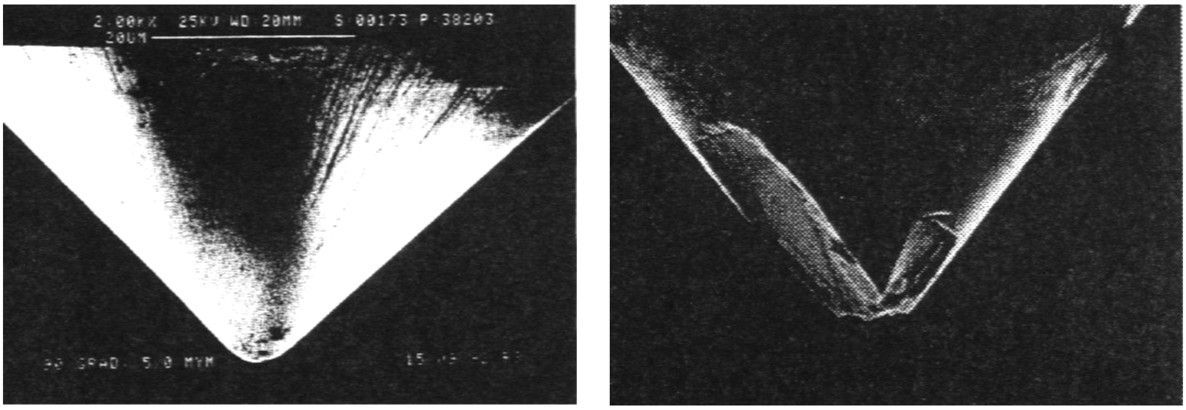

Fig. 2. New (a) and damaged stylus tip (b)

Stylus tip does not penetrate narrow valleys or wavelengths smaller than tip radius. Shunmugam and Radhakrishnan found that mechanical filtration caused distortion of features 10 times larger than stylus tip size [Shunmugam, 1976]. Distortion of surfaces after typical manufacturing processes owing to surface measurement by stylus tip with probe radius of 2 μm is low, but application of 10 μm radius causes decrease of the Ra parameter of 10-15% [Whitehouse, 1974]. However due to use of tip of smaller dimension distortion of very fine (smooth) surfaces can be large, because these surfaces contain very small wavelengths [Hillman, 1984]. Usually for surfaces created in one machining process bigger height corresponds to larger wavelengths, however this problem of two-process textures (plateau-honed cylinder surface is the typical example) is more complicated and therefore distortion of the measurement results of such surfaces can be sometimes substantial [Pawlus, 2004; Pawlus, 2002]. The problem is not only stylus tip curvature, but also its local changes [Vorburger, 1979]. The authors of the papers [Elewa, 1986; Trumpold, 2000; O'Donnell, 1993; Poon, 1995; Chetwynd, 1979; Mendeleyev, 1997; Wu, 1999; Shunmugam, 1974; Radhakrishnan, 1970; Vorburger, 1998; de Vries, 1985] also analysed measurement errors caused by mechanical filtration, most of them simulated co-action between the stylus tip and surface.

Because the problem of surface measurement results distortion by stylus tip of finite sizes is of great practical importance, scientists tried to solve the task of surface reconstruction. Since the mentioned problem is very substantial for very smooth surfaces, the scientists analysed mainly the results of measurement by Scanning Probe Microscopes (SPM). However reconstruction of surfaces measured by stylus method was also studied [Villarubia, 1994]. Some stylus instruments contain software for measured surface topography reconstruction.

Methods of surface topography reconstruction

Methods of surface texture reconstruction can be divided into 2 groups:

- when the shape of tip in unknown,
- when the shape of tip is known.

In the first group it is first necessary to obtain the shape of the stylus tip (blind reconstruction methods). Two approaches are commonly used. In the first of them the shape of tip can be obtained using similar technique to razor-blade method. The razor-blade profiles are clearly the best for showing the actual shape of the stylus tip (see Figure 3).

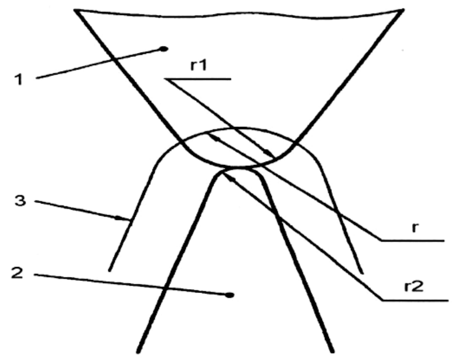

Fig. 3. The idea of razor-blade method [Wieczorowski, 1996]

Figure 4 presents idea of blind reconstruction method. It was described in papers [Villarubia, 1994, 1996, 1997; Dongmo, 1996, 2000]**.** In Figure 4a the shape of tip is presented as well as the fragment of original (simulated) profile. The idea of this method consists on the overlapping of the maxima 1 and 2, searching for their joint parts (shaded in the Figure 4b) being the new peak. Its peak is superimposed on the third maximum 3 (see figure 4c). Then the upper envelope of its new peak is found similarly to razor-blade technique. The reconstructed stylus tip is shown in Figure 4d.

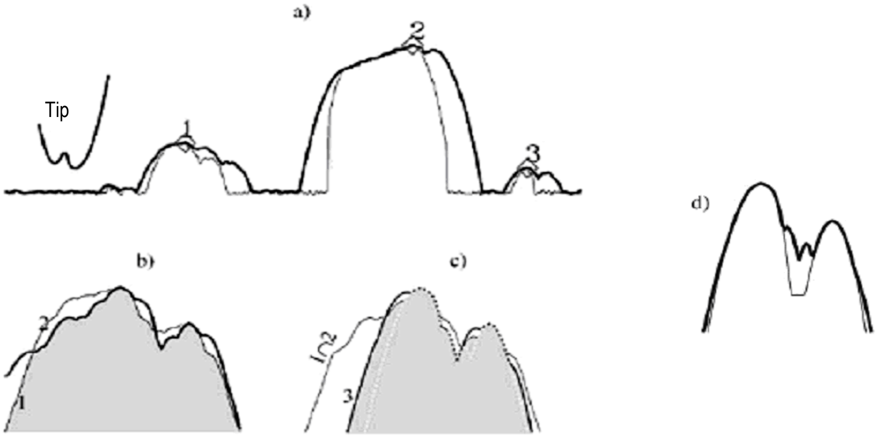

Fig. 4. The idea of method of blind tip reconstruction (description in text)

Usefulness of this method was checked [Górka, 2011]. The authors of paper [Dongmo, 1996] presented the method of the radius of tip estimation. It consists of erosion (lower envelope) following by dilation (upper envelope) of image when radius of envelope "r" increased. Erosion followed by dilation is called opening procedure. The difference between the experimental image and the open image can be quantified repeating several tomes the opening procedure, for r smaller and larger than the real tip radius and evaluating the differences allows us to fix the upper limit for the effective tip radius (see Figure 5). This method was detailed described in Reference [Górka, 2009].

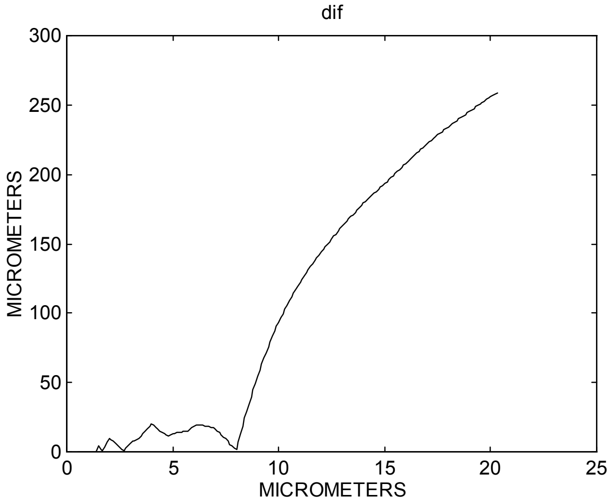

Fig. 5. Plot of the difference between open images and original images – the radius of peak was 8 μm

When the shape of tip is known the reconstruction relies on using the upper envelope of measured profile.

There are several methods of reconstruction of measured surface topography. The first of them depends on the analysis of initial profile parameters on these distortion. The aim of this approach is to find what tips cannot be used for surface topography after selected machining Dongmo et al. [Dongmo, 1998] used this method with regard to measured surfaces if known shape.

Reconstruction of surface topography on the basis of known shape of stylus tip is another possibility. The initial approaches used geometrical dependences [Chicon, 1987;Keller, 1991;Odin, 1994; Pingali, 1994; Reiss, 1990; Watts, 1997]. Figure 6 presents an idea of method used in work [Watts, 1997].

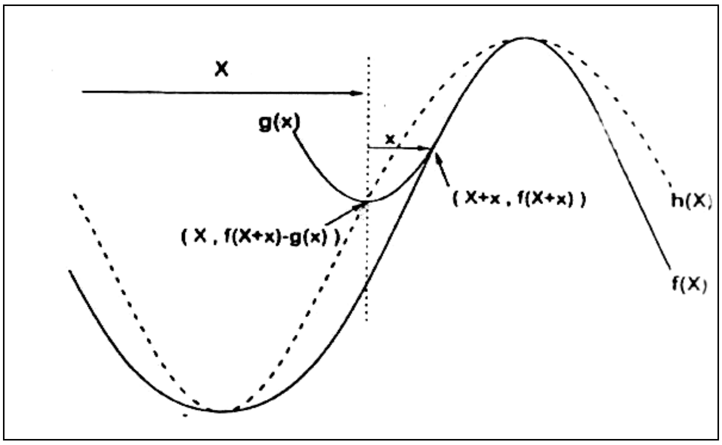

Figure 6. Scheme of method of surface profile reconstruction by geometric method - f(X) is original surface, h(X) – distorted surface, g(x) – shape of stylus tip. Point (X+x, f(X+x)) is contact point of stylus tip with measured surface. Point (X, f(X+x)-g(x)) is obtained position of stylus tip as the result of measurement.

Profile (shape) of stylus tip is determined by the following equation:

$$g(x) = f(X+x) - h(X) \quad (1)$$

x is lateral distance between position of peak of stylus tip and its contact point with surface. One can find:

$$g'(x) = f'(X+x) \quad (2)$$

It means that in contact point slopes (derivatives) of tip and surface are the same. Therefore:

$$g'(x) = \frac{d}{dx} f(X + x) - \frac{d}{dx} h(X)$$
$$g'(x) = f'(X + x)\left(1 + \frac{dX}{dx}\right) - h'(X)\frac{dX}{dx} \tag{3}$$

After inserting for left side of equation (3) value from equation (2) one can obtain:

$$\frac{dX}{dx} f'(X + x) - h'(X) = 0 \tag{4}$$

so:

$$f'(X + x) = h'(X) \tag{5}$$

It means that slope in contact point of the tip with surface (equal to slope of stylus tip) and slope of distorted profile is the same. Therefore it is possible to obtain coordinates of the original surface on the basis of measured profile and the shape of stylus tip. The application of this method to areal (3D) surface topography measurement is possible, however its idea was presented in relation to 2D profile.

However in majority of methods presently used the lower envelope of distorted surface profile is applied [Villarubia, 1997; Dietzsch, 2004, 2005; Keller, 1993; Krystek, 2004]. It is not necessary to use derivative, therefore this method this method is not sensitive on presence of individual peaks. However not all the surface points can be correctly reconstructed. Figure 7 presents an idea of this method on the basis of paper [Dietzsch, 2004].

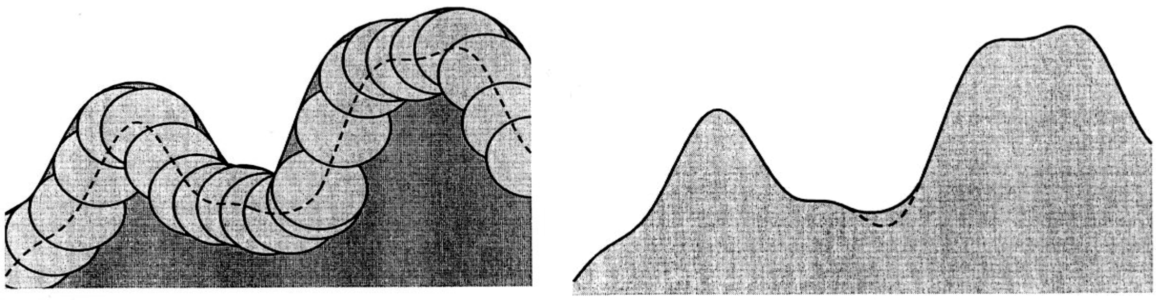

Fig. 7. Scheme of surface profile reconstruction by lower envelope method. Solid line – reconstructed profile, dashed line – original profile

Scope of research

In order to proper asses the quality of surface profile reconstruction the shapes of the original profiles should be known. Therefore the mechanical filtration was simulated. The method elaborated by Wu [Wu, 1999] was used (see Figure 8)

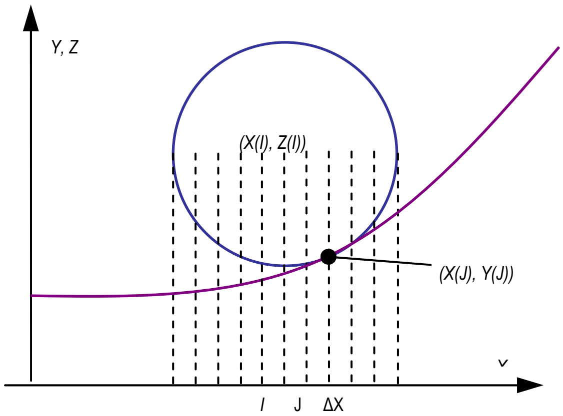

Fig. 8. Method of mechanical filtration simulation

It was assumed in model that the radius of stylus tip is equal to r and that elastic and plastic deformation didn't occur.

Point of contact has coordinates X(J), Y(J), but center of stylus tip: X(I), Z(I). Index J of contact point was found as the result of searching of discrete points in order to obtain maximum of the function:

$$H(J)+Z(J)=Z(I)=\max_k(H(k)+Y(k))$$

where:

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

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

The so-called edge problem on outer profile details exists. It was solved by the assumption that profile close to end points was flat. The special software was developed. Its correctness was verified by comparing the results of the calculation with those obtained with application of software elaborated by Villarbia [ftp.nist.gov/pub/spm_morph]. The mechanical filtration by probe tips with radii of 2 μm, 5 μm and 10 μm was done.

The sensitivity of the profile type on surface profile distortion due to mechanical filtration and then reconstruction may be better assessed when surface profiles of desired shape can be simulated. One-process random profiles of Gaussian ordinate distribution was modeled using the procedure developed by Wu [Wu, 2000]. Each profile of exponential shape of the autocorrelation function is characterized by the following parameters: standard deviation of height Pq and correlation length (horizontal parameter) – the distance at which autocorrelation function slowly decayed to the desired value (0.1) [Whitehouse, 1970].

Reconstruction results of 2-process profiles is more complicated. The parameters describing surface after 2 processes can be calculated from the probability plot of material ratio curve (ISO 13565-3). The intersection point on normal probability graph of abscissa Pmq defines the separation of plateau and base textures and is an important feature of the model. The proposed plateau roughness Ppq, valley roughness Pvq and Pmq are three parameters characterising two-process surface. The slope of each presented straight lines gives the Pq roughness of the corresponding process. Also the transition characteristic (plateau depth Pd) can be estimated [Pawlus, 2008].

The following procedure should be done in order to simulate two-process profile:

1. Creation two Gaussian profiles PP (plateau) and PV (valley) with correlation lengths and standard deviations as parameters characterizing them.
2. The choice of the distance (Pd) between the mean lines of the profiles (the centres of the 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) [40].

Figure 9 presents example of creation of 2-process profile.

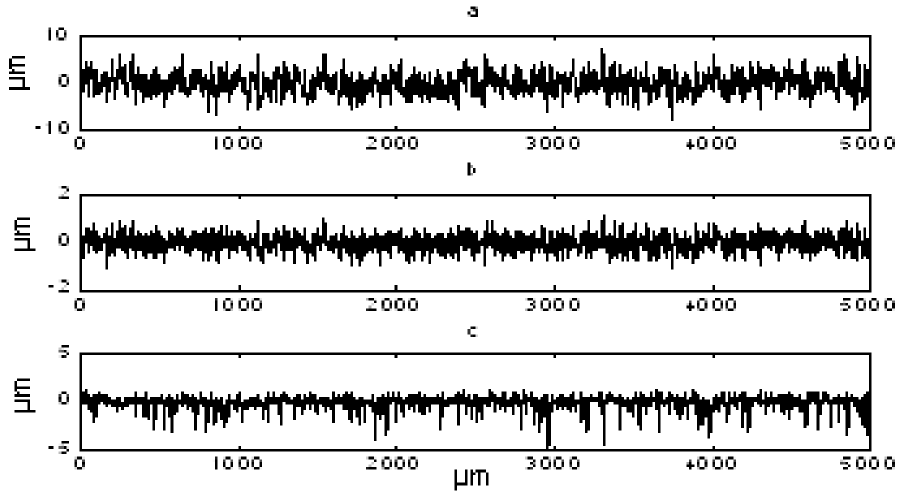

Fig. 9. Computer creation of two-process profile: valley profile (a), plateau profile (b), resulting two-process profile (c)

- Profiles measured by stylus tip of 2 µm radius were also subjected to mechanical filtration.
- In order to analyse the possibilities of reconstruction of simulated profile the special software was elaborated. First, geometrical method presented above was used. It is possible to reconstruct only some points of the profiles. Three methods were used to determine coordinates of the other points:
  - these points were connected by straight line (GS),
  - points of distorted profile were left (GD).
  - these points were connected by curve resulting from enveloped method (GE).

The envelope method (E) was also used.

The geometric methods (GS, GD and GE) depend on calculation of the radius of distorted profile and then checking slope of stylus tip. It is possible to find in what point tip slope is equal to measured profile slope and using mathematical (trigonometric) dependences obtain point of reconstructed profile. Since slopes of surface image and profile are not the same, the absolute values of slope differences were calculated on the basis of it, the smallest value was selected.

Envelope method (O) relies on application of lower envelope of the distorted profile. Envelope means position of the centre of the wheel. The especially elaborated software was used for stylus tip of wheel shape. For other tip shapes, the software developed by Villarubia [Chicon, 1987] can be applied. The correctness of reconstruction was assessed using coefficient of linear correlation.

Results and discussion

First, the reconstruction of one-process profiles will be analysed.

It was found that after reconstruction information about profile was not substantially improved when profile distortion be mechanical filtration was high. Due to reconstruction, the statistical parameters characterizing amplitude such as Pa and Pq usually decreased. However changes in parameter describing maximum height like Pz was small. Better values of profile slope, peak curvature and usually peak density and horizontal parameters were obtained as a result of reconstruction. Application of reconstruction caused also improvement of estimation of peak height above mean line. After reconstruction the parameters characterizing valleys like density, curvature and height had worse values in comparison to measured profiles.

However the coefficient of linear correlation between reconstructed and original profiles was usually higher than that between measured and original profiles. Only application of GE method assured sometimes smaller values of linear correlation coefficient. Information about ratio of Pda/Pdq (ratios of average slope to rms. slope) was more distorted after this method usage. However some other parameters were improved after this method usage. In all the cases applications of GS and GD methods caused increase in the linear correlation coefficient. After GD method application the resulted standard deviation of height was comparatively high. Application of GS method caused similar results to those after use of the envelope method (E), although standard deviation of profile amplitude was a little smaller after the GS method application.

Reconstruction of profile by envelope method (E) caused the biggest increase of linear correlation coefficient of reconstructed profile with original profile from the use of all the tested methods, for example from 0.24 to 0.35 or from 0.39 to 0.52.

Generally profile reconstruction using all the analysed methods caused similar results. The proper effect of profile reconstruction was larger when the distortion of profile by mechanical filtration was smaller. Better results were obtained when sampling interval was smaller than the radius of tip. For larger sampling interval errors of parameters depending on it (like slope) can be larger.

Figure 10 presents original profile, distorted profile and profile reconstructed using GS and E methods. The linear coefficient of correlation increased from 0.39 to 0.49 after using GS method, but from 0.39 to 0.51 after E method application.

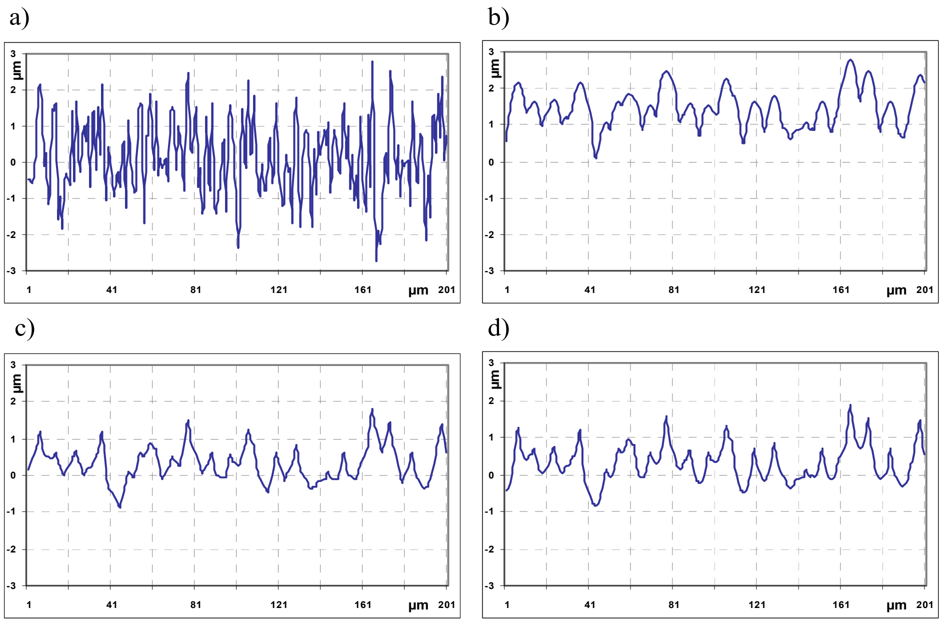

Fig. 10. Details of original (a), distorted profile (b), reconstructed profile using GS method (c) and E method (d)

Figure 11 presents modeled profile after mechanical filtration by spherical tip of radii r = 2 µm, 5 µm, 10 µm (upper envelopes) and lower envelopes of distorted profiles (reconstructed profile) using the same tips. As seen, only the envelope method as the best from al the tested methods was used here.

The radius of stylus tip was 2 µm (left), 5 µm (middle) and 10 µm (right).

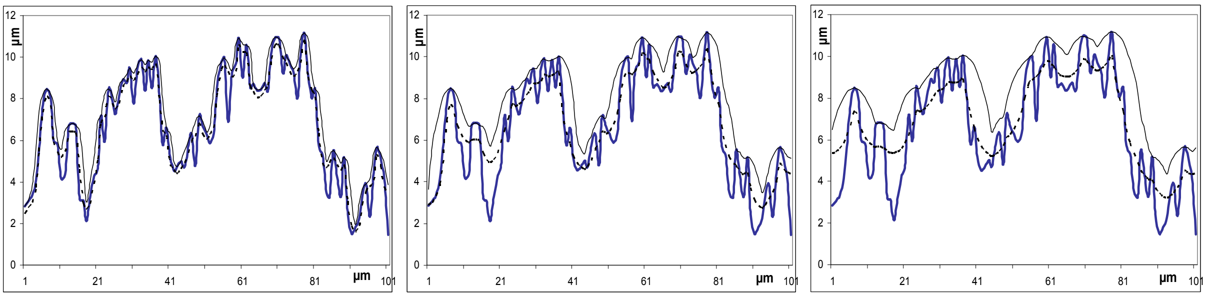

Fig. 11. Fragment of irregularity profile (Rq = 5 µm – thick line), profile detail after mechanical filtration by spherical tip (thin line) and detail of lower envelope of distorted profile (dashed line)

In addition measured profiles after grinding by stylus tip of 2 µm radius were analysed. These profiles were not seriously distorted by mechanical filtration therefore after reconstruction their parameters were improved. It concerns horizontal parameters like PSm and correlation length which decreased after reconstruction, average height parameters like Pa and Pq, slope and peak height and density (these parameters increased after reconstruction). In the majority of cases profile reconstruction led to increase of linear correlation coefficient between measured (reconstructed) and original profiles.

Next, the reconstruction of 2-process profiles will be analysed. It was found that after reconstruction, parameters characterizing the maximum height decreased or increased. When lower envelope was used (E method) the parameters characterizing the average height increased, so reconstruction improved these values. After using geometrical method, this parameter increased or decreased, however the errors were the lowest after using the GS method, larger after GD and the largest after GE method application. Similarly to profiles of Gaussian ordinate distribution GE method usage caused the biggest errors of the ratio of slopes Pda/Pdq estimation, although some other parameters were reconstructed properly. The asymmetry of the ordinate distribution is very important feature of two-process surface. It can be characterized by the emptiness coefficient Pp/Pt or the skewness Psk. It is difficult to say what method is the best in the emptiness coefficient estimation. However in most cases the values of skewness Psk (and of kurtosis Pku) was the closest to that of initial profile when reconstruction was done by envelope method (E). Application of envelope method did not cause peak and valley density changes comparing to distorted profile. Similar observation was done with regard to profiles of Gaussian ordinate distribution.

Generally reconstruction led to better values of profile slope, peak curvatures and usually peak density as well as horizontal parameters. Reconstruction method allowed to better estimation of standard deviation of peak height and peak height above the mean line.

In general, the reconstruction caused increase of the linear correlation coefficient in comparison to pair: measured profile-distorted profile. Only in some cases after GE method application this coefficient decreased, in other cases – increased. The worst results were achieved after GE method application, but better after GD and then GS method usage. But generally envelope method (E) assured the best results of profile reconstruction. The highest values of linear correlation coefficient were achieved for not distorted profiles (about 0.99) – it corresponds to the case of larger correlation length of valley part in comparison to that of plateau part (plateau honed cylinder is typical example of such profile).

The increase of sampling interval caused some changes of errors of parameters depending of sampling interval like slope and peak curvature of reconstructed surface.

Similar research were done with regard to plateau-honed cylinder profiles measured by stylus tip of 2 µm radius. The mechanical filtration by probe tip of 10 µm radius was done with subsequent reconstruction by envelope method (E). Generally the results were similar above (of simulated profiles).

Figure 12 presents detail of modeled 2-process profiles distorted by simulated mechanical filtration of 10 µm radius and the same details of reconstructed profile using GS and E method. The correlation coefficient between modeled and distorted profiles was 0.81, the profile reconstruction by GS method led us to increase this coefficient to 0.87, by E method to 0.89. The values of selected profile parameters are also presented.

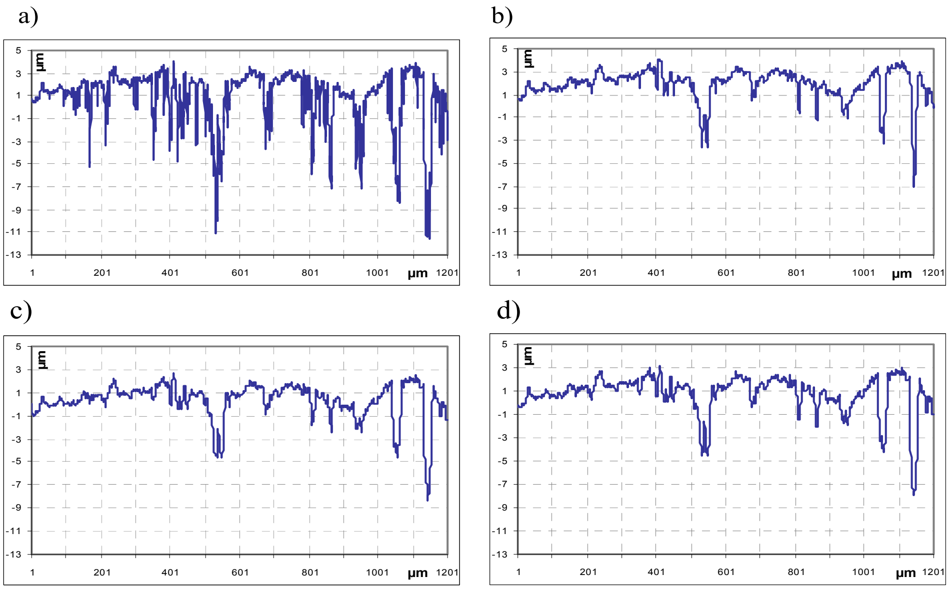

Fig. 12. a) Detail of modeled profile – Pq = 2.74µm, PΔq = 1.12, PSk = -1.34, b) its profile after simulated mechanical filtration by stylus tip of 10 µm radius – Pq = 1.52 µm, PΔq = 0.26, PSk = -1.3, c) reconstructed profile by GS method – Pq = 1.68 µm, PΔq = 0.24, PSk = -1.27, d) reconstructed profile by E method - Pq = 1.77 µm, PΔq =0.26, PSk = -1.29

Conclusions

Geometrical and envelope methods of surface profile reconstruction were studied and compared. From among these methods the lower envelope method and geometrical method depending on not-reconstructed point connection by straight line are the best for one-process profiles. However the envelope method was recommended by the present authors. It is especially useful for surface profile not seriously distorted by mechanical filtration.

Envelope method was also found as the best for two-process (stratified) profiles reconstruction. After this method application the values of amplitude parameters Pa and Pq were usually improved.

Generally, the profile reconstruction caused increase of linear correlation coefficient in comparison to pair: measured profile – original profile.

Computer simulations of one-process and two-process profiles as well as of co-action between stylus tip and surface topography (mechanical filtration) are useful tools during analysis of surface reconstruction.

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