Detection of surface defects on thin metallic wires by geometric conical diffraction

This optical defect detection method, suitable for online systems, uses measurements of the intensity variations on the diffraction cone to identify scratches along the wire surface.

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The determination of the surface quality of thin metallic wires is important for effective quality control in the manufacturing process. However, the traditional methods for surface characterization[1,2] cannot be implemented in online systems. The authors propose an optical method to detect the main defects on the wire surface, based on geometric conical diffraction technology that may be used in online inspection and control systems. When the light source that illuminates the wire is a monochromatic, plane wave at an angle of incidence of θ_1 respective to the wire axis, the reflected light generates a cone.[3,4] The angular distribution of the intensity provides information about the defects that appear on the surface.[5] Because a defect on a wire surface prevents that zone from being truly cylindrical, it reflects the rays in a different direction than would a cylinder without flaws. Therefore, the defects can be detected by a lack of intensity. Since the concern is not generally about the location of the defects, but about the quality of the wire surface, the authors present a parameter to measure the surface quality. If the density of the defects is so high that statistical methods need to be applied, the proposed method is still valid, but the parameters to be obtained are then the correlation distance between defects and their mean heights.[6]

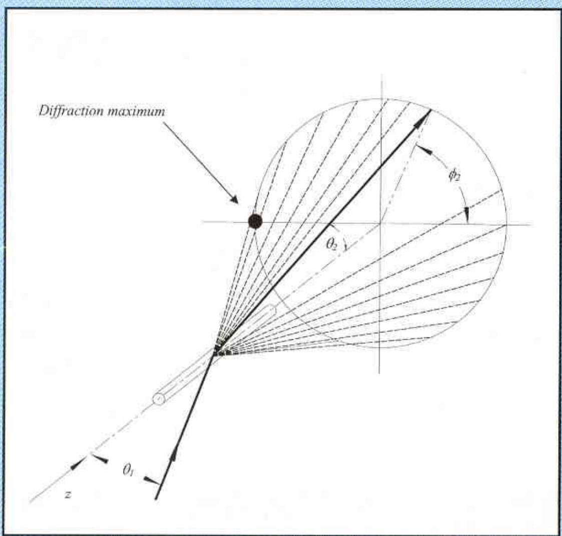


Fig. 1a. 3-D sketch of the conical diffraction. All the output rays have the same θ_2 angle, but different ϕ_2 angles.

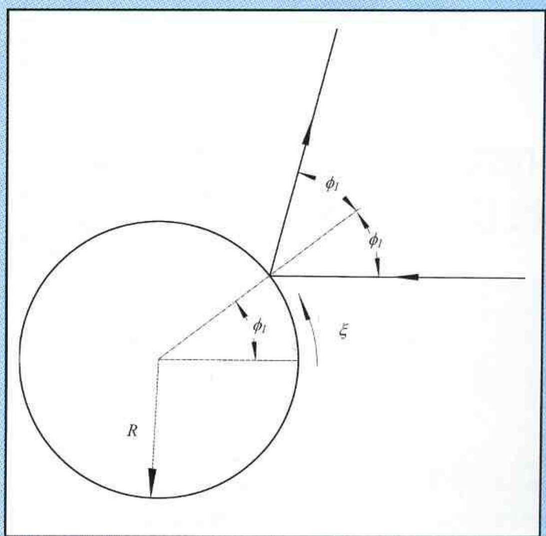


Fig. 1b. Transverse section of the wire. The ϕ_1 input angle is different for each incident ray.

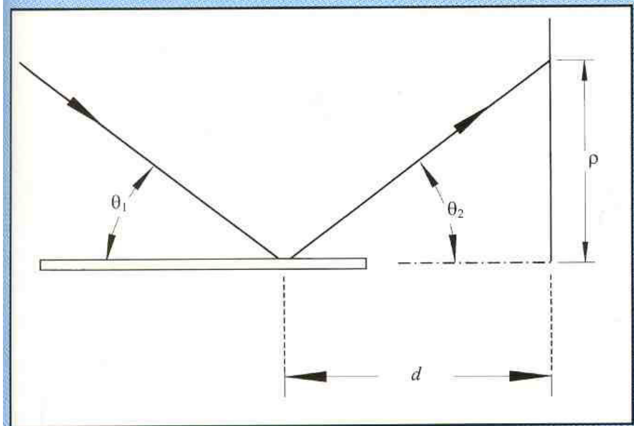


Fig. 1c. Longitudinal section.

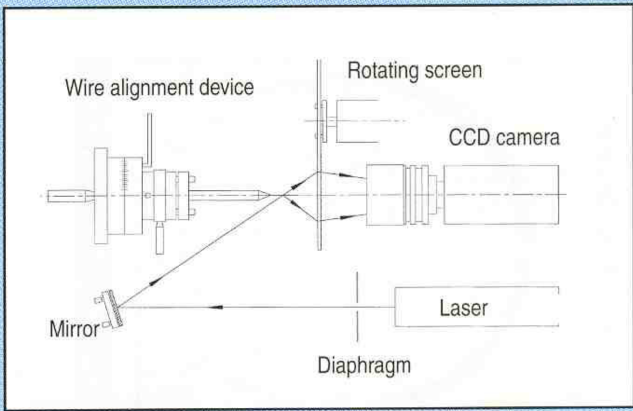


Fig. 2. A schematic diagram of the experimental setup.

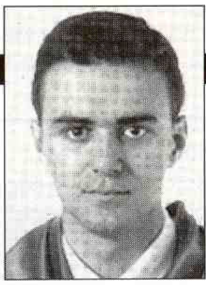
In order to check the model the authors compared the results of the wire surface obtained with conical diffraction with those obtained from measurements by Scanning Electron Microscopy (SEM).

Geometric conical diffraction

When a laser beam impinges a wire in a direction that is not perpendicular to the wire axis, the scattered beam generates a cone.[3,4] See Fig. 1. By interposing a screen transverse to the wire axis a circumference is observed. Except for angles close to the diffraction maximum angle, where the diffraction effect is important, a geometric model can be used to study the scattering of light by a metallic wire.[7] Consider an incident beam with a direction of $\mathbf{k}_1 = k(\cos\theta_1 \cdot \hat{z} - \mathrm{sen}\ \theta_1 \cdot \hat{x})$. The beam strikes the wire surface and, according to geometric optics, the output rays are specularly reflected satisfying $\theta_1 = \theta_2$, where θ_1 and θ_2 are the angles of the input and output rays with respect to the wire axis. However, each ray of the beam impinges at a different angle ϕ_1 forming a cone. See Fig. 1b. The angle ϕ_2 of the output rays is related with ϕ_1 by

$$\phi_2 = 2 \cdot \phi_1 \qquad \text{Eq. (1)}$$

By using a simple geometrical calculation, assuming an ideal reflector with a reflectance factor of $R=1$, it is shown that the intensity at a given direction on the cone is



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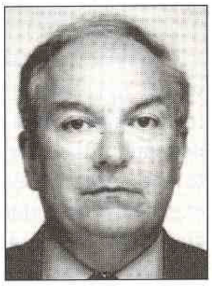

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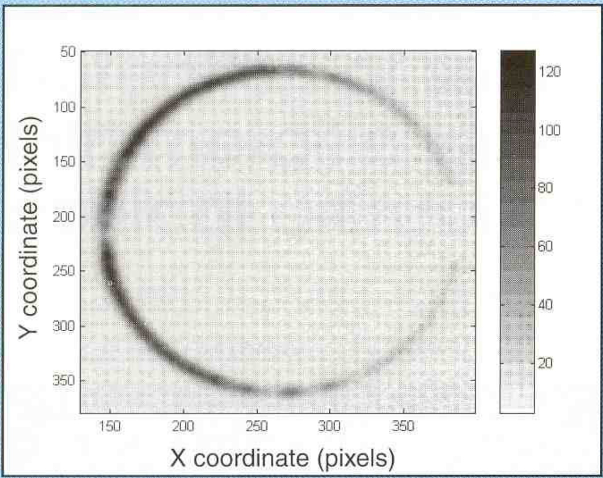

Fig. 3. Image of the ring detected by the CCD camera for a steel wire with 340 μm diameter.

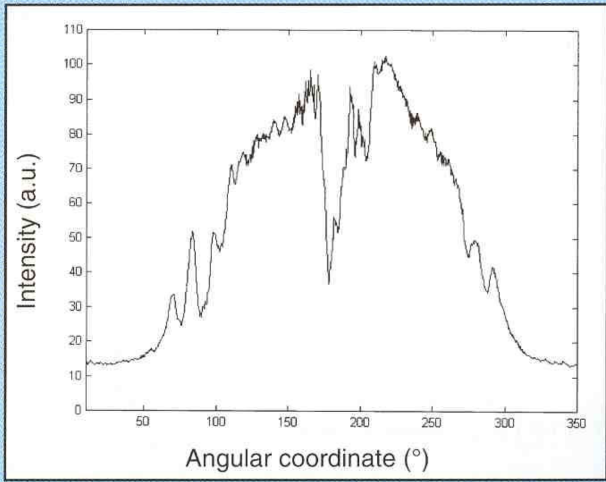

Fig. 4. Observed intensity on the ring referred to in Fig. 3. As it is observed, the scratches are well detected. The maximum intensity is close to the minimum intensity due to the rearrangement of the intensity.

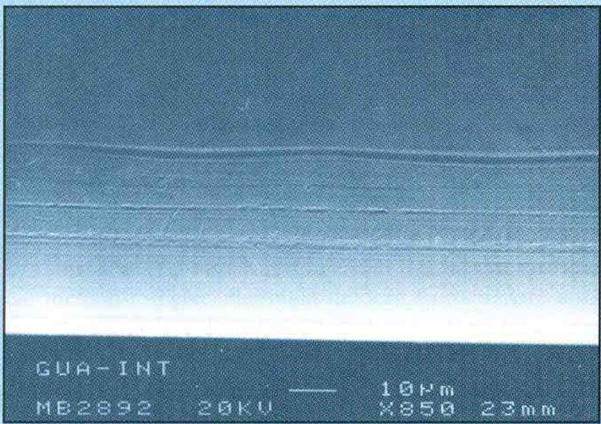

Fig. 5. An SEM view (850x) of the test wire presented in Figs. 3 and 4 reveals a corresponding series of longitudinal defects.

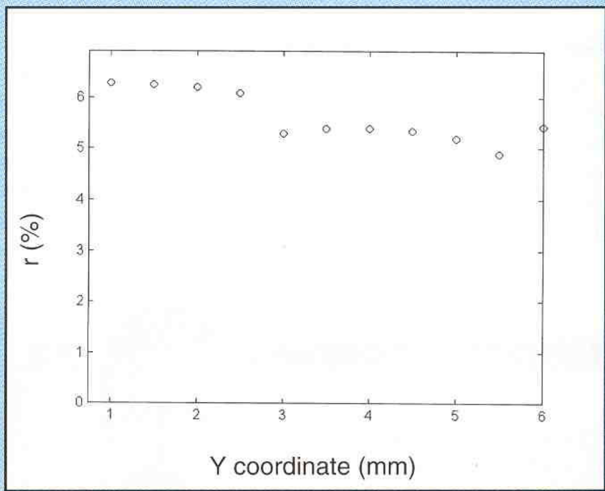

Fig. 6. Quality parameter Γ(y) for *W3*. Note that the value of Γ does not vary much for different locations z, since the defects that *W3* presents are scratches.

$$I(\theta_2,\phi_2) = I_0 \cdot \left|\cos(\phi_2/2)\right| \cdot \delta(\theta_2 - \theta_1) \qquad \text{Eq. (2)}$$

where I_0 is the intensity at $\phi_2 = 0$. It is interesting to note that Eq. (2) does not depend on the wire diameter. According to this, for perfect wires there is an exact correspondence between the circumference obtained at the screen and the wire surface that allows the locations ξ (see Fig. 1b) on the wire and the locations (ϕ_2, θ_2) on the ring to be related as

$$\xi = R \cdot \phi_2 / 2 \qquad \text{Eq. (3)}$$

where R is the radius of the wire. The distance between the illuminated point of the wire and the screen d can be obtained by

$$d = \rho / tan(\theta_2) \qquad \text{Eq. (4)}$$

where ρ is the radius of the circumference at the screen. See Fig. 1c.

Geometric conical diffraction can be used for surface characterization of thin metallic wires. When the metallic wire presents surface defects the correspondence depicted in Eqs. (1) to (4) is no longer valid for the location of the defect, because rays at this location are reflected in different directions than those predicted by Eq. (2). Then, there is a relationship between the lack of light on a given point of the circle and a defect at this location. The defects are placed at the locations where

$$I_M(\phi_2) < I(\phi_2) \qquad \text{Eq. (5)}$$

where $I_M(\phi_2)$ is the experimental intensity at the ring and $I(\phi_2)$ is the theoreti-

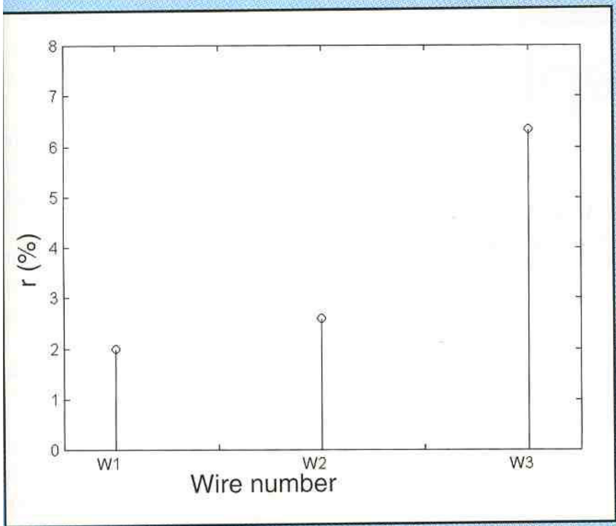

Fig. 7. Γ parameter for three wires with different surface quality. *W1* is a steel wire (diameter = 125 μm) with a maximum defect that is a scratch of 0.3 μm, *W2* is a steel wire (diameter = 250 μm) with a scratch of 2 μm and *W3* is a steel wire (diameter = 340 μm) with several scratches at widths of 1 to 3 μm.

cal intensity distribution given by Eq. (2). In online systems, the goal is not to identify the location of the defects, but to measure the surface quality of the wires. Since the fluctuation of intensity at the diffraction ring increases as the density of defects increases, the authors define Γ as a parameter to measure the quality of the wire, based on statistical considerations

$$\Gamma = \left\{ \frac{1}{2\pi} \int_0^{2\pi} \left[\frac{I_M(\phi_2) - I(\phi_2)}{I_0} \right]^2 d\phi \right\}^{1/2}$$

Eq. (6)

The experimental setup is represented in Fig. 2. An He-Ne laser beam of 20 mW ($\lambda = 632.8$ nm) falls upon a sample wire with an angle $\theta_1 = 45$ degrees with respect to the wire axis. A 2-D CCD camera records the images formed on a rotating screen to eliminate the speckle. Fig. 3 shows the ring obtained with the CCD camera for this wire and how the defects are detected. The intensity of the ring is obtained from the image with a MATLAB algorithm and it appears in Fig. 4. It is interesting to compare this function with the image of the wire obtained by SEM in Fig. 5.

Fig. 6 shows the quality parameter Γ(y) for different values of y. This parameter does not vary much for the same wire. The Γ parameter has also been measured for two other thin steel wires (diameters 125 and 250 μm). SEM measurements indicate that *W1* has a 0.3 μm scratch on its surface. *W2* shows only a small scratch with a width of approximately 2 μm and *W3*, shown in Fig. 5 (diameter 340 μm), includes several scratches with widths between 1 to 3 μm. The mean values of Γ are represented in Fig. 7 for these three wires. As shown, the bigger the defects are, the larger the Γ value will be.

Conclusion

The authors propose an optical method, based on geometric conical diffraction, to detect surface defects on thin metallic wires. The defects are detected by measuring the intensity variations on the diffraction cone. This procedure allows an accurate detection of the scratches along the wire, since the setup amplifies the wire transversally.

Acknowledgments

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