Beyond the Code Requirements of Welding an In-service Procedure Qualification Record

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Abstract

The in-service welding of pipelines i.e., sleeves and hot taps, presents unique challenges from accelerated cooling, residual stresses, and risk of burn-through. While adherence to relevant welding codes is essential, it may not be sufficient to ensure the weld integrity. This paper explores factors beyond code requirements that must be considered when qualifying welding procedures for in-service applications with fillet, groove and overlay welds. The typical standards that are followed are API 1104 [1], CSA Z662 [2], and ASME B31.3 [3] (which references ASME BPVC Section IX [4]). The essential variables of these codes are generally similar to ASME BPVC Section IX, with some additional requirements, such as closer attention to heat inputs, cooling rates, and the resulting hardness.

Standards require that the cooling rate and welding restraint be considered, but do not state specific requirements. Hardness requirements are specified but the hardness test locations are open to interpretation and higher hardness values are permitted if they can be justified. Further, methods for determining acceptable heat inputs for minimizing the risk of burn-through in a thin-wall pipe is not specified. These aspects of the codes that require consideration and determination of acceptable heat inputs are critical to ensure safety of the welding crew and long-term integrity of the in-service welds. This paper brings to attention these considerations and provides some best practices for addressing them.

Introduction

In-service welding is a critical technique involving welding repairs or modifications to components while they are in service. Although there are additional risks and complexities involved, this technique is necessary to avoid having to shut down process flows. The necessity for performing an in-service weld is typically to perform a repair, such as install a pressure containing sleeve over a compromised section of a pipe or to install a hot tap to re-route the process flow. Less commonly, an area of metal loss may be overlaid with weld metal to restore thickness.

During in-service welding, there are two primary concerns. First is the safety, due to the potential for the welder to burn-through the pipe wall, releasing the material to the environment, which may also create a fire/explosion risk [5]. Second is the potential for microstructural hard spots due to rapid cooling during welding from a liquid or gas flowing through the pipe [6]. Because of these risks, constructions codes specify additional welding requirements specific to in-service situations.

The primary codes that specify the welding requirements for in-service welding are API 1104 in the United States and CSA Z662 in Canada. Other construction codes contain welding sections, but refer to API 1104, specifically Appendix B, for the qualification requirements.

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The purpose of this paper is to highlight aspects of in-service welding that the codes do not address or do not provide specific guidance on. With these additional considerations, a better welding procedure specification (WPS) may be developed, ensuring personal safety and line integrity.

Code requirements

Code requirements generally attempt to capture the necessary requirements for all welding within the code's scope, but there may be few aspects that the codes do not address. The requirements for in-service welding, as specified by API 1104 and CSA Z662, involve welding a procedure qualification record (PQR) coupon that records the necessary variables (as stated in the code) and then tests the weld in both non-destructive and destructive methods. PQR coupons may be fillet welded sleeves, grooves with reinforcing fillets for branches, or overlays directly deposited onto the surface of a pipe.

Welding of the PQR coupons should simulate the operating conditions that affect the removal of heat from the pipe wall. For example, a flow loop of water (or another medium, depending on the desired cooling rate) may be set up to flow through the coupon being welded. PQRs are often welded in a more severe condition than anticipated for production welding. However, it should be considered that a cooling rate effects the hardness but does not eliminate the risk of a burn-through. The codes provide some guidance for determining what conditions to use, but ultimately leave it to the user to decide if the adequate welding variables, pipe grade and thickness, and flow conditions are evaluated by testing.

The unique variables for in-service WPSs are the carbon equivalent, calculated differently for API 1104 vs. CSA Z662, which is limited to the maximum that is tested. The weld cooling rate is an essential variable, but there are exceptions allowed and no firm guidelines on how to determine the weld cooling rate. Weld bead sequence is an essential variable in API 1104 when a temper bead procedure is specified, but CSA Z662 only states that weld beads deposited directly onto the carrier pipe shall be tempered by an additional weld pass. Other essential variables are more in line with typical welding requirements but the qualification range in some cases are restrictive.

The testing required for in-service welds varies slightly for mainline PQR testing. As hydrogen induced cracking (HIC) is one of the primary concerns, hardness testing must be conducted on multiple cross-sections with maximum specified hardness. Also required are macroexaminations, bend tests, with unique geometry relative to typical groove weld bend tests (Figure 1), and nick-break tests.

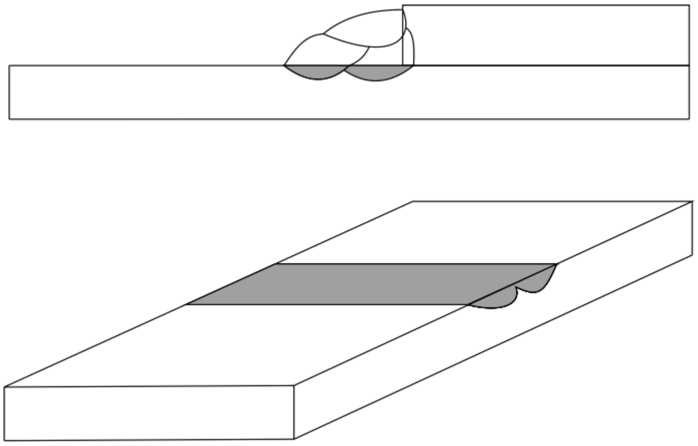

Figure 1. Bend test specimen geometry with the sleeve (or branch) ground off in preparation for bending.

Are the codes enough?

The codes provide requirements to ensure that conditions are not more severe than the conditions used when welding the PQR, but guidance is not provided how to determine the severity. This requires an engineer’s interpretation. Although failures are quite rare, they do occur in terms of cracking and burn-throughs.

Beyond the code

The codes acknowledge much of the potential concerns, however, they defer the responsibility to a competent engineer to determine what constitutes a more severe condition and what is required to validate a particular set of parameters. The following are areas requiring additional consideration:

Burn-through

It is generally accepted that wall thicknesses ≥ 0.25 in. (6.4 mm) have a low likelihood of burn-through. CSA Z662 requires a PQR to be welded on the thinnest material (if joining run pipe < 0.25 in. (6.4 mm)) to be qualified, whereas API 1104 only suggests (should, not shall) WPS qualification for thinner material to be evaluated for burn-through.

Previous studies have been performed and software has been developed for the prediction of burn-through. As an alternative, additional testing may be conducted on a PQR coupon of the thinnest qualified wall thickness in the absence of cooling; this represents a conservative scenario for a burn-through assessment.

A full suite of testing may be conducted on such PQR or it may be sufficient to conduct a macroexamination to evaluate depth of the weld pool relative to the thickness of the material. An evaluation of the thermal gradient in the heat affected zone may also be calculated and verified in the macroexamination. During welding of the non-cooled PQR, the inside surface temperature of the pipe may also be measured with thermocouples or an infrared pyrometer.

Correct placement of the measuring locations, on the inside surface, is able to be established through several quick welding trials (Figure 2). Testing of an intentional burn-through PQR with a pressurized pipe provides the real-world data to support calculations of when a burn-through actually occurs; that is, the welding parameters (mainly heat input and amperage) that lead to burn-through for a particular wall thickness.

This testing has the added benefit of allowing the welder to experience an actual burn-through event, so that they may be more familiar with the conditions leading up to it, enabling them to prevent it from happening in the field. Conducting such a test should be done under the design of a competent engineer.

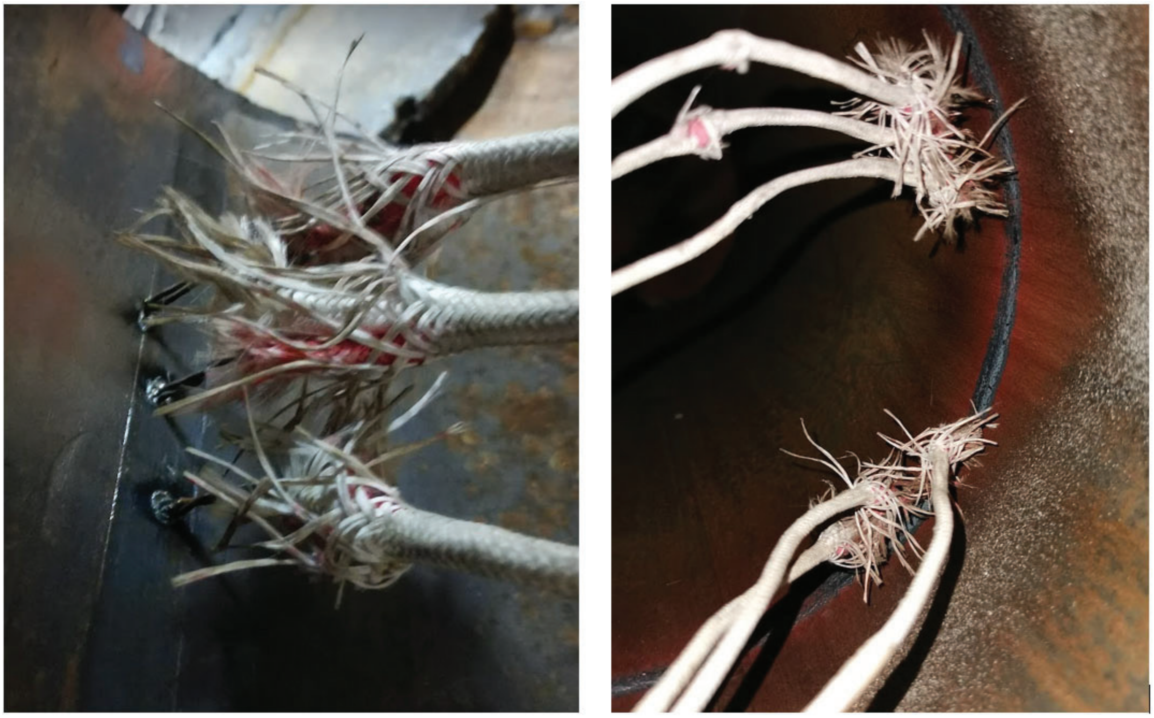

Figure 2. Thermocouple placement to measure inside surface temperature of in-service sleeve weld. Left figure shows three thermocouples longitudinally spaced to capture maximum temperature of root pass and second pass against carrier pipe. Right figure shows two sets of thermocouples for redundancy in measurements.

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Hardness

Hardness testing is a relatively easy way to quantify the microstructure's susceptibility to HIC. It is in fact, the microstructure rather than the hardness that influences the susceptibility to HIC, but the microstructure is more difficult to quantify [7]. CSA Z662 provides a single maximum value of 350 HV, under which is considered safe to avoid HIC. However, there is the allowance to evaluate the WPS to ensure it is suitable to avoid HIC. API 1104 provides more guidance by providing a table of thickness ranges, CE ranges, and electrode hydrogen levels, as well as the allowance for alternate values specified by the user. The research used to establish Table B.4 of API 1104 outlines the experiments used and some criteria to consider [8]. Both codes specify making the indents in the coarse-grained HAZ, but don't acknowledge if testing should be in both the carrier pipe HAZ and sleeve HAZ, or the weld toe and root. It is possible that either component may exhibit excessive hardness, although it is more common in the toe of the carrier pipe. Within the coarse-grained HAZ, there is flexibility to move indents to areas of higher and lower hardness, which unfortunately, may be decided upon by the desperation to pass the test rather than the desire to develop a reliable WPS. Figure 3 shows a comprehensive sleeve indent layout with five indents at the toe of each material's coarse-grained HAZ and an indent in the HAZ of the root for each material; additional indents are in the parent metal and weld metal, for comparison purposes.

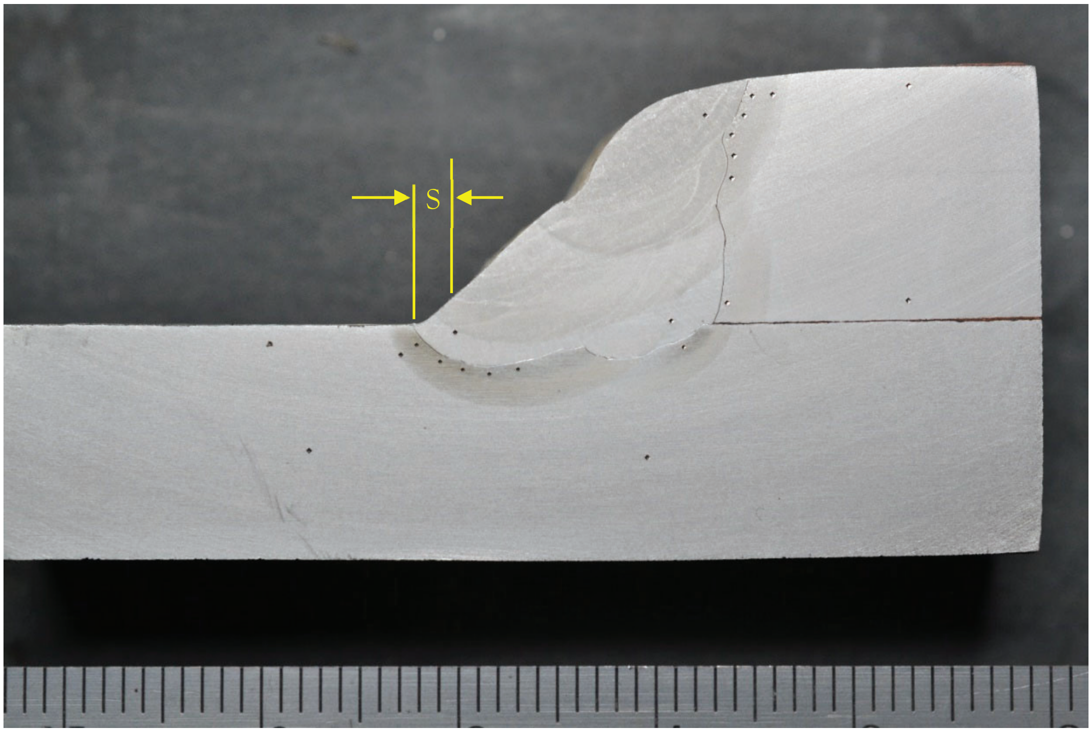

Figure 3. In-service sleeve PQR macroexamination and Vickers hardness test specimen. Five hardness indents have been placed at the toe of each CGHAZ, plus one indent at the CGHAZ root of each material. Nital etch. Scale increments in mm.

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Carbon equivalence (CE)

The CE dictates the hardenability of the material, but the individual carbon content dictates the maximum potential hardness of the material. Hardenability is the relative ability of a steel to form martensite (a microstructure susceptible to HIC) when quenched from a temperature above the upper critical temperature [9]. Both should be considered when evaluating hardness results. If a CSA Z662 PQR is being evaluated for a higher hardness and Table B.4 of API 1104 is used as a guideline, remember to use the correct CE formula.

Cooling rate

Cooling rate applies to two aspects of an in-service weld and may be mistakenly used interchangeably. The cooling rate of the pipe refers to the flowing medium removing heat from the pipe wall and is relatively easy to measure. The codes do not mandate how this is measured, but a common technique is to heat a specific area of the pipe to a temperature and then record the time taken for that area to drop to a certain temperature; it is common to record the elapsed time from 250°C to 100°C. Although this test is easy to perform, it is also easy to perform it incorrectly and a detailed procedure should be followed to maintain consistency. The second aspect of cooling rate is the time taken for the weld to cool from 800°C to 500°C, which is termed the t8-5 time [7]. This time dictates the likelihood of forming a HIC susceptible microstructure. Of the two cooling rates (or cooling times), the t8-5 is more meaningful, but much more difficult to measure, as such, it is not typically referenced in an in-service PQR.

Temper bead welding

A temper bead technique is typically performed in some sense. No particulars of the temper bead variables are required to be recorded, but unless careful attention is paid to the "S" distance (shown in Figure 3), the effectiveness of the tempering is nullified. Furthermore, the effective tolerance in a temper bead technique is very tight and requires a highly skilled welder. Repair welding to correct a temper bead placement can often cause more harm than good.

Joint restraint

The restraint of a joint is acknowledged in the code as something to be considered, but it is also acknowledged that it is not simple to quantify and is thus not an essential variable. The restraint of a joint while welding will result in a certain residual stress. This may be modelled with finite elements or semi-destructively tested by the blind-hole drilling method. Recent efforts are being worked on to develop a repeatable technique to quantify the residual stress through non-destructive testing. It is generally accepted that thicker material will result in increased restraint, so one suggestion would be to weld a PQR on the thickest material qualified. Diameters also influence the restraint with larger diameters typically exhibiting higher restraint [10].

Conclusion

All of these potential variables to consider ultimately need to be incorporated into a WPS with an allowable welding parameter range for the welders to follow. The codes specify the allowable ranges based on the PQR parameters; however, it may not be appropriate to permit the maximum allowable ranges. For example, if a burn-through test is performed on thin material and the tested heat input shows inner surface temperatures or penetrations of particular isotherms near the safe limits, then it might be appropriate to restrict the maximum heat input to that tested with no allowance to go higher. A similar restriction might be placed on the minimum heat input if hardness testing showed values reaching the safe limit.

Additional Considerations

These are some additional considerations for WPS development that are not addressed in the codes:

- The substance being transported may be sensitive to temperature; in which case the inner surface temperature is important, beyond the risk of burn-through. A test with cooling may be required to determine the inner surface temperature and/or a finite element analysis (FEA) with heat transfer modelling.
- High strength steel may be sensitive to HAZ softening, necessitating additional testing to ensure that the pipeline is not compromised in axial loading.

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