Non-contact thickness measurement for ultra-thin metal foils with differential white light interferometry

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A new differential white light interference technique for the thickness measurements of metal foil is presented. In this work, the differential white light system consists of two Michelson interferometers in tandem, and the measured reflective surfaces are the corresponding surfaces of metal foil. Therefore, the measuring result is only relative to the thickness but not the position of metal foil. The method is non-contact and non-destructive, it has the advantages of high accuracy, fast detection, and compact structure. Theoretical analysis and preliminary experimental verifications have shown that the technique can be used to measure the thickness of foil in the range of 1 to 80 μm with accuracy better than 0.08 μm.

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At present, ultra-thin metal foils, of which the thickness varies from 1 to 100 μm, have been widely used in many industries and some scientific studies. In order to control the quality of ultra-thin metal foils and reduce the cost of raw materials, the foil thickness needs to be measured accurately during the rolling process. However, it is a hard work to measure the thickness since ultra-thin metal foils are too pliable.

Many kinds of methods have been proposed to measure the thickness of thin objects. The X-ray absorptive method[1] and the fluorescent X-ray analytic approach[2] can be used to measure the thickness of metallic membrane platings. However, the calibration of measurement has to vary with the metal materials. In addition, the high dangers of X-rays also restrict their extensive applications. The eddy-current technique[3] can be used to measure conductive sheet, strip, and foil, but the objects to be measured cannot be too thin and a lot of calibrations also should be made according to the materials. There are many optical techniques that have been applied to measure the thickness of transparent films and coatings[4−8]. However, they are not suitable for the measurement of the opaque ultra-thin metal foils. Therefore, we carry out a new kind of differential white light interferometric technique for measuring the thickness of ultra-thin metal foils during the rolling process.

Figure 1 shows the optical system based on the differential white light interferometric technique. The system consists of the following parts. a) A 20-W halogen lamp, which generates light with a wavelength ranging from 300 to 1100 nm, is used as the broadband light source with low coherence-length. b) Two tandem Michelson interferometers (MIs) linked with a multimode fiber compose a differential system to provide interference fringes that include thickness information of the measured metal foils. c) A USB2000 fiber spectrometer (Ocean Optics, Incorporated) is used as charge-coupled device (CCD) array spectrometer to measure the interference spectrum. Inside this spectrometer, a near infrared grating combined with a 2048-pixel CCD gives 0.3-nm spectral resolution. d) A PC system is used as signal receiving and processing system.

As shown in Fig. 1, two corresponding surfaces of the measured metal foils act as the measurement reflecting surfaces of two MIs, respectively. The light from a halogen lamp collimated by lens L_1 is split by a beam splitter BS_1 into the object beam and the reference beam. The object beam is reflected by the upper surface of the metal foil and the mirror M_1 reflects the reference beam. The two beams interfere with each other, and then the interfered light is focused by lens L_2 into the incident surface of the optical fiber.

In the same way, the two beams split by BS_2 can be reflected by M_2 and the lower surface of the metal foil and interfere with each other. So the resultant light focused by lens L_4 includes the information of both surfaces of the metal foil. A CCD array spectrometer receives the signals of interfering fringes. The intensity distribution of the received light on the spectrometer, I, can be expressed by[9]

$$I = \frac{1}{4} I_0 \left\{ A + B \left|\gamma\left(\Delta_1\right)\right| \cos\frac{2\pi}{\lambda}\Delta_1 \right.$$

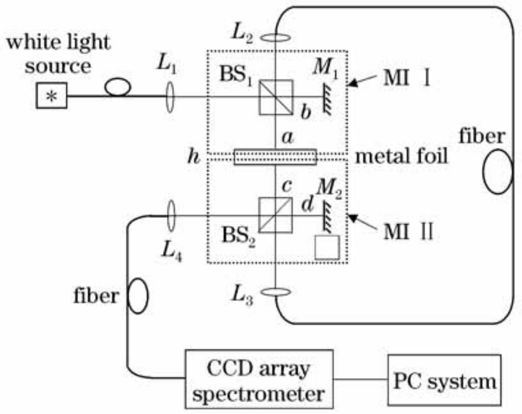

Fig. 1. Experimental arrangement of the scheme for thickness measurement of metal foils.

$$+C\left|\gamma\left(\Delta_2\right)\right|\cos\frac{2\pi}{\lambda}\Delta_2$$

$$+D\left|\gamma\left(\Delta_1+\Delta_2\right)\right|\cos\frac{2\pi}{\lambda}\left(\Delta_1+\Delta_2\right)$$

$$\left.+D\left|\gamma\left(\Delta_1-\Delta_2\right)\right|\cos\frac{2\pi}{\lambda}\left(\Delta_1-\Delta_2\right)\right\}, \qquad (1)$$

where I_0 is the output power of the light source; λ is the wavelength of the halogen lamp; A, B, C, and D represent the constants determined by reflection coefficients of M_1, M_2, and the two surfaces of metal foil, respectively; $\left|\gamma\left(\Delta_i\right)\right|$ $(i=1,2)$ is the absolute value of the normalized source autocorrelation function, where Δ_1 is the optical path difference (OPD) of the interferometer I, and Δ_2 is that of the interferometer II, the measurement is always done in the air, so they are given by

$$\Delta_1=2(b-a), \qquad (2)$$

and

$$\Delta_2=2(d-c), \qquad (3)$$

where a, c, b, and d are the distances between BS_1 and the upper surface of foil, BS_2 and the lower surface of foil, BS_1 and M_1, BS_2 and M_2, respectively. For a low-coherence source, the autocorrelation function usually has a Gaussian profile determined by the form of the spontaneous emission. We assume $a+c+h=b+d$, where h is the thickness of metal foil. This process leads to

$$I=\frac{1}{4}I_0\left\{A+B\exp\left[-\left(2\Delta_1/L_{\mathrm{c}}\right)^2\right]\cos\frac{4\pi}{\lambda}\left(b-a\right)\right.$$

$$+C\exp\left[-\left(2\Delta_2/L_{\mathrm{c}}\right)^2\right]\cos\frac{4\pi}{\lambda}\left(d-c\right)$$

$$+D\exp\left\{-\left[2\left(\Delta_1+\Delta_2\right)/L_{\mathrm{c}}\right]^2\right\}\cos\frac{4\pi}{\lambda}h$$

$$\left.+D\exp\left\{-\left[2\left(\Delta_1-\Delta_2\right)/L_{\mathrm{c}}\right]^2\right\}\cos\frac{4\pi}{\lambda}\left(2a-2b+h\right)\right\}, \qquad (4)$$

where L_{c} is the coherence length of the source. This equation indicates that the interference patterns consist of five parts, and the forth term only relates to the thickness h. In comparison with the other items ($b-a$, $d-c$, and $2a-2b+h$), the thickness h is very small. So it can be considered the low frequency term and the others are high frequency terms. In this experiment, three micrometric settings are used to control mirrors M_1, M_2, and the metal foil, and thus to control Δ_1 and Δ_2. In order to get the thickness h, we have to use an effective filtering method to get rid of the effect of the noise, average out the high frequency terms by means of wavelet transform to obtain the envelope of interference fringes, and a suitable algorithm[10] must be used to identify the pixel (or sample point) corresponding to the envelope peaks, then the thickness of metal foil can be calculated.

Figures 2(a)−(c) show that the different interference spectra can be received by the CCD array spectrometer when the position of the metal foil varies between two splitters in a definite range. But the envelope shapes of the different spectra are same, which represent the forth term of Eq. (4). Therefore, the envelope is insensitive to the vibration of the foil and the results obtained from the experiment are in good agreement with the theoretical analysis. Figures 2(d) and (e) show the output interference fringes and the corresponding low frequency envelope.

To check the repeatability and stability of the differential white light interference method, thickness measurements of metal foil were carried out in different initial positions. The results of the apparent thickness values in three different measurements are shown in Fig. 3. It can be seen that the apparent thickness values are approximately same with an error of less than 0.08 μm when the position of the metal foil varies in the vertical

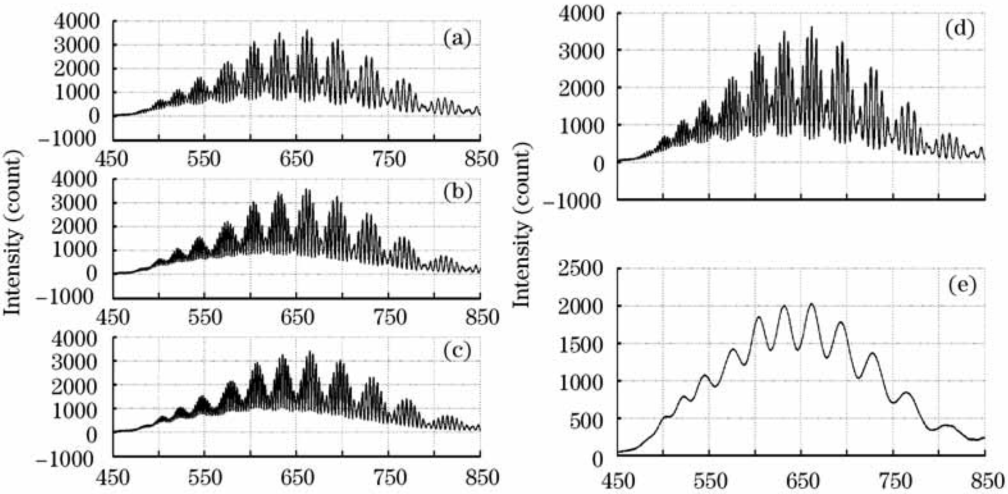

Fig. 2. (a)−(c): Experimental output interference spectra of the system when metal foils in the different positions, which move the first position calibrated in vertical direction in Fig. 1 with the distance of 0 (a), 10 (b), 20 μm (c). (d) and (e): Experimental output interference fringe and the corresponding low frequency component.

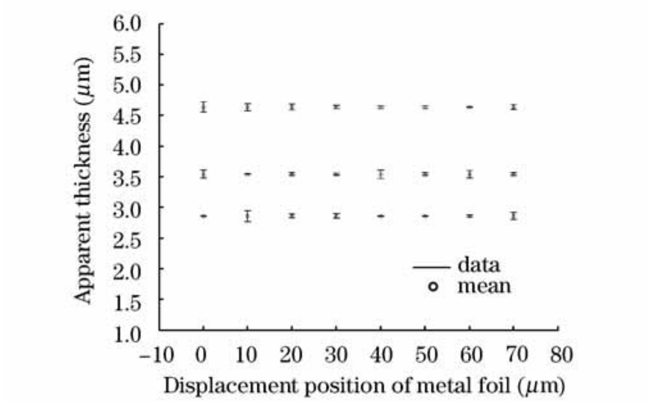

Fig. 3. Three different experimental results of the relation between the positions of metal foil and the apparent thickness values show that the thickness is independent on the position of the metallic foil.

direction in Fig. 1 in the range from 1 to 80 μm, as expected.

In summary, the new optical method has been developed to measure the thickness of ultra-thin metal foils. The two tandem interferometers compose a differential system insensitive to the vibration. At the same time, this method is non-contact, non-intrusive, easy to calibrate, and it can be implemented at relatively low cost. The theoretical analysis and preliminary experiments indicate that the technique can be used to measure the thickness of foils in the range of 1 to 80 μm with accuracy better than 0.08 μm. In the further work the noise of signals should be removed and a suitable algorithm should be used in filtering to obtain thickness value fast and accurately, and realize the real-time dynamic measurement in industrial production.

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