



AEROSPACE INFORMATION REPORT

AIR6162™

Issued 2017-04
Reaffirmed 2024-10

Fusion Splicing for Optical Fibers

RATIONALE

The aerospace industry has successfully integrated fiber optics as a viable technology for transmission of light. Fiber optic connectors, both for new connections and field repairs, continue to present issues with acquisition and life cycle costs. Fusion splices can be used for permanent fiber connections with a significant reduction in cost and improvement in loss and stability. Another application being discussed is the use of fusion splicing to splice pre-installed fiber optic cable assemblies onto pigtailed connectors, allowing non-terminated cables to be easily routed into a structure and terminated during the final assembly phase. Specifically designed fusion splicers can be used in explosive environments found in aerospace.

AIR6162 has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This document provides an orientation to fusion splicing technology for optical fibers and fiber optic cable. It is intended for managers, designers, installers, and repair and maintenance personnel who need to understand the process of fusion splicing. This technology is widely used in telecommunications and industrial applications, and is finding acceptance in aerospace applications.

2. REFERENCES

2.1 Applicable Documents

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP5061	Guidelines for Testing and Support of Aerospace, Fiber Optic, Interconnect Systems
AS5382	Aerospace Cable, Fiber Optic
AS5675	Characterization and Requirements for New Aerospace Fiber Optic Cable Assemblies - Jumpers, End Face Geometry, Link Loss Measurement, and Inspection
AS5750	Loss Budget Specification for Fiber Optic Links
AIR6031	Fiber Optic Cleaning
AIR6258	Fiber Optic Sensors for Aerospace Applications
AS6479	Splicer, Fusion, Fiber Optic, Aerospace

2.1.2 Military Specifications

Copies of these documents are available online at <http://quicksearch.dla.mil>.

A-A-59799	Commercial Item Description: Fusion Splicer and Cleaver, Optical Fiber MIL-PRF-24623/6 Splice, Fusion, Fiber Optic Cable, Protector
MIL-PRF-24623/7	Splice, Mechanical, Simplex Fiber Optic Cable, Aircraft
MIL-PRF-49291	Optical Fiber, (Metric) General Specification for
MIL-PRF-85045	Cables, Fiber Optic, (Metric) General Specification for

2.1.3 Military Standards

Copies of these documents are available online at <http://quicksearch.dla.mil>.

MIL-STD-810G	Environmental Engineering Considerations and Laboratory Tests
MIL-STD-1678	Fiber Optics Test Methods and Instrumentation
MIL-STD-46855	Human Engineering Requirements for Military Systems, Equipment, and Facilities
NAVAIR 01-01A-505-4	Installation & Testing Practices, Aircraft Fiber Optic Cabling
NAVAIRINST 4200.25D	Management of Critical Application Items Including Critical Safety Items



2.1.4 ANSI Accredited Publications

Copies of these documents are available online at <http://webstore.ansi.org/>

ANSI Z136.2 Standard for the Safe Use of Lasers

2.1.5 Aeronautical Radio (ARINC) AEEC Committee, Fiber Optics Subcommittee (FOS) Publications

Available from Aeronautical Radio, Inc., 2551 Riva Road, Annapolis, Maryland 24101-7435, www.arinc.com.

ARINC 805 Fiber Optic Test Procedures

ARINC 806 Maintenance and Repair of Fiber Optic Cables

2.1.6 Comité Européen de Normalisation (CEN) Publications

Available from Avenue Marnix 17, B-1000 Brussels, Belgium.

EN 2591 Aerospace Series, Elements of Electrical and Optical Connection – Test Methods

EN 3745 Aerospace series, Fibers and Cables, Optical Aircraft Use – Test methods

2.1.7 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC60793 Optical Fibres, Measurement methods and test procedures

IEC60794 Optical Fibre Cables

IEC-61300 Fiber optic interconnecting devices and passive components, Basic test and measurement procedures

2.1.8 International Telecommunications Union Publications

Available from the International Telecommunication Union (ITU), Place des Nations 1211 Geneva 20 Switzerland. www.itu.int.

G.657 Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network

2.1.9 Radio Technical Commission for Aeronautics (RTCA) Publications

Copies are available from the Radio Technical Commission for Aeronautics Secretariat, One McPherson Square, Suite 500, 1425 K Street NW, Washington, DC 20005.

RTCA DO-160/EUROCAE ED14 Environmental Conditions and Test Procedures for Airborne Equipment

2.1.10 Telcordia Publications

Available from Telcordia Technologies, Inc., 1 Telcordia Dr., Piscataway, NJ 08854-4151, Tel. 732-699-2000.

GR-765-CORE Single Fiber Single Mode Optical Splices and Splicing Systems

2.1.11 TIA/EIA Publications

Copies are available from IHS Global Inc., Tel. 800-854-7179 (U.S. and Canada), +1-303-397-7956 (Outside U.S. and Canada), <http://global.ihs.com>.

TIA/EIA-440B	Fiber Optic Terminology
TIA/EIA-455	Fiber Optic Test Procedures
TIA/EIA-455-6B	Cable Retention Test Procedure for Fiber Optic Cable Interconnecting Devices
TIA/EIA-455-8 (FOTP-8)	Measurement of Splice or Connector Loss and Reflectance Using an OTDR (ANSI/TIA/EIA-455-8-2000)
TIA/EIA-455-20 (FOTP-20)	Measurement of Change in Optical Transmittance
TIA/EIA-455-34 (FOTP-34)	Interconnection Device Insertion Loss Test (ANSI/TIA/EIA-455-34A 95)
TIA-455-57B	Preparation and Examination of Optical Fiber Endface for Testing Purposes
TIA -455-107	Fiber optic test procedure: return loss
TIA/EIA-455-171 (FOTP-171)	Attenuation by Substitution Measurement for Short-Length Multimode Graded-Index and Single-Mode Optical Fiber Cable Assemblies (ANSI/TIA/EIA-455-171-A)
TIA-526-7 (OFSTP-7)	Measurement of Optical Power Loss of Installed Single-Mode Fiber Cable Plant
TIA-526-14 (OFSTP-14)	Optical Power Loss Measurement of Installed Multimode Fiber Cable Plant

2.1.12 Other Documents

- [1] Yablon, A. D., *Optical Fiber Fusion Splicing*, Springer: Berlin, 2005.
- [2] Decker, G. A., Jr., "Method of fabricating an optical attenuator by fusion splicing of optical fibers," U.S. Patent: 4,557,556, Dec. 10, 1985.
- [3] Limin Xiao; Demokan, M.S.; Wei Jin; Yiping Wang; Chun-liu Zhao, "Fusion Splicing Photonic Crystal Fibers and Conventional Single-Mode Fibers: Microhole Collapse Effect," *Lightwave Technology, Journal of*, vol.25, no.11, pp.3563,3574, Nov. 2007.
- [4] Sanghera, J., *Infrared Fiber Optics*, CRC Press: Boca Raton, FL. 1998.

2.2 Acronyms

CTE	Coefficient of Thermal Expansion
FBG	Fiber Bragg Grating
FW	Fusion Welder
IFOG	Interferometric Fiber Optic Gyroscope
kV	Kilovolt
LDF	Large Diameter Fiber
LID	Local Injection And Detection
LPD	Long Period Grating
MFD	Mode Field Diameter
MM	Multimode
MMF	Multi-Mode Fiber
OTDR	Optical Time Domain Reflectometer
PAS	Passive Alignment System
PCF	Photonics Crystal Fiber
PM	Polarization Maintaining
SMF	Single Mode Fiber
TIG	Tungsten Inert Gas (Welding)

3. BASIC FUSION SPLICING

3.1 History

In the 1970s engineers realized that if optical fibers could be welded together, end-to-end, superior splices could be achieved, with consistently low insertion loss and low back reflection. An early method tried was to align the two fibers with each other with micrometer-driver positioners, under a microscope, heat the two ends with a hydrogen torch, and push the ends together as quickly as possible. This method was used to install fiber cables for the Lake Placid Winter Olympic Games in 1976. With manual control, however, this was a very difficult process to perform successfully. Failures tended to outnumber successes.

By 1978 IBM first published the results of experiments in fusing optical fibers with electric arcs. This was basically tungsten inert gas (TIG) welding, applied to silica fibers. Given precise alignment fixtures, an electric arc could be developed, applied, and controlled precisely enough in the lab to make good welded (fused) joints with reasonably high yield.

Engineers working at Sandia National Labs then converted the technique into a manufacturable product, forming a new company called Orionics Products. Orionics pioneered the first portable, self-contained, commercially-available arc fusion splicer; since the technique was based on TIG welding, they named it "FW" for Fusion Welder. Fiber alignment was still performed manually by the user, but the heat was applied by a high voltage arc which was precisely controllable in time and current.

Over the years the welding/fusion splicing technique has been repeatedly and highly refined:

- Precise v-groove alignment to relieve the user from aligning manually
- Automatic precision optical fiber alignment mechanisms (piezoelectric)
- Automatic control of arc current and time

- Video imaging
- Extension of the technique from multi-mode optical fibers to single mode optical fibers
- Local Injection and Detection (LID) to allow power-peaking optical fiber alignment
- Image processing for automatic optical fiber alignment
- LID power processing for automatic optical fiber alignment
- Loss estimation based on image processing
- Loss estimation based on coupled power
- Splicing specialty optical fibers (bend-resistant, PCF, Er-doped, large core, NZDF, small core (4 μm), etc.
- Ever smaller and more rugged packages
- Rotational alignment and splicing of polarization-maintaining optical fibers
- Splicing several optical fibers at once, in parallel (e.g., 4, 8, 12, or 24)
- Splicing multi-core optical fibers
- Splicing high-power optical fibers (cores up to 1 mm)
- Splicing mismatched optical fibers
- Producing tapers or balls on the ends of optical fibers
- Misaligning optical fibers to create attenuators
- Remote control of splicers by computer
- Automatic detection of the types of optical fibers presented for splicing
- Creation of long-period gratings by linearly-indexed application of arcs
- Creation of collimators by expansion of mode field
- Splicing optical fibers with non-circular claddings, e.g., pentagonal or heptagonal
- Splicing optical fibers made of materials other than silica, such as borosilicate and chalcogenide glasses
- Splicing optical fibers with coatings such as polyimide, carbon, titanium dioxide, gold, or aluminum left in place
- Splicing optical fibers smaller in diameter than 125 μm , down to just 50 μm
- Improvements in optical fiber alignment precision and fusion process, to regularly achieve insertion losses on the order of 0.02 dB or better on single mode optical fibers
- Miniature modular configuration, separating splicing head from controller
- Explosion-proofing
- Adaptation to the military and aerospace environments

- Development of more rugged optical fiber/fiber optic cable restorations post-fusion

3.2 Why Fusion Splicing?

The basic goal is to create a robust joint between two optical fibers that imposes minimum excess loss and back reflection and is as stable as possible with the passage of time and environmental stresses.

It was found that welding or fusing two optical fibers provides a high quality, low loss solution. When carried out correctly, a fused joint between two fibers can be virtually the same as “no joint at all”. When core and cladding are aligned accurately, and fused together the joint is practically invisible – glass-to-glass, core-to-core, doping profiles matched. Insertion losses are routinely 0.01 to 0.02 dB, and back reflections are usually unmeasurable (below the limit of measurement). Changes due to adverse environments are usually no different from those of pristine fiber or fiber optic cable.

The economics of optical fiber connections favor fusion splicing. Fiber optic connectors must be designed and manufactured to provide sub- μm alignment over the lifetime of the connection through all of its intended environments. A fusion splice is a permanent and durable weld. The mechanical precision is provided by the fusion splicer itself. Therefore, mechanical precision is not a recurring cost. Components that cover and protect fusion splices need not be produced using high-precision techniques.

The quality of optical fiber connections favors fusion splicing. Modern fusion splicing equipment performs proof testing and splice loss estimation during the splicing operation, in order to immediately identify latent defects. Testing of connector loss, on the other hand, is a separate process in addition to the connector assembly. Diagnosis of link performance issues in subsequent operations often uncovers connector defects only when it is expensive to mitigate them.

In aerospace field environments, fuel vapor, liquid oxygen, or flammable liquids may be present. Curing ovens, heat shrink guns, fusion splicers, and other high voltage sources are normally prohibited in these areas. Here, splicing of fibers can be accomplished using (a) explosion-proof fusion splicers, or (b) alternate high-precision mechanical splices.

4. THE FUSION SPLICING PROCESS

4.1 Fiber Preparation

An optimum fusion splice is dependent of the accuracy of the optical fiber cleave and cleanliness. Poor quality cleaving and cleaning leads to high loss and weak fusion splices, and therefore the correct preparation prior to splicing is extremely important.

Silica optical fibers are coated with protective layers to provide protective qualities, allowing ease of handling, ruggedizing and protecting the optical fiber, and increased strength. These layers have to be removed prior to any fusion splicing, as it is only the silica fiber core and cladding that are involved in the splicing process.

Figure 1 illustrates a typical optical fiber construction with the various coatings/buffers added to the optical fiber. The primary coating/buffer is usually an ultraviolet cured acrylate or silicone, providing a protective cushion as well as protecting the optical fiber from external contamination and damage.

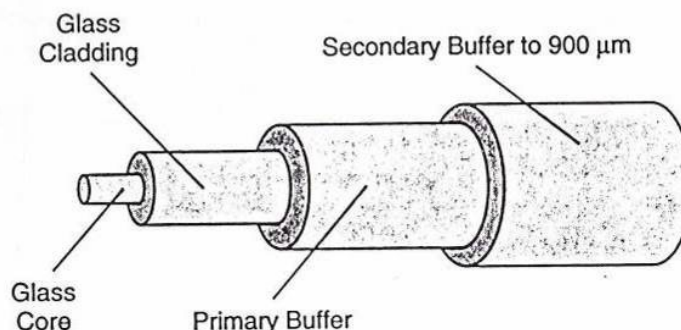


Figure 1 - Basic fiber construction with primary and secondary coatings/buffers

Optical fibers designed for aerospace applications are typically manufactured with additional coatings/buffers for protection, additional ruggedness, and improved temperature capability. Typically, a secondary coating/buffer of high temperature polymer is applied during the manufacturing process and can be tightly bonded to the primary coating/buffer or drawn as a loose assembly to allow movement of the primary coated/buffered fiber within the cable assembly. These types of assemblies are known as tight buffer or loose tube accordingly. Figure 2 shows examples of the different types of construction.

Other 'exotic' coatings/buffers can also be found on specialized optical fibers, including polyimide, carbon, and metals, but the underlying message is that to carry out a successful, high quality, fusion splice these coatings need to be completely removed from the cladding of the optical fiber.

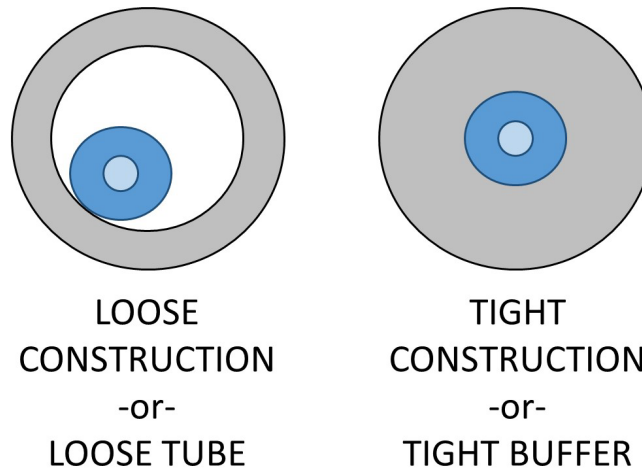


Figure 2 - Tight buffer versus loose tube cable constructions

4.1.1 Preparation

In an aerospace fiber optic cable the optical fiber is further protected with the inclusion of a strength member comprised of a woven or straight laid yarn laid onto the secondary coating/buffer providing longitudinal strength. An outer jacket of high temperature polymer material is then extruded over the previous layers, providing protection against external contamination and extrinsic mechanical damage. The typical outside diameter of an aerospace fiber optic cable is between 1.8 and 3.0 mm.

Prior to fusion splicing these various layers need to be removed. The fiber optic cable or optical fiber should be prepared using the manufacturer's detailed fusion splice process that includes precise stripping lengths of each of the layers of the fiber optic cable or optical fiber. The correct tooling should be used at all times. Refer to ARP5061 for details on stripping tool types and methods. Note that Personal Protective Equipment (PPE) may be required.

Cable jackets are removed first. For this, cable strippers are used. It is important to insure that the inner elements are not kinked or crushed during jacket stripping (see Figure 3). In any splicing operation, it is important to note the specified length of jacket that is to be removed from the end of the cable. Specific tooling or dimensional settings may be required for a particular cable type. This will also be a factor in any subsequent restoration, to prevent damage to the cable.

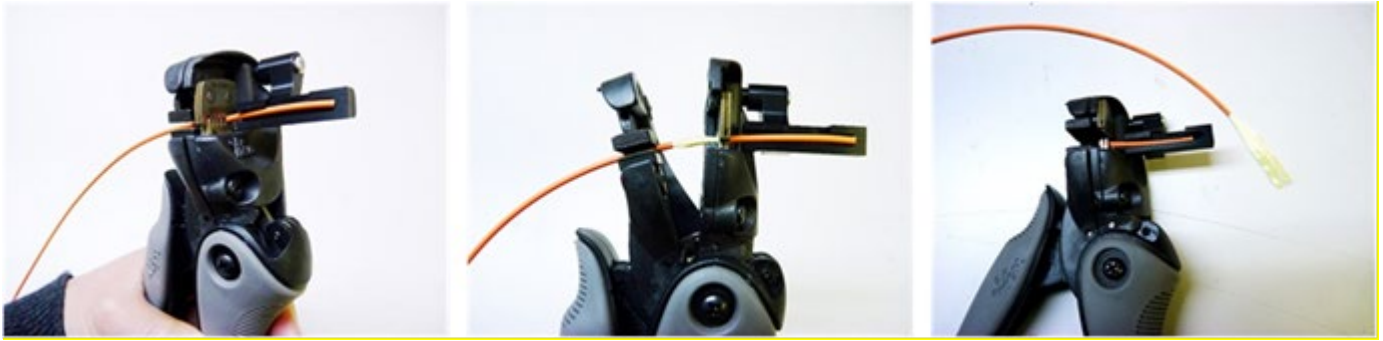


Figure 3 - Removing cable jacket with a standard cable stripper

The strength members are usually next to be removed. Note that aramid and glass yarns are tough and abrasive, and wear ordinary scissors out faster than other materials would. It is important to monitor the sharpness of cable preparation scissors and sharpen or replace them when they show signs of dullness. Ceramic scissors or cable cutters with tungsten carbide blades are often chosen for this, as they last longer than basic steel-bladed cutters. Also, the length of yarn to be removed or allowed to remain needs to be controlled as appropriate to the splicer and process being followed, as it may be needed for the cable restoration process.

The buffer layer or layers are removed next. At this point the choice of tool depends on the nature of the coating(s), and it is difficult to specify any particular best practice. 900 μm buffer or upjacket is often removed with strippers made for the purpose (see Figure 4). Again the length of fiber to be stripped depends on the nature of the protection or restoration which will be applied post splice. Loose tube buffer is easy to remove with a common strip tool, as once it has been cut through nothing prevents it from simply falling off the fiber. Tight 900 μm buffer can be very hard to remove, as it is often both tough and tightly bonded to the primary-coated fiber. When using a “mechanical” stripper, as in Figure 4, the fiber will often break if the length of coating being stripped is longer than a few mm, especially if the tool is not used very carefully. Users can often get around this by taking many small “bites”. More often a “thermal stripper” is used (see Figure 5). This contains a heating pad and the length of fiber to be stripped is laid or pressed against the pad until the coating has softened. It can then usually be pulled off easily, in one piece, without risking damage to the fiber.

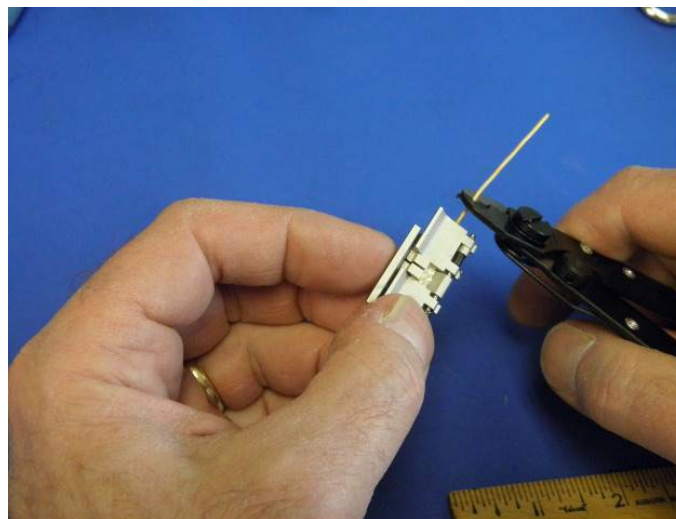


Figure 4 - Removing a 900 μm loose buffer tube

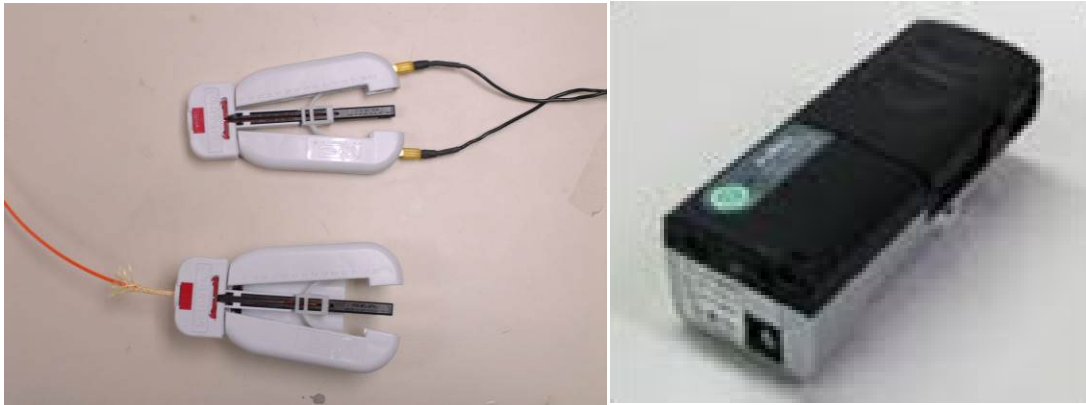


Figure 5 - Two different thermal strippers for removing hard-to-remove secondary coatings

The coating must finally be removed, thoroughly, leaving the fiber bare. 250 μm acrylate coatings are usually easy to remove mechanically, as in Figure 6. Two or three “swipes” with the strip tool, and sometimes fewer, usually get almost all of the coating off. Thermal strippers are commonly employed for this process as well to make the process easier and require less skill.

In rare situations, chemical stripping process are used for stripping coatings that are resistant to mechanical stripping. In these situations, chemical stripping requires compliance with safety requirements and certainly takes more time to execute. However, the use of chemical stripping on rugged fiber coatings carries less probability of damage to the fiber itself.



Figure 6 - Removing 250 μm acrylate primary coating (courtesy Thorlabs)

Some primary coatings are difficult or impossible to remove mechanically, yet most fusion splicers require that they be removed. Some of common examples are listed in Table 1. A plasma fiber coating cleaner, directed toward us on difficult coating geometries or materials, is shown in Figure 7.

Table 1 - Removal methods for hard-to-remove coatings

Type of Coating	Common Methods of Removal
Polyimide	Dissolve in hot concentrated sulfuric acid (non-hazardous environment)
Polyimide	Burn off with low-temperature flame (non-hazardous environment)
Polyimide	HFE-7100 with additives that may not be plastic safe but appropriate for this application.
Amorphous carbon	Burn off with fusion splicer or dedicated removal device
Aluminum	Dissolve in hydrochloric acid
Gold	Dissolve in aqua regia



Figure 7 – Example of plasma coating strip (courtesy SAE International)

4.1.2 Cleaning

Prior to cleaving and fusion splicing, the optical fiber must be very clean to prevent the possibility of defective or high loss splices. The fusion splicing operation may be compromised and cause issues like bubbles during the fusion process if the contamination is too great for the pre-clean arc to clear. Once the coatings/buffers are removed the bare fiber should be prepared by removing any remaining residue of the coating/buffer material. This can be accomplished using the following methods.

A common manual method is to dampen a suitable (non-cellulose) lint free wipe with a non-flammable, static dispersing optical grade solvent. The dampened wipe is then applied to the bare optical fiber with light pressure and wiped down its length without applying any bending motion, as shown in Figure 8. For certain materials, such as silicone, it may be necessary to carry out several wipes using a clean piece of dampened material on each occasion. Care must be taken not to apply too much pressure or bending motion to the bare fiber as damage may occur that could result in weaknesses within the fiber.

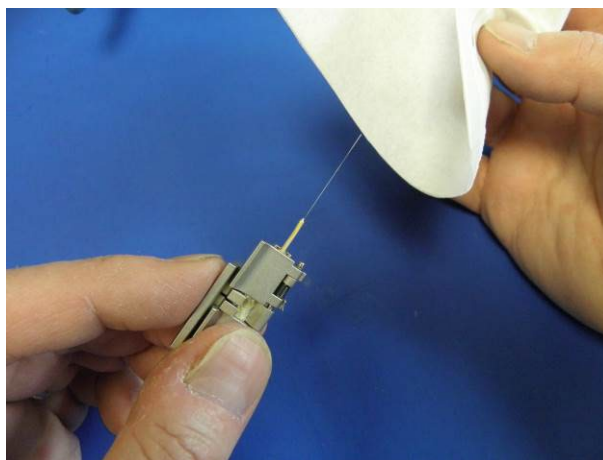


Figure 8 - Cleaning the optical fiber by wiping with a lint free wipe moistened with optical grade solvent

Another widely accepted method of cleaning is to use an ultrasonic cleaner, again with a non-flammable, static dispersing optical grade solvent. Fiber optic ultrasonic cleaners are available with fixtures to hold fusion splicing fiber holders, immerse the fibers to the proper depth, and time the duration of the process. An advantage of ultrasonic cleaning is that no mechanical contact is applied to the bare fiber, with less risk of degrading the fiber's strength. A disadvantage of this method of cleaning is that it is best suited for laboratory or clean production environments only. See Figure 9.



Figure 9 - Typical ultrasonic cleaner for optical fibers (courtesy AFL)

4.1.3 Cleaving the Optical Fiber

Precision cleaving of the optical fiber is important to achieve a high quality, low loss fusion splice. Precision cleaving is achieved using dedicated cleaving tools. An acceptable precision cleaver should create a flat end face on the optical fiber that is perpendicular to the fiber axis to within 1° , close to planar, and with as few as possible defects such as chips, lips, roll-off, and “hackle”, a pattern of tiny ripples near the center of the fiber face caused by excess stress.

These come in a variety of designs, sizes, complexities, and costs, ranging from simple rugged models for field use to computer controlled automatic systems for production. Figures 10 and 11 show precision manual cleavers. Figure 12 shows an ultrasonic cleaver which applies tension and ultrasonic vibration to the fiber during the cleaving process.

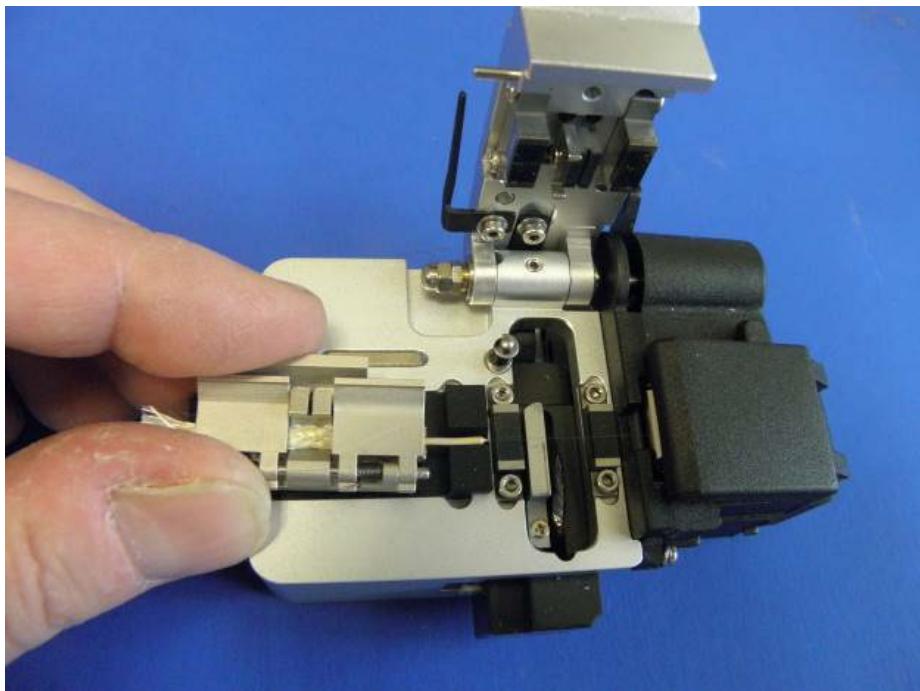


Figure 10 - Cleaving an optical fiber with a precision cleaver



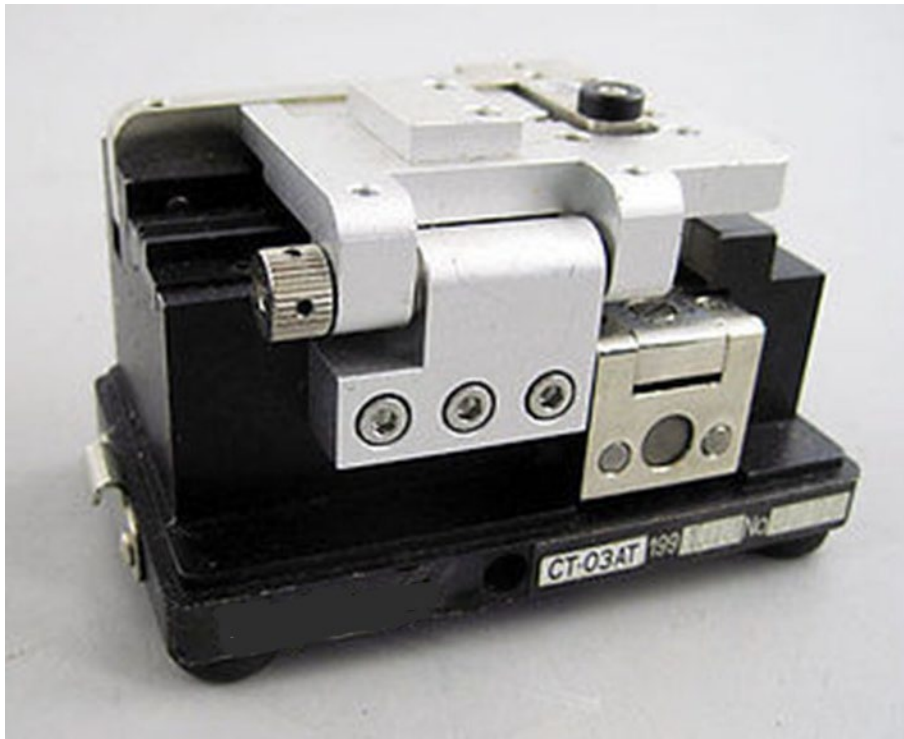


Figure 11 - Another typical precision single fiber cleaver (courtesy Fujikura)



Figure 12 - Ultrasonic precision single fiber cleaver (courtesy Ericsson/York)

Most precision cleavers use the same basic technique: score the outer cladding of the optical fiber with a very sharp blade to introduce a scratch or 'flaw' in the surface, then break it under tension. A very sharp carbide, or sometimes diamond, blade is used, so that it will inflict the smallest possible scratch or flaw in the fiber surface consistent with making a good cleave. Then a controlled push or level of tension is applied to the fiber, which breaks straight across the diameter beginning at the flaw, as illustrated in Figure 13.