On-Line Defect Detection of Aluminum Coating Using Fiber Optic Sensor

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Abstract: Aluminum metallization using the sprayed coating for exhaust mild steel (MS) pipes of tractors is a standard practice for avoiding rusting. Patches of thin metal coats are prone to rusting and are thus considered as defects in the surface coating. This paper reports a novel configuration of the fiber optic sensor for on-line checking the aluminum metallization uniformity and hence for defect detection. An optimally chosen high bright 440 nm BLUE LED (light-emitting diode) launches light into a transmitting fiber inclined at the angle of 60° to the surface under inspection placed adequately. The reflected light is transported by a receiving fiber to a blue enhanced photo detector. The metallization thickness on the coated surface results in visually observable variation in the gray shades. The coated pipe is spirally inspected by a combination of linear and rotary motions. The sensor output is the signal conditioned and monitored with RISHUBH DAS. Experimental results show the good repeatability in the defect detection and coating non-uniformity measurement.

Keywords: Fiber optic sensors, on-line defect detection, aluminum coating, corrosion resistance, color detection, exhaust pipes of vehicles

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1. Introduction

Untreated aluminum has very good corrosion resistance in most environments. This is primarily because aluminum spontaneously forms a thin but effective oxide layer that prevents further oxidation. Aluminum oxide is impermeable and unlike the oxide layers on many other metals, it adheres strongly to the parent metal. If damaged mechanically, aluminum's oxide layer repairs itself immediately. This oxide layer is one of the main reasons for aluminum's good corrosion properties. A semi-empirical approach using the root-mean-square roughness σ_h and correlation length of surface heights L_c shows that gloss of coated samples is roportional to $(L_c/\sigma_h^2)^n$. The exponent "n" is found to depend on the angle of illumination [1]. Thus the aluminum coating on the surface shows a significant change in the surface characteristics such as the surface roughness and color. A number of techniques are used for coating the surface of material such as exhaust pipes of vehicles to avoid the corrosion. The spray coating with aluminum is the most commonly used technique. This technique has the disadvantage of the uneven coating thickness on the pipe. This causes the corrosion of the pipe over the period of time. To avoid this, it is necessary to detect the uniformity of the coating thickness over

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the pipe before actual installation on the vehicle. With the development of modern industry, measuring and testing techniques are improved continuously. With the advanced measuring technology welling up continuously, to ensure that the surface to be measured is undamaged, measuring equipments must avoid to contact with the object detected during the test process in the area of surface elaborate measurement [2]. And then the appearance of laser makes testing methods more flexible and convenient. Realization of contactless measurement of the object by the optical technique is an important part of modern measuring techniques. By the contactless measurement, the measurement of speed can be improved greatly. It also has many other advantages, such as the high accuracy of measurement, little ambient electromagnetic interference, broad operation scope, favorable to expand the measurement range and avoid collisions during measurement [3, 4]. Surface coating uniformity is a very important index that cannot be ignored in modern surface manufacturing.

In the paper, a retro reflective fiber optic sensor is proposed for on-line uniformity detection of the aluminum coating on the exhaust pipes of the vehicle. The uniformity of the coating is inspected as the variation in the gray shades of the surface. It is modeled mathematically on the basis of the diffused reflection phenomenon due to the surface. Selection of the light-emitting diode (LED) for the gray shade detection, the sensing distance (Z), and current through the LED are optimized by performing experimentation. The sensor is fabricated and tested on the surfaces with different aluminum coating thicknesses using a data acquisition system. The coated pipe is spirally inspected by a combination of linear and rotary motions. The sensor output is a signal conditioned and monitored using NI DAS. Experimental results show a good repeatability in the defect detection and coating non-uniformity measurement.

2. Modeling relationship between the intensity of reflected light and coating uniformity

When a beam illuminates the object surface to be detected, according to the law of reflection, the scotch light relates to the incident angle and surface reflectivity. If the object to be detected is opaque and its surface is coarse, then the reflection at the surface can be taken as diffuse reflection. If the surface of the object to be detected is an ideal mirror plate, then the reflection occurring at the surface is ideal diffuse reflection which obeys to the law of reflection, and the incident angle equals to the reflected angle [5]. The intensity of the reflected light can be expressed as

$$I(\theta)=K_1 I_0 \cos\theta_1 \tag{1}$$

where $I(\theta)$ is the intensity at a point that the inclination of the reflected light and the normal is θ, K_1 is the diffused reflectance, and I_0 is the intensity of the incident light. In fact, the surface of the object to be detected is not a mirror plate, so at the surface both the diffuse reflection and normal reflection occur at the same time. The intensity of the reflected light can be expressed as [6]

$$I(\varphi)=K_2 I_0 (\cos\varphi)^n \tag{2}$$

where $I(\varphi)$ is the intensity at a point that the inclination of the reflected light and normal is φ, K_2 is the diffused reflectance, n is the rough coefficient of the object surface, and the smoother the surface is, the bigger the value of n is. Reflection models in two different cases are shown in Figs. 1 and 2, respectively.

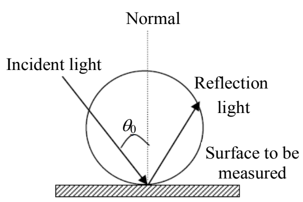


Fig. 1 Model of ideal diffused reflection.

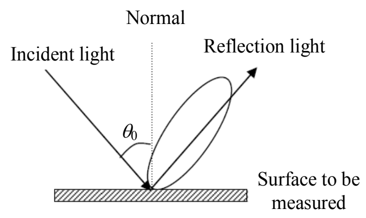


Fig. 2 Model of non ideal diffused reflection.

Uniformity is a physical quantity to reflect the object smoothness. It is similar to the roughness of the metal surface, but only that the textures of the materials are different. Relatively, light absorption of a sorter material is bigger than that of a stiffer one [7]. Uniformity is depended on the diameter of the particles of the surface material, which behaves as the variance of the coating thickness at the same surface. When a beam illuminates the surface of the object to be measured at a certain angle, most of the beam will be reflected and scattered. The smoother the surface is, that is to say, the smaller coating particles are, the larger the reflection proportion is. When the diameter of the coating particle is lager than □, the wavelength of the incident beam, the scattered light plays a predominant role, and the scattered intensity is a Gaussian distribution as a variable of the space angle. Also correspondingly, the distribution of the beam incident angle has a relationship with the smoothness of the surface [8]. In practical measurement, because of the randomicity of the surface to be measured, the scattered light is random too. The spatial distribution of the scattering light field will be varied with the difference of the incident angle, and consequently the received power changes.

The scattering light field reflects the uniformity of the surface coating, which can be represented by an eigenvalue β [9, 10]. The relationship among β, the reflecting light field, and scattering light field is

$$\beta = \frac{E_{\text{inner}}}{E_{\text{outer}}} \tag{3}$$

where E_{inner} is the received energy at the center of the reflected light spot, and E_{outer} is the received energy at the band of scattered light. According to the scattering statistical theory, the coating uniformity γ can be expressed as

$$\gamma = \exp\left(\frac{I_1}{2M^2\sigma_1^2}\right) \tag{4}$$

where M is a proportionality coefficient determined by the relative position of the surface to be measured, light source, and received plane as well as the wavelength of the light source adopted, and σ_h is the root mean square deviation of the surface height.

$$E_{\text{inner}} = KI_0q^2, \quad E_{\text{outer}} = KI_0\gamma^2, \quad \gamma^2 + q^2 = 1,$$

such that

$$\beta = \frac{E_{\text{inner}}}{E_{\text{outer}}} = \frac{q^2}{\gamma^2}. \tag{5}$$

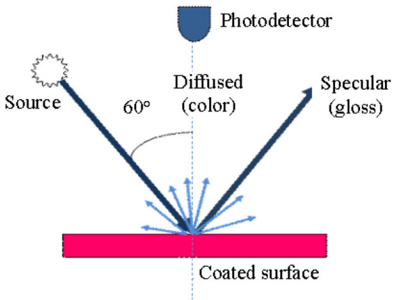
Seen from the analyses above, β is not affected by the intensity of the incident light, I_0, and the coating reflectivity K, but relates to γ, q, and M. That is to say, β is related to the surface uniformity and geometric shape only [11].

For opaque materials most of the incident light is reflected. Color is seen in the diffused reflection, and gloss is seen in the specular reflection. The reflection at the specular angle is generally the greatest amount of light reflected at the single angle. However, the specular reflection only represents less than 4% of the total reflected light. The remaining reflection of the light is in the diffused reflection.

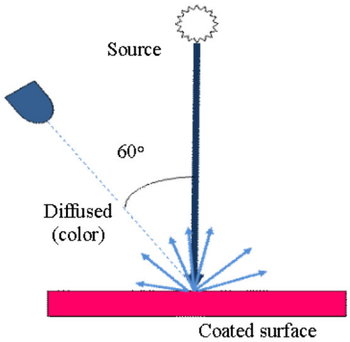
When one looks at the surface having the same color but different surface characteristics, apparent color seen is different for each. Glossy surfaces appear darker compared to matte finished or textured surfaces. An increase in the surface roughness dilutes the pigment of the color, and hence it appears lighter and less saturated. This is because of an increase diffused reflection due to more scattering of the light. Figure 3 shows the light distribution from different types of surfaces

Fig. 3 Reflection from different type of surfaces.

There are two types of geometries which can be used to detect the color variation namely 60°/0° or 0°/60°. This refers to the orientation of the source with reference to the detector. The 60°/0° geometry is chosen for the sensor prototype as shown in Fig. 4.



(a) 60°/0° geometry



(b) 0°/60° geometry

Fig. 4 Geometry of the sensor for the detection of the gray shades.

3. Experimental setup

An optimally chosen high bright 440 nm BLUE LED launched light into a transmitting fiber inclined at an angle of 60° to the surface under inspection placed adequately, as shown in the Fig. 5.

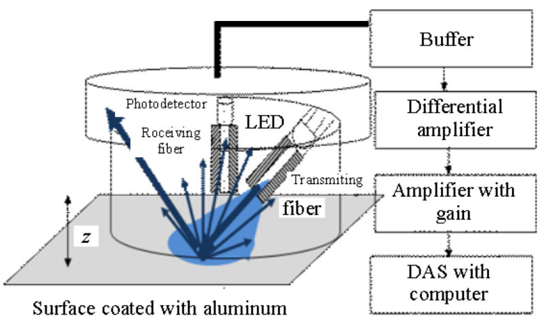


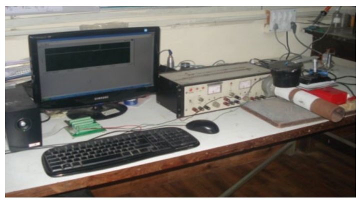
Fig. 5 Experimental setup of the sensor with DAS.

The current through the LED is optimized to 100 mA for getting a good sensitivity. The reflected light is transported by a receiving fiber to a blue enhanced photo detector UDT 10. The distance between the fiber end faces and the surface under the inspection is optimized to 3.5 cm. The aluminum coated surfaces with different thicknesses are inspected by the developed sensor probe. The sensor output is signal-conditioned and monitored using RISHUBH DAS, as shown in Fig. 6. The sensor probe was fabricated with optimized specifications in Bakelite material. The lower cylindrical section of 3.6 cm is added to make the sensor immune to stray light.

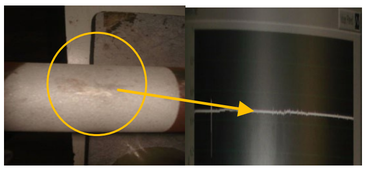
Fig. 6 Photograph of the system with the sensor.

3.1 Field test

A developed sensor probe with optimized parameters was then used to detect the uniformity defect on the rotating aluminum metalized pipe. The sensor probe was scanning the rotating pipe laterally, as shown in Fig. 7(a). The sensor output was monitored.



(a)



(b) (c)

Fig. 7 Defect detection using a data acquisition system for the sensor: (a) photograph on-line monitoring of the defect using the DAS and sensor probe, (b) pipe with non uniform coating and (c) defect monitoring using NI and LABVIEW using the NI card for defect inspection.

4. Results and discussion

Before doing the actual on-line testing, laboratory tests were performed in order to optimize parameters associated with the sensor such as:

(1) Wavelength used for the detection

(2) Sensing distance (Z)

(3) Current flowing through the LED

Selection of the wavelength

RED, GREEN and BLUE LEDs were used to optimize the wavelength of the light in order to detect coating uniformity defects in terms of variation in the gray shades of the coated surface. Figure 8 shows the photographs of four different samples used for the experimentation.

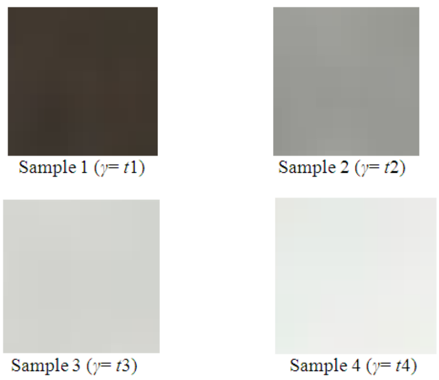


Fig. 8 Photographs of the samples of the surfaces having different aluminum coating thicknesses γ ($t1<t2<t3<t4$).

These samples were coated with aluminum using the spray metallization technique for different time intervals which resulted into different gray shades of the surfaces. Here, Sample 1 was a surface without the aluminum coating with i.e. $\gamma = t1$ only MS surface. Sample 2 was a surface with the low aluminum metallization/coating ($\gamma = t2$) as it was processed for less time. Sample 3 was a surface with the medium aluminum metallization ($\gamma = t3$). And Sample 4 was a surface with the high degree of aluminum metallization ($\gamma = t4$). Experiments were carried out with only RED LED, only GREEN LED, and only BLUE LED as well as their combination for the fixed distance $Z = 3.5$ cm between the sensor probe and the surface. The results are shown in Fig. 9. It is observed from the graph shown in Fig. 9 that the sensor output shows a significant variation of 200 mV for the successive change in the type of the sample surface from Type 1 to Type 4 for BLUE LED. Hence, one can conclude that the BLUE LED is to be chosen for the detection of variation in the aluminum coating on the surface. As the white color is the merge of the entire visible spectrum of colors, it is found that the less white light reflection a surface is produced, the less blue color wavelength is presented on the measured spectrum of the reflected light of such surface [12]. Then, it is necessary to find light sources and sensors that have their working ranges at the blue color wavelength.

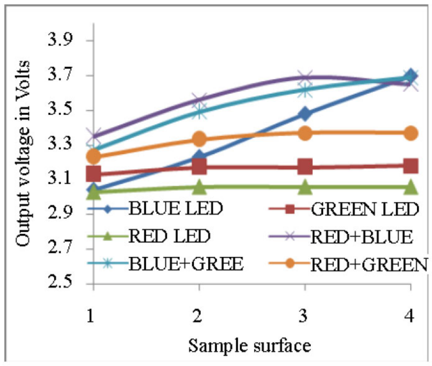


Fig. 9 Optimization of the wavelength.

4.1 Optimization of the distance "Z"

As explained earlier, the fiber optic displacement sensor has three significant regions such as the blind region, linear region, and non linear region [13]. The sensitivity of the sensor depends on the region over which it is operated. In order to get the maximum sensitivity of the sensor, it must be operated over the linear region. The sensor fabricated for the detection of coating defect is an extrinsic type fiber optic displacement sensor having the fixed distance "Z" between the sensor probe and the surface under test. This surface acts as a reflector. Thus, it is necessary to optimize the "Z" for getting the better performance of the sensor. The optimization is done by performing a number of experiments for different values of the fixed "Z" considering BLUE LED as a source. Figure 10 shows the results of the experiments performed. Thus from the graphs, one can conclude that the Z =35 mm is the most suitable distance for getting the better sensitivity of the sensor.

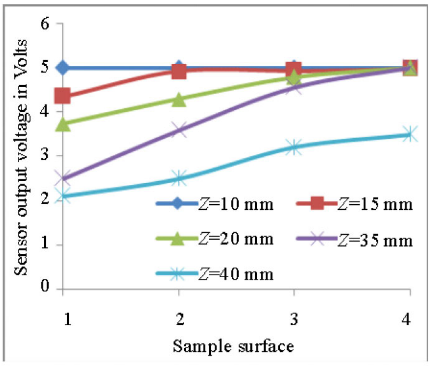


Fig. 10 Optimization of the distance "*Z*".

4.2 Optimization of current through LED

The current through the BLUE LED varied from 10 mA to 40 mA in order to find out the maximum response of the sensor for the optimized distance of Z=35 mm. Experimentation was carried out in order to get the better sensor performance. Figure 11 shows the variation in the sensor output for different values of the current flowing through the LED.

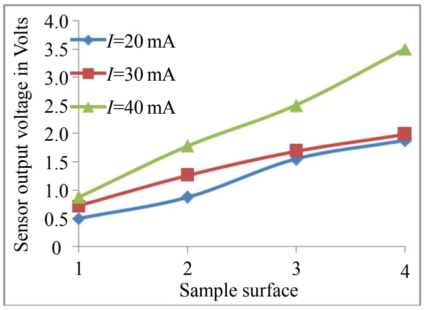


Fig. 11 Optimization of the current.

Figure 11 shows a significant variation in the sensor output for I=40 mA. For smaller values of current through LED, no significant variation in the sensor output was observed because the intensity of the light incident on the surface was less. This caused less sensitivity of the sensor for variations in the coating on the surface. The maximum value of the current flowing through the LED was limited by the maximum current rating. One has to operate the LED in the middle range of the current rating to improve the life of the LED. In this way by carrying out the experiments, the wavelength of the light (BLUE LED), "*d*"=35 mm, and the source current = 40 mA were optimized for the maximum sensitivity of the sensor. The sensor acts as a metallization detector which is useful in detecting the coating defects on the surface. Figure 12 shows the data acquired by DAS RISHUBH showing defects in the coating on the surface.

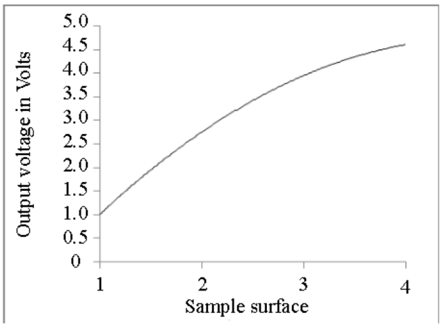


Fig. 12 Sensor output using optimized parameters.

As this sensor has 60°/0° geometry and detects the uniformity of the coating in terms of variation in the gray shades, the defect detection is based on the amount of diffused light after reflection from the surface. Retro reflective and non contact type detection of the defect in the coating is novelty in the sensor.

This sensor scans the surface horizontally to detect the defect. The usage of optical fibers in the sensor makes the sensor to detect the defects over small area in the order of 1 mm^2 as well.

This sensor was specifically developed for the detection of defect in the coating on the exhaust pipes of the tractor. Any non uniformity in the coating causes the rusting of the pipe which definitely affects the life of the tractor.

5. Conclusions

A sensor was developed for detecting the uniformity defects on the aluminum coated exhaust pipes of vehicles. The sensor parameters were optimized by performing experimentation with the specially coated surfaces having different coating thicknesses. The sensor data were monitored using a data acquisition system in the laboratory. The field test was carried out by laterally scanning the rotating pipe and monitoring the sensor output on the LABVIEW platform. Experimental results show a good repeatability in the defect detection and coating non-uniformity measurement.

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