Post Galvanizing Toe Cracks in Welds:
Can We Continue to Rely on a "First Aid" Approach to this Problem?

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Can We Continue to Rely on a "First Aid" Approach to this Problem?

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ABSTRACT

Galvanized, tubular steel pole projects have long been known to have a susceptibility for the discovery of post galvanizing weld toe cracking in the fracture critical flange/base plate to pole shaft welds. Dating back to the early 1970's, numerous technical papers have been written and presented on this critical structural reliability issue. So why haven't we been able to "cure" or eradicate this critical weld cracking issue? Or can we, but the collective will power is not in place to enforce the welding "health regimens" that are known to ensure this type cracking doesn't occur in the first place? This paper/presentation will first review and summarize the several factors that have been shown to cumulatively contribute to the occurrence of post galvanizing "toe cracking" in these type welded joints in tubular steel poles. And secondly, the paper/presentation will discuss the merits of our industry in continuing to rely on programs for repairing these cracks as they are found post galvanizing – a "first aid" approach, instead of requiring diligent manufacturing quality programs and robust manufacturing procedures that serve to prevent them in the first place.

Background

The tubular steel pole industry has been dealing with the challenges of post galvanizing toe cracks in "T-Joint" type welds for more than 45 years. A visual schematic describing a toe crack is shown in Figure 1 (excerpted from EPRI Procedure M-8: Toe Cracks). In 1973, an article appeared in the ASCE Journal of the Structural Division entitled "How Safe Are Your Poles"[1] by Mr. Joseph R. Arena. The article was among the first published that began to outline the importance of welding and weld inspection in the fabrication of tubular steel poles for electrical transmission and substation structures. In the few years prior to the publishing of that article, several large utilities had experienced serious weld cracking issues on their galvanized tubular steel poles. Many of those weld cracking issues were determined through examination to be post galvanizing toe cracks. A toe crack is a crack in a weld that initiates at the toe of the weld where the deposited weld metal and the heat affected zone (HAZ) of the base metal adjoin. When this cracking occurs during, or immediately following the galvanizing process, we have come to refer to it as a "post-galvanizing toe crack". The major fabricators of tubular steel poles manufacturers are well aware of the issue due to the very specific inspection requirements that

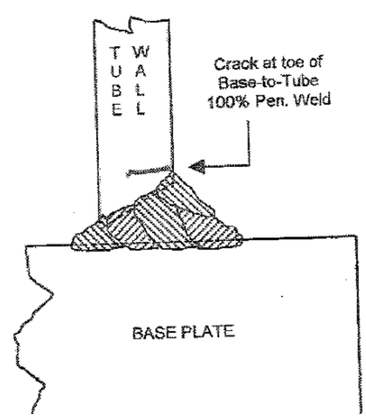

Figure 1

[1] Arena, Joseph R., "How Safe Are Your Poles?" Journal of the Structural Division, ASCE, Vol. 99, No. ST7, July 1973, pages 1333-1347.

are included in the ASCE 48 Standard. A very thorough review of the matter was also published in a 2006 paper titled "Toe Cracks in Base Plate Welds – 30 Years Later"[2] by Richard Aichinger, and Warren Higgens. Their study included a very thorough investigative process that covered the many steps involved with manufacturing tubular steel poles – everything from design, materials, welding, etc. through the galvanizing processes being used. This was an important roadmap provided to the industry on recommended actions and improvements. This roadmap was provided 12 years ago, and it provided a number of actionable recommendations that could be taken to minimize, if not eliminate, the occurrence of post-galvanizing toe cracks.

Yet, as an industry, despite this in-depth knowledge of the contributing factors, and recommendations to minimize their occurrence, there appears to be an increasingly significant number of post galvanizing toe cracks occurring on galvanized tubular steel poles. Fortunately, many of these cracks can be discovered by diligent inspection following galvanizing, and when found, can be repaired before the material ships to be installed on a line. But when such weld cracks are not discovered, the results can be catastrophic. Many of the steel pole suppliers appear to be content with adopting reactive measures to this post galvanizing issue, preferring to "find and fix", rather than adopting the proactive measures to prevent such cracks from happening in the first place. This might be a risky choice since these cracks, occurring on fracture critical welds, can lead to catastrophic failure of a steel pole.

The Contributing Factors?

The Aichinger and Higgins study, the most comprehensive study published to date, uncovered a number of contributing factors leading to a root cause of the occurrence of post-galvanizing toe cracks in large "t-joint welded connections. In no particular order of importance, they are summarized to be:

- High base plate to pole shaft volume ratio (measured as base plate weight per bottom 12" of shaft weight).
- High residual tensile stress in the deposited weld during solidification
- High heat input during the welding process
- Highly restrained joint characteristics
- Stress concentrations or stress risers due to the weld profile being deposited
- Stress concentrations or stress risers due to welding techniques being used (i.e. stops and starts especially at the bend lines)
- High carbon equivalency of the steel comprising the welded joint
- High tensile strengths of the steels being joined
- Steel or weld consumable chemistry that includes high silicon content.
- Exposure to the thermal gradients of hot-dipped galvanizing

In addition to the above factors, an additional potential contributing factor to the issue of post galvanizing toe cracks, is hydrogen from the "pickling" acids (HCL, or H2SO4) used to clean the steel. Either can tend to infuse hydrogen into the steel and welds during the cleaning, or "pickling" process, although H2S04 has been found to be a higher contributor to such hydrogen infusion. As a result, hydrogen

[2] Aichinger, Richard, Higgins, Warren, (2006). "Toe Cracks in Base Plate Welds, - 30 Years Later", Proc., ASCE Electrical Transmission Line and Substation Structures Conference, ASCE, Reston VA, 274-285.

induced cracking (HIC), also referred to as hydrogen assisted cracking (HAC), can occur on the welds and in the HAZ of those welds, if the dwell times in these tanks are not monitored carefully. Most galvanizers today appear to do an adequate job of controlling this.

Again, the question that needs to be asked is this. If we know generally the contributing factors to the occurrence of post galvanizing toe cracks, why haven't most steel pole suppliers been able to eradicate, or at least minimize, this critical weld cracking issue? Part of the answer to that question is in the attention to details that is necessary to diligently attack the post galvanizing toe crack issues. Let's review what that attention to detail requires.

What Attention to Detail is Necessary to Prevent Post-Galvanizing Toe Cracks?

All the contributing factors mentioned above require significant attention to the details of fabrication surrounding those factors. Some suppliers do a better job of monitoring these details than others and accordingly have a lower incidence of post galvanizing toe cracks. A review of each of the factors than have been found contributing to the occurrence of post galvanizing toe cracks follows. Attention to these details will proactively minimize these contributing factors.

High base plate to pole shaft volume ratio (measured as base plate weight per bottom 12" of shaft weight).

This is a product design detail. Very few steel pole suppliers are likely providing design limits of the base plate to pole shaft volume ratio. The lower the base plate to pole shaft volume ratio as calculated by the base plate weight divided by the weight of the bottom 12" of pole shaft, the lower the probability of post galvanizing toe cracks occurring. However, minimizing this ratio may not result in as efficient a design as would be possible without such consideration. Without limits, a design engineer will most likely strive for optimized material efficiency in both the base plate/flange plate and the pole shaft and override the contribution of this ratio to the toe cracking issues.

High residual tensile stress in the deposited weld during solidification

High residual tensile stresses in the deposited weld will generally be caused by the cooling rate of the weld. The application of pre-heat to the materials being joined will serve to slow down the cooling rate of the weld. Most fabricators will strive to meet the minimum pre-heat required by AWS D1.1 for the thickness of the plates being welded. The Aichinger and Higgins study actually recommended that the pre-heat exceed the minimum AWS D1.1 requirements. Few, if any suppliers follow this recommendation.

High heat input during welding the welding process

Heat input during welding is a measurable variable and is a function of volts, amps and travel speed of the deposited weld. Again, the Aichinger and Higgins study recommended that the heat input for these welds with a susceptibility for post-galvanizing toe cracks be limited to less than 65 kJoules per inch of deposited weld. The heat input calculation can be performed based on the weld procedure specification (WPS) qualified by the supplier. Many times, we find higher heat inputs than the 65kJoules per inch will be realized based on the WPS parameters. If the welding parameters are not being adhered to on the shop floor, the welding heat input recommendation can be further exacerbated.

Highly restrained joint characteristics

This characteristic is a geometric problem with diameter and thickness of the tubular shaft and base plate. By providing direct and close attention to pass sequencing, size of passes, etc., the influence of a highly restrained joint can be minimized. Few suppliers vary their welding practices based on improving joint restraint conditions.

Stress concentrations or stress risers due to the weld profile being deposited

The weld profile can greatly contribute to the stress concentration at the toe of the weld. The Figure below illustrates this. Both fillet welds are considered identical in strength, however the abrupt intersection of the reinforcing fillet weld of the profile on the left is far more susceptible to toe cracking than the gradual transition of the fillet weld on the right. Fabricators paying attention to this detail during welding and quality control checks can minimize the influence of this type stress concentration / stress riser.

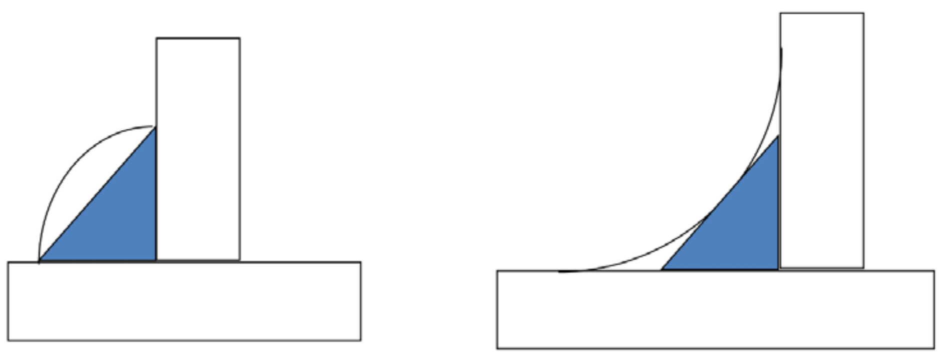

Figure 2

Stress concentrations or stress risers due to welding techniques being used (i.e. stops and starts especially at the bend lines)

Weld pass "starts" and "stops" can create stress concentration or stress risers, particularly if they occur on the bend lines of the pole shaft. This is illustrated in Figure 3 below. The circled toe crack that occurred is on a bend line, and the pass "starts" and "stops" are evident on the individual passes at that location as well. A better practice would be to minimize this contributing factor by welding the passes from mid-flat to mid flat, thereby placing these potential stress concentrations / stress risers in a lower stress region of the weld.

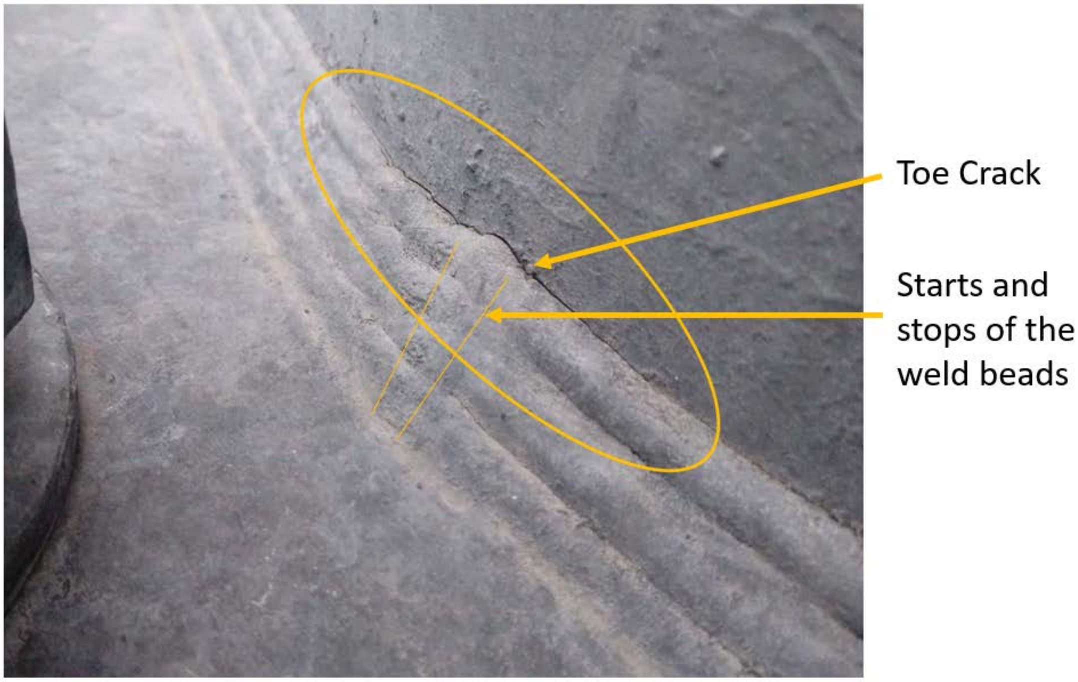

Figure 3

High carbon equivalency (CEV) of the steel comprising the welded joint

Carbon, and the alloying elements in the steel chemistry that mimic carbon from a weldability perspective need to be addressed in a very detailed way (generally by addition of more pre-heat) if the total carbon equivalency of the steel being welded exceeds certain thresholds. General guidance from the welding community is that a CEV of less than 0.45 is desired. Any CEV higher than that would necessitate special precautions to ensure "weldability". The CEV values are generally included on the Material Test Reports (MTR's). It is not uncommon to find these are not being adequately checked prior to the steel being placed into production. It is also not too uncommon in recent observations to find CEV values exceeding 0.50. Without knowledge of this on the shop floor, the needed special attention will not be realized.

High tensile strengths of the steels being joined

ASTM specifications define "minimum" tensile and yield strengths required. However, it is more commonly being observed that, without maximum limits being established with the suppliers of the steel, the "minimum" tensile and yield strengths can be exceeded by a 20%-40% or more. This is a case where more strength is not better. Welding procedures are established with the expectation that the steel will be a certain strength. Sample plates are welded and tested to confirm performance of the weld. When the steel tensile strength and yield strength varies by such a significant amount above the strength used in the procedure qualification test plates, there is no assurance that the provided weld will perform as expected. Welding effects on the higher strength steel can have a negative influence.   A number of steel pole suppliers do attempt to place limits on the tensile and yield strength maximum values that will be accepted on materials that will be galvanized. But several do not require such maximum limits.

Steel chemistry that includes high silicon content.

A high silicon content in the steel being welded can potentially lead to a higher likelihood of liquid metal embrittlement (LME) during galvanizing. Most steels used by fabricators of galvanized steel poles limit the silicon content to provide a better aesthetic (more uniform coloration of the deposited zinc coating). By default, this helps limit the possibility of LME. However, almost all steel pole fabricators use dual purpose welding wire (one that qualifies for both weathering steel and galvanized steel weldments) but is not silicon controlled. More studies are needed to understand if the use of dual purpose could be contributing to higher incidences of toe cracking following galvanizing.

Exposure to the thermal gradients of hot-dipped galvanizing

The hot-dipped galvanizing process consists of dipping a steel pole section into an 840 deg. F. molten bath of zinc. This can create considerable thermal gradients on a section depending upon the speed at which the steel heats up during immersion as well as the speed at which the section cools down following extractions. This is generally out the hands of the steel pole suppliers, but they should be monitoring this work as any other subcontracted work would be monitored to make sure best galvanizing practices are being followed.

On Being Proactive (A Prevention Approach) Rather Than Being Reactive (A Detection Approach)

Taking a reactive approach to this problem is not necessarily trying to prevent an opportunity for toe cracks to occur, but rather appears to focus on detection of toe cracks after they occur. Given the low probability of detection (POD) that some steel pole suppliers have in effectively locating and then remediating post galvanizing toe cracks, this reactive approach seems risky and unreliable. In other industries where such POD studies have been made[3], the POD of weld cracks at least ½" long using any of the conventional nondestructive testing (NDT) methods, has been shown to be less than 70%. And that does not include the added challenge of performing this inspection over galvanized coatings as is necessary on galvanized tubular steel poles. In other words, almost 1/3 of weld cracks could go undetected, and of course, could propagate into more serious cracking under stress. Most of the poor detection rate can be attributed to lack of experience and skill by the individual inspector. But even skilled technicians can lose focus and attention at times during an inspection. Taking care to prevent these toe cracks from forming in the first place would seem to be a preferable and a more reliable approach.

[3] "Railroad Tank Car Nondestructive Methods Evaluation" U.S. Department of Transportation, Federal Railroad Administration Office of Research and Development, 1120 Vermont Avenue, NW, Washington, DC 20590

Why is this important? As stated above, these cracks can propagate and get larger when the welded joint must resist an applied load creating stress. These toe cracks can also serve as discontinuities that facilitate and increase the susceptibility of the joint to fatigue fracture. When these welded joints are “fracture critical” (meaning failure of the joint will likely result in catastrophic failure of the structure), attention to prevention is warranted.

Conclusions

In our opinion, the steel pole industry has the knowledge, skills, and tools to prevent the occurrence of post galvanizing, toe cracks on “T-Joint” welds such as base plate or flange plate to pole shaft welds. It can be argued that post galvanizing toe cracks might be an issue on large arm shaft to bracket welds as well. To prevent such cracks from occurring requires diligent attention to the several critical details that have been found to be highly influential to the development of post galvanizing toe cracks throughout the entire process of fabricating a steel pole. With the average post galvanizing toe crack inspection detection rate of these initially small, bend line weld cracks likely being something less than 70% with currently available NDT technology used by the average NDT technician, it would make sense that a better, more reliable approach, would be a focus on prevention, rather than rely on detection to provide a cure to these potentially catastrophic defects.

REFERENCES

ASCE (American Society of Civil Engineers). (2011) *Design of Steel Transmission Pole Structures*, Standard ASCE/SEI 48-11. ASCE, 1801 Alexander Bell Dr., Reston, VA

AWS (American Welding Society) (2015) *Structural Welding Code – Steel*, 23rd Edition, AWS D1.1/D1.1M:2015, AWS , 550 N.W. LeJeune Road, Miami, FL

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