Non-destructive Neutron Imaging Analysis for Small Internal Structures of Power Electronic Module

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Abstract

Non-destructive two- and three-dimensional neutron imaging was conducted for evaluation of small internal structure in the power module with double-sided copper heat spreaders under thermal fatigue cycles. Although two-dimensional radiography could not visualize small internal structures, three-dimensional laminography was capable of the visualization. As an application, the commercially available power module was measured by neutron laminography before and after thermal fatigue. It was non-destructively found that the power module was free of degradation at least in the size of 100 µm for 1,000 cycles under this fatigue condition.

Keywords: Neutron Imaging, Computed Tomography, Computed Laminography, Power Electronic Module, Thermal Fatigue

1. Introduction

Electrifying and improving efficiency of automobiles has been strongly demanded for sustainable development by zero CO₂ emissions. Evaluation and improving reliability of the automobiles’ components are necessary for promoting such eco-friendly vehicles. Power control unit (PCU) is one of the important components for such electrified vehicles, which plays a role of converting DC from batteries and/or fuel cells to high-voltage AC for motors and vice versa. Since the reliability of the power electronic module, stressed under thermal fatigue cycles, should be paid attention as well as the energy efficiency and the safety, long-term intermittent non-destructive observation during service is desirable. Another reason why non-destructive evaluation is necessary is that destructive observation such as serial sectioning leads to crack initiation due to changes in stress distribution or crack closure due to solder flowing. For this purpose, two types of non-destructive observation and diagnosis are considered: on-board evaluation and off-board one. Although the former one is conducted by embedded sensors, it will be difficult to obtain whole degradation information. In the present work, authors focused on the latter one by small internal structural observation based on three-dimensional neutron imaging technique.

The typical power module consists of Si power semiconductors, heat sink plates, their jointing lead-free solder, and the surrounding mold resin. There are two types of typical power modules commercially installed in the PCU: single-sided cooling structure and double-sided one.[1] Since the former one has ‘open’ structure, the power semiconductors are optically visible, and its delamination or cracking are easily detected from outside. On the other hand, in the case of the latter structure, the semiconductors are fully sandwiched with the heat sink plates. High resolution imaging methods are desirable for the visualization of such complex structure. Although the authors have demonstrated the synchrotron x-ray imaging at BL33XU of SPring-8 (Toyota beamline),[2–7] it has been almost impossible to visualize its small internal structure due to
x-ray shielding by double-sided copper heat sink plates. On the other hand, since thermal neutron penetrates the copper better than x-ray, the authors assumed that the neutron imaging could visualize the small internal structure of the module. Furthermore, authors assumed that laminography setup would be more suitable for the measurement of the flat plate-like module with layered structure, although the interplanar resolution should be improved.\[8\] In the conventional computed tomography setup, neutron beam can hardly penetrate through the low transmittance resin layer, resulting in low image quality. On the other hand, in the laminography setup, higher quality transmission images are expected because the images can be taken without penetration through the resin layer. However, it hasn’t been demonstrated whether this neutron laminography would provide sufficient resolution for the internal structure measurement of the power module.

Therefore, possibility of highly-resolved neutron imaging for the double-sided cooling type power module was studied in this research. First, authors prepared a model sample to verify the visualization capabilities of the power module structure. Two- and three-dimensional neutron imaging techniques were applied to the artificial structures introduced in the sample. Then, as an application of this method, the obtained neutron imaging technique was applied to the commercially available power module before and after thermal fatigue cycles to evaluate its internal fatigue behavior.

2. Experimental
2.1 Samples

Two kinds of samples were prepared as mentioned above. One was a model sample with similar constituent materials to the power module with double-sided cooling structure. Artificial holes and cracks with known dimensions were introduced in the internal layers for the visualization resolution analysis. Figure 1 shows the schematic drawing and the photograph of the overview. The sample consists of a borosilicate glass plate with drilled holes, stainless-steel (SUS304) plate with the holes, Sn-3Ag-0.5Cu as lead-free solder plate with holes, and mechanically cracked borosilicate glass plate sandwiched by cupper plates. The internal layers with the thicknesses of 100 µm have 100 µm-holes or approximately 100 µm-wide cracks as artificial structures to imitate the in-plane degradation morphology inside the modules. The lead-free solder and cupper are widely used in the actual power modules.\[1\] The borosilicate glass and the stainless-steel plates were included as the sample components for reference in the internal structure evaluation because they have larger neutron cross-sections than those of tin or cupper. The whole sample size was ca. 50 mm × 50 mm × 5 mm.

The other sample was a commercially installed power module[1] in the PCU of automobile, as shown in Fig. 2.
This sample was prepared from a PCU used in the market for demonstrating non-destructive three-dimensional evaluation by neutron imaging. The size of the samples was ca. 50 mm \times 58 mm \times 5 mm, except the electrodes. The schematic cross section is also depicted in Fig. 2. The module consists of approximately 100 \mu m-thick Si power semiconductors, aluminum electrodes, their jointing tin-based lead-free solder layers, and ca. 2 mm-thick cupper heat spreaders on the both sides. The periphery of this layered structure is molded by epoxy resin compound. After the initial neutron imaging, the sample was subjected to 1,000 cycles of thermal fatigue under conditions between 233 K and 473 K, which was much more severe than the conventional fatigue. Figure 3 shows part of the temperature history where the sample was kept for 30 minutes at each temperature under air atmosphere. The sample was observed by neutron imaging again after the fatigue test.

### 2.2 Neutron imaging

Authors tried two types of neutron imaging: two-dimensional radiography and three-dimensional laminography. Although the laminography resembles the tomography, the sample rotation axis is not perpendicular to the neutron beam and the method has advantages for the measurement of flat plate-like samples like the power module.

[8] Figure 4 is the typical setup of 30-deg inclined laminography with the actual mounted sample on the middle-size stage of beamline BL22 (RADEN) in Materials and Life Science Experimental Facility of J-PARC.[9] Neutron beam can penetrate through the sample target position where the solder layers are located without penetration through
the low transmittance resin mold compound (black part), leading to obtaining the higher quality transmission images. The sample was mounted by the aluminum plates and bolts, which was almost transparent to the neutron beam. The sample was located at ca. 18 m from the neutron source, and the neutron camera system was placed right behind the sample. On the other hand, the 2-dimensional radiographs were obtained with the similar optical system, in which the sample was placed perpendicular to the neutron beam. We adopted two types of camera system in this study. The one with high resolution was the Hamamatsu Photonics K.K. CMOS camera system (2048 × 2048 pixels², 16-bit of dynamic range) with 100 μm-thick GAGG (composition: Gd₃Al₂Ga₃O₁₂:Ce) scintillator.[10] The optical system in detail was described elsewhere.[9] This system was applied for the radiography of the model sample and the laminography of the power module sample after the fatigue test. The other one with large field of view was the Andor CCD camera system (2048 × 2048 pixels², 16-bit of dynamic range) with 50 μm-thick ⁶LiF/ZnS scintillator,[9] before optical modification.[10] The field of view was 50 mm square. This system was applied for the laminography of the power module sample before the fatigue test. In both systems the distance between the sample and detector was about 40 mm. The L/D value was 420, where D is the width of an aperture and L is the distance from the aperture to the detector.

The beam power of J-PARC was 500 kW to 700 kW, the neutron energy range was adjusted from 2 meV to 40 meV using a disk chopper, and the exposure time was 120 sec corresponding to 3,000 beam pulses. For a single projection, three-time exposures were merged with a median filter for noise reduction. The 720 projections were obtained with 0.5 deg steps for sample rotation of laminography, resulting in a measurement time of more than three days for a observation. The three-dimensional image was reconstructed using the software package published the Japan Synchrotron Radiation Research Institution (JASRI).[11–13] The correspondent radiographs were also measured by the similar condition without sample rotation.

### 3. Results and Discussion

#### 3.1 Model sample

Figure 5 shows the neutron radiographs and laminographs of the model sample. The radiograph of each layer was taken individually with a pair of the sandwiching attachment made of 2 mm cupper plates, and the laminographs were obtained from the 3D reconstructed images with the thickness of 100 μm. In the radiographs, the brighter region corresponds to the higher transmittance, whereas the relationship is opposite in the laminographs. These images correspond to similar location as the sche-

| Radiograph | Cross-section of laminograph | Structure |
|------------|----------------------------|-----------|
| (1). Borosilicate glass with holes | (2). Stainless steel with holes | (3). Lead-free solder with holes |
| (4). Borosilicate glass with cracks |

Fig. 5 Neutron radiographs and the laminographs of the model sample.
matic structure. The dark stripe in radiograph of Fig. 5(4) is considered to be overlapped edges of cracked glass. The morphologies of the cracks and edges in the inserted layers are recognizable in the radiographs of the borosilicate glasses. Because the boron in the glasses has larger neutron cross-section than the elements of the other layers, the existence of the material is considered to yield higher contrast in the image. It should be noted that the neutron radiograph of the lead-free solder layer, which often plays a key role in the reliability of power module,[1–5] could not show the internal voids because of the lack in the contrast. On the other hand, from all the cross-sections of laminographs, clear morphologies of the holes, cracks and edges were recognized. It should be notable that the internal voids in the lead-free solder layer are surely visualized by the neutron laminography. In the 2D radiographs, the signal-to-noise ratio is low probably because the layer and the attachment in the neutron path are integrated, which weakens the contrast. On the other hand in laminographs, only the internal layer of interest can be extracted from the 3D image and visualized, resulting in the improved recognition. It also may be possible that the laminographic artefact emphasize the contrast of material edges. This difference shows the advantage of non-destructive 3D imaging such as laminography. Although the laminography of the right column of Fig. 5 includes an artefact from outside the sample, it was easy to identify whether it was a crack or not by observing it together with the upper and lower layers of interest.

3.2 Thermally fatigued power module sample

Figure 6 and 7 show the reconstructed cross-sections of the power module sample before and after 1,000-cycle thermal fatigue test, respectively. In Fig. 6, we can recognize several internal structures such as rectangle semiconductors in layer (b), ten aluminum electrode wires in (b) – (e) at the bottom of figures, and top and bottom copper heat spreader plates in (a) and (i). In addition, some a-few-100 μm micro-voids in the mold resin are detectable in layer (a), (b), (c), (e), (h) and (i), whereas no obvious voids or crack are found in the lead-free solder layer on the semiconductors. Taken these results into account, the laminography observation after the thermal fatigue test was focused on one of the semiconductor corner regions, where the largest thermal stress concentration would be
expected due to the thermal expansion mismatch. In Fig. 7 at the corner region, any voids or cracks are not found in the whole field of views. Based on the results of the stacked model sample, this imaging technique is expected to be able to capture internal in-plane degradation morphology as small as 100 µm. Therefore, the power module sample can be evaluated to be free of degradation at least in the size of 100 µm for 1,000 cycles under this severe thermal fatigue condition. On the other hand, interfacial cracks or delamination were not evaluated, since it is not possible to clearly distinguish between contact of delaminated surface from the adhesion by the images, which was an issue to be addressed in the future.

4. Conclusion

The authors conducted two-dimensional and three-dimensional neutron imaging for the evaluation of small internal structure in a power module with double-sided copper heat spreaders at the beamline BL22, Materials and Life Science Experimental Facility, J-PARC. Although two-dimensional radiography could not visualize small internal structures, three-dimensional laminography was capable of the visualization of those morphologies. As an application, the commercially available power module was measured by neutron laminography before and after thermal fatigue. It was non-destructively found that the power module was free of in-plane degradation at least in the size of 100 µm for 1,000 cycles under this fatigue condition.

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