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CHALLENGES FOR TESTING HYDROGEN-ASSISTED COLD CRACKING IN WELD SEAMS OF HIGH-STRENGTH STEEL GRADES

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ABSTRACT

Hydrogen can cause weld cold cracking even days after fabrication. In this respect, higher strength steels present a challenge to established cold crack testing. In general, the tolerable hydrogen concentration for crack prevention decreases with increasing material strength. In addition, advanced welding processes require changes in weld geometry and heat input. This directly influences the formation of crack-critical microstructures, e.g. in hardened areas of the heat-affected zone. The limits of use and application of modern cold cracking tests are evaluated by (1) the externally loaded Implant-test and (2) the self-restraint Tekken-test. In particular, external mechanical stresses, which cause additional mechanical loads on the components during welding, must be considered due to the component-specific stiffness of high-strength steels. Accompanying test methods for determining hydrogen concentration and diffusion in welds are presented, such as carrier gas hot extraction for determining hydrogen concentration (ISO 3690) or temperature-dependent diffusion coefficients. These values are of great importance for a holistic approach to the evaluation of the cold cracking sensitivity of high strength steels.

KEYWORDS: hydrogen, cold crack, test, welding, high-strength steel

COLD CRACKING IN HIGH-STRENGTH STEEL WELDING JOINTS

High-strength structural steels have been used successfully in mechanical and plant engineering for several decades, especially increasingly for offshore wind turbines and bridge construction. Manufacturers offer numerous base materials and adapted welding consumables for this purpose. However, the increasing strengths place significantly higher demands on welding processing due to narrower process limits [1, 2]. Improper weld processing can result in weld damage. Hydrogen-assisted cracking (HAC) is a major risk because it can occur with a significant time delay. HAC microcracks are caused by the critical interaction of local crack-critical microstructure (e.g., hardened heat-affected zone — HAZ), diffusible hydrogen concentration, and local strain/stress. The main sources of hydrogen are moisture (electrode coating and flux) or contamination of the welded parts by hydrocarbon oils, greases, etc. or humid ambient conditions, e.g. during field welding.

During the last 20 years, the strength of high strength steels has been continuously improved by the addition of microalloying elements (V, Nb, Ti) [3]. The alloying concepts result in different weld microstructures and mechanical properties [4] and have a considerable influence (due to the precipitates formed) on the increased time delay of hydrogen diffusion [5]. Welded structures with yield strengths ≥ 960 MPa can be susceptible to HAC at hydrogen concentrations of

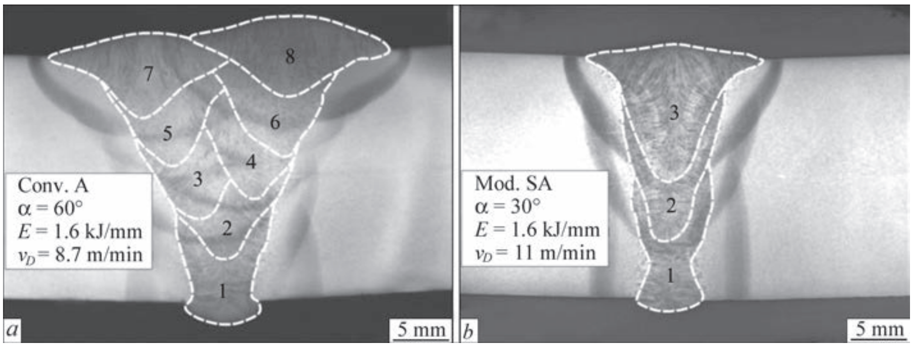

Figure 1. Influence of welding process/arc type on necessary weld bead number for constant weld heat input: *a* — conv. A, 60°, eight runs; *b* — mod. SA, 30°, three runs (Figure unchanged and taken from ref. [7], open access license CC-BY-4.0)

HD ≥ 1 ml/100 g [6]. To determine the cold crack resistance of base and filler materials, a test method is required that can reproduce realistic stresses at a practicable specimen level. The high strengths of modern materials and advanced welding processes, such as the arc form for focusing the welding heat input, e.g. by modified spray arc (“Mod. SA” in Figure 1, *b*) compared to the conventional arc (“Conv. A” in Figure 1, *a*), pose challenges for the cold crack testing [7, 8]. Figure 1, *a* and *b* are taken from ref. [7] (open access license CC-BY-4.0)

The old simplification/”general rule” that the risk of cracking increases almost exclusively with the hydrogen concentration does not apply to high-strength materials and especially to modern welding processes such as the modified spray arc (“mod. SA”). These influencing factors therefore require an adaptation of the existing cold crack tests.

CHALLENGES FOR COLD CRACKING TESTING

GENERAL REMARKS

More than 200 methods are available for the cold crack testing of a welded joints [9]. However, only a small number have found practical application. They are among the test methods for weldability, i.e. the ability of a component to be welded under given production conditions and design requirements so that it can perform its function. The susceptibility of the base metal (BM) and deposited filler metal to cold cracking must therefore always be determined as a function of the welding process and parameters used. Particular attention must be paid to the stiffness of the welded structure, i.e. its resistance to deformation due to external stresses. This has a significant influence (and associated thermomechanical effects during welding and cooling) on the susceptibility to cold cracking. Depending on the test method, cold crack tests provide qualitative (crack/no crack) or quantitative (parameter limit curves for crack-free welds) results for the materials/filler materials or welding parameters tested. According to [9–12], cold cracking tests are categorized by the test load:

SELF-RESTRAINT COLD CRACKING TESTS

impose a structural stress on the specimen resulting from its own design stiffness (resistance to shape and position change during welding). For example, these may be slit specimens with varying weld seam geometry or lap welds as circumferential welds. A phase transformation can add additional residual stresses to the overall level.

IN EXTERNALLY LOADED COLD CRACKING TESTS

the specimen is subjected to specific mechanical stresses in a preferred direction. The applied load is always superimposed on existing welding-specific residual stresses. The external load can be applied independently of the welding parameters and must be selected to reflect the practical application as realistically as possible, i.e. stressing the material up to the yield point for a selected geometry.

The most common cold cracking tests are standardized and can be found in the three parts of ISO 17642 [10–12]. The tests reach their limits for modern high-strength materials or adapted welding processes and must be adapted. Two examples of a self-loaded and externally loaded cold cracking test are presented below. In addition, hydrogen determination according to ISO 3690 [13] is briefly discussed.

TEKKEN-TEST

For the cold cracking TEKKEN test, according to ref. [11], a flat slot specimen with an inclined Y-groove is prepared to create a test weld closed at both ends with a length of 80 mm (see Figure 2, *a*). A single-pass weld is made in the Y-groove using the welding process parameters and filler materials to be tested. The

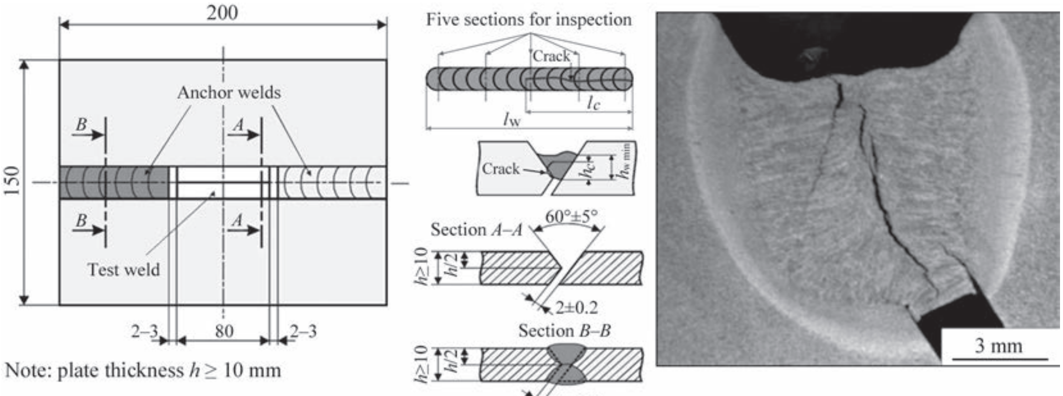

Figure 2. TEKKEN-Test: *a* — weld sample; *b* — welded Y-groove with cold crack, taken with permission by Springer Nature from ref. [9]

Y-groove serves as a mechanical notch, i.e. to increase the notch stress and locally preferential crack initiation. The sample geometry results in a hindered shrinkage during cooling of the weld seam, i.e. a self-restraint cold cracking test. Due to the slow diffusion of hydrogen, a waiting time of 48 hours after welding must be observed. The weld is then visually inspected. Any cracks found that are open to the surface are determined using the crack length coefficient (in %) from the total length of the cracks and the weld seam length. In addition, a light microscopic crack inspection is carried out in the weld metal (WM) and in the HAZ on five metallographic cross sections (see Figure 2, *b*). Both Figures 2, *a* and *b* were taken from the work of Boellinghaus et al., see ref. [9], with permission by Springer Nature.

Although the TEKKEN represents a cold cracking test, it can also be used as a hot cracking test due to the high mechanical restraint imposed by the specimen geometry. On the one hand in design specific hot cracking investigations under the high restraint conditions of the Tekken test. This must be evaluated especially in case of (1) higher alloyed materials or (2) when the main crack propagation is parallel to the welding direction [9]. In that case, a fractographic evaluation should be performed to distinguish between hot cracks in terms of solidification cracks. Actually “hot cracking safe” low-alloyed steels can show unexpected hot instead of cold cracking at very high mechanical strength level [14]. In addition, the root-cause of the cracking can be misinterpreted. It was recently reported that micro hot cracking in low-alloyed steels can be a potential site for further propagating cold cracks [15, 16].

The TEKKEN sample should have a minimum thickness of 10 mm to safely exclude distortions during welding and cooling and to ensure a sufficient stiffness [17]. It is standardized in the EN ISO 17642-2 [11]. Unfortunately, the applicability of this test is limited, and some boundary conditions should be considered.

- In the past, welded specimens were usually made from two individual sheets using anchor welds. Especially for high-strength materials, the issue of the anchor weld can fail due to the simple unavailability of adequate welding consumables. An alternative is to machine the Y-groove directly from the steel plate by EDM.
- In the case of high filler material strengths, the base material must have a similar strength or a significant plate thickness, otherwise the residual stresses in the WM will be distorted compared to real components. In addition, the specimen geometry is too “soft” and provides insufficient stiffness ratios. Therefore, the base and filler material combination should have similar values in terms of the yield strength (R_{eH}) or proof stress ($R_{\mathrm{P}0.2}$) level. Alternatively, the specimen thickness, i.e. the sheet thickness, can be increased.
- For advanced welding processes such as mod. SA with a very short arc, it is necessary to adapt the weld geometry because the weld depth is smaller. This must be taken into account in the Y-joint in order to achieve the required root formation.

IMPLANT-TEST

The Implant-test (see ref. [12]) belongs to the group of externally loaded cold cracking tests. The load is applied via a welded-in cylindrical rod (implant pin with helical notch geometry), which is loaded in tension by a defined weight. The basic test setup is shown in Figure 3. Figure 3, *a* shows the so-called implant pin (left-hand side) and the machined annular or helical notch, of which the geometry is checked by a profile projector or stereomicroscope (see right-hand side of Figure 3, *a*). This notch ensures the concentration of the mechanical stresses, i.e. tightened local HAC conditions. The implant pin itself consists of the material to be tested. Figure 3, *c* shows the general assembly of the test-setup. Figure 3, *a* to c were taken from ref. [18] (via open access license CC-BY-4.0).

The implant pin is inserted into the hole (6 mm diameter) in the support plate (see Figure 3, *c*). The support plate and implant pin are joined by bead-on-plate welding using the appropriate filler material and welding parameters. After cooling to ambient temperature, the specimen is subjected to a static tensile load for ≥ 16 h. To determine the maximum test load, the load is successively increased with several welded specimens. The time-to-failure (“TTF”) is recorded for each specimen. Occurring cracks are evaluated using metallographic methods. The implant specimen is then annealed at 250 to 300 °C for one hour. Free crack surfaces of the crack oxidize and can thus be distinguished from the unaffected residual fracture surface (after opening of the sample in the laboratory, if not fractured). The Implant-test permits a qualitative “crack or no crack” statement. Quantitative values such as minimum preheating temperature or welding heat input can be determined, as well as the maximum allowable stress for crack-free welds. This so-called “critical implant stress” represents the highest test load/stresses at which neither fracture nor incipient cracking occurs [7, 9, 18] and exemplarily shown in Figure 4, *c*. The corresponding remaining “critical” hydrogen concentration can be determined either by the analysis of the broken implant pin as well as by ISO 3690 samples to identify the initial diffusible hydrogen concentration [9, 12, 13].

Figure 4 shows different weld penetration depth for different implant specimens made of a high-strength

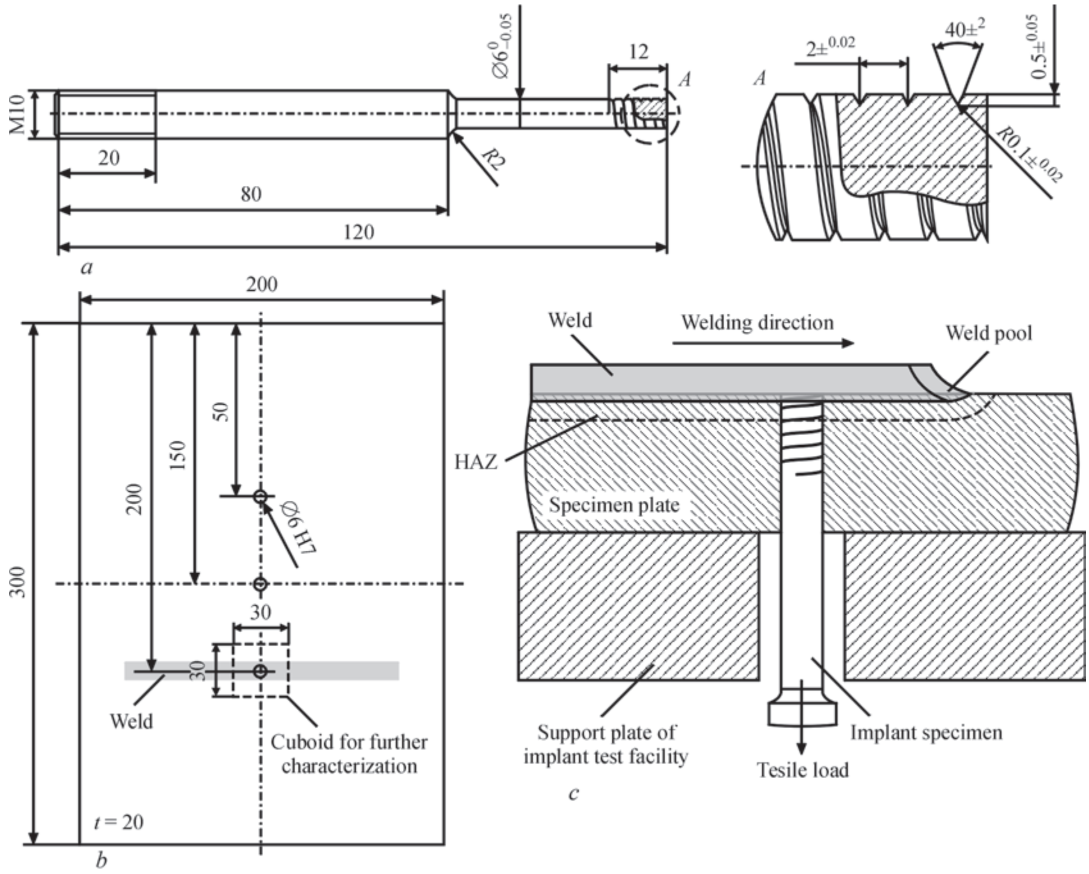

Figure 3. Implant test: *a* — implant pin with circumferential notch; *b* — BM support plate; *c* — schematic of test-setup, (unchanged Figure taken from ref. [18] with open access license CC-BY-4.0)

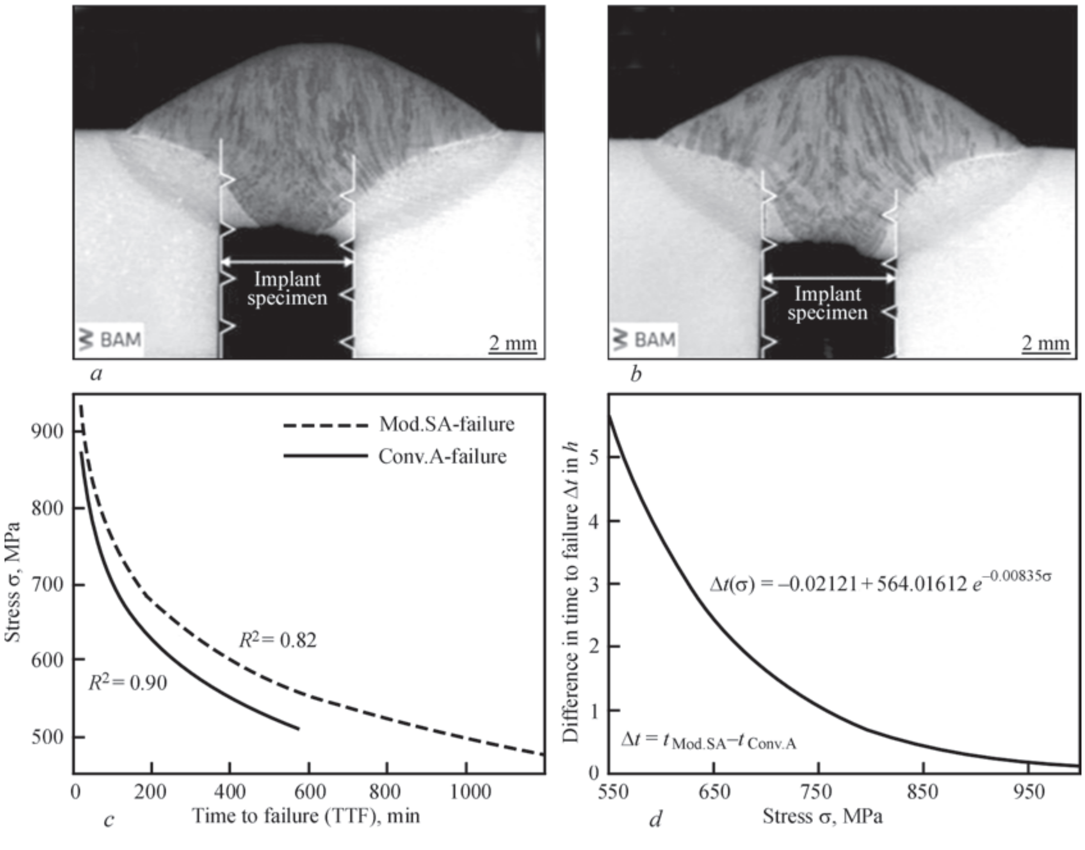

Figure 4. Implant-test: cross-sections of samples welded with: *a* — conv. A; *b* — mod. SA; *c* — calculated regression curves of implant samples; *d* — corresponding residuals, (Figure parts unchanged and rearranged, taken from ref. [7] with open access license CC-BY-4.0)

structural steel S960. Both samples were welded by metal active gas welding (GMAW) using conv. A (see Figure 4, *a*) or mod. SA (see Figure 4, *b*). It is evident that the penetration depth changes with the conventional or modified arc, regardless of the material grade tested. Thus, the Implant-test results differed significantly in terms of the time to failure achieved. For this reason, Figure 4, *c* shows the corresponding regression curves for both implant test series, and Figure 4, *d* shows the calculated differences in the TTF. The detailed work and results can be found in ref. [7]. Figure 4, *a* to *d* were taken from [7] (via open access license CC-BY-4.0).

In general, the Implant-test is used to standardize the cold cracking testing of base materials for coated electrode manual metal arc welding (MMAW), shielded metal arc welding (SMAW) with solid and flux-cored wire, and submerged arc welding (SAW) [9, 12]. However, similar restrictions apply to the Implant-test as to the Tekken test.

- Cold crack testing of filler materials is generally possible but requires extensive preparation of the Implant pin. This means that for newly developed filler materials, the suitability of weld crack testing must always be assessed first. For example (and as mentioned in section 2.2), hot microcracks must be anticipated as they may propagate as cold cracks at ambient temperature [15, 16].
- Advanced welding processes (such as mod. SA) require an adjustment of the weld geometry as the penetration depth is increased (see Figure 1, *b*). This affects the layer thickness, changes the hydrogen diffusion and in some cases significantly affects the crack resistance/critical implant stress (see Figure 3, *c* and *d*).
- The influence of the material must be amplified by the specific welding processing. In other words, the weldability of materials (especially for newly developed materials) must be of special interest prior to the industrial applications.
- In this context, the available minimum sheet thicknesses of the investigated high-strength steel limits the manufacturability of the Implant pins [18]. From that point of view, a critical evaluation of the implant pin geometry could be perhaps beneficial in the future.
- Another factor is that existing testing concepts are usually designed for specific material strength. The use of high-strength materials (e.g. S960 vs. S355 structural steel, i.e. 960 N/mm² vs. 355 N/mm² yield limit) requires correspondingly higher test loads to be applied. This requires stiffer test frames and advanced measurement technology (such as appropriate mechanical load frames).

DETERMINATION OF HYDROGEN CONCENTRATION IN ACCORDANCE WITH ISO 3690 USING CARRIER GAS HOT EXTRACTION

The measurement of hydrogen content, i.e. the extent to which a particular filler material introduces hydrogen into the weld pool, is essential in the welding process. An example of this is the HD classification. According to [13], an "HD5" specification guarantees that deposited weld metal contains ≤ 5 ml/100g Fe hydrogen. Considering the curves in Figure 2, *c*, this requirement becomes clear (degradation S960QL already at about 1.0 to 1.5 ml/100 g Fe hydrogen content in the WM [7, 18]. The ISO 3690 standard specifies requirements for test piece preparation (see Figure 5, *a*) and determination of the diffusible hydrogen in the WM for steels and applies to arc welding processes. For this purpose, the test piece is welded with a bead on plate seam, the run-off and run-off pieces are removed, and the center

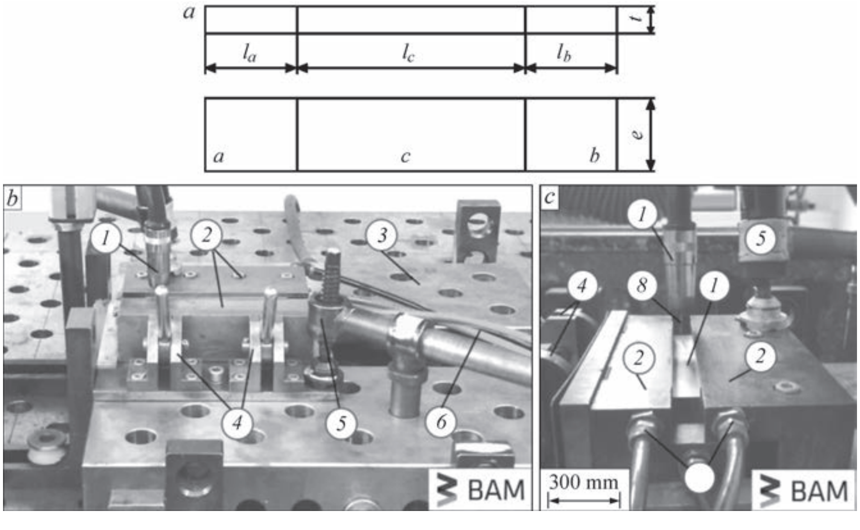

Figure 5. ISO 3690-welding: *a* — test sample; *b–c* — welding fixture, taken with permission from Springer Nature from ref. [19]: *1* — welding torch; *2* — copper clamps; *3* — fixing plate; *4* — toggle clamps; *5* — attachment; *6* — cooling water; *7* — specimen; 8 — welding consumable

section is stored deep-frozen in liquid nitrogen before hydrogen analysis, see Figure 5, *a*.

A major challenge is to quickly dissipate the welding heat from the sample, otherwise hydrogen will immediately escape at higher temperatures and falsify the measurement. For this purpose, the sample is welded in a water-cooled device that allows the sample to be removed within seconds after welding (Figure 5, *b* and *c*). The hydrogen is then quantified using carrier gas hot extraction (CGHE), as described in [19, 20]. Similarly, the fractured implant samples are analyzed for residual hydrogen content by CGHE. In addition, the CGHE measurements provide a starting point for the calculation of pre- or post-heating temperatures to remove hydrogen after welding [21].

CONCLUSIONS AND OUTLOOK

Hydrogen can cause delayed cracking in the weld of high-strength steel components. Modern welding processes such as mod. SA influence the heat input and thus the formation of crack critical microstructures (e.g. the HAZ) or the introduced hydrogen content. The cold crack tests have to be adapted accordingly. The following conclusions can be drawn from this study.

● For both self-restraint and externally loaded cold cracking tests, the occurring mechanical stress must be high enough to cause HAC-critical conditions. This can be achieved either by sufficient test loads and/or critical geometric conditions such as notches.

● For very high mechanical strength (especially high-strength low-alloyed steels with yield strength > 800 MPa), the available plate thickness can be a problem for sufficient cold cracking testing. On the one hand, for the self-restraint (e.g. TEKKEN) cold cracking tests, a minimum plate thickness is necessary to reproduce realistic restrain conditions. On the other hand, externally loaded cold cracking tests may require a minimum plate thickness for further machining of samples like in the case of the implant pin geometry.

● Advanced weld processing (e.g. conventional vs. mod. SA) can result in completely different cold crack resistance for similar welding conditions (as shown in [7, 18] and Section 3.2). The reason for this is, among other things, the changed weld seam geometry and welding run sequence, which affects the diffusion path length for the hydrogen. This must be considered when evaluating the test results.

● The determination of the hydrogen concentration (e.g. for implant or ISO 3690 tests) by CGHE is strongly recommended, as this is the only way to quantify the hydrogen. Further determination of diffusion coefficients is of great importance for welding practice, e.g. to derive holding times for hydrogen annealing, e.g. according to [21].

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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