

# SCATTEROMETRY OF MACHINED SURFACES

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*Abstract: Measurements of surface roughness by scattering methods are the subjects of this paper. Theoretical and experimental studies of the light scattering from machined surfaces are presented. Two-dimensional fast Fourier transform (2-D FFT) algorithm for computer simulation of diffraction field is applied. A discussion of modelling scattered light from periodical and random surfaces is given as well. Survey of scattering methods for measuring of rough machined surfaces is concise presented. A description of method for evaluation of moving rough surface is also given. This method involves measurements of the angular distribution of scattered light. Experimental results of measurements of machined rough surfaces are presented. These results show applicability of this method in process control.*

*Keywords: scatterometry, measurements of surface roughness*

## 1 INTRODUCTION

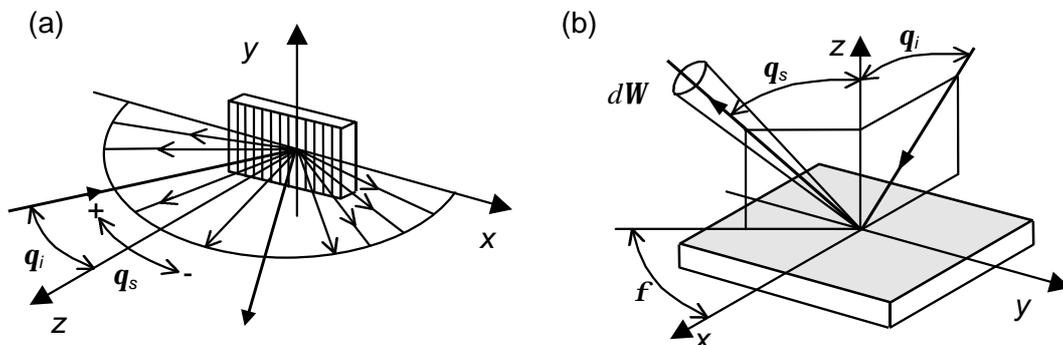
An important problem in metrology of manufactured parts is measurement of surface roughness in production [1]. Machined surfaces are usually investigated by stylus methods. These techniques are great versatility, but sometimes can be non-suitable. Measurements of surface roughness in production should be usually fast and non-destructive. In such applications it is often not important to measure the exact values of surface roughness parameters, but to detect deviations from a rated value. Various optical methods are served for the surface roughness measurements and have been applied to the inspection of precise machined surfaces. These methods sometimes use scatterometry [2], [3].

## 2 PRINCIPLE OF SCATTEROMETRY

Scatterometry is an optical method for measurements and analysis of surface roughness. This method is based on scattering of light waves from surface irregularities. Essence of scatterometry consists in measurements of intensity and the angular distribution of scattered light. Scatter pattern is measured in one or two directions, depending on surface structure and light up. Schematic diagram showing the scattering geometry is given in Fig. 1. Measuring of scattered light in two directions allows determine the so-called bi-directional reflectance distribution function (BRDF):

$$BRDF = \frac{dP_s / d\Omega}{P_i \cos q_s} \quad (1)$$

Here  $dP_s/d\Omega$  is the power scattered per incremental solid angle,  $P_i$  is the incident power, and  $q_s$  is the scattered angle. Surface roughness is calculated from measurements of scattered light.



**Figure 1.** Scattering geometry: (a) in incident plane, (b) in three dimensions. The incident, polar and azimuthal scattering angles are  $q_i$ ,  $q_s$  and  $f$ , respectively; an incremental solid angle is  $dW$ .

Measurements of surface roughness by scatterometry are used in two cases. Firstly, this method is applied when we should measure roughness of very smooth surfaces, such for example how optical surfaces and silicon wafer surfaces. Secondly, scatterometry is used when we ought to execute fast evaluation of surface roughness in production particularly during motion of workpiece.

There are three ways of assessing surface roughness through measuring of reflected light from rough surface. These are: measuring the specularly reflected light, measuring the total integrated scatter (TIS) and measuring the angular distribution of scattered light.

In the sixtieth several investigations of the relation between the roughness and specular reflectance of machined surfaces have been reported [4], [5]. At this time theory of specular reflection and dependence between standard deviation of surface roughness  $\sigma$ , and specular reflectance was established. This dependence expresses equation:

$$\frac{R_s}{R_o} = \exp \left[ - \left( \frac{4ps \cos q_i}{\lambda} \right)^2 \right] \quad (2)$$

where  $R_s$  and  $R_o$  are specular and total reflectance, respectively,  $\sigma$  is standard deviation of surface roughness,  $q_i$  is incident angle and  $\lambda$  is wavelength of light.

For very smooth surfaces, the ratio  $R_s/R_o$  is close to unity. Then it is easier to measure the integrated scattered light. The total integrated scattering is defined as

$$TIS = \frac{R_d}{R_o} = \frac{R_o - R_s}{R_o} = 1 - \exp \left[ - \left( \frac{4ps \cos q_i}{\lambda} \right)^2 \right] \approx \frac{R_d}{R_s} \approx \left( \frac{4ps \cos q_i}{\lambda} \right)^2 \quad (3)$$

where  $R_d$  denotes the diffuse reflectance. Thus standard deviation of surface roughness  $\sigma$  can be expressed in the form:

$$\sigma \approx \frac{\lambda \sqrt{TIS}}{4p \cos q_i} \quad (4)$$

There are also estimation methods of surface roughness using measurement of the angular distribution of scattered light. Using these methods we measure the light intensity and scattering angle simultaneous. Measured intensity is treated as function of scattering angle. These methods are called as the angle-resolved scattering (ARS) or differential scattering (DS). Measured angular distribution of scattered light or BRDF is a basis for estimations of surface roughness. BRDF is measured according to equation (1). For very smooth surfaces the conversion of BRDF into surface power spectral density can be made by several diffraction theories [6], [7]. One of these is Kirchhoff diffraction theory [8]. Kirchhoff diffraction theory is a base of effective optical technique for determining the roughness of surfaces called optical Fourier transformation (OFT) [8], [9]. During measuring the surface roughness for precise-machined part we can use similar methods as DS and OFT.

### 3 NUMERICAL MODELLING OF DIFFRACTION FIELD

Many papers and several books [5], [7], [10], [11], [12] have been published on the subject of scattering from rough surfaces. Main idea presented in these publications, is a research on the relationship between surface topography and the scattered light. The mathematical expression of this relationship is based on various theories, primarily on the Rayleigh-Rice perturbation theory and on the Kirchhoff theory. Computer techniques can be applied for modelling and study of light scattering from surface roughness. Computer simulations make it possible to investigate the direct and inverse problem for light scattered by rough surfaces.

Diffraction analysis of coherent light scattered from rough surface shows, that complex amplitude of light in Fraunhofer zone is proportional to two-dimensional Fourier transform complex amplitude of light in surface [8], [9], [13]. Dependence between intensity of diffraction light in Fraunhofer zone and complex amplitude of light on surface describes equation:

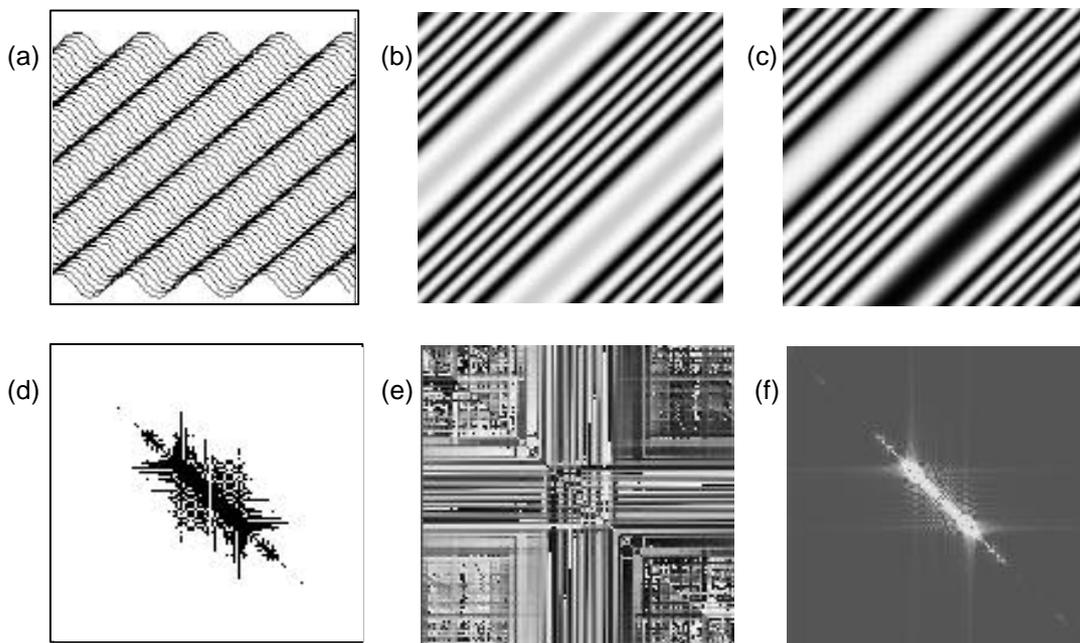
$$I(x_f, y_f) = \left| C \mathfrak{F}[U(x_0, y_0)] \right|^2 \quad (5)$$

$U(x_0, y_0)$  is complex amplitude of light in scattering surfaces given by

$$U(x_0, y_0) = r_A(x_0, y_0) \exp[-jkf(x_0, y_0)] \quad (6)$$

where  $I(x_f, y_f)$  is light intensity in Fourier plane,  $x_f, y_f$  are co-ordinates in Fourier plane,  $C$  is constant,  $\mathfrak{F}[U(x_0, y_0)]$  denote Fourier transformation,  $U(x_0, y_0)$  is complex amplitude of light on scattering surfaces,  $x_0, y_0$  are co-ordinates in scattering surfaces,  $r_A(x_0, y_0)$  is amplitude reflection coefficient of surface,  $j$  is imaginary unit,  $f(x_0, y_0)$  is surface,  $k = 2\pi/\lambda$  is wave number and  $\lambda$  is wavelength of light.

The analysis of equation (5) was made by specially worked out software. During the model investigations we assumed, that amplitude coefficient of reflection  $r_A(x_0, y_0)$  is equal to 1 in all points of investigated surface, while wavelength of light  $\lambda = 632.8$  nm. Fraunhofer diffraction field was modelling for two-dimensional periodic and random surfaces. Illuminated area of this surface was square  $256 \times 256$  pixels. Maximum height of the modelling surface roughness did not exceeded  $2 \mu\text{m}$ . Fig. 2 shows results of modelling the diffraction field, obtained for sinusoidal surface. Amplitude of this surface is equal to  $1 \mu\text{m}$  and spatial wavelength is  $50 \mu\text{m}$ . Figures 2b, 2c, 2e and 2f are monochrome images with 8-bit grey values for each pixel. Fig. 2d is negative bilevel image (1 bit/pixel). Investigations showed usefulness of worked out software for modelling of light scattering by some rough surfaces. More exact results can be received improving the bits per pixel number and spatial resolution of model function.

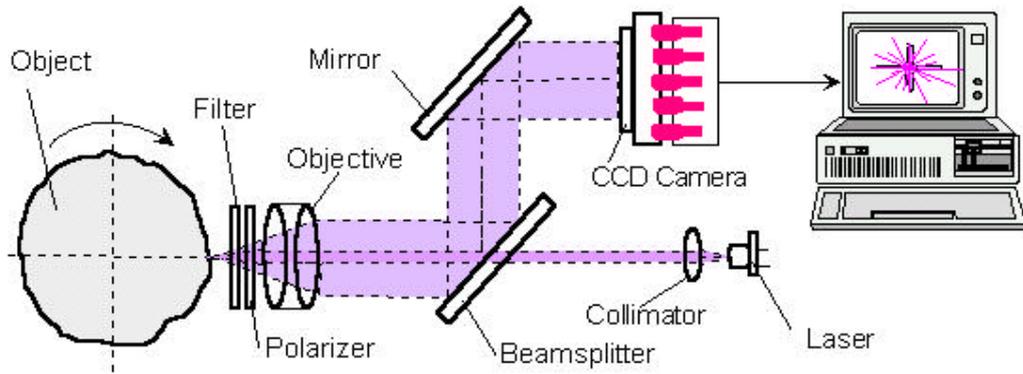


**Figure 2.** Results of modelling the diffraction field scattered from two-dimensional sinusoidal scattering surface  $z = f(x_0, y_0) = A \sin [2\pi f(x_0 + y_0)]$  in Fraunhofer zone, for  $A = 1 \mu\text{m}$ ,  $f = 20$  1/mm and wavelength  $\lambda = 632.8$  nm; isometric plot of scattering surface (a), pattern of  $\text{Re}[U(x_0, y_0)]$  - real part of complex amplitude distribution  $U(x_0, y_0)$  on the scattering surface (b), pattern of  $\text{Im}[U(x_0, y_0)]$  - imaginary part of complex amplitude distribution  $U(x_0, y_0)$  on the scattering surface (c), negative pattern of real part of  $\hat{A}\{\text{Re}[U(x_0, y_0)]\}$  (d), phase pattern of  $\hat{A}[U(x_0, y_0)]$  (e), calculated the light intensity distribution  $I(x_f, y_f) = |\hat{A}[U(x_0, y_0)]|^2$  in Fraunhofer zone.

#### 4 MEASUREMENTS OF MACHINED SURFACES

Increasing automation of production process requires the use of improved methods for a fast and non-contact testing of machined surface. Scattering methods can permit an automatic full testing, measuring in the machine area and continuous process control. These techniques can be used as advantage here since they offer not only a high measuring sensitivity and short measure time but also non-invasive measurements. Such measuring systems, using scattering the light by machined surfaces are described in works [14], [15]. These measuring systems are all the time improved.

Experimental set-up shown in Fig. 3 has been for investigations of machined surfaces. This set-up contains semiconductor laser, beam-splitter, optical lens, optical filter, polarizer, mirror, CCD matrix sensor and microcomputer. Software has been intended for control of set-up, acquisition and processing measuring signals. Laser beam is projected onto the object surface by optical system.



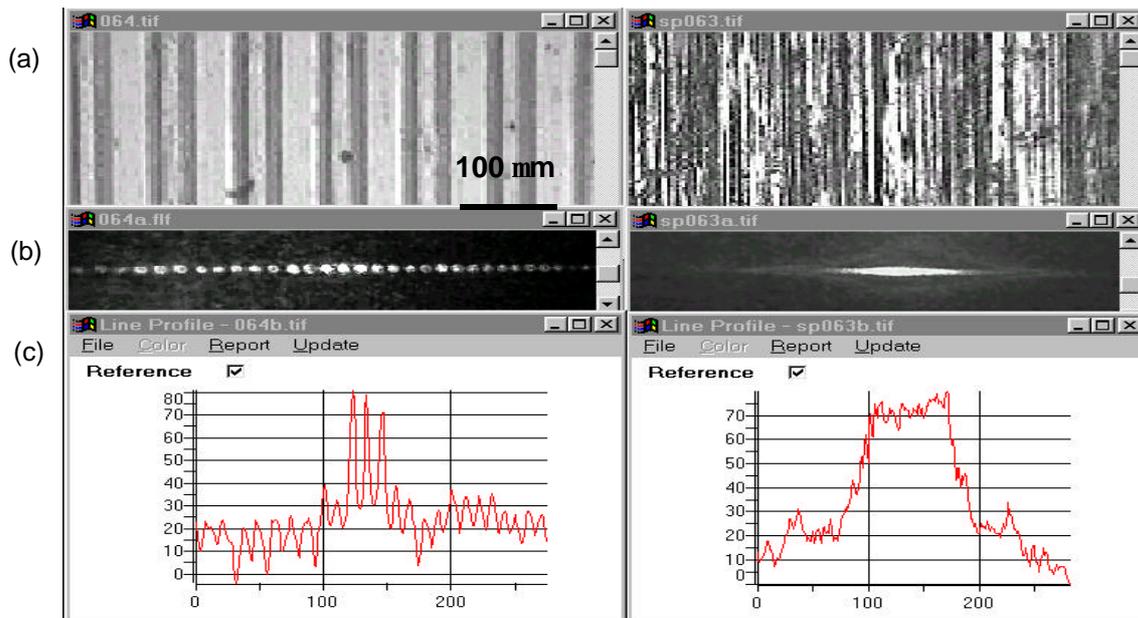
**Figure 3.** Experimental set-up for investigations machined surfaces.

The light reflected and scattered from the object surface is directed to CCD matrix sensor. The electric signals obtained from CCD matrix sensor are processed in the microcomputer. Motionless and moving surfaces can be measured by experimental set-up.

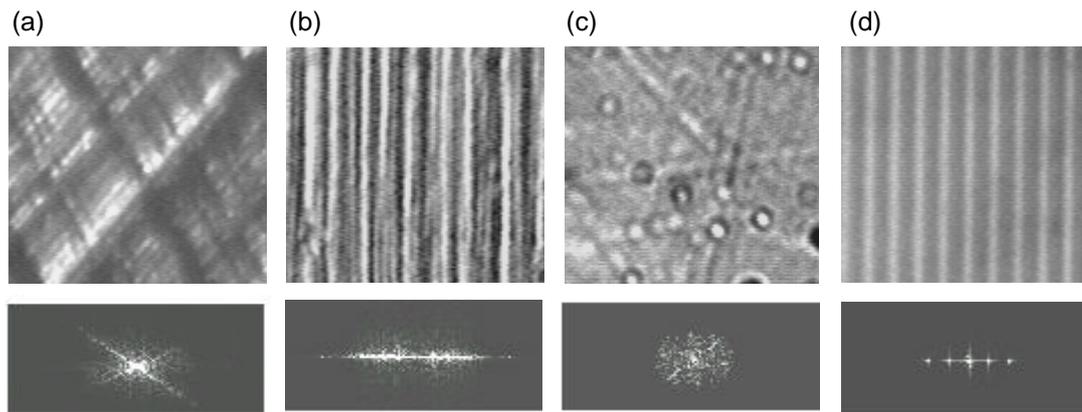
Polished, ground, lapped and microfinished surfaces made of glass and objects made of metal have been investigated by experimental set-up. Some objects have had periodical surfaces and other of random surfaces. Recorded distributions of scattered light have been analysed by microcomputer. In the analysis of scattered light the Program Image-Pro Plus (Media Cybernetics USA) has been used. This program executes many operations such as intensity analysis, fast Fourier transformation, spatial frequencies filtering, convolution and non-convolution filtering. Parameters of surface roughness have been measured by stylus method for all surfaces. Relationships between scattered light and surface roughness for machined surfaces have been also investigated.

Two microscopic images of periodical and random surfaces are shown in Fig. 4. Furthermore there are images of the scattered light from these surfaces and intensity plots of the scattered light. Amplitude parameters of these surfaces have been evaluated by computer analysis of the scattered light images. In addition spatial wavelength of surface has been determined for periodical surface. Parameters of the surface roughness were measured also by stylus method for all surfaces.

The microphotographs of some machined surfaces and their images of Fourier spectra are shown in Fig. 5. Texture and anisotropy of shown surfaces can be easily evaluated by observation of these images.



**Figure 4.** Microscopic images of two surfaces (a), images of the scattered light (b), and intensity plots of the scattered light (c). The lapped glass surface with periodical grooves,  $R_a = 0.64 \mu\text{m}$  (left). The ground steel surface,  $R_a = 0.63 \mu\text{m}$  (right).



**Figure 5.** Microscopic images of machined surfaces and their modules of Fourier spectra obtained for different surfaces: honed (a), finished (b), polished (c), lapped with periodical grooves (d).

## 5 CONCLUSIONS

Scatterometry is powerful method for characterisation and evaluation of geometrical microstructure of machined surfaces. In principle, it can be used to measure the amplitude and spatial parameters of machined surfaces. The anisotropy of rough surfaces can be determined by this method.

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