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Deformation behavior of woven glass/epoxy composite substrate under thermo-mechanical loading

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ABSTRACT

The deformation behaviors of woven glass/epoxy composite substrate under four thermo-mechanical loading paths, i.e. rectangular and triangular paths in clockwise and anticlockwise directions within a temperature range of 25–250 °C were investigated. Temperature scanning tests were conducted to identify the viscoelastic property of the material. The glass transition temperature of the composite substrate was 138 °C, above which significant reduction of storage modulus was observed. The deformation behavior of the composite substrate was temperature and history dependent, and change of deformation rate resulted from state transition was noticeable. The residual deformation of specimen following the anticlockwise rectangular loading path was the largest in contrast with the lowest in clockwise rectangular path. The residual deformations in two triangular paths were close after each cycle.

1. Introduction

Electronic products are finding more applications in high-tech industries and the consumer markets, and printed circuit boards (PCB) are the most fundamental and critical component in them [1–4]. As a basic component support and circuit insulating material in PCB, woven glass/epoxy composite substrate is widely used in electronic products because of its high specific stiffness, high strength and low density [5–7]. The performance of woven glass/epoxy composite substrate plays an important role in electronic package quality. Electronic components and PCB have to go through a reflow process to get connected during which solder joints melt at elevated temperature and then solidify after cool-down [8,9]. The mismatch of the coefficients of thermal expansion (CTE) among various package materials may cause thermal stress and warpage during the reflow process [10–12], which in turn may cause solder joints to experience fatigue sooner or even fail. The reflow profile generally covers the glass transition region of woven glass/epoxy composite substrates, and during which significant change of strength and stiffness may occur [6,13]. At temperatures near the glass transition, the viscoelastic effect dominates material response [14–17]. The resulting time–temperature dependent composite properties lead to undesirable dimensional changes such as inner layers shrinkage or out-of-plane warpage of PCB after cool-down [18]. This has severe influence on the geometric uniformity and may impair the reliability of PCB assembly.

The individual thermal and mechanical effects on woven glass/epoxy composite have been explored extensively in literatures [19–28]. Ray [19] evaluated the deleterious effect of temperature on shear strength of glass/epoxy composites during hygrothermal aging, and found that higher temperature not only increased the moisture uptake rate but also stimulated the delamination nucleation. Dong and Davies [20] employed finite element analysis and classic lamination theory to model the flexural behavior of S-2 glass fiber reinforced composites, and analyzed the effect of fiber volume fractions, hybrid ratio and span-to-depth ratio with the aid of the model. Reis et al. [21] conducted a series of tensile tests of glass fiber reinforced polyurethane at different strain rates, and proposed a one-dimensional viscoelastic phenomenological damage model to describe the strain rate sensitivity of the material. Baucom et al. [22,23] studied the damage accumulation in two-dimensional and three-dimensional woven glass fiber-reinforced composite panels under transverse drop-weight impact loading conditions. Mahdi et al. [24] and Almeida et al. [25] studied the fabric layout configuration effect on the mechanical property of glass fiber/epoxy composites, and found that fiber orientation had great influence on energy absorption capacity and shear strength of the composites. Sakin and Ay [26] investigated the bending fatigue behavior of eight different glass fiber reinforced composite plates, and statistically analyzed their fatigue life

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data with the two-parameter Weibull distribution. Taheri-Behrooz et al. [27] and Zhang et al. [28] developed fatigue life prediction models based on test results of glass fiber reinforced composite, which provided good results.

Despite the above studies, however, investigations on the response of woven glass/epoxy composite substrate under thermo-mechanical loads are limited. In this paper, four thermo-mechanical loading experiments of woven glass/epoxy composite substrate were designed and conducted. The deformation behaviors were discussed comprehensively. Temperature scanning tests of dynamic mechanical thermal analyses were also conducted to identify the viscous property of the material.

2. Materials and methods

The manufacturing of woven glass/epoxy composite substrate included several stages. The 7628 E-glass plain weave fabric was impregnated with epoxy resin and partially cured to yield a prepreg. Several layers of prepreg were then consolidated under a prescribed temperature and pressure in a hot press for a specified length of time, and woven glass/epoxy composite substrate with multiple layers of glass fabric was made after being cooled down to room temperature. The composite substrate was a large board with a thickness of 1.5 mm, and rectangular shaped specimens with a length of 60 mm and width of 6 mm were cut from the board. The cross-section photograph of woven glass/epoxy composite substrate is shown in Fig. 1. The composite substrate is composed of epoxy resin and 8 layers of plain glass weave fabric, which act mainly for reinforcement.

All tests were conducted on a dynamic mechanical analyzer (DMA-Q800) and a three point bending clamp was used, as shown in Fig. 2. The temperature range of reflow process was adopted [11], i.e. from 25 °C to 250 °C with a changing rate of ±10 °C min^{-1}. Force control mode was used in the tests, and the applied force changed from 0.1 N to 3 N at a rate of 1.5 N min^{-1}. The minimal load of 0.1 N instead of zero was aimed to keep the floating end of the clamp in constant contact with the specimen during tests, which was important to get reliable displacement. Four thermo-mechanical loading paths were applied to the composite substrates, i.e. rectangular loading paths in clockwise (hereafter referred to as CW) and anticlockwise (ACW) directions, and triangular loading paths in anticlockwise (ATRI) and clockwise (CTRI) directions, as shown in Fig. 3(a)–(d) respectively. All loading cases were cycled three times to investigate the possible deformation behavior of the composite substrate in a long run.

The CW rectangular path starts by applying force at 25 °C, while force is applied at 250 °C in ACW path, as shown in Fig. 3(a) and (b). In these tests, thermal load and mechanical load were applied alternatively in each step until the whole cycle was completed. The ATRI path starts by elevating the temperature to 250 °C, and then force and temperature were set to change reversely. Because DMA is single-channel control mode, only one type of load can be applied at a time. Therefore step "B" in ATRI loading path was achieved by dividing it into small discrete periods, and alternating mechanical load and thermal load were imposed in each period. This approach provided a good approximation for the designed loading step. The first two steps in CTRI path were the same as in CW path, but force and temperature were designed to change from peak values to valley values simultaneously in the unloading step, i.e. step "C" in Fig. 3(d), which was achieved by the same way as in the ATRI loading case.

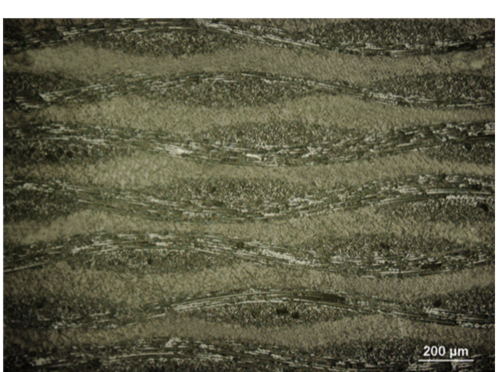

Fig. 1. Photograph of woven glass/epoxy composite substrate (100×).

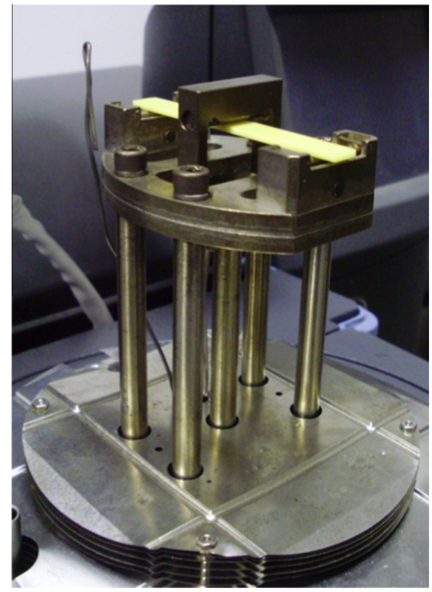

Fig. 2. Three point bending clamp of DMA-Q800 installed with the test specimen.

The temperature scanning tests were conducted in order to investigate the viscoelastic behavior of woven glass/epoxy composite substrate, and to elucidate the relationship between state transition and the deformation behavior in thermo-mechanical loading tests. The same clamp and sample geometry were used, and the sample was oscillated under 1 Hz as temperature increased from 25 °C to 250 °C at a rate of 5 °C min^{-1}.

3. Results and discussion

3.1. Temperature scanning tests

Two temperature scanning tests of dynamic mechanical thermal analyses were conducted to determine the glass transition temperature, and corresponding test results are plotted in Fig. 4 by open and solid symbols respectively. The tested storage moduli of these two specimens vary a little, and the uneven reinforcement of glass fabric may be responsible for the variation. But the glass transition temperature defined as the inflection point of the storage modulus curve (denoted as T_g) are the same and T_g is about 138 °C. The temperature corresponding to the peak of loss modulus is also used by some researchers as the glass transition temperature (denoted as T_{gl}), and T_{gl} is about 155 °C, a few degrees higher than T_g.

Storage modulus characterizes the elasticity of the material and relates to the amount of recoverable energy, while loss modulus characterizes viscosity and relates to the amount of unrecoverable energy lost. The storage modulus of composite substrate decreases but still is relatively high when temperature rises from 25 °C to