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Do You Know That Your Laminates May Contain Hollow Fibers?

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The presence of hollow glass fibers in laminates used in today's printed circuit boards, chip carrier substrates, and plastic ball grid arrays can have a significant impact on reliability.

In the manufacture of laminates used for the electronic industry, glass fibers are used for reinforcement. Laminates are composed of several plies of glass fabrics encapsulated with a polymeric resin. The most common fabric fiber material used today in laminate manufacture is E-glass, a continuous filament glass yarn with a chemical composition by weight of mostly SiO_2, but also containing various amounts of CaO, Al_2O_3 and other materials. Advantages of E-glass lie in its high tensile strength, water resistance, bond stability with resins, and relatively low cost. The dielectric constant (6.3 at 23 ^{o}C and 1 MHz) is high, but acceptable for most low frequency applications.

The manufacture of glass fiber begins with the dry mixing of silicas, limestone, clay, and boric acid in appropriate proportions. In the direct-melt process, the mixture is melted in a refractory furnace at temperatures between 2600 and 2800 ^{o}F and fed directly into bushings, which are platinum alloy plates with nozzles. Alternatively, the melt can be formed into marbles, cooled to room temperature and stored for future use. Additional information about this process is supplied by Loewenstein [1983].

A homogeneous melt composition with negligible impurities is necessary for the successful manufacture of glass fibers. Solid inclusions of even submicron dimensions will act as stress concentrators that reduce the fiber strength. Furthermore, the decomposition of raw materials during glass melting can lead to trapped gases. In the raw materials, water, carbonates (CO_3), and organic materials will decompose with heat to form gases. Depending on the viscosity of the glass mixture and various manufacturing processes, these gases can get trapped as bubbles, called seeds. Seeds are a naturally occurring part of the process and thus methods to remove them are necessary. One approach is *fining*. Fining removes gases by adding gases (i.e., SO_2) which create nucleation sites for bubbles to coalesce and escape the melt. Fining can also be defined as increasing the temperature and modifying the heat flow pattern so bubbles are moved in positions to readily reach the surface to escape. The interested reader is referred to Shand [1958] for more information about the formation and removal of seeds.

If the molten glass contains a sufficient level of impurities, air bubbles may become trapped inside the fibers while being drawn through the bushing. These air bubbles, unless very large, do not cause fiber breakage but end up as capillaries in the glass fibers, otherwise known as hollow fibers. These hollow glass fibers increase the opportunity for failure between close conductors because the capillary provides a convenient path for the formation of conductive filaments.

After drawing, the fibers are cooled by a water spray. A polymeric coating is then applied to protect and lubricate the fiber surfaces during subsequent processing. The fibers are gathered into a bundle of filaments and are wound into yarns on a collet (rotating cylinder). Once wound, yarns are interlaced to form a conventional plain weave fabric. Yarns that run in the machine direction are called warp yarns, while those that run across are named fill yarns. A laminate is created by dipping one or more layers of fabric into a resin mixture and curing the combination in an oven. The number of layers of glass fabric used per laminate depends on the desired dielectric constant, mechanical strength, and cost.

Hollow Fibers

To detect hollow fibers within a typical woven glass fabric, laminates are usually cut along the diagonal into 10 x 10 cm test coupons. This is chosen to facilitate handling, sample preparation, and observation through an optical microscope. Samples are then placed in an oven at 538 ^{o}C (1000 ^{o}F) for approximately one hour to burn off the resin and expose the bare glass bundle matrix (Fig. 1). The number of bundles per inch of fabric can be counted to identify the fiber style and the direction of warp and fill yarns. The edge of each side of the test specimens is then dipped in wax to prevent wicking (capillary action of a fluid into a hollow fiber), and the sample is allowed to sit in a refracting oil overnight. Light is then directed onto the sample, where it travels freely until it hits a hollow fiber (air). The change in refractive index at the fiber/air boundary partially reflects it. The unreflected light continues to propagate until it hits the outgoing air-fiber boundary, where again it is partially reflected (Fig. 2). Although hollow fibers are visible with the naked eye, a microscope with a camera attachment is best to identify them (Fig. 3).

Hollow fibers usually span the entire length of a laminate, and may in fact "weave" back and forth. If the edges of the sample are not dipped in wax, the oil will flow into and along the hollow fiber. Figures 4a and 4b show the distance oil travels in 20 minutes. The speed of water may be higher.

Findings

The CALCE Consortium examined various laminates from different suppliers. The number of hollow fibers in each 10 x 10 cm coupon, ranged from 0 to approximately 115, although the average number in a coupon was about 2 hollow fibers. Fabric (and glass) from Owens-Corning, a dominant glass supplier in the United States, exhibited the most number of hollow fibers. In fact, one laminate from them had more than 100 hollow fibers.

We learned that IBM has manufactured "hollow-free fabric laminates" in order to combat the conductive filament formation problem since 1980. While IBM does not make the fibers, they have developed a process by which their fabric supplier, Clark-Schwebel, screens for very low hollow fiber content [IBM 1996]. However, IBM states that even their hollow-free fabric is not truly hollow-free. In our tests, we did note that IBM fabric was better than most of the other fabrics tested, but was clearly not hollow-free.

The most apparent solution for the elimination of hollow fibers is to improve manufacturing processes and controls. Clearly, some glass fiber manufacturers have accomplished this, probably by making sure that impurities or gas bubbles are not introduced into the molten glass so that capillaries cannot get trapped in a fiber. Another method would be to screen the fibers using the measurement technique described in this paper. But since a typical manufacturer produces millions of E-glass fibers per day, screening may be an impractical, time-consuming, and costly technique.

Laminates composed of hollow fibers pose a threat to the reliability of electronic systems in that they provide a convenient open path for conductive filament formation (CFF). CFF involves the transport of metallic ions from one conducting element in a printed circuit board to another. If a hollow fiber connects two conductors, moisture being the transport medium will allow metallic copper ions to migrate from one conductor to the next, eventually forming a continuous bridge, and hence a leakage path or a short. This poses a special problem for fine-line printed circuit boards, laminated multichip modules, and plastic ball grid arrays used in high-reliability applications where even a short hollow fiber can connect two conductive elements.

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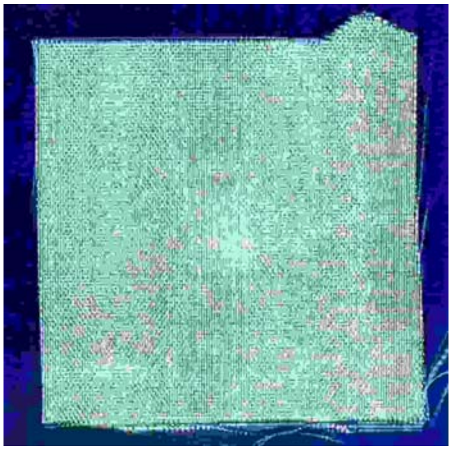

Figure 1. Remaining fiber glass bundles after resin has been burnt off at 538^{o}C (1000^{o}F). This process takes approximately 1 hour.

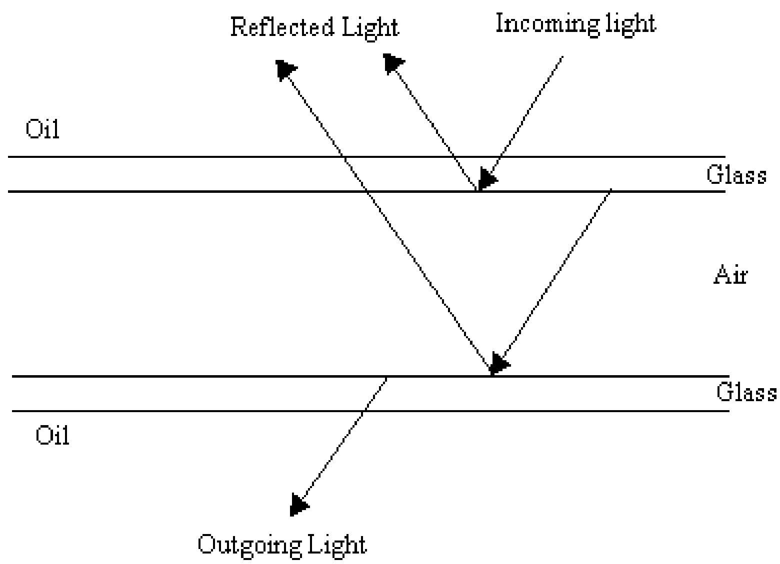

Figure 2. Light travels freely until it hits a hollow fiber (air). The change in refractive index at the fiber/air boundary partially reflects it.

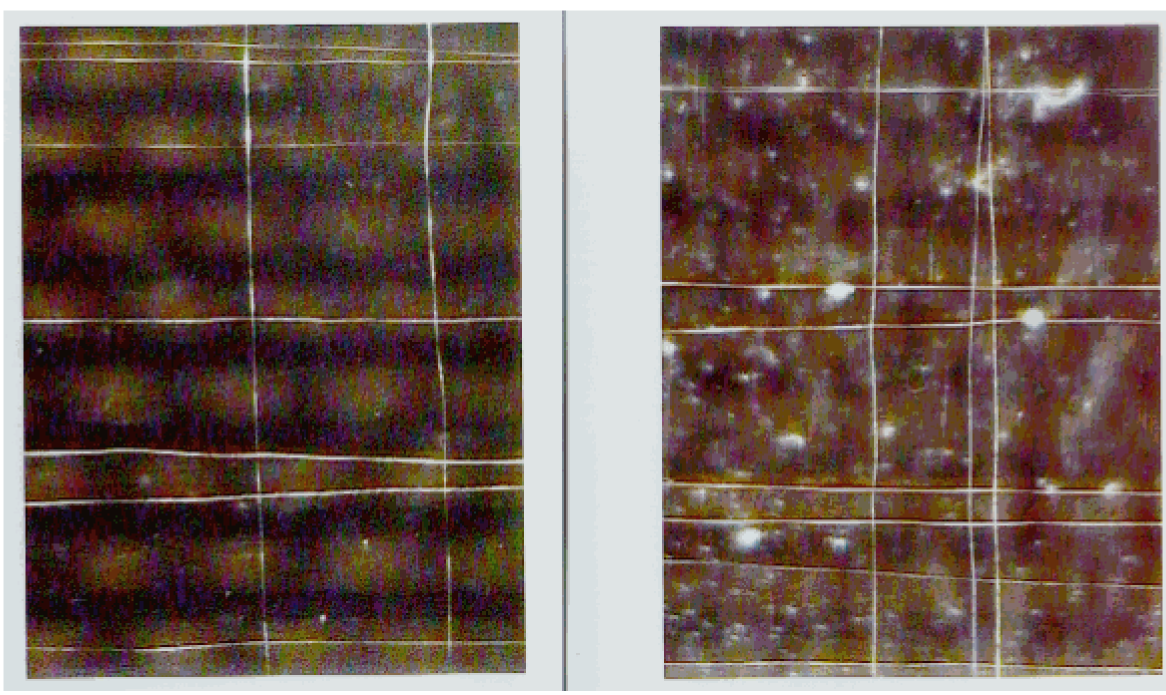

Figure 3. Hollow fibers can be seen as bright white lines traversing the vertical and horizontal directions. They usually span the entire length of the laminate and may also weave back and forth. Therefore, some of the hollow fibers that run in the same direction may infact be connected and due to the same trapped air bubble.

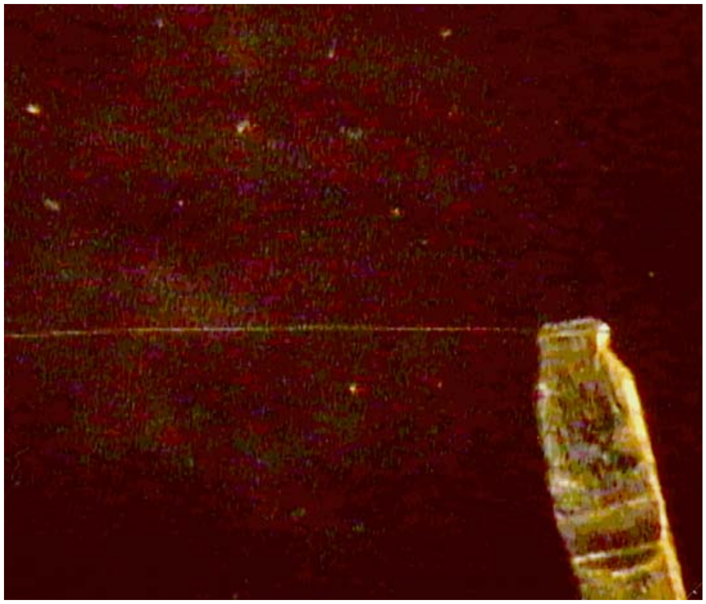

Figure 4a

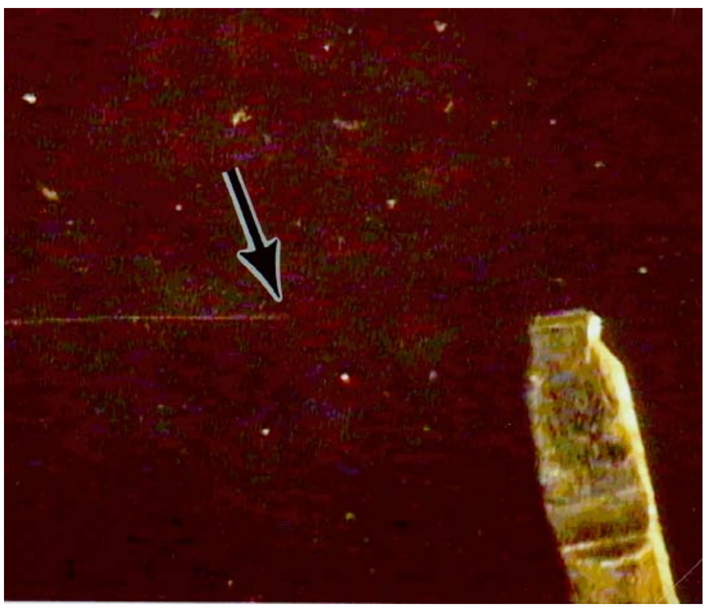

Figure 4b

Figures 4a (before) and **4b** (after) show the distance of movement for oil traveling through a hollow fiber due to capillary action. Elapsed time is approximately 20 minutes.