Illumination methods for optical wear detection

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Abstract. *The paper presents some results of a study on optical wear detection. The focus of the paper is on the illumination, to optimize the contrast of the images. Various illumination methods are compared: bright field versus dark field illumination, and various kind of light sources: laser light, diffuse light and ring-light.*

Keywords: wear detection, illumination.

1. Introduction

Wear plays an important role in determining the life span of products or machine elements. The lifetime of a component depends on wear. Detection and monitoring of wear are rather important in tribological research as well as in industrial applications. Some typical examples are: measurement of dynamics of wear processes, engineering surface inspection, coating failure detection, tool wear monitoring and so on.

With wide and extensive use of wear resistant materials, wear itself is becoming smaller and smaller, in some precision application, for instance, down to nanometer dimensions. Due to dynamics and complex nature of a wear process, measurement of wear is usually conducted offline, i.e. during measurement the wear process needs to be interrupted and the specimen to be removed from the tester periodically to measure the evolution of wear as a function of time, number of cycles, or sliding distance.

Reliable online detection and monitoring of wear, in which the wear process is not interrupted and the wear environment (temperature, humidity, lubrication etc.) is not changed, remains a challenge to tribological research as well as to the industry.

The main objective of the current research project is to do online wear detection and monitoring by an imaging system, the first element of which is image acquisition. One aspect that is often overlooked in computer vision is the acquisition of adequate images: a proper illumination should have sufficient contrast and be effective in revealing the features of interest of the specimen (here wear phenomena), in order to identify small surface defects on an otherwise textured surface.

2. Measurement setup

Figure 1 shows the measurement set-up, consisting of a rotary table with a pin-shaped wear intender, and an imaging system which is a combination of a video zoom microscope and a monochrome CCD sensor. The pin is mounted on a stiff lever and held stationary whereas the disk rotates. The load applied on the test sample is varied by removing or adding weights on the lever. A servo motor control with a rear-mounted optical encoder ensures accurate indexing. The wearing surface is monitored continuously by the imaging system.

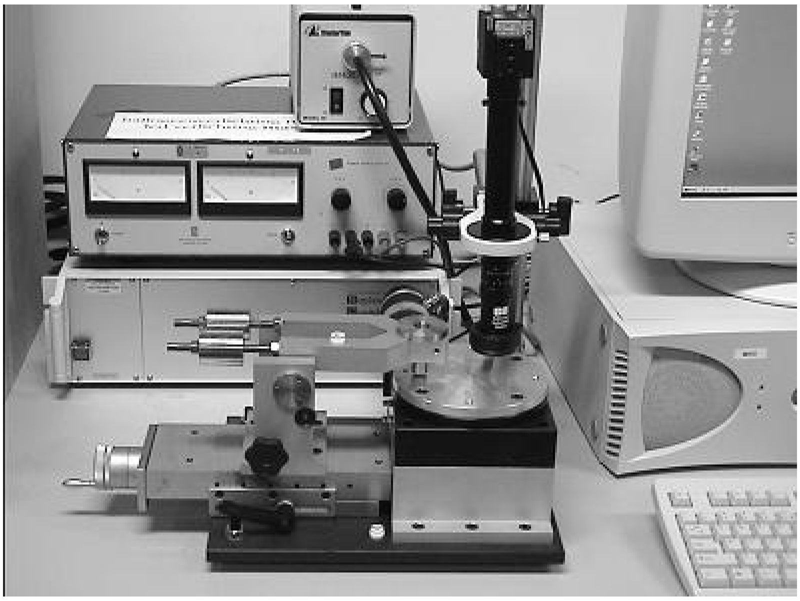

Fig. 1. Picture of the wear testing and monitoring apparatus

As an illustration, figure 2 shows a sequence of images taken from a specimen during a wear test. They clearly demonstrate that surface defects can be observed by changes in contrast and texture. The goal of this part of the research is to find the optimal illumination strategy allowing the detection of small defects.

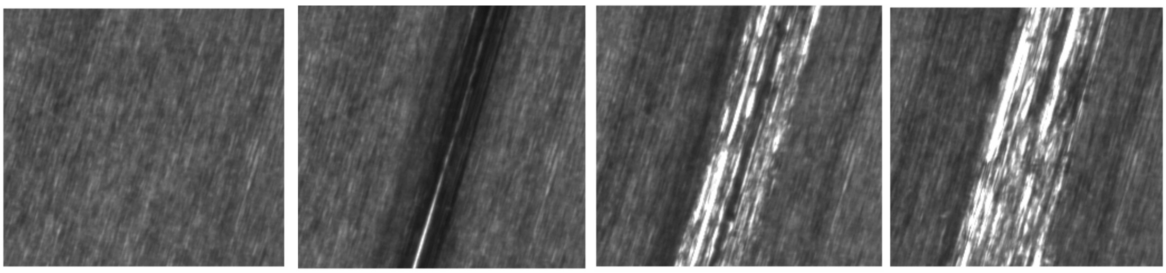

Fig. 2. Sequence of pictures during a wear process, conducted by a steel pin on a rotating specimen of aluminium.

3. Results

The reconstruction of wear parameters from a two-dimensional radiometric image requires understanding of how light reflects from a rough surface. Obviously, a radiometric image of a surface is not identical to a geometric image (height image), as is clearly demonstrated in figure 3. The upper part of this figure shows the intensity image of a textured surface with a scratch. The right side presents the intensity distribution along the line indicated in the left side. The lower part of figure 3 shows the topographical image of the same surface detail, measured by a white light interferometer. The left part is a grey-coded representation of this depth image, and the right part shows the depth profile along the line indicated at the left side. Although the pictures have slightly different scales and the lines are not exactly along the same position, it is clear that both profiles differ substantially, showing that an intensity image is not the same as a geometric image.

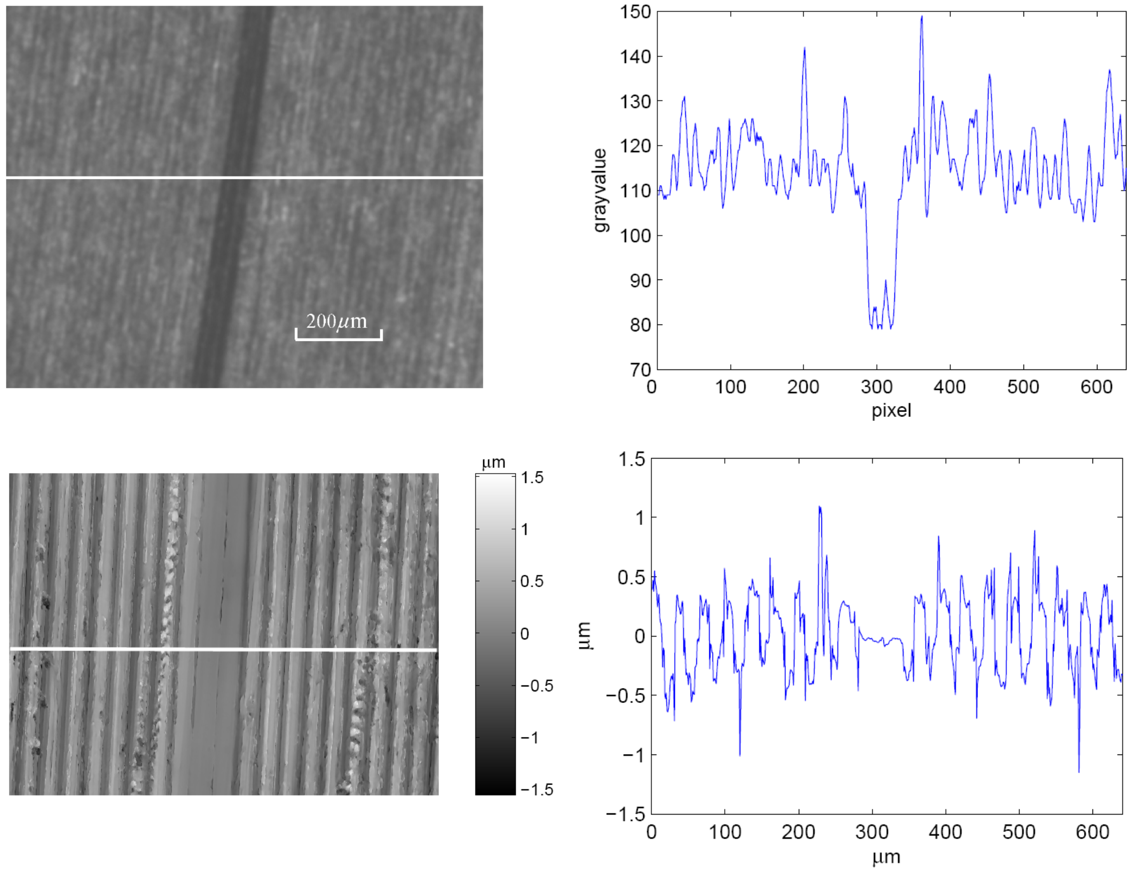

Fig. 3. Comparison of radiometric and topographic images of the same surface, and the corresponding intensity profile and height profile.

Various models have been investigated to describe the relation between surface properties on the one hand and intensity distribution of the images on the other, for different light sources and different illumination strategies [2]. In the experiments a ring light illuminator is applied. From the geometry of the setup an illumination model can be derived. Figure 4 shows the geometry and the illumination for various distances *h* between the ring light illuminator and the surface under test. Note that for the larger values of *h* the region of interest is uniformly illuminated.

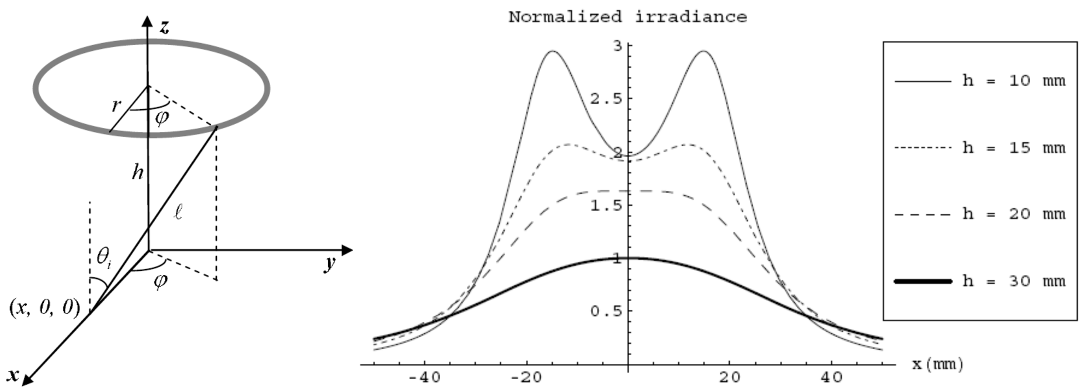

Fig. 4. Geometry of the ring illumination (left) and the corresponding illumination model (right).

Assuming a normally distributed surface height, a reflection model has been developed, describing the surface reflection and hence the intensity as seen by the camera. As an example, figure 5 shows radiance curves along the *x*-axis for different surface roughness σ_α for h = 20 mm and r = 16 mm. Obviously, roughness σ_α has a significant effect on the radiance: larger roughness gives larger radiance in the direction ($\theta_r = 0$, $\phi_r = 0$). This is due to the fact that specular reflection is assumed to occur on each surface facet. For rougher surfaces, light is scattered in more directions and more light reflects into the direction ($\theta_r = 0$, $\phi_r = 0$), whereas for smoother surfaces light rays are more reflected to a small range of specular directions. In addition, over a specific range of surface roughness ($0.4 < \sigma_\alpha < \pi/3$), uniform reflection is achieved.

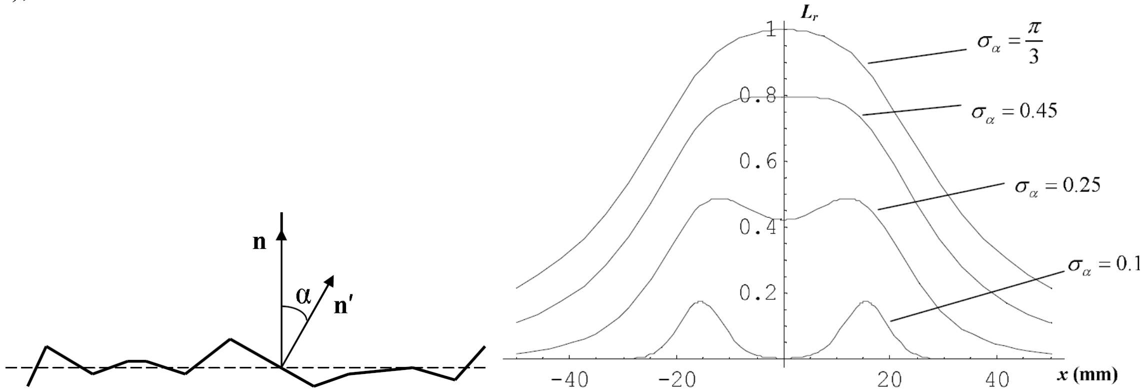

Fig. 5. Ring-light modelling. Left: surface built up from randomly oriented patches; right: calculated radiance (normalized) along the *x*-axis viewed into the direction $\theta_r = 0$, for different surface roughness.

Apart from bright-field illumination, as in the previous example, also dark-field illumination has been investigated. In this approach, the specimen is illuminated from the side, under a narrow angle. In that case, only a small part of the light is reflected upwards into the direction of the camera. However, when the surface shows irregularities, for instance due to wear, more light will arrive at the camera, so it can be expected that scratches could be detected much better by using dark-field illumination. For this purpose a special dark-field ring-light adapter was mounted on the microscope (figure 6).

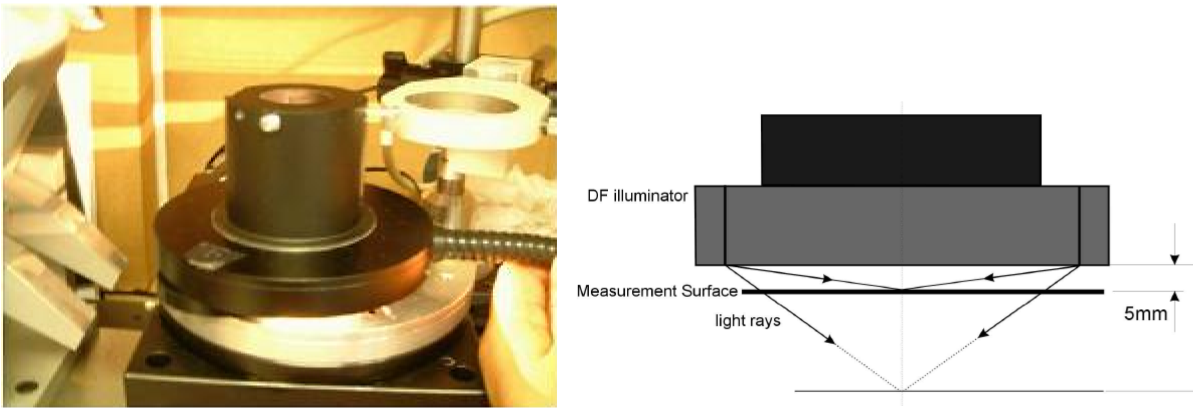

Fig. 6. Special ring-light adapter to create dark-field illumination. Left: photograph of the adapter; right: direction of light rays [3].

The dark-field ring-light source transmits light in radial direction over the full circumference. To enhance contrast in a particular direction, optical masks of various angles have been mounted in front of the dark-field illuminator. The idea is to discriminate between scratches running in different directions and also to discriminate between scratches and the original (linear) texture.

Figure 7 shows a typical result, in which four types of illumination are compared. The original surface has a grooved machined structure. Two scratches are applied: one oriented in almost the same direction as the machined grooves, another under an angle of about 45 degrees.

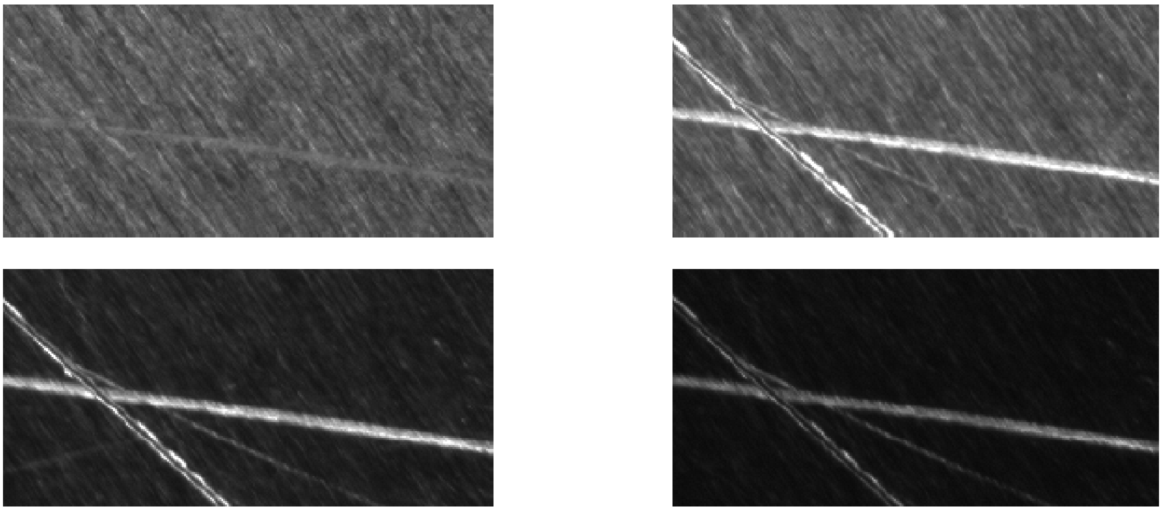

Fig. 7. Four types of illumination for the same region of interest. Top left: bright field illumination; top right: dark-field illumination all around; down left: dark-field, with 90 degrees mask; down right: same, with 30 degree mask.

4. Discussion

Bright field illumination gives good results for rather large surface defects. By proper filtering, the surface area of the worn region can be determined rather easily [2, 4]. Smaller defects give lower contrast, hence detection becomes more difficult or impossible. Dark-field illumination reveals better contrast in this case, as shown in figure 6. In order to better discriminate between linear texture and linear defects, an optical mask is applied, that let pass the incident light over a restricted segment only. However, the narrower this filter, the lower the average intensity. Further investigations aim to replace the optical masks by digital filters, and to automatically optimize the width and the orientation of the filter.

Acknowledgements

The authors like to thank A.P de Vries and C.W Cheng for the design and implementation of the optical system and the special accessories.

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