Epitaxial films of garnet ferrite with anisotropy "easy plane" for magneto-optical eddy current flaw detection

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Abstract. The possibilities of magneto-optical sensors based on ferrite garnet films with various types of magnetic anisotropy are studied in the visualization of eddy current images of linear defects in the test object from aluminum alloys. Potentially high efficiency of sensors based on an easy-plane anisotropy films is shown.

1. Introduction

In the modern world with new technologies, the diagnosis and detection of all the smaller defects of various designs become more important. In some areas where structures are under heavy loads, different pressures and high speeds, it is important not to allow the use of an industrial design, even with micron damage. To determine such defects, it is best to use the eddy current (EC) method [1-2]. An important factor in the development of this method can be considered the creation of new composite materials, their implementation in many important areas of industry and the fact that most of these materials are conductive and can therefore be subjected to EC flaw detection method. But this method has a number of disadvantages. The possibility of applying magneto-optical (MO) sensors to the eddy current method will eliminate some of them and will allow adding to the EC method the observation of defects in real time, visualization of the shape and topology of the defect, the implementation of faster defectometry, which will shorten the total time of investigations.

2. Installation and objects of research

The method of magneto-optical eddy current (MOEC) flaw detection is based on the reaction of the magnetic structure of a thin-film sensor to the magnetic fields of eddy currents. The registration of these changes is carried out using the Faraday Effect. As indicators of the magnetic field, transparent epitaxial films of ferrites-garnets (FGEF) with a given type of magnetic anisotropy are used. The sensitivity of this method and the contrast of the resulting image essentially depend on the film parameters. These parameters include the type of magnetic anisotropy of the film ("easy axis" or "easy plane"), the period of the domain structure (DS), the saturation field $H_s$, and the value of the Faraday specific rotation. The frequency $f$ and the amplitude $H_i$ of the alternating magnetic field exciting the eddy currents, as well as the value of the bias field $H_0$ also affect the sensitivity of the MOEC method [3-5]. The purpose of this paper is to compare the possibilities of using films with the "easy plane" (EP) and “easy axis” (EA) anisotropy on the example of MOEC visualization of linear defects in non-magnetic material.

Films, used as sensors, with the general composition $(Bi,Re)_{3}(Fe,Me)_{5}O_{12}$, where Re - Y, Lu, Pr, Me - Al, Ga, Sc were grown by liquid phase epitaxy (LPE) on paramagnetic GGG (gadolinium gallium garnet) substrates. The films had the following characteristics: EA films - thickness $h = 7.2$ μm, period DS $2ω = 17$ μm, saturation field $H_s = 77$ Oe; EP films: thickness $h = 12$ μm, saturation field $H_s = 235$
Oe. For the study test samples of linear defects of the "through-slot" type in aluminum with the width of 40 μm were taken. The study was conducted under the same conditions in the frequency range f from 8 to 80 kHz. The intensity of the alternating field of the inductor $H_i$ could vary from 2 to 400 Oe, and the bias field $H_\perp$ from 0 to 40 Oe.

3. Experiment and results

Figures 1-2 show MOEC comparative images obtained using EA and EP films at 15 and 30 kHz. The results of analysis of these images for epitaxial films with anisotropy of the easy axis are presented below.

- At low intensity of the alternating field $H_i$ linear defects are visualized by light bands (Fig. 1a, d). With an increase of the field $H_i$, the intensity of the bright bands increases. For fields larger than some critical value $H_{cr} = 14$ Oe at $f = 15$ kHz, the defect is displayed in a dark band, and the image acquires a clear binary structure (Fig. 1b, c, e, f).

- An increase in the amplitude of the excitation field $H_i$ leads to an increase in the width of the binary image of the MO. Thus, when $H_i$ increases by a factor of 2, the width of the magneto-optical image increases by a factor of 6 (Fig. 1e, f). This effect indicates a potential possibility of detecting defects much smaller than 40 μm.

- When the frequency increases, fragments of the labyrinthine domain structure appear in the dark band, complicating the binary image and reducing the clarity of the magneto-optical image (Fig. 1g - i).

- Increasing the bias field $H_\perp$ leads to partial or complete suppression of the structure of the labyrinth domain and restoration of a clear binary image (Fig. 1b, e; 1c, f).
The results of visualization for films with anisotropy of the easy axis:

- At any amplitudes of the alternating field linear defects are displayed by light bands. An increase in the amplitude of the alternating field leads to an increase in the contrast (brightness) and an increase in the bandwidth (Fig. 2 a-d).
- Increasing the frequency of the alternating field leads to an increase in contrast, increasing the sensitivity of the epitaxial sensor film (Fig. 2 e-g).
- Increasing the bias field does not affect the magneto-optical image of defects.

Figure 2. Effect of the alternating field $H_\sim$ (a-d) and frequency $f$ (e-g) on the detection efficiency of a 40 $\mu$m slit in Al sample by means of the EP film MO sensor. Top row: $f = 30$ kHz, $H_\sim = 12$ (a), 16 (b), 20 (c), 32 Oe (d); bottom row: $f = 15$ (e), 30 (f), 60 kHz (g) in the fields $H_\sim = 8$ Oe, $H_\sim = 2$ Oe.

All these results indicate that both films with the easy axis and easy plane anisotropy can be used as sensors in magneto-optical eddy current flaw detection. Each of the types of anisotropy has its own peculiarities, advantages and disadvantages, which will enable them to solve various problems. For example, EA films show complex patterns with a domain structure and EP films are a simple binary picture, and therefore more optimal for transferring the image to a digital signal for further automation of the flaw detection process.

4. Calculations and modeling

The modeling and distribution of eddy currents and magnetic fields induced by them in the vicinity of a linear defect was carried out by the finite element method in the CAD system Comsol Multiphysics. Objects of modeling: the aluminum sample (plate) measuring 100 mm by 100 mm, 0.15 mm thick with a 40 $\mu$m defect (slit) in the center; inductor with diameter of 50 mm, a height of 25 mm, a wire diameter of $3 \times 10^{-6}$ m, the number of turns is 80, the conductivity of the wire is $6 \times 10^7$ sm/m, the current strength is up to 1 A.

Figure 3 shows the model distribution of the normal component of the vortex magnetic field in the vicinity of the defect for different frequencies of eddy currents excited by the inductor. It is seen that as the frequency increases, the maximum of $B_z$-component of the EC field increases, and the width of the distribution decreases. For comparison with the experimental data, it was necessary to present in the form of a digital dependence the brightness of the MO of the defect image recorded by the easy-plane MO sensor as a bright light line.

For processing and analysis, obtained experimental magneto-optical images, an image analysis program written in the Matlab package was compiled. It is based on the translation of a graphic file into a special matrix, which contains the brightness value of all pixels of the MO image. Further with this matrix it was possible to perform various mathematical operations. In particular, the brightest fragment of the
image (corresponding to the defect) and the darkest (background) are selected to determine the image MO contrast, and the matrices of the selected regions are constructed, then the average value is found for these matrices. Contrast is defined as the ratio of these mean values.

Figure 3. The frequency dependences of the $B_z$ component of the EC field distribution near the defect (theory) (a), the maximum and the width of the $B_z$ (FWHM) distribution (theory) and the width of the EP film MO image (experiment) (b).

The electrodynamic simulation of the EC magnetic fields in the sample under study adequately describes the change in the brightness of the MO of the image of the sensor obtained by the EP film with increasing amplitude and frequency of the alternating field. For example, Fig. 3b shows the dependence of the half-width of the experimental MO image in the frequency range from 8 to 60 kHz and theoretically predicted values of this parameter found by mathematical processing. We can see that they are in good agreement. In accordance with theoretical calculations, an increase in the amplitude of the maximum with a frequency (Fig. 3b) also leads to an increase in the contrast of the magneto-optical image in the experiment (Fig. 2).

5. Conclusion
The type of magnetic anisotropy of FGEF determines the character of the MO image. The reason for this phenomenon lies in the various processes that occur when magnetization of such films is reversed. Thin magnetic films with an easy-plane anisotropy make it possible to obtain contrasting MOEC images of defects at a lower excitation field intensity, they do not require the imposition of large displacement fields and they do not cause visual interference when operating at high frequencies. Eddy current MO sensors, created based on these films, will have a sufficiently high sensitivity and low power consumption in the conduct of flaw detection of structures made of conductive materials.

Acknowledgments
The authors acknowledge support by the RF Ministry of Education and Science in the framework of the state task (project no. 3.7126.2017/8.9).

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