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Structure oriented parameters for the function related evaluation of dates for 3D surface roughness

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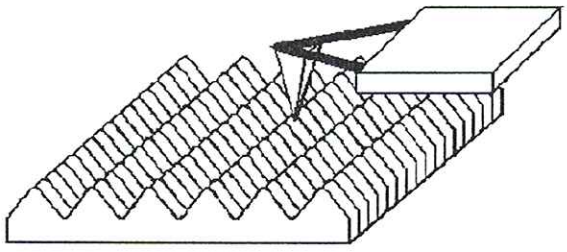
Arbeitskreis 3D Rauheitsmesstechnik

XI. ICS



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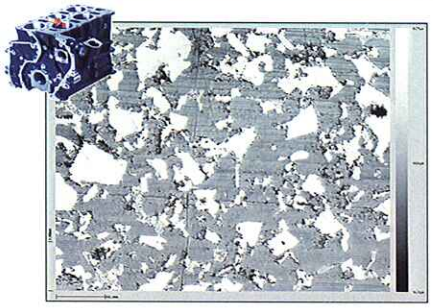
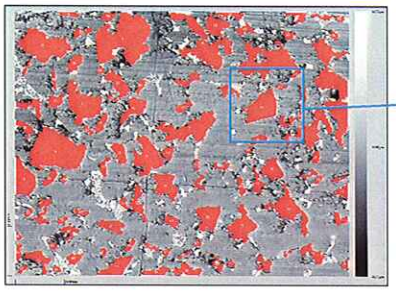
Structure oriented parameters for function related evaluation of 3D surface roughness data

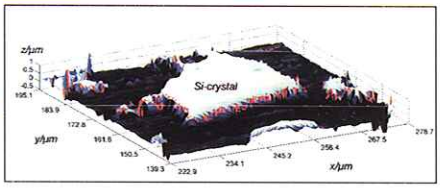
Structure detection



Cylinder liner: casted hypereutectic AlSi-alloy is etched to expose the Si-crystals from the Al-matrix (gray coded height picture)



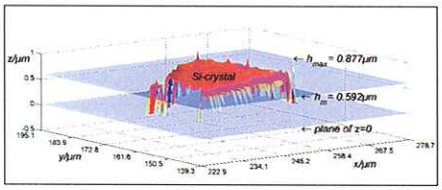
Detected Si-crystals: the Si-crystals are separated against the Al-matrix by local thresholds and marker based watershed transformation



Si-crystal structure with border line

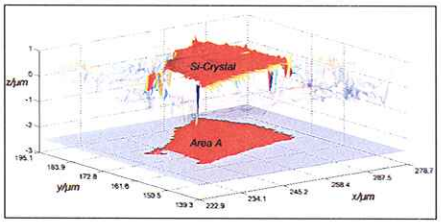
Separation of possible function relevant surface structures by adapted image processing algorithms

Characterization of the structure - size

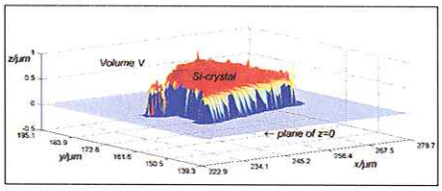


Mean height h_m: mean of the z-values of all structure points

Max. height h_{max}: z-value of the highest of all structure points



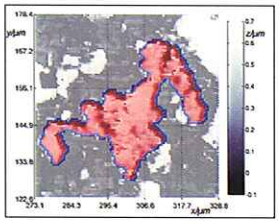
Area A: size of the projected structure points (projected into the x/y-plane)

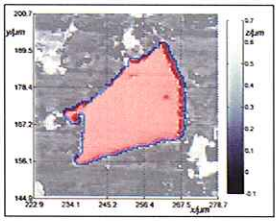


Volume V: size of the space between the structure points and the plane of z=0

Every detected structure is described by a set of parameters to characterize its size, shape and orientation. With this parameters it is possible to select the function relevant structures to generate by statistics a descriptive statement for the surface.

Characterization - shape

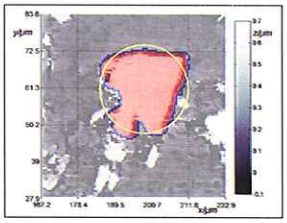


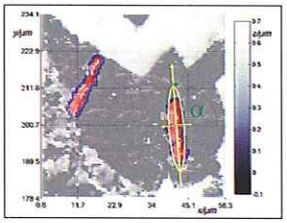


Roughness of the boundary line: fractal dimension
frequency analysis of the peripheral point noise
standard deviation against a mean radius

(similiar parameters are suitable to describe the roughness of the structure head)

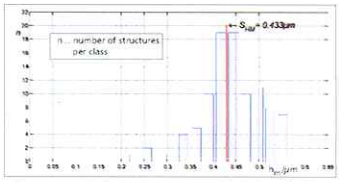
Characterization - orientation



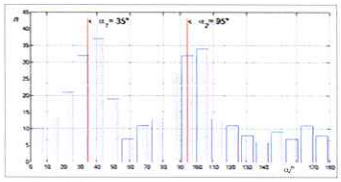


Karhunen-Loeve transformation: Does a dominant direction exist?
angle between main structure axis and x-axis

Surface parameters



Exposure height S_{HM}: mean height of all relevant structures for the shown cylinder liner surface



Angle of the dominant directions of the grooves of a honed cylinder liner surface

Define meaningfull surface parameters by statistical analysis of the structure parameters

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Structure oriented parameters for the function related evaluation of data for 3D surface roughness

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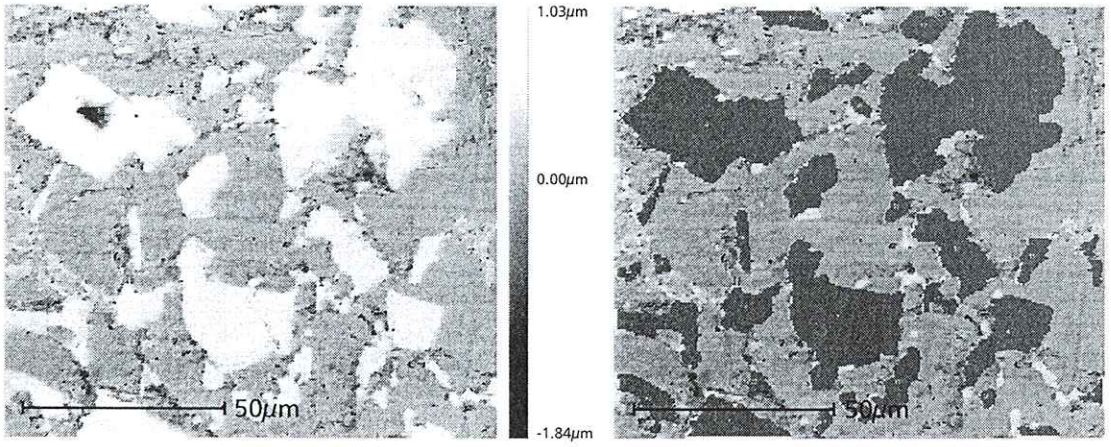
Abstract

With modern manufacturing methods it is possible to bring structures in the micrometer and submicrometer range into the surface and influence with this the functional characteristics of the surface. These spatially expanded structures can only badly described with common 2D measuring and evaluation procedures. Increased efforts are undertaken to describe these spatial structures with particularly adapted 3D measuring and evaluation procedures, to use the additional information contained in 3D data sets.

This paper proposes a function-oriented 3D evaluation procedure on the basis of structure-oriented parameters for aluminum/silicon - cylinder liner surfaces. By segmenting function-crucial structures with a following statistic evaluation, a classification of the microstructure and indirectly the functional behaviour of the surface is possible.

1. Introduction

Modern cylinder liner manufacturing methods allow to design surface structures in the size of the roughness to optimize the tribology between the piston ring and the cylinder liner. It is aimed at producing wear resistant bearing surfaces for boundary friction conditions, sufficient void volumes for lubricant supply and to optimize the evaporation of oil into the combustion chamber. The goal behind that is the minimization of blow by, friction, engine weight and pollutants. Manufacturing methods for realizing these general requirements with designated structures on tribological stressed surfaces are laser honing[1], laser exposure[2] and casting of metal-matrix-composits MMC[3],[4],[5].



a) AlSi-surface b) AlSi-surface with detected Si-crystals

Figure 1: Aluminum silicon alloy surface. Gray coded height plot. The white points belong to Si-crystals, the gray points to the Al-matrix. Figure b) shows the same area like figure a) but with the detected Si-crystals marked in dark gray.

Particularly MMC surfaces leaved the development stage and are industrially used today in form of aluminum silicon alloys. To produce this surfaces hypereutectic AlSi-alloys are casted in a special way so that some of the silicon gets separated from the alloy and settles as crystal structures in the matrix. This Si-crystals are exposed by a following finishing process to form a wear resistant bearing surface. The gap to the taken back aluminum matrix provides the void volume for storing lubricants. Function crucial for this AlSi-surfaces is the size, shape, distribution and spatial density of the Si-crystals.

With industrially established 2D roughness parameters only limited characterization of the Si-crystals, their distribution and hence the functional behaviour of the surface is possible. 3D Parameters transfered by Stout et.al. [6] from the common 2D parameters do not provide the desired results, too, because they ignore the additional information of the 3D data set. Only the suggested summit density uses the advantages of the 3D measurement by evaluating the number and distribution of summits in the surface, but stable computation due to over segmentation resulting from measuring instrument noise is a problem.

3D parameters based on void and material area ratios are proposed by Pfestorf et.al. [7] for rolling sheet metals. The closed void area ratio exhibits a characteristical maximum for porous surfaces, which can be used to determine the functional behavior of the surfaces. AlSi-surfaces show superproportionally few closed void areas, since the Si-crystals do not provide a closed border around the void volumes. Therefore the oil pressure to separate the piston ring and the bearing surface is only built up dynamically by the movement of the piston.

The 3D roughness evaluation proposed in this paper identifies the functional important structures of the surface and characterizes them. In the case of AlSi-surfaces the important structures are the Si-crystals. These crystals are detected and separated aganist the Al-matrix by adapted image processing methods. The crystals can be described not only over height, number and distribution density, but can also be indicated by an area, a volume, an orientation and a boundary characteristic.

In the following the detection algorithm is described briefly. Further structure oriented parameters to describe the recognized Si-crystals are introduced. Characteristic parameters for the entire surface are developed by meaningful combination of the structure oriented parameters of the Si-crystals.

2. Structure detection

The structure detection bases on the algorithm proposed by Lemke et.al. [8]. It was speeded up and modified to improve the detection of Si-crystal structures in AlSi-surfaces, especially with noisy measurement data of optical topography microscopes (wight light interferometer, confocal microscope).

The goal of the structure detection algorithm is the identification of surface areas which intuitivly look like Si-crystals. These surface areas are significantly higher than their environment and they are separated by a steep edge against the Al-matrix. As a result

of the detection process a quantity of points of the surface are mapped to individual structures. Therefore the structure is identified by a local maximum and separated against the Al-matrix with a boundary line at the steepest edge.

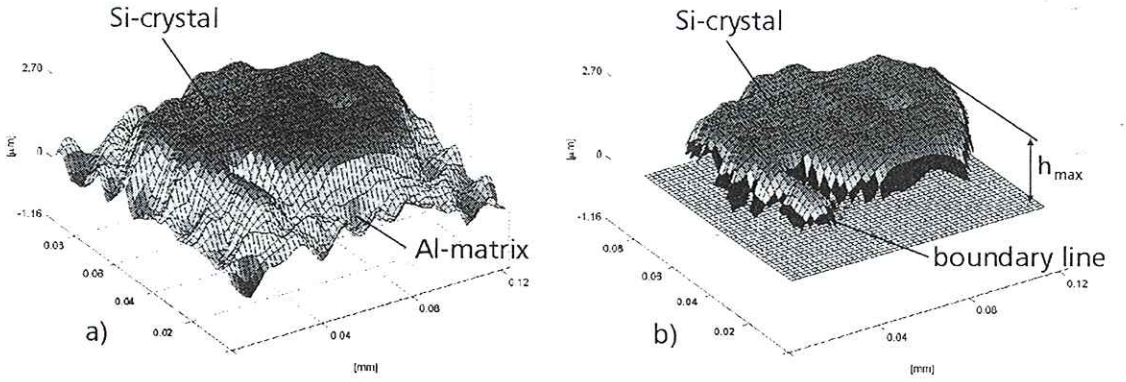


Figure 2: a) Si-crystal in the Al-matrix. b) Detected and separated Si-crystal with the boundary line

In the first step of the algorithm the hill change tree after Scott [9] is developed with a graph-based watershed transformation [10]. The over-segmented watershed picture is pruned by a local threshold operation into markers for the background and markers for the Si-crystals. The Si-crystals identified by the markers are separated against the Al-matrix by marker-based watershed transformation of the gradient picture.

For a reliable detection and evaluation robust filtering of the surface is compellingly necessary. In the first step an elimination of the form with robust fitting in algorithms takes place. Possibly existing waviness is filtered if necessary in the second step with second order robust Gaussian filters [11],[12]. The goal of this robust prefiltering is the stable determination of the Al-matrix within the range of the largest accumulation of material without distorting the Si-crystal structures. The matrix position serves during the further evaluation as the origin which against all the heights are measured.

3. Structure oriented parameters

The detected and separated structures can be described in size, shape and orientation. Interesting parameters for each structure are for example the area, the volume, the height etc.. The goal of this structure oriented evaluation is the detailed description of every individual structure detected in the surface.

Size of a structure

The area A of a structure computes itself from the number n of the points belonging to the structure multiplied by their expansion in lateral direction Δx and Δy:

$$A = n \cdot \Delta x \cdot \Delta y. \tag{1}$$

The volume V describes the space enclosed by the points of the structure $P(i) = P(x_i, y_i)$ and the Al-matrix. It can be computed by summation of the heights $z_i = z(x_i, y_i)$ of the points multiplied by their lateral expansion:

$$V = \Delta x \cdot \Delta y \cdot \sum_{i=1}^{n} z_i. \tag{2}$$

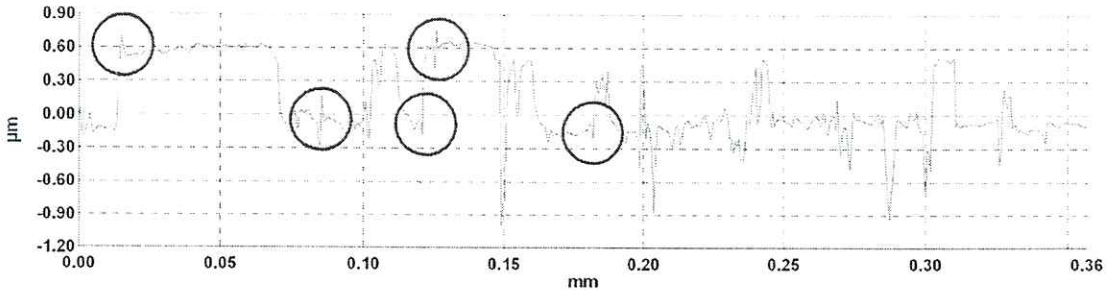


Figure 3: Surface profile measured with a white light interferometer. Typical systematic errors are marked with a circle.

The maximum height h_{max} of the structure is directly stored in the hill change tree. However this value is very sensitive to outliers. Thus systematic measuring errors mainly of optical measuring instruments affect the maximum height h_{max} unpredictable. Typical systematic errors of optical measuring instruments are shown in figure 3.

$$h_{max} = \max(z_i) \tag{3}$$

A more meaningful value for the height of a structure is the mean height h_m as an average value of the heights z_i of the Points P_i belonging to the structure. The mean height h_m can be computed as quotient of the volume V and structure area A:

$$h_m = \frac{V}{A}. \tag{4}$$

A more stable alternative to the maximum height h_{max} is the five point height h_z, which computes itself as the mean value of the five highest points of the structure (quite similar to R_z).

Shape of a structure

Optimal Si-crystal structures have a compact shape with a flat top and a smooth boundary line. Parameters to describe an optimal structure are presented now.

Lemke et al.. [8] develop the form filling degree G_{FF} as a measure for ruggedness of the top of the structure. A form filling degree nearby zero stands for a heavy rugged structure top and a degree of one for a flat structure top. The form filling degree measures how far the top of the actual structure approximates the optimal structure:

$$G_{FF} = \frac{V}{h_{max} \cdot A} = \frac{h_m}{h_{max}}. \tag{5}$$

The form filling degree G_{FF} is based on the maximum height h_{max}. Thus the form filling degree is not stably calculable. A more stable parameter G_{FZ} would be calculable with the five point height h_z:

$$G_{FZ} = \frac{V}{h_z \cdot A} = \frac{h_m}{h_z}. \tag{6}$$

To improve the description of the ruggedness of the top of a structure the descriptive comparison of the volumes has to be leaved. By attempts the standard deviation G_S of the height values around the mean height h_m turned out as a meaningful parameter. This also meets better the commonly used practice of tolerating measurment data. The standard deviation G_S is computed as follows:

$$G_S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (z_i - h_m)^2. \tag{7}$$

The boundary line of a structure should be smooth because small projections can break out if the bearing surface is stressed. For the computation of the boundary line peripheral points are defined as the points P_r of the structure points P_i, which possess at least one point in the four point neighbourhood [10], that does not belong to the structure.

An ideal structure has a circular boundary line. In this case the boundary length is minimal in relation to the area of the structure. With all other shapes of the structure this "edge-to-interior ratio" would become larger. Therefore this ratio is often suggested as a parameter to measure the ruggedness of the boundary line[13].

The problem with the "edge-to-interior ratio" is the fractal character[14] of natural shapes like it is to be found on boundary lines of the Si-crystal structures, too. Due to the fractal character the boundary length cannot be determined independently from the resolution of the measuring instrument. The more exactly the structure is resolved, the longer becomes the boundary line, whereas the area remains constant. The "edge-to-interior ratio" would have to be indicated as a function of the resolution of the measuring instrument or the ruggedness of the boundary line has to be limited by prefiltering.

The fourier transformation of the peripheral point noise turned out to be a suitable method to characterize the ruggedness of the boundary line. For each of the peripheral points the distance to the center of the structure is computed. The center is the arithmetic mean of all peripheral point coordinates. The sequence of the radii of the peripheral points is transformed with the fourier transformation into the frequency domain. Only amplitudes of small multiples of the angular frequency are decisive for the ruggedness of the boundary line. On the contrary the fractal character influences only higher multiples of the angular frequency presuming a sufficient measuring resolution. By suitably priorizing low frequencies a parameter G_{FFT} can be introduced to measure the ruggedness of the boundary line.

A further possibility to describe the ruggedness of the boundary exists in the computation of the fractal dimension G_{FDR} of the boundary line. The higher this fractal

dimension becomes, the more rugged is the boundary line. To calculate the fractal dimension there exist a whole set of methods[15], whereby the Minkowski sausage was used because it can be realized well with morphological operators[10].

Orientation of a structure

Additionally to the ruggedness of the shape of the structure it is also interesting if the structure has an oblong or a round shape. If it has an oblong shape the orientation of the structure on the surfaces is important: In which direction points the dominant axis of the oblong structure?

An algorithm to calculate orientations of structures is suggested by Wagner[16]. He looks at every transition from the matrix to every structure in the surface. However he defines two independent parameters for transitions in arbitrarily specified directions along the sampling grid of the measuring instrument: one parameter for the vertical/horizontal transitions and one for the diagonal transitions. Thus he describes the isotropy of the surface with two independent parameters.

To determine the dominating shape of the structure the Karhunen-Loeve transformation[17] worked satisfactorily. With this transformation it is recognizable whether the structure has a dominant oblong shape and if so in which direction it is pointing to. The quotient G_{HQ} of the eigenvalues of the covariance matrix indicates if a preferred direction exists. If so the dominant direction as the direction with the largest variance can be determined by the angles G_{HA} of the eigenvectors.

4. Surface parameters based on the structure oriented parameters

By examining all the structures of a surface the presented structure-oriented parameters can be combined to meaningful parameters for the entire surface. Furthermore it is possible to calculate spatial statistics[18],[19] like number and distribution of the structures in the surface.

The first step is the sorting of the structures into relevant and irrelevant ones according to the function of the surface. The surface area size A turned out to be a meaningful parameter to separate the structures. For the moment a rectangle distribution is used, with which a minimum and a maximum size for a structure can be defined. Only structures with a size between minimum and maximum are considered in further computations.

A certain minimum height is not considered as selective parameter, as it is done for example with wolfpruning ($h_{max>} \geq 5\%S_z$) of the density summit[6],[20]. The experience with common AlSi-surfaces showed that structures possessing a sufficient large area fulfill the minimum height criterion, too.

The exposure height of the Si-crystals S_{HM} is computed as the mean value of the mean height h_m of all relevant structures T. The number of the relevant structures is named k:

$$S_{HM} = \frac{\sum_k h_m(T)}{k}. \tag{8}$$

The material-free volume S_{MFV} between the level of exposure height and the matrix approximates the void volume that is present for the storage of lubricants. Is the height z of a point O of the surface smaller than the exposure height S_{HM} the point O contributes to the void volume:

$$z_{HM} = \begin{cases} S_{HM} - z & : \quad S_{HM} - z > 0 \\ 0 & : \quad S_{HM} - z \leq 0 \end{cases} \tag{9}$$

$$S_{MFV} = \Delta x \cdot \Delta y \cdot \sum z_{HM} \tag{10}$$

One spatial parameter is the summit density as it is suggested by Stout et.al.[6]. This density describes how many relevant structures are present in a certain amount of the surface area. The relevant structures are defined as described above by their area size.

Another meaningful spatial parameter is the relative funtctional area S_{AF} as the relation between the cumulated structure area size A_c and the size of the whole measuring field A_{MF}. With this it is possible to specify a dimensionless parameter which characterizes the relative amount of function crucial structures in the surface: 35% of the surface area are occupated by functional relavant Si-crystals. It is computed as follows:

$$S_{AF} = \frac{A_c}{A_{MF}} = \frac{\sum_k A(T)}{xDim \cdot \Delta x \cdot yDim \cdot \Delta y} \tag{11}$$

5. Summary

With the structure-oriented evaluation of 3D roughness measuring data it is possible to use the additional information contained in 3D surface data. A first parameter set was presented. This parameter set works very well with AlSi-surfaces used in modern cylinder liners but has to be extended to other types of technical surfaces like porous surfaces with function crucial void volumes.

6. Acknowledgement

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