Local Analysis of Honed Surfaces in Microscopic Images

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1. Introduction

A large number of studies of the honing texture have shown that oil consumption and longevity of combustion engines are closely related to the surface structures of the cylinder wall. The presence of two bands of honing grooves is intended and desired in the manufacturing process, as they improve the lubrication between the cylinder wall and the piston. Due to the imperfectness of the metal working, honing grooves are smeared and interrupted by the folded metal. These undesired material defects increase the frictional losses and accelerate the wear of the piston. This paper focuses on the image analysis based inspection of the folded metal. Image data are acquired by a scanning electron microscope (SEM), as honing textures influence the surface function in a roughness scale. Two approaches are presented for the segmentation of defective edges. The first one distinguishes the folded metal from other surface components with respect to the structural features; the second one considers the inspection task as a problem of texture suppression. Furthermore, a new measure derived from the segmented image data is utilized to assess the surface quality in terms of the defect severity. The tests illustrate that objective and reliable quality assessments of cylinder liners can be achieved by the automated inspection.

2. State of the art

Currently, the grading of the defect severity is still a demanding work. In most cases, metal folds are manually analyzed in SEM images. The obtained inspection results are subjective and not reproducible. Although a part of the surface samples can be automatically inspected with 3D image data [Xin08] [Dim10], the application of these technologies is restricted by two drawbacks: firstly, the acquisition of 3D data is time consuming; secondly, the detection of the folded metal depends on the reconstruction of honing grooves, since it searches the folded metal merely in the blocked area of deep grooves. Unfortunately, the recognition of some smeared grooves is also a challenging work in itself. In this case the groove parameters, such as position, angle and width, can not be measured accurately. Measurement errors will be transferred to the evaluation of defect severity. For these reasons, the study of new methods is in demand. This paper intends to improve the prior global description of the honing texture proposed in [Bey01]. The main advantage of local analysis lies in the relaxed constraint on the intactness of honing grooves. Hence, the local model describes real honing textures more precisely.

3. Methods

3.1 Detection with structural features (DSF)

The folded metal is likely to possess interrupted edges. Therefore, only cut edges are relevant for this inspection task. Honed surfaces are modeled as a combination of three spatially separable components, i.e., straight edges, rough edges and smooth patches. They together affect the tribological performance of cylinder liners.

It turns out that the gradient distribution can well represent these surface components. Fig. 1 shows some small surface pieces of different structures and their gradient distributions. The principal direction of a gradient distribution indicates the local orientation, while the extent in the perpendicular direction denotes the divergence of gradients. Based upon this interpretation, shape analysis of gradient distributions is useful to distinguish surface components. Rough edges are regarded as the folded metal.

The technical implementation consists of two parts: pre-processing and tensor analysis. At the beginning of the algorithm, the original image is enhanced by noise reduction and contrast homogenization. These operations aim to remove the irrelevant image signals that affect the accuracy of the algorithm when calculating the gradients. The proper methods could be anisotropic diffusion and homogenization of second degree. In the enhanced image (see Fig. 2 (a)-(b)) we investigate gradient distributions using tensor analysis. A structure tensor has two non-negative eigenvalues, which encode the magnitude of local orientation and the divergence of gradients. In order to obtain contrast-invariant features, eigenvalue images are normalized in this algorithm. After that, disturbances of intersected structures are smoothed by tensor regularization. In the last step, metal folds are detected in the small eigenvalue image; see Fig. 2 (c)-(f). For more detailed explanations we refer to [Wan10].

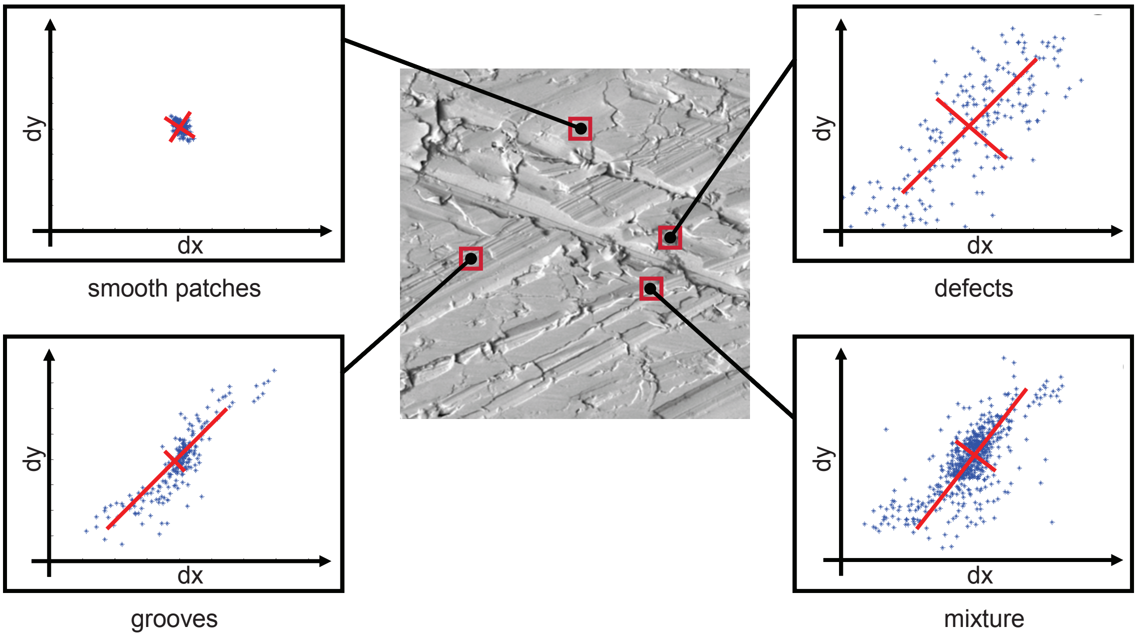


Fig. 1. Gradient distribution of surface structures.

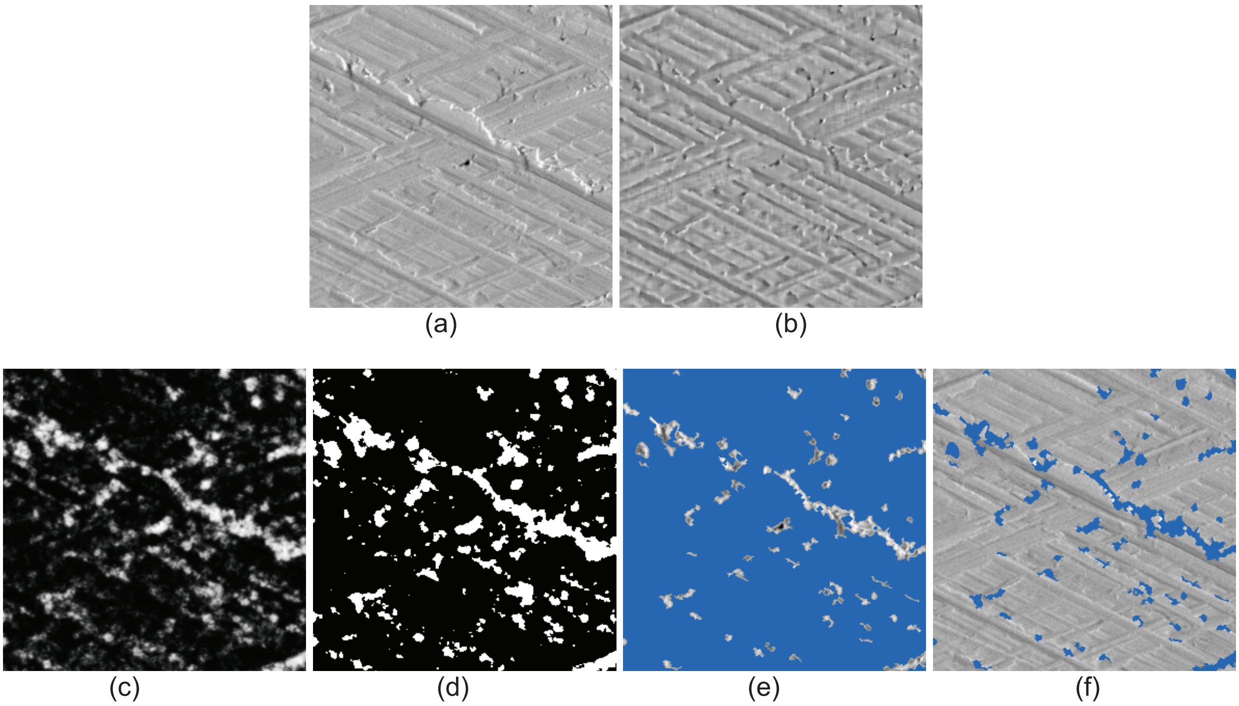


Fig. 2. Results of DSF: (a) original image, (b) enhancement of (a), (c) small eigenvalue, (d) segmentation of (c), (e) localized defective edges (unmarked parts), (f) groove regions (unmarked parts).

3.2 Detection by texture suppression (DTS)

The idea of DTS is to eliminate groove textures from the edge map of honed surfaces. The remaining edges are considered as the folded metal. This method adopts an energy-based edge detector proposed in [Köt03], as it integrates the detection of step edges, roof edges and junctions in one operator. The resulting edge map is known as boundary energy in literature. It can be further decomposed into the edge energy and the junction energy.

Fig. 3 shows the principle of DTS in a block diagram. An individual groove set is suppressed by multiplying the boundary energy with an oriented weighting mask. The same procedure is repeated at another honing angle. The map of defective edges is a fusion of two intermediate results by a minimum operator. Groove edges can be revealed by subtracting defective edges from the boundary energy.

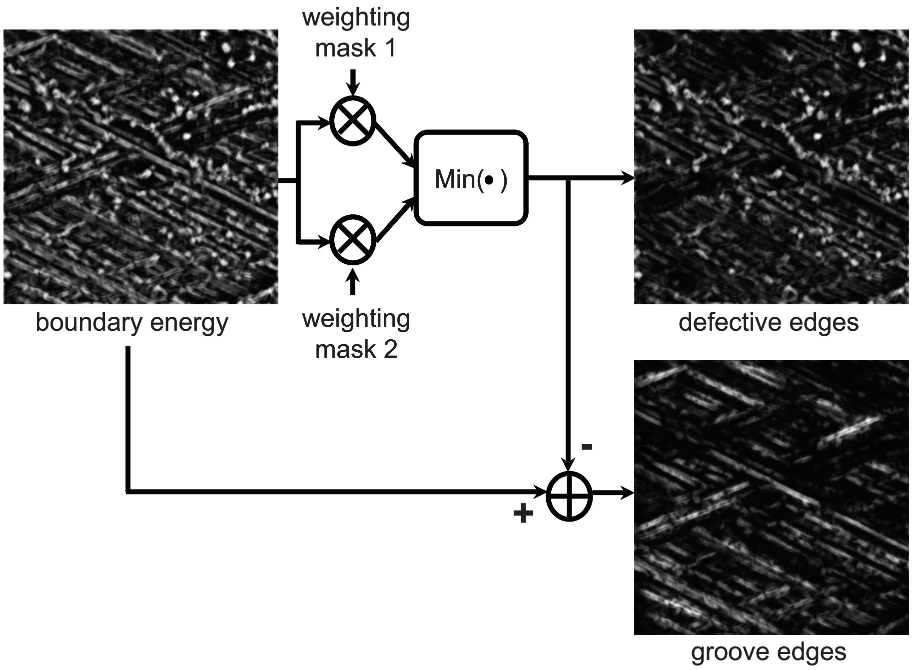


Fig. 3. Suppression of groove textures.

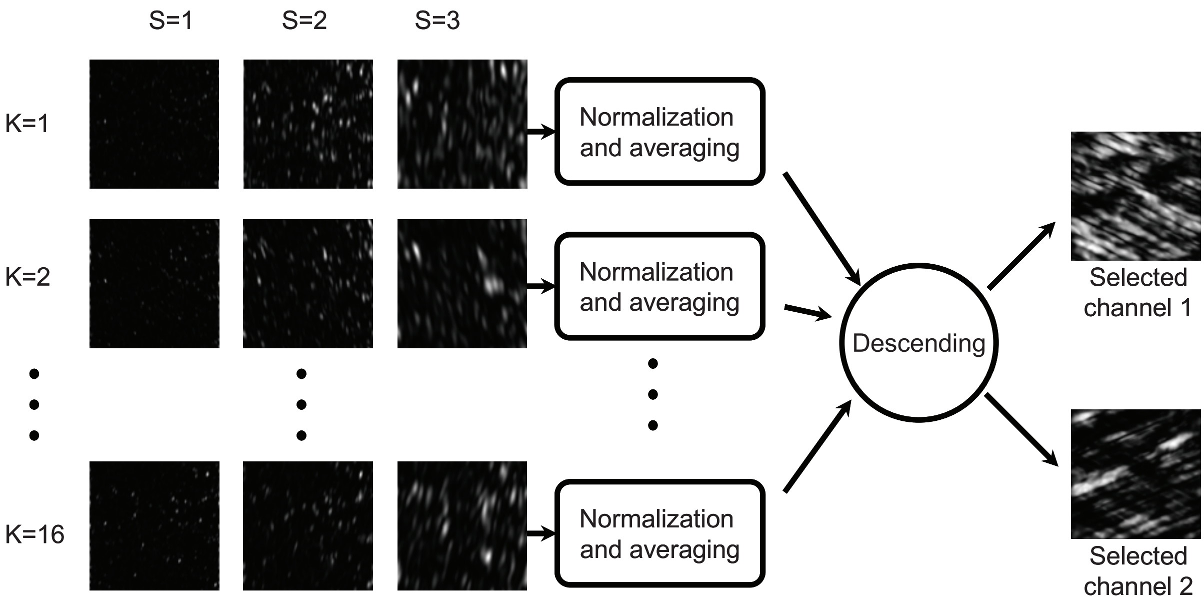
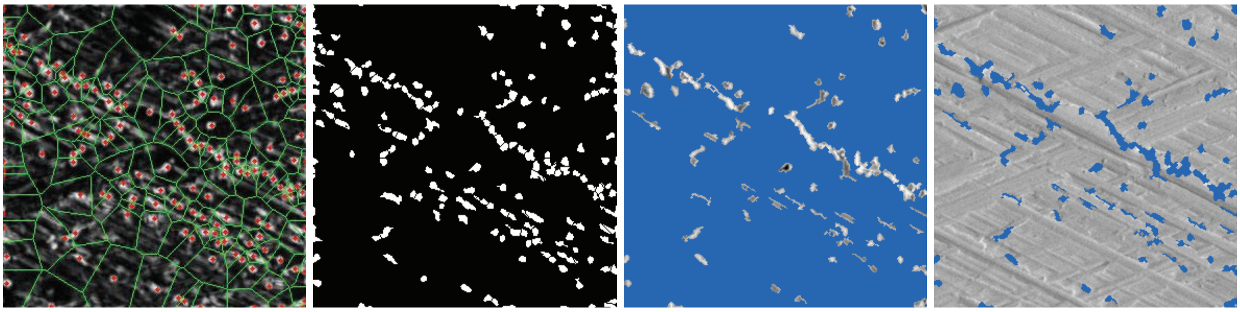


Fig. 4. Extraction of weighting masks: Left image matrix: Gabor filter responses. K is the orientation index; S is the scale index. Right two images: selected channels.

The critical task for texture suppression is deriving the weighting masks. Fig. 4 introduces an effective scheme, which is detailed as follows. At first, a Gabor filter bank with 3 scales and 16 orientations is designed to identify the oriented structures. Afterwards, the filter responses belonging to a single orientation are normalized at each pixel with their maximum value. This step achieves contrast-invariant representations of oriented structures [Kam06]. In fact, honing grooves have random widths. Therefore, a maximum operation is further performed on the 3 normalized scales. So far, 16 scale-invariant channels corresponding to 16 orientations are obtained in this scheme. By descending the channels according to their globally averaged intensities, the first two channels are regarded as the main groove sets. It is evident that groove regions stand out from selected channels because of their large intensities and compact distributions. The weighting masks are the intensity reversal of them.

Lastly, we segment defective edges with adaptive thresholds. The segmentation strategy proceeds according to some basic observations: the strong contrast often appears at sharp points on metallic surfaces; important edges are usually contained in the neighborhoods of these points. High curvature points are detected at local maxima of the junction energy. Their neighborhoods are partitioned by the well-known Voronoi diagramm. The local threshold for each Voronoi cell is the half peak energy of defective edges. Fig. 5 shows the binarized edge maps.



(a) (b) (c) (d)

Fig. 5: Results of DTS: (a) Voronoi diagramm, (b) segmentation of (a), (c) localized defective edges (unmarked parts) (d) groove regions (unmarked parts).

3.3 Post-processing

It is noted that the edge regions acquired by DSF and DTS are over-segmented. This subsection contributes to the localization of the folded metal. Except that, we ignore some weak scratches, as they have little influence on the performance of cylinder liners. To tackle these problems, modified image gradients are computed following the steps sketched in Fig. 6. In the over-segmented regions, obvious defects are located at the places with gradient magnitudes larger than a threshold (0.1 is chosen in this paper). Moreover, we deal with double edges induced at roof edges by morphologic closing. Some small fragments are also removed. The end results are shown in Fig. 2 (e) and (f) as well as Fig. 5 (c) and (d).

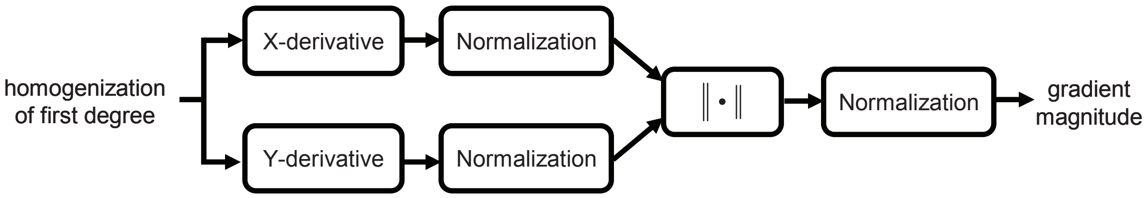


Fig. 6. Modified image gradient

4. Evaluation

In the field of computer vision, precision and recall are standard benchmarks for evaluating detection performance [Mar04]. To calculate these parameters, the inspection results are corrected by manual drawings. We mark real defective edges with single-pixel curves. If they place inside the automatically segmented edge regions, they are regarded as correct detections (true positive, tp). Otherwise, they are labeled as missed detections (false negative, fn). Incorrect detections (false positive, fp) are the groove edges that are contained in the inspection results. We define tp, fp and fn with curve lengths. Consequently, precision (P) and recall (R) are expressed as follows:

$$P = \frac{tp}{tp + fp}, \ R = \frac{tp}{tp + fn}.$$

For testing, a series of surface samples is randomly collected in the same image magnification. Fig. 7 illustrates an example of corrected detections. More surface samples are provided in Fig. 8. The false-negative errors of DSF may occur at some straight defective edges as their structures are the same as honing grooves, while defects parallel to the main honing angles sometimes are missed by DTS. Nevertheless, both approaches feature high precision and high recall; see Table 1.

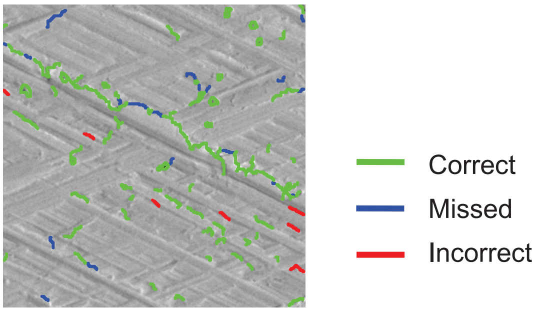


Fig. 7. Corrected detections of DTS.

5. Quality control

In practice, assessment of surface qualities concerns the overall impression of the surface status, including the balance of groove sets, the defect severity and the formation of plateaus. The presented methods concentrate on quantifying the defect severity. Visually, a poor quality is associated with densely scattered long and strong defective edges. However, it is unrealistic to characterize these features in a "brute-force" manner. Especially, the accurate measurement of edge length is difficult. It usually needs non-maximum suppression and gap filling to get single-pixel edges in the image, which greatly increases the computational complexity. Hence, a reasonable approximation of this metric is more feasible for practical applications.

In this paper, a simple measure of defect severity (DS) is developed in the following formula:

$$DS = \frac{\sum_{\mathbf{x} \in localized\ defect\ edges} weight(\mathbf{x})}{image\ height \times image\ width}$$

This measure describes the density of defective edges. The numerator denotes a weighted area of localized defective edges. It estimates the effective edge length of the folded metal. The weighting term is composed of modified gradient magnitudes, which indicate the strength of edges. The denominator is the whole image area. Without loss of generality, all the results presented in this paper use pixel units in the measurement. According to actual needs, pixel units can be substituted by physical units after calibration.

6. Experimental results

The new measure enables an automated assessment of surface samples. The usefulness of this measure is evidenced by comparison with the visual sorting of surface samples obtained in Section 4 (according to the order from "seriously defected" to "slightly defected"). The sorted images are numbered from 1 to 5. Fig. 9 plots DS values against image indices. It is noted that most measures by DSF are larger than those by DTS. It may be due that DTS produces more false-negative errors, i.e. lower recall, than DSF. Nevertheless, all the samples are correctly classified by both approaches.

7. Conclusion

This work introduced a route map from the image segmentation to the quality assessment of honed surfaces. The presented inspection strategy turned out to be a robust and efficient solution for automated quality control. Defect detection using local image analysis is independent of the position of honing grooves. That enables the parallel computing of different surface features. The new algorithms can be embedded into other image analysis tools and applied to the online visual inspection.

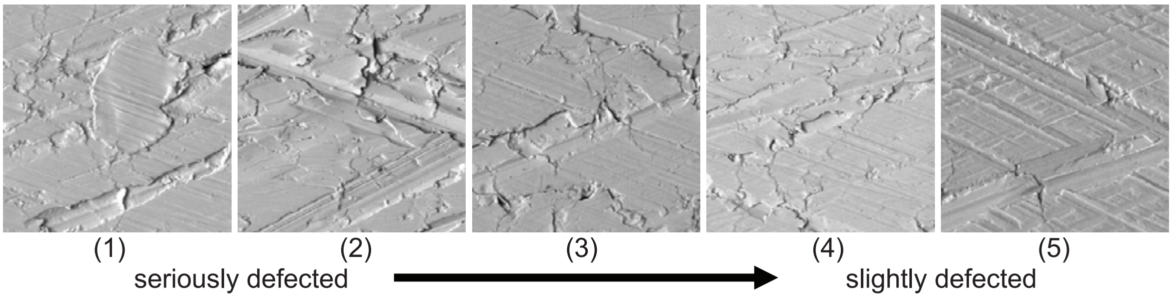


Fig. 8: Visual sorting of surface samples.

Table 1: Detection performance.

Methods	Measures	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
DSF	precision	0.99	0.99	1	1	0.99
	recall	0.94	0.90	0.91	0.90	0.91
DTS	precision	0.99	0.98	1	1	0.98
	recall	0.86	0.85	0.84	0.82	0.94

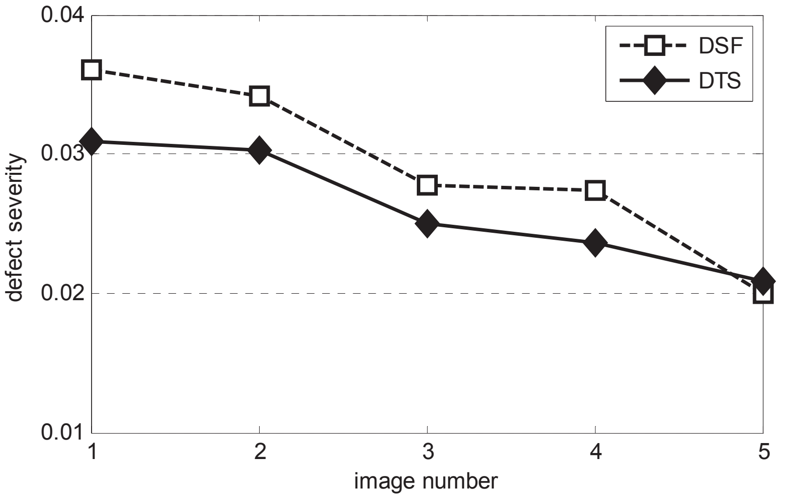


Fig. 9: Automated quality assessment of surfaces data from Fig. 8.

References

[Xin08] B. Xin: Auswertung und Charakterisierung dreidimensionaler Messdaten technischer Oberflächen mit Riefentexturen. Ph.D. Dissertation, Universität Karlsruhe, Karlsruhe, 2008

[Dim10] Z. Dimkovski et al.: Characterisation of Worn Cylinder Liner Surfaces by Segmentation of Honing and Wear Scratches. doi:10.1016/j.wear.2010.04.024, 2010

[Bey01] J. Beyerer, D. Krahe and F. Puente León: Characterization of Cylinder Bores. Metrology and Properties of Engineering Surfaces, Chapter 10, Kluwer Academic Publishers, Boston, 2001

[Wan10] L. Wang and F. Puente León: Segmentierung glatter Flächen an gehonten Oberflächen. Forum Bildverarbeitung, pp. 193-203, KIT Scientific Publishing, Karlsruhe, 2010

[Köt03] U. Köthe: Integrated Edge and Junction Detection with the Boundary Tensor. Proceedings of the Ninth IEEE International Conference on Computer Vision (ICCV 2003), Vol.1, pp. 424-431, 2003

[Kam06] J. Kamarainen, V. Kyrki, and H. Kälviäinen: Invariance Properties of Gabor Filter-Based Features: Overview and Applications. IEEE Transactions on Image Processing, Vol. 15, No. 5, 2006

[Mar04] D. Martin, C. Fowlkes and J. Malik: Learning to Detect Natural Image Boundaries Using Local Brightness, Color and Texture cues. PAMI, 2004