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Gloss inspection of metallic products by diffractive optical element based sensor

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A sensor was developed to measure the gloss of curved metal objects. The crucial part of the sensor is a diffractive optical element (DOE). The advantages of the present sensor are non-contact measurement mode, normal incidence of the probe light, and possibility to measure gloss of curved surfaces. The sensor yields information also on the surface texture, such as finishing marks, of curved metal surfaces. The operation of the sensor was verified by measuring draw-off pipes of water cranes, which were obtained from metal industry.

Keywords: gloss, curved metallic products, surface texture, diffractive optical element (DOE).

1. Introduction

It is well known that gloss is a subjective perception. However, it is visually difficult to observe small differences on gloss, for instance, when comparing the gloss of peel of two oranges. In engineering gloss is an important parameter in quality inspection when evaluating the visual appearance of a surface. Indeed, the gloss is often used as a criterion to assess the quality of a product, especially in the case of products, which require aesthetic appearance. Visual gloss assessment includes many subjective errors and therefore is not usually sufficient in industrial optical inspection. Therefore, to be objective, it is necessary to have a quantitative measure of gloss. The international standard ISO 2813 (nearly identical to ASTMD523) defines specular gloss. The definition is based on the ratio of luminous flux of light, which is reflected from an object in the specular direction for specified source and receptor angle, to the luminous flux reflected from highly polished glass (refractive index 1.567) in the specular direction. To this glass shall be assigned a specular gloss value of 100 gloss units (GU) for all geometries [1,2]. The device that measures gloss is called a glossmeter. In order to achieve highly accurate and repeatable results, the test specimen should be ideally flat, free of surface texture, similar in colour and lightness and non- luminescent material. Finishing marks on the surface will result on different gloss value, which depends on the measuring direction. Unfortunately, there are several problems in the measurement of gloss such as temporal stability of reference standard and light source, polarization degree of incident light beam, scattering of the light, and the shape of the surface [3–6]. For these reasons, there is a continuous need for a gloss meter, which would improve the accuracy and reliability of the gloss measurement.

A general problem with a commercial glossmeter is that it usually fails to measure gloss of curved or strongly curved surface. Furthermore such devices require contact with surface and therefore they may not be utilized for detection of gloss of fragile surfaces. In industry, many of the surfaces will be curved or inaccessible, and moreover subject to on-line monitoring of gloss.

In this paper we study an application of a diffractive optical element based sensor (DOES) for the estimation of gloss of curved metal products. Similar sensor was already reported to detect surface roughness and waviness of metals [7,8], and thickness of float glass in industrial site [9] using a plane wave probe obtained from a laser. However, here the DOES is different from the device presented in Refs. 7, 8, and 9 because the beam from the laser is now focused on the inspected surface. We propose that the present sensor can avoid problems of conventional glossmeters such as requirements of flatness of the sample and contact on the surface. For the present purpose we investigated draw-off pipes of water cranes which were obtained from metal industry.

2. Experimental and discussion

In this study we used the setup (DOES) shown in Fig. 1 for the surface inspection. Important part of the sensor is a diffractive optical element (DOE), which was calculated by using Rayleigh-Sommerfeld diffraction integral [10]. The element was an on-axis, binary amplitude element. The element is a focusing type and therefore the measurement system does not need a focusing lens between DOE and CCD detector array, which simplifies the measurement construction. The element was fabricated by sputtering about

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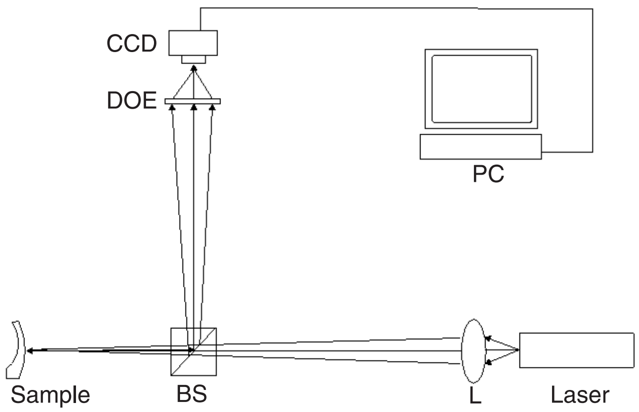

Fig. 1. Schematic diagram of the DOES. CCD = charge coupled device, BS = beam splitter, DOE = diffractive optical element, PC = personal computer and L = lens.

120-nm thick layer of chrome on fused -silica substrate. Next positive electron-beam resist was spin-coated on the chrome layer. Furthermore, the resist was exposed by an electron-beam writer. After the resist was developed, the chrome layer was wet etched. The planar DOE produces a 4×4 light spot matrix in its focal plane [Fig. 2(a)]. Because of the relative large number of light spots (16), we can use statistical analysis to increase the accuracy and reliability of the sensor. The size of the aperture of the DOE was 4×4 mm^2 and the focal length was 100 mm. The distance between nearest adjacent light spots in the focal plane was 125 µm when reconstructing source is in infinity. The imaging properties of the DOE sensor follow the laws of hologram imagery [11,12]. The DOES consists of a stable HeNe-laser, a DOE, a charge coupled device (CCD) and a personal computer (PC). In the experiments a HeNe-laser beam with a low power was focused, using a lens, on the sample surface. The focusing of the laser beam on the surface makes it possible to detect gloss of curved surface due to the small spot size, which was 30 µm at $1/e^2$ level in the present case. The laser beam was normally incident on the sample surface. This scheme is completely different from the measurement mode of conventional glossmeters which operate at oblique angle of incidence. Note that in the measurement mode of the DOES the role of polarization degree of reflected light is not so crucial than with the other glossmeters used in detection of the gloss of rough surfaces. We emphasize also that using the present geometry the distance between the sample and beam splitter (BS) in Fig. 1 can vary, which makes remote on-line monitoring of objects feasible. Here we use monochromatic light whereas conventional glossmeters usually employ white light.

In Fig. 1, the reflected wave front was guided with a beam splitter to the DOE and the chip of the CCD camera was located at the focal plane of the DOE. The CCD-camera detects the image of the light spot matrix, which is produced by the DOE in specular direction, and this image is grabbed into the memory of the PC for analysis. To analyse the gloss of the curved samples, which were nine draw-off pipes presenting parts of water crane (Fig. 3), we calculated the total intensity I of the DOE image. The grid lines with equal spacing of 125 µm shown in Fig. 2(a) indicate the specific areas for each light spot. The double arrows indicate the image pattern area from which the total intensity is calculated. Total intensity is defined by

$$I = \frac{1}{nm} \sum_{i=1,j=1}^{n,m} I_{ij}, \qquad (1)$$

where $I_{i,j}$ is the image intensity observed by the $(i,j)^{th}$ element of the CCD camera array. The samples were mounted on a computer controlled translation stage, which made it possible to scan the draw-off pipe during the measurement. In the present study, the measurements were accomplished in a manner that 3-mm scans were taken from each sample.

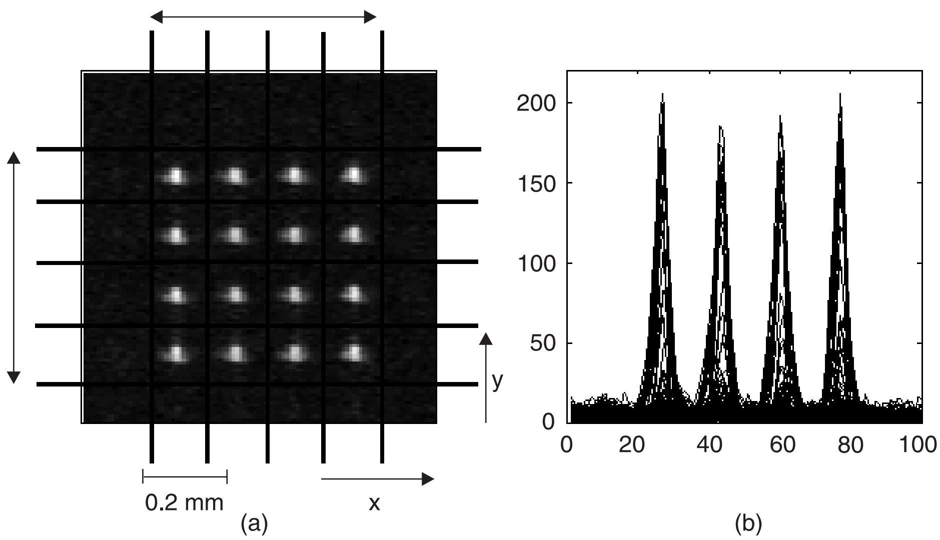

Fig. 2. (a) Image pattern of 4×4 light spot matrix recorded by DOES from a draw-off pipe and (b) intensity plot in x –direction obtained from Fig. 2(a). In Fig. 2(b), numbers shown on the horizontal and vertical axis are pixel numbers for distance (8.3 µm) and intensity.

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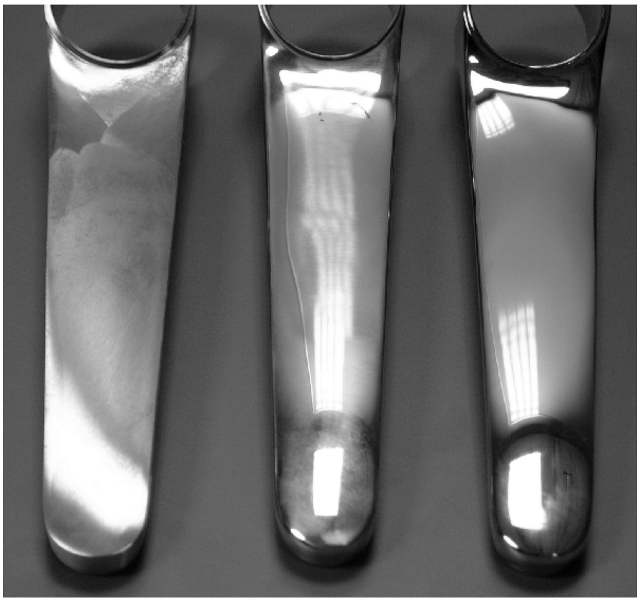

Fig. 3. Images of ground brass (left), polished brass (middle) and chrome plated brass (right) draw-off pipes.

This means that 100 images were taken from each draw-off pipe. Figure 4 shows the results of calculations using Eq. (1). In Fig. 4, the lowest gloss, i.e., the intensity *I*, was detected for dull draw-off pipe made of brass and having ground surface finishing. The gloss of this draw-off pipe was remarkably better when it was polished. The highest gloss was observed when the polished draw-of pipe, made of brass, was chrome plated. The results of Fig. 4 are consistent with visual inspection. For the sake of comparison the gloss of the draw-off pipes was measured also with a commercial glossmeter. The gloss of ground brass, polished brass and chrome plated brass draw-off pipes was 75, 530, and 520 GU, respectively. The first two values are reasonable, however, the last gloss value is not. This is due to the fact that the chrome plated draw-off pipe resembles a convex mirror and tends to expand reflected light to directions other than the direction of the input aperture of the detector of the mechanically labile glossmeter. The lability of the glossmeter is due to poor contact of the measuring head with the sample surface. Actually poor contact of the measuring head was present for all of the samples of the present study.

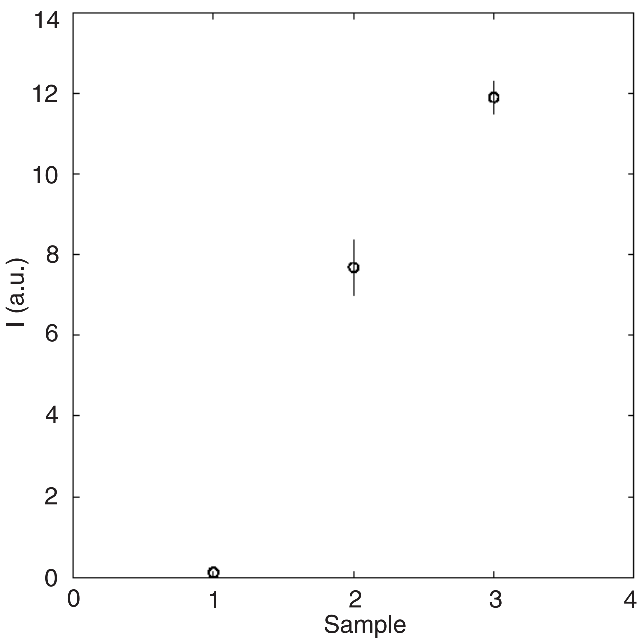

Fig. 4. Gloss, i.e., the intensity *I* obtained by DOES from draw-off pipes. Sample number (1) ground brass, (2) polished brass, and (3) chrome plated brass. The open circle represents the mean value of measurements. The vertical lines shown on the open circles are respective standard deviations.

By conventional glossmeter it is possible to observe surface texture such as finishing marks which are due to machining process. Then it means that the glossmeter has to be rotated with respect to the normal of the surface. In the case of DOES information of the surface texture is detected without sensor rotation. Information on surface texture is obtained by defining the visibility of the 4×4 light spot image pattern as follows

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad (2)$$

where I_{max} is the mean of 16 peaks areas and $I_{min} = I_{min}(x,y)$ is the mean of the minimum areas between the peaks. The visibility was calculated for both directions *x* and *y*. In Fig. 2(b), the intensity plot in *x* direction is shown. Difference between visibility values V_x and V_y give information about surface anisotropy. Figure 5 shows the results of calculations based on Eq. (2) and measured data for the

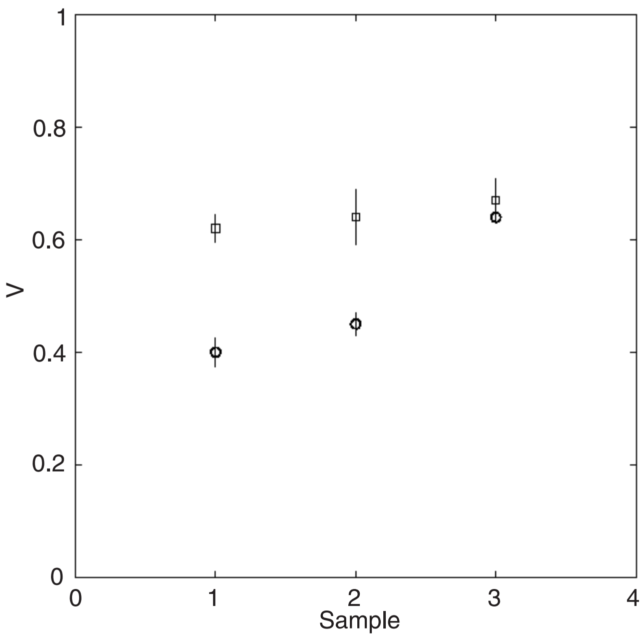

Fig. 5. Respective visibility values obtained by DOES from the data of Fig. 4; square *x*–direction and open circle *y*–direction.

draw-off pipes. In Fig. 5, we can observe that the finishing marks, due to the grinding process, have an effect on the visibility. In addition, polishing process only slightly changes the anisotropy of the surfaces of the draw-off pipes. However, the chrome plating process makes the finishing marks to disappear (it can be visually conformed), which means that visibility $V_x = V_y$.

As a conclusion we propose that the present sensor, which at its present stage is a laboratory device, can be developed to an on-line monitoring gauge of gloss of metal or fragile products in industrial environment. The device can be constructed to a robust apparatus using a stable semiconductor laser instead of HeNe laser as a light source. The measurement time can be made shorter by exploiting a progressive scan camera which captures the image within 10^{-4} s. A portable system is possible.

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