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Fiber-optic sensor to estimate surface roughness of corroded metals

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A fiber optic sensor system is developed to probe the surface texture of corroded metals. The present work is based on the principle of scattering of light by objects. A light beam from an LED source is focused onto the corroded surface. Specular and diffuse reflection of the surface is measured vertically at normal incidence of a fiber. The observed response agrees well with mechanical stylus measurements, with $R^2 > 0.89$. The fiber optic sensor system can be used to estimate the roughness of metals due to any type of corrosion without erosion. The obtained results show a consistent relationship between measured and surface roughness levels.

Keywords: fiber optic sensor, scattering principle, surface roughness, corrosion.

1. Introduction

Surface roughness of corroded metal could effortlessly be analyzed even by visual comparison with a standard polished surface of the same metal. Obtaining quantitative roughness estimation entails many different methods, using several different units of measurement [1, 2]. Even though a number of techniques prove their competent ability to quantify the roughed surfaces, the optical method, due to its non-contact nature and its applicability to in-process measurement, has been considered as best to perform measurements of surface roughness very quickly, often while the sample is in motion [3–5]. The most familiar optical methods applicable to measure the surface roughness are interferometry, speckle, light scattering and focus [6–9]. The work uses the light scattering technique that has been dealt with by, *e.g.*, BECKMANN and SPIZZICHINO [10], KIM [11], LAVIN [12], BENNETT *et al.* [8], OGILVY [13], and STOVER [14]. TANNER and FAHOUM [15] have measured specular and diffuse reflection from ground and lapped metal surfaces. When the metal transits from smooth surface, which reflects light specularly, to a rough surface, a higher proportion of incident light is scattered diffusely. This transition can be related to surface roughness and it can be described as a point quantity using light scattering methods, averaging over the incident spot of the beam [5]. The main limitation in using the optical method to measure surface roughness is the absence of standardized and accepted roughness parameters R_a, and R_q and the difficulty in translating from light scattering parameter V, to R_a or R_q [16]. The intensity of scattered light is a function of concentration of a corroding agent. By correlating the surface roughness – measured by a stylus instrument – with the results of scattered light, it is possible to calibrate the fiber optic sensor measuring the intensity of scattered light in terms of surface roughness. The complexity in direct estimation of the surface roughness parameter R_a, using the fiber optic sensor system was experienced by CAHILL and EL BARADIE [5], PERSSON [16] and DINGHAI *et al.* [17]. Average surface roughness between 0.025 μm and 0.8 μm was estimated through vertical displacement at an incident angle of 60° by CAHILL and EL BARADIE [5].

The goals of this study are to develop fiber optic sensors to measure spatially resolved profiles of scattered light in a corroded surface and correlate the measurements with the surface texture measured using a conventional stylus instrument. A translational stage is used to hold the source and detector fiber as well as to move the fiber holder in vertical direction to the sample surface. The source fiber is used to focus the light on the surface. The scattered and reflected intensities are measured using the detector fiber at normal incidence. The stylus instrument is used to measure the roughness of metals at the same locations where the intensity profile study is made. These two different sensor measurements at the same location are used to correlate scattered light to surface roughness of metals. To check the sensor reliability, the measured intensity of standard reference aluminum coated mirror surface is correlated with the theoretical values.

2. Intensity profile study

The intensity profile study is considered for many reasons, and includes fixing the distance between fibers tip and a sample, separating source from detector fibers and checking the sensor performance. The working model of the sensor is based on a two-fiber model, one of them acts as an emitting fiber and the other as a receiving fiber. The emitting light angle and receiving fiber capturing light angle depend on the refractive index of medium n_0 and numerical aperture NA of the fiber. When the fibers have the same numerical aperture, the maximum emitting angle θ_{NA} is given by

$$\theta_{\mathrm{NA}} = \sin^{-1}\left(\frac{\mathrm{NA}}{n_0}\right) \tag{1}$$

The optical output efficiency factor $\eta(2h, n_0)$ is given as the ratio between the light power captured in the receiving fiber $P_0(2h, n_0)$ and the total power P_t launched into the incoming fiber [18]

$$\eta(2h, n_0) = \frac{P_0(2h, n_0)}{P_t} =$$

$$= 2\int_{R_1}^{R_2}\int_{0}^{\phi_c} R_m\, T_i(n_0)\, T_0(r, 2h, n_0)\, \frac{2}{\pi R^2(h)}\left[1 - \frac{r^2}{R^2(h)}\right] r\, \mathrm{d}\phi\, \mathrm{d}r \qquad (2)$$

where, P_t is the total optical power transmitted through the input fiber, $P_0(2h, n_0)$ is the light power captured by the receiving fiber and R_m is the mirror reflectivity. The $T_i(n_0)$ and $T_0(r, 2h, n_0)$ are Fresnel transmittance coefficients of the emitting fiber and receiving fiber, respectively. The r is the distance from the incoming fiber axis, ϕ is the azimuth angle, a_i and a_r are input and receiving fiber radii, respectively. The s is the spacing between the fiber cores, h is the distance between the mirror and the fiber tip and R is the radius of the light cone at the distance $2h$, and R is given by $R = a_i + 2h \tan(\theta_{\mathrm{NA}})$.

3. Materials and methods

A mild steel plate having weight composition of 0.54 Mn, 0.05 Si, 0.01 S, 0.01 P, 0.16 C and the rest of Fe is used in this study as a test coupon. The test sample is polished with silicon carbide papers up to 1000 grades and the intensity profiles are measured before corroding them. Each test sample is consented to corrode using a test solution of various concentration of sulphuric acid (8 ml, 16 ml, 24 ml, *etc.*) in distilled water. A total of 100 ml of the test solution is sprayed uniformly on each test material to obtain different corrosion levels. It is assumed that a rise in the concentration of sulphuric acid, increases the number of sulphur ions reacting with metal ions in the surface leading to samples with various surface corrosion levels. The assumption is subsequently justified by the results obtained. The optical system consists of input and receiving fibers that have the numerical aperture of 0.48, core diameter of 200 μm (M/s Thorlab Corporation, USA). The source LED has the wavelength of 670 nm, and the detector silicon photodiode is sensitive to optical radiation from 300 to 1100 nm, with optimum wavelength close to 670 nm (M/s Hamamatsu Corporation, USA). A mechanical stylus instrument is used to make a reference measurement (model: Perthen; tip diameter: 2 μm).

3.1. Experimental

Scattered intensity measurements are made at normal incidence of a fiber. The source fiber emits light while the detector fiber receives light from the surface of metal by vertical displacement of a translational stage. The experimental setup is shown in Figure 1.

The source and detector fibers are held parallel to each other and perpendicular to the sample surface. The source and detector fibers are 2.0 mm and separated from each

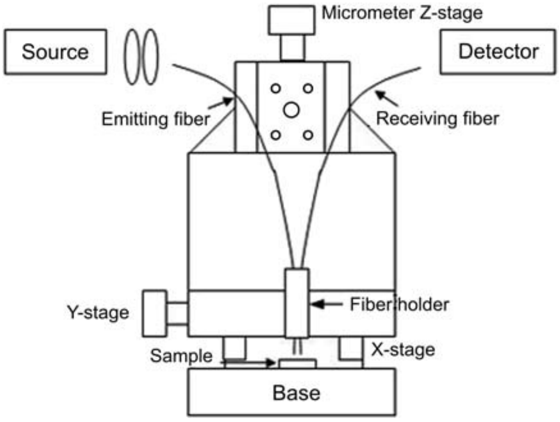

Fig. 1. Experimental setup.

other. The metal area of 1 cm × 1 cm is constituted for an intensity measurement study. In each measurement, the intensities are measured for many randomly selected locations along the surface in vertical direction. The locations in the constituted area, at which the measurements are made, are not known. Displacement measurements are carried out by mounting the input and receiving fiber holder at a distance very close to the sample surface. The data points are taken at 20 μm intervals until the measurements reach the initial value after certain peak intensity is observed. The constituted area, at which intensity measurement is carried out, is subjected to surface roughness measurement using a stylus instrument. The average values of obtained displacement measurements are well correlated with the measured average surface roughness. It should be noted that the experiment is conducted in controlled atmospheric conditions for all the measurements. The fiber lead must be kept in a fixed orientation during data collection to minimize signal variations that are due to bend-induced losses. Figure 2 shows the normalized theoretical and experimental vertical trace of reference mirror surface. A theoretical curve is generated using the Eq. (2) for $a = 0.1$ mm, NA = 0.48 and $n_c = 1.495$ for air medium [18]. It can be seen that

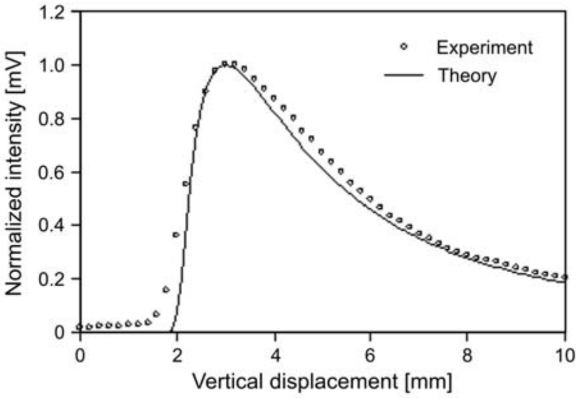

Fig. 2. Theoretical and experimental vertical trace of fiber-optic sensor.

the developed sensor is free from errors due to intensity fluctuations, *e.g.*, microbending in the fiber, power supply fluctuations and thermal effects in the source or measurement region. The intensity profile between the theoretical and experimental trace of an aluminum coated mirror has satisfied the profiles reported in literature [18, 19]. The fiber optic sensor is calibrated both before and after measuring the intensity profiles of each sample using the standard reference aluminum coated mirror.

4. Results and discussion

The results of a typical data run are shown in Fig. 3. The stylus instrument measurement is shown for comparison. Intensity of light reflected from the surface depends upon the texture of the reflecting surface and the separation between the source and detector fiber. The scattered optical signal at 670 nm is decreased with increasing concentration of a corroding agent. Initially, when the concentration of the corroding

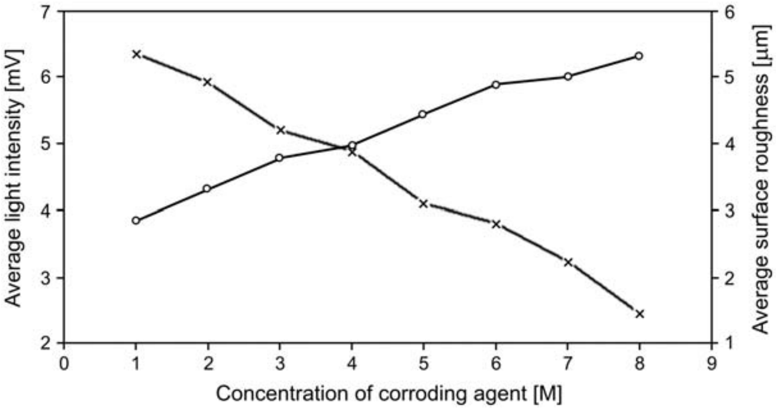

Fig. 3. Estimation of average light intensity (×) and average surface roughness (○) for each molar concentration of corroding agent.

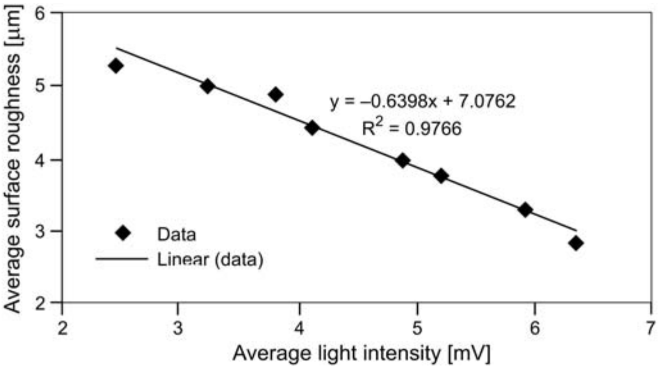

Fig. 4. Correlation between average light intensity and average surface roughness.

agent (H_2SO_4) is low, the surface is lightly corroded. Hence, the metal surface reflects more light than it scatters. As the concentration increases, the scattered light component increases and the reflected light component decreases. Moreover, the variations observed are well correlated with the surface roughness. These results are highly repeatable. The data in Fig. 4 show the correlation between the optical scatter at 670 nm and the stylus instrument measured value (data extracted from Fig. 3). The correlation coefficient R^2 over many trials is always greater than 0.89 and as high as $R^2 = 0.97$ in some tests (as presented in Fig. 4). Further experiments are under way to resolve the mechanisms involved in the measured optical response and to develop a unique correlation between surface roughness and scattered light intensity.

5. Conclusions

The developed fiber-optic sensors show a large optical response in roughed surface. The observed response agrees well with mechanical stylus roughness measurements, with $R^2 > 0.89$. The surface roughness measured in the present work represents an average value for a surface area of 1 cm^2. The surfaces measured with this optical system are classified in the same order as when using a stylus instrument. Using a thin-beam laser as a light source, the differential surface roughness at various points may be measured and, by scanning the surface, the whole area may be corrosion mapped. One of the limitations of this technique is that surface roughness of a metal is expected to reach the saturation value when the top layer gets completely corroded, resulting in total scattering of light. Any further increase in the thickness of the corroded layer may be detected by analyzing other characteristics of the scattered electromagnetic wave.

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