Scatterometry of Ground Surfaces

Cz. Łukianowicz, T. Karpiński

Department of Mechanical Engineering, Technical University of Koszalin
PL – 75-620 Koszalin, Poland, E-mail: czel@tu.koszalin.pl

Abstract: *The paper presents the method for evaluation of the geometrical structure of ground surfaces by means of measurements and light scattering analysis. The most important factors affecting the spatial form of distribution of scattered light intensity were examined. The rough-estimate method for the spatial form of this distribution was presented. The experimental results obtained by this method for flat ground surfaces were provided. The way to make use of the light scattering techniques for active measurements of surface roughness in the process of tool grinding was also demonstrated.*

Keywords: Light Scattering, Surface Roughness, Ground Surfaces

1. Introduction

It is often required during the precise grinding of machine elements to monitor the geometric quantities. The quantities subject to control determine the shape and dimensions of a given workpiece including roughness of manufactured surfaces. One of the methods for assessing the geometrical structure of manufactured surfaces, especially the surface roughness, is scatterometry [1], [2]. It consists in the analysis of the intensity distribution of light scattered by the surface followed by the evaluation of respective geometric quantities. Scatterometry also may be used to control the ground surfaces, including flat and cylindrical ones.

In order to use scatterometry as a method allowing the geometric quantities to be evaluated indirectly, it is necessary to determine the relation between the distribution of scattered light intensity and the parameters of surface geometry. The spatial distribution of light reflected from the surface is defined by a two-dimensional function called bi-directional reflectance distribution function (BRDF). The function BRDF, i.e. the distribution of light reflected from the surface is relatively easy to measure. However, the theoretical determination of accurate values of this function is a very difficult task because the problem of the light diffraction on rough surfaces needs to be solved. The present paper determines an approximate form of this distribution, depending on various factors. For this purpose the principles of geometric optics and so-called mirror facet model were applied.

2. Distribution of Scattered Light Intensity

The spatial distribution of light intensity scattered by rough surfaces depends on many factors. Dimensions and configuration of irregularities, a nominal surface-form and its way of illumination influence its form as well. If the height of surface irregularities exceeds the light wavelength, one can determine the approximate form of its distribution using a simple, geometric model of light scattering.

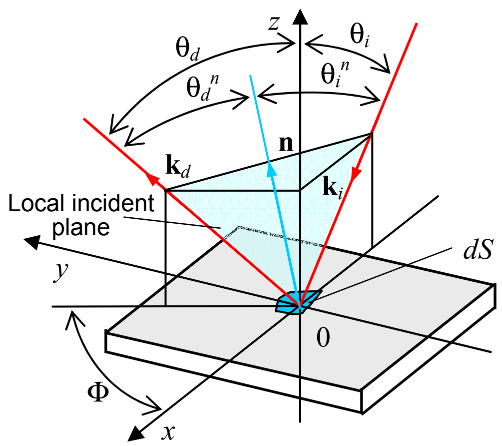


Fig.1. Specular reflection of light from surface element *dS*.

Let a plane light wave incident the small reflecting element *dS* of the surface defined by the function $z = f(x, y)$, as can be seen in Fig. 1. The vector of the normal **n** is perpendicular to the element *dS*. The wave vectors of the incident wave $\mathbf{k}_i$ the reflected wave $\mathbf{k}_d$

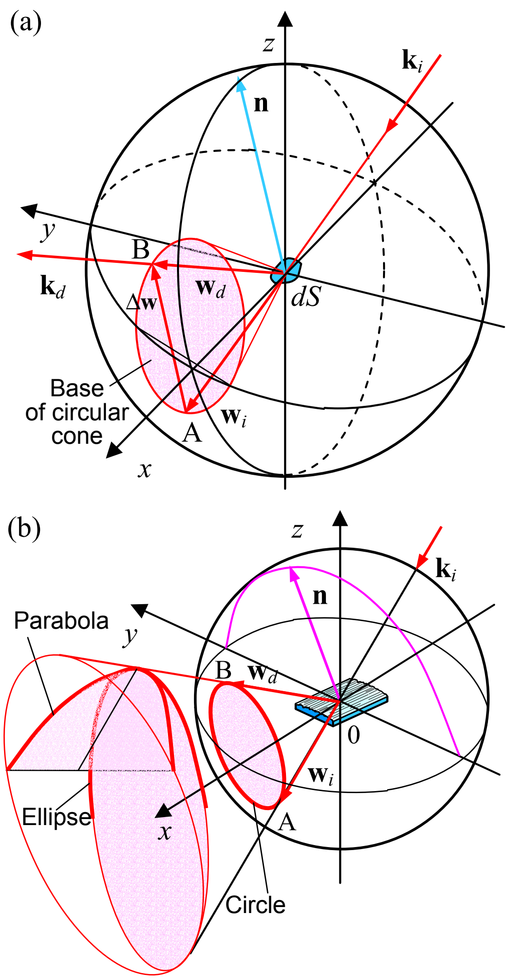


Fig. 2. Scattering geometry: (a) sphere for scattering analysis, (b) form of scattered light distribution obtained from $z = f(y)$ depending to position of observation plane.

and the vector of the normal **n** lie in the same plane, so-called incident plane.

The projection length n_x, n_y and n_z of the vector of the normal **n**, on Cartesian co-ordinate axes (xyz), are defined by relations:

$$n_x = -n_z \tan \gamma_x \ , \tag{1}$$

$$n_y = -n_z \tan \gamma_y \ , \tag{2}$$

$$n_z = \frac{1}{\sqrt{1 + \tan^2 \gamma_x + \tan^2 \gamma_y}} \ , \tag{3}$$

where γ_x, γ_y are angles between axes x and y, and tangents (at the reflection point) to the line intersecting the surface $z = f(x, y)$ with planes parallel to (xz) and (yz).

The angles γ_x, γ_y of inclination of the tangents to the surface $z = f(x, y)$ do not exceed the range from $-\pi/2$ to $\pi/2$ radian. One can determine them by the first-order partial derivatives of the function $z = f(x, y)$, by solving the equations:

$$\gamma_x = \arctan \frac{\partial f(x, y)}{\partial x} \ , \tag{4}$$

$$\gamma_y = \arctan \frac{\partial f(x, y)}{\partial y} \ . \tag{5}$$

In a given co-ordinate system, values of the angles γ_x and γ_y depend on a nominal surface-form, configuration and dimensions of irregularities.

This simplified model of the light reflected from the mirror elements dS forming the surface $z = f(x, y)$, makes it possible to determine the approximate form of distribution of scattered light intensity. In general, one can examine for this purpose the space position of the set of wave vectors – definite for elementary waves, forming the incident wave and the reflected wave – in accordance with [3] and [4].

Direction of the reflected light, determined by the vector $\mathbf{k}_d$ or the versor $\mathbf{w}_d$, depends on direction of the incident light – next determined by the vector $\mathbf{k}_i$ or the versor $\mathbf{w}_i$ – and on direction of the normal **n**. This dependence is expressed by the relation:

$$\mathbf{w}_d = \mathbf{w}_i + \Delta\mathbf{w} \ , \tag{6}$$

where

$$\Delta\mathbf{w} = -2(\mathbf{n} \cdot \mathbf{w}_i)\mathbf{n} = [-2 \, |\mathbf{n}| \, |\mathbf{w}_i| \cos \, (\pi - \theta_i^n)] \, \mathbf{n} \ , \tag{7}$$

and

$$|\Delta\mathbf{w}| = \mathrm{AB} = 2 \cos \theta_i^n . \tag{8}$$

The vector $\Delta\mathbf{w}$ is a difference of $\mathbf{w}_d$ and $\mathbf{w}_i$. It is parallel to the vector **n**.

In case of the ground surface one can assume that irregularities form grooves parallel to the one of co-ordinate axes, e.g. to the axis x. They are defined by the function $z = f(y)$. The surface with such irregularities consists of many elements dS with the angle γ_x near zero but with different values of the angle γ_y. Analysis of light scattering by such surfaces was conducted in Ref. [4]. It has revealed that the general form distribution of light intensity scattered by such surfaces is in the shape of a second-degree curve, which is illustrated in Fig. 2b.

The type of curve depends on the direction of the wave vector $\mathbf{k}_i$ and the position of the observation plane in relation to the cone drawn by the vectors $\mathbf{k}_d$ as well. Mostly it is an ellipse, a circle or a parabola. In a special case when the wave vector $\mathbf{k}_i$ lies in the plane (yz), the distribution of light intensity scattered by the surface $z = f(y)$ is positioned on a line segment forming the line of intersection with (yz) plane and the observation plane. The vector $\Delta\mathbf{w}$ is then positioned in the plane (yz) irrespective of the values of the angles γ_y.

The angles γ_x for ground surfaces vary to some limited extent. It is the reason for some slight lateral scattering. Second-degree curves describing the distribution of scattered light intensity undergo some lateral broadening. This phenomenon will be more intense if the range of changes in the angles γ_x is enlarged.

The fact that the distribution of scattered light intensity is only a fragment of a second-degree curve generally results from the limited scope of changes in the angles γ_y for real surfaces. But even then if this angle changes within the scope from $-\pi/2$ to $\pi/2$ radian, the distribution of the light scattered by non-transparent surfaces cannot be observed at these points of the observation plane where the co-ordinate z is negative. It is caused by multiple reflections that certainly will appear when the absolute value of the angle of reflection θ_d, measured towards the axis z, exceeds $\pi/2$ radian.

Analysis of the intensity distribution of light scattered by manufactured surfaces is generally applied to surface roughness measurements [5], [6] or evaluation of surface anisotropy [1]. It is shown below that on the basis of such analysis one can also evaluate the surface shape of precise ground cutting edges, e.g. razor blades, surgical scalpels, circular tools and other tool cutting edges.

3. Scatterometry of Ground Blades

The grinding of precise cutting edges, e.g. razor blades or surgical scalpels, is carried out on automated machine lines. In this case the automated and efficient in-process control is required. It should be applied to the surface roughness and the shape of cutting edges.

Precise cutting edges have one, two or even three ground surfaces. Fig. 3 illustrates a typical shape of a razor blade with a marked directional geometric structure of ground surfaces. These blades have surfaces next to cutting edges additionally polished. Micrographs of real blades are presented in Fig. 4. The geometrical structure of ground surfaces was examined using the light scattering method.

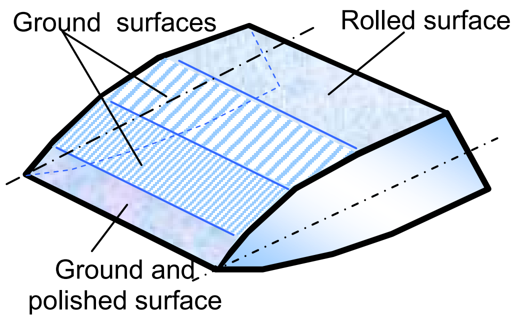
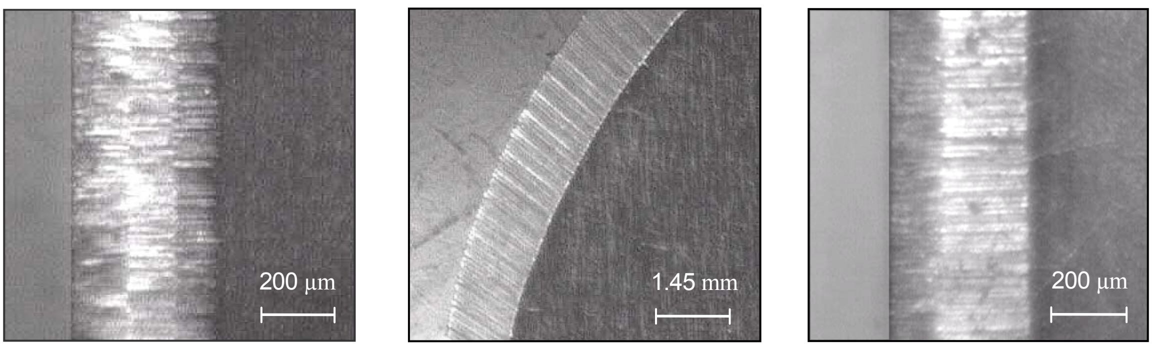


Fig. 3. Typical shape of a razor blade edge.

Making advantage of a light scattering phenomenon 4 types of razor blades, 3 types of surgical scalpels and 3 types of tool cutting edges were



(a) (b) (c)

Fig. 4. Microscopic images of blade surfaces: (a) razor blade, (b) surgical scalpel, (c) technical cutting blade.

examined. Fig. 5 exemplifies the results of light scattering obtained for various cutting edges. According to Fig. 5, one can identify the regions in distribution of light scattered by edges under control where the light scattered comes from consecutive surfaces of the blade. Owing to that, it is easy to determine the number of ground surfaces on the blade. It is also possible to determine the angles of inclination of respective blade surfaces and evaluate the roughness of these surfaces.

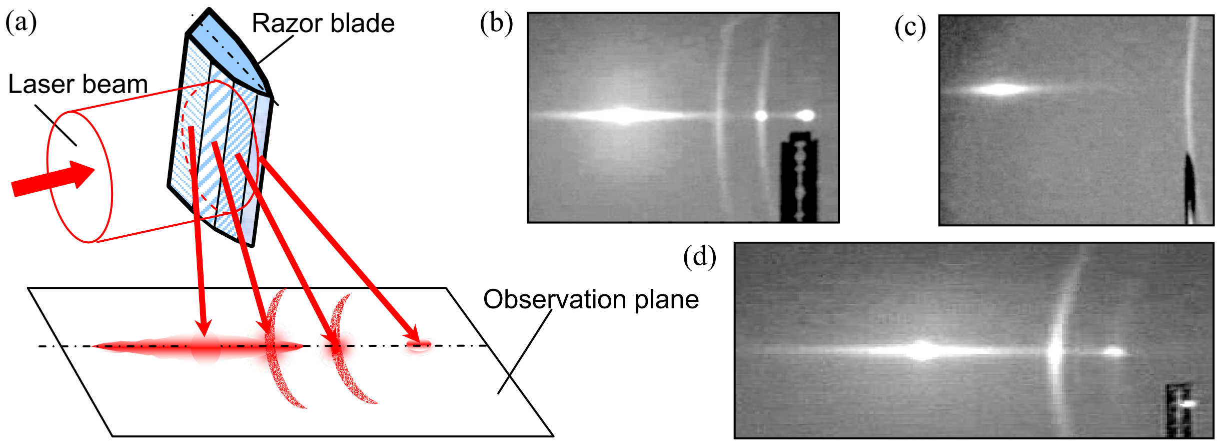


Fig. 5. Scattering geometry (a) and distributions of scattered light obtained for blades that are presented in Fig. 4: (b) razor blade, (c) surgical scalpel, (d) technical cutting blade.

4. Conclusions

It results from the investigations that the form of scattered light distribution depends on the nominal surface shape, its geometrical structure, and the position of the light incident plane and the observation plane in relation to the examined surface. The proposed analysis allows the approximate shape of distribution of light intensity scattered by ground surface to be predicted. Distribution of scattered light is base for evaluating the directional geometric structure of blade surfaces. Making use of this distribution one can also determine the position of the surface in relation to the incident plane. This method can be also used for control of precise ground cutting edges, e.g. razor blades, surgical scalpels etc.

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