An Algorithm for the Characterization of Surface Crack by Use of Dipole Model and Magneto-Optical Non-Destructive Inspection System

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Leakage magnetic flux(LMF) is widely used for non-contact detection of cracks. The combination of optics and LMF offers advantages such as real time inspection, elimination of electrical noise, high spatial resolution, etc. This paper describes a new nondestructive evaluation method based on an original magneto-optical inspection system, which uses a magneto-optical sensor, LMF, and an improved magnetization method. The improved magnetization method has the following characteristics: high observation sensitivity, independence of the crack orientation, and precise transcription of the geometry of a complex crack. The use of vertical magnetization enables the visualization of the length and width of a crack. The inspection system provides the images of the crack, and shows a possibility for the computation of its depth.

Key Words : Leakage Magnetic Flux(LMF), Nondestructive Evaluation(NDE), Faraday Effect, Magneto-Optical Sensor, Dipole Model

Nomenclature

A_1 : Approximated area where d_C and C_4 exist
B_S : Saturated magnetic induction of the MO sensor
$B_{Z,BASE}$: Distribution of the magnetic induction in the non-crack area
$B_{Z,CRACK}$: Distribution of the magnetic induction in the crack area
$C_1(\delta)$, $C_2(\delta)$: Coefficients used to express I_{OUTPUT} as a linear equation of H
C_3 : Constant proportional to the base power of detected light from the non-crack area
C4 : Constant proportional to the permeability of the specimen and m
C_4^0 : Initial approximation of C_4
d_C : Depth of the crack
d_C^0 : Initial approximation of d_C
E : Electric field of the light
f_3 : Measured distribution of Output 1
f_4 : Theoretical distribution of the LMF
fsum : Sum of the squares of differences between f_3 and f_4
H : Intensity of the external magnetic field
Hs : Magnetic field for saturating the MO sensor
Hz : Vertical component of LMF
I_{MAX} : Upper limit of the power of detected light
I_{MIN} : Lower limit of the power of detected light

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I_{OUTPUT} : Intensity of the reflected light from the MO sensor
l_C : Length of the crack
m : Magnetic charge per unit area
n : Total number of points equally spaced on the measurement area
r_0 : Radius of the laser spot
w_C : Width of the crack
(x, y, z) : Location of detection
z_0 : Lift-off

Greek Symbols
δ : Angle between the polarization plane and the analyzer
θ_S : Faraday rotation angle

1. Introduction

Advantages of the nondestructive inspection (NDI) of magnetic materials using a magneto-optical sensor (MO sensor) and leakage magnetic flux (LMF) are no need for paint removal because cracks are detected in a non-contact manner, indication of leakage flux distribution around a crack on the MO sensor with a high spatial resolution, possibility for high speed inspection, easy documentation of results on a video tape, and easy analysis of the image (Fitzpatrick G. L. et al., 1993, Ishihara M. et al., 1996, Lee J. et al., 1997).

A crack can be visualized by the observation of magnetic domains, and the LMF around the crack can be quantified utilizing a novel magneto-optical nondestructive inspection (MONDI) system and reflected light (Lee J. et al., 1998a, 1998b, 1999a, 1999b). A novel vertical magnetization method was developed by Lee, et al. (1998b). This method has the following characteristics: high observation sensitivity, independence of the crack orientation, and precise indication of the geometry of a complex crack such as a multiple crack. The use of the vertical magnetization method and the MONDI system makes it possible to directly detect the length and width of a crack, while its depth should be computed.

This paper proposes a new algorithm for the nondestructive evaluation (NDE) of surface cracks by the MONDI system and an improved magnetization method based on the vertical magnetization method. A new equation for the power of the detected light is derived. The depths of several cracks are computed, using a regression of the measured unidirectional distribution of the intensity of LMF.

2. Principles of Operation

2.1 Faraday rotation and MO sensor

When linearly polarized light is transmitted through a magneto-optical film (MO film), the degree of rotation of the polarization plane of the light is characterized by the angle of Faraday rotation (Sato K., 1994). The intensity of the transmitted light through a particular point of the MO film depends on the intensity of the external magnetic field at the point, and the setting of the fixed analyzer.

The MO sensor contains a MO film ($(GdBi)_3(FeAl)_5O_{12}$) grown on a $(GdCa)_3(MgZrGa)_5O_{12}$ substrate and a vaporized aluminum reflecting film (Ishihara M. et al., 1996, Lee J. et al., 1997, 1998a, 1998b, 1999a, 1999b). The Faraday rotation is almost doubled by this reflection-type optical system. A crack can be visualized by a high-contrast dark and bright areas on the sensor. This is possible due to the presence of two types of large magnetic domains on the MO film in the vicinity of the crack, namely the domains with their magnetization polarized, respectively, along and perpendicular to the normal to the sensor surface.

2.2 Quantification of LMF by reflected light intensity

Magnetic domains could be visualized by the Faraday rotation when the spot of light source used is smaller than the magnetic domain's width, as the small circles on the micrograph in Fig. 1. If the spot of light is much larger than the magnetic domain's width shown as the large circle in Fig. 1, an averaged magnetization of the domain is obtained by the MO sensor. This means that the intensity of the magnetic field could be analyzed by using the reflected light from the MO sensor.

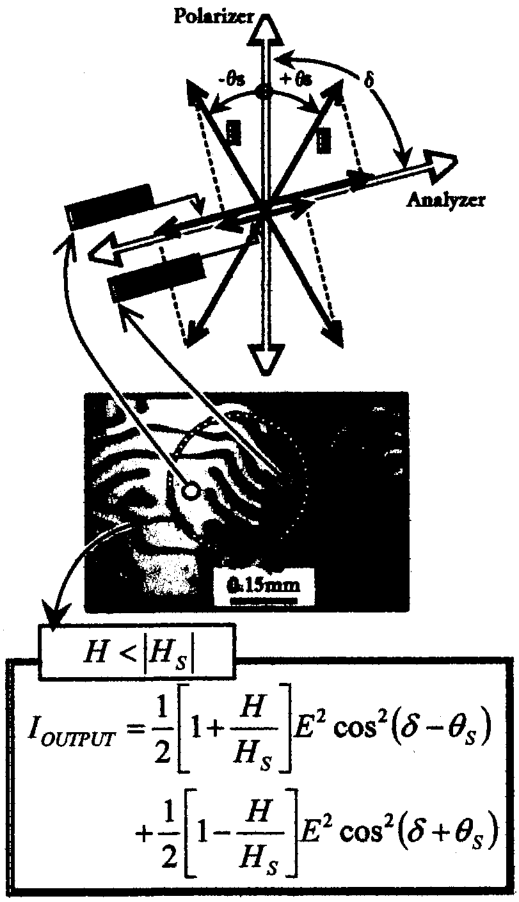

Fig. 1 Observation of the magnetic domains and intensity of the reflected light

The intensity of the reflected light is described by the following equation which takes into account the ratio of the areas magnetized upward and downward in the domains of the MO sensor (Ishihara M. et al., 1996).

$$I_{OUTPUT}=\frac{1}{2}\left(1+\frac{H}{H_S}\right)E^2\cos^2(\delta-\theta_S)+\frac{1}{2}\left(1-\frac{H}{H_S}\right)E^2\cos^2(\delta+\theta_S) \quad (1)$$

where $H(<|H_S|)$, H_S, and E are, respectively, the intensities of the external magnetic field, the magnetic field for saturating the MO sensor, and the electric field of the light which is transmitted to the analyzer, while δ and θ_S are, respectively, the angle between the polarization plane and the analyzer, and the Faraday rotation angle. It is possible to express Eq. (1) in terms of two functionals $C_1(\delta)$ and $C_2(\delta)$ as

$$I_{OUTPUT}=C_1(\delta)+C_2(\delta)\cdot H \quad (2)$$

where $C_1(\delta)=\frac{1}{2}E^2[\cos^2(\delta-\theta_S)+\cos^2(+\theta_S)]$

and $C_2(\delta)=\frac{1}{2H_S}E^2\sin(2\delta)\sin(2\theta_S)$

Equation (2) is a linear equation with respect to H when δ is fixed. This indicates that the LMF from the crack could be measured by using the reflected light intensity.

2.3 Improved magnetization method

When a magnetic field is applied in the normal direction to the surface of a magnetic specimen, the magnetic charge per unit area, m, is generated on the surface of the specimen. If there is a crack on the specimen's surface, m is measured beneath the crack. Therefore, the distribution of the magnetic induction of the MO film in the non-crack area, BZ, BASE, is almost constant, but the magnetic induction in the crack area, BZ, CRACK, is lower than BZ, BASE. If BZ, BASE is slightly higher than the saturated magnetic induction BS of the MO sensor, the magnetic domains of the sensor are not saturated above the crack because BZ, CRACK is lower than BS. Therefore, the MO sensor transcribes only the crack geometry information, and it may be stated that the NDI method using the vertical magnetization and an MO sensor is suitable for obtaining information about the length and width of surface cracks.

Both the vertical and horizontal magnetization can be generated by a simple procedure. When the current flows in the same direction through the two magnetic coils wound on the two parallel branches of a C-shaped magnetizer, the generated magnetic fields at both poles of the magnetizer (Lee J. et al., 1998b) are in the same direction. Then, if a specimen is put between the two coils, the magnetic flux flows vertically through the specimen. However, when the current in the two coils has opposite directions, the specimen is magnetized horizontally. Thus, it is possible to

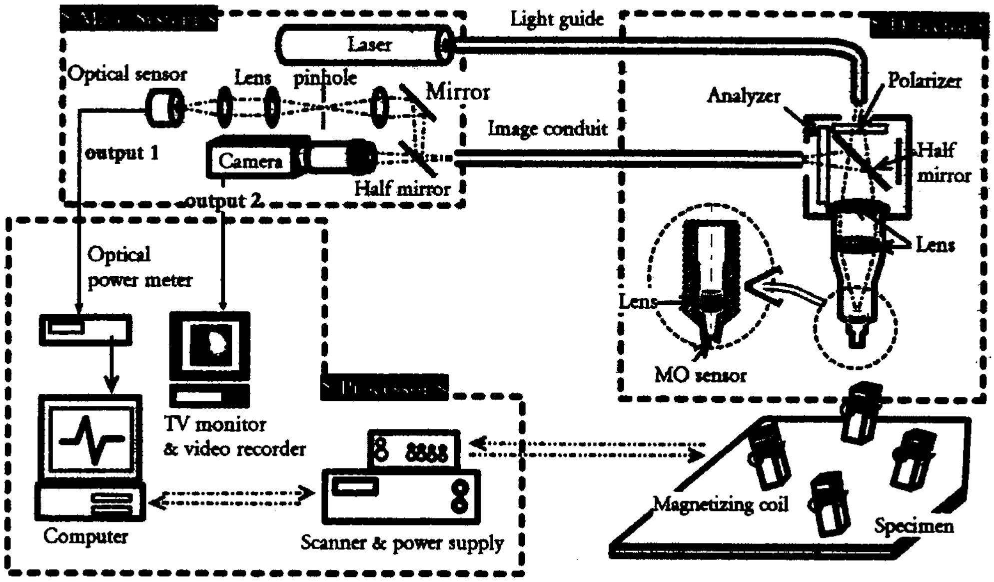

Fig. 2 Magneto-optical nondestructive inspection system

obtain either horizontal or vertical magnetization of the specimen by using a single C-shaped magnetizer and a bipolar DC power supply.

2.4 MONDI system

The MONDI system (Lee J. et al., 1999a) consists of a main system, detector, and processor as illustrated in Fig. 2. The main system and detector are connected by a light guide and an image conduit.

A laser beam is transmitted from the main system through the light guide to the detector, where it is polarized by a polarizer. The polarized beam passes through the half mirror and several focusing lenses and is reflected by the MO sensor positioned at the tip of the detector. The laser beam which contains information about the crack transcribed on the MO sensor is reflected by the half mirror, and then it passes through the fixed analyzer and the image conduit, and returns to the main system. Two laser beams, divided by the half mirror in the main system, are transmitted to a CCD camera and an optical sensor after passing through several lenses and a pin hole.

Output 1 from the optical sensor is saved and processed by an optical power meter and a computer. Output 2 is recorded and observed by a video recorder and a TV monitor, respectively. Computer control is employed when using the scanner and bipolar DC power supply of the magnetization equipment, and the DC meter for determining the position of MO sensor and magnetizer above the specimen.

2.5 Experimental results using the MONDI system

Plate specimens with a dimension of 100 mm × 200 mm × 5 mm are prepared with the material SS400 used for the bottom plates of oil tanks. Simple cracks with 0.5 mm width, 10 mm length and 1. 5, 3, 4. 5 mm depths are formed on the surface of the specimen by electro discharge machining.

A photograph taken using a polarizing microscope and an MO sensor on a vertically magnetized specimen is shown in Fig. 3(a). The micrograph is almost the same as the image data with the MONDI system and was used for a more macroscopic observation. The input current to the magnetizer was 1. 1 A and the depth of the crack was 3 mm. The bright striped patterns on Fig. 3 (a), which are magnetic domains with opposite direction to the vertical magnetization, coincide with the width and length of the crack as shown

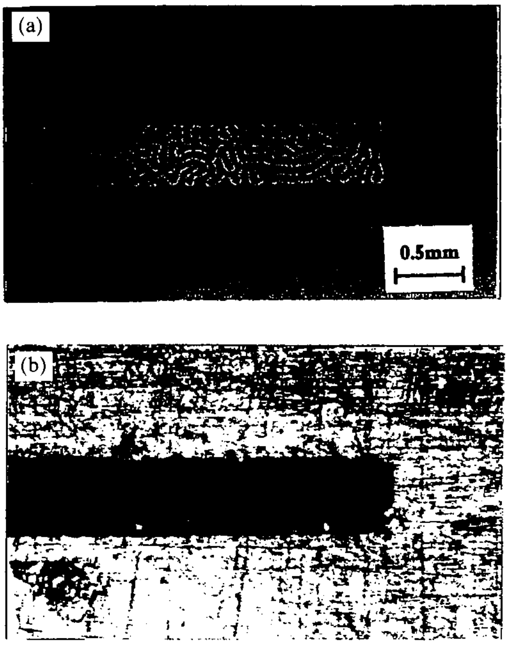

Fig. 3 Macroscopic observation of the MO sensor on the vertically magnetized specimen: (a) observation of the MO sensor using a polarizing microscope, (b) specimen

in Fig. 3(b). The dark area around the bright striped patterns is a magnetic domain with the same direction as the vertical magnetization. It shows that just one magnetic domain appeared because BZ, BASE was sufficiently larger than BS. Figure 4 shows experimental results obtained using the MONDI system with horizontal magnetization. Data points represent the scanned optical power which contains the LMF information, as well the images recorded by the CCD camera. It is worth mentioning that the image data and the LMF information can be processed at the same time. The scanned optical power data correspond to a typical distribution of LMF along a line parallel to the short axis x of the surface crack. Additionally, the CCD camera image, containing large dark and bright areas as shown in Fig. 4(a), represents the center of the crack because it is clearly different from the cases of Fig. 4(b) and (c) where no crack exists.

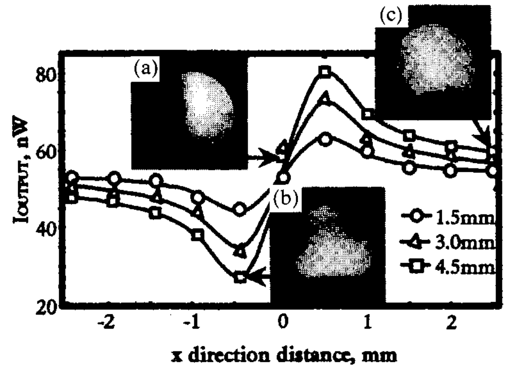

Fig. 4 Experimental results obtained by the MONDI system with horizontal magnetization

3. Numerical analysis and algorithm

3.1 Equation for the power of detected light

In the framework of the dipole model, the vertical component of LMF (Mukae S. et al., 1988, Minkov D. et al., 2000), H_Z, of a right angular parallelepiped crack is expressed as

$$H_Z(x,y,z) = \frac{m}{4\pi\mu}\int_{-\frac{l_C}{2}-y}^{\frac{l_C}{2}-y}\int_0^{d_C}\frac{z+u}{\left\{\left(x+\frac{w_C}{2}\right)^2+y^2+(z+u)^2\right\}^{3/2}}du\,dy - \frac{m}{4\pi\mu}\int_{-\frac{l_C}{2}-y}^{\frac{l_C}{2}-y}\int_0^{d_C}\frac{z+u}{\left\{\left(x-\frac{w_C}{2}\right)^2+y^2+(z+u)^2\right\}^{3/2}}du\,dy \quad (3)$$

where l_C, w_C, d_C are the length, width and depth of the crack, m is the magnetic charge per unit area, and (x, y, z) is the location of detection. This equation is not directly applicable to the MONDI system because it measures the power of the detected light over the area of laser spot, rather than at a point. Consequently, the radius r0 of the laser spot on the detector has to be considered in the expression for the power of the detected light. r_0 is determined by the radius of a pinhole of the main system in Fig. 2. If the radius of a pinhole is 0.5 or 1.0 mm, r_0 is 170 or 330 μm. Furthermore, r_0 is about 0.6 mm when no is pinhole used. Using Eq. (2), the power of the detected light may be expressed as

$$I_{OUTPUT} = C_3 + C_4 \cdot H_Z$$

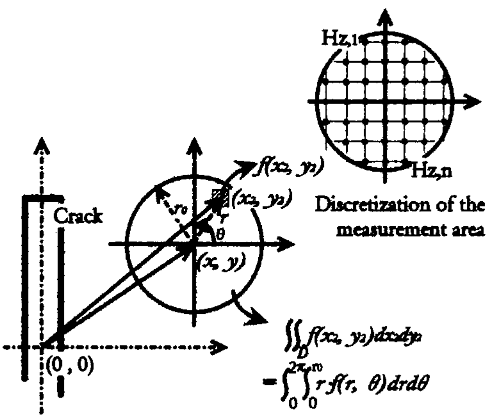

Fig. 5 Positioning of the laser spot in the detection plane

$$= C_3 + C_4 \cdot \iint_D f(x_2, y_2)\, dx_2 dy_2$$
$$= C_3 + C_4 \cdot \int_0^{2\pi}\int_0^{r_0} r + f(r, \theta)\, dr d\theta \quad (4)$$

where C_3 is a constant proportional to the base power of the detected light from the non-crack area of specimen, C4 is a constant proportional to the permeability of the specimen and m, and the point (x_2, y_2) corresponds to an arbitrary point $(r \cdot \cos\theta + x, r \cdot \sin\theta + y)$ within the laser spot in the detection plane as shown in Fig. 5. The integral in Eq. (4) is inconvenient for practical use, and thus the following approximation is used for an easy and fast calculation.

$$I_{OUTPUT} = C_3 + C_4 \cdot \sum_{i=1}^{n} Hz, i \quad (5)$$

Where n is the total number of points equally spaced on the measurement area as in Fig. 5, and HZ, i is the vertical component of LMF at the point i. In this paper, $n=37$ is used for computations.

3.2 Algorithm for NDE of surface cracks

It is assumed that there are nine parameters associated with the NDE of surface cracks: namely, the location of the center of the sensor (x, y, z), three dimensions of the crack (wc, lc, dc), the radius of the laser spot r_0, and the constants C_3, and C_4. It is also assumed that the MONDI system is operated automatically by a robot and computer.

A new algorithm for sizing a surface crack is shown in Fig. 6. In the first step of the algorithm, the current for horizontal magnetization is generated by a bipolar power supply, while all of the nine parameters of a crack listed above are unknown. Then, the upper and lower limits of the power of detected light, I_{MAX} and I_{MIN}, in the presence of a crack are determined experimentally. Output 1 of the MONDI system, I_{OUTPUT}, is then compared with I_{MAX} and I_{MIN}. If I_{OUTPUT} is greater than I_{MAX}, or less than I_{MIN}, a warning message is issued and the position (x, y, z) is recorded. Now, the coordinates (x, y, z) are known and the radius r_0 used in this paper is known to be 0.6 mm. Thus, the remaining unknown parameters are w_C, l_C, d_C, C_3, and C_4. In the next step of the algorithm, the magnetization direction is changed to vertical by changing the direction of the input current flowing in the magnetic coil. The width and length of the crack are then determined from the image data.

Furthermore, the constant C_3 averages I_{OUTPUT} over the non-crack regions $x > 10$ mm and $x < -10$ mm in Fig. 4. Therefore, the unknown parameters in this step of the algorithm are dc and C_4 only. dc and C_4 are subsequently solved through a numerical analysis.

3.3 Computation of unknown parameters d_C and C_4

The investigated crack is sized by a regression based on the minimization of the error (Minkov D. et al., 2000), fsum[W^2], which is the sum of the squares of the differences between the measured distribution of Output 1 from the MONDI system along the x axis, $f_3(x_i, 0, z = \text{const} = z_0)$ and the corresponding theoretical distribution $f_4(x_i, 0, z = \text{const} = z_0)$ of I_{OUTPUT} given by Eq. (5). That is,

$$fsum = \sum_{i=1}^{N} [f_3(x_i, 0, z_0) - f_4(x_i, 0, z_0)]^2 \quad (6)$$

where $f_4(x_i, 0, z_0)$ depends on the unknown parameters d_C and C_4. The minimization of fsum is performed using a multivariable minimization procedure which requires an initial approximation (dc^0, C_4^0) to d_C and C_4. The dependency of $fsum(d_C, C_4)$ on d_C and C_4 is investigated for the

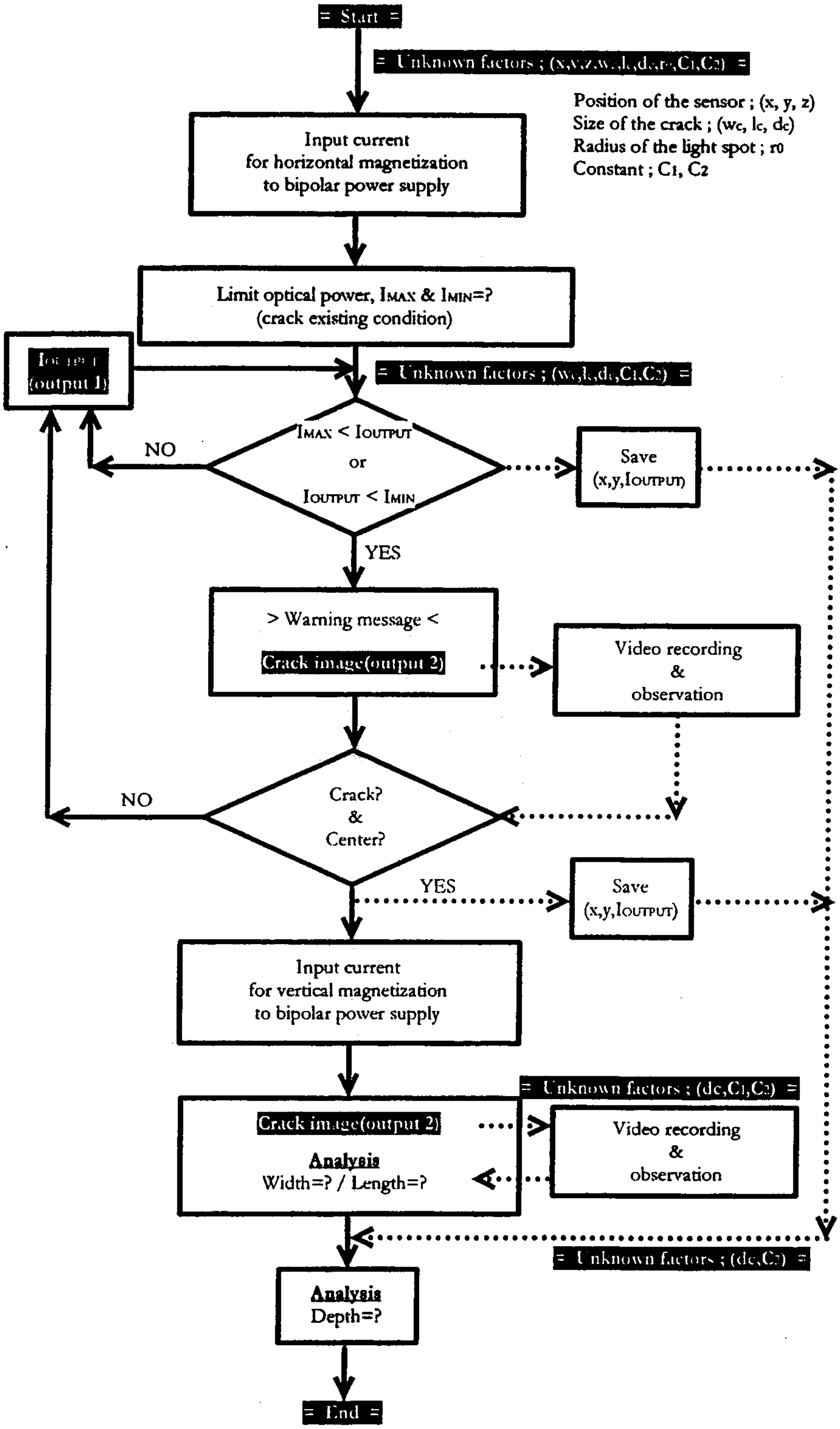

Fig. 6 Unknown parameters and algorithm for NDE of cracks

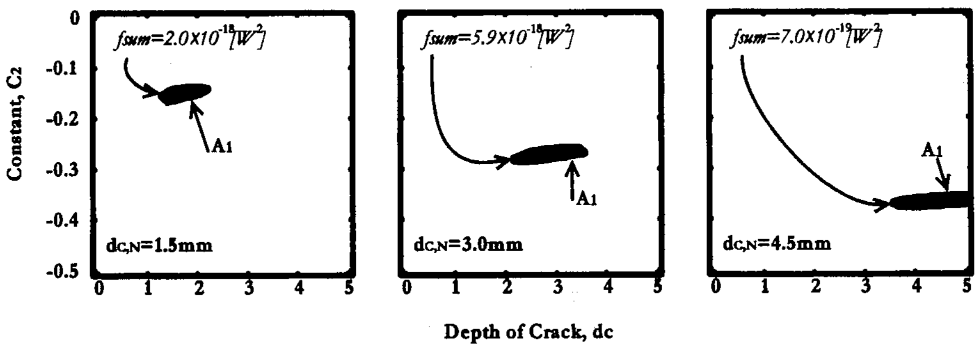

Fig. 7 Constant-error cross sections of the surface fsum(d_C, C_2)

Table 1 Values of seven unknown parameters determined by the algorithm for NDE of cracks

Nominal Crack Depth	lift-off, z[mm]	r_0[mm]	w_C[mm]	l_C[mm]	d_C[mm]	C_1	C_2
1.5 mm	0.1	0.6	0.5	10	1.60	53.9	−0.15
3.0 mm					2.77	54.6	−0.27
4.5 mm					4.52	55.4	−0.36

determination of the initial approximation. As a result, several constant error cross-sections of the 2-D surface fsum(d_C, C_4) are projected over the basis (d_C, C_4) as shown in Fig. 7. The minimum value of fsum is located somewhere inside the contour line A1, which gives an initial approximation (d_C^0, C_4^0). The precise values of d_C and C_4 can be computed using fsum, an initial approximation inside A_1, and the Nelder-Meade simplex minimization (Dennis J. J. et al., 1987).

The unknown parameters are computed for three specimens with crack depths 1.5 mm, 3.0 mm, and 4.5 mm. The values of the seven of the unknown parameters, except for the position of the center of the crack (x, y), which are determined by the algorithm described above are listed in Table 1. It shows a good agreement between the nominal and measured crack depths.

4. Summary

An algorithm for the NDE of surface cracks is proposed. The algorithm uses a magneto-optical nondestructive inspection system and an improved magnetization method, as well as a new equation for the power of the detected light. The vertical magnetization and an MO sensor are suitable for obtaining information about the length and width of surface cracks. The depths of cracks evaluated by the proposed algorithm are in good agreement with the actual values.

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