

Crimping History and Quality Control for Polymer Insulators

Edward Niedospial - Technical Sales Director Transmission
ENiedospial@macleanpower.com

Zachary Umansky – Business Development Manager Transmission
ZUmansky@macleanpower.com

MacLean Power Systems – SC, USA

Abstract

Since their emergence in the 1980s, polymer insulators have seen continuous innovation in materials, seal designs, and manufacturing techniques. Among these advancements, the evolution of end fitting attachment methods has played a pivotal role in improving reliability and performance. Early designs employed wedge-based mechanical interference and epoxy bonding—techniques inherited from ceramic disc insulators. By the 1990s, the industry shifted toward compression-based attachment, which introduced new challenges, including rod cracking during the process. To address this, manufacturers temporarily adopted acoustical emission devices to detect cracks, a solution that ultimately proved insufficient. Modern crimping technology has since redefined the attachment process, eliminating the root causes of rod cracking and rendering acoustical monitoring obsolete. This paper explores the engineering enhancements behind the crimping process and its impact on the production of current-generation polymer insulators.

Crimping History

1980's

First Generation Wedge Epoxy Attachment Method was developed based on proven ceramic insulator assembly techniques. See *Figure 1* below for examples.

In ceramic designs, the pin incorporates a wedge that is cemented inside the shell, which is then bonded to the cap. When tensile load is applied to the cemented wedge end of the pin, the resulting force translates into a compressive load within the shell, enhancing mechanical integrity. This same principle was adopted for first-generation polymer insulators.

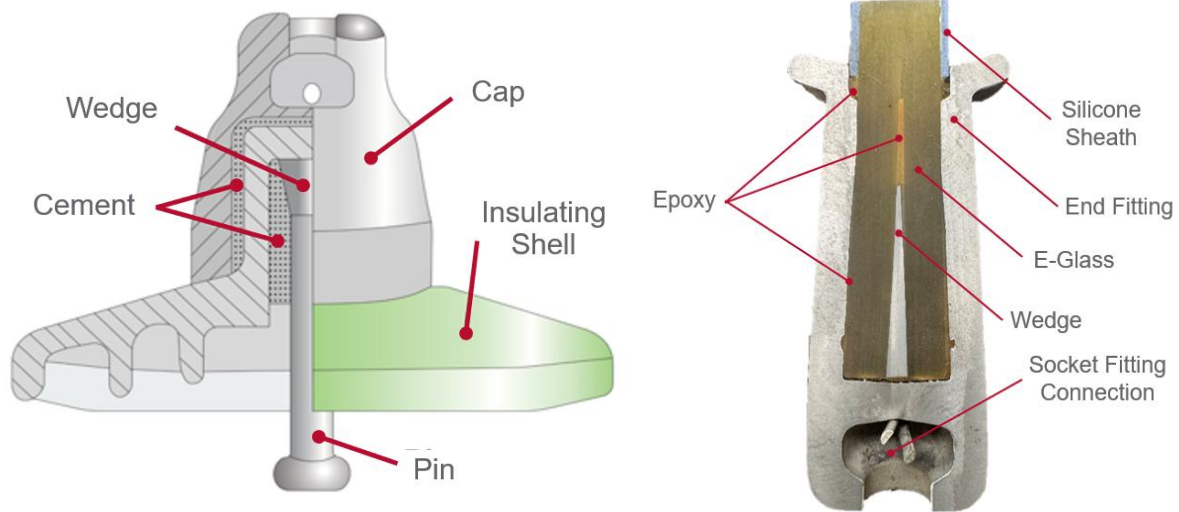


Figure 1: Ceramic (left) and Polymer (right) Wedge Epoxy Attachment Examples

In polymer applications, the end fitting, typically a socket and ball configuration—was engineered with a tapered end fitting shape: a smaller inner diameter at the top and a larger inner diameter at the bottom. To facilitate attachment, the fiberglass rod was split along the axis of the rod at the end, and a steel wedge was inserted into the tip of the split. As the rod was driven into the end fitting, the wedge forced the split rod to expand at the base, locking it into place. During this insertion process, epoxy resin was applied and allowed to cure, completing the mechanical and chemical bond. While effective, this method had design and quality limitations, prompting further innovation in attachment technologies.

1990's

The introduction of the first compression attachment method marked a significant advancement in polymer technology, revolutionizing how end fittings were secured to core rods. This innovation enabled the use of smaller-diameter core rods that could withstand higher tensile loads, while also allowing for more compact and lightweight end fittings without compromising strength. However, the compression process varied widely among manufacturers, with some employing 2-die tooling and others using 4, 6, or even 8-die configurations. As with any emerging technology, this evolution came with challenges—one of the most critical being the management of rod cracking during compression, which required careful process control and ongoing refinement to ensure reliability and performance.

Hydraulic Press and Die Tooling

Compression of the end fitting onto the rod was typically performed using hydraulic presses, which provided the necessary force to achieve a secure mechanical bond. A variety of die concepts were employed in this process, ranging from simple two-die setups to more complex configurations involving four, six, or even eight dies. These die arrangements influenced the uniformity of pressure distribution and the overall effectiveness of the compression, with each manufacturer tailoring their approach to optimize performance and minimize issues such as rod cracking.

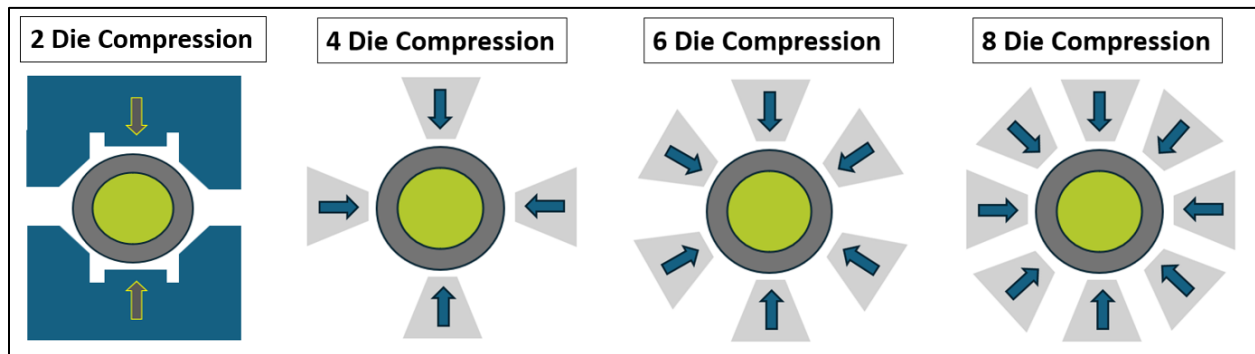


Figure 2: Compression Die Configurations

Core Rod Cracking

Rod cracking during the compression process was caused by a variety of factors. These included excessive or uneven compression forces, which could introduce stress concentrations in the rod material, and poor alignment between the rod and end fitting during pressing. Material incompatibility, such as mismatched thermal expansion rates or inadequate bonding surfaces, also contributed to cracking. Additionally, environmental conditions like temperature and humidity, as well as insufficient surface preparation or contamination, could weaken the rod structure. Variations in die design and tooling setup further influenced stress distribution, making process control and consistency critical to minimizing failures. An example of a cracked rod is shown below in *Figure 3*.



Figure 3: Example of Radial Crack from Compression

What caused the rod to crack during the compression process?

- **Excessive Compression Force**
 - Applying too much pressure can exceed the rod's material limits, leading to fractures
- **Uneven Pressure Distribution**
 - Poor die design or misalignment can cause localized stress concentrations
- **Rapid Compression Cycle**
 - Fast or abrupt compression can shock the material, especially in brittle or thermoset rods
- **Improper End Fitting Design**
 - End fitting material quality
 - Material too soft or too brittle
 - Wall thickness too thick or too thin
- **End Fitting Parting Line Mismatch** (*figure 4*)
 - During end fitting manufacturing process, the end fittings are made with 2-piece cavities that leave a parting line along the axis of the end fitting. Even a small mismatch (0.01") can cause uneven compression force application (Point Loading).
- **End Fitting Barrel OD & ID Not Concentric** (*figure 4*)
 - The rod is not centered inside the end fitting. Early compression end fittings were not machined to assure concentricity of the ID and OD. Machining also eliminated parting line mismatch, so it was a critical requirement for reliable end fitting attachment.
- **Compression Over the Rod End**
 - When the crimp die compresses the end fitting over the end of the rod, the rod will have a higher propensity to crack. This was an issue with the compression process, where the length of the die may have been too long, or the end fitting was not properly aligned in the compression press. In any case, it was a lesson learned that improved attachment performance.
- **Point Loading**
 - The result of most of the issues defined above resulted in point loading during the compression process. Regardless of how many dies were used, point loading occurred when only 2 dies applied force to the end fitting, deforming the rod from the applied force. See *Figure 5* below, where when the 2 dies compress, the rod ovalized (step 2). As the remaining dies then make contact with the end fitting and ovalized rod, the secondary compression causes the rod to crack radially.

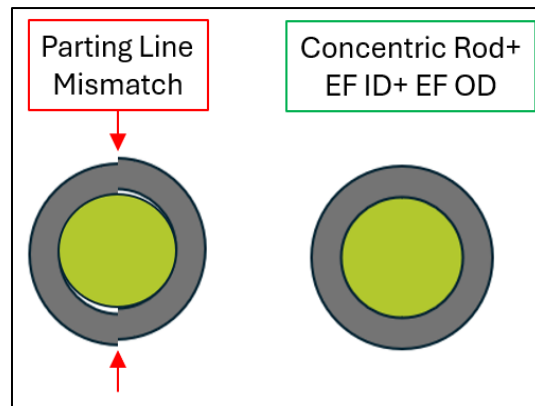


Figure 4: Parting Line Mismatch & Concentricity

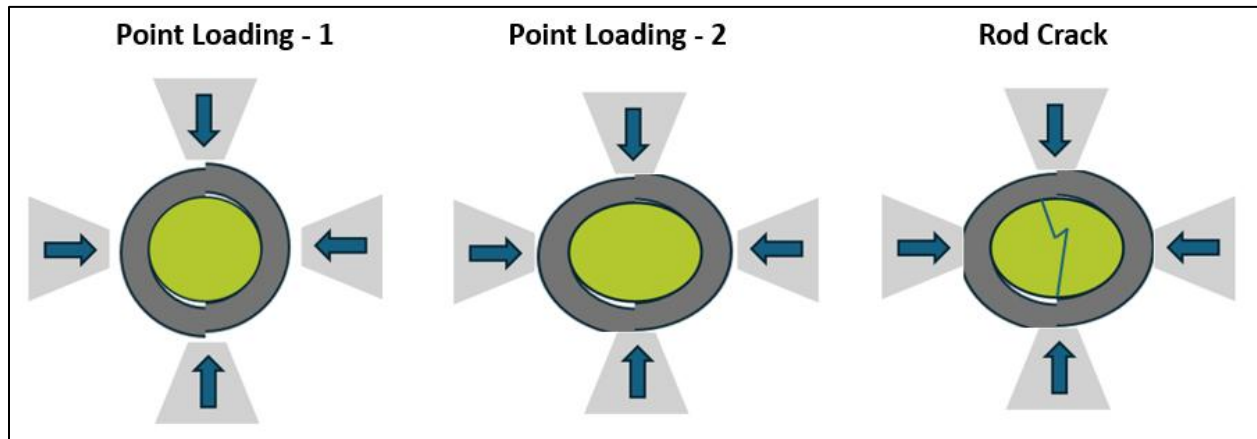


Figure 5: Point Loading Causing Rod Cracks

What steps were taken to mitigate concerns of rod cracking during compression?

A combination of solutions was implemented to address rod cracking concerns—some manufacturers refined their compression designs & processes to reduce stress on the rod, while others developed detection methods to identify cracks during production and prevent defective insulators from being shipped. The Improvement made to the compression process will be addressed in detail in the next section. This section will focus on the detection methods used to identify when rods had cracked.

Detection Method #1 - Mechanical Tensile Validation

ANSI requires that every insulator is RTL tested prior to shipment to the customer. RTL is the Routine Tensile Load, which is the working tensile limit the insulator is to be used for in service. The RTL is 50% of the SML (Specified Mechanical Load), which is the ultimate tensile load that the insulator can withstand before failure.

RTL Testing – every insulator made and shipped must be RTL tested. This test is designed to determine that the end fitting attachment was completed correctly. It could identify some internal cracked rod issues, but it is not a 100% accurate test for rod cracking. Depending on the location of the rod crack, there may be sufficient mechanical strength to withstand the RTL load. Therefore, this alone was not and is not a viable solution to identify internal cracked rod.

SML Testing – Ultimate strength testing is typically completed as part of Design Test, Batch Test, or Lot Test. Testing an insulator to SML rating is not practical, as the result would most likely lead to some deformation and reduction of the original tensile strength. This test does play an integral role in establishing the compression process as reliable and consistent, and it would identify a crack internal crack, but as these are sacrificial designs used for validation, this test method did not provide any validation to the remaining production units that were only tested to RTL.

Detection Method #2 - Acoustic Emission Testing

A listening device equipped with specialized sensors can detect AE (Acoustic Emission) waves to identify and monitor cracks in a rod as part of a non-destructive testing (NDT) method. The AE listening device would be integrated with the compression process. AE sensors are attached to the end fitting. These sensors are highly sensitive and convert the received mechanical energy from the AE waves into electrical signals that can be recorded and analyzed. The recorded signals are processed to identify crack-related acoustic events.

Was the use of acoustic emission devices the answer to rod cracking concerns?

The use of Acoustic Emissions did help identify cracked rods, and listening for the rod crack defect to prevent it from getting out of the field was a good short-term fix, but it was not the true solution to the problems that caused the rod cracks.

Acoustic listening devices were found to be extremely sensitive pieces of equipment and unreliable for a variety of reasons. The first reason is because of all the unwanted background noise inside of a manufacturing plant that is picked up by the sensor. These devices ultimately needed significant correlation studies to determine what reading signified rod cracking. Even still, the device unfortunately could produce false positives and false negative results, potentially allowing a crack rod to get shipped,

and sometime identifying a crack when in fact it did not. This was uncovered as part of rigorous testing and evaluation of production units identified as bad and good.

The bigger issue with using Acoustic Emissions is that it only identifies a defect after it has been made. These suspect units are scrapped, leading to higher scrap rates, which increase overhead cost of the insulators. Ultimately, the solution to rod cracking was to identify the root causes of the rod cracking and engineer them out of the process, eliminating the need to listen for defects after they were made. From this point on, the Compression process will be referred to as Crimp Technology, as every aspect of the process has been upgraded and improved.

Current State Crimping Technology

Radial crimping leads to an even distribution of pressure across the entire circumference of the fitting. This results in consistent material deformation in the fitting and mechanical interference with the rod. As was previously discussed, every aspect of the old compression process has been improved. One of the most significant improvements was the upgrade of equipment controllers. Old controllers on crimpers had variability of up to 25 bar of crimp pressure, and it was up to the manufacturer to catch these pressure spikes. Significant enhancements in repeatability were achieved via better hydraulic control systems and two stage hydraulics which lowered crimp pressure variability down to 5 bar. This is one of the key criteria of a proper crimp process where crimp cracking is completely designed out of the process and acoustic emissions testing is obsolete.

With the addition of automation and sensing integrated into the crimping process, it is possible to compensate for small component deviations since the crimp pressure and process are monitored by the equipment as abort criteria and controlled with upper and lower control limits.

Automation has allowed for the integration of RFID (Radio Frequency Identification) technology into crimping equipment which has significantly enhanced the reliability and repeatability of mechanical connections in polymer insulator manufacturing. By embedding RFID tags into crimping dies and tools, machines can automatically verify tool identity, load the correct crimping parameters, and prevent manual operator input error. RFID-enabled systems also log critical process data such as die ID, crimping force, and operator credentials, creating a digital record for each insulator. This level of control ensures consistent mechanical bonding and long-term field performance.

This emphasizes the importance of proper crimping equipment in addition to the materials and design choices previously discussed.

Crimp Studies & Testing

Through proper crimp studies and quality control testing, the risk of cracking a rod during crimping can be eliminated. Crimp die length, crimp die width, rod diameter, contact surface area, and many other variables are used to calculate the theoretical pressures applied to the fitting and the rod. These equations plus years of crimp test history and data ultimately result in a predictive calculator that can be used as the basis for a crimp ramp up study. In this study, a specific crimp pressure is applied to the polymer insulator, and the resulting tensile test performance is documented. This process is repeated numerous times with incremental increases in crimp pressure, and a resultant line graph is formed.

As would be expected, the results show that the tensile capability increases as the crimp pressure increases. This increase has a limit, which is represented by a plateau in tensile strength. When the crimp pressure is so high that it overcomes the interlaminar shear strength of the fiberglass, a radial crack forms across the rod. This perpendicular crack breaks the rod into two pieces and completely compromises the mechanical integrity. This explains the sharp drop in tensile performance after the plateau. An example of a crimp ramp up study is shown in *Figure 6* below.

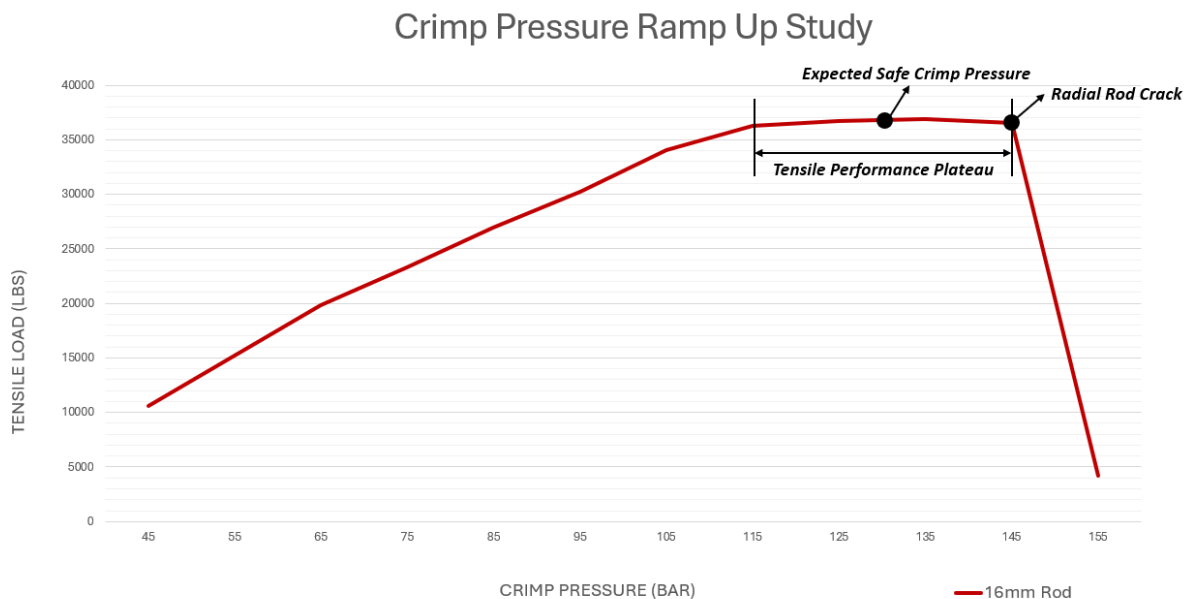


Figure 6: Example Crimp Ramp Up Study for 16mm Rod

From this study, a nominal crimp pressure is chosen from the middle of the plateau in order to maximize performance while eliminating the risk of cracking the rod. This nominal crimp pressure is further verified by crimping a batch of insulators to that same value and measuring their tensile performance. These testing results can be evaluated through statistical analysis to ensure that the selected crimp pressure meets the desired mechanical rating to a certain level of statistical confidence. This leads to statistical process control by setting upper and lower control limits and full confidence in the published ultimate load ratings (SML).

Conclusion

The evolution of crimping in polymer insulator manufacturing has transformed the reliability and repeatability of end fitting attachment. Through decades of material refinement, equipment innovation, and rigorous testing, processes have been developed that ensure high mechanical performance without compromising the integrity of the fiberglass rod. By carefully selecting materials, optimizing crimp geometry, and employing servo-driven equipment with integrated RFID tracking, manufacturers can achieve consistent, crack-free crimps.

Crimp ramp-up studies and statistical process control further validate the process, allowing engineers to define safe operating windows and eliminate the risk of rod cracking. When design, equipment, and testing are thoughtfully engineered and executed, the need for acoustic crack detection during crimping is eliminated. Listening for rod fractures may have once been a reactionary measure, but with today's predictive modeling and high precision systems, success is built into the process from the start.