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THE CONTROL OF CRACKS IN PRESSURE VESSELS EXPOSED TO AGGRESSIVE MEDIA

KONTROLA RAZPOK V POSODAH POD PRITISKOM ZA AGRESIVNE MEDIJE

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In this article the parameters affecting cracking and the crack types that are detected at various stages of a pressure vessel's fabrication and in-service use are described. The inspection for cracking with NDT methods, the repair procedure of pressure vessels (PVs) and the mitigation of cracking are also considered.

Key words: pressure vessels, cracks, aggressive media, non-destructive testing (NDT), welds

Opisani so parametri, ki vplivajo na pokanje in razpoke v različnih fazah izdelave posod pod pritiskom. Tudi preiskave pokanja po NDT-metodah, procedura popravil posod in blažitev pokanja so opisani.

Ključne besede: posode pod pritiskom, razpoke, agresivni mediji, neporušne preiskave, varjenje

1 INTRODUCTION

Pressure vessels (PVs) play a very important role in power and processing plants. The regulations relating to PVs include obligatory actions in design, production and exploitation. With welded PVs exposed to aggressive media the cracking that can occurr after long service times is a very serious problem. The growth of cracks during service results in leaks of corrosive media or even the fracture of a PV with very serious consequences. Especially dangerous media include wet H_2S and liquid ammonia because they may cause sulphide cracking (SC) and hydrogen blistering in weldments. The first case of wet-H_2S cracking of welds in Croatia was discovered in 1982 on four spherical storage tanks in the oil Sisak refinery. Some of the cracks were through-thickness cracks causing the leakage of propane-butane gas. All four spherical tanks were scrapped. Many cases of cracking due to wet H_2S and ammonia have subsequently been reported in a number of countries [1-5].

The mechanism of cracking was investigated in many countries and especially in the USA. In 1996 some important papers on the subject were pubblished by the NACE (National Association of Corrosion Engineers). In addition guidelines for the detection, the repair and mitigation of cracking for existing equipment in a wet H_2S environment were printed in Europe and USA. In 1993 the International Institute of Welding prepared recommendations for avoidance of cracking [6-11].

Inspectio reports for a total of almost 5000 weldments in oil refineries operating in a wet-H_2S environment were prepared and 1285 vessels were found to be cracked. Similar cracks were also observed in pressure vessels and piping for storage, transportation and process equipment for aggresive media causing hydrogen or ammonia attack in the process, pulp and power industries [1].

2 PARAMETERS OF CRACKING

The significant parameters which affect the cracking are:
- the presence of wet H_2S,
- the partial pressure of H_2S,
- pH value,
- operating temperature,
- H_2S concentration.

A H_2S concentration of 50 ppm or more in the aqueous phase is considered dangerous for the integrity of structures in refineries. Some authors, however, propose a threshold concentration even the presence of 10 ppm wet-H_2S [2].

Results of investigations in oil- and gas-production environments have shown that 0,35 kPa and greater partial pressures of H_2S in the presence of free water may cause SCC cracks in susceptible steels [2].

The rate of the hydrogen permeation flux in steels has been found to be the lowest in neutral solutions (pH 7) with increased rates observed at both lower and higher pH values [2].

The highest incidence of cracking occurred in the operating range 65 to 95 °C, however cracking was found to occurr for all temperatures in the range 38 °C to 150 °C [2]. In general the incidence of cracking increases with the increasing concentration of H_2S in water, nevertheless, 17% cracking was detected in weldments for environments with less than 50 ppm H_2S in solution in the aqueous phase [2].

3 CRACK TYPES AT VARIOUS STAGES OF MANUFACTURING AND SERVICE

Four types of hydrogen damage can occur:
– sulfide stress cracking (SSC), which is a form of stress corrosion cracking (SCC - **figure 1**);
– hydrogen-induced cracking (HIC - **figure 2**);
– stress-oriented hydrogen-induced cracking (SOHIC);
– hydrogen blistering (**figure 3**).

All four types of cracking require the presence of nascent hydrogen atoms on the steel surface, these are usually produced through a corrosion reaction in H_2S aqueous solution, since only atomic hydrogen can diffuse into the steel[1].

Sulfide stress cracking (SSC) may cause rapid crack growth and a catastrophic vessel failure. It is defined as metal cracking under the combined action of tensile stress and corrosion in the presence of water and H_2S. SSC usually occurs in steels over 600 MPa tensile strength or in hard areas of steel weldments. In the NACE standard MR 0175 for ferritic material the hardness maximum of 22 HRC (≈238 HB) is considered to be resistent to the occurence of SCC.

With hydrogen-induced cracking (HIC) internal cracks propagate stepwise and connect adjacent hydrogen blisters or isolated cracks in the metal. HIC is generally found in steels with high impurity level and/or in regions with anomalous microstructure due to the segregation of impurities and alloying elements in the steel.

Stress-oriented hydrogen-induced cracking (SOHIC) is generally observed in the base metal adjacent to the heat-affected zone (HAZ) of a weld oriented in the through-trickness direction. Tensile stress or residual stress are required to produce SOHIC.

Figure 1: SSC cracking in the heat-affected zone (HAZ)
Slika 1: SSC-pokanje v toplotni zoni zvarov

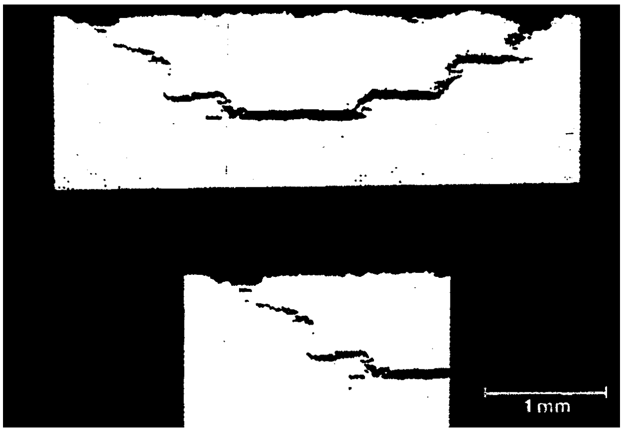

Figure 2: Hydrogen-induced cracking HIC-SWC (stepwise)
Slika 2: Stopničasto inducirano vodikovo pokanje HIC-SWC

Hydrogen blistering is the formation of subsurface planar cavities in a metal. It results from an excessive hydrogen pressure. Typical sites for the formation of hydrogen blisters are large nonmetalic inclusions, laminations or other discontinuities in the steel (more frequently found in lower strength carbon steels).

4 INSPECTION OF CRACKING

The required standard for a PV is obtained by a quality asssurance system. Different methods are used in practice to verify the reliability, e.g. stress-strength, fault analysis, failure rate etc. The cracks found during in-service inspection may originate at various stages of the PV's manufacturing and use. The best reliability is obtained from the fault tree analysis-crack detected in service with five phases of cracking [1].

New cracks may initiate, propagate, and become detectable and non-destructive testing (NDT) should be performed after each phase of manufacturing. The following types of defects have been identified [7]:
– manufacturing cold cracks in welds,
– pre-service hydro-test cracks in welds,

Figure 3: Hydrogen blister
Slika 3: Vodikov mehurček

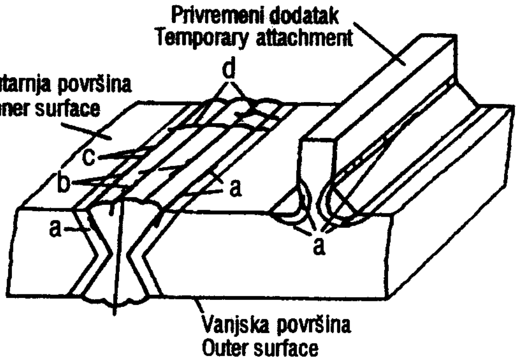

Figure 4: General location and site of cracks: a - HAZ longitudinal cracks in welds, b - WM longitudinal cracks in multipass welds, c - HAZ transversal cracks, d - WM transversal cracks, e - new cracks after hydrostatic testing

Slika 4: Lega in lokacija razpok: a - vzdolžne razpoke v toplotni zoni zvarov, b - vzdolžne razpoke v večvarkovnih zvarih, c - prečne razpoke v toplotni zoni, d - prečne razpoke v zvaru, e - nove razpoke po hidrostatskem preizkusu

- in-service low-temperature hydrogen damage (SCC, HIC, SOHIC, blistering),
- in-service hydro-test cracks in welds,
- in-service weld-repair cracks.

The location and orientation of cracks detected in the HAZ and welded material (WM) are shown in **figure 4**.

The majority of all detected cracks were inner-surface cracks exposed to corrosion media. The number of revealed cracks varies from less than 10 to several hundreds [7]. NDT methods have a major role in cracking control and are aimed at [9-14]:

1. the detecting of cracks during preventive cracking control;
2. to confirm the completion of a welding repair and detecting possible new cracks caused by repair welding;
3. to detect defects initiated or propagated during hydrostatic testing.

Most of the detected cracks were small inner-surface cracks which are difficult to reveal. It was recognised that radiography, ultrasonic, visual and dye-penetrant examinations were not sufficiently sensitive to small surface cracks and that the magnetic particle method should be used.

The inspection of weldments is mandatory. It includes circumferential, longitudinal, nozzle and internal attachment welds. Inspection areas should include repair or vessel-alteration welds and areas of the vessels that exhibit visible blistering, significant corrosion, or other defects. The surface of the weld and the adjacent area base metal to a distance of about 150 mm on both sides should be cleaned of all scale and residue.

Visual examination (VT) must be performed in suitable conditions, however, fine cracks may remain invisible.

Magnetic particle examination (MT) is the best method for the detection of fine surface cracks. This method is the most sensitive and it reveals many cracks that are not detected by other methods with a lower defect sensitivity. AC yoke WMFT is preferred over DC or prod methods. DC methods are not as sensitive and prod methods may leave arc strikes that, if not ground out, can serve as crack initiators.

Dye-penetrant examination (PT) is used only occasionally, is less sensitive than MT, it is however, easier to perform.

Ultrasonic examination (UT) with straight and angle-beam probes is the main method for the detection of subsurface and deeper surface defects of sufficient size. UT shear waves, longitudinal waves, and crack-tip diffraction ultrasonic inspections are used. UT may also be used for the examination of a vessel under pressure without discharging of the liquid gas from the vessel.

Radiography (RT) is used in cases of volume defects revealed by ultrasonics as an additional method for the characterisation of the defects. In cases of weld repair it is always recommended to use RT.

Acoustic emission (AET) monitoring during some vessel pressure tests is recommended for the detection of possible crack propagation. AE will detect any crack propagation at a sufficient stress level. Existing cracks, which are stable, will not be detected.

Eddy-current testing (ET) is used for crack detection and depth measurement.

Sequence and volume of NDT. Magnetic and ultrasonic examinatioust, are used for a 100% testing of welds for the life-cycle phases when cracks may initiate or propagate. The use of other NDT methods depends on the type of defects expected and other influencing factors such as the availability of instrumentation, location and position of defects.

Besides NDT methods for crack control other methods are used for inspection and control:

- metalographic and SEM examinations;
- hardness measurement (SCC/SSC is generally avoided for a hardness below 250 HV10);
- Ch V and FM parameters (CTOD, J_{Ic}, K_{Iscc});
- Measurement of dimensional and shape deviations.

The use of plates of "clean steel" is recommended to improve the resistance to blistering, HIC, and SOHIC. The contents of sulphur and phosphorus are limited up to 0.002% and up to 0.01%, respectively. A maximum carbon equivalent value of CE = 0,43 is recommended for carbon-steel pressure-retaining components for ensuring an acceptable microstructure, HAZ hardness, and tensile strength of the base material.

In the absence of surface corrosion, hydrogen cracking (SSC, HIC, SOHIC) or blistering cannot occur. Various practices are recommended for manufacturing new pressure vessels and for the operating conditions of existing units, such as:

Liners separating the carbon-steel wall from the process environment to prevent corrosion, (e.g. alloy weld overlay, alloy integral lining, alloy strip lining, thermal spray processes).

Several methods of mitigation in operation may be employed, for example:
- water washing,
- polisulfide injection,
- corrosion inhibitor injection.

The assessment of the degradation of the material and of the cracking revealed by in-service inspection requires a careful analysis, and the consideration of specific details for each vessel and application are required. The generic procedure for failure analysis and reliability/remaining-life assessment should cover:
1. the collection and review of manufacturing and construction records;
2. the review of ISI records;
3. the review the operating history;
4. the stress analysis and fracture mechanics parameters evaluation;
5. the estimation of the tensile properties and of the fracture toughness for the material (HAZ, WM, BM) at the end of the next operating period (EONOP);
6. the evaluation of the vessel reliability;
7. the establishment of actions to be taken;
8. the establishment of the plan for the next ISI.

5 REPAIR PROCEDURE FOR THE PRESSURE VESSELS

The following steps are used for the repair procedure of PVs:
- **defect removal and repair by grinding only**. If the depth of cracking is less than the corrosion allowance, the careful removal of the crack and the blending of the cavity with the surrounding is recommended;
- **repair by welding**. In case of deep cracks arc-air gouging and grinding are used for the preparation of the weld groove. Manual arc-air welding is mostly used for repair welding, (also TIG and SAW are used in special cases);
- **welding qualifications and welding variables** have to be strictly implemented and inspected;
- **weld reinforcements** should be flush ground, at least for main seams, to improve the detectability of weld defects by NDT, to remove stress raisers and to relieve residual tensile stresses, that are higher in the last layer or the last pass;
- **new weld cracks** have often been revealed by NDT after HT test and then the complete sequence of NDT and weld crack repair was to be repeated.

6 CONCLUSIONS

The cracking of pressure vessels that operate in aggresive media was a serious problem over the last 35 years in many countries. Wet-H_2S and liquid-ammonia cracking of exposed equipment are especially dangerous in service. Sulphide cracking (SCC) and hydrogen blistering occur in the presence of wet-H_2S in weldments, which are not heat treated.

The basic parameters affecting the cracking and four types of crack that occur at various stages of manufacturing and service are described. NDT inspection plays a very important role in the detection of cracks. The monitoring and control of aggressive constituents in the vessel medium and the vessel purging during service contribute to prevention of SCC and to the reliable pressure-vessel operation.

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