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Improving Measurement Repeatability of Ball Crater Method by Using Image Processing Techniques

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***Abstract*—A method of improving coating thickness measurement repeatability of the ball crater method is proposed. The improvement is realized by using image processing techniques to measure the radii of crater circles from a microscope image. While traditional methods use a limited number of operator-selected points on a circle edge to calculate the radius value, the new method measures the radius by fitting a circle to all edge points of a crater circle edge, which is automatically extracted from the microscope image of the crater by image processing techniques. This eliminates the randomness introduced by human operators in the traditional methods and improves the measurement repeatability. Experimental results confirm the feasibility of our method and its potential in improving the measurement repeatability and increasing measurement accuracy of the ball crater method.**

***Index Terms*—Digital image processing, measurement repeatability, thickness measurement, coatings**

I. Introduction

THE ball crater method is a low cost method of determining coating thickness and is widely used in both the laboratory and industry [1]. Fig. 1 illustrates the method in measuring a coating layer on a substrate. A depression into both the coating and the substrate is first created by rotating a ball with a known radius R in the presence of an abrasive paste. The depression is then observed under an optical microscope to determine the radii of the two circles R_1 and R_2. The thickness d of the coating can be obtained as:

$$d = \sqrt{R^2 - R_1^2} - \sqrt{R^2 - R_2^2} \quad (1)$$

Thus, a crucial step in this method is to determine the radii of the crater circles from the microscopic image. The repeatability of the thickness value measurement is mostly defined by the repeatability of the radius measurements.

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Traditional methods of measuring the radii of the circles are subjective as they involve the use of human operators. For example, one method (two point method) is to move the sample stage by a micrometer drive in a direction normal to a line on the microscope eyepiece reticles and record the readings of the micrometer at two positions, where the line becomes the tangent of the circle [2]. The subtraction of the two readings provides the diameter of the circle. These two positions are defined by the operator. The other method (three point method) is to calculate the radius by using the coordinates of three points on the circle [2]. In the latter method, the locations of the three points are chosen by the operator.

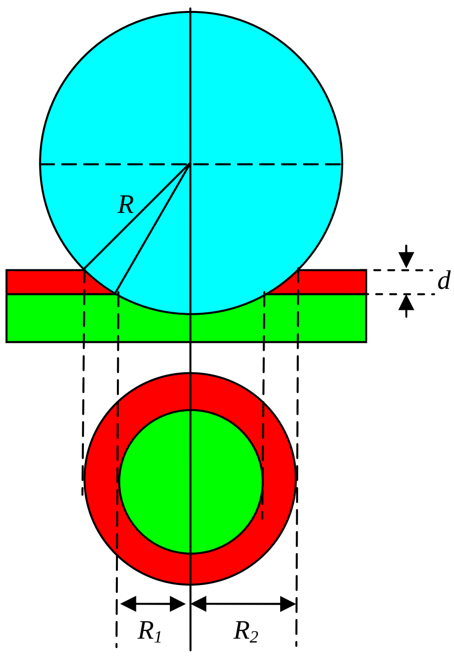


Fig 1. Schematic illustration of ball crater method for coating thickness measurements.

The involvement of human operators inevitably decreases the measurement repeatability of the ball crater method since people perceive an image subjectively and even the same person may perceive the same image differently at different times. Hence, the traditional approaches introduce randomness through the subjective selection of a limited number of points on the circle edge and subsequently the estimation of the radius, which is based on the point coordinates. The circle edges of a real crater do not resemble a perfect circle. The random nature of the points' selection, thus decreases measurement repeatability.

In this work, we propose a method of measuring the radii with the aid of image processing. This method measures a radius by fitting a circle to all the edge points of the optical microscope image of a crater circle, using image processing techniques. It can easily be implemented in a microscope with a video camera/computer. The proposed method will always result in a specific thickness value for a given crater image. Therefore, it improves the measurement repeatability of the ball crater method. Furthermore, the use of all edge points in the estimation of the radius increases measurement accuracy.

II. IMAGE PROCESSING AND THICKNESS CALCULATION

Fig. 2(a) shows the image of a crater taken under a microscope with ×10 objective magnification. The crater is created by rotating a 30mm diameter chromium steel ball in the presence of 0.25µm diamond abrasive agent against a flat coated sample. In this example, the coated sample is composed of a titanium alloy substrate, a pure, metallic interlayer and a multi-element alloy topcoat. We now illustrate the method by providing the details of the process of extracting the radius value of the top circle edge, i.e. the edge separating the crater from the top surface of the coating (as shown in Fig. 2(b)).

To calculate the radius of the top circle edge, we first need to extract all the edge points from the image. This can be divided into six steps:

i) Thresholding [3] (Fig. 3(a)): The top surface area and the crater area are segmented by choosing an appropriate threshold value. Figure 3(a) shows the binary image obtained at this step. One can see that thresholding does not lead to perfect segmentation, rather there are noise pixels originating from both the top surface and the crater area.

ii) Dilation [3] (Fig. 3(b)): The mathematical morphology operator of dilation is used to connect the pixels of the top surface area into one component so that it becomes the largest object in the image.

iii) Low pass filtering [3] (see Fig. 3(c)): All small objects inside the crater area are removed by a low pass filter.

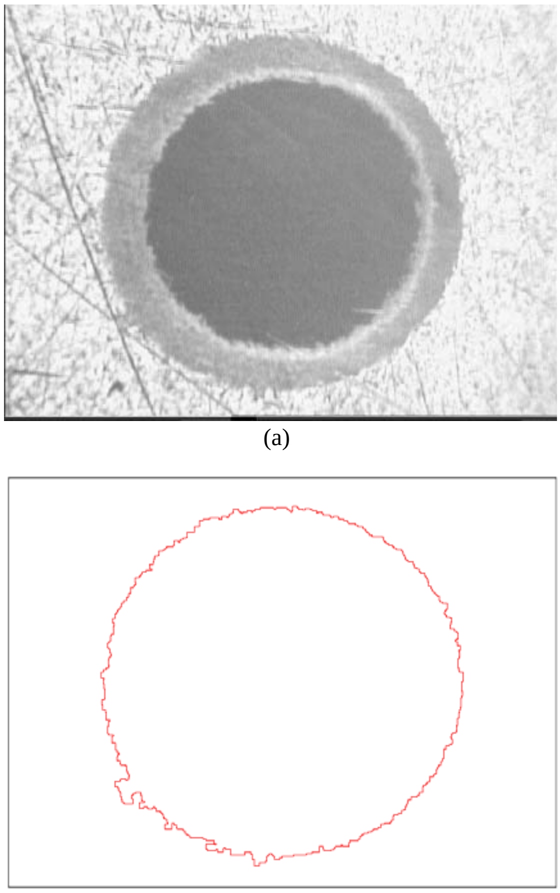
iv) Image inversion [3] (Fig. 3(d)): The image is inverted so that the crater area now becomes the largest object in the image.

v) Low pass filtering (Fig. 3(e)): All small objects on the top surface area corresponding to scratches and defects are removed by a low pass filter.

vi) Dilation (Fig. 3(f)): Dilation is used to reverse the effect of dilation in step ii) on the circle edge. Since the image was inverted in Step iv), this dilation now corresponds to erosion [3].

Following these six steps, the edge points of the top circle (Fig. 2(b)) can be obtained by a simple edge detection scheme. Once the coordinates of the edge points are known, the best fit circle can be obtained using the Levenberg-Marquardt least squares fitting [4]. We can consider the radius value of the best fit circle as the radius value of the circle edge.

According to Equation (1), thickness value estimation requires two radius values. Here, we take the measurement of the total thickness of the two layers of the coating as an example. For this purpose, we need the radius values of the top circle edge and the bottom circle edge (i.e. the edge separating the substrate from the first, pure metal, coating). Fig. 4 shows the edge points and the best fit circles for both circle edges. The bottom circle edge can be obtained by the procedure described above.



(a)

(b)

Fig. 2. (a) Crater image and (b) top circle edge of a coating sample (a titanium alloy substrate, a pure, metallic interlayer and a multi-element alloy topcoat) viewed under a microscope with ×10 objective magnification.

Theoretically, the two boundaries are co-circular. In real measurements, however, the coordinates of the circle centres given by the two best fit circles vary. We choose the one from the circle with the smallest fitting residue as the common centre for both circular boundaries. The average distance from this common centre to all edge points of the boundary is then taken as the radius value of the circular boundary. The radii of the bottom and the top circular boundaries measured using our method are 299.29 µm and 400.69µm, respectively. By inserting these values into Equation (1), we obtain the total thickness of the two layers to be 2.02 µm.

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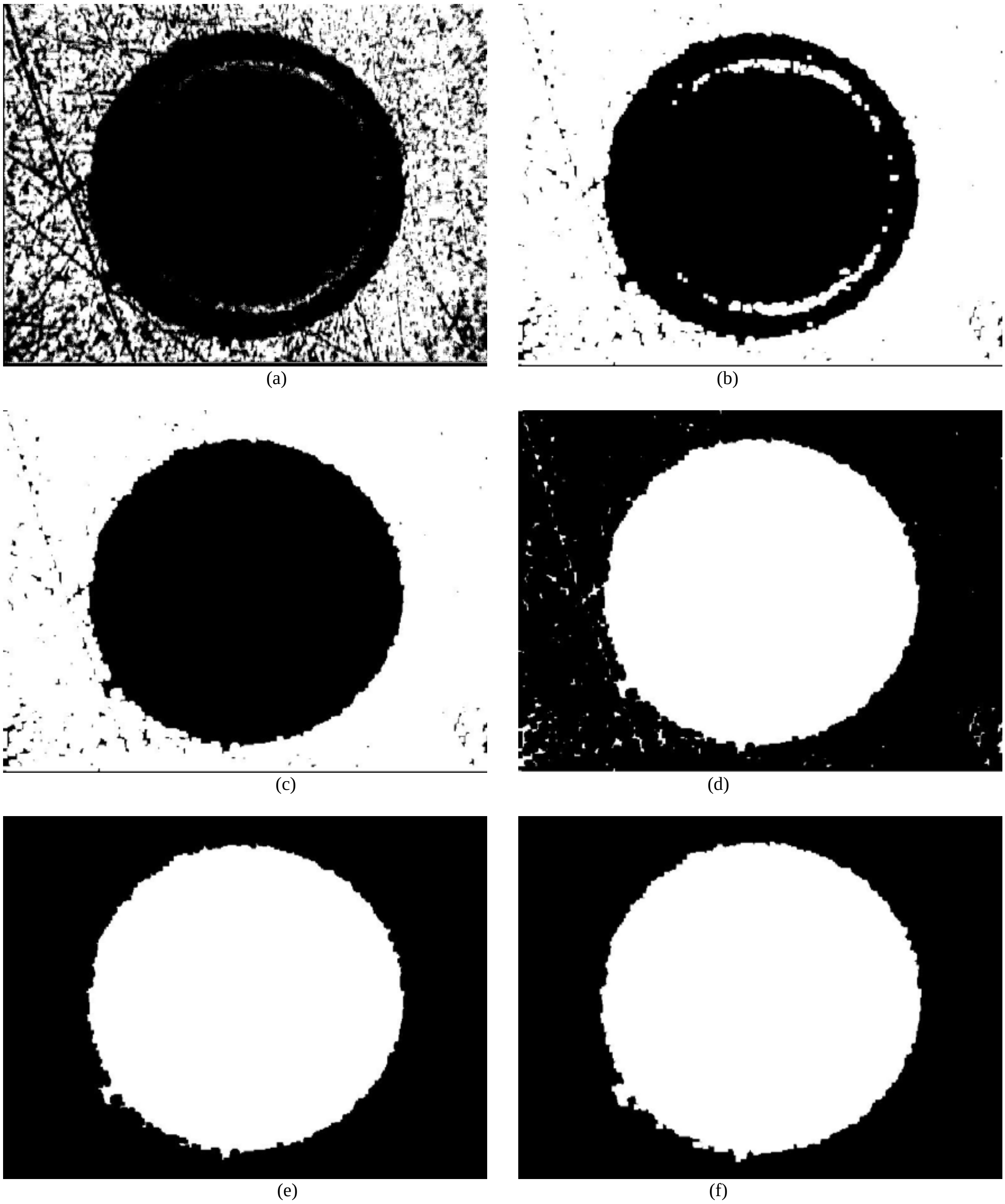

Fig. 3. Intermediate stage images when processing Fig. 2(a) to obtain Fig. 2(b): (a) thresholding; (b) dilation; (c) low pass filtering; (d) image inversion; (e) low pass filtering; (f) dilation.

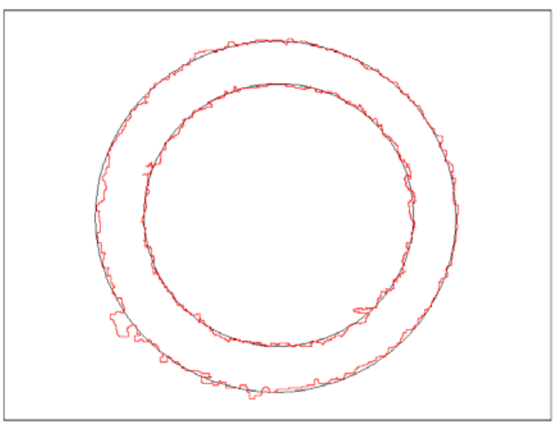

Fig. 4 Best fit circles on the two edges of the crater.

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III. ESTIMATING MEASUREMENT

By making use of the coordinates of the edge points and the previously obtained boundary centre, we can estimate measurement uncertainty introduced by interactive methods. We assume that the distance between the boundary centre and an edge point is a possible radius value obtained from random measurements, each with equal probability of occurrence. There are 2233 and 2382 points in the bottom and top circular boundaries, which give 5319006 combinations, equivalent to the number of random measurements. The thickness value calculated for each combination has a 1/5319006 of probability of occurrence in a measurement.

The histogram of these 5319006 thickness values is shown in Fig 5(a), and Fig. 5(b) shows the probability density distribution of thickness values. It is evident that it resembles a Gaussian distribution. The mean value is 2.02 µm and the standard deviation is 0.23 µm. There is direct correspondence between the above procedure of radii estimation and the one relying on human operators, and thus the obtained results are highly relevant.

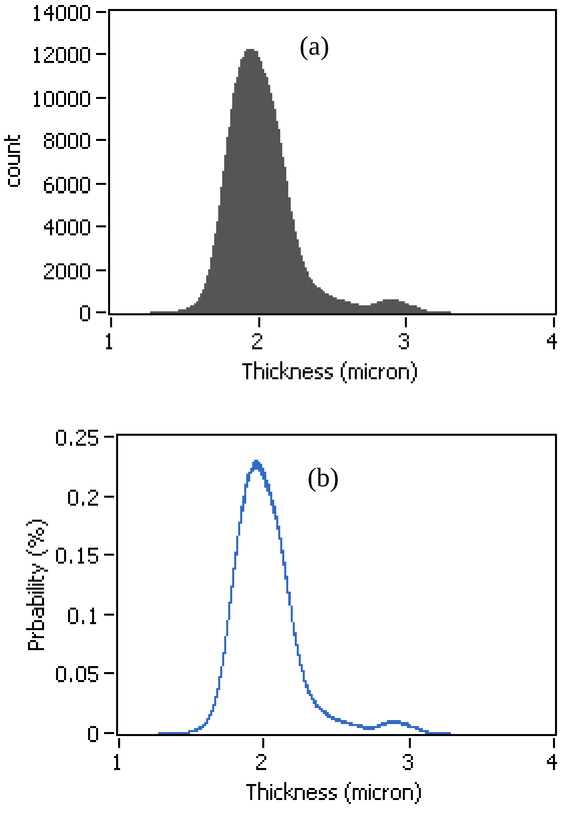

Fig. 5. (a) Histogram and (b) probability distribution of thickness values obtained by a traditional method (estimated by using the 5319006 combinations of all points from the top and bottom circular boundaries in Fig. 4).

While current methods result in a standard deviation of 0.23 µm in the radius estimation, which reflects the degree of uncertainty, the proposed technique always results in the mean radius value. As such, it improves the measurement repeatability by reducing measurement uncertainty. Furthermore, because it utilizes all edge points to estimate the radius value, it has the potential to increase measurement accuracy.

IV. CONCLUSIONS

Compared with the traditional ball crater radius measurement methods, which use a limited number of points on a circle edge to calculate the radius value, the proposed method can reduce the measurement uncertainty introduced by human operators and, therefore, improves the measurement repeatability and potentially increases measurement accuracy of the thickness measurement of ball crater method.

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