High Performance Epoxy Curing System for Fiber Optic Terminations

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A recent Navy ManTech funded development program entitled Fiber Optic Interconnect Technology (FOIT) is aimed at advancing manufacturing technology associated with high reliability/ performance fiber optic assemblies. This technology consists of the development of an automated work cell made up of 5 discrete stations which perform the major processes with fiber cable manufacture; Cable Preparation, Terminus Assembly, Epoxy Cure, End Face Polish, and Test/ Inspection. Benefits realized with automated manufacturing are reduced touch labor with improved performance and consistency of the end product. As part of this development process, the Epoxy Cure Station has been developed to precisely control the thermal curing process of epoxy used in the termination of fiber optics. This paper describes the potential performance benefits for this newly developed curing system.

The most widespread technique for curing epoxy in the manufacture of fiber optic cables is the use of a thermal block oven. An example of a typical block oven is shown in Figure 1. The block is typically manufactured from aluminum and has embedded heating elements. Different control schemes are used, some with a simple on-off type controller and some microprocessor controlled to accommodate elaborate multi-step thermal profiles. The use of these devices entails manually placing an assembled, but uncured, termination into the hole and activating the controller. Excess fiber cable is coiled on a rack that resides above the block.

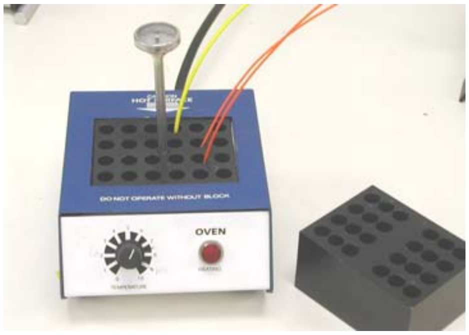

Figure 1: Conventional heating block oven

There are many types of epoxies used in the termination process. In curing the epoxy, the objective is to achieve a glass transition temperature, T_g, that is higher than the most extreme operating temperature that the termination will experience to ensure the utmost mechanical integrity. The importance of achieving the proper T_g further grows with fiber assemblies used in high reliability aerospace applications with demanding operating temperature extremes. Typical epoxies used in these applications will exhibit varying T_g's depending on the cure schedule conditions. Thus, it is important that the epoxy within the termination experiences the expected temperatures required for the curing process to be effective.

In the curing process, there are other factors that drive the actual cure schedule as well. It is not as simple as heating the termination to a fixed temperature for a predetermined time. In many cases, controlled ramp rates and "stepping" of the temperature to different plateaus is required in order to minimize stress build-up in the epoxy interface between the fiber and the terminus ferrule. If the epoxy is cured very fast, the residual stress can fracture the fiber rendering the termination useless. In other circumstances the fiber may not necessarily fracture, but instead the stress is relieved as the fiber cable is used in its applications where it undergoes temperature cycling. The stress relieving anomaly can cause the fiber to "piston" within the ferrule which results in high loss. This failure mode is not as severe in applications where the fiber assembly is operating in a constant environment, such as an office environment. It is more likely to occur is situations where the fiber assembly is thermally stressed, such as in an aircraft or exposed to harsh environments where cyclic temperatures are experienced.

Another scenario exists where fiber pistoning can result from a curing process that is not precisely controlled during manufacture. In this case, the T_g is never achieved and the epoxy can transition to its "rubbery" state when exposed to higher operating temperatures. This situation is highly likely with the use of block ovens unless extreme care is taken to calibrate and fixture the terminus in process.

For example, testing was performed on 6 different cavities on a block oven with data represented in Figure 2. The test was conducted where a small thermocouple was placed inside a M29504/4 terminus with epoxy and the terminus was run through the same curing schedule as those in production. The thermocouple inside the terminus was placed such that it was reading the temperature the epoxy would experience during the curing process. As shown in the data, the difference between the desired temperature and the actual indicates the programmed temperature has not been adjusted for any offset between the control point of the block and what is truly experienced by the epoxy inside of the ferrule. Secondly, and more important, the variation across the 6 block cavities is as much as 20° C. The epoxy is not being cured as expected in this case and can lead to a lower than expected T_g resulting in fiber pistoning issues in use.

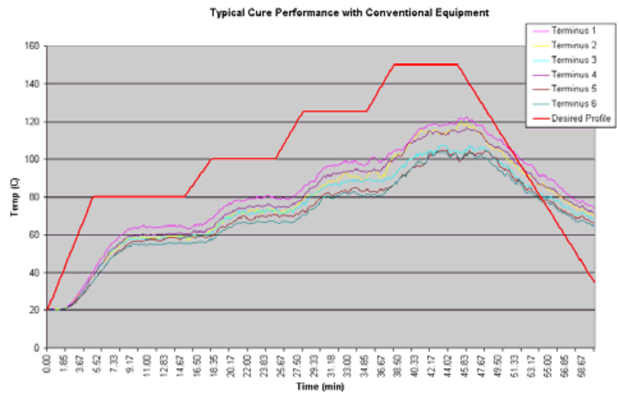

Figure 2: Example Block Oven Performance and Variation

The variation of temperature between cavities can be explained in one circumstance by the position of the terminus within the cavity. The terminus is placed in the block manually in these ovens. As such, the position can vary greatly, some deeper in the cavity, some skewed to one side of the cavity closer to the wall, and some even contacting the cavity wall. In all of these cases the thermal transfer is different causing variations in the actual temperature that the epoxy experiences. These variations can cause differences in T_g as noted in the chart in Figure 3.

EPO-TEK 353ND Tg versus Cure Cycle

Cure condition	Residual Exotherm (J/g)	Peak exothermic Temperature (C)	% NOT cured (% unreacted)	Calculated Tg (C)
80 C / 30 minutes	328.5	134.6	65	87
80 C / 1 hr	253	137.4	50.7	87
80 C / 2 hr	212.3	138.8	42.5	87
100 C / 30 minutes	83.1	155.2	16.6	103
100 C / 1 hr	86.14	155.5	17.3	103
100 C / 2 hr	51.94	155.1	10.4	103
120 C / 30 minutes	20.16	158.2	4	110
120 C / 1 hr	8.67	159	1.7	110
120 C / 2 hr	0.8	155.6	0.2	110
150 C / 30 minutes	N/A	N/A	N/A	120
150 C / 1 hr	N/A	N/A	N/A	119.4
150 C / 2 hr	N/A	N/A	N/A	116.4
80 C / 1 hr + 120 C / 1 hr	19.9	158.4	4	110
80 C / 1 hr + 150 C / 1 hr	N/A	N/A	N/A	129.4
80 C / 1 hr + 120 C / 1 hr + 150 C / 1 hr	N/A	N/A	N/A	128.8
150 C / 15 second hot plate cure	N/A	N/A	N/A	137.3

Figure 3: EpoTek's information for cure schedule vs. T_g.

There is a new method of thermal curing specific for mil/aero applications where high reliability and quality is of utmost importance. A picture of the manufacturing system is shown in Figure 4. This system utilizes a forced convection means of heating the terminus in process and employs a sophisticated computer control system that calibrates offsets for different cure profiles and termination types. This method ensures that the epoxy within the termination is experiencing the desired temperature for curing within 2° C. In addition, the system utilizes precision fixturing of the terminus with respect to a forced-convection heating nozzle, so that consistency from run to run and nozzle to nozzle is maintained (Figure 4 inset). All of these improvements in the process alleviate the variability associated with the use of block ovens and provide a highly consistent cable assembly product. Figure 5 shows typical temperature traces for 2 cable assembly ends that were processed on the system. The differences between the two are barely noticeable.

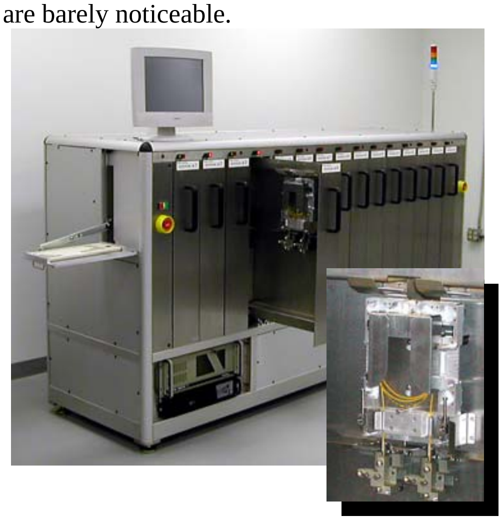

Figure 4: High performance curing system (Inset: Aerospace cable assembly in precision mechanical fixture)

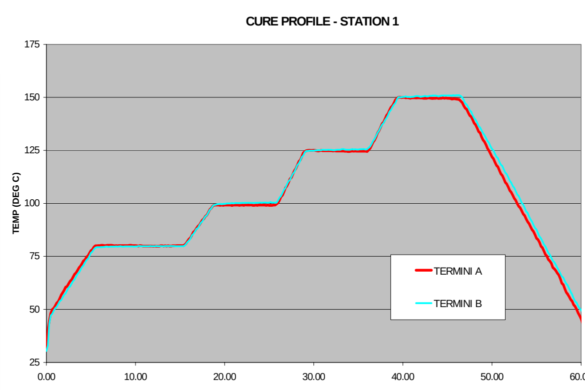

Figure 5: Typical temperature response for 29504/4 termini cured within system (both cable ends shown).

The results shown for this system demonstrate the capability to precisely control temperature profiles for curing fiber optic termini with high repeatability to ensure maximum T_g and mechanical integrity. This is especially important for cables exposed to harsh temperature extremes, such as those used in military and aerospace systems.