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Reconstruction of stylus tip geometry

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Abstract

Two existing methods of stylus tip geometry reconstruction were studied. Computer generated and measured random surfaces were the objects of the investigations. The benefits of creating connected profiles for tip reconstruction was discussed. The effect of quantisation error on tip reconstruction accuracy was analysed.

Keywords: surface topography; roughness; stylus measurement; tip shape reconstruction.

Rekonstrukcja kształtu stykowej końcówki pomiarowej

Streszczenie

Istnieją dwie najczęściej stosowane metody rekonstrukcji kształtu końcówki pomiarowej stosowanej podczas pomiarów stykowych struktury geometrycznej powierzchni. Zasadą pierwszej z nich jest znajdowanie części wspólnej kolejnych wierzchołków. Metoda druga polega na stosowaniu obwiedni dolnej, a następnie górnej mierzonego profilu, przy stale wzrastającym promieniu obwiedni, co prowadzi do określenia promienia końcówki pomiarowej. Metody te były analizowane w niniejszej pracy. Przedmiotem analizy były powierzchnie mierzone oraz generowane komputerowo o zróżnicowanym rozkładzie rzędnych. Zastosowano bezwymiarowe ilościowe i jakościowe wskaźniki dokładności rekonstrukcji. Oryginalną propozycją autorów jest łączenie kolejnych profili ułatwiające szacowanie kształtu końcówki pomiarowej. Przeanalizowano również wpływ błędu kwantyzacji na dokładność rekonstrukcji. Stwierdzono przydatność obu analizowanych metod. Metoda polegająca na estymacji promienia końcówki pomiarowej jest mniej wrażliwa na błędy pomiaru.

Słowa kluczowe: struktura geometryczna powierzchni, pomiary stykowe, rekonstrukcja kształtu końcówki pomiarowej.

1. Introduction

Stylus measurement is the most known profiling method. 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. The filtering behaviour of tip depends on not penetrating narrow valleys or irregularities of wavelengths smaller than tip radius. This effect is similar to frequency low-pass digital filtering, so is called "mechanical filtration". The smallest measured wavelength is similar to dimension of measuring tip. Whitehouse found that the application of probe radius of 2 μm for the measurement of typical engineering surfaces caused very small decrease of *Rq* parameter. But after 10 μm tip radius using the profile height was decreased to 10-15% [1]. However the application of tips of smaller sizes can cause distortion of the results of very smooth surfaces measurement [2]. It was shown that the measuring error strongly depended on ratio of the correlation distance (at which the autocorrelation function decays to 1/e value) to the *Rq* parameter [3]. Similar research was done in order to study distortion of simulated fractal profile by mechanical filtration [4]. The authors of [5] presented a 3D computer simulation of measuring non-Gaussian random surfaces with arbitrary tip shapes, studying both the surface distortion and the stylus contact distribution.

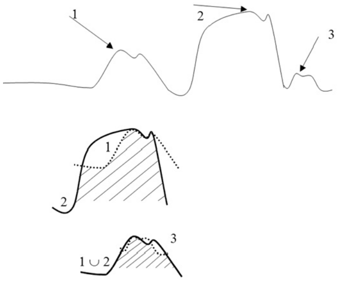
Because the shape and size of the stylus tip strongly influences the measuring results, there is a widely recognized need for checking the tip size of stylus-type surface measuring instruments [6, 7, 8]. When the tip geometry is known the surface reconstruction can be done. In the majority of papers the mathematical morphology erosion (lower envelope) operation was used [9, 10]. The authors of papers [11, 12, 13] compared slopes of the tip, true profile and image profile in true and apparent points of contact. The authors of [11] developed an algorithm to reconstruct the real sample surface from the apparent surface image seen by a scanning tunnelling microscope and found that the differences between the apparent image and the reconstructed surface were significant. It was shown that the local curvature of the true, undistorted sample surface was the sum of curvatures of the tip and the distorted image surface [12]. The authors of [13] showed by comparing the optical and mechanical measurement that it is possible to determine the effective radius of curvature of the Talystep and AFM styli. The authors of [14] introduced correction factors between the true and experimental rms roughness height values in order to obtain real values of this parameter. Wang and Whitehouse used the neural networks for the reconstruction of image [15].

The fundamental aims of the investigations are to modify existing tip reconstruction methods and to study the effect of measurement errors on the tip reconstruction accuracy. The present authors also compared two methods of stylus tip reconstruction.

2. Methods and materials

The methods of tip reconstruction are presented in papers: [9, 10, 16, 17, 18, 19, 20 and 21]. Figure 1 presents the idea of most frequently used method (after [16]). Firstly, the operation of producing surface image should be modelled as dilation [22]. The purpose of blind reconstruction is to extract the part concerning the tip [16]. All image protrusions (peaks) can be considered as tip images, each broadened in different ways by the different underlying surface features. Figure 1 shows surface image. Three of the maxima are labelled 1, 2 and 3 (see upper graph). Middle graph shows two curves corresponding to the actual tip. We rule out any tip larger than the intersection of the two independently derived tips. This intersection, represented by the shaded area is a better estimate of tip shape than either curve taken alone. Lower graph presents the improvement by including maximum 3 along with the result of the previous step. The extension of additional maxima follows in a similar manner [16].

The authors of paper [18] presented the other method of the radius of tip estimation. It depends on an erosion following by a dilation when radius of simulated tip "*r*" increases. Dilation consists of calculating the maximum value of an original image in a given neighbourhood.



Rys. 1. Ilustracja metody rekonstrukcji kształtu końcówki pomiarowej
Fig. 1. The idea of the method of blind tip reconstruction

The neighbourhood is called the structuring element (here the structuring element is the tip itself). The dilation is performed over the specimen surface represented by it height variation. The result of applying the erosion process [22] to the dilated image is to shrink the protrusions. The restored image is then improved. An erosion followed by a dilation is called an opening procedure. The difference between the open image and the experimental (dilated) image can be quantified by difference function being the sum of absolute values of experimental image and open image heights for all surface points. Repeating several times the opening procedure, for values of r smaller and larger than the real tip radius r_r and evaluating the differences and allows us to fix the upper limit for the effective tip radius. When $r > r_r$ the difference should rapidly increase since the narrowest structures of the image are destroyed during the erosion step and cannot be restored during the dilation step.

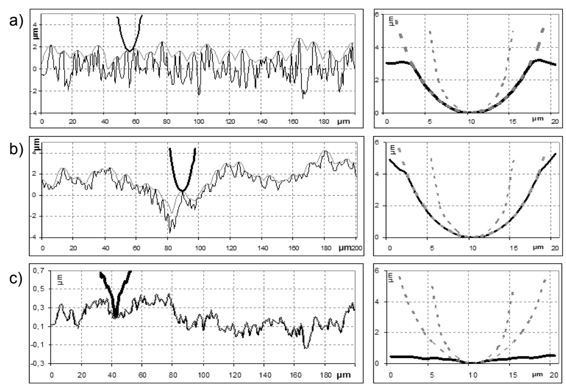
Computer generated random profiles were the objects of investigations. The measured surface topographies were also analyzed. The experimental investigations were carried out using Perthometer S8P measuring equipment. It operated with tips of 2 µm, 5 µm and 10 µm radii. The sampling interval was 0.7 µm in the measurement direction. In order to obtain the information about the real shapes of the stylus tips, the razor-blade technique was applied.

3. Results and discussion

3.1. The analysis of simulated surfaces

True and reconstructed tip shapes were compared when points of tip peaks coincided. The average values of absolute height distance between reconstructed and true tips were calculated. In the first criterion the distance d_1 was computed on horizontal length equalled to diameter of stylus tip. This criterion was used for the assessment of all the tip reconstruction accuracy. In the second criterion the distance d_2 was computed only in places when height distance between true and reconstructed probes was smaller than $0.05r$. When this criterion was applied, usually only reconstruction near the tip peak was assessed. The tip shape reconstruction was better when d_1 and d_2 distances were smaller (they approach zero). These distances were divided by true radius of probe tip – therefore the non-dimensional coefficients $W_{n1} = d_1/r$ and $W_{n2} = d_2/r$ were obtained. Third quantitative criterion is the ratio of the number of points n_2, for which the height distance between real and simulated probes was smaller than $0.05r$ to the number of points n_d corresponding to the diameter of stylus tip $I_2 = n_2/n_d$ (it approaches 1). The qualitative criterion $J_2 = W_{n2}/(I_2\ n_2)$ was applied (it approached 0 for good tip reconstruction accuracy). When only tip radius was estimated, the absolute values of relative errors were calculated.

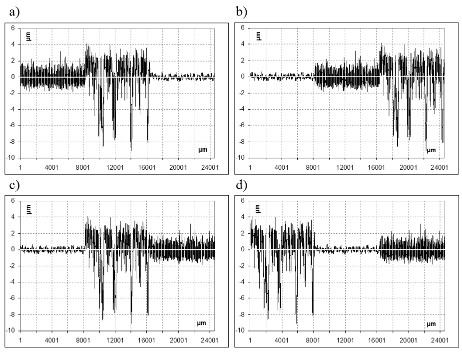
We analysed a lot of simulated surface topographies similar to real random surfaces. The computer generated profiles were subjected to simulated mechanical filtering by 2D wheels of commonly used radii (2, 5 and 10 µm). The use of method proposed by Villarubia [9, 10] leads to correct estimation of stylus tip shape. We found that when profile distortion by mechanical filtration was small, the tip reconstruction method gave good results only in zone near the peak of the tip, because stylus only close to its peak contacted the surface. The tip shape was better estimated when profile change was big, since more stylus points were in contact with the surface. It was found that distortion of Gaussian profile caused by tip mechanical filtration could be great when roughness height was big and spacing (horizontal) parameters small. Distortion of profiles after 2 processes can be great especially when spacing parameters of plateau part are larger than those of valley part. Figure 2a shows the fragment of the original Gaussian profile, of profile obtained after mechanical filtration (r = 10 µm) and shape of reconstructed tip. This profile of small main wavelength seems to be seriously distorted by mechanical filtration. Figure 2b presents similar graphs concerning profile after 2 processes, also subjected to comparatively great distortion. In these 2 cases the shape of tip was correctly reconstructed. However Figure 2c presents analogical graphs concerning Gaussian profile of small amplitude and large main wavelength. We see that the tip reconstruction (right graph) assured good results only near the peak of the stylus tip. These findings were confirmed during the analysis of tip reconstruction accuracy measures: for curves shown in Figure 2a W_{n1} was 0.0995, W_{n2} was 0, I_2 was 0.714, J_2 was 0, in Figure 2b W_{n1} was 0.0576, W_{n2} was 0, I_2 was 0.81, J_2 was 0, but in Figure 2c W_{n1} was 0.2334, W_{n2} was 0.0073, I_2 was 0.333, J_2 was 0.0031.



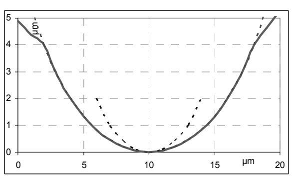
Rys. 2. Rysunki lewe: fragmenty profili oryginalnych (linie grube), ich obwiednie (linie cienkie) oraz kształty rekonstruowanych końcówek pomiarowych. Rysunki prawe: kształty rekonstruowanych końcówek pomiarowych (linie ciągłe), kształty nominalnych końcówek o promieniach 5 µm i 10 µm (linie przerywane). Rysunki (a) i (c) dotyczą profili o normalnym rozkładzie rzędnych o znacznym i niewielkim zniekształceniu mechaniczną filtracją, rysunek (c) dotyczy profilu dwu-procesowego
Fig. 2. Left graphs: details of the original profiles (thick line), their upper envelopes (thin line) and shapes of reconstructed stylus tips. Right graphs: shapes of reconstructed stylus tips (solid line), the shapes of the nominal stylus tips of radii 5 µm and 10 µm (dashed lines). Figures (a) and (c) correspond to Gaussian profiles subjected to large and small distortion by mechanical filtration, respectively, Figure (b) corresponds to two-process profile

In order to obtain precise shape of the stylus tip one should analyse the profiles considerably distorted. The analysis of set of profiles can be helpful. Two methods can be used. The analysis of the distortion of some individual profiles is the first of them. However this method is difficult and time consuming. It is necessary to study many reconstructed stylus tips. The procedure of selection of proper stylus shape is not easy. The study of connected profiles is the second possibility. It is original contribution of present authors. The following procedure should be used. Firstly, after levelling, straight mean lines of separate profiles should be determined. Next, all the profiles should be positioned in this way that their mean lines should be on the same height of 0 ordinate. In order to eliminate of the false curvature in the place of profiles connection few points from the preceding and following profiles should be removed and they ought to be replaced by points of straight mean line of 0 ordinate. The distance between the neighbouring profiles connected by straight line should be not smaller than the probe tip diameter. We found that this method was easier and usually gave better results than the analysis of some separate profiles. As the example the profiles, which details were shown in Figure 2 were joined. The value of W_{n1} relative error was 0.0576, of W_{n2} and J_2 were 0, of I_2 was 0.81. However the measures of reconstruction accuracy of 3 connected profiles were: (average values) W_{n1} = 0.1302, W_{n2} = 0.0024, I_2 = 0.619, J_2 = 0.001. As can be seen, all the measures of tip reconstruction accuracy were improved. The reconstruction accuracy of connected profiles were the same as for the profile, for which the tip shape was the best reconstructed, independently on the profiles order. Figure 3 presents various successions of connected profiles measured by tip of 10 µm radius. Detail of the first profile shown in Figure 3a was presented in Figure 2a, second – Figure 2b, third – Figure 2c. Figure 4 presents the shape of reconstructed tip and of nominal tips of 5 µm and 10 µm radii. In each case the same results of tip shape reconstruction were obtained.

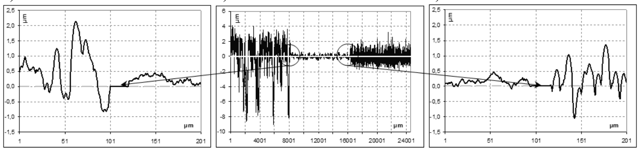
Figure 5 is helpful for explanation of the profile connection. Middle graph (b) presents joined profiles from Figure 4d; left (a) and right (c) graphs show details of profiles connections. The effect of quantisation error on the accuracy of tip reconstruction was also studied. So far only high-frequency noise influence was analysed [9, 10]. When the number of height levels is smaller than 20 the errors of tip shape reconstruction are great. However for 50 and more levels it can be possible to precisely determine the tip radius. Table 1 presents the average values of measurement accuracy for reconstructed profiles, dependent on signal resolution. It was found that when reconstruction of tip shape was not good the effect of measurement errors on deterioration of reconstruction accuracy was small.



Rys. 3. Profile nierówności po filtracji mechanicznej (r=10 µm) składające się z połączonych profili przy różnej ich kolejności
Fig. 3. The view of connected profiles measured by tip of 10 µm radius, for various profile succession



Rys. 4. Kształt rekonstruowanej końcówki pomiarowej (linia ciągła) otrzymanej jako rezultat analizy połączonego profilu z rysunku 3 oraz kształty nominalnych końcówek o promieniach 5 µm i 10 µm (linie przerywane)
Fig. 4. The shape of reconstructed tip profile (solid line) obtained after analysis of connected profile shown in Figure 3 and shapes of nominal tips of 5 µm and 10 µm radii (dashed lines)

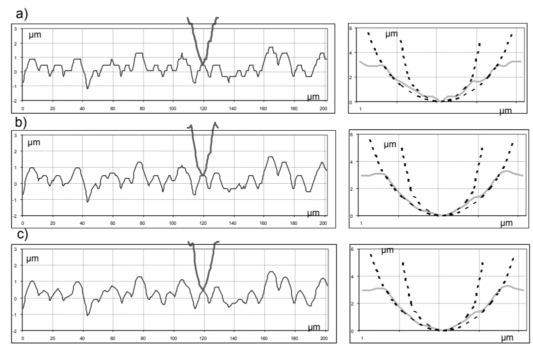


Rys. 5. Fragmenty łączenia między pierwszym i drugim profilem (a), między drugim i trzecim profilem (c) profilu połączonego (b)
Fig. 5. Details of connections of the first and second profile (a), of the second and third profile (c) from the joined profile (b)

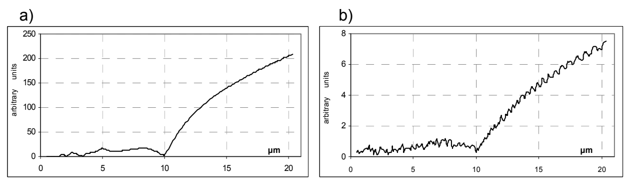
The greatest errors were obtained for small number of quantization levels (10 and then 20). Figure 6 presents the changes of measured profile when the number of height levels were 20, 50 and 100 as well as shapes of the reconstructed stylus tip and of nominal stylus tips of 5 µm and 10 µm radii. The second method based on the estimation of tip radius (described above) [18] was also used. Only the radii of true and reconstructed tips were compared. In the majority of analysed cases it was possible to obtain precise results. Figure 7 shows difference graphs with regard to profiles of low and great distortion by mechanical filtration. The radius of modelled stylus tip was 10 µm. The relative errors of tip radius estimation Δr were 0.5%. The quantisation errors caused lift of the difference graph. Usually the errors Δr was smaller than 1% when the number of quantisation levels was 100 and 50.

Tab. 1. Miary dokładności rekonstrukcji końcówki pomiarowej w zależności od rozdzielczości pionowej
Tab. 1. Quality of profile tip reconstruction dependent on signal resolution

Criterion of accuracy	W_{n1}		W_{n2}		I_2		J_2	
	Range	Average value	Range	Average value	Range	Average value	Range	Average value
r = 10 µm, 1000 quantization levels	0-0.234	0.107	0-0.0073	0.0025	0.33-1	0.674	0-0.0031	0.0007
r = 10 µm, 20 quantization levels	0.101-0.233	0.139	0.0061-0.0216	0.0146	0.333-0.714	0.516	0.0015-0.0056	0.0028
r = 10 µm, 50 quantization levels	0.065-0.231	0.128	0.0034-0.0203	0.0109	0.333-0.734	0.595	0.0006-0.0027	0.0015
r = 10 µm, 100 quantization levels	0.044-0.233	0.124	0.0086-0.0192	0.0118	0.333-0.762	0.587	0.001-0.0044	0.002



Rys. 6. Rysunki lewe: kształty profili (linie cienkie) oraz kształty rekonstruowanej końcówki pomiarowej (linie grube). Rysunki prawe: kształty rekonstruowanej końcówki pomiarowej (linie ciągłe) oraz kształty końcówek o nominalnych promieniach 5 µm) oraz 10 µm (linie przerywane). Analiza dotyczy 20 (a), 50 (b) i 100 (c) poziomów kwantyzacji
Fig. 6. Left graphs: the profile details (thin lines) and shapes of reconstructed stylus tip (thick lines). Right graphs: shapes of reconstructed stylus tip (solid lines) and of nominal stylus tips of 5 µm and 10 µm radii (dashed lines). The numbers of height levels were 20 (a), 50 (b) and 100 (c)

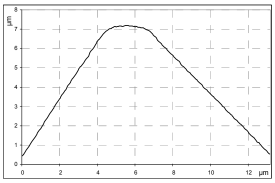


Rys. 7. Wykresy różnic pomiędzy profilem otwartym i zmierzonym profilu o większym (a) i mniejszym (b) zniekształceniu filtracją mechaniczną
Fig. 7. Plots of differences between open and dilated (measured) profiles of great (a) and small distortion (b) by mechanical filtration

3.2. The analysis of measured surfaces

The tip shape was reconstructed in the measurement direction. This procedure can be used during the analysis of anisotropic surface across the lay.

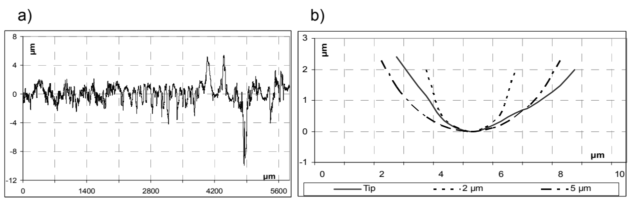
Because the shape of the stylus tip was obtained using not precise razor-blade method, only qualitative comparison of tip contours was done. When only tip radius was estimated, the absolute values of relative errors Δr between estimated and nominal tip radius were calculated. Figure 8 shows the shape of razor blade obtained after using one of the analysed styli.



Rys. 8. Wynik pomiaru ostrza żyletki z zastosowaniem profilometru Perthometer S8P beż ślizgacza. Promień zaokrąglenia końcówki pomiarowej wynosił 2 µm
Fig. 8. Results of the measurement of razor blade with the stylus tip of radius 2 µm of Perthometer S8P profile measurement gauge (without the skid)

In order to improve reconstruction it is necessary to study the results obtained after the analysis of few profiles. The nominal shape of the tip probe should be taken into consideration. It is possible to estimate the tip shape basing on the mean of tip shapes obtained after the analysis of few profiles.

This procedure be accelerated by the analysis of connected profiles. Figure 9 presents the results of this consideration. The obtained shape is very similar to shape presented in Figure 6. However, some sources of errors obtained during profiles connection should be taken into consideration. Profiles should be measured in similar time in order to eliminate the errors caused by tip wear. Measured surface should be well levelled, because the stylus location in reference to the surface (slope) can cause some errors.



Rys. 9. Widok połączonych profili (a) oraz widok rekonstruowanej końcówki pomiarowej o promieniu 2 µm (linia ciągła) profilometru Perthometer S8P oraz kształty nominalnych końcówek pomiarowych o promieniach 2 µm i 5 µm (b)
Fig. 9. Connected profiles (a), reconstructed probe shape of the stylus of radius 2 µm (solid line) of Perthometer S8P profile measurement gauge and shapes of nominal stylus tips of 2 µm and 5 µm radii (b)

The method of reconstruction of tip probe radius [18] was also analysed. The results were often better than obtained by the method of tip shape estimation [9, 10]. In order to obtain the correct tip radius it is necessary to plot tangents of the two linear parts of the obtained curve and search for the point of their crossing. However in some cases it was difficult to obtain straight lines fragments. It was then necessary to analyse various profiles or (better) to connect them. The improvement of the results is then very possible. We can then usually obtain the fragments of two straight lines and obtain the correct radius of the probe. However the errors Δr can be large (up to 10%).

4. Conclusions

1. The applications of two analysed methods of stylus tip probe reconstruction lead to proper results. This finding is based both on qualitative comparisons and quantitative results. The first method allows us on the reconstruction of the tip shape, however the second – on the tip radius estimation. The second method is more robust than the first.
2. When profile distortion by mechanical filtration was small, the tip reconstruction method gave good results only in zone near the peak of the tip. The tip shape was better estimated when profile change was big, because stylus only near its peak contacted the surface. Therefore in order to obtain precise shape of the stylus tip one should analyse the profiles considerably distorted. The analysis of set of profiles is necessary. The study of connected profiles can be helpful. It is original contribution of present authors. Ordinates of the arithmetical mean lines of joined profiles should be the same. The distance between the neighbouring profiles connected by straight line should be not smaller than the probe tip diameter in order to avoid errors in points of profiles connections. We found that this method was easier and usually gave better results than the analysis of some separate profiles.
3. Quantisation errors caused tip reconstruction difficulties. The errors were small when the number of height levels was 100 and more.

5. Literatura

[1] Whitehouse D. J.: Theoretical analysis of stylus integration. CIRP Annals 23/1, 1974, p.181-182.
[2] Hillman W., Kranz O., Eckolt K.: Reliability of roughness measurements using contact stylus instruments with particular reference to results of recent research at the Physikalisch-Technische Bundesanstalt. Wear 97, 1984, p.27-43.
[3] Wu J-J.: Spectral analysis for the effects of stylus tip curvature on measuring isotropic rough surfaces. Meas. Sci. Technol. 13, 2002, p.720-730.
[4] Wu J-J.: Spectral analysis for the effects of stylus tip curvature on measuring fractal profiles. Meas. Sci. Technol. 11, 2000, p.1369-1376.
[5] Tian A., Liu X., Chetwynd DG., Cai Z.: Stylus contact on short wavelength random surfaces: a simulation study. Measurement Sci. Techol. 18, 2007, p.1694-1702.
[6] Rubert P., Frenzel C.: The use of standard specimens to check stylus tip size in surface measuring instruments. XI International Colloquium on Surfaces, Chemnitz (Germany) 2004, part II p.129-138.
[7] Pawlus P.: Mechanical filtration of surface profiles. Measurement 35, 2004, 325-341.
[8] Michalski J., Pawlus P.: Characteristic features of roughness measurement by Form Talysurf Intra profile measurement gauge. Manufacturing Engineering 6/3, 2007, p.59-63.
[9] Villarubia JS.: Morphological estimation of tip geometry for scanned probe microscopy. Surface Science 321,1994, p.287-300.
[10] Villarubia JS.: Algorithms of scanned probe microscope image simulation, surface reconstruction, and tip estimation. J.Res. Natl. Stand. Technol. 102, 1997, p.425-454.
[11] Chicon R., Ortuno M., Abellan J.: An algorithm for surface reconstruction in scanning tunneling microscopy. Surface Science 181,1987, p.107-111.
[12] Keller D.: Reconstruction of STM and AFM images distorted by finite-size tips. Surface Science 253, 1991, p.353-364.
[13] Watts RA., Sambles JR., Hutley MC., Priest TW., Lawrence CR.: A new optical technique for characterizing reference artifacts for surface profilometry. Nanotechnology 8, 1997, p.35-39.
[14] Dongmo S., Vautrot P., Bommet N., Troyon M.: Correction of surface roughness measurement in SPM imaging. Appl. Phys. A 66, 1998, p.819-823.
[15] Wang WL., Whitehouse DJ.: Application of neural networks to the reconstruction of scanning probe microscope images distorted by finite stylus tip. Nanotechnology 6, 1995, p.274-280.
[16] Dongmo LS., Villarubia JS., Jones SN., Renegar TB., Postek MT., Song JF.: Experimental test of blind tip reconstruction for scanning probe microscopy Ultramicroscopy 85, 2000, p.141-153.
[17] Villarubia JS.: Scanned probe microscope tip characterization without calibrated tip characterizers J. Vac. Sci. Technol. B14(2), 1996, p.1518-1521.
[18] Dongmo S., Troyon M., Vautrot P.: Blind restoration method of scanning tunneling and atomic force microscopy images. J. Vac. Sci. Technol B14(2), 1996, p.1552-1556.
[19] Machleidt T., Franke K-H.: Reconstruction of measurements with scanning force microscopes with special image processing algorithms. XI International Colloquium on Surfaces, Chemnitz (Germany) part 1, 2004, p.268-273.
[20] Odin C., Aime JP., El Kaakour Z., Bohaucina T.: Top's finite effects on atomic force microscopy in the contact mode: simple geometrical considerations for rapid estimation of apex radius and tip angle based on the study of polystyrene latex balls. Surface Science 317, 1994, p.321-340.
[21] deVries WR., Li C-J.: Algorithm to deconvolve stylus geometry from surface profile measurement ASME J. Eng. Industry 107, 1985, p.167-174.
[22] ISO 14406: Geometric product specifications (GPS). Extraction 2008.

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