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Pipeline Girth Weld Strength Matching Requirements in Industry Codes and Standards

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Introduction

- Fundamental rule of welding engineering:
  - Strength of a weld should be greater than the strength of the base materials
- Little difficulty has been experienced in meeting this fundamental rule during construction of cross-country pipelines in the past
- As the use of higher strength line pipe material has increased (and as those materials have become more sophisticated), achieving overmatching strength has become more challenging
  - Particularly when girth welds are made manually using cellulosic-coated (AWS EXX10-type) electrodes
- Presentation includes:
  - Contributing factors to recent girth weld failures
  - Strength matching requirements for pipeline girth welds in industry codes and standards
  - Importance of ensuring adequate strength so that axial strains do not accumulate at pipeline girth welds

Background

- Many changes in the pipeline industry have occurred over the past few decades
  - Higher-strength line pipe steels – e.g., X70, X80
  - High-productivity mechanized welding equipment
  - Automatic ultrasonic inspection used in conjunction with fitness-for-purpose-based acceptance criteria

- Many of the construction practices that were used prior to these changes are still used today
  - Conventional "stove-pipe" welding methods (i.e., using cellulosic-coated electrodes)
  - Radiographic inspection and workmanship-based acceptance criteria
- Tie-in and repair welds for modern pipelines are often made using conventional methods
- Cellulosic-coated electrodes continue to be used extensively for pipeline construction activities
  - Well suited for depositing one-sided welds
  - Capable of high deposition rates when welding with vertical down progression

Recent Pipeline Girth Weld Failures

- A number of girth weld failures in newly-constructed pipelines have occurred in North America recently
  - During pre-service hydrostatic proof testing
  - Soon after being placed in service
- Some from pipeline construction quality issues
- Others from undermatching strength and/or HAZ softening in otherwise "acceptable" girth welds
  - All in manual welds made using shielded metal arc welding (SMAW) and cellulosic-coated electrodes
  - Most in large diameter (30 inch [762 mm] and above) constructed using API 5L Grade X70 (L485) line pipe material
  - None in mechanized gas-metal arc (GMA) welds

Stresses in Pipeline Girth Welds

- The rate of pipeline incidents (leaks and ruptures) attributed to defective girth welds has traditionally been low
  - Axial stresses (i.e., perpendicular to girth welds) from pressure loading are significantly lower in a completed pipeline than those in the circumferential (hoop stress) direction
- Axial stresses in completed girth welds
  - Occur during lifting and lowering-in
  - Soil loading in non-flat terrain and at points of inflection
  - Occur when the pipeline does not fit the ditch
- Undermatching strength girth welds can be due to:
  - Pipe strength in axial direction is greater than weld metal strength
  - Softening in the heat-affected zone

Girth Weld Strength Matching

- When axial loads are applied to a completed pipeline in which the strength of the girth welds is less than the strength of the base materials, strains can accumulate in the understrength weld
- If the loads are sufficient to cause plastic strains, the available plasticity in the girth weld can be exceeded and failure by plastic collapse can occur
- Evidence of accumulated plastic strain in recent failures include necking in and adjacent to the weld and cracks in epoxy field joint coating
- When the strength of the welds is greater than the strength of the base materials, strains from axial loads are distributed within the base materials

Recent Industry Trends

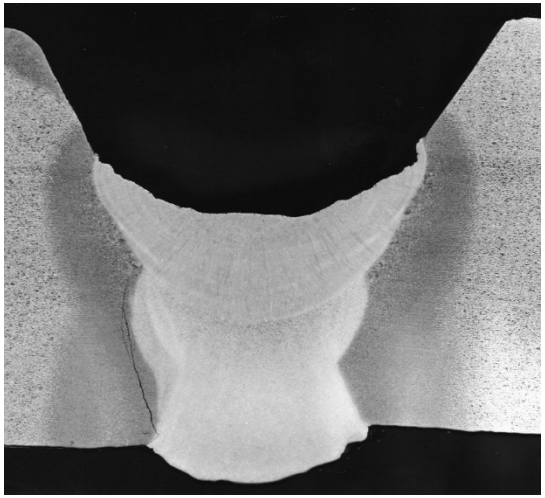
- Pipelines in the United States are regulated by the Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)
- PHMSA issued two advisory bulletins in 2009 and 2010 to alert pipeline operators about recent trends that affect the safety of newly-constructed pipelines
  - ADB–10–03 – "Girth Weld Quality Issues…"
    - Followed a rash of girth weld failures and subsequent observations by PHMSA inspectors
    - Specifically mentions improper transitioning, high-low misalignment, and welding practices in general (e.g., welders not following qualified welding procedures)
  - ADB–09–01 – "Potential Low and Variable Yield and Tensile Strength… …Line Pipe"
    - Followed several hydrostatic test failures in pipe material in what was suspected to be the result of line pipe with low strength
    - Resulted in pipe material being removed from newly-constructed pipelines and tested by third-party labs to confirm adequate 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

Pipe Material Yield Strength

- The maximum allowable yield strength in API 5L for PSL 2 pipe is typically 20 ksi (150 MPa) above the specified minimum yield strength (SMYS)
  - e.g., ~87 ksi (600 mPa) for X65 (L450), ~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
- Manufacturers are aiming higher within the acceptable range for yield strength to account for variability in tensile testing practices by third-party labs
  - Flattening procedure, Bauschinger effect, extensometer placement, etc.
- Most deviations from ideal tensile testing practice will tend to reduce the apparent strength
  - Has negative implications on quality for the line pipe manufacturer

Evolution of High Strength Line Pipe – 1 of 3

- 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%, Pcm ~0.15
  - Results in high resistance to hydrogen-assisted cold cracking (hydrogen cracking) in the HAZ but results in a high susceptibility to HAZ softening
- Early high strength line pipe steels (e.g., X52s [L360s] in the late 1950s and X60s [L415s] in the early 1960s) achieved required strength levels through additions of conventional alloying elements such as carbon and manganese
- Produced the desired strength levels but had an adverse effect on weldability
  - Carbon equivalent levels (CE_{IIW}) were routinely in the 0.50 range
- High CE_{IIW} promoted the formation of hard crack-susceptible microstructures in the HAZ
  - Resulted in a significant risk of HAZ hydrogen cracking when welded using cellulosic-coated electrodes



Evolution of High Strength Line Pipe – 2 of 3

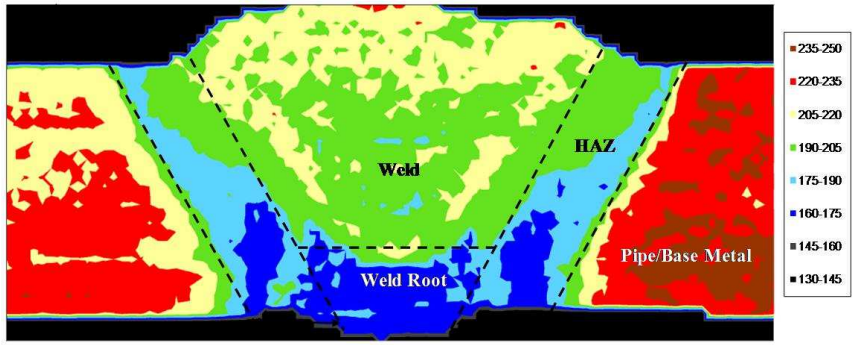
- As steel making technology improved, higher strength steels developed in the following decade (e.g., X65s [L450s] and X70s [L485s]) began to rely on microalloying additions and thermo-mechanical controlled processing to achieve the required strength level
- This resulted in higher strength line pipe 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

Evolution of High Strength Line Pipe – 3 of 3

- As the cost of microalloying additions began to rise and availability of these alloying elements became uncertain because of geo-political reasons, steelmakers began to rely more heavily on thermo-mechanical controlled processing such as water quenching and finish rolling at lower temperatures
  - This further reduced the need for alloying element additions 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 hydrogen cracking in the HAZ has all but been eliminated
- However, carbon equivalent levels have now decreased to the point where softening in the HAZ in now an issue
  - The welding community asked the line pipe manufacturers for low carbon equivalent materials and they gave them to us

Undermatching Strength Electrodes for Root Pass Welding – 1 of 2

- 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 remaining passes
- Conventional wisdom indicates that the strength level of the root pass electrodes has little effect on the overall strength of the completed weld
  - A portion of the root pass protrudes into the inside diameter of the pipe
  - 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 E6010 consumables for the root pass
  - Particularly in thinner materials where the root pass makes up a significant portion of the weld thickness



- Note:
  - 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
    - Minimum required yield strength for E8010 electrodes is 67 ksi (462 MPa)

Undermatching Strength Electrodes for Root Pass Welding – 2 of 2

- The use of E6010 consumables for root pass welding in higher strength line pipe became prevalent following work at Welding Institute of Canada in the early 1980s
  - At that time, high strength line pipe had to be highly alloyed in order 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
  - Allows 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 back to the use of matching strength electrodes for root pass welding

Procedure Qualification Requirements

- In API Standard 1104 – Welding of Pipelines and Related Facilities – there is no requirement for the actual strength of the weld to be greater than 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 (or otherwise test) 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 grade of pipe (same grade or highest grade within a group)
  - Different pipe materials of the same grade can have widely different tensile properties depending on when they were made, the method of manufacture, by whom they were made, etc.
- For many applications (e.g., pipelines in non-flat terrain), it is good practice to at least match the actual yield strength of the project pipe
- The requirements in many other international codes and standards for pipeline girth welding simply mirror those in API 1104

Supplemental Requirements – 1 of 2

- 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
  - The use of good engineering judgement is critical
  - User must choose what acceptance criteria is appropriate for a given application, which may be over-and-above the minimum requirements
- For large diameter pipelines constructed using modern high strength line pipe materials, supplemental requirements should be incorporated into construction contract documents that require:
  - Welding procedures to be qualified on project pipe and
  - Acceptance criteria for cross-weld tensile testing should be failure of the specimens in the base material away from the weld
- Particularly for pipelines in hilly terrain or subject to subsidence or other forms of ground deformation

Supplemental Requirements – 2 of 2

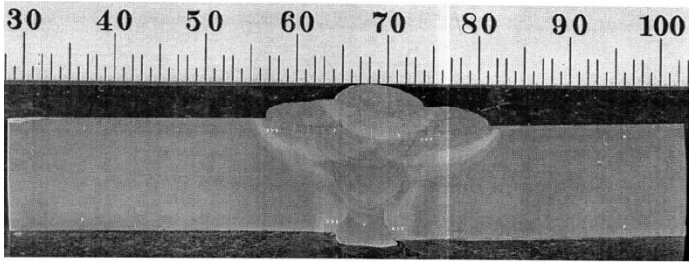
- The use of matching strength girth welds prevents longitudinal strains from accumulating in the weld region, which is a natural stress concentration and is more likely to contain imperfections than the pipe material
- Matching strength in this context means:
  - Deposited weld metal with yield strength that matches or overmatches the actual yield strength of the pipe material
  - No significant HAZ softening
- Where do we go from here?

Weld Metal Strength

- E9010 electrodes have been known to produce a significant risk of hydrogen cracking in the weld metal:
  - For all but relatively thin-wall (0.250 inch [6.4 mm] and less) pipelines constructed in relatively flat terrain in warm climate
  - Unless very high preheat temperatures, which contribute to softening in the HAZ, are used
- Combination procedures (cellulosic-coated electrodes for the root pass and hot pass followed by the use of a hydrogen controlled welding process or consumable for fill and cap passes) have been used successfully recently
  - SMAW with low-hydrogen vertical down type electrodes (e.g., E9045 or E10045)
  - Flux-cored arc welding (FCAW)
    - Result in higher heat input, which contributes to softening in the HAZ
- SMAW with low-hydrogen vertical down type electrodes seems to be the most promising candidate for fill and cap passes going forward in the short term
- 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 thickness

Other Short Term Preventative Measures

- API 1104 currently *recommends* a maximum weld cap height of 1/16 inch (1.6 mm), presumably for reasons related to inspectability using radiography
  - This recommendation should be reconsidered, as a tall, wide cap can protect against strain accumulation at understrength girth welds



- Close attention should be paid to quality control during field bending operations to make sure that the profile of the pipe string matches the profile of the ditch
  - Ensure that high axial stresses do not occur after lowering-in from soil loading in non-flat terrain and at points of inflection

- Practice close control of heat input to avoid softening in the HAZ
  - Difficult for manual welding

Longer Term Preventative Measures

- Requirements that owner companies can impose in the purchase specifications for line pipe that can reduce the potential for girth weld strength undermatching include:
  - Tensile testing in the axial direction can be specified and maximum-allowable axial strength requirements can be imposed
    - Ensure that girth weld have a chance at matching or overmatching the strength of the base material
  - Both maximum-allowable and minimum-required carbon equivalent can be imposed
    - Protect against both the risk of hydrogen cracking and softening in the HAZ
- Flattened strap tensile testing practices should be standardized
  - Remove the uncertainty in results that has resulted in pipe manufacturers aiming higher within the acceptable range for yield strength

Summary and Conclusions

- For pipelines constructed using cellulosic-coated electrodes and workmanship-based acceptance criteria, there are no requirements for overmatching strength in API 1104 and many other industry codes and standards around the world
  - None require procedure qualification on project pipe
  - All allow tensile test specimens to break in the weld as long as they do so above the specified-minimum tensile strength of the pipe material (or 95% thereof)
- Failures like the ones described here are often attributed to the weld – "it was a weld that failed…" – which puts the welding community in a bad light
- Just because a weld is perfectly 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
  - What tensile testing acceptance criteria is appropriate
  - May be over-and-above minimum requirements in the applicable code or standard
- The use of welding procedures that result in over-matching strength and are resistant to softening in the HAZ will prevent axial strains from accumulating at understrength girth welds

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