Pipeline Girth Weld Strength Matching Requirements

Requirements for pipeline girth welds in industry codes and standards are reviewed

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Cross-country pipelines are enormous engineering structures and represent the safest, most cost-effective way to transport crude oil, refined products, and natural gas over long distances — Fig. 1. Many changes in the pipeline industry have occurred over the past few decades, although many construction practices that were used prior to these changes are still used today. Significant changes include higher-strength line pipe steels, high-productivity mechanized welding equipment, and automatic ultrasonic inspection used in conjunction with fitness-for-purpose-based acceptance criteria. Despite these developments, many pipelines are still constructed using conventional “stove-pipe” welding methods (i.e., using cellulosic-coated electrodes), radiographic inspection, and workmanship-based acceptance criteria. While many long-distance transmission pipelines are constructed today using modern methods, tie-in and repair welds for these pipelines are often made using conventional methods.

A fundamental rule of welding engineering is that, in general, the strength of a weld should be greater than the strength of the base materials being joined. In the past, little difficulty has been experienced in meeting this fundamental rule during construction of cross-country pipelines. As the use of higher-strength line pipe material has increased, overcoming the strength of the base material with the weld has become more challenging, particularly when the girth welds are made manually using cellulosic-coated electrodes.

Several girth weld failures in newly-constructed pipelines have occurred in North America recently, either during pre-service hydrostatic pressure testing (Fig. 2) or soon after being commissioned. Some of these failures have been attributed to construction quality issues (Ref. 1), while others have been the result of undermatching strength and/or heat-affected zone (HAZ) softening in what would otherwise be considered “acceptable” girth welds. All the recent failures have been in girth welds made manually using the shielded metal arc welding (SMAW) process and cellulosic-coated (AWS E70X10-type) electrodes. Most of the failures have been in large diameter (30 in. [762 mm] and above) pipelines constructed using API 5L Grade X70 (L485) line pipe material. None of the recent failures have involved girth welds made using mechanized gas metal arc welding equipment.

Recent Industry Trends

Several recent industry trends that affect pipeline girth weld performance are outlined below.

Pipe Material Yield Strength

Transmission pipelines in the United States are regulated by the U.S. Department of Transportation (U.S. DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA). PHMSA issued two advisory bulletins in 2009 and 2010 to alert pipeline operators about recent trends that affect the safety of newly constructed pipelines. The most recent bulletin (ADB-10-03) (Ref. 2) pertains to girth weld quality issues and specifically mentions improper transitioning, high-low misalignment, and welding practices in general (e.g., welders not following qualified welding procedures) during the construction of large-diameter pipelines. The need for this bulletin followed a rash of girth weld failures and subsequent observations by PHMSA inspectors in the field. The prior year, PHMSA had issued an advisory bulletin (ADB-09-01) (Ref. 3) that alerted pipeline operators of the potential for low and variable yield and tensile strengths as well as chemical composition properties in high-strength line pipe. The need for this followed several instances of pipe diameter expansion during hydrostatic tests that were suspected to be the result of line pipe with low strength.
While ADB–10–03 would seem to be the most relevant to girth weld failures, it is ADB–09–01 that is influencing the most recent rash of girth weld failures.

The maximum allowable yield strength in API 5L (Ref. 4) for PSL 2 pipe is typically 20 ksi (150 MPa) above the specified minimum yield strength (SMYS) (~ 87 ksi [600 MPa] for X65 [L450] and ~ 92 ksi [635 MPa] for X70 [L485]). Since ADB–09–01, the trend for as-received line pipe strength levels has been toward the upper end of the acceptable range in API 5L. Some operating companies are specifying higher yield strength within their internal pipeline procurement specifications, and in turn, manufacturers are aiming higher within the acceptable range for yield strength (70 to ~ 92 ksi [485–635 MPa] for PSL 2 X70 [L485]) to account for variability in tensile testing practices by third-party labs (flattening procedure, Bauschinger effect, extensometer placement, etc.). Most deviations from ideal testing practices will tend to reduce the apparent strength, or increase the variability of results, which has negative implications on quality for line pipe manufacturers.

In addition, for large-diameter line pipe, there are no requirements in API 5L for tensile properties in the longitudinal (cross girth weld) direction. The strength in the longitudinal direction is sometimes higher than that in the transverse direction, particularly for helical seam welded line pipe. The yield strength in recently delivered helical seam welded X70 (L485) line pipe material was measured to be as high as 94 ksi (648 MPa). Weld metal from the use of cellulosic-coated electrodes is unlikely to overmatch this strength.

**Softening in the HAZ**

The alloying strategy currently being used by major line pipe manufacturers results in very lean chemical composition (e.g., carbon content less than 0.05%). This results in high resistance to hydrogen-assisted cold cracking in the HAZ but also a high susceptibility to HAZ softening.

In the early days of high-strength line pipe steels (e.g., X52s [L360s] in the late 1950s and X60s [L415s] in the early 1960s), the prevalent mechanism for achieving the required strength levels was to add conventional alloying elements such as carbon and manganese. This produced the desired effect in terms of strength levels but had an adverse effect on weldability. Carbon equivalent levels of these early high-strength line pipe steels were routinely in the 0.50 range based on the International Institute of Welding (IIW) formula. These high carbon equivalent levels promoted the formation of crack-susceptible microstructures in the HAZ, which combined with high weld hydrogen levels from the use of cellulosic-coated electrodes, resulted in a significant risk of hydrogen cracking. Fortunately, as steelmaking technology improved, higher strength steels that were developed in the following decade (e.g., X65s [L450s] and X70s [L485s]) began to rely on microalloying additions and thermomechanical-controlled processing to achieve the required strength level. This resulted in higher-strength line pipe steels with lower carbon equivalent levels and good weldability. What followed was a period where overmatching strength could be easily achieved using cellulosic-coated electrodes with a relatively low risk of hydrogen cracking in the HAZ.

In the twenty-first century, as the cost of microalloying additions began to rise and availability of these alloying elements became uncertain because of geopolitical reasons, steelmakers began to rely more heavily on thermomechanical-controlled processing such as water quenching and finish rolling at lower temperatures. This further reduced the need for alloying, and carbon equivalent levels of high-strength line pipe continued to decrease. This would seem to be an ideal scenario for the welding community, as the risk of HAZ hydrogen cracking has all but been eliminated. However, carbon equivalent levels have now decreased to the point where softening in the HAZ is now an issue. The welding community asked the line pipe manufacturers for low carbon equivalent materials, and they gave them to us. However, this approach may now be producing alternative negative impacts based on the current welding technology and practices.

**Undermatching Strength Consumables for Root Pass Welding**

Current practice for manual girth welds in X70 (L485) line pipe involves the use of E6010 electrodes for the root pass and E8010 electrodes for the remainder of the passes (see footnote). Conventional wisdom indicates that the strength level of the root pass electrodes has little effect on the overall strength of the completed weld be-

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1. For X70 (L485) line pipe, “70” represents 70 ksi [485 MPa] minimum required yield strength. For E8010 electrodes, “80” represents 80 ksi (551 MPa) minimum required tensile strength. The minimum required yield strength for E8010 electrodes is 67 ksi (462 MPa).
cause a portion of the root pass protrudes into the inside diameter of the pipe, and the portion within the pipe wall thickness is mostly ground away prior to hot pass welding.

A contributing factor to undermatching strength is the use of EB6010 consumables for the root pass, particularly in thinner materials where the root pass makes up a significant portion of the weld thickness — Fig. 3.

The use of EB6010 consumables for root pass welding in higher-strength line pipe was common in the 1960s and became more prevalent following work at the Welding Institute of Canada in the early 1980s (Ref. 5). At that time, high-strength line pipe was highly alloyed to achieve required strength levels. This resulted in high hardenability in the HAZ and an increased susceptibility to hydrogen cracking. The use of lower strength consumables for the root pass was shown to reduce the risk of hydrogen cracking by allowing strains in the root pass to be accommodated in the lower strength (i.e., more ductile) weld metal as opposed to the more highly susceptible HAZ.

Now that modern high-strength line pipe has a much leaner chemical composition, and a subsequent high resistance to hydrogen cracking in the HAZ, it may be time to revert to using matching strength electrodes for root pass welding.

Procedure Qualification Requirements

The purpose of qualifying a welding procedure is to demonstrate that the parameters specified in that procedure can produce sound welds under production conditions. However, production conditions are not often simulated during procedure qualification, so the use of common sense is required when determining suitable welding parameters and acceptance criteria. For pipelines constructed using cellulosic coated electrodes and workmanship-based acceptance criteria, there are no requirements for overmatching strength in industry codes and standards around the world.

In API Standard 1104, Welding of Pipelines and Related Facilities (Ref. 6), there is no requirement for the actual strength of the weld to exceed the actual strength of the pipe material. During procedure qualification, cross-weld tensile specimens are allowed to break in the weld as long as they do so above the specified-minimum tensile strength of the pipe material. In addition, there is no requirement to qualify the welding procedure on pipe material that is representative of what will be used for a specific project (i.e., on "project pipe"). It is only necessary to use a procedure that was qualified on the appropriate pipe grade. Different pipe materials of the same grade can have widely different tensile properties depending on whether they were made, the manufacturer, the method of manufacture, etc. For many applications (e.g., pipelines in nonflat terrain), it is good practice to at least match the actual yield strength of the project pipe. The requirements in other international codes and standards for pipeline girth welding simply mirror those in API 1104.

Tensile Testing Requirements in API 1104

The tensile test requirements (Section 5.6.2.3) in the 21st edition of API 1104 for pipelines constructed using workmanship-based acceptance criteria (Section 5) are as follows:

"The tensile strength of the weld, including the fusion zone of each specimen, shall be greater than or equal to the specified minimum tensile strength (SMTS) of the pipe material. If the specimen breaks outside the weld and fusion zone (i.e., in the base metal) at a tensile strength not less than 95% of that of the SMTS of the pipe material, the weld shall be accepted as meeting the requirements.

If the specimen breaks in the weld or fusion zone and the observed strength is greater than or equal to the SMTS of the pipe material and meets the soundness requirements of 5.6.3.3, the weld shall be accepted as meeting the requirements.

If the specimen breaks in the weld and below the SMTS of the pipe material, the weld shall be set aside and a new test weld shall be made.

If a specimen breaks outside of both the weld and the HAZ at a tensile strength not less than 95% of the SMTS of the pipe material, that specimen shall be accepted as meeting the test requirements.

Any specimen that fails due to improper specimen preparation or testing may be replaced and retested."

In API 1104, it is acceptable for the measured tensile strength across the weld to be less than the actual tensile strength of the pipe material. However, some pipeline designs (e.g., for high longitudinal strain applications) require matching or overmatching strength girth welds. The use of filler metal with yield strength that matches or overmatches the actual yield strength of the pipe material prevents longitudinal strains from accumulating in the weld region, which is more likely to contain imperfections than the pipe material. Such requirements should be specified in construction contract documents.

For the 21st edition of API 1104, the requirement was relaxed such that the tensile strength of the weld be greater than or equal to 95% of the specified minimum tensile strength of the pipe material. This accounts for API 5L only requiring tensile strength requirements be met in the transverse (circumferential) direction for welded line pipe 8 in. (219.1 mm) diameter and larger. The cross-weld tensile test required in Section 5 is performed in the longitudinal direction, and the longitudinal tensile strength of some line pipe materials can be lower than the transverse tensile strength.
Tensile Testing Requirements in Other Codes and Standards

Tensile testing requirements in the following codes and standards were reviewed and compared with API 1104:

- CSA Z662-15 — Oil and Gas Pipeline Systems (Ref. 7)
- BS 4515-1 — Specification for Welding of Steel Pipelines on Land and Offshore — Part 1: Carbon and Carbon Manganese Steel Pipelines (Ref. 8)
- ISO 13847 — Petroleum and Natural Gas Industries — Pipeline Transportation Systems — Welding of Pipelines (Ref. 9)
- ASME Section IX — Welding, Brazing, and Fusing Qualifications (Ref. 11).

Many of the international pipeline welding codes and standards have their roots in API 1104, and for pipelines constructed using workmanship-based acceptance criteria, the tensile testing requirements mirror those in API 1104. Only AS2885.2 requires procedure qualification on project pipe and all allow tensile test specimens to break in the weld if they do so above the specified-minimum tensile strength of the pipe material (or 95% thereof).

Choosing an Appropriate Acceptance Criteria

Just because these industry codes and standards allow the actual strength of the weld to be less than the actual strength of the base material does not mean that this is good practice. As with many other requirements, the use of good engineering judgment is critical. The user must choose what acceptance criteria is appropriate, which may be over and above the minimum requirements in the applicable code or standard.

For large-diameter pipelines constructed using modern high-strength line pipe materials, particularly those in hilly terrain or subject to subsidence or other forms of ground deformation, supplemental requirements should be incorporated into construction contract documents, such as welding procedure qualification on project pipe and cross-weld tensile testing failure in the base material away from the weld — Fig. 4.

Where Do We Go from Here?

The use of matching strength girth welds prevents longitudinal strain from accumulating in the weld region, which is a natural stress concentration and is more likely to contain imperfections than the pipe material. Matching strength in this context means deposited weld metal with yield strength that matches or overmatches the actual yield strength of the pipe material and no significant HAZ softening.

Regarding weld metal strength, there are several measures that can be taken in the short term. While weld metal from E8010 electrodes has difficulty matching the axial strength of modern X70 (L485), there is the possibility of using E9010 electrodes. However, the use of these electrodes for all but relatively thin-wall (0.250 in. [6.4 mm] and less) pipelines constructed in relatively flat terrain in warm climates has been known to produce a significant risk of hydrogen cracking in the weld metal unless very high preheat temperatures are used. Unfortunately, the use of very high preheat temperatures contributes to softening in the HAZ.

Success in producing overmatching strength girth welds in modern X70 (L485) line pipe has been achieved using combination processes that use cellulosic-coated electrodes for the root and hot pass followed by a hydrogen-controlled welding process or consumable for the remainder of the pass. Examples of a hydrogen-controlled process or consumable include SMAW with low-hydrogen downhill-type electrodes (e.g., E9045 or E10045) and flux-cored arc welding (FCAW). The use of FCAW tends to result in higher heat input, which contributes to softening in the HAZ, than does the use of low-hydrogen downhill electrodes, so SMAW with low-hydrogen downhill-type electrodes may be the most promising candidate currently. The use of matching strength electrodes for root pass welding should also be considered, particularly for thinner materials where the root pass makes up a significant portion of the weld.

API 1104 currently recommends a maximum weld cap height of 5/8 in. (1.6 mm), presumably for reasons related to radiographic inspectability. This recommendation should be reconsidered because a tall, wide cap can protect against strain accumulation at understrength girth welds.

In addition, close attention must be paid to quality control during field bending operations to make sure the profile of the pipe string matches the profile of the ditch so that high axial stresses do not occur after lowering-in from soil loading in nonflat terrain and at points of inflection.

There are also requirements owner companies can impose in the purchase specifications for line pipe that can reduce the potential for girth weld strength undermatching. For example, tensile testing in the axial direction can be specified and maximum-allowable axial strength requirements can be imposed to ensure girth welds have a chance at matching or overmatching the strength of the base material. Also, both maximum-allowable and mini-
mum-required carbon equivalent can be imposed to protect against both the risk of hydrogen cracking and softening in the HAZ.

Lastly, flattened strap tensile testing practices should be standardized to remove the uncertainty that has resulted in pipe being manufactured at higher yield strengths within the acceptable range.

Summary and Conclusion

For pipelines constructed using cellulosic-coated electrodes and workmanship-based acceptance criteria, there are no requirements for overmatching strength in industry codes and standards. Only one requires procedure qualification on project pipe and all allow tensile test specimens to break in the weld if they do so above the specified minimum tensile strength of the pipe material (or 95% thereof).

Failures like the ones described are often attributed to the weld — “It was a weld that failed” — which negatively impacts the welding community. One may be inclined to argue that the weld was acceptable from a code-compliant perspective and the real culprits were high axial loads and line pipe material that is too strong. This results in accumulation of strain at undermatching strength girth welds, which can exceed the available strain capacity and result in failure by plastic collapse.

Just because a weld is acceptable from a code-compliance perspective does not mean it is fit for its intended service. Sound engineering judgement must be used to choose what material is used for procedure qualification and what tensile testing acceptance criteria is appropriate for a given application, which may be over and above the minimum requirements in the applicable code or standard. The use of welding procedures that result in matching or overmatching strength girth welds and are resistant to softening in the HAZ will prevent axial strains from accumulating at understrength girth welds.

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