CASE HISTORY

Developing Welding Procedures for Sour Service

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Controlling the hardness of the weld heat-affected zone (HAZ) in sour service is essential to help prevent sulfide stress cracking. It is important to evaluate HAZ properties when developing welding procedures. The behavior of specific alloys during welding presents roadblocks to HAZ hardness control. Two cases are presented to show that weld thermal simulation is an efficient tool for developing welding procedures for sour service.

The presence of sour, hydrogen sulfide (H₂S)-containing environments poses problems that affect material behavior. The corrosion reaction between H₂S and steel produces atomic hydrogen, which can enter the material and promote degradation that may lead to cracking. To cope with the susceptibility to sulfide stress cracking (SSC), a system of hardness control has been used for many years because generally softer structures are less sensitive to SSC. Design to avoid SSC of materials like C-Mn steels is almost universally based on the adoption of the 22 Rockwell C hardness (HRC) [243 Vickers hardness (HV)] criterion.1

Even though the susceptibility to SSC depends on many factors, including strength, stress level, and microstructure of the material, the hardness criteria have been adapted by the industry because hardness is convenient and easy to quantify. Therefore, in general, control of SSC requires limitations on material hardness levels. This is especially important in welded structures where a hardened heat-affected zone (HAZ), together with significant residual welding stress, could develop.

General Characteristics of Weld HAZ

During welding, the HAZ of base metals is subjected to thermal cycles; this produces a change in both HAZ microstructure and mechanical properties, including hardness. The microstructure in each region of the HAZ is related to the temperature cycle experienced during welding. In multipass welds, each of the HAZ regions can experience multiple temperature excursions that can further alter its microstructure. The mechanical properties vary across the different regions of the HAZ.

Additionally, postweld heat treatment (PWHT) is commonly applied to welded steel construction to improve the me-
Mechanical properties, in particular the toughness across the welds; reduce the high level of residual stresses that are induced along and across weldments, and decrease the hardness across the weldment to avoid the risk to stress corrosion cracking (SCC). The changes in strength, hardness, and toughness during PWHT are the net results of various metallurgical reactions. The relative magnitude of these changes to the metal is, of course, dependent on the steel composition and microstructure.

Among the HAZ regions, the coarse-grained HAZ (CGHAZ), which experiences the most severe thermal cycle, usually possesses the maximum hardness. As such, this region is usually given the most attention regarding alloy design and welding procedure, including PWHT. Evaluation of HAZ properties after PWHT is important not only for selection of suitable chemical composition of microalloyed steel pipes but also for development of welding procedures, including PWHT, for sour service.

Practical Roadblocks to HAZ Hardness Control

There are practical and fundamental issues that need to be taken into account in order to determine a realistic approach to control the susceptibility to SCC of structural materials during service. One practical obstacle in resolving HAZ hardness control problems is that the HAZ hardenability of materials like C-Mn steels varies markedly from type to type, cast to cast, and even from sample to sample. Therefore, in some cases, the scatter in the maximum HAZ hardness values is so high that carbon equivalent (CE) parameters are not of much value in selecting batches of steel for welding procedure development to meet some maximum HAZ hardness level. In addition to the problem of scatter, there are indications that increasing the cleanliness of the steel increases the HAZ hardenability of the current C-Mn steels.

In the case of high-strength low-alloy (HSLA) or V/Nb-bearing steels, the hardness of the HAZ sometimes increases following PWHT due to V/Nb carbonitride precipitation. Therefore, it is necessary to determine the effect of PWHT on the HAZ of microalloyed steels in a case-by-case approach.

In other materials, like the supermartensitic stainless steels (SS) that can play an intermediate role between conventional 13Cr and duplex SS regarding both corrosion resistance and material cost, reliable attainment of NACE International Standard MR0175 requirements (23 HRC) can be extremely difficult. Use of short PWHT cycles is desirable for productivity reasons and to avoid embrittlement of duplex- or superduplex-weld metals that are normally used to join these steels. Unfortunately, a reliable relationship between chemical composition and transformation temperatures needed to design proper PWHT cycles is not available for these steels. Therefore, recognizing the diffusional reactions involved in tempering, the effect of short PWHT on partial reaustenitization, and the degree of softening of the HAZ need to be evaluated for different supermartensitic SS.

Predicting Microstructure and Properties of HAZ

The ability to determine or make predictions of the microstructure and properties of the CGHAZ or any other sub-zones of the HAZ requires knowledge of the amount and extent of grain growth or any other metallurgical reaction and the weld thermal cycle experienced by the corresponding region of the HAZ. There are basically three approaches that can be used to determine or predict the microstructure and properties of the HAZ. First, carry out large-scale tests of the welded joint as part of qualifying the welding procedures. This is likely to be expensive and may not lead to a procedure that meets the hardness requirements. Second, try to make predictions based on a combination of theoretical models including weld continuous cooling transformation (CCT) diagrams, weld microstructure diagrams, or grain growth diagrams and a few small-scale experiments.
reliability of this approach depends on the accuracy of the theoretical model and its applicability to the specific chemistry or type of material being evaluated. However, this approach is much less expensive than large-scale tests and may provide general trends that can be used as general guidelines in the decision-making process. Third, use small-scale weld simulations to determine the Charpy V-notch, crack-opening displacement (COD), or hardness of a specific subzone of the HAZ. This approach is reliable and less expensive than the other two.

Gleeble Weld Thermal Simulation

Gleeble weld thermal simulation is an inexpensive, simple, and rapid test method to investigate fundamental phenomena that take place in the HAZ of a welded joint using a limited number of specimens. It is used to simulate the weld thermal cycles under laboratory conditions in order to obtain information about microstructural and property changes in the HAZ. Although in principle, these changes can be observed and measured from real welds, in practice, it is more convenient to work with test pieces representative of one, not a range, of microstructures and grain sizes, particularly if mechanical property measurements are required.

Weld simulators are usually based on resistance heating and water cooling of samples. The samples are clamped between water-cooled jaws that serve as grips to hold the samples, provide a means for introducing the current to the specimen during heating, and ensure a rapid cooling when the current flow is interrupted. With weld simulators, it is possible to program the required thermal cycle to any required temperature-time profile and plot this thermal cycle and record phase transformations using a dilatometer. If necessary, a tensile or compressive load can be applied to the sample simultaneously with heating and cooling. Typical operating ranges for commercially available simulators provide maximum heating and cooling rates that allow most practicable weld processes to be simulated. The exceptions are gas tungsten arc welds (GTAW) or gas metal arc welds (GMAW) of very low heat input, and other low heat input processes.
such as laser- and electron-beam welds. The effect of preheat or reheat is easily accommodated by suitable programming of the corresponding thermal cycle.

**SSC Resistance of CGHAZ in V-Microalloyed X60 Steel Pipe**

The investigators determined the effect of weld cooling rate—representing a broad range of welding conditions—on CGHAZ hardness and microstructure, as well as the tempering response of CGHAZ with different as-welded hardness levels to different PWHT schedules and their resulting resistance to SSC.

Single CGHAZ thermal cycles with a peak temperature of 1,320 °C (2,408 °F) and cooling rates ranging from 5 to 80 °C/s through the temperature range of 800 to 500 °C were imposed on the V-microalloyed X60 steel pipe specimens. Figure 1 shows the correlation between CGHAZ cooling rate and CGHAZ hardness. The hardness of the CGHAZ increases from about 233 to 392 HV number 10 as the cooling rates increase from 5 to 80 °C/s.

Following HAZ simulation, CGHAZ samples with a nominal “as-welded” hardness of 280, 300, 325, and 350 VH-10 were subjected to specific PWHT with a holding temperature between 635 to 670 °C and holding times between 3 to 15 h. Figure 2 shows the microhardness of the CGHAZ as a function of original hardness, and holding time at 650 °C. Figure 3 shows the softening observed in the CGHAZ in the V-microalloyed X60 steel pipe as a function of the Larson-Miller tempering parameter.

A PWHT CGHAZ specimen with an average and maximum hardness of 250 and 264 VH-10, respectively, did not show cracking after H₂S testing according to the procedure specified in NACE TM0177 (Method A).

These results provided a good understanding of the behavior of this V-microalloyed X60 pipe steel during welding and were used to design a proper welding procedure including PWHT for sour service.

**Effect of Short PWHT on HAZ Properties of Supermartensitic Stainless Pipe Steels**

In this case, the transformation temperature, \( A_{c1} \), and martensite start formation of three supermartensitic SS pipes were determined by dilatometric analysis. After that, the influence of short PWHT on the HAZ mechanical properties (hardness and impact Charpy V-notch energy) and on the microstructure of each one of the steels was evaluated. HAZ simulations were performed with an average peak temperature of roughly 1,350 °C and a cooling rate between 800 to 500 °C of 40 °C/s simulating normal GMAW heat input welding conditions. Short PWHT was performed at temperatures equal to \( A_{c1} + 40 °C \), and \( A_{c1} - 40 °C \), for 5 and 10 min.

Table 1 shows the transformation temperatures of the three supermartensitic pipe steels. Figure 4 shows the change of average hardness of the simulated HAZ of one of the supermartensitic steels as a function of weld thermal and PWHT cycles. Figure 5 shows the resulting microstructure of HAZ after a PWHT of 10 min at 640 °C. The fraction of retained austenite in the grain boundaries increases with holding time during PWHT at this temperature. The resulting microstructure may have an important effect on the corrosion performance of the pipe.

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<th>Transformation temperatures of pipes S, N, and K steel</th>
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\( ^{(A)} \) As determined based on chemical composition.
supermartensitic SS pipe. It has been observed that there is no harmful influence of retained austenite on the corrosion resistance of supermartensitic SS. Additionally, a higher content of retained austenite reduces the diffusible hydrogen and the SSC susceptibility of the supermartensitic steels.9

These results help determine the optimum short PWHT schedule to decrease the hardness of the supermartensitic steel HAZ to a level similar to those of the base material in the as-received condition and to develop a microstructure that would increase the resistance of the HAZ to SSC.

Conclusion

Gleeble thermal simulation is an efficient and powerful tool for developing welding procedures, including PWHT for sour service application.

Acknowledgments

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