

A detailed, high-magnification microscopic image of a surface, showing a complex, interconnected network of ridges and valleys, characteristic of a rough or porous material. The image is rendered in a blue and yellow color scheme.

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Precise calculation of wear based on comparison of initial and worn surface topographies

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Abstract

Wear characterization is an important component of researches in tribology. A method to precisely calculate the wear volume and to determine the topographical change of the surface, based on comparison of initial and worn surface topographies, has been developed for 3D optical measurements. By rotating the worn surface into a parallel position with the initial surface and subsequently correlating both surfaces, rotation and translation errors can be eliminated. In order to reconstruct the surface topography after rotation, diverse interpolation methods are implemented. The topographical difference of both surfaces and the deviation of the surface matching will be also presented.

Keywords: Wear measurement, Surface matching, Interpolation

1. Introduction

Wear characterization is an important component of researches in tribology. Calculation of wear volume and observation of topographical changes are often needed in the tribological researches. For this reason methods of wear measurement based on comparison of initial and worn surface topographies have been developed. These methods can be summarized in solving an image “matching” problem. In Ref. [1], the matching process was carried out by using several correlation kernels extracted from one surface to correlate with a second surface and simultaneously by varying the tilt angles and elevation of the surface. This method has been optimized in Ref. [2], in which the matching problem is considered as a mathematical optimization problem to solve the unknown parameters (3 rotation errors and 3 translation errors). In this paper a method, in which linear features outside the wear zone of the surfaces are used as references, will be presented. This kind of feature can be created by mechanical processing, laser machining or may be already present on the surfaces. These features are also very useful to find the approximately same location before and after wear in the measurements.

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2. Wear measurement method

A rolling test was carried out to investigate the influence of the anti-wear additives on surface topographies in the running-in process. The topographical data was acquired by a white-light interferometer with a 20x objective. Fig. 1 shows the stitched topographies of the initial and worn surface.

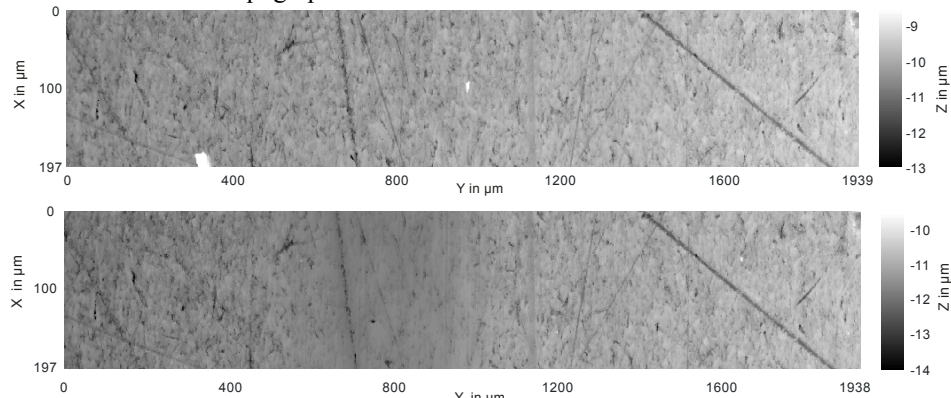


Fig. 1. above: Stitched topography of the initial surface; below: Stitched topography of the worn surface.

In general, the wear can be defined as difference between the initial and the worn surface topography. But translation and rotation errors always exist in the measurements. These errors can be corrected by image processing techniques as follows:

1. The worn surface is rotated to an orientation that is parallel to the initial surface.
2. The worn surface is rotated around the normal vector of the surface in order to eliminate the rotation error remaining in this direction.
3. The translation errors can be removed by shifting the worn surface to the best fit position with the initial surface.

2.1. Elimination of the tilting error

The tilting errors between the initial and the worn surface can be eliminated by rotating the worn surface parallel to the initial surface. This problem is equivalent to rotating the worn surface by the intersecting angle between both normal vectors around an axis perpendicular to these normal vectors (Fig. 2). However, the areas chosen to calculate the surface normal vectors should be located outside the wear zone.

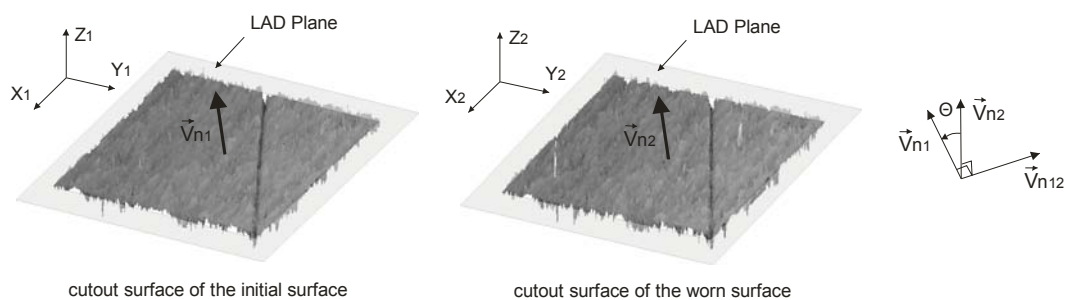


Fig. 2. Surface normal vectors, rotation angle and axis for elimination of the tilting error. (LAD: Least Absolute Deviation)

A plane fitting according to the least absolute deviation method (LAD, L1-norm) is used to obtain the normal vector of the surface. In comparison to the least square deviation method (L2-norm) the L1-Norm is more robust

against the outliers which occur often in the optical measurements due to the optical artefacts (e.g. “spikes”). After plane fitting, the normal vector of the surface can be obtained from

$$\vec{v}_n = \frac{(-a, -b, 1)}{\sqrt{a^2 + b^2 + 1}}, \tag{1}$$

where the fitted plane is described as

$$z(x, y) = ax + by + c. \tag{2}$$

In order to eliminate the tilting error between the initial and the worn surface, the worn surface should be rotated around an axis \vec{v}_{n12} by an angle θ .

$$\vec{v}_{n12} = \frac{\vec{v}_{n1} \times \vec{v}_{n2}}{|\vec{v}_{n1} \times \vec{v}_{n2}|}, \tag{3}$$

$$\theta = \arccos\left(\frac{|\vec{v}_{n1} \cdot \vec{v}_{n2}|}{|\vec{v}_{n1}| \cdot |\vec{v}_{n2}|}\right). \tag{4}$$

Then the rotation matrix has the following form

$$R(n, \theta) = \begin{bmatrix} x^2(1 - \cos\theta) + \cos\theta & xy(1 - \cos\theta) - z \sin\theta & xz(1 - \cos\theta) + y \sin\theta \\ xy(1 - \cos\theta) + z \sin\theta & y^2(1 - \cos\theta) + \cos\theta & yz(1 - \cos\theta) - x \sin\theta \\ xz(1 - \cos\theta) - y \sin\theta & yz(1 - \cos\theta) + x \sin\theta & z^2(1 - \cos\theta) + \cos\theta \end{bmatrix}, \tag{5}$$

where $n = \vec{v}_{n12} = (x, y, z)$.

2.2. Elimination of the rotation error

It should be mentioned that the rotation error here means the remaining error between both surfaces around their common normal vector after the surface tilting described in section 2.1. If a reference vector at both surfaces is known respectively, then the rotation error will be eliminated by rotating the worn surface to the position, where both reference vectors are parallel. The reference vector can be obtained by detection of the orientation of linear features at the surfaces (Fig. 3. left).

At first, the image is binarized by setting a threshold value, as shown in Fig. 3, middle. Then, the binarized image is transformed in Hough space [3]. A straight line through the linear feature can be obtained by identifying the maximal peak in the Hough transform matrix. The dark regions in the binarized image, which this straight line passes through, are selected as the regions of the linear feature. But the detected regions L' only represent the coordinates of the linear feature in the x-y-plane, as shown in Fig. 3, right. In order to identify the orientation of the linear feature, its coordinates should be calculated in the LAD-plane of the surface. This orientation can be determined by fitting a line.

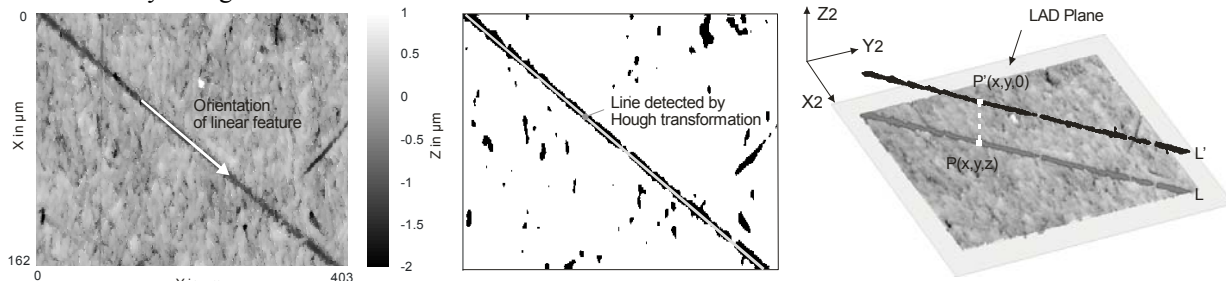


Fig. 3. left: Residual topography of a linear feature; middle: Result of Hough transformation; right: Result of linear feature detection. (LAD: Least Absolute Deviation, L' : Detected linear feature in x-y-plane, L : Detected linear feature in LAD plane)

After the reference vectors are known, the rotation error can be eliminated by using the same method which was described in the last section.

2.3. Topography reconstruction of worn surface after rotation

As shown in Fig. 4 (left), after the rotation, the worn surface topography has to be reconstructed because its measuring grids are no longer equidistant. For this reason, the measuring grids are reconstructed so that the distance between the grids equals that in the initial surface topography (Fig. 4, middle). The heights of the resampled measuring grids are estimated by using triangle based interpolation. The triangulation is carried out according to Delaunay's criteria. Diverse interpolation methods have been applied and their influence on the results will be discussed in section 3.

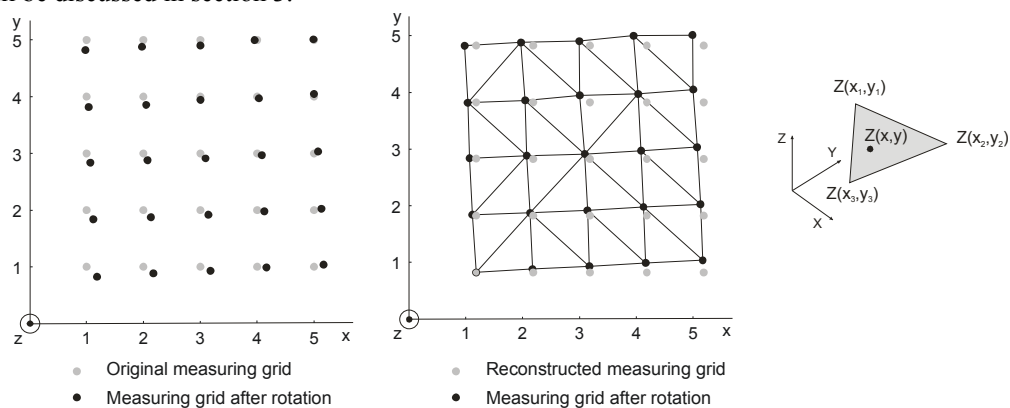


Fig. 4. left: Measuring grids before and after rotation; middle: Triangulation of measuring grids after rotation; right: Triangle based interpolation.

2.4. Elimination of the translation errors

After elimination of the tilting and rotation errors, the initial and the worn surface have been positioned parallel to each other and only the translation errors are remaining. In order to eliminate these errors a cross correlation is used to search the best matching position of both surfaces. A reference area, chosen from the initial surface topography, correlates with an area which shifts over the worn surface topography in x and y directions. The position of best fit corresponds with the maximum of the correlation coefficient. The difference between the medians of topographical values within the areas, which are chosen to tilt the surfaces in section 2.1, can be considered as the translation errors in z direction.

2.5. Second iteration step

In the first iteration step, which has been described from section 2.1 to section 2.4, there is no guarantee that the sampling areas, chosen for tilting the surface and detecting the feature orientation, are exactly the same areas of the initial and the worn surface. Therefore another iteration step, where the exact same sampling areas are selected from the worn surface, is necessitated in order to increase the accuracy of the surface matching. Because the rotation and translation errors are known from the first iteration, the sampling area chosen from the initial surface can be transformed back into the coordinates of the worn surface. Then the topographical data located in these areas are selected as new sampling data and the same algorithm used in the first iteration step is repeated.

3. Results and discussion

The difference between the initial and the worn surface topography is presented in Fig. 5. Table 1 shows the standard deviation of the topographical difference within the dashed white lines. In comparison to the methods “nearest neighbour” and “cubic”, “linear” interpolation shows a better result. In addition, the errors in the location, where the steep topographies occur (e.g. in scratch and linear features), are bigger than in the flatter surface areas.

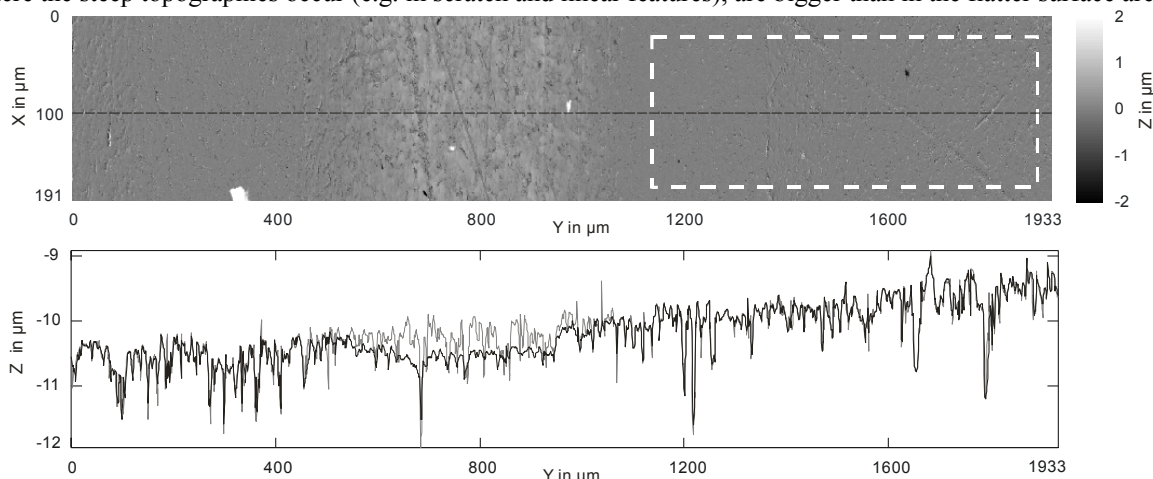


Fig. 5. above: Difference between the initial and the worn surface topography (the standard deviation is calculated within the dashed white line); below: Profiles of both surfaces at $x=100\mu\text{m}$. Interpolation method: linear.

Table 1. Standard deviation after using diverse interpolation methods.

Interpolation method	Standard deviation after 2. iteration step
Nearest neighbour	0.1221 [μm]
Linear	0.1118 [μm]
Cubic	0.1153 [μm]

4. Summary

A method to calculate the wear volume and to determine the topographical changes has been presented. This method focuses on the identification of the surface orientation by means of plane fitting and linear feature detection in order to eliminate the rotation errors between the initial and the worn surface. The translation errors can be corrected by correlation of both surfaces. The advantage of the method is that the computational efforts required are low.

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