Application of a NDI Method Using Magneto-Optical Film for Micro-Cracks

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Leakage magnetic flux is occurred in the cracked area of magnetized specimens, and also it changes the magnetic domain area of the magneto-optical film positioned on the specimen. It causes the change of the optical permeability of the magnetic domain on the crack area. So crack images can be obtained easily using this principle. On the other hand, utilizing a laser in this method makes possible to perform a remote sensing by detecting the light intensity contrast between cracked area and normal area. This paper shows the application of non-destructive inspection system taking advantage of magneto-optical method for micro-cracks and presents examples applied to the several types of specimens having fatigue cracks and fabricated cracks using this method. Also the authors prove the possibility of this method as a remote sensing system under the oscillation load considering application to real fields.

Key Words: NDI (Non-Destructive Inspection), MO Film (Magneto-Optical Film), Leakage Magnetic Flux (LMF), Lift-off, Faraday Effect

1. Introduction

The defects of aging aircraft or nuclear power plants by various factors under working conditions cause lots of damages such as safety accident and economic loss. But it is difficult to detect the defects of structures under operation. Recently, non-destructive methods using leakage magnetic flux (J. H Lee, 1993) have been developed to solve these problems. The advantages of NDI methods using magneto-optical films are high inspection speed, no need of paint removal, easy documentation of results and mitigation of the worker' fatigue (Fitzpatrick, 1993; Lee, 1998a, 1998b, 1998c). Of course, this method is effective to investigate the position and approximate dimension of crack, but has difficulty to apply, as a remote sensing tool, to the structures under operation. The use of laser as a light source allows remote sensing of defects by detecting two bright areas corresponding to the crack and its centerline.

The method is based on the three characteristics of the magneto-optical film as follows; Faraday rotation of the magnetic domains, optical permeability of domain walls and diffraction of laser rays by magnetic domain walls (Mincov, 2000a;

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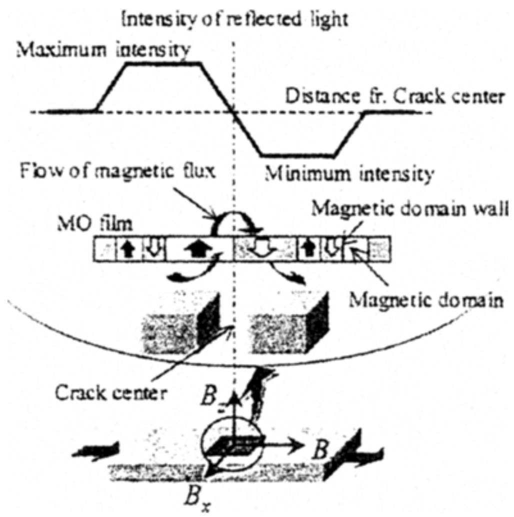
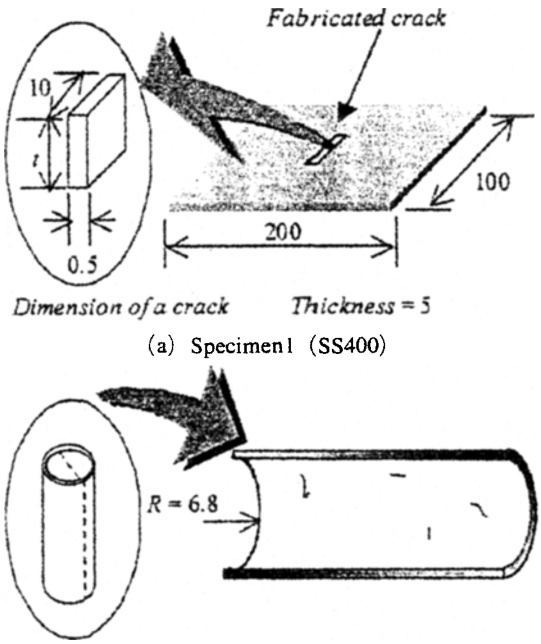


Fig. 1 Principle of leakage magnetic flux around defect



(a) Specimen1 (SS400)

(b) Specimen2 (JST410)

Fig. 2 Dimension of two specimens, *sp*1 and *sp*2

Lee, 1999a, 1999b).

Figure 1 shows the leakage magnetic flux and the magnetic domain change near the crack when light is reflected on the magneto-optical film. As shown in this figure, the intensity of the reflected light becomes either maximum or minimum on both sides of the crack.

For horizontal magnetization of the specimen surface, two large magnetic domains occur on both sides of a crack in the magneto-optical film due to the vertical component of the leakage magnetic flux. A crack image can be visualized by the observation of magnetic domains changed by the leakage magnetic flux around the cracks.

The purposes of this paper are to investigate the application of the NDI method using a magneto-optical method to micro-cracks and to present examples of inspections using the MO sensing system.

2. Experimental Method

2.1 Test specimen

Four types of specimens (*sp1*, *sp2*, *sp3*, *sp4*) are used in this experiment. Figure 2 shows the dimensions of specimens *sp1* and *sp2*. Here, *sp1* (SS400) has a fabricated defect on the center of its surface. The dimensions of the defects formed by electric discharge processing are 10mm×0.5mm×1.5/3.0/4.5mm. Mean while, *sp2* (JIS STS410) is a part of a tube with an internal radius, R of 6.68mm approximately, having a few of micro fatigue cracks on the inner wall; crack 1 (700μm) and crack 2 (250μm) approximately, and it is cut in the axial direction after fatigue test (in the dissolved oxidation concentration of 1 ppm, temperature of 290μm). And, *sp3* is a CT specimen that was used for fatigue test, and then sliced to the thickness direction, 1/2/4/6/8/mm, respectively, for investigating the correlation of the specimen thickness with the change of defect images. Lastly, *sp4* (SA336F22B) is a CT specimen for testing the possibility of remote sensing.

2.2 Experimental Procedure

The schematic diagram of an apparatus is shown in Fig. 3. Wavelength of laser is 670nm and output power is 10mW. The magneto-optical film is composed of a film ($(GdBi)_3(FeAl)_5O_{12}$) and a vaporized aluminum layer. The Faraday rotation becomes doubled almost in this reflection-type film (Lee, 2000b; Minkov, 1999, 2000b).

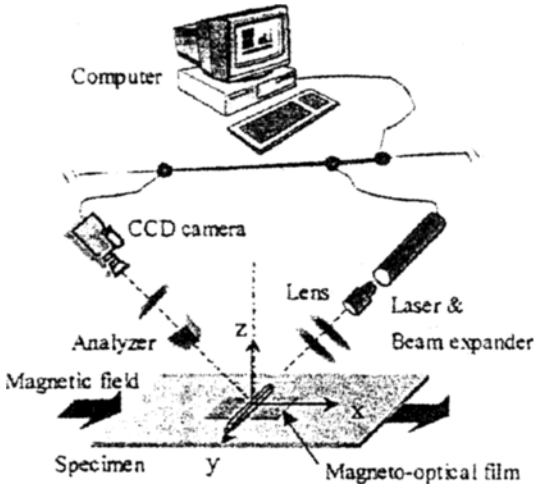


Fig. 3 Schematic apparatus of a new inspection system

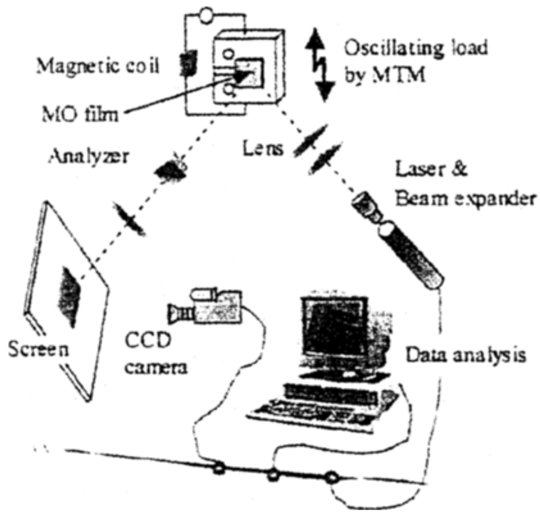


Fig. 4 Experimental apparatus for application under oscillating loads

Leakage magnetic flux used in this method has 2 components, B_z vertical to the specimen surface and B_x, horizontal to the specimen surface. In case that the methods taking advantage of B_z component of leakage magnetic flux are applied to the inspection of curved specimens (*sp2*), the degradation of inspection sensibility is indispensable because of lift-off occurred by the interval between the specimen and the magneto-optical film. In order to overcome this disadvantage, the minimized MO films and the B_x component of leakage magnetic flux are tested in this method (Lee, 2000a).

Experimental procedures are as follows; straightened laser beam is expanded by a beam expander, then passed to the magneto-optical film positioned on the specimen that is magnetized by direct current magnetic fields. The reflected beam from MO film is got to a screen through a polarizer and lenses. And CCD camera catches the image on the screen. Polarized light is used in the second test instead of laser beam to compare its crack images, but the basic system is almost similar to that by use of laser.

2.3 Application of system under oscillating loads

In order to prove the possibility of this method as a remote sensing inspection tool, fatigue test is conducted under oscillating loads. Schematic apparatus is shown in Fig. 4. The specimen magnetized by a magnetic coil is tested under oscillating loads. A crack will initiate and propagate at the notch of the specimen with time. During the test, CCD camera catches the image of cracks with real time when cracks initiate and propagate.

In the 3-D coordinate system of magnetic fields, the x-direction directs to the anticipated crack propagation, y is the load direction and z is the vertical direction to the x-y plane. In this experiment, the magnetic domain of MO film is affected only by the B_z component of leakage magnetic flux, the vertical direction to the MO film surface. The conditions of this test are as follows; input current of the magnetic coil is DC 3.19 A, the polar distance is 48mm, winding number of coil is 130times, the frequency is 1 Hz and the interval from the laser to the specimen is 1m. The thickness of the specimen is 25mm and the interval from load point to notch is 15mm.

3. Experimental Results and Discussion

3.1 Inspection results by system using laser

The advantage of this inspection system is to obtain the defect images of the defects in the real time fashion and also to be applied to the structures under operation as a remote sensing tool.

Figure 5 shows the defect image of the fabricated defect formed by electric discharge processing on the center of the specimen (SS400). As seen in this figure, the defect image is transcribed on the magneto-optical film located on the specimen. The magnetic domains of MO film react very sensitively to the leakage magnetic fluxes, so tcoo-dimensional defect images occurred by the leakage magnetic fluxes are transcribed on the magnetic domain of the MO film. Especially, there are two important factors to affect the inspection reliability. One is the polarized angle of the polarizer, the other is the incident angle of beam from laser to the magneto-optical film positioned on the specimen.

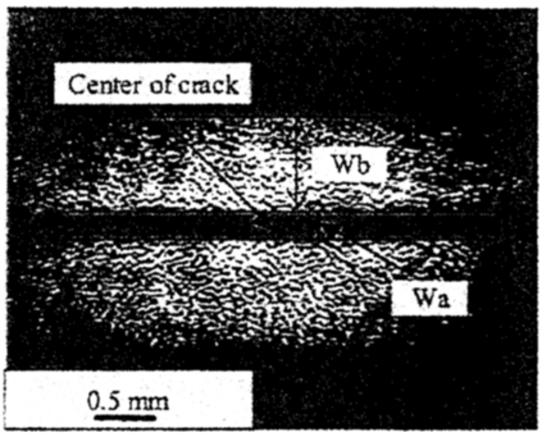


Fig. 5 Defect image of the specimen *sp*1

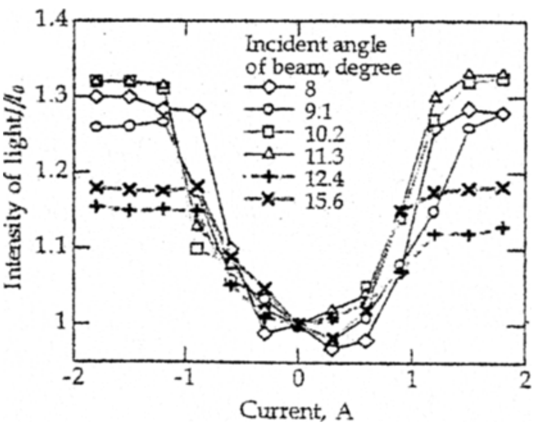


Fig. 6 Relationship between current and intensity of light

Figure 6 shows the graph of the optimum incident angles of light. The angle of the polarizer is fixed to 90μm. The maximum intensity of the incident light was acquired as about 8μm~11.3μm when incident angles vary from 8μm to 15.6μm.

This result is important because the stronger intensity of the incident light, the higher contrast between a bright and a dark area in defect images is obtained. After all, for the high resolution in crack images, the strong intensity of the incident light is required.

3.2 Inspection results by system using polarized light

The methods using laser beam and polarized light are very similar in their configuration. Figures 7 shows defect images of the specimen *sp3* (t=6mm), after fatigue tests. These images are obtained by the inspection system using polarized light. As shown in this figure, defect images change by the current intensity that changes the magnetic field intensity. This result is similar to those of *sp1* that was obtained by the inspection system used laser.

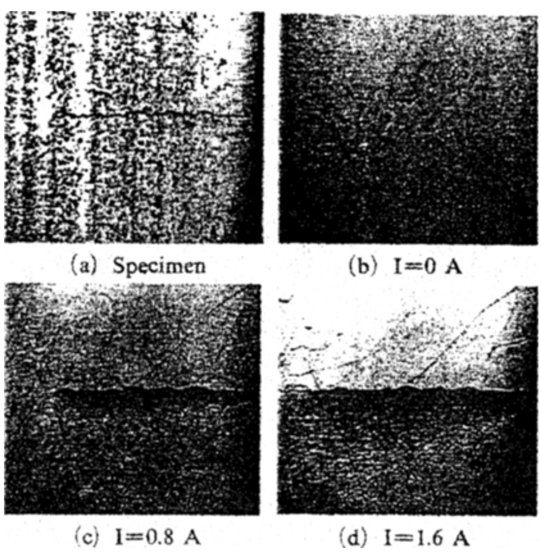


Fig. 7 Photographs of the crack by the MO sensing system (*sp*3 (t=6mm))

3.3 Correlation of defects with intensity of current

The relation between the current intensity and the bright/dark area in the defect images of the specimen *sp3* is shown in Fig. 8 (also in Fig. 5). Here, the current intensity is proportional to the magnetic field intensity.

In Fig. 8, the increment of dark areas (lines) shows the almost same tendency in all of the thickness of the specimens, and also there are little changes in the width of dark areas for current equal to or over 1.2 A.

Figure 9 shows the relation between the specimen thickness and the width of dark areas in the defect images (also shown in Fig. 5). It means that leakage magnetic fluxes become decreased in the thicker specimen than the thinner one even the length of the defect is same. In practice, for application of this inspection method to the real fields, this characteristic of the thickness effect of samples should be fully considered.

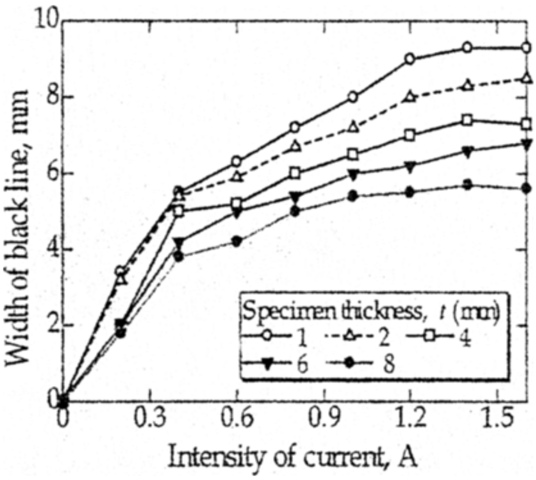


Fig. 8 Relationship between current and width of black line

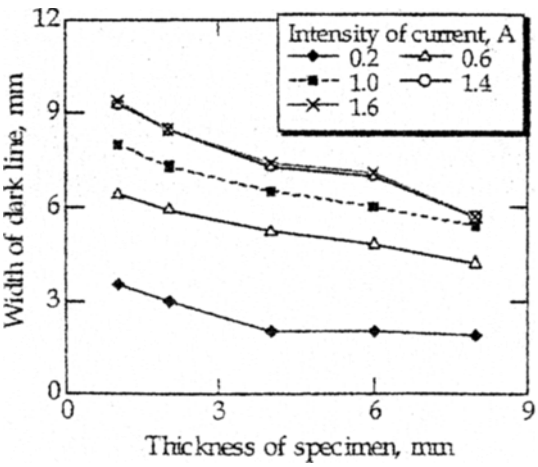


Fig. 9 Relationship between the thickness of specimens and the width of black line

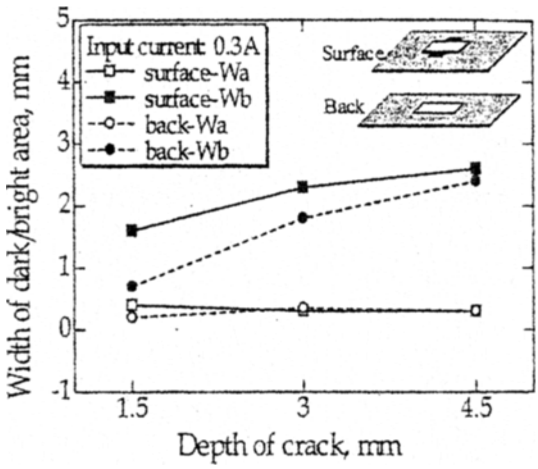


Fig. 10 Relationship between the depth of cracks and the width of bright/dark lines (*sp1*)

The relation between the depth of defects and the bright/dark lines in the crack images of *spl* (in Fig. 5) is shown in Fig. 10. The bright area increases with in creasing the depth of defects. These results ane almost same with the case of the specimen *spl*. This result verifies that the bright/dark lines are important factors to analyze the defect information such as the width and the depth of defects.

3.4 B_z and B_x components of magnetic flux

From now, The B_z component only of leakage magnetic flux has been used in the conventional methods using magneto-optical films. But there are some difficulties in applying these methods to the specimens having curvature because of lift-off. Figure 11 shows the lift-off phenomenon of the specimen with curvature. The off is the main factor to determine the inspection sensitivity. In order to improve the inspection sensitivity, the interval between the specimen and the MO film should be reduced, but actually, it is almost im-

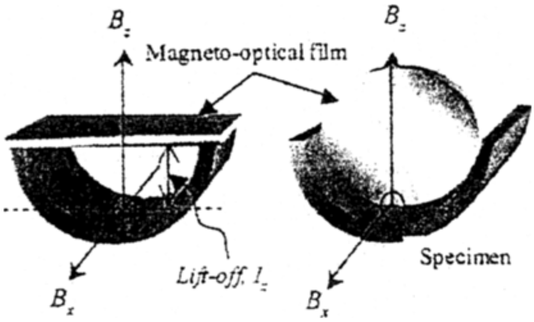


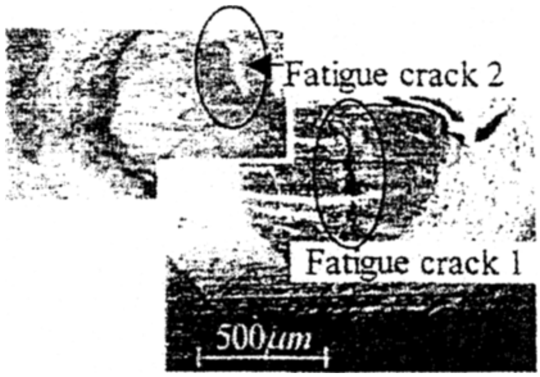
Fig. 11 Lift-off on specimen having curvature

possible to get rid of an interval in case of using B_z component of leakage magnetic flux, except for miniaturizing the size of MO film itself.

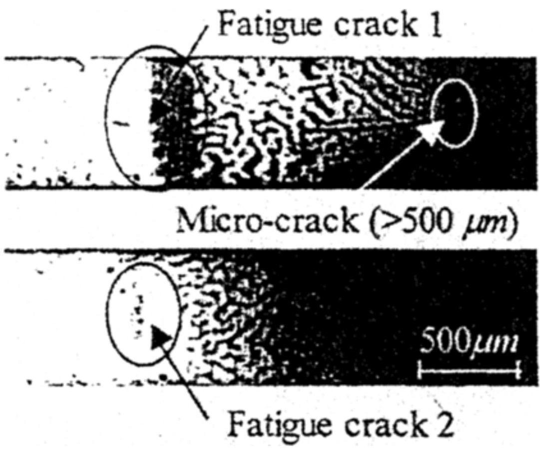
In order to improve this problem, B_x component of leakage magnetic flux is proposed instead of B_z component. In case of the inspection system taking advantage of B_x, the vertical component to the specimen surface, leakage magnetic fluxes flow from one side of the specimen to another with making loop and the B_x component only of leakage magnetic fluxes react to the magnetic domain of the MO film. Thus, this method can reduce lift-off and provide more accurate image data.

Figure 12 shows the fatigue crack images of the specimen *sp2* by two components. Figure 12(a) shows the crack image obtained by B_z component of leakage magnetic flux. The width of MO film used is 0.8mm approximately. And Fig. 12(b) shows the crack image of fatigue crack 2 obtained by B_x component. As seen in this figure, the defect areas of the specimen are found easily.

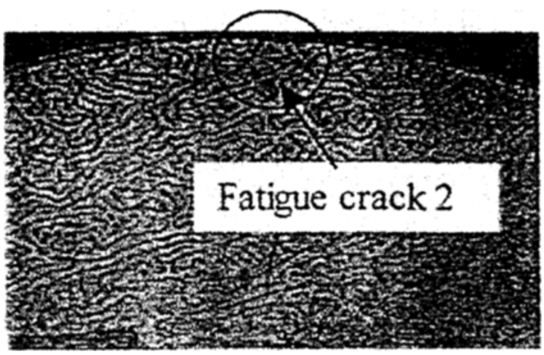
In above results using two types of magnetic flux, B_z and B_x, it is case-dependent to select which components are better for accurate image data, because their inspection sensitivities depend on types and shapes of specimens. Both do almost same function in the systems except that the color of data images is different.



(a) Photograph of cracks, *sp2*



(b) Crack images by B_z component of magnetic flux



(c) Crack images by B_x component of magnetic flux

Fig. 12 Crack images by the new inspection system taking advantage of B_z and B_x components of magnetic flux respectively (*sp2*)

3.5 Application of system under oscillating loads

Figure 13 shows experimental results under oscillating loads when $P_{max}=38kN$, and it is impossible to catch crack images when minimum load is $P_{min}=1.9kN$ because the intensity of leakage magnetic flux varies with the width of cracks and the loads. The crack length is 3.6mm approximately, and the minimum size of the crack

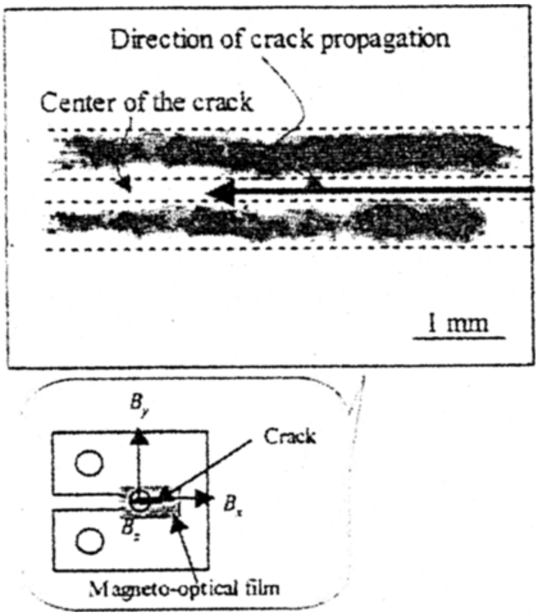


Fig. 13 Crack image of the CT specimen *sp*4 under oscillating loads (P_{max}=38 kN)

to be detected by this inspection is about 500μm. This result shows that the bigger the magnitude of loads, the more accurate image data are obtained.

From the above results, it is clear that defect images depend on lift-off, incident angles of beam and the magnetic flux intensity. So these factors should be considered when the inspection is conducted.

In the near future, this inspection method can be applied to the real fields easily if the system is linked by LAN cable or ethernet network.

4. Conclusion

NDI method using magneto-optical film was applied to investigate micro-cracks of structures. When a specimen is magnetized, the leakage magnetic flux leaks near the defect and the magnetic domains of the MO film located on the specimen react to the leakage magnetic flux. By using these principles, the defect images are obtained. The main results were as follows:

(1) It was proved that the micro-crack of structures be detected by NDI method using magneto-optical film.

(2) Relation between the depth of defects and the bright/dark areas was the important factor to evaluate the length and the depth of surface defects on plates, and also this system can be applied to the specimens having curvature by use of cutting processed MO film and Bx component of leakage magnetic flux.

(3) The possibility of a remote sensing of this method was proven by fatigue test. This system caught the crack image in the real time fashion during the test when the crack in the specimen initiates and propagates in the process of time.

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