

AUTOMATION: The Means to High Reliability Aerospace Fiber Optic Cables

Anthony J. Christopher
Vice President, Engineering
kSARIA Corporation
439 South Union Street
Lawrence, Massachusetts 01843
Email: tchristopher@ksaria.com

John Mazurowski and David Ditto, Penn State University ElectroOptics Ctr.
David Enlow and Jeff Sroga, Lockheed Martin Space Systems Newtown Pa
Michael Hackert, US Naval Air Systems, Patuxent River, MD

Abstract

Photonics, with its virtually infinite bandwidth, electrical noise immunity, small size, low cost, and increased capacity are being inserted into a number of military platforms to handle higher data rates and larger traffic volumes. Such increased data rates between the various subsystems drive the interconnect solution to be fiber optics. These military fiber optic cables are meant for severe environments, with shock, vibration, and wide temperature ranges not typically required for commercial applications. The Fiber Optic Interconnect Technology (FOIT) program began in 2001 as a Navy ManTech effort at fiber optic cable assembly automation to improve cable performance, reliability and reduce life cycle cost for fiber optic insertion into military applications. Process steps for military and commercial cable assembly manufacturing were systematically identified, partitioned, and optimized within an automated process flow. Five process islands were designed and fabricated at kSARIA using systems engineering assistance from Lockheed-Martin. Cable assemblies are presently being produced by this automated system. Independent qualification tests to verify the performance and reliability of the FOIT produced cables within a range of operational environmental conditions are currently ongoing. Results of the system production capabilities and qualification tests will be presented.

Keywords: Fiber Optics, Automated Manufacture, High Reliability Fiber Optic Interconnects

Fiber Optic Termination Overview

The termination of optical fiber requires many discrete steps, well over 30 in many cases. All of these process steps are very critical in governing the performance and reliability of the final fiber optic assembly. Throughout much of the mil/ aero industry where reliability is so crucial, the termination process is performed with a manually intensive process. As with any manual processes, the accuracy, consistency, and overall quality are dictated by the skill level of the operator performing the functions. Because an operator is involved in carrying out the detailed process steps, the manual process is left prone to human error and is limited as to what can be achieved manually.

The FOIT development program was successful at automating this complex process and removing operator limitations to produce a highly consistent and reliable termination. The results of the program produced a work cell consisting of 5 major workstations, each of which performing a series of the many process steps. A flow chart of the work cell is shown in Figure 1.

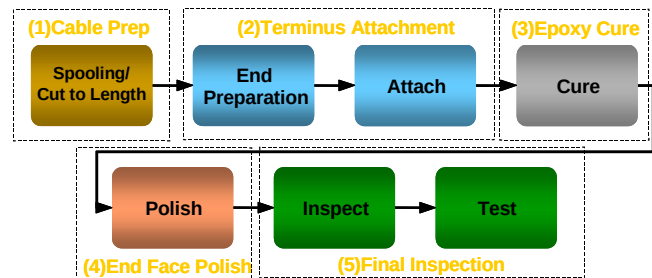


Figure 1: Flow Chart of Automated Work Cell

The system was designed to address all of the critical attributes associated with high reliability and consistency. The work cell has processed well over 100,000 terminations since inception. The major work cell elements and critical termination reliability attributes that are addressed are described herein.

Terminus Attachment Workstation

The terminus attachment workstation is shown in Figure 2. Fiber optic cable to be terminated is transferred through the workstation on a work pallet (Figure 3) where the fiber ends are presented to a series of process tools. The tools are programmed to automatically prepare the end of fiber cable to accept a terminus. This involved removing the various layers of protective coatings to specific lengths defined by the terminus to be installed. Generically, the progression of steps performed to the fiber end is depicted in Figure 4.



Figure 2: Terminus Attachment Workstation

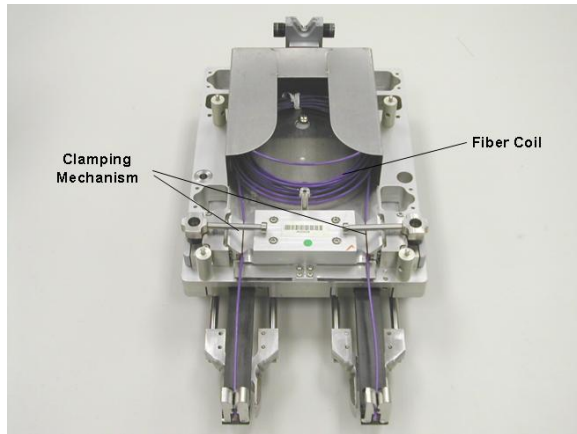


Figure 3: Work Pallet

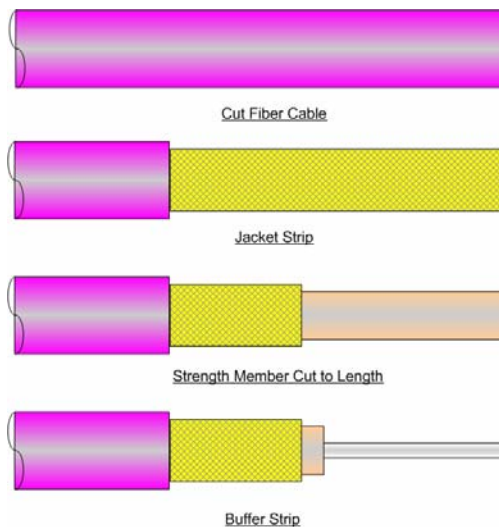


Figure 4: Fiber End Preparation Steps

Once the fiber cable end has been prepared, a terminus is installed. The terminus is fed automatically from a magazine, loaded with a precise amount of epoxy, and then robotically aligned and slid over the bare glass fiber to a predetermined depth. After the terminus is over the fiber, the strength member is automatically attached to the terminus body with a crimp sleeve. All the individual parts of the cable assembly are held fixed within the work pallet as it moves on to the next major workstation – Epoxy Cure.

Epoxy Cure Workstation

The Epoxy Cure Workstation has been developed to precisely control the thermal curing process of epoxy used in the termination of fiber optics specifically for high reliability applications. A picture of the workstation is shown in Figure 5. 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 / termination types and infers curing temperatures with the terminus itself – where the epoxy resides. 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 5 inset). All of these improvements in the process alleviate the variability associated with the more commonly used block ovens and provide a highly consistent cable assembly product. Figure 6 shows typical temperature traces for 2 cable assembly ends that were processed on the system. The differences between the two are barely noticeable.



Figure 5: High performance curing system (Inset: Aerospace cable assembly in precision work pallet)

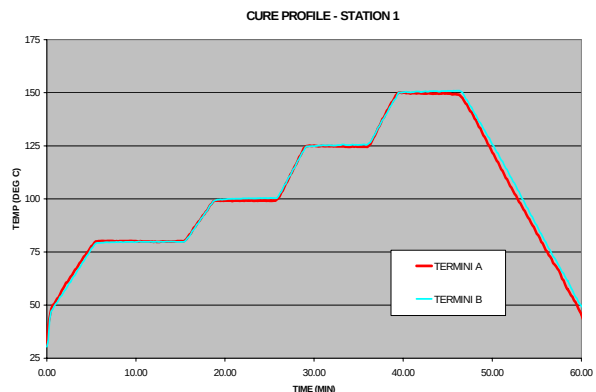


Figure 6: Typical temperature response for 29504/4 termini cured within system (both cable ends shown).

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.

Once the fiber cable assembly is fully cured, the work pallet is then transferred downstream to the Polish Workstation.

Polishing Workstation

Fiber optic polishing processes will vary depending on the application and terminations type. A generic polish process is shown in Figure 6 with a typical example of a termination end ready for polish shown in Figure 7. Generally, the termination is polished with successive stages of finer and finer polishing films in order to obtain the desired surface finish and geometry of the end face. The end face of the termination is pressed against the film while it is in relative motion. The make-up of the film, pressure applied, and film backing compliance are all parameters that are optimized.

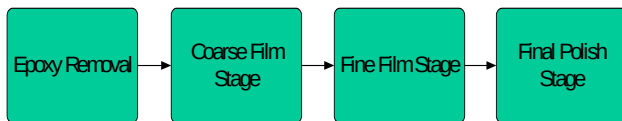


Figure 6: Generic Polishing Process Steps.

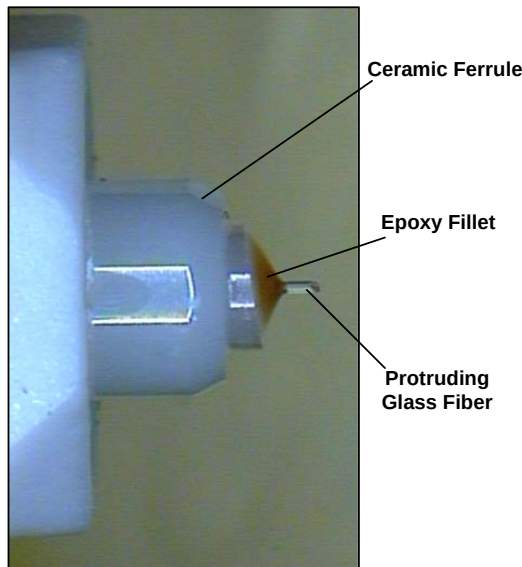


Figure 7: Termination Ready For Polishing

Typically, the first step in the process removes the excess epoxy from the face of the termination. This is typically done with a coarse polishing film so that the epoxy does not load the film too quickly, allowing it to last longer.

Once the epoxy is removed, the end face will be introduced to a series of polishing films at stages referred to as the forming steps. These steps create a geometry on the end face to exacting tolerances in order for the termination to achieve correct intermateability. Most commonly the geometry created has a spherical shape, however other geometries are utilized as well. In order to achieve the correct geometry, the pressure applied, type of film, and

backing material compliance will be altered to obtain the desired geometric results.

The process is finished with a final lapping polishing film which yields an optical surface that is suitable for the application.

Due to the critical nature of the polishing process in order to obtain a high quality fiber termination, the automated Polish Workstation was developed (shown in Figure 8).



Figure 8: kSARIA Corporation's Automated Polishing Workstation

This system utilizes a method called “one-up vertical polishing”. This means that all polishing is done on individual terminations, (not ganged in a multi-up format as with bench-top methods) and with the polishing media in a vertical orientation as opposed to a horizontal configuration used in other traditional methods. The polishing mechanism is shown in Figure 9. The polishing media is used in a roll format as opposed to a disc format used in previously described systems. The roll is held on a feed mandrel and is threaded through the mechanism over a backer to a take-up mandrel. During operation, a termination (one at a time) is automatically pressed against the media at the backer location. A closed loop force control scheme is employed in order to tightly monitor process conditions. As the force is applied, the media is moved in an orbiting pattern with velocity control in order to maintain surface speed for consistency in polishing.

The backer plate is an interchangeable piece of tooling that can be substituted with various pads made from different durometer materials. This design feature allows the system to accommodate all of the different varieties of optical connectors on the marketplace and end face geometries comprised of flat, spherical, or angled.

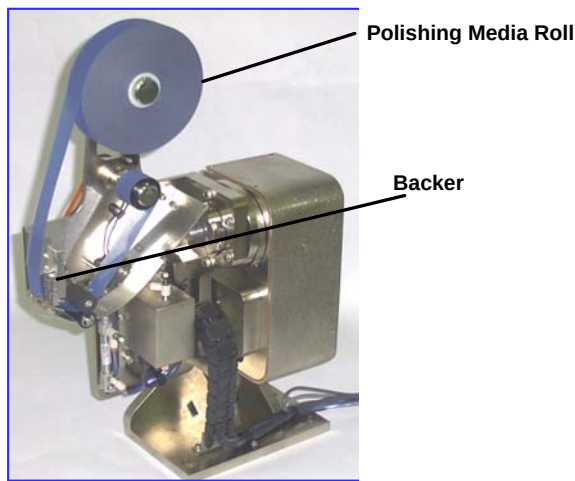


Figure 9: Polishing Mechanism

As the polishing is occurring, the termination is flushed with filtered water in order to remove any particulates that are generated as a result of polishing. Due to the vertical orientation of the polishing film, all contaminants are immediately removed from the polishing zone providing a well-controlled environment and greatly reducing the risk of carrying contaminants to downstream polishing stages.

After polishing is complete, the force is removed from the termination and it withdraws back away from the polishing media. A flushing water jet is again employed to automatically clean the termination prior to moving on to the next polishing stage.

The system utilizes the same work pallets previously discussed to transfer WIP through the system, so that the termination ends engage each successive polishing stage. Each stage will have a pre-programmed recipe for all of the key process parameters to be controlled. A recipe will contain settings for surface speed, polishing pressure, film advance rate, and polishing time. The pallet will progress through each stage automatically and then be output to an unload stage, where the operator will remove the pallet from the system.

Key Assembly Characteristics for High Reliability

High quality and reliability of fiber optic terminations are governed not only by the constituent components, but to a much larger extent, the termination process itself. By automating this process and controlling its consistency, the key characteristics for a highly reliable assembly can now be attained. Specific reliability/ quality attributes controlled with each of the major automated processes is discussed below.

Terminus Assembly Contribution

In examining the cross section of a properly assembled terminus there are 2 main attributes that are critical for high reliability. Shown in Figure 10, epoxy voids and proper insertion depth are key items to control during the assembly

process. Inadequacies in either can result in lower performance when exposed to the stresses of a harsh environment or in outright failure of the terminus through a fiber fracture.

The first, epoxy voids, are caused by inconsistent dispense volume or dispense technique. Obviously if too little epoxy is dispensed voids can be present within the terminus. However, even with the most consistent volume control on the dispenser, the technique used to deposit the epoxy in the terminus can have a greater effect in the generation of voids. If the syringe needle is drawn back too quickly, then epoxy will not completely fill the internal cavities of the terminus. If it is drawn back too slowly, then the epoxy flows around the needle and wets its surfaces. When the needle is withdrawn, epoxy is removed from the cavity with the needle, leaving voids.

Only with precise automated motion control can this technique be mastered to provide consistency. The automated system can be programmed to coordinate the needle motion with dispense volume speed such that termini are assembled void-free.

In manually assembled termini, the insertion depth consistency is purely left to the skill level of the operator which is prone to human error. Additionally, even with very careful consideration of an operator, the insertion depth can be altered in handling the terminus while it is uncured, to move it to downstream curing processes. In the automated method, the insertion depth is governed by a robotic manipulator and held steady in the work pallet so that these elements are performed properly.

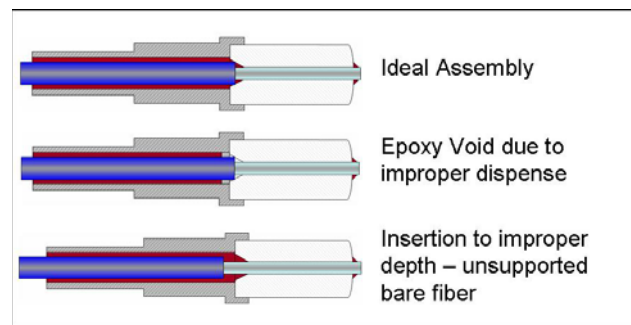


Figure 10: Terminus Cross Section Examples

These anomalies do not necessarily cause any adverse effects under ambient environments. However, as the termini are stressed thermally, the wide mis-match of CTE's of the constituent components can cause bending of the fiber within the terminus. In less severe cases, the fiber experiences micro-bending losses. In more severe circumstances, the fiber can fracture within the terminus body.

As a means of demonstrating the adverse effect of these issues, sample fiber optic cables were manufactured with both automated methods and manual methods. The samples were exposed to harsh environment testing conditions

(temperature cycling and vibration) to highlight differences in performance.

The samples were fabricated with standard M29504/4 & /5 termini. The samples were placed into an environmental testing chamber while optical performance was measured over the test duration. The chart in Figure 11 shows the results.

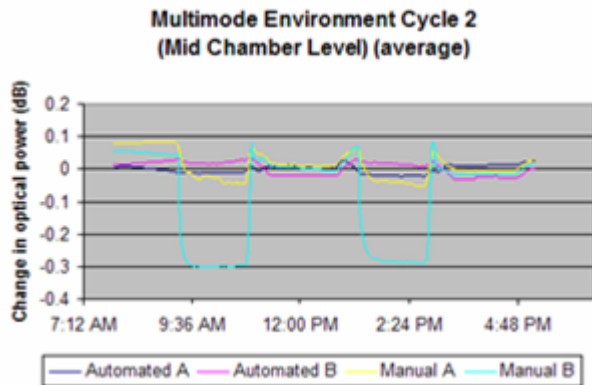


Figure 11: Side by Side Comparison of Optical Performance during environmental testing.

As can be seen in the chart, there is a sizable fluctuation in optical performance on the manually made samples vs. the automated samples. Further investigation of the samples through cross sectioning reveals both improper insertion and epoxy voids prevalent within the manually assembled terminus as shown in Figure 12.

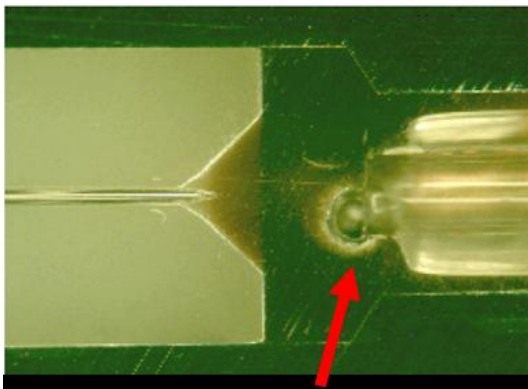


Figure 12: Cross Section of Manually Assembled Terminus

To further show the effects of improper insertion, terminus samples were fabricated with deliberate poor insertion vs. the correct standard process insertion. These samples were evaluated with environmental testing with results shown in Figure 13.

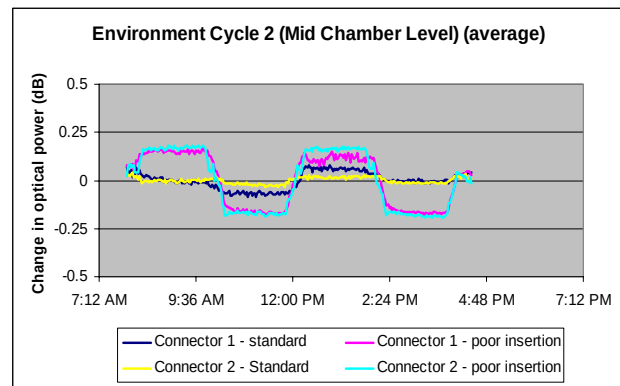


Figure 13: Comparison of standard termini samples vs. samples with poor insertion of the fiber.

As expected, the samples with poor insertion show a much larger fluctuation in optical performance over the testing range.

Curing Contributions

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 14. 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.

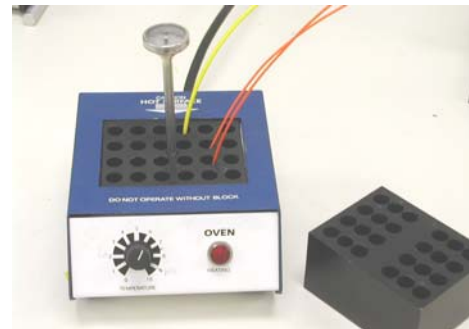


Figure 14: Conventional heating block oven

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 cycles. 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 in 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 15. 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 that 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.

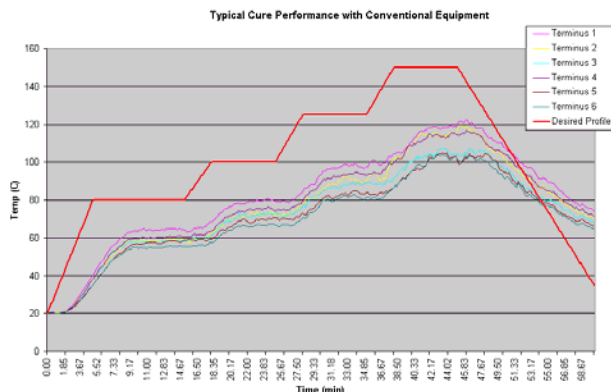


Figure 15: Example Block Oven Performance and Variation

The variation of temperature between cavities can be explained by the position of the terminus within the cavity or the fixture variations which create inconsistencies in heat transfer to the terminus. These variations in cure temperature can cause differences in T_g as noted in the chart in Figure 16.

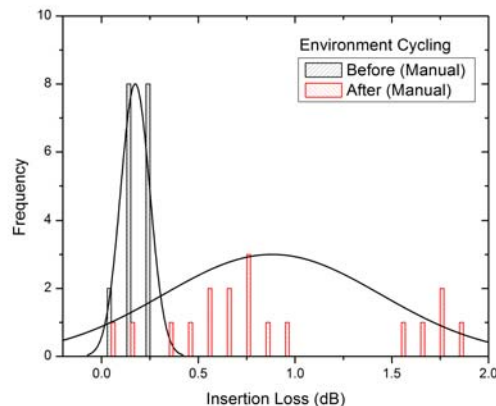
EPO-TEK 353ND T_g versus Cure Cycle

Cure condition	Residual Exotherm (J/g)	Peak exothermic Temperature (°C)	% NOT cured (% unreacted)	Calculated T_g (°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	155.5	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 16: EpoTek's information for cure schedule vs. T_g for commonly used epoxy

The automated Cure Workstation eliminates this variation with independent temperature control for each terminus and precise calibration which infers the temperature within the terminus to ensure the epoxy experiences the correct thermal cure profile.

In order to demonstrate differences between the automatic Cure Workstation and manual methods, sample fiber cables manufactured with each method were exposed to environmental testing to draw comparisons. The test sample termini were characterized before and after testing by measuring end face geometry and insertion loss. The before and after insertion loss comparisons for each sample set are shown in Figure 17.



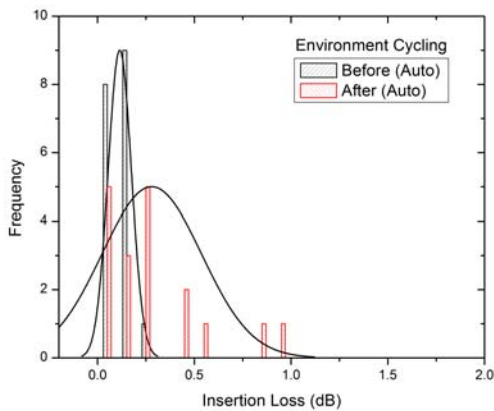


Figure 17: IL comparisons before and after environmental testing for terminations made manually and automatically.

As indicated in the charts, both sample sets demonstrate similar insertion loss groupings before undergoing environmental testing. After, each shows a degradation in loss characteristics. However the manually made samples show a much wider spread with a significant percentage of the samples falling outside of the maximum loss threshold of 1.5dB for these termini making them unusable in their intended system.

In examining the end face geometry of the samples, the manually made samples indicated a severe amount of fiber pistoning, as opposed to those cured with the automated Curing Workstation. The permanent loss degradation in the manually made samples is attributed to the excessive pistoning. The precision of the cure within the Cure Workstation enables the epoxy to achieve the maximum Tg, thus minimizing fiber pistoning at elevated operating temperatures and making a more reliable product.

Polishing Contributions

All optical connectors must be polished to a set of specifications that consist of the following:

- Geometry
- Visual inspection criteria (scratch/ pit)
- Optical performance

However termini that fall outside of the geometric tolerance window can affect the long-term reliability, optical performance, and intermateability between connectors which make it the most critical polishing criteria.

Specifications for end face geometry are set forth in a number of standards documents and primarily consist of the following for the most common PC style polishes and are illustrated in Figure 18.

1. Radius of curvature between 7 and 25mm.
2. Fiber protrusion less than 50nm, or, if undercut, then no more than 125 nm.
3. Apex offset less than 50um.

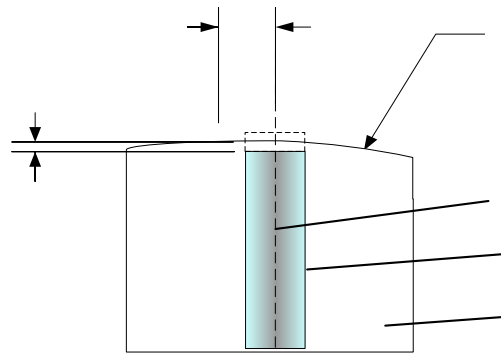


Figure 18: Definition of Geometric Specifications

Achieving the tight geometric tolerances consistently with manual processes is very difficult. Control of process parameters such as polishing force, ferrule orientation, and polishing surface speed is crucial in obtaining the correct geometry. Inspection for the end face geometry is measured using an optical interferometer. An image of a connector interferogram is shown in Figure 19.

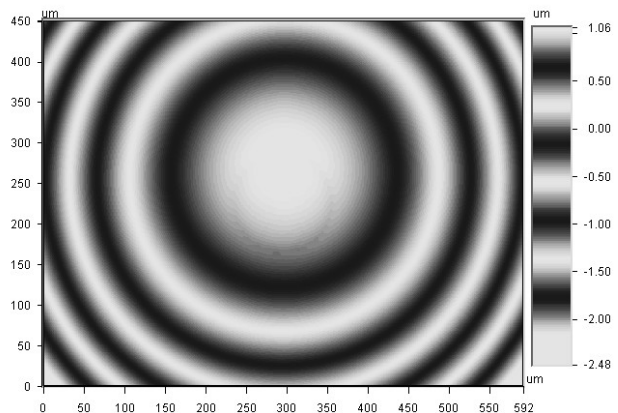


Figure 19: Interferogram of a Connector

The faint outline of the glass fiber is apparent near the center of the image, while the many concentric rings reveal the location of the domed topography on the end face. Figure 20 is an enhanced 3D view of this same connector, where the lack of concentricity between the fiber and ferrule dome is more easily visualized.

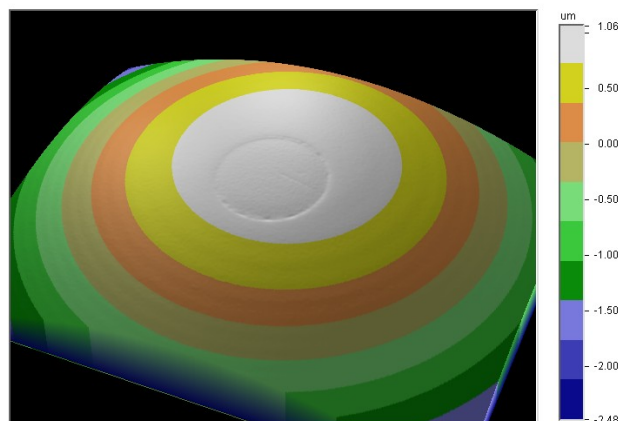
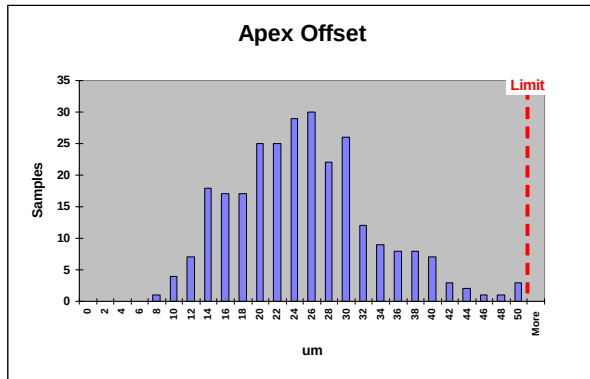


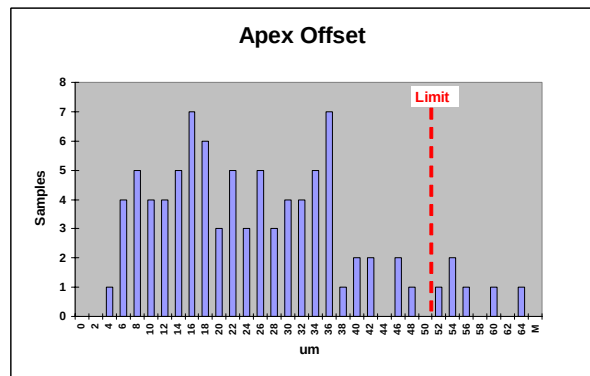
Figure 20: 3D Mapping of a Connector End Face

The apex offset parameter is typically affected by variation in the polishing force and orientation of the ferrule with respect to the polishing surface. The automated system precisely controls these process parameters because it operates on one connector at a time, which negates any influences from adjacent connectors, which are present in a multi-up polish fixture.

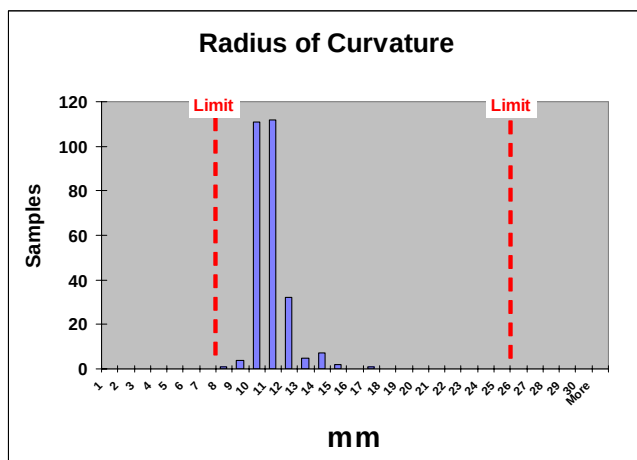
Example comparisons of conventional polishing and polishing with the automatic Polish Workstation for Radius of Curvature and Apex Offset is provided in Figure 21 below.



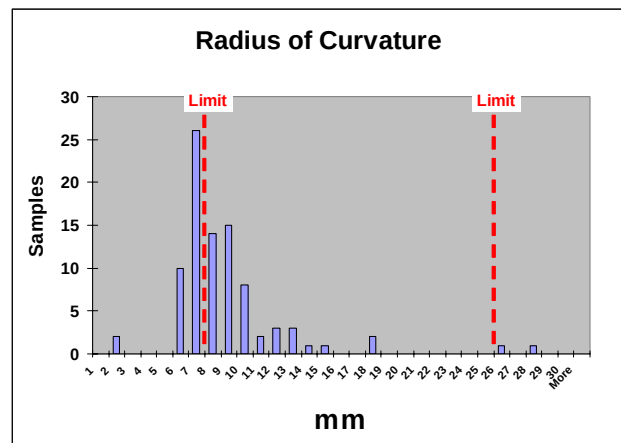
Automated



Manual



Automated



Manual

Figure 21: Geometric Parameter Comparisons

As shown in the charts, the automated process produces a tighter, more consistent distribution for key geometric parameters. The manual samples shown in the charts indicates a fair number of samples outside of the requirements making them prone to intermateability and reliability issues.

For example, the table in Figure 22 provides typical effects and failure modes specific to geometric parameters that fall outside of the tolerance requirements. Unless the manufacturing process adheres to the tolerances, the end user of the fiber optic cable can experience these issues in the field.

Polish characteristic	Defect	Potential Failure Mode
Apex Offset	a. Large Apex offset	a. Improper mating of termini resulting in signal loss
	b. High back reflection	b. High back reflection
Radius of Curvature	a. Small radius	a. Excessive end face pressure causing fiber cracks at face under vibration
	b. Large radius	b. Improper mating of termini resulting in signal loss
Fiber height	a. Excessive fiber protrusion	a. High axial forces on unsupported glass causing fracture
	b. Excessive fiber undercut	b. Insufficient contact between mated fibers causing signal loss and high back reflection

Figure 22: Geometric Defect Failure Modes

Conclusions

By deploying automated manufacturing for fiber optic cable assemblies, significant benefits can be realized in both quality and reliability. Automation eliminates the variances that are introduced in the process by an operator that can lead to issues in the fielded cable products. Hidden defects within the terminus, which cannot be inspected, can be eliminated to ensure operation in demanding environments. With the existence this automated technology, benefits can be realized today for mission critical, military/ aerospace applications.

Acknowledgements

This work was supported through the Penn State Electro-Optics Center by the Naval Air Systems Command under contract N00421-03-D-0044 and by the Office of Naval Research under contract N00014-99-2-0005.