White Paper 01-10: *MIL-PRF-29504/14 & /15 Shipboard Optical Termini*

Abstract

Since 1997, MIL-PRF-29504/14 & /15 has provided dimensional and environmental requirements of what constitutes a fiber optic terminus appropriate for US Navy shipboard use, leading some to the conclusion that all qualified product is as good as another. However, as a performance-based specification, subtle differences of design and product realization, as well as latitude in the interpretation and reduction to practice of both MIL-STD-790 and the Navy's MIL-STD-2042 specifications, leads to different optical and reliability performance of what appear equivalent competitive offerings on the Qualified Material List (QML-29504-QPD). In this paper, we explain these subtle differences of design and product realization and the corresponding impact to cable assembly yield, optical performance and reliability in the Navy shipboard harsh environment.

Figure 1. STRAN MIL-PRF-29504/14 (l) and /15 (r) termini featuring construction of corrosion resistant alloys, low durometer seals and highest quality ceramics contribute to a terminus of singular reliability and optical performance.

Introduction

With its genesis in the video broadcast (SMPTE-358) and mining markets, the M29504/14 & /15 fiber optic pin and socket terminus, were the first optical termini to be used in a shipboard multi-terminus connector (MIL-PRF-28876) designed as a fiber optic connector from the ground up. Prior to this, M29504/4 & /5 fiber optic termini were seeing some mixed success as an 'electrical pin' replacement in the MIL-DTL-38999 connector ubiquitously found in the military aerospace community. Though more than adequate for the robust and reliable mating of the 'pin and socket' contacts of an electrical connector, the modest dimensional tolerances of the M38999 connector, subsequently imposed design compromises of the /4 and /5 termini which in turn, ultimately led to less than reliable performance in the high mechanical shock environment characteristic of the shipboard platform. With the compact and high spring force offered by its novel Belleville washer spring design; a removable alignment sleeve for field cleaning and proven front release terminus retention crown clip, the SMPTE-358 terminus enjoyed extraordinary market-pull of a Naval community in search of a solution. As we shall see, realizing the performance promise of this terminus is very much a study of *the Devil-is-in-the-Details!*

Belleville Washer Spring Stack

A fundamental difference between electrical and optical terminus design is the requirement that the optical mating endface never part during operation if optical discontinuity and irreversible damage to the pristine optical terminus endface is to be avoided. From Newton's F = m•a, for high amplitude vibration and mechanical shock environments, this amounts to designing a pin terminus and attendant spring to have a mass and spring force that satisfies:

$$Acceleration_{max} \le \frac{Spring\ \ Force}{Terminus\ \ Mass} \qquad (1$$

Clearly, to satisfy eq-1 (and maximize performance robustness), the designer must maximize spring force while at the same time minimize the total mass of the terminus. Unfortunately, for the familiar coiled torsion spring, it is hampered by the inherent force per unit volume the coil spring can develop before considerations like solid height of the coils and material modulus limit mate force.

By virtue of its geometry, the Belleville washer can exert a very high spring force for its volume. The spring force for a Belleville washer of thickness, *t*, and outer radius, *R*, is given by:

$$Force(s) = \frac{E \cdot s}{(1-\mu^2) \cdot M \cdot R^2}\left[\left(h - \frac{s}{2}\right) \cdot (h - s) \cdot t + t^3\right] \quad (2$$

Where μ is the Poisson Ratio, and *M* is a constant of geometry given by:

$$M = \frac{6}{\pi \ln\left(\frac{OD}{ID}\right)} \cdot \frac{\left(\frac{OD}{ID} - 1\right)^2}{\left(\frac{OD}{ID}\right)^2} \quad (3$$

By comparison to the coil spring, the Belleville washer's '*Achilles Heel*' is it's relatively short stroke linearity range. To counter this, the designer can affect a spring of longer stroke by stacking Bellevilles in alternating direction schematically as follows: <><><><><>. Ten washers arranged in this fashion will have 10x the stroke, yet produce the same force as a single washer. Other arrangements can be accomplished by 'nesting' 5 washers and stacking with 5 nested in the other direction, (schematically <<<<<>>>>>) yielding a spring with 5x the force and 2x the stroke of a single washer. In the case of the M29504/14 pin terminus, 11 alternating Belleville washers are used as shown in Figure **2**.

Figure 2. A stack of 11 Belleville washers comprise the M29504 spring.

Because the Belleville washer stack is exposed to the environment, corrosion resistant alloys must be used for the spring. Making use of its excellent corrosion resistance properties, high modulus and stress corrosion fatigue characteristics, STRAN uses specially heat treated Beryllium copper precision thickness sheet stock to yield Belleville springs of consistent performance and high cyclic stress reliability.

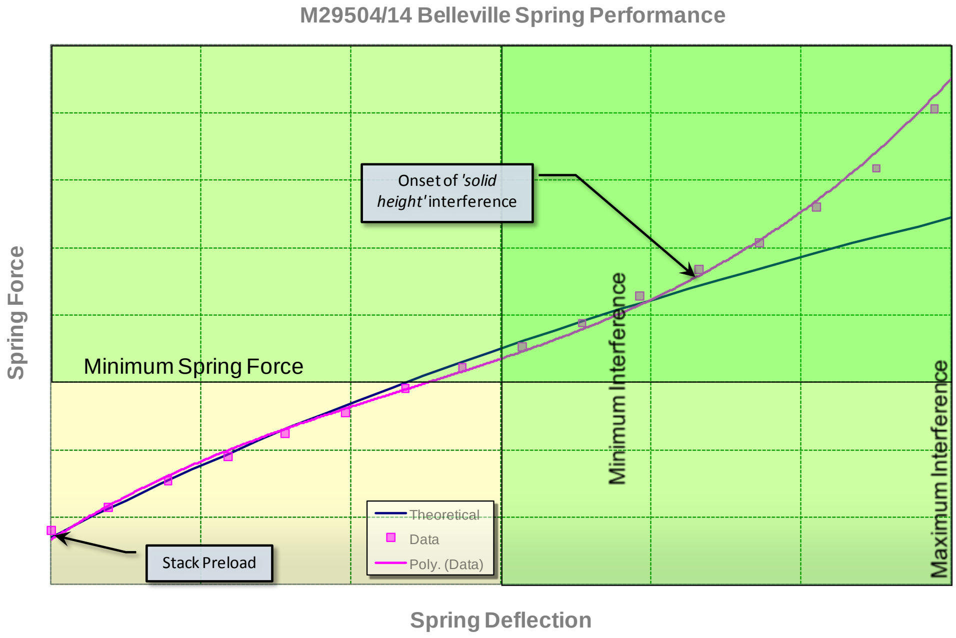

Figure 3. M29504/14 spring performance showing operational envelope as the intersection of minimum spring force and minimum terminus interference.

From equations (2) and (3), and using the material characteristics for Beryllium copper, we can model the force vs. stroke characteristics of a Belleville spring consisting of 11 washers stacked in alternating orientation as shown in Figure **2**. From equation (1), we have chosen a minimum spring force corresponding to the upper ‘green shaded’ rectangle. From a detailed tolerance analysis of the relevant M28876 and M29504 specifications, we assign a minimum and maximum terminus interference range represented by the ‘green shaded’ rectangle on the right side of the chart. The intersection of these two rectangles, is the operational envelope for the termini in which we can be assured the termini will robustly operate in the intended dynamic shipboard environment.

From Figure **3**, we make the following observations and conclusions:

- In spite of stacking as many as 11 Bellevilles, the range of acceptable terminus interference before ‘solid height’ non-linearity becomes unacceptable, is quite small. For the M29504/14 terminus, this is usually on the order of less than 0.030” interference.
    - *With an average 0.0015” – 0.0020” ferrule length erosion per re-polish, this in combination with the minimum mate force, sets a maximum number of 3 re-polishes before the terminus runs the risk of inadequate interference mate force.*
- In order to maximize mate force and minimize variation of force in the ‘zone of goodness’, the M29504 terminus is assembled with a small amount of preload force.
    - Termini that exhibit Belleville washers that are loose on the terminus, are an indication that the terminus does not have the benefit of the preload and the mate force will be up to 1/3 lighter than it should be.
    - Conversely, termini that exhibit Belleville washers that are too tightly pre-loaded on the terminus, are an indication that the terminus will not exhibit adequate stroke which will lead to damaged termini and/or connectors that will loosen during vibration due to solid height collision of the termini rather than the connector inserts.

Ferrule Geometry

As shown in Figure **4**, MIL-PRF-29504/14 & /15 sets strict requirements for overall dimensions, including ferrule diameter, protrusion and drilling options. The specification however is silent on the requirements of the ferrule lead-in chamfer leading to a range of interpretation by the industry ranging from almost no chamfer to STRAN’s generous 0.030” chamfer. STRAN purposefully,

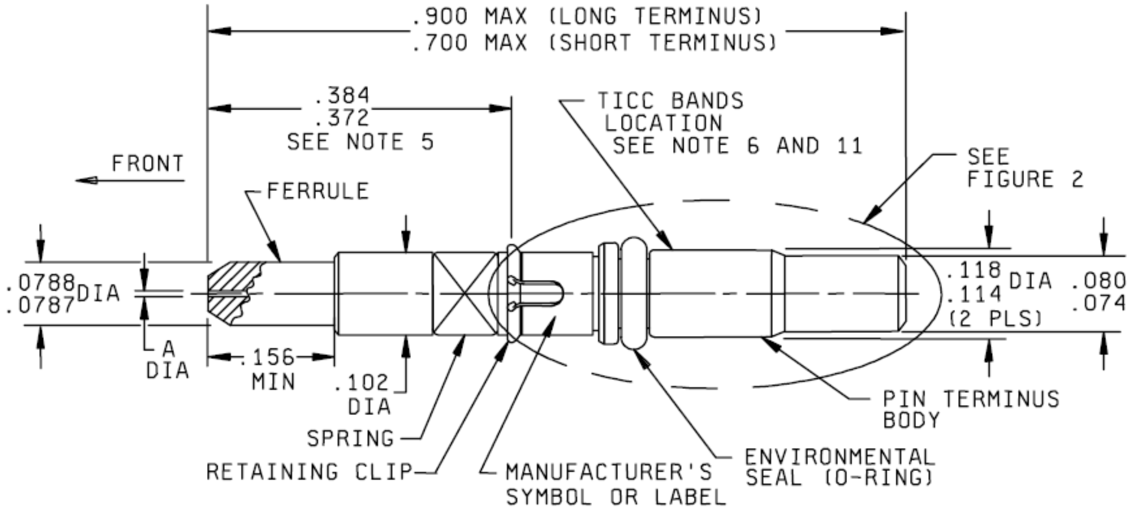

Figure 4. M29504/14 Figure – 1 showing dimensional requirements of the pin including a notional representation of the ferrule chamfer.

chose this amount of chamfer for the following reasons:

- Facilitates self-alignment of the terminus upon pre-mate of the connector with the minimum chance for damage to the receiving alignment sleeve.
- Reduces the terminus endface from 2mm to 0.58mm, which in turn reduces the consumption of expensive diamond faced polishing film by almost 12 fold!

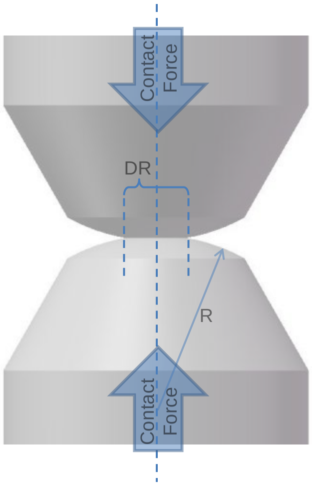

Figure 5. Mated shipboard termini with 15mm ROC and 200µm diameter deformation radius.

Endface Geometry

During polishing, the ferrule endface interacts with the compliant lap pad and automatically produces a spherical surface with a radius of curvature (ROC). The achieved ROC is dependent upon the relative lap hardness (durometer) and the applied contact pressure. Figured in this way, as two termini are mated, the spherical endface of the ceramic ferrule and glass fiber of the termini will flatten to a certain deformation radius, *DR*, dictated by terminus spring force and ROC as illustrated in Figure 5. As long as the spherical surfaces of both the glass and the ceramic ferrule satisfy certain undercut[1] requirements, the mated termini will squeeze out any entrapped air forming a hermetic[2] glass-to-glass interface of very low reflective loss. Whereas the telecommunications industry has a prescribed range of ROC based on connector spring forces of approximately 1.5lbs, the nominal mate force for the shipboard M29504/14 must be at least twice this if discontinuity and terminus damage is to be avoided during mechanical shock events.

From Hertzian contact stress theory and assuming the entire ferrule endface behaves as monolithic ceramic, we find that the M29504/14 terminus with a ROC of 15mm, will have a deformation radius of approximately 100µm. When the ROC drops below 10mm, the deformation radius decreases to less than 90µm. Due to the poor fracture toughness of glass by comparison to the adjacent ceramic, decreasing ROC below 10mm leads to proportionally higher contact stress on the comparatively fragile glass of the fiber. Not only does this stress result in a higher probability of damage to the terminus during high mechanical shock loads, the higher axial load on the fiber will increase the shear forces on the epoxy bond between the fiber and the ferrule resulting in fiber pushback (creep) over time. Unfortunately, achieving acceptable values of *undercut* and *linear offset*[3] is made more difficult as ROC increases.

As a method to improve manufacturing yield, the dependency of *undercut* and *linear offset*, has lead some in the industry to purposefully polish M29504 termini with ROC's on the low end of the Telcordia dictated minimum of 7mm. For shipboard termini, this practice puts almost all of the contact force bearing on the fiber itself leaving the fiber endface susceptible to mechanical fracture during high mechanical shock. As a matter of policy, all STRAN shipboard termini are polished such that the ROC satisfies:

$$10\text{mm} \le ROC \le 25\text{mm}$$

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[1] *Undercut* is the relative height the polished fiber is below the surrounding ceramic of the terminus endface. The maximum amount of undercut is a function of both ROC and diameter, *d*, of the fiber. For all high contact force termini, STRAN uses NAVSEA's recommended maximum undercut values given by: $UC_{max} = ROC - \sqrt{ROC^2 - (d/2)^2}$

[2] *Hermetic* seal refers to the degree to which the seal prevents the diffusion of water vapor (or other gases) thru the barrier. The glass-to-glass interface of two mated termini is one of the few examples of a true hermetic barrier in the fiber industry today.

[3] *Linear Offset* is the offset between the axial center of the terminus and the apex of the polished terminus endface and is set by Telcordia GR326 as ≤50µm.

To assist our customers achieve a more reliable termination, STRAN M29504/14 and /15 termini are delivered with the ferrule endface pre-radiused at 15mm.

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Epoxy Fill

As a consequence of the relatively short stroke of the Belleville spring (~0.030"), M29504/14 & /15 dictates fairly tight tolerances on the ferrule protrusion and distance from the 'crown clip' to the terminus endface. In order to meet these length tolerances, many on the QML press the ferrule to a predetermined depth in order to compensate for tolerance stack-up error of the terminus sub-components. From a mechanical integrity perspective this is perfectly acceptable and presents little chance, for example, of the ferrule pulling out as a result of this practice. However, when it comes to epoxy filling the terminus and avoiding the inclusion of air bubbles in proximity to the fiber, the void behind a non-bottom-pressed ferrule can foil the efforts of even the most diligent technician in achieving a bubble-free termination. Bubbles, particularly in the region of the ferrule forcing cone, give rise to stress concentrations that have been shown to lead to spontaneous mechanical failure of the fiber during thermal shock testing. Though this problem is particularly troublesome for the /14 owing to the long length of bare fiber in the region of the Belleville washer stack, in the case of the /15, by virtue of the terminus inner bore allowing the buffer to be 'bottomed' into the ferrule forcing cone, the socket terminus is subject to the deleterious effects of air bubbles, but to a much lesser extent.

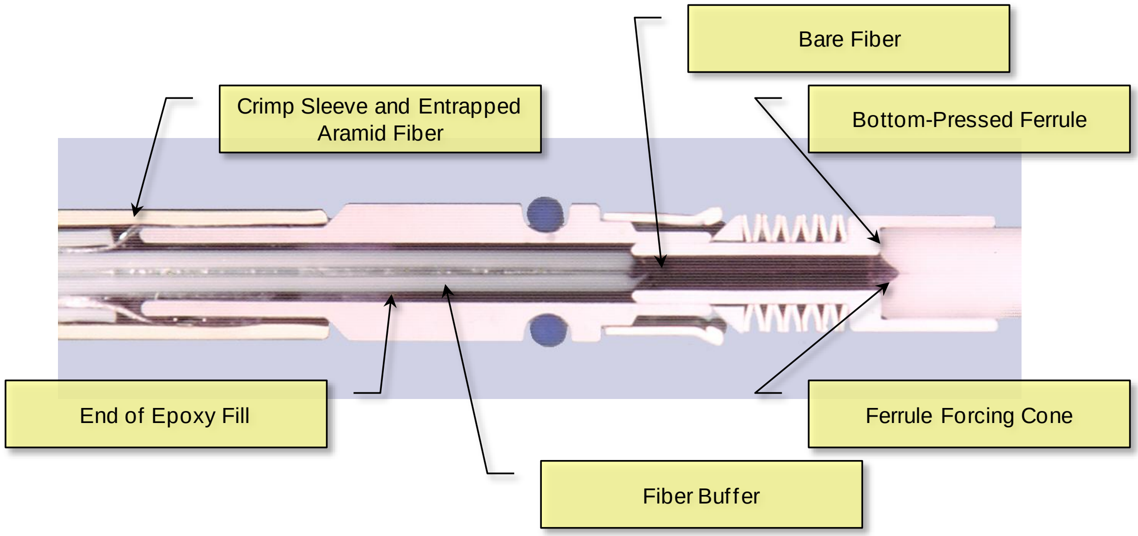

Figure 6. Cross-section inspection of STRAN M29504/14 terminus showing bottom pressed ferrule and the complete absence of air bubbles in the epoxy that have been shown to cause spontaneous mechanical failure of the fiber during thermal shock testing.

Mechanical failure aside, the stress applied to the fiber by the presence of nearby voids in the epoxy can produce microbend[4] loss in the fiber. As a general rule, graded index, multimode fiber is more susceptible to microbend loss than singlemode fiber by virtue of the low doping levels at the extreme edges of the fiber core. Low numeric aperture fiber, like the recent emergence of high bandwidth 50/125µm fiber on shipboard systems, has been found to be even more susceptible to this problem than the more prevalent its 62.5/125µm shipboard counterpart.

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[4] Microbend Loss of an optical waveguide arises from the application of external stress on the waveguide of a microscopic scale, perturbing the waveguide index of refraction via the photoelastic characteristics of the waveguide media.

Terminus Seal

The operating temperature range of the MIL-PRF-28876 connector of -28C to +65C, puts considerable demand on the choice of 'o'-ring material particularly for the lower operating temperatures. Since, all elastomers experience a reduction of compliance as the material approaches its glass transition temperature[5], T_g, it is critical to select an 'o'-ring with a T_g well below the minimum operating temperature so as to ensure the 'o'-ring remains sufficiently compliant in its secondary role of isolating the terminus from external strains, stemming from minor connector misalignment during operation . Although Viton™ is well known for its excellent resistance to petroleum based solvents and mechanical durability, its T_g of ~25C is not low enough for the shipboard environment. Reflecting this concern and the need for a non-fungal nutritive material, STRAN's M29504/14 & /15 seals feature non-carbon backbone material with T_g of -50C. So as to avoid damage to the 'o'-ring as well as unintended fungal growth, we recommend lubricating both the 'o'-ring and the insert cavity with a non-carbon-based 'o'-ring lubricant available from STRAN. Standard 'o'-ring greases, such as Parker 'O'-ring lube, are not recommended for the shipboard environment.

Viton™'s T_g of ~25C is not low enough for the shipboard environment. Reflecting this concern and the need for a non-fungal nutritive material, fluorosilicone, with a T_g of -50C, is STRAN's choice for M29504/14 & /15 seals.

Crimp Sleeve

The terminus crimp sleeve performs two functions: (1) secures the Aramid fiber to the terminus body, isolating the fiber from tensile stress and (2) captures the OFCC jacket, isolating the fiber from cable twist. To ensure the Aramid fiber and jacket are adequately captured, a good crimp sleeve design begins with choice of a sleeve material that does not rebound after the sleeve has been swaged down onto the terminus during the crimping operation. If the sleeve shows signs of cracks or dimensionally rebounds after crimping, it is likely that the Aramid fiber and/or jacket will not be captured adequately leaving the fiber susceptible to external stresses and potential mechanical failure.

To avoid these problems, STRAN uses specially heat treated crimp sleeves to achieve a 'dead soft' temper to ensure long-term mechanical reliability of the optical termination. As a demonstration of this heat treating process, STRAN sleeves can be completely flattened using a pair of pliers without the sleeve material showing signs of cracks! To prevent any adverse effects of a corrosive environment, our crimp sleeves receive a flash plating of inert gold. As a final '*belts and suspenders*' insurance, STRAN recommends the user apply a small drop of termination epoxy to both the Aramid fiber and OFCC jacket under the crimp sleeve.

Summary

Though compliant to the MIL-PRF-29504/14 & /15 specification, not all QML fiber optic termini will exhibit the same reliability, optical performance, cost of termination and robustness to variation of workmanship experienced in the field. In this paper, we have presented a number of concepts affecting these characteristics including:

- Belleville Washer design
- Ferrule Geometry
- Terminus Endface Geometry
- Epoxy Fill
- Terminus Seal
- Crimp Sleeve

To the casual observer, these may be seen as matters of nuance. At STRAN Technologies, these are matters of mission criticality! For more information, we invite you to contact us through our website or emailing us at info@strantech.com.

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[5] Glass Transition Temperature, T_g, is the temperature a material transitions from liquid to solid. For organic materials, the onset of this transition of state impacting material characteristics such as modulus, can begin 10's of degrees C from the material's T_g cited in the literature.