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Hollow Fibers Can Accelerate Conductive Filament Formation

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Abstract

Increases in failures due to internal board shorting by conductive filament formation have driven glass and laminate manufacturers to consider screens and qualification tests to assess the hollow fiber concentration of circuit cards. This article describes the hollow fiber problem, methods to deter conductive filament formation, a hollow fiber screening technique, and the impact of next generation technology on conductive filament failure mechanism.

Background: Conductive Filament Formation

Conductive filament formation (CFF), also referred to as metallic electromigration, is an electrochemical process (see Figure 1). This process requires, as do all other migration phenomena, the transport of a metal through or across a nonmetallic medium, under the influence of an applied electric field. Conductive filament formation can be defined as a process by which a metal, in contact with insulating materials and under an electric potential, is removed ionically from its initial location and is redeposited at some other location.

Multi-layer organic laminates which make up over 90% of the present types of interconnecting substrates in today's electronics (standard FR-4 represents 85% of the resin systems), can develop a loss of insulation resistance between two biased conductors due to the CFF phenomenon [1 – 6, 8 - 10]. The probability of CFF is a function of temperature, moisture content, the voltage bias and other environmental conditions and physical factors.

The filament formation appears to arise in two steps: a degradation of the resin/glass bond followed by an electrochemical reaction. Bond degradation provides a path along which electro-deposition may occur due to electrochemical reaction. The path may result from poor glass treatment, from the hydrolysis of the silane glass finish and from mechanical stresses. Once a path is formed, an aqueous medium can develop through the adsorption, absorption, and capillary action of water at the resin/fiber interface. The presence of hollow fibers makes the CFF a one step process, effectively removing the first step – the need for path formation. The path in the PWB may be viewed as an electrochemical cell in which the metal conductors are the electrodes and the driving potential for the electrochemistry is the potential of the circuit.

The occurrence of conductive filament formation deep within the PWB can easily be misdiagnosed as "Failure Unknown". The Failure Analysis Laboratory at CALCE has examined numerous electronic assembly failures due to PWB shorts, permanent and intermittent. Many of these failures, sent back after customer complaints, could only be duplicated in relatively high humidity environment since moisture was required to complete the electrical path. CFF is difficult to detect in the field because once it occurs, sufficient heat is generated to "vaporize" the conductive filament and "clear" the failure. Furthermore, observation of a partial filament formation requires destructive analysis.

Hollow Fibers Assessments

Laminate manufacturing in the electronics industry consists of four fundamental steps: conversion of raw materials into molten glass, fiber drawing, fabric weaving, and resin coating. The raw materials of E-glass are batched together in a furnace and melted at temperature in excess of 2500 F. After the molten mixture is deemed homogeneous, it is allowed to flow into a forehearth where it drops through bushing nozzles. While in the nozzle, each drop converts into a glass fiber that is pulled in tension and simultaneously cooled. 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 [13].

To detect hollow fibers within a typical finished laminate with woven glass fabric, laminates are cut along the diagonal into 10 cm x 10 cm (4 in x 4 in) test coupons. Since hollow fibers usually traverse the entire length of the laminate, samples cut along the diagonal ensure that each hollow fiber is accounted for only once. The 10 cm x 10 cm size is chosen to facilitate handling, sample preparation, and observation through an optical microscope. Samples are then placed in an oven at 538 oC (1000 oF) for approximately one hour to burn off the resin and expose the bare glass bundle matrix. The number of bundles per inch of fabric can be counted to identify the fiber style and the direction of warp (machine direction) and fill (weft, woof) 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 (see Figure 2). The unreflected light continues to propagate until it hits the outgoing air-fiber boundary, where again it is partially reflected. Although hollow fibers are visible with the naked eye, a microscope with a camera attachment is best to identify them (see Figure 3). Examples of hollow fibers can be seen in Figures 4 and 5.

The number of hollow fibers found in 10 cm x 10 cm woven glass fabric layers examined by the Failure Analysis Laboratory at CALCE ranges from 0 to over 300. Thus in some of the laminates, there is a good opportunitie for CFF to occur considering that multilayered laminates may have up to 15 fabric layers. A CFF failure due to a hollow fiber between two plated through holes (PTHs) can be seen in Figure 6.

Methods to Deter Conductive Filament Formation

Prevention of CFF begins at the raw material supplier and continues through the supply chain and manufacturing processes. Screening procedures implemented by the original equipment manufacturer (OEMs) can only guarantee that they are receiving hollow fiber content ratios as low as specified by the supplier; hollow fiber content can not be reduced at this stage; lots with unacceptable hollow fiber content can only be discarded. Corrective action steps include optimization of the glass surface finish, reduction of ionic contaminants in resin, optimization of the copper surface preparation process, and design and layout optimization.

Based on CALCE EPSC’s recommendations, hollow fiber assessment has now become a standard screen (a process by which hollow fiber concentrations may be determined), allowing board fabricators and contract assemblers to qualify suppliers and discard lots with hollow fiber concentrations above specifications. The CALCE specification being used by laminate manufacturers for this screen is, no more than 1 hollow fiber per 10 cm x 10 cm. This guideline specification reduces the CFF opportunity to less that 1% based on calculations done by Pecht et. al. [1]. As a result of CALCE EPSC’s efforts, Nanya Plastics, one of the world's largest glass fiber manufacturers, revised their glass production process and experienced a sharp drop in hollow fiber concentration. In addition, we have learned that Sanmina also asks their laminate suppliers to include hollow fiber assessments in their raw material specifications. The specification that Sanmina uses is the same as the CALCE specification of no more than 1 hollow fiber per 10 cm x 10 cm.

It was 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. However, IBM states that even their hollow-free fabric is not truly hollow-free. In tests, the authors noted that IBM fabric was better than most of the other fabric tested, but was clearly not hollow-free.

It is the authors’ belief that the IBM specification guideline for their hollow free fabric is no more than 4 hollow fibers/1000 square inches (31.6 in x 31.6 in or 80.3 cm x 80.3 cm). Compared to the CALCE specification guideline of no more than 1 hollow fiber/10 cm x 10 cm, it can be seen that IBM is twice as stringent as CALCE in their specification; for the same area of 10 cm x 10 cm, IBM would allow 0 hollow fibers, compared to 1 allowed by CALCE.

Summary

Laminates composed of hollow fibers pose a threat to the reliability of electronic systems in that they provide a convenient open path for CFF. 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, by making sure that impurities or gas bubbles (seeds) are not introduced into the molten glass so that capillaries cannot get trapped.

References

1. M. Pecht, C. Hillman, K. Rogers and D. Jennings, Conductive Filament Formation: A Potential Reliability Issue in Laminated Printed Circuit Cards with Hollow Fibers, IEEE/CPMT, Vol. 22. No. 1, pp. 80-84, January 1999.

2. K. Rogers, C. Hillman, M. Pecht and S. Nachbor, Conductive Filament Formation Failure in a Printed Circuit Board, Circuit World, Vol. 25 (3), pp. 6-8, 1999.

3. K. Rogers, P. V. D. Driessche, C. Hillman and M. Pecht, Do You Know That Your Laminates May Contain Hollow Fibers? Printed Circuit Fabrication, Vol. 22. No. 4, pp. 34-38, April 1999.

4. Anand A. Shukla, Terrance J. Dishongh, Michael Pecht, and David Jennings, Hollow Fibers in Woven Laminates, Printed Circuit Fabrication, Vol. 20, No. 1 pp. 30-32, January 1997.

5. A. Shukla, M. Pecht, J. Jordan, K. Rogers and D. Jennings, Hollow Fibres in PCB, MCM-L and PBGA Laminates May Induce Reliability Degradation, Circuit World, Vol.23 No.2, pp. 5-6, 1997.

6. Balu S. Rudra and Michael Pecht, Assessing Time-to-Failure Due Conductive Filament Formation in Multi-Layer Laminates, IEEE Transactions on Components, Packaging and Manufacturing Techniques, Part B, Vol. 17, No. 3, pp. 269-276, August 1994.

7. Keith Rogers, Andre Fowler and Michael Pecht, Characterization of a Non-Woven Randomly Dispersed Short Fiber Laminate, Circuit World, 24/3, pp. 34-37, 1998.

8. M. Li, M. Pecht and L. Wang, The Physics of Conductive Filament Formation in MCM-L Substrates, Proceedings of the INTERpack'95, Lahaina, Maui, HI, pp. 517-527, March 26-30, 1995.

9. B. Rudra and D. Jennings, Tutorial: Failure-Mechanism Models for Conductive-Filament Formation, IEEE Transactions on Reliability, Vol. 43, No. 3, pp. 354-360, September, 1994.

10. M. Pecht, B. Wu and D. Jennings, Conductive Filament Formation in Printed Wiring Boards, 13th IEEE Intern. Electronics Manuf. Techn. Symp., pp. 74-79, 1992.

11. Simeon J. Krumbein, Metallic Electromigration Phenomena, IEEE Trans. Components, Hybrids. Manufacturing. Technology, vol. CHMT-11, pp. 5 - 15, March 1988.

12. Welsher, T.L., Mitchell, J.P. and Lando, D.J., CAF in Composite Printed-Circuit Substrates: Characterization, Modeling and A Resistant Material, Intemational Reliability Physics Symposium, 1980, p.235

13. K.L. Loewenstein, The Manufacturing Technology of Continuous Glass Fibres, 2nd Edition, Vol. 6, Amsterdam, Elsevier Science Publishers, 1983.

14. J. P. Mitchell and T. L. Weisher, Conductive Anodic Filament Growth in Printed Circuit Materials, Proceedings of the Printed Circuit World Convention II, pp. 80, 1981.

15. D. J. Lando, J. P. Mitchell and T. L. Weisher, Conductive Anodic Filaments in Reinforced Polymeric Dielectrics: Formation and Prevention, International Reliability Physics Symposium, pp. 51, 1979.

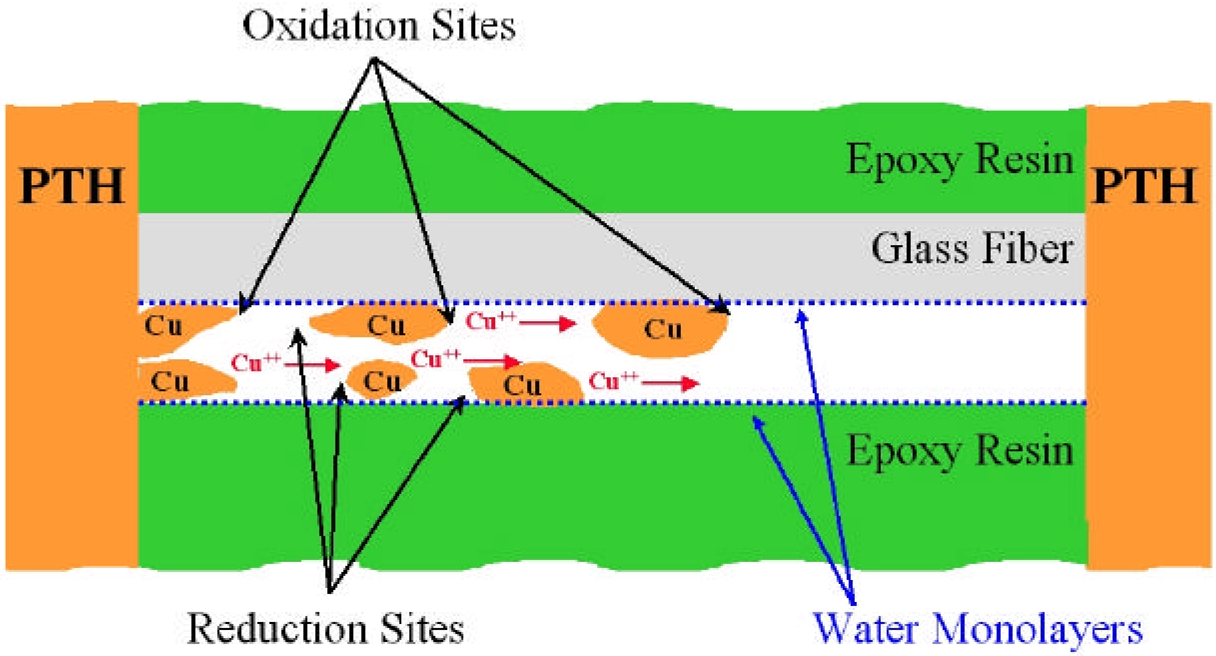

Figure 1. The most common corrosion path for CFF is between a glass fiber and the epoxy resin. Once this delamination occurs, next step is the introduction of the electrolyte – water. When the moisture level increases, an oxidation reaction will occur, forming copper ions, which under bias will migrate towards the negatively biased conductor.

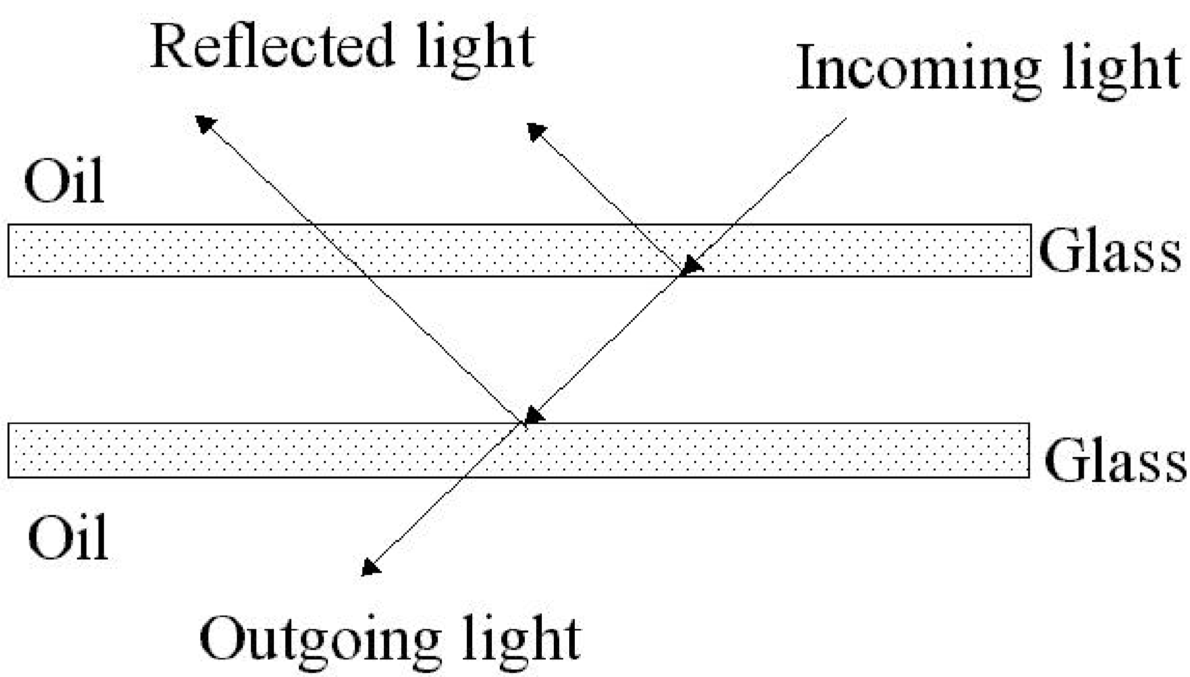

Figure 2. Light is then directed onto the sample, where it travels freely until it hits a hollow fiber (air). The change in refractive index at the fiber/air boundary partially reflects it. The unreflected light continues to propagate until it hits the outgoing air-fiber boundary, where again it is partially reflected.

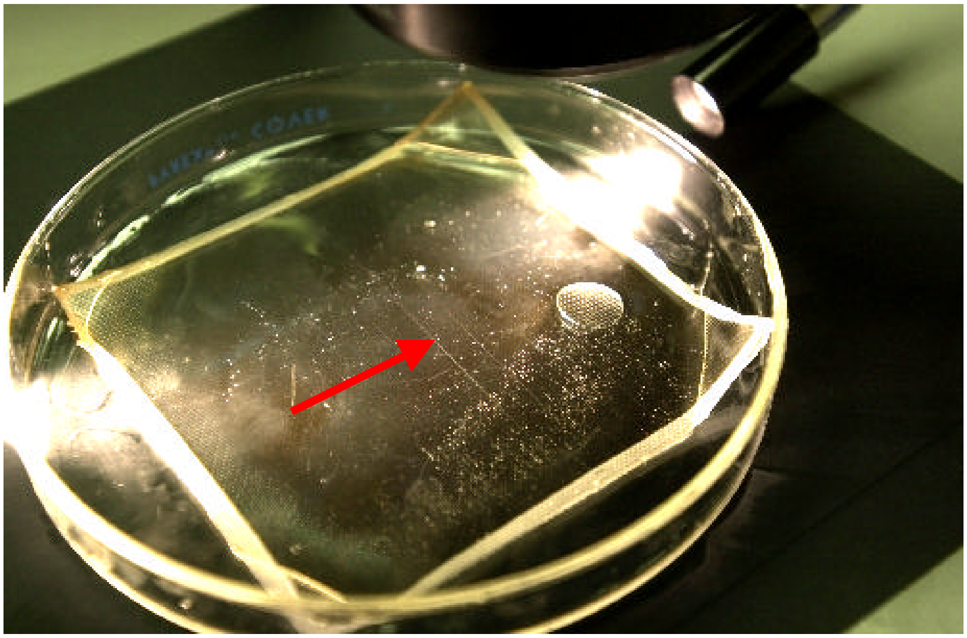

Figure 3. A change in the refractive properties is evident through an optical microscope by a bright white line. In this case, a hollow can be detected with the unaided eye (see red arrow). They usually span the entire length of the laminate and may also weave back and forth.

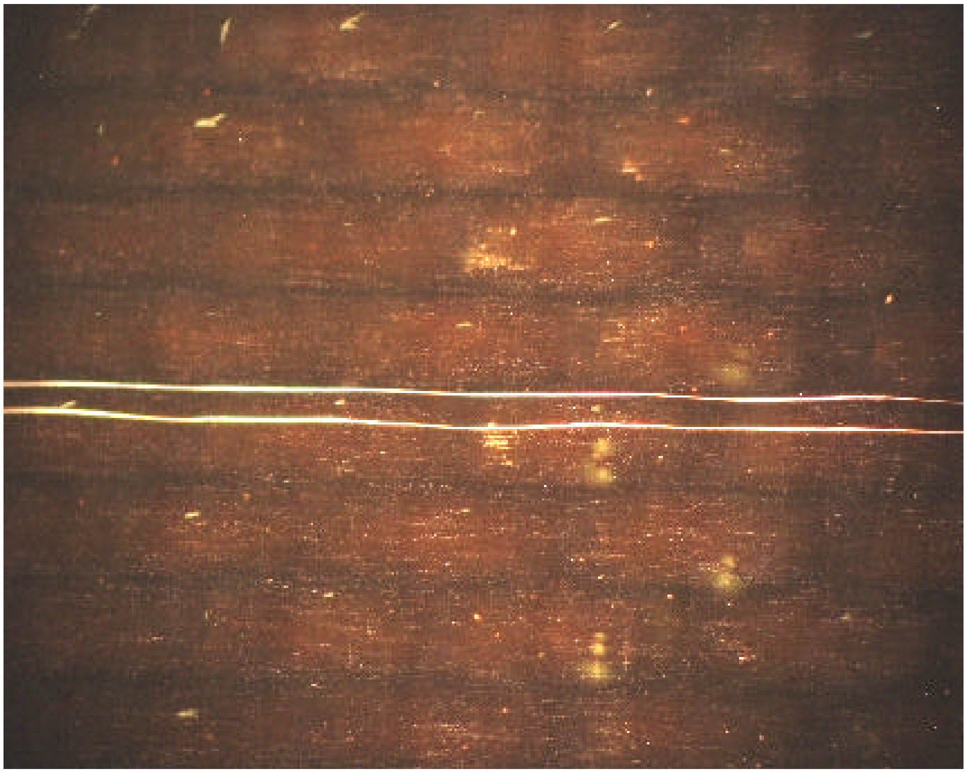

Figure 4. Two hollow fibers can be seen as bright white lines traversing the horizontal direction. They usually span the entire length of the laminate and may also weave back and forth. Therefore, some of the hollow fibers that run in the same direction may in fact be connected and due to the same trapped air bubble. Magnification = 50X

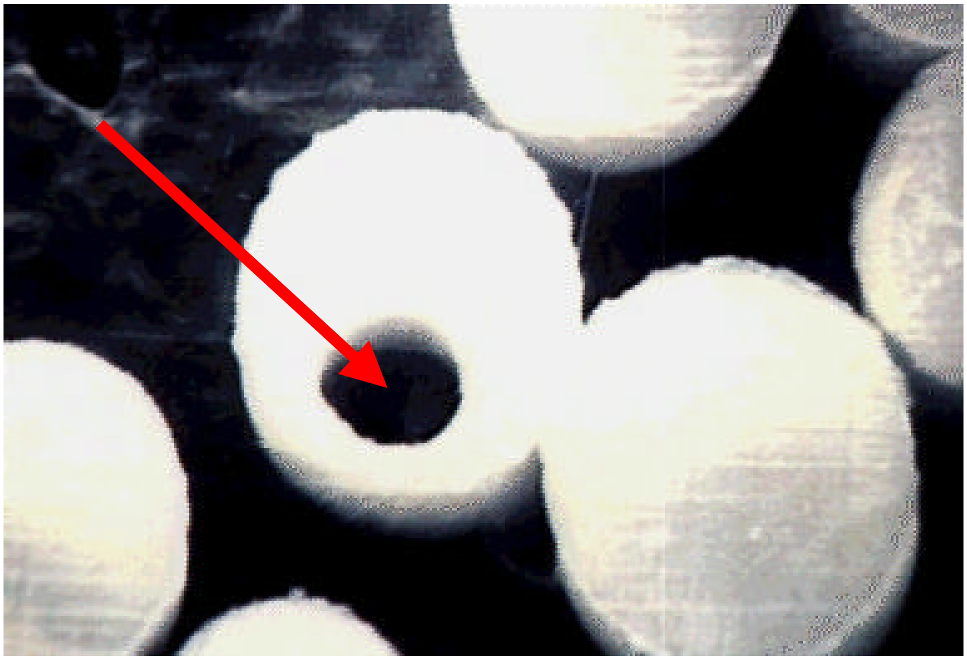

Figure 5. A cross-section of a hollow fiber can be seen in the middle fiber in this photo. Magnification = 6000X

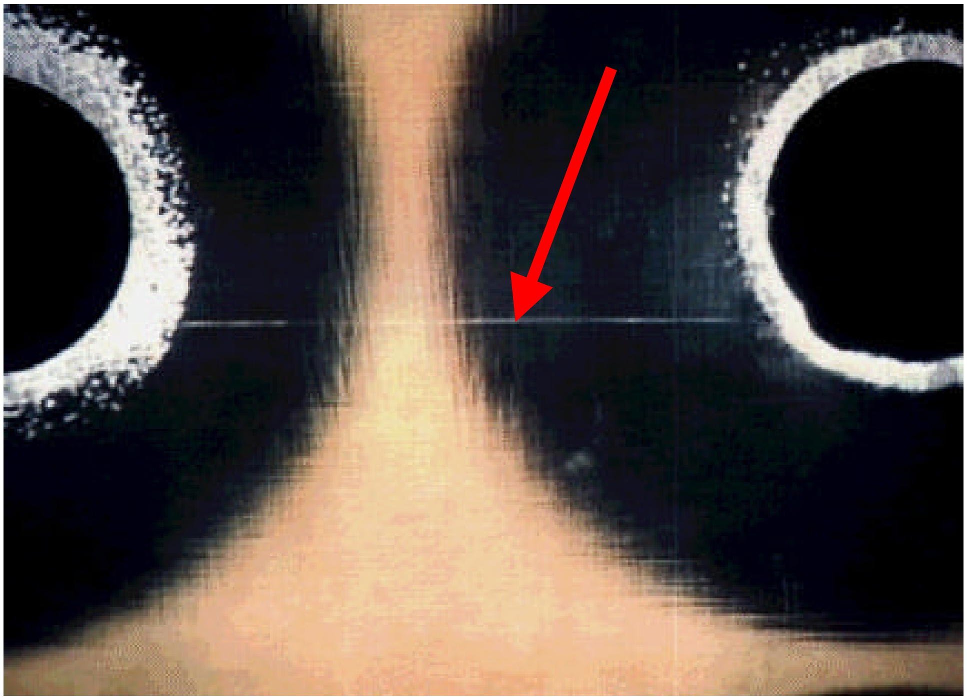

Figure 6. This hollow fiber, seen as a bright white line traversing the horizontal direction (see arrow), was responsible for failure of this PWB assembly by causing a short between the two conductors it electrically connected. Magnification = 125X