Magneto-optical imaging with drone for non-destructive inspection

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1. BACKGROUND

Electrical non-destructive inspection methods are widely used for detection of cracks on a metal surface. A high-spatial resolution method is required to keep high reliability and safety. Magneto-optical (MO) imaging is one of advantageous methods for the non-destructive inspection[1][2]. The MO imaging can visualize the magnetization distribution in a MO indicator which magnetized by the stray field leaked from defects on a metal surface. The MO indicator rotates plane of linear polarization which passes through a magnetic film via the Faraday effect. The Faraday rotation angle is converted to light intensity using by the polarizers positioned the Cross-Nicol alignment. This light intensity is obtained as a photograph by the image sensor such as charge-coupled device (CCD) camera. Therefore, the stray field from defects can be visualized by two-dimensional image of the converted light intensity via MO indicator.

The intensity of converted light can be calculated as follows:

\[ I_{\text{out}} = I_{\text{in}} \times \%T \times (\sin^2 \theta_f) \]

where \( I_{\text{out}} \) means the intensity of converted light, \( I_{\text{in}} \) means the intensity of the light source, \%T means transmissivity of the MO indicator and \( \theta_f \) means the Faraday rotation angle of polarization plane.

The spatial resolution of a MO image depends on the magnetic domain size of the MO indicator. In generally, the magnetic domain size of the magnetic material is micro meter order. Therefore, the MO indicator possesses great potential as a high-spatial resolution sensor for the electrical non-destructive inspection[3].

A thin film of bismuth substituted yttrium iron garnet (Bi:YIG) is used as a material of a MO indicator because the Bi:YIG indicates large Faraday rotation angle in visual light range. In our previous research, MO indicators had been formed by the iron beam sputtering[3][4]. Deposited films are amorphous. Therefore, deposited films are necessary to be crystallized by heat-treatment in approximately 800 degree. Because of this, a formed MO indicator was not able to deal with the curved surface of specimens, i.e. the inspection was limited to a flat surface of that. The substrate of the MO indicator was limited to highly heat resistance materials such as quartz glass, because the substrate was required highly heat resistance in order to be tolerant of heat treatment. Figure 1 (a) shows a schematic image of a MO indicator deposited on the glass substrate placed on a curved surface. In the case of a glass substrate, there is a gap between an indicator and a specimen surface. The stray field intensity is decreased depending on the distance from a specimen surface. Because of this gap, it becomes difficult to detect stray field by the MO indicator. On the other hand, fig.1 (b) shows a MO indicator formed on a flexible substrate. In this case, it can be placed closely to a specimen surface. Therefore, it is required for detection a defect on the curved surface to fabricate a MO indicator on a flexible substrate.

**Figure 1:** MO indicators using for each substrate. (a) In the case of a glass substrate, (b) A flexible substrate.
In this study, we fabricated a flexible MO indicator to enable non-destructive inspection on a curved surface. The Bi:YIG of a MO indicator material was obtained in the state of particles. The Bi:YIG particles previously crystallized were mixed in organic binder solution. After that, this solution was deposited by coating process on a flexible plastic substrate. By crystallizing materials before deposition, it was realized to fabricate a MO indicator on a flexible substrate.

Additionally, we developed a MO imaging device mounted on a drone for remote non-destructive inspection. A MO imaging device was composed of an image sensor, polarizers, a light source and a mirror. These optical elements were held in frames. These frames were made by plastic assemblies as integrated as possible using by the three-dimensional printer in order to reduce in size and weight. A developed device was mounted on a drone controlled to keep altitude, direction and horizontal condition in hovering flight.

2. EXPERIMENT

2.1 Fabrication of a flexible MO indicator

The Bi:YIG particles were purchased from HOSOKAWA Powder Technology Research Institute. The chemical composition of particles was Bi₀.₅Y₂.₅Fe₅O₁₂. The average particle size was approximately 100 µm. It was too large as a high-spatial resolution indicator material. Therefore, particles size was reduced by the planetary ball milling. Table 1 shows a condition of the planetary ball milling. As a result of a measurement of the particles size by Field emission scanning electron microscope (FE-SEM) image, the average size was less than 10 µm. Polyvinyl alcohol (PVA) solution was used as an organic binder to hold the Bi:YIG particles on a substrate. The PVA powders were dissolved in deionized water heated to 90 degrees. This prepared PVA solution and Bi:YIG particles were mixed in the ratio of mass 2:3 and 1:1. This Bi:YIG compound liquid was deposited on a glass substrate by the spin-on process. Table 2 shows a condition of the spin-on process.

The Faraday rotation angle of deposited film was measured as an optical property of a MO indicator. The Faraday rotation angle was measured by the rotation analyzer method at the wavelength of 550 nm.

Table 1: A condition of the planetary ball milling.

<table>
<thead>
<tr>
<th>Ball material</th>
<th>Zirconia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball diameter</td>
<td>5 mm</td>
</tr>
<tr>
<td>Particle weight</td>
<td>5 g</td>
</tr>
<tr>
<td>Buffer liquid</td>
<td>Isopropyl alcohol</td>
</tr>
<tr>
<td>Liquid weight</td>
<td>100 g</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>300 rpm</td>
</tr>
<tr>
<td>Milling time</td>
<td>5 hours</td>
</tr>
</tbody>
</table>

Table 2: A condition of the spin-on process.

<table>
<thead>
<tr>
<th>Step number</th>
<th>1st step</th>
<th>2nd step</th>
<th>3rd step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation speed / rotation time</td>
<td>500 rpm / 5 seconds</td>
<td>2000 rpm / 60 seconds</td>
<td>5000 rpm / 1 second</td>
</tr>
</tbody>
</table>
2.2 Development of a remote MO imaging device with drone

A MO imaging device to mount on a drone was developed for remote non-destructive inspection. This device was composed of an image sensor, polarizers, a light source and a mirror. An image sensor observes distribution of light intensity corresponding to stray field from defects via a MO indicator as a two-dimensional image. Two polarizers positioned the Cross-Nicol alignment convert from the Faraday rotation angle to light intensity. A light source illuminates a MO indicator with linear polarization. A mirror changes direction of incident light between a light source and a MO indicator.

These optical elements were held in frames. These frames were designed using by the three-dimensional Computer Aided Design (3D-CAD). Designed frames were made by plastic assemblies as integrated as possible using by the three-dimensional printer in order to reduce in size and weight.

3. RESULTS AND DISCUSSIONS

3.1 Fabrication of a flexible MO indicator

3.1.1 Deposition Of The Bi:YIG Particles With PVA Binder By Spin-on Process

Figure 2 (a) shows an optical image of a film surface of a PVA binder without Bi:YIG particles on a glass substrate. Transmissivity in visible light range was over 95%, which was enough transparency as an organic binder. Figure 2 (b) shows an optical image of a film surface which mass ratio of PVA and Bi:YIG was 2:3. In this case, ununiformly distribution of the particles was observed. This result indicates that the mass ratio of the Bi:YIG particles was too much to flow on a surface of the substrate. Following this result, we reduced the mass ratio of a PVA binder and the Bi:YIG particles from 2:3 to 1:1 (Fig.2 (c)). A relatively uniform distribution was indicated in this condition. However, whole surface of substrate was not uniformly deposition.

Therefore, we improved a condition of a spin-on process in order to deposit the Bi:YIG particles more uniformly. The rotation time of 1st step in table 2 was increased from 5 seconds to 10 seconds to make a smooth flow of the particles. Additionally, the Bi:YIG solution was put a few drops on a substrate after beginning rotation. Improved condition of spin-on process indicated good uniform distribution of the Bi:YIG particles. In the same condition, deposition of the Bi:YIG particles on a flexible substrate was succeeded (Fig. 3).

![Figure 2: Optical images of deposited film surface.](image)

(a) without Bi:YIG particles, (b) the mass ratio of PVA and Bi:YIG was 2:3, (c) the mass ratio 1:1.

![Figure 3: Optical images of deposited film surface after improve of spin-on process condition.](image)
3.1.2 The Faraday Rotation Angle Of A Flexible MO Indicator

Figure 4 shows the Faraday rotation angle of a substrate and a fabricated MO indicator. Each rotation angle was measured at the wavelength of 550 nm. A rotation angle of a substrate was 0.04 degrees. On the other hand, a rotation angle of a fabricated MO indicator was 0.06 degrees. A rotation angle of a fabricated MO indicator was 1.5 times larger than a rotation angle of a substrate because it was including the Bi:YIG particles. However, this rotation angle was exceedingly small value as a MO indicator. In generally, a rotation angle of the Bi:YIG thin film is few degrees. A rotation angle of a fabricated MO indicator was less than one hundredth. A transmissivity and a Faraday rotation angle spectra of the Bi:YIG were calculated by matrix approaching method in order to investigate this reason. Calculation parameters were decided based on an experimental result.

Figure 5 shows calculation results of a transmissivity and a Faraday rotation angle. A graph on the top shows a transmissivity and a bottom one shows a Faraday rotation angle. A dot-line shows a wavelength used in the experiment (at 550 nm). A calculation result indicates that a transmissivity is almost 0% at the wavelength of 550 nm. In other words, incident light is absorbed by the Bi:YIG particles. Therefore, majority observed rotation angle was a result of measuring the light passing through gaps between the particles. On the other hand, dashed line shows calculation result at the wavelength of 700 nm. Transmissivity at the wavelength of 700 nm was over than 90%. Because the long-wavelength light is low energy, the absorption of the light is suppressed. Therefore, the long-wavelength light has the potential to observe a light passed through in particles. As a future work, we would like to measure the Faraday rotation angle at the wavelength of 700 nm.

Figure 4: The Faraday rotation angle of a substrate and a fabricated MO indicator.

Figure 5: A calculation result of the transmissivity and the Faraday rotation angle.
3.2 Development of a remote MO imaging device with drone

Figure 6 shows a design of a MO imaging device frame drawn by the 3D-CAD. The incident light from light source is converted to linear polarization by a polarizer in polarizer holder. A direction of an incident light converted to linear polarization is rotated 90 degrees in the direction of a MO indicator by cubic half mirror in mirror holder. A polarization plane of reflected light from the MO indicator is rotated via the Faraday effect. This rotation angle is converted to a light intensity by polarizer in analyzer holder. This light intensity is obtained as the MO image by a CCD camera in image sensor holder. Figure 7 shows an optical image of the optical elements installed at each holder of fabricated frames. A laser pointer was used as the light source. A weight of all assembles including all optical elements were approximately 0.5 kg.

A drone for remote non-destructive inspection was controlled to keep altitude, direction and horizontal condition in hovering flight by computer programming. A drone was consisted of frame, control system and propellers. A drone control system can be programmed via Arduino software (i.e., the Arduino IDE). This programmed drone can keep attitude own self and can obtain images remotely.

As a future work, we would like to obtain MO images of cracks by a fabricated MO imaging device mounted on a drone.

![Figure 6: A 3D-CAD design of the MO imaging device frame.](image1)

![Figure 7: An optical image of the MO imaging device.](image2)
4. CONCLUSIONS

We fabricated a MO indicator on a flexible substrate. The Bi:YIG particles were used as a MO indicator material. The Bi:YIG particles were deposited on a substrate using the spin-on process. By improved a condition of the spin-on process, deposition of the Bi:YIG particles on a flexible substrate was succeeded. The Faraday rotation angle of a fabricated MO indicator was 0.06 degrees. This rotation angle was 1.5 times larger than a rotation angle of a substrate without the Bi:YIG particles. However, this rotation angle was exceedingly small as a MO indicator. In order to investigate this reason, we calculated a transmissivity and a Faraday rotation angle spectra of the Bi:YIG by matrix approaching method. A calculation result indicated that a wavelength used for measuring should be shifted to the long-wavelength.

Additionally, we developed a MO imaging device. The frames of a device designed by 3D-CAD were made by the three dimensional printer. A drone to mount a MO imaging device was controlled to keep altitude, direction and horizontal condition in hovering flight by computer programing. This drone can be programmed via Arduino software (i.e., the Arduino IDE). This programmed drone can keep attitude own self and can obtain images remotely.

As a future work, we would like to obtain MO images of cracks by a fabricated MO imaging device mounted on a drone.

REFERENCES