IMPLEMENTATION OF NARROW-GAP IMPROVED ELECTROSLAG WELDING FOR BRIDGE FABRICATION

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BIOGRAPHY

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SUMMARY

Narrow-gap improved electroslag welding (NGI ESW) is an updated version of an old process, optimized to provide better toughness and fewer defects while increasing productivity. Since the Federal Highway Administration (FHWA) lifted its moratorium on electroslag welding for bridge welding in 2000, the American Welding Society has been working to include NGI ESW in its D1.5 Bridge Welding Code, and a number of fabricators have purchased equipment for using the process.

Use of the process is expected to lead to considerable labor savings, but thus far implementation has demonstrated additional costs and process limitations that cut into the potential savings. The implementation of NGI ESW required close collaboration among researchers, code-writers, owners, and fabricators, each of whom had independent priorities and philosophy.

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INTRODUCTION AND BACKGROUND (1–5)

History

Electroslag welding (ESW) is a single-pass full-penetration vertical-up process in which the heat is generated not by an arc but by the resistance of a molten slag pool at the top of the weld. Because the weld is made in a single pass for virtually unlimited thickness, its deposition rate is many times higher than the dominant bridge welding process, submerged arc welding (SAW), with weld completion times measured in minutes rather than in hours. A weld that might take 8 hours with SAW could be done in about 20 minutes with ESW, not including setup time. With computer-controlled equipment, ESW can be a fully automatic process and thus far less dependent on operator skill than typical bridge welding processes; SAW is usually semi-automatic. Because it is a single pass, there are no interpass slag inclusions. The square groove configuration of ESW takes less time to prepare than the typical bevel groove of SAW. Figure 1 shows a typical NGI-ESW cross section.

Figure 1. NGI-ESW cross section.

The electroslag process was developed in the 1940s and 50s. It was widely used in the 1960s and into the 1970s, when concerns about weld quality led to the FHWA placing a moratorium in 1977 (FHWA Notice N 5040.23) on the use of ESW for bridge members under tension or reversal of stress, which effectively put an end to the use of ESW for bridge construction in the United States.

The ESW process in use at that time was not very robust. It was highly susceptible to piping porosity; any restarts in the weld created a full-thickness defect, all the more severe because ESW is typically used for thicker material; and both the heat-affected zone (HAZ) and the weld itself had very low toughness. Other typical defects included inclusions along the fusion line and poor fusion near the weld face.

Development of NGI-ESW

After the imposition of the moratorium, the FHWA instituted a research project to improve the ESW process. The result of this research was the Narrow-Gap Improved Electroslag Welding (NGI-ESW) process. After a series of demonstrations of the improved process in the late 1990s, the moratorium was rescinded in 2000 and the NGI-ESW process was explicitly permitted. The memorandum rescinding the moratorium and summarizing the research was issued March 20, 2000, and is currently available on the FHWA website at <http://www.fhwa.dot.gov/bridge/esw.htm>. The full research reports are also available from the FHWA (1−3). The principal findings are summarized in this section.

NGI-ESW eliminated most of the drawbacks of ESW. The primary means of improving the weld and HAZ toughness was lowering the heat input. Typical heat input in standard ESW had been around 2000 kJ/in, whereas the target heat input for NGI-ESW is below 1000 kJ/in. A lower heat input means faster cooling of the weld and thus smaller grain size, which increases toughness. Fortunately for fabricators, heat input can be lowered without sacrificing productivity, because a faster travel speed means less energy input per inch of weld. This can intuitively be thought of in terms of “dwell time”. Considerable research effort was devoted to determining optimum travel speed—the general rule was “the faster, the better,” but at extremely high speeds, solidification cracking or incomplete fusion can occur.

In the case of ESW, travel speed is the “fill rate” or “vertical rate of rise” as the consumable electrode is fed into the gap between plates. The travel speed was increased not only by increasing the wire feed speed but also by narrowing the gap between plates (hence the “narrow gap improved” name for the process), giving a much smaller cross-section to fill with the same input volume of consumable. In addition, the voltage, which is another contributor to heat input, was lowered significantly.

The welding wire chemistry was adjusted to optimize weld metal properties, improving toughness without encouraging cracking. The use of a tubular wire provides a shallower puddle, reducing solidification cracking. Solidification cracking is also reduced through the use of a low-carbon consumable guide. A diffusible hydrogen limit of 4 ml/100 g (“H4”) and the use of fused flux reduce moisture and hydrogen cracking (the diffusible hydrogen limit was added during the demonstration phase of the project). Prohibiting oscillation of the consumable guide reduces slag inclusions along the fusion line, and the use of a rectangular consumable guide allows for better fusion toward the weld face. Restarts within the weld are prohibited.

The research project did not investigate the use of NGI-ESW for fracture-critical members or AASHTO temperature zone III, so the process is still not permitted for these applications.

Figures 2 and 3 show the NGI-ESW setup. The guide cross-section shown in Figure 3 is a stylistic representation and not typical of proprietary guide designs currently used in production.

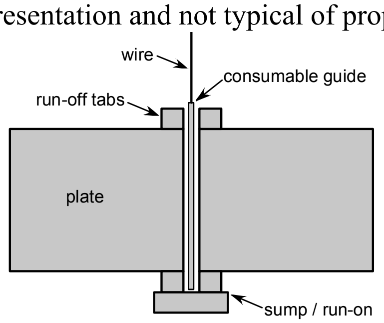


Figure 2. Top view of NGI-ESW setup

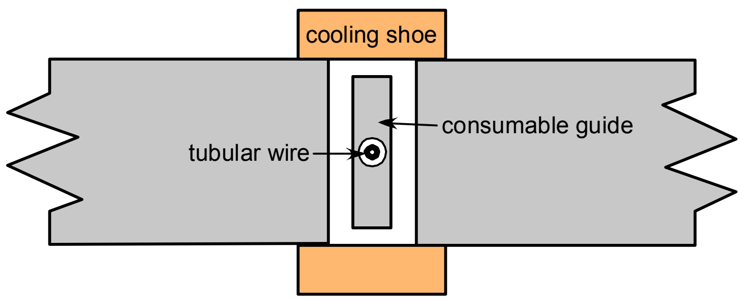


Figure 3. Side view of NGI-ESW setup

Figures 4 and 5 show a test plate in the fixture.

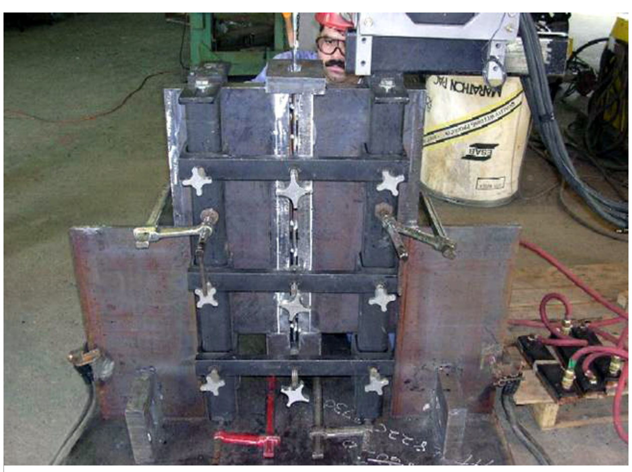


Photo courtesy of the University of Texas at Austin

Figure 4. NGI-ESW test plate without cooling shoes

Photo courtesy of the University of Texas at Austin

Figure 5. NGI-ESW test plate with cooling shoes

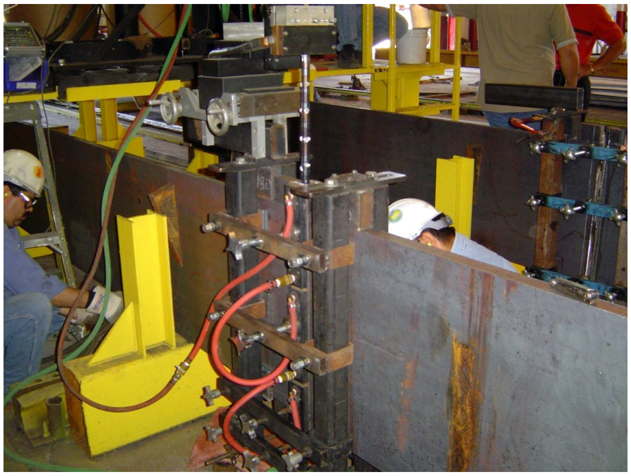


Figure 6. Girder flange in NGI-ESW setup

Figure 6 shows a full-sized plate girder flange in the NGI-ESW setup.

Implementation

Although the FHWA has been promoting the use of NGI-ESW for primary bridge members since the issuing of the 2000 memorandum, the process has yet to catch on. The primary reason has been that the AASHTO/AWS D1.5 Bridge Welding Code (6) still does not permit ESW in any form to be used for members subject to tension or reversal of stress. Over the last few years, proposed revisions to AWS D1.5 have been developed and at the time of writing are under ballot; a handful of states have agreed to permit the process even before the revisions to AWS D1.5 are published, although the earliest publication date would be several years from now; and a number of fabricators have purchased the equipment. Surprisingly, the biggest obstacle to implementation has not been technical difficulties but rather the struggle to convert academic research findings into useable specifications. The remainder of this paper will address some aspects of that struggle and look ahead to implementation in bridge girder production.

THE PATH TO IMPLEMENTATION

Implementation of the research conclusions was more difficult than anticipated, because of both technical and human factors.

"When Worlds Collide"

Researchers must understand how complex a set of interacting variables can be, and for them to speak in absolutes would be inaccurate. On the other hand, code and specification language must be clear-cut and enforceable. Where a researcher may say, "There are no guarantees," a code writer may say, "We have to draw the line somewhere." For code provisions to be written, the researchers had to distinguish firmly between which of their conclusions should be requirements and which could be considered merely as guidance, and choose cutoff points for various parameters that gave a reasonable expectation of success. Neither task was an easy one for researchers trained to consider all contingencies.

In addition, no research experiment can predict all the variability that will ensue when independent humans start to implement technology, and production never exactly replicates research conditions. When fabricators started making test welds, they sometimes chose combinations of parameters never considered by the researchers, and did not use identical equipment or consumables, which led to the discovery of new problems to be resolved.

Finally, the question of precedence of fabrication and code implementation can be an obstacle to both. Some members of the AWS Bridge Welding Subcommittee objected to amending AWS D1.5 to include a process that had no track record in bridge girder production. However, many if not most states will not allow use of NGI-ESW before the code is amended. Implementation will be led by a handful of states willing to allow use of NGI-ESW in accordance with the proposed but unpublished code revisions. This, however, leads to a risk for fabricators that the requirements may change when the proposal is modified as it moves through the committee process, and in fact some losses were incurred as problems with the proposed code language were discovered during welding procedure qualification.

Obstacle: Procedure Qualification

A major distinction between specification and academic philosophies, causing several months of delay in implementation, was the difference between qualification and optimization approaches. AWS D1.5 is formulated in terms of acceptable ranges for essential variables. Typically, welding procedure qualification tests are performed on a test weld, and the acceptable range of welding procedure parameters is determined with respect to the values used for the test weld. The focus of the research project, on the other hand, was to identify the parameters controlling weld quality and find the optimal combination—to find what worked well, not to discover how far the parameters can be pushed before problems occur.

This problem was, in essence, the question of whether NGI-ESW should be considered a full-blown welding process, or merely a procedure or specific method. The moratorium was rescinded with the success of NGI-ESW in mind as tested and demonstrated in the research project. The research recommendations include very rigorous testing requirements for the acceptance of alternative ESW processes. However, there is no clear definition of the difference from laboratory conditions that would classify a procedure as “alternative” instead of NGI-ESW.

The most conservative option would be to dictate that NGI-ESW production welding use exactly the same parameter values as those tested in research—for example, a set of prequalified welding procedure specifications could be published. A less conservative option that would allow the most fabricator flexibility would be the “if you can qualify it, you can use it” approach of AWS D1.5, in which any combination of variables that can pass a qualification test may be used.

Initially a test-based approach was attempted. The researchers provided allowable deviations from tested values for various welding parameters, and fabricators ran qualification tests accordingly. It was not until the procedure qualification stage that the relationships between the production and qualification procedures were examined closely. At that point it was noted that the interdependence of many welding parameters makes restriction of variables a very different matter for ESW. In multiple-pass processes, various plate thicknesses can be welded with the same procedure by adding more passes. Plate thickness is independent of other parameters. With ESW, the plate thickness, travel speed, and wire feed speed or current (current is a function of wire feed speed) are interrelated. Welding a thicker plate with the same number of electrodes requires changing either the travel speed or the wire feed speed. Independently qualified ranges for these various parameters could not be used as planned.

The approach ultimately taken was one that could be termed “semi-prequalified.” A range of allowable combinations of plate thickness and travel speed was set based on the researchers’ testing experience and the expected effect of variation, bearing in mind typical operating ranges already tested by fabricators. Current and wire feed speed are directly related to travel speed and so only one of these three parameters needs to be governed by specification. Other variables such as voltage were given tight operating windows. Under this proposal, a test weld must be made for each consumable configuration, but production procedures may be anywhere within the allowed ranges, regardless of the exact parameters chosen for the test. (5)

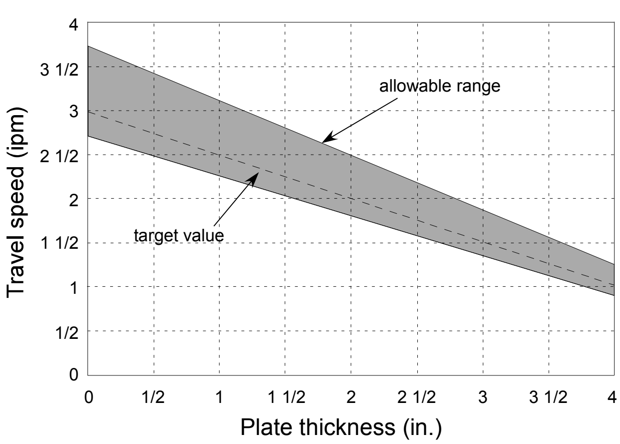


Figure 7. Allowable thickness and travel speed.

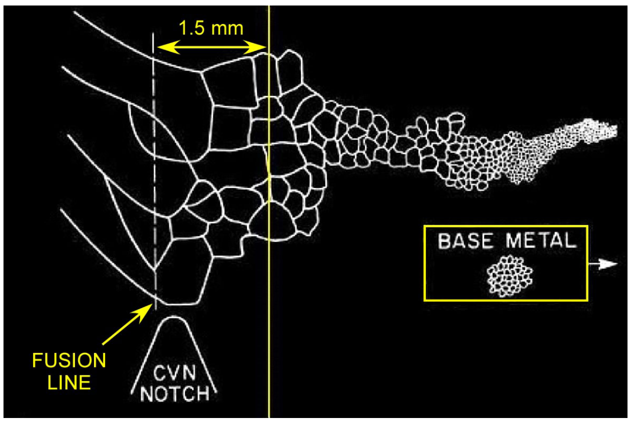
Figure 7 shows the proposed allowable thickness and travel speed combinations.

Despite the fact that production parameters will not be as tightly tied to test values as they are in other processes, the qualification test may be no less indicative of production weld quality. Medlock (9) showed that SAW production welds often have significantly lower toughness than qualification test welds because of differences in groove geometry and in workmanship. Since NGI-ESW is automated, workmanship is typically not a concern, and the weld geometry, other than variations in thickness, will be similar. (9,10)

Obstacle: Heat-Affected Zone Testing

One of the more difficult ESW weaknesses to resolve has been the toughness of the heat-affected zone (HAZ). The lower heat input of NGI-ESW has greatly improved HAZ toughness. In the research, extensive HAZ testing was conducted, and initially it was assumed that such tests would be part of the required qualification testing.

However, HAZ testing in practice is difficult and unreliable. Because HAZ toughness is highly dependent on base metal toughness, it is not possible to extrapolate production quality from test plate quality because the toughness of the base metal used in production may not be the same as that used in the test. In addition, the area of interest, the coarse-grained HAZ closest to the fusion line (see Figure 8), is a very small target, and the shape of the weld nugget makes preparation of the test specimen very difficult. HAZ toughness is required to match the specified toughness of the base metal. Both the HAZ sampling procedure used in the NGI-ESW research project and longstanding base metal specifications (7) require testing at the quarter thickness. Even in the relatively flat weld nugget seen in Figure 1, the HAZ is not perpendicular to the plate surface, and many electroslag welds are even rounder. It is next to impossible to machine a Charpy V-Notch (CVN) specimen (8) so that the notch falls squarely along the HAZ. Instead, an attempt is made to locate as much of the notch as possible inside the HAZ, as close as possible to the fusion face, without having any of the notch in the weld metal, which has much higher toughness.



Drawing courtesy of Portland State University

Figure 8. Coarse-grained HAZ

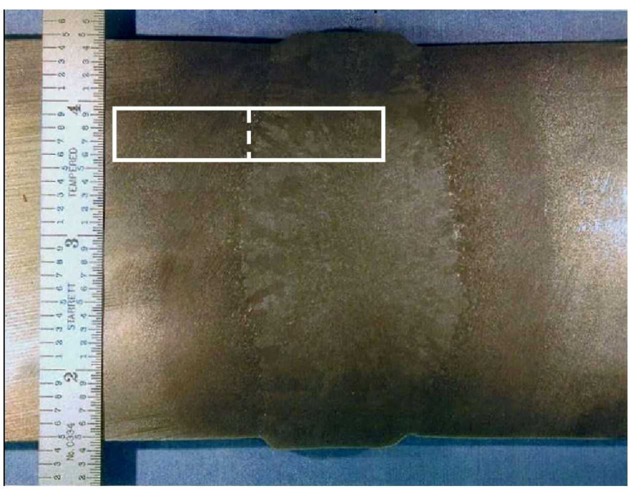


Figure 9. Location of CVN specimen with respect to weld

Figure 9 shows the location of the CVN specimen in relation to the weld nugget. Figure 10 illustrates "optimal" placement of the V-notch with respect to an HAZ that is not orthogonal to the specimen. The dotted line indicates the approximate depth of the coarse-grained HAZ. Not only will part of the notch lie further into the finer-grained HAZ and therefore reflect the higher toughness of that area, any error in notch placement will place even more of the notch away from the coarse-grained HAZ or even into the weld metal. Thus the test is inherently unconservative—most specimens will have higher toughness measurements than the true coarse-grained HAZ toughness.

The problems with HAZ toughness measurement are another reason to abandon test-based qualification. The HAZ CVN test is not reliable enough to determine from a single test weld whether a set of chosen parameters will give sufficient HAZ toughness. The operating ranges discussed in the previous section have been

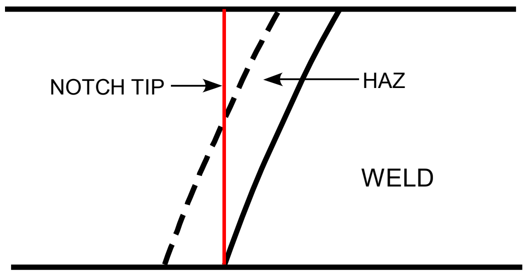


Figure 10. Location of weld with respect to HAZ.

demonstrated through research to give satisfactory HAZ toughness, and so reliance on the HAZ test is unnecessary as long as the welding is performed within those limitations.

It should be kept in mind that HAZ toughness is lower than that of unaffected base metal or weld metal in all welding processes, but HAZ testing is even more difficult in multiple-pass processes with small HAZ than it is with ESW. However, HAZ toughness is somewhat more of a concern in ESW because the HAZ is continuous.

Obstacle: Trace Elements in Wire

The research project looked very closely at the effects of certain elements, particularly nickel, titanium, and molybdenum. Limitations on trace elements were not investigated. The recommendations for maximum trace element content were formulated in the mid-1990s and were based on what was reasonably achievable at that time. Since then, the steel scrap supply has changed, and higher trace element levels are typically found in many steel products, including welding wire. When NGI-ESW test welds were made in 2004, wire meeting the trace chemistry requirements was not available. The researchers had to revisit their chemistry recommendations and re-establish "reasonably achievable" levels that were still well within what they consider to be safe limits. (5)

The Push

There were several forces propelling implementation of NGI-ESW past the obstacles. Initially, the FHWA promoted the use of the process through its demonstration projects and other announcements. Once fabricators had purchased the equipment, there was economic pressure to start using that equipment. There were also fears among some of the code-writers that too long of a delay in presenting a code proposal would cause the whole implementation process to founder.

Many research projects include a "beta" phase in which the research products can be tested in a real-world setting. This project did not formally include such a phase. Pressures described above thwarted attempts to delay submittal of a final code proposal until after production was well under way (an unofficial beta test of the code proposal). Problems uncovered during initial attempts at production use caused the researchers to revisit some of their recommendations—in essence, the initial group of fabricators and owners are participating in the continuation of the research project, assuming all of the expenses and financial risks (including time spent) of implementing an untried process, without the benefit of research funding.

Without enthusiasm and encouragement, a new process will never be implemented. However, in this case the pressure toward implementation led to several steps being taken prematurely. Adoption of NGI-ESW was promoted long before usable code provisions were developed—for instance, fabricators were encouraged to use NGI-ESW even before firm requirements for filler metal chemistry were in place—and those code provisions were sent to ballot before there was enough production experience or beta testing to verify that they would function as intended. Ultimately, all concerns are expected to be adequately resolved and no dubious welds have gone into service, but there were difficulties along the way that could have been avoided with some patience and proper beta testing.

FUTURE PROSPECTS

Production

Several fabricators have run successful qualification tests in accordance with an earlier draft of the proposed code modifications. At least one fabricator has tested successfully in accordance with the version under ballot, and began production in June 2005.

There are a number of economic factors that partially offset the high deposition rate of NGI-ESW:

1. Consumable costs are significantly higher than those for SAW. The consumable guides are particularly expensive. It is likely that as NGI-ESW comes into more use, more manufacturers will enter the market, and consumable prices will drop.
2. Setup takes longer than for SAW. Positioning the plates in vertical fixtures is more difficult than laying them flat, and there is more work involved in preparing to weld—not only must runoff tabs and sump be attached, but the shoes must be installed as well. Plate manipulation is a two-person operation, which effectively doubles the economic impact of the increased setup time.
3. At this time, NGI-ESW requires much more nondestructive evaluation than SAW. Both ultrasonic and radiographic testing (UT and RT) are required for both tension and compression welds made with ESW. For other processes, only RT is required for tension welds, and either UT or RT is required for 25% of compression welds. It is likely that as owner confidence increases, the RT requirement will be dropped for compression welds, and it is possible that the inspection levels for compression welds will be reduced to the 25% required for other processes. (It is less likely, but still possible, that the RT requirement will be dropped entirely, especially if automated UT is adopted by the steel bridge industry.) In the meantime, however, NGI-ESW carries a significantly increased inspection cost. Compounding this problem is the increased need for repairs to base metal defects discovered with UT. AWS D1.5 requires certain laminations to be repaired if they are discovered, whether the weld would be in tension or compression, but in 75% of compression welds made with SAW, there is no UT and so these laminations would not be discovered.

There are also operational factors that will make it easier for some shops than for others to implement NGI-ESW:

1. If a shop's "bottleneck" is its splicing operations, the increased efficiency of NGI-ESW will have a significant effect on the shop's productivity. However, if the shop's splicing operations are already getting ahead of other steps in the fabrication process, there is less to gain.
2. It has long been established that ESW is more efficient for thicker welds, because the deposition rate increases while setup time remains the same. Shops that tend to work with larger structures with thicker flanges will be better able to take advantage of this efficiency.
3. ESW is also known to be more efficient for longer welds, because setup time takes proportionally less of the total splicing time. Shops that find it economical to "strip" flanges after splicing wider plate will be able to make more efficient use of NGI-ESW.
4. The NGI-ESW fixtures can occupy considerable floor space. A shop that is tight on space may have sacrificed some of its conventional splicing area room in order to use NGI-ESW, and may not be able to afford to leave this area idle. They may have to either use NGI-ESW even when it is not at its most efficient (e.g., thinner plates), or spend time taking down and setting up the NGI-ESW fixtures to allow more SAW to be accomplished on projects that are not as well-suited to NGI-ESW.

High-Performance Steel (HPS)

Preliminary studies have been made of the use of NGI-ESW for Grade HPS 70W and HPS 50W steel. Although matching strength is achievable, the very high CVN requirements for HPS cannot be matched at this time. It is possible that NGI-ESW can be used when HPS 70W is chosen for strength rather than for toughness, but appropriate toughness criteria would need to be determined.

Fracture-Critical Welding

Although some have predicted that NGI-ESW HAZ toughness should be able to meet fracture-critical base metal toughness requirements, so far this result has not been reliably obtained. It is possible that with future refinement to the process and further development of fabricator expertise, toughness levels appropriate to fracture-critical work can be achieved. It is also possible that future research may indicate that lower toughness levels are acceptable for typical NGI-ESW applications.

AASHTO Temperature Zone III

Because toughness drops dramatically at lower temperatures, NGI-ESW HAZ toughness is not expected to match base metal requirements for Zone III, but this has not been tested. As with fracture-critical welding, the possibility of using NGI-ESW for Zone III applications at some time in the future has not been ruled out.

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