
MICROTOPOGRAPHY – THE PHOTOGRAMMETRIC DETERMINATION OF FRICTION SURFACES

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ABSTRACT

The understanding of friction processes assumes numerous methods for analysing the features and changes of surfaces in micro- and nanoscale. One of these features is the three-dimensional characterisation of the topography of friction surfaces. The combination of digital photogrammetric methods with image acquisition through Scanning Electron Microscopes (SEM) offers the possibility to derive topographic information over a wide scale, the integration of different data sets and the detection of changes. This paper discusses the photogrammetric methods, which are necessary to measure the three-dimensional shape of friction surfaces in microscale and its changes. This includes a bundle adjustment with different imaging geometries, image correlation by least-squares-matching, three-dimensional point determination and the generation of Digital Surface Models. The processing software, developed for this special task, is presented together with some results, which were processed in relation with the Special Research Project „Elementary Friction Processes“ at the Technical University of Berlin.

1 INTRODUCTION

The determination of the topography of friction surfaces is a basic requirement for the analysis, interpretation and understanding of mechanical friction processes. Different models for the description of friction are existing. Physical models describe the processes in atomic dimensions, phenomenological models give explanations for friction processes in macro-scale. Because of these wide ranges in scales, methods for microtopographic surface determination are required, which operate in micro-scale as well as in nano-scale.

Photogrammetric methods, providing solutions for surface determination work nearly independently of the scale. In general, three requirements must be fulfilled: First, an adequate data acquisition system has to be available, second, equations for geometric modeling of the imaging process must be defined, and last, these imaging equations have to be inverted. Thus surface topographies can be derived in different object scales, and also combined in an integrated object space with different model resolutions.

Images from SEM have an excellent depth of focus and can be acquired over a wide range of magnification. Because of these features they are suitable for digital image matching methods. In order to make use of the advantages of digital photogrammetry it is necessary to acquire the image data directly from the SEM without any signal pre-processing. This fact is of importance because of the high requirements in accuracy of 3D-measurement. Beside this, a direct connection enables the operator to choose a suited area for photogrammetric surface determination and offers an image acquisition under optimal conditions concerning the image quality.

In microsciences probes with very different surface structures and texture features are investigated. In order to achieve a largely automated determination of the surface geometry it is necessary to apply suitable processing approaches. The investigated friction surfaces have nearly continuous surfaces, which can be described best with Digital Surface Models (DSM). They have mostly good textures, which make it possible to use area-based matching methods for the determination of correspondent points.

The developed photogrammetric processing software takes special properties of electron microscope images into consideration, i.e. nearly parallel projection and changing imaging conditions. In order to increase the accuracy of three-dimensional point determination, a special bundle adjustment with different imaging models has been implemented, which also offers the possibility of photogrammetric calibration of SEM.

With the known calibration data of the SEM and some rules for the image data acquisition the photogrammetric processing of Digital Surface Models requires mostly only two images. They have to be achieved by tilting the sample on the working stage (Figure 1). A second software package was developed for this task, including image matching by least-squares-adjustment and the processing of Digital Surface Models.

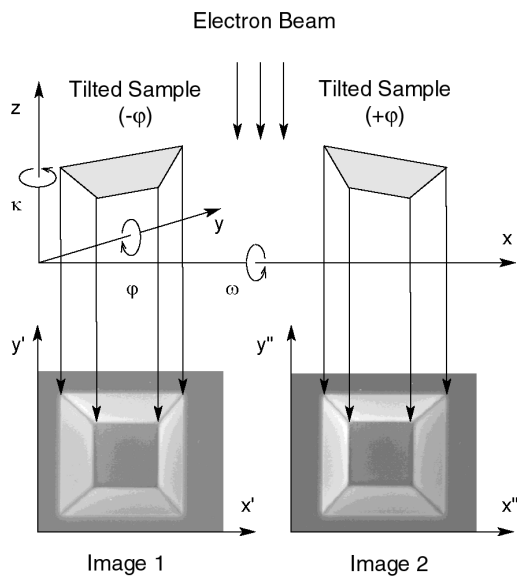


Figure 1. Acquisition of stereo SEM images for photogrammetric evaluation

2 CALIBRATION OF SEM

The calibration of SEM includes the determination of the particular magnification (image scale) and the tilting angles. Depending on the chosen imaging model, the focal length has to be calculated too. Because of the necessity to rotate the sample in a fixed imaging system (like the SEM) the calibration data describe the motion of the working stage. There are two ways to calculate the calibration parameters including the orientation data of the images: First by self calibration techniques and second by using a calibration standard, like special grids with known measures. In addition we have to consider different imaging models depending on the magnification applied: In general a parallel projection model is used as imaging geometry (Figure 2). Only in case of lower magnification, the classical model of central projection is appropriate (Burkhardt 1981, Figure 3).

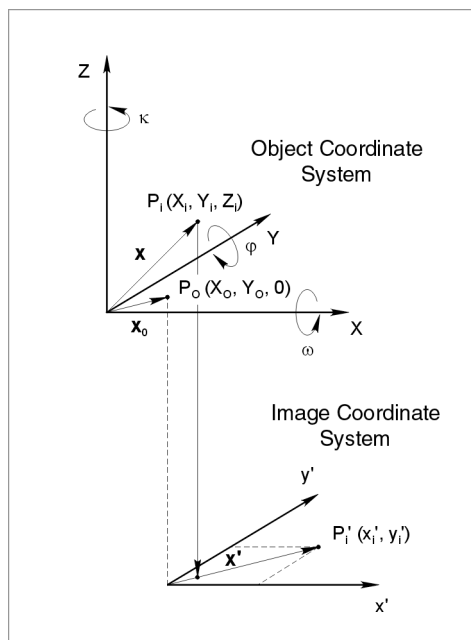


Figure 2. Parallel imaging geometry

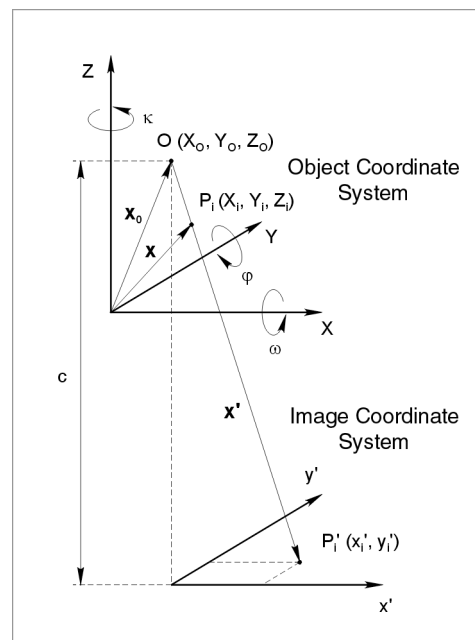


Figure 3. Central projective imaging geometry

Both cases, as well as the possibility to perform a self calibration were implemented in the developed software. Besides the choice of different imaging geometries every parameter can be switched off. This feature makes it possible to reduce the number of unknown parameters, which is very important because of the unsuitable geometrical imaging conditions by using SEM. In general photogrammetric processing of the orientation parameters is based on the calculation of six parameters for every image: three rotations and three translations. In case of using parallel projection, the number of degrees of freedom is reduced to five. If only the tilting angle is used, the unknown parameters are reduced to three per image. Additional parameters for image distortion and scale (in x- and y-direction) have to be investigated, because the conditions of image acquisition do not remain constant in the SEM. The spatial distribution of the control-points plays a very important role for calibration and especially self calibration. Because of the necessity of spatial distributed control points, when using central projection, a suitable calibration object has to be chosen. We used a silicon sample with defined edge length (Figure 4). For higher magnifications an industrial grid may be used, because, applying parallel projection, there is no need to use control points in depth. In this case we used a grid with known measures (Figure 5).

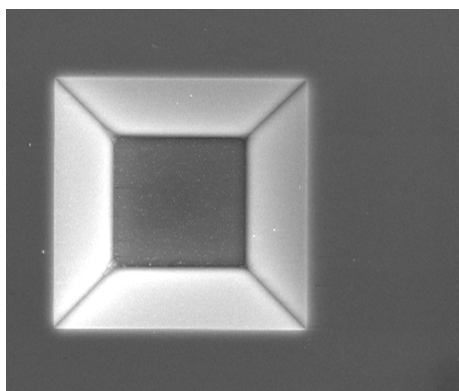


Figure 4. SEM image of silicon sample (magnification 500:1)

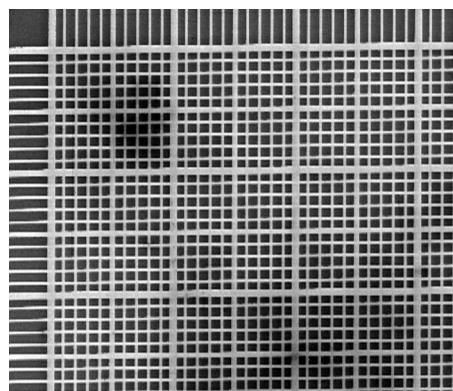


Figure 5. SEM image of industrial grid (magnification 500:1)

The photogrammetric calibration of the SEM Zeiss DSM 960 yields very small imaging errors. The geometric image distortions, especially the spiral distortion (which is typical for SEM-imaging), are below the accuracy for point measurement and matching in sub-pixel-range (see Table 1).

Calibration of REM Zeiss DSM 960	
Magnification 500:1 Reference object: Industrial grid (Figure 5) Number of Images: 7 Number of control points per image: 12	Distortion model: $\Delta x' = k_1 \cdot (x'^3 + x' \cdot y'^2)$ $\Delta y' = k_2 \cdot (y'^3 + x'^2 \cdot y')$
Projection type	Parallel projection
Parameters per image	4
Scale [Pixel/ μm]	2,742
Radial distortions	$k_1 = 0,0293 \cdot 10^{-6}$ $k_2 = 0,0053 \cdot 10^{-6}$
Redundancy	136
m_0	1,865

Table 1. Calibration of SEM with industrial grid, determination of distortion parameters

Because of the spatial distribution of the control points of the silicon sample, we could perform a comparison between calibration results using central versus parallel projection (Table 2). The results show the unstable mathematical conditions in case of using central projection in this scale. Changes in the geometrical model, like the reduction of the number of unknown orientation parameters lead to very different results for the focal length. These and further investigations show that applying parallel projection is the adequate method for photogrammetric processing in higher scales.

Calibration of REM Zeiss DSM 960				
Magnification 500:1				
Reference object: Silicon sample (Figure 4)				
Number of Images: 6				
Number of control points per image: 8				
Projection type	Central projection		Parallel projection	
Parameters per image	4	6	3	5
Tilt angle ω_1 [°]	14,53	14,47	15,44	15,44
Tilt angle ω_2 [°]	9,78	9,74	10,27	10,30
Tilt angle ω_3 [°]	6,00	5,94	6,18	6,19
Tilt angle ω_4 [°]	-2,90	-2,90	-3,23	-3,26
Tilt angle ω_5 [°]	-7,54	-7,47	-8,23	-8,25
Tilt angle ω_6 [°]	-11,31	-11,26	-12,13	-12,15
Focal length [μm]	-1138	-1704		
Scale [Pixel/ μm]			2,863	2,865
Redundancy	71	59	77	65
m_0	4,098	1,644	3,517	3,055

Table 2. Calibration of SEM with silicon sample, comparison between different image geometries

3 PHOTOGRAMMETRIC PROCESSING OF DIGITAL SURFACE MODELS

For the processing of the topography of friction samples with nearly continuous surfaces and good texture features an area-based matching method is applied. Assuming successful results from the matching process, the data obtained can be used for a Digital Surface Model (DSM) after the three-dimensional point determination.

The applied method of image correlation is widely used, yielding reliable results with images presenting a good surface texture (König et al., 1987). First, a normalised cross-correlation is applied in order to calculate approximate values for the least-squares matching (LSM). The LSM-method uses a geometric and a radiometric transformation on the basis of a least-squares estimation in order to compensate both distortions of the image information and differences in brightness and contrast. Resolving a system of equations containing all geometric and radiometric coefficients yields results in the subpixel range.

The next step is the determination of the 3D point coordinates. If only a small number of points is considered it is advantageous to determine these points within a bundle adjustment, because this method yields the highest accuracy. Because the same software package - as already described for calibration - is used, different geometrical models and orientation parameter sets can be applied. For the determination of a large number of points, required for instance to reconstruct a whole surface, a spatial intersection on the basis of parallel or central projective imaging equations, using known orientation parameters from the calibration of the SEM, is used. On the assumption that the images are only tilted, it is possible to determine object coordinates for the corresponding image coordinates with simple triangulation formulas (Burkhardt, 1981). Tilting angle, scale factor and, in case of central projection, the focal length must be known from a previous calibration. If these parameters are only known approximately, the resulting object coordinates from this algorithm may serve as approximate values for a bundle adjustment.

With the aim of making photogrammetric processing for a high number of data sets easier, a software package with graphical user interface was developed beside the already described bundle adjustment. This software comprises image matching with least-squares-adjustment, object point determination and DSM generation with height triangulation. For the processing of the Digital Surface Models and derived products as presented in this paper we use commercial software. Best results were achieved by using Kriging as DSM generation method which is provided for instance from Golden Software's Surfer.

4 EXAMPLES

In relation with the photogrammetric determination of the topography of friction surfaces there are two different main tasks. The first task is bridging of different scales in the topography data. Figures 6, 7 and 8 illustrate the possibilities, which are provided through photogrammetric methods. The used sample consists of a polymer friction material, which can be seen in SEM-images with a scale of 100:1 (Figure 6) and 1000:1 (Figure 7). The contour line plots, which represent the evaluated DSM are made from SEM-image pairs in scales 100:1, 250:1, 500:1 and 1000:1 (Figure 8).

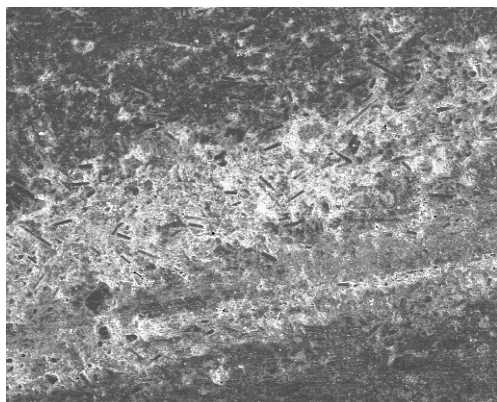


Figure 6. SEM image of polymer friction sample (magnification 100:1)

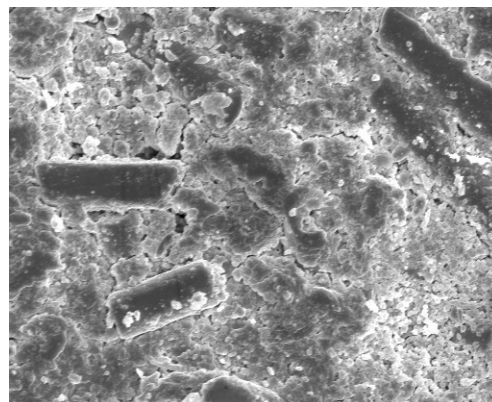


Figure 7. SEM image of polymer friction sample (magnification 1000:1)

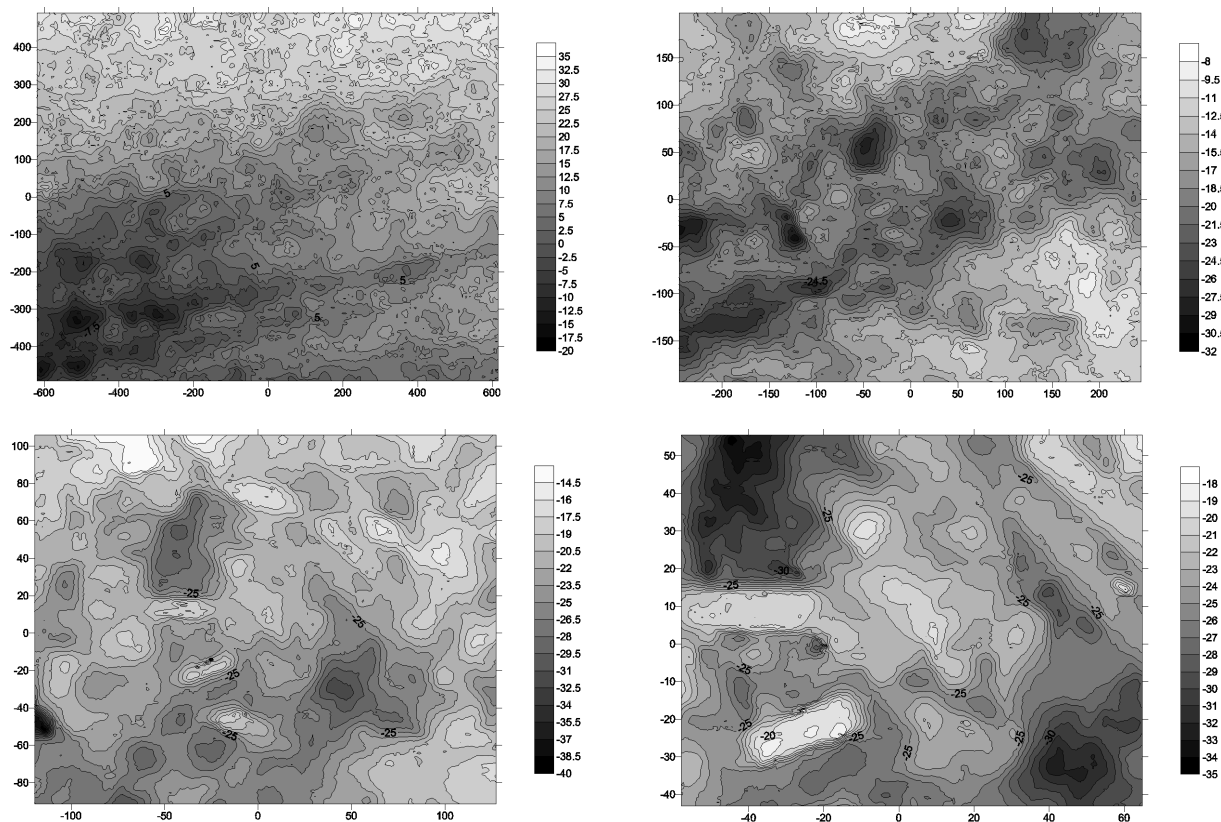


Figure 8. Polymer friction sample, contour maps of four DSMs with different resolution (all measures in μm)

The second task is the detection of changes from friction processes. For that purpose another friction sample in shape of a disk with a diameter of about 50 mm was prepared. A radial groove serves as marking for the assignment of the different data sets before and after the friction process (Figures 9 and 10). Figure 11 and Figure 12 show the DSM before and after the treatment in a friction experiment. For the assignment of the surface models, an image matching between the ground of the groove of the different data sets was performed. From this points the object coordinates were calculated, which serve as reference points in a spatial least-squares transformation. After the transformation of the surface data, a difference DSM was calculated. A part of it was chosen for further analysis (Table 3). It is presented in Figure 13 and Figure 14, showing the erosion volume of the friction process.



Figure 9. SEM image of sample before friction process (25:1)



Figure 10. SEM image of sample after friction process (25:1)

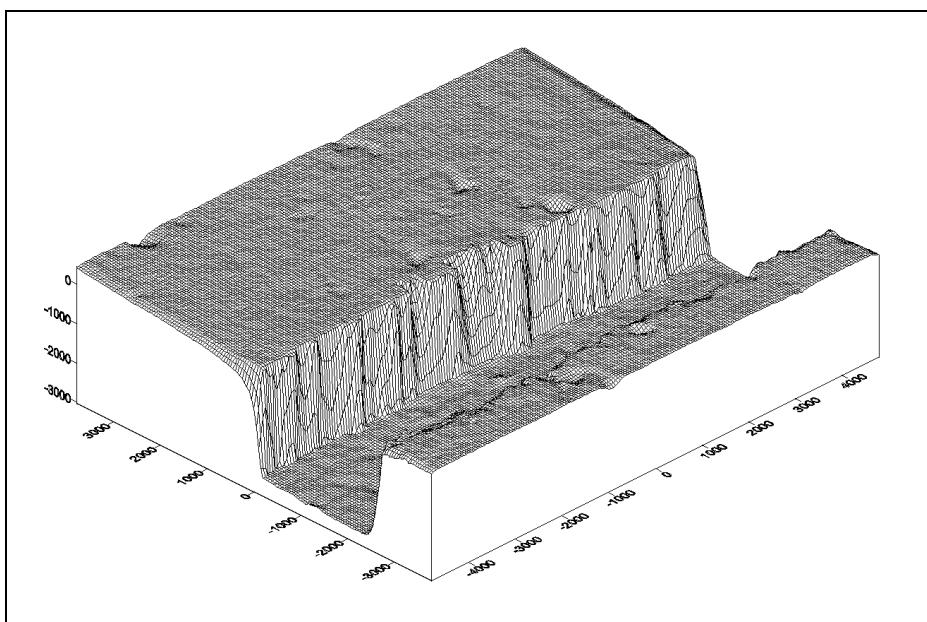


Figure 11. DSM of sample before friction process (measures in μm)

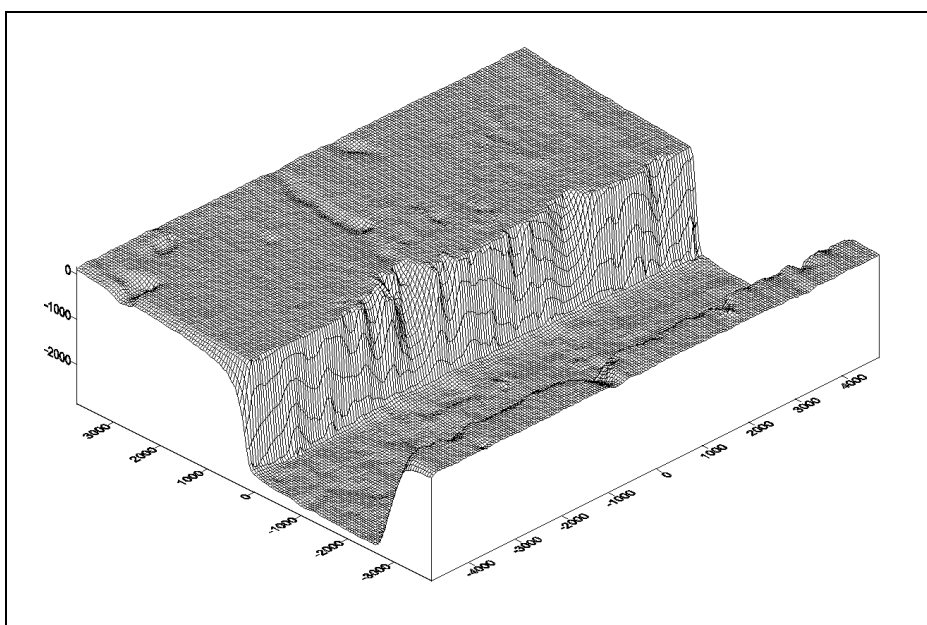
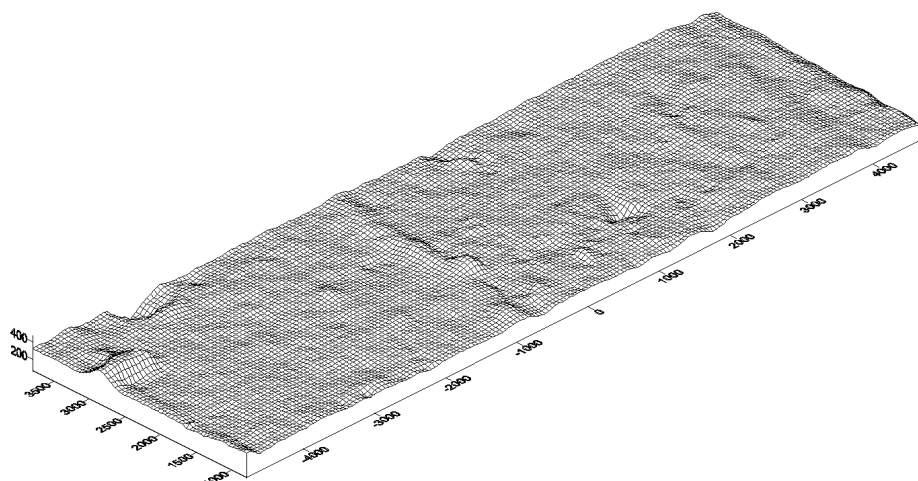
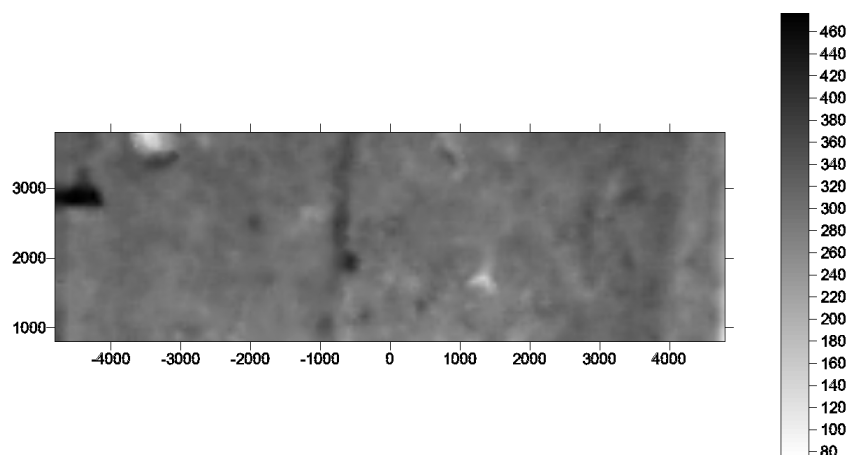


Figure 12. DSM of sample after friction process (measures in μm)

Area [mm ²]	28,8
Erosion volume [mm ³]	8,75
Minimal erosion height [mm]	0,07
Maximal erosion height [mm]	0,48
Mean erosion height [mm]	0,30

Table 3. Volume calculations

Figure 13. Difference DSM of the upper part of the friction sample (measures in μm)Figure 14. Erosion of the upper part of the friction sample (measures in μm)

5 CONCLUSIONS

Photogrammetric processing of the topography of friction surfaces, as well as the surfaces of other samples in microsciences is an effective and accurate method for the geometrical quantisation of chemical and physical processes in micro-scales. In order to achieve highest accuracy a special bundle adjustment and efficient image correlation is necessary, which was developed especially for that purpose. All calculations have to be performed in subpixel range, because of the low resolution of SEM images. The presented results demonstrate, that photogrammetric techniques provide high quality and accurate microtopographic data for further analysis. This will contribute to a better understanding and visualization of friction processes in a wide range of different object scales. Further work is to be done in the integration of SEM-images and relating DSM data of different regions and times over a wide scale in a spatial information system, which provide this data for material scientists and others.

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