Ramo Bakić [1], Ljubica Milović [2], Radomir Jovičić [3], Stojan Sedmak [4]

QUALITY ASSURANCE OF STORAGE TANKS AFTER IN-SERVICE CRACK REPAIRS

OSIGURANJE KVALITETA REZERVOARA U EKSPLOATACIJI POSLE POPRAVKE PRSLINA

Naučni rad / Scientific paper
UDK /UDC: 620.172.24:66-988
Rad primljen / Paper received: 28.03.2013.

Adresa autora / Author's address:
[1] Tehnička škola, Tutin. Serbia, ramo.bakic@gmail.com
[2] University of Belgrade, Faculty of Technology and Metallurgy, Belgrade, Serbia
[3] University of Belgrade, Faculty of Mechanical Engineering – Innovation Centre, Belgrade, Serbia
[4] Society for Structural Integrity and Life (DIVK), Belgrade, Serbia

Keywords
- storage tank
- cracks in welded joint
- heat-affected-zone (HAZ)
- normalized structural steel
- stainless steel
- structural integrity assessment

Ključne reči
- rezervoar
- prslina u zavarenom spoju
- zona uticaja toplote (ZUT)
- normalizovani konstrukcijski čelik
- nerđajući čelik
- ocena integriteta konstrukcije

Abstract

According to the Pressure Equipment Directive (PED 97/23/EC) a new produced storage tank can be accepted on the market only if the required quality is proved. In this way the structural integrity might be at the requested level. However, it is not possible to apply all rules and standards for the quality during service and after performed repairs that are necessary to sustain the structural integrity of the storage tank. Storage tanks of steel are produced in general as cylindrical or spherical, and individual segments are joined by welding. Welded joints are prone to crack occurrence, and for that they are critical locations for safety and structural integrity. According to standard EN ISO 5817 cracks are not acceptable defects in welded structures, and detected cracks have to be removed. The applicability of quality assurance approach to repaired pressure equipment is analysed and discussed in this paper. In the first case welded joints in spherical storage tanks produced of normalized high strength steel (460 MPa yield stress) microalloyed with vanadium are analysed, considering repair and structural integrity assessment. In the second case, dissimilar welded joints of structural and stainless steel are examined.

Izvod

Prema Direktivi za opremu pod pritiskom (PED 97/23/EC) novo proizvedeni rezervoari se mogu prihvatiti za tržište samo ako je zahtevani kvalitet i dokazan. Na taj način integritet konstrukcije može biti na zahtevanom nivou. Ipak nije moguće sprovesti sva pravila i standarde za kvalitet tokom eksploatacije i posle izvedenih popravki, potrebnih da se održi integritet konstrukcije rezervoara. Rezervoari od čelika se uglavnom proizvode kao cilindrični ili sferni, na kojima su pojedinačni segmenti spojeni zavarivanjem. Zavareni spojevi su skloni pojavi prslina, i zbog toga su oni kritična mesta za sigurnost i integritet konstrukcije. Prema standardu EN ISO 5817 prsline nisu dopuštene greške na zavarenim konstrukcijama, i otkrivene prsline treba da se eliminišu. Primenljivost pristupa osiguranja kvaliteta na popravljenu opremu pod pritiskom je u ovom radu analizirana i diskutovana. U prvom primeru su analizirani sferni rezervoari izrađeni od normalizovanog čelika visoke čvrstoće (napon tečenja 460 MPa) mikrolegiranog vanadijumom, razmatranjem popravke i ocene integriteta konstrukcije. U drugom primeru su ispitivani raznorodni zavareni spojevi konstrukcijskog i nerđajućeg čelika.

INTRODUCTION

Welded tanks for storage of fluids under pressure are inevitably used in the industry, from simple units, up to large structures as in oil refineries or process- and power plants. The consequences of failure of storage tanks can be from negligible till catastrophic, with human loss and great material damage. The most critical location for failure is the welded joint. A quality assurance (QA) system developed for new products accepts for the market only new products of certified quality, that means with defects and imperfections of acceptable size, according to relevant standards. Cracks, as possible initiation of fracture, present a serious damage in welded structures. In general, they are not acceptable in welded structures (EN ISO 5817). However, only cracks greater than the sensitivity threshold of applied equipment for non-destructive testing (NDT) can be detected and repaired, if required. During operation, cracks can initiate from microcracks and defects under applied load and the environment. Inspection and maintenance of storage tanks in service is necessary to ensure structural integrity, and thus safe and reliable operation. Redesign, reconstruction and repair of storage tanks in service has to be performed frequently. It is almost impossible to repair pressure equipment components without welding. Weld repairs should be performed in accordance with all previous decisions regarding the design of a considered structure, materials, standards processes and procedures. However, the repair welding procedure needs to be specified for each case separately. Basic elements of QA system prescribed for new equipment might be applied also for repaired equipment in service, but this approach is complex and in this case is not standardized yet. Hence, quality assurance and structural integrity of storage tanks in service have to be verified after the performed reconstruction or repair.

Structural integrity of two examples, a repaired spherical and a cylindrical storage tank, is presented to analyse the applicability of the quality assurance approach for storage tanks after in-service crack occurrence and repair.

QUALITY ASSURANCE (QA) SYSTEM AND ACCEPTANCE OF EQUIPMENT FOR SERVICE

In order to improve the quality of produced industrial components as well as to avoid possible misunderstanding regarding the quality of products, several years ago the standardization system has been introduced with the aim to meet the requirements of increased industrial production.

Introduction of ISO 9000 /1/ standards for quality assurance and ISO 9001 and ISO 9002 for quality systems is, far and away, the most influential initiative that grew from the quality movement of the late 1980s, followed by a number of different series of standards (e.g. ISO 14000). In principle, quality of final new equipment has to be evaluated on the product itself. However, in some cases this is not sufficient for the verification of the product quality, as this is the case with welded structures.

ISO 9000 defines welding as a “special process” because welded joints cannot be fully inspected according to standard requirements for a complete verification. In the case of welding, the quality cannot be verified on the product but has to be built into the product. This generally accepted approach is dictated by the nature of fabrication in welding. Anyhow, the quality of a welded joint can be endangered: (1) by imperfections and defects induced during manufacture or in service, and (2) by inevitable heterogeneity in the microstructure and corresponding mechanical properties, induced by the nature of welding processes which consist of the subsequent heating-cooling cycles and corresponding melting and solidification of steel.

For new welded products the QA system has to assure:

- defect free welded structure when it is accepted for exploitation;
- tolerable level of imperfections according to standards;
- well defined microstructure and mechanical properties, and analysed effects of their heterogeneity on the behaviour of the structure in loaded and environment condition.

It is necessary to preserve sufficiently high quality level during service, up to the end of the required or expected operational life of the structure. Accordingly, the same requirements need to be applied for repairing. In complex systems of high risk level, as welded structures, introduced maintenance has to include everyday supervision and periodical inspections, and today an increased use of continuous monitoring, in order to assure structural integrity and reliable operation. After analysing the results of periodical inspection, continuation of operation can be approved, or some repair actions need to be done before that in order to re-establish an expected quality level, or when detected damages are serious, the system operation can be stopped before a final solution of the problem is found, /2, 3/.

Maintenance of complex systems has to be capable to act promptly and efficiently in order to enable continuous operation at high level of safety and reliability. Periodical and systematic overhaul required by design has to be included in service, sometimes with temporary break-down of the system.

It is to have in mind that storage tanks in the pressure equipment system might be endangered by very small damages, as cracks. Local leakage in long pipelines can occur through a small crack, requiring to stop the use of the entire pipeline or to disconnect a separate segment in the pipeline. Problem of experienced leakage has to be solved with priority in order to re-establish the operating process. Welding is in most cases the only solution, but it has to be performed in all circumstances according to qualified welding procedure specification (WPS), accepted by inspection as temporary in order to avoid greater financial loss.

Accepting the significance of safe operation of complex systems for safety and environmental protection, national authorities for pressure equipment have been established worldwide. A quality assurance system developed for new products, as the defined in Pressure Equipment Directive (PED 97/23/EC) /4, 5/, enables easier correspondence between equipment manufacturers and users. It increases the equipment security level, preventing failures in service.

At first glance, one can conclude that PED 97/23/EC defines everything regarding new pressure equipment security. More detailed examination will reveal that irregularities in welded joints in the form of imperfections, defects and heterogeneities have an important effect, which can not be completely controlled in service, thus contributing to failure. To emanate substantial aspects of this effect, it is necessary to find out what is covered by PED 97/23/EC and supplementary documents.

Requirements for design, manufacture, testing, marking, labelling, instructions and materials of pressure equipment, where the hazard exists, are mandatory and must be met before products may be placed on the European Community market in the, compulsory Essential safety requirements (ESRs) (Annex I of 97/23/EC). In that sense, “Pressure equipment must be designed, manufactured and checked in such a way as to ensure its safety when put into service in accordance with the manufacturer’s instructions, or in foreseeable conditions” with the hazard treated according the significance (Guidelines: 8/15,8/7-97/23/EC).

It is to notice the important difference in the application of quality assurance approach for new equipment offered to market and for the equipment repaired in service. In a very simplified scheme of manufacture and maintenance during service of pressure equipment, three main subjects responsible for quality assurance might be recognised.

The first subject is the manufacturer. His role is to produce new equipment of required quality.

The second subject is the customer, i.e. the user of the equipment. After the acceptance of equipment from the manufacturer for exploitation and expired warranty period, the user is responsible for safe operation and environmental protection.

The third subject is the national institution for safety and environmental protection, responsible for the verification of equipment quality. In addition to new equipment, this institution has to verify also the quality level of repaired components in service. It has to be included by the manufacturer for new equipment and also by the user for equipment in service so to verify the quality during inspection and after performed repairs.

According to PED 97/23/EC the contract between equipment manufacturer and user should define the requested quality. The national institution for quality assurance has to be included to supervise the application of codes and standards in manufacturing process in order to confirm the quality level. Similarly it should be included for quality supervision in the case of repair.

Pressure equipment must be properly designed taking all relevant factors into account. The design must incorporate safety coefficients using comprehensive methods which are known to adopt safety margins against all relevant failure modes, and designed for loads expected in its intended use for foreseeable operating conditions. Internal/external pressure, ambient and operational temperatures, static pressure and mass of contents in operating and test conditions are most important factors. For special products it is necessary to account the traffic, wind, earthquake loads, reaction forces and moments resulting from supports, attachments or piping, corrosion and erosion, fatigue, decomposition of fluids.

The calculation method of pressure containment and other loading aspects include allowable stresses, limited regarding to reasonably foreseeable failure modes under operating conditions. To this end, safety factors must be applied to fully eliminate any uncertainty arising in manufacture, actual operational conditions, stresses, calculation models and the properties and behaviour of the material. This can be achieved by applying design by formula, by analysis, fracture mechanics, or combining these approaches.

Material characteristics to be considered include:
- yield strength, 0.2% or 1.0% proof strength at calculation temperature,
- tensile strength,
- time-dependent strength, i.e. creep strength,
- fatigue data,
- Young’s modulus (modulus of elasticity),
- appropriate amount of plastic strain,
- impact strength and toughness,
- fracture toughness,
- appropriate joint factors, applied to material properties depending, i.e. on the type of non-destructive test, the materials joined and the operating conditions envisaged (e.g. corrosion, creep, fatigue).

The next important stage is manufacture. The manufacturer must ensure the competent execution of the provisions set out in the design stage.

Preparation of component parts must not give rise to defects, cracks or changes in the mechanical characteristics likely to be detrimental to the safety of pressure equipment. Permanent joints and adjacent zones must be free of any surface or internal detrimental defects. For pressure equipment, permanent joining of components which contribute to the pressure resistance must be carried out by suitably qualified personnel (EN 287), according to suitable operating procedures (EN 288).

Inspection is an important step in the QA system. As in the welding procedure applied for the manufacture of new components, during and after the weld repair supervision and tests, are necessary till final inspection of performed welded joints. For this delicate and responsible third part task, a respectable independent company should be engaged.

Weld repair success or additional correction should be estimated during manufacture. This is important also for maintenance. Before the examination level, no action is required (Fig. 1). Corrective actions must be taken after detection of indication and its evaluation regarding the type, size and significance at its recording level. The next step is the acceptance level by the quality assurance system. If the decision at the quality assurance level is questionable or negative, especially when a crack is in question, less strict fitness-for-purpose criteria might be applied and subsequent repairs performed in order to avoid the rejection of a defective component after final evaluation. Acceptance of the repaired component in that case has to be supported by theoretical and experimental analysis, as well as by numerical modelling when appropriate. In the case that weld repair is not successful, the problem should be determined for a possible further action. This involves re-evaluation of the preparedness of the welder, and appropriateness of the repair procedure, including the fit-up procedure, thermal treatments, and specifications. This also could involve re-evaluation of the welding process selected. That means, the welding procedure specification (WPS) should be re-defined and qualified again, if required. Proper visual inspection procedures during fabrication and repair can increase product reliability over that based only on final inspection.

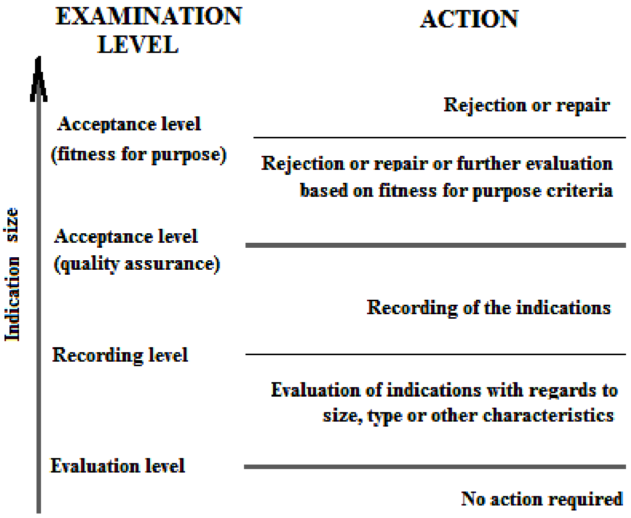


Figure 1. Classification of indications and actions - EN 12062.
Slika 1. Klasifikacija indikacija i akcija - EN 12062

For pressure equipment, non-destructive tests of permanent joints must be carried out by qualified personnel, and for categories III and IV, the personnel must be approved by a third-party organisation.

Pressure equipment must be subjected to assessment through final inspection, proof test and inspection of safety devices. Proof test is performed by hydrostatic pressure corresponding to maximum loads to which pressure equipment may be subjected in service, multiplied by prescribed coefficient.

Materials used for manufacturing pressure equipment must be suitable for such application during the scheduled lifetime. Welding consumables and other joining materials need to fulfil the relevant requirements in an appropriate way, both individually and in a joined structure. This means (a) appropriate properties for all operating conditions and for all test conditions, with sufficient ductility and toughness, but also being capable to prevent brittle-type fracture, when necessary; (b) sufficient chemical resistance to the fluid contained in pressure equipment; (c) not to be affected by ageing; (d) to be suitable for intended processing procedures.

The pressure equipment manufacturer must define values necessary for the design calculations and characteristics of materials and their treatment, and must provide elements in technical documentation related to the compliance with materials specifications of the Directive 97/23/EC and take measures to ensure that the material used conforms to the specification. If a material manufacturer has an appropriate quality-assurance system, its issued certificates are presumed the conformity with the requirements.

Detailed quantitative requirements for certain pressure equipment given in corresponding provisions 97/23/EC can be applied as a general rule.

Introduction of PED 97/23/EC was justifiable and beneficial. The increased quality level of produced and repair welded equipment has improved the situation in all aspects. This is important for extended use of oil and gas for energy supply. The implementation of PED 97/23/EC required changes and improvements of practice in pressure equipment design, manufacture and service. It helps to solve many problems in use of pressure equipment and more economical production.

It is to remind here that quality assurance of welded joints has been implicitly involved in the very early stage of welding introduction in the fabrication of pressure vessels, about a hundred years ago. Expensive riveting of vessels is replaced with more comfortable and cheaper welding, but users required proof evidence that quality and safety are assured. The reason was limited knowledge and experience in welding, since welded joint quality mainly depended on welder skills. Since the quality in that period had to be proved on a finished joint, only the available non-destructive test, radiography, was involved for inspection, and it has saved its position of priority in regulation up to now. However, radiography is rather expensive and cannot be successfully applied for crack detection. Much cheaper reliable methods are developed in the meantime (ultrasonic, magnetic, dye penetrant, continuous video monitoring).

The experience in service was, and still is, fundamental support for the development and improving of the quality assurance system. Next two case studies can serve to describe the benefits for pressure equipment quality assurance gained after detailed analysis of experienced failures.

The first refers to well analysed failure by brittle fracture of a thick-wall welded pressure vessel, /6/.

This failure was caused by cracks in facet form in HAZ of the welded joint. A large pressure vessel had been designed for use in an ammonia plant at a pressure of 350 bar and 120°C. It was fabricated from ten Mn-Cr-Ni-Mo steel plates 150 mm thick, rolled and welded to form ten cylindrical shell sections, and of three forgings of similar material for two end closures and one flange. Plates are supplied in normalised-and-tempered condition, the forgings are annealed, normalised and tempered. Longitudinal welds are ground to match the curvature of the shell, in order to reduce stress concentration. During various stages of manufacture, all seams are examined by gamma radiography, automatic and manual ultrasonic tests, and magnetic-particle inspection.

The specified maximum test pressure was 480 bar at an ambient temperature above 7°C. At 340 bar the customary halt was made, and about 30 s later, the flange end of the vessel exploded without warning. The flange forging was found to be cracked completely through at two locations, and the first two cylindrical sections were totally shattered. The failure did extensive damage to one end forging and three adjacent shell sections.

It was possible to conclude that failure stemmed from the formation of transverse fabrication cracks in the HAZ of the circumferential weld joining the flange forging and first shell section. Fracture surfaces were typical for steel brittle fracture, originating from two points, flat facets (sized 9 and 11 mm), located partly in the HAZ on the forging. The structure just below each facet in the HAZ was a mixture of bainite and austenite (hardness 426 to 460 HV). Elsewhere, the structure of HAZ was coarse and jagged bainite (hardness 313 to 363 HV). Stress relief of the vessel had been inadequate, leaving residual stresses and hard spots and providing low notch ductility in the weld (Fig. 2).

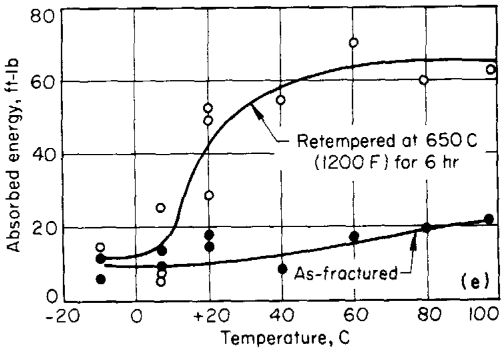


Figure 2. Absorbed energy for Charpy V specimen tests: lower curve for weld metal of fractured part; upper curve after heat treatment at 650°C for 6 h.

Slika 2. Energija udara Šarpi V epruvete: donja kriva za metal šava slomljenog dela; gornja kriva posle termičke obrade na 650°C tokom 6 h

The determined impact fracture energy confirmed brittle appearance of the fracture surface, but not plane strain condition necessary for such a fracture.

The investor decided to apply postfestum the fracture mechanics tests, already well developed. Proof is obtained, comparing applied stress field and tested plane strain fracture toughness that size of detected crack can be the cause of brittle fracture. It is to notice catastrophic consequence of failure, with total material separation.

Based on results of performed investigation, after repair, in 1968 the pressure vessel was accepted for service.

Here presented is only a small part of the performed complex and extended investigations and the tests show the significance of fracture mechanics when applied for assessment of the quality assurance. It is to underline that applied NDT examination, radiography in particular, was not sensitive enough to detect embedded crack-like defects, hard facets in this case. This was in fact a first clear warning of very small crack significance, and two conclusions are derived:

- it is important to detect possible defects in structures such as pressure vessels and pipelines;
- it is necessary to assess the possibility of the initiation of a detected defect.

The second example represents fitness-for-purpose evaluation based on fracture mechanics as accepted evidence of allowable crack size applied in the case of Trans-Alaska pipeline, enabling significant economic effects, /7/.

Proof pressure testing of oil pipelines is, due to the distribution of longitudinal and hoop stresses, relevant for pipes and longitudinal welds, but not for circular welds joining pipe ends. Circular welds are tested only 10% regarding welders and welding quality. Additional analysis of performed radiography revealed that in many cases standards for quality of circular welds are not fulfilled. Required repairs were too expensive and the occurrence of new similar cracks can be avoided. The solution is found by fracture mechanics analysis of flaws, /7/, which has shown that the acceptable crack size might be larger. However, this requested a more sensitive test method, as based on electromagnetic acoustic transducer (EMAT), developed at the National Bureau of Standards (NBS), /8/.

Findings of these two case studies have been respected in development of quality assurance systems, as well as other similar achievements from experience.

The quality assurance system for new products has solved many important problems between the manufacturer and user, as opponents on the market. However, for in-service pressure equipment, the opponents are state government authority and user. The user has to prove the assured quality by inspection in order to obtain permission for next exploitation of components operating under pressure in the specified environment. Hence, new procedures for inspection, maintenance and repair are considered and introduced, necessary for risk evaluation, /9, 10/.

SPHERICAL STORAGE TANKS

A spherical vessel is preferred for storage of fluids under high pressure. An advantage of spherical storage vessels is that they have uniform distribution of stresses and a smaller surface area per unit volume than any other shape of vessel. Spheres, however, are more expensive than cylindrical vessels due to serious problems in manufacture. Application of new developed high strength low-alloy (HSLA) steels has enabled reduction of wall thickness and production costs. The benefit was twofold: significantly reduced weight of used steel and reduced cost of welding due to reduced weld metal volume (less work, less consumable).

Leakage of spherical storage tanks

In the seventies of last century, normalised fine-grained steel of 460 MPa nominal yield strength (St 47), micro-alloyed with vanadium (V), was developed and world-wide applied, also for spherical storage tanks.

It turned out that applied fine-grained V micro-alloyed steel NIOVAL 47 (Steelworks Jesenice) is sensitive to cold cracking in the HAZ. Many cracks were detected on inner surface by ultrasonic and magnetic tests during inspections, /11/.

After several years in service, at the start of the eighties, a large number of spherical storage tanks made of this steel leaked in succession, as reported. Faced with frequent failures of spherical storage tanks, several national inspection offices decided to forbid the production of new tanks applying this steel. Large number of such tanks had been already in service, some of them are still in use, and many of them were repaired after failure. Well known companies (e.g. British Petroleum) decided to withdraw spheres of this steel from service to avoid frequent unexpected failures and brake-downs of operation.

The most intensive reaction regarding leakage, including repair, took place in former Czechoslovakia, /12/. Analyses have shown that cracks propagated in shielded metal-manual-arc (SMAW) welded joint through the fusion region between weld metal (WM) and parent metal (PM), in the zone of high hardness, containing 90% of martensite. Through-wall cracks were attributed to the initiation of existing cold hydrogen induced cracks (HIC). Lot of short cracks had been revealed in welded joints, on the inner side. During the removing of cracks by grinding, new cracks were revealed by dye penetrants in the fusion regions.

Many of about 100 tanks in service failed in Yugoslavia due to cracking. The first storage tank of liquefied natural gas failed in 1982 by leakage at ambient temperature 20°C, under pressure of 12 bar, some weeks after regular in-service inspection and proof pressure test at 24 bars.

By regular in-service inspection of several spherical tanks, in 1993, many crack-like defects had been detected on the inner side, /13/. In several tanks, cracks developed through the wall. Crack initiation and growth had been attributed to following causes:

- the attack of hydrogen sulfide (H_2S);
- cracks from imperfections in welded joints induced during manufacture;
- effect of high pressure during required proof test;
- quality of applied steel and presence of brittle microstructure in HAZ;
- other factors (residual and thermal stress, geometrical stress concentration).

Repair of spherical storage tanks

A specific situation with spherical storage tanks in Czechoslovakia required their repair, /14/, and the details about performed action are reported by I. Hrivnak.

In Yugoslavia tank owners had concluded that it is still better to maintain properly existing spheres by regular in-service inspection and to repair them if necessary, than to withdraw them from use and replace with new tanks. This approach is shortly presented here, using one case study of storage tank for VCM, /13, 15/. It rather comprises improvement in inspection than to define the optimal repair welding procedure specification (WPS), reduction of proof test pressure level, and personnel education.

Cracks had been grinded in layers with grindstone rotation axes normal to the axes of the welded joint. The crack depth was monitored by magnetic flux. It was found that cracks were positioned in HAZ and in WM, with tips ending in pores or inclusions. Notches less than 5 mm deep were only grinded. Notches deeper than 5 mm were welded according to Fig. 3.

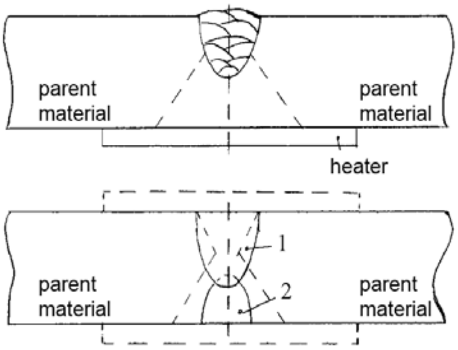


Figure 3. Repair welded joints: one side (up) and both side welds (down).
Slika 3. Popravljeni zavareni spoj: zavarivanje sa jedne strane (gore) is a obe strane (dole)

It was strictly required to follow the sequence of passes. Welding started in the weld root and continued alternately on both sides. The final passes had to be performed so that the HAZ hardness was limited by tempering and residual stress relaxation. Sides were flattened by grinding and had ended by welding reinforcement, at least at 3 mm distance from the fusion region.

Properly dried coated electrodes ASW E 8018-G 3.25 mm in diameter, were applied for re-welding of grinded notches above 5 mm deep. Used welding parameters were: pre-heating temperature 150°C (using an electrical heater), current $I = 100$ A, voltage $U = 21$ V, heat input $E = 1.32$ kJ/mm, welding speed 13.5 cm/min. Calculated value of the cooling temperature was $\Delta t_{8/5} = 4.83$ s for 20 mm material thickness, and the measured value was 7.5 s.

This approach is accepted in the company HIP AZOTARA, Pančevo, /15/, after the analysis of the occurrence of defects and prescribed convenient repairing procedure. It is applied to several tanks of wall thickness 20 mm that failed due to leakage.

Hydrogen content in consumables, disrespect to welding technology specification (WPS), stress corrosion and damages in service caused the initiation of cold cracks induced by welding /16, 17/.

An adverse effect of specified proof test (cold-water test with pressure to 50% higher than operating pressure) was accentuated. Testing of the tanks before and after inspection by non-specified additional test has clearly shown that the proof test in service can cause new cracks at the positions of “old”, but not repaired welded joints, /13/. For that reason the proposals of tank owners had been addressed to by the competent Boiler Inspection Office in Serbia to reduce test pressure, especially in service. Experience has shown that the pressure vessel repaired by welding should not be subjected to pressure tests, only periodical ultrasonic tests of typical repaired positions from the outer side should be performed, e.g. immediately after repair (“initial” state) and after the operating parameters are reached. If no crack is detected, these tests should be repeated every 6 to 12 months, until the term of regular periodical proof test. Due to significant financial expenses in repeated cycles: testing, repair with testing, testing after repair, proof test, testing after proof test, periodical inspection, selective approach to testing and repair of vessels prevailed, so that only overfills on critical locations (radial welded joints and crossings) should be grinded and subjected to ultrasonic tests. This procedure had been accepted by Boiler Inspection Office in Serbia as satisfactory for repaired storage tank acceptance for continuous use. The main requirements were that the tank has passed proof test and is put into service crack free.

Specific case of fitness for service assessment

During the exploitation it is frequently necessary to allow the use of cracked storage tanks for limited time. In this case, crack significance assessment by fracture mechanics parameters might be decisive. as shown in Ref. 16.

Upon the request of the spherical storage tank owner, fracture mechanics analysis by J-integral was applied for an atypical case of cracking. These cracks occurred in weldments of temporary fixtures which have served solely for further operations of welding and assembling on the tank inner surface (Fig. 4).

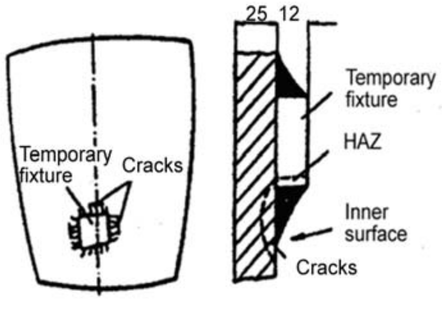


Figure 4. Temporary fixture on inner side.
Slika 4. Privremeni držači na unutrašnjem zidu

Being temporary, fixtures had not been specified in the design documentation, and after use they had to be removed. Cracks, up to 4 mm deep and 30-50 mm long had been initiated in HAZ and arrested in the PM. Cracks occurred because the specified SMAW welding technology was disrespected in-situ. The welding of fixture, being temporary was considered as unimportant, inspection of welding and welded joints was not done. Hence, this welding was left to the skill of welders. Neither the specified preheating was applied nor the required procedure for drying electrodes was used. High content of diffusible hydrogen enabled crack initiation. Thus, the crack nuclei were already present in the tank and grew to macroscopic size in proof pressure testing. After the occurrence of first cracks of this type, careful inspection revealed cracks up to 5 mm deep in the HAZ of the temporary fixture in the wall 25 mm thick, with fixture being removed or not. This situation dictated extended non-destructive tests. In order to provide necessary sensitivity, the weld overfills on inner and outer sides were ground.

Further extension of these crack was possible in the virgin PM, not affected by welding, but in both the rolling- and cross-rolling direction.

These cracks are prone to corrosion and stress corrosion, what might contribute to their extension. Critical locations have to be repaired either by grinding of small cracks or by additional qualified welding, if the crack size is large. The aim of the structural integrity assessment by applying the J integral was to assess possible operation in short time, before the final decision regarding the repair.

Considered spherical storage tank was of an outer diameter D_s = 12500 mm and wall thickness h = 25 mm, designed for pressure p_d = 6 bar and proof test pressure p_0 = 10 bar at temperature t_0 = 15°C. It was produced of NIOVAL 47 steel, yield stress 460 MPa. Its properties, obtained by testing (480 MPa yield stress, 680 MPa ultimate tensile strength, impact toughness at –20°C from 55 to 200 J/cm^2 and hardness HV10 180–200) satisfied the specification.

The following assumptions for J integral calculation had been involved:

1. Plane stress condition is assumed, and membrane stress is dominant since wall thickness vs. diameter ratio is small (25/12500 = 0.002).
2. Spherical shell is shallow and can be analysed as plane plate, /18/.
3. Maximum crack size is supposed to be 5 mm in depth and 100 mm in length.

J integral testing had been performed using standard C(T) ASTM E1152 specimen and unloading compliance method to evaluate J_{Ic}, a measure of fracture toughness, and to define *J-R* resistance curves (Fig. 5). Resistance curves are determined for PM, with cracks located in the rolling direction (CT1, CT2) and transversal to it (CT3, CT4).

The transfer of experimentally obtained results to the real construction requires many assumptions to be fulfilled, due to different stress states for quasi-static loading applied to the specimen, and in full-scale structure. Cracks in tanks occurred in HAZ of temporary fixtures (Fig. 4), and could extend in PM only. Brittle fracture significance is evaluated by fracture toughness K_{Ic} value of PM. The K_{Ic} lowest value of 111 MPa√m was for crack in the rolling direction, still two times higher than the applied K_I value (63.7 MPa√m), indicating that brittle fracture is not probable.

A set of CDF diagrams for applied shell factor $\lambda = 3$, normalised by applied stress σ with yield stress σ_Y, on one side, and relative crack, the ratio of virtual crack depth, a, equal to maximum d = 5 mm and wall thickness, h = 25 mm (ratio d/h = 0.2) was compared with *J-R* curves for PM in rolling (CT1) and cross-rolling (CT4) directions. The conclusion was that stable crack growth is not critical since the required CDF for detected small cracks corresponded to pressure of 22 bar, and the pressure in proof test is 10 bar.

So, the described cracks were not significant. After a requested period for use of the cracked tank, cracks were removed by grinding out and rounding of the root. Original dimensions were recovered by surfacing, if necessary.

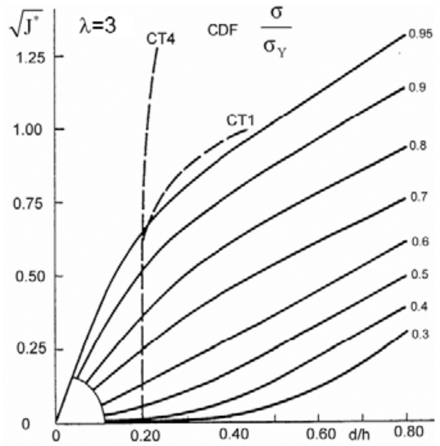


Figure 5. Crack resistance *J-R* curves (C1 rolling, C4 transversal direction) and J crack driving force (CDF), King's model.
Slika 5. *J–R* krive otpornosti prema prslini (C1 pravac valjanja, C4 poprečni pravac) i J krive razvoja prsline (CDF), model Kinga

LEAKAGE FROM DISSIMILAR WELD ON STORAGE TANK

The analysis presented here is performed for a damaged storage cylindrical tank for liquefied CO$_2$, /2, 3/. It is a pressure vessel (Fig. 6), 12.5 m^3 in volume, 1600 mm in diameter, 7180 mm long; class II, working pressure 30 bar, proof pressure 39 bar, minimum operating temperature –55^{o}C.

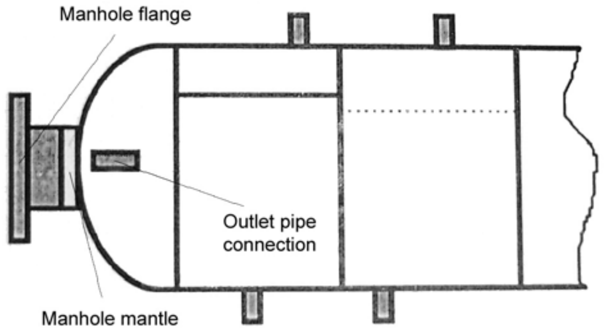


Figure 6. Storage tank for liquefied CO$_2$ with dissimilar welded joint in the manhole.
Slika 6. Rezervoar za tečni CO$_2$ sa raznorodnim zavarenim spojem na otvoru

The vessel is made of 14 mm thick steel NIOVAL 47, designated as steel M. High-alloyed austenitic steel (designated as steel X) has been selected for manhole flange and outlet pipe connection. The dissimilar austenite-ferrite welded joint was produced by welding steels M and X, using INOX 29/9 as consumable.

Damage significance

To evaluate the damage level caused by cracks, cracks had been removed by grinding, but up to the middle of the flange neck wall cracks had not been eliminated. Two water droplets occurred outside from detected two pores, located 5 mm and 15 mm from fusion lines. The flange was cut on the lathe along the fusion region in steel M, the damaged zone had been eliminated and after non-destructive tests, it was re-welded. It is to say that detected pores were positioned on the surface of through cracks.

On the side edge of the ring, through the inner side of flange neck cross section, cracks with pores were detected by dye penetrant. After repair welding no damage was detected by non-destructive tests and no leakage occurred during the proof pressure test. Based on this finding, detected damages were considered as negligible. The dye penetrant from the inner side did not detect cracks in the manhole. However, some growing cracks in steel M, presented in Fig. 9, met the pores, linked them in a crack and produced leakage.

The first type of defects was the leakage of the manhole flange – austenitic steel X, indicating that the storage tank really failed. Careful examination during proof pressure test confirmed existence of two tinny cracks, passing through the flange wall, but also many pores in the same region, induced probably in casting. They were close to the welded joint. In previous inspections the noticed leakage was considered as condensation on the outer wall due to the temperature effect, but the last inspection revealed drops and indicated through-wall leakage. The solution for this problem was to cut the flange, eliminate the defective region reducing the length, and re-weld the joint using proper welding procedure, that was verified and qualified on samples by welding.

The second problem were cold cracks, detected after tests in HAZ of steel M (Fig. 7) as well as cracks in WM. Detected cracks were irregular, longitudinal (60; 46 and 9 mm long, about 3.5 mm deep), parallel to the fusion line, and circular cracks (10; 9 and 5 mm long, 6.5 mm deep).

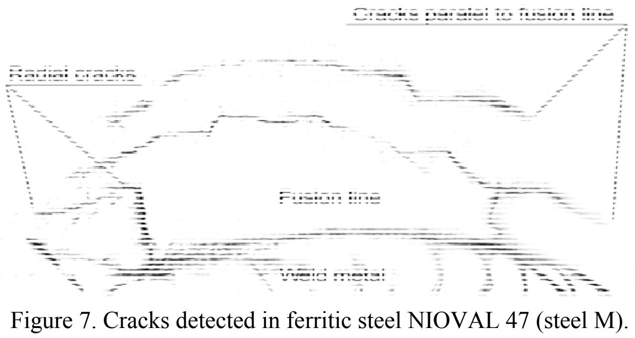


Figure 7. Cracks detected in ferritic steel NIOVAL 47 (steel M).
Slika 7. Prsline otkrivene u feritnom čeliku NIOVAL 47 (čelik M)

With replicas it was possible to reveal microcracks 1.8 mm long, in HAZ of steel M (Fig. 8), and a coarse grain structure with martensite in the bainite steel structure, and an austenite microstructure with 35% of δ-ferrite in the weld metal.

In order to get closer insight of revealed leakage a series of mechanical tests (tensile test, impact toughness test, and hardness measurement) and investigation of microstructures had been performed, /3/. However, this was not sufficient for final conclusion, and fracture mechanics test completed this experimental investigation.

A different microstructure of dissimilar welded joint constituents, parent metals of steel M and steel X, and weld metal, /2/, indicated their different tensile properties and different local response to tensile loading (Fig. 9), affecting also crack growth behaviour.

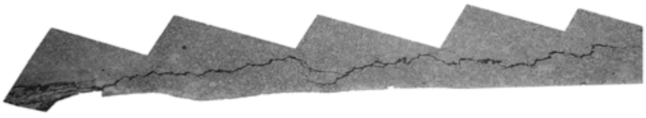


Figure 8. Microcrack in the HAZ of HSLA steel M.
Slika 8. Mikroprslina u ZUT HSLA čelika M

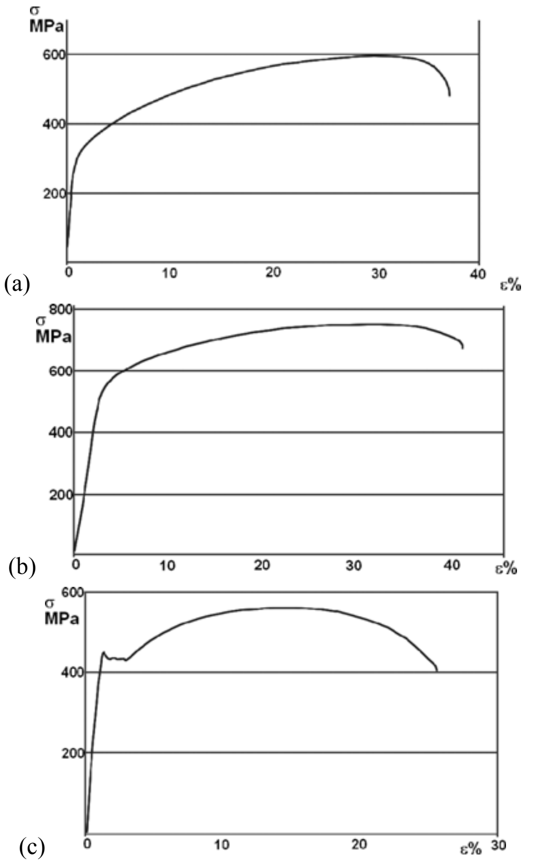


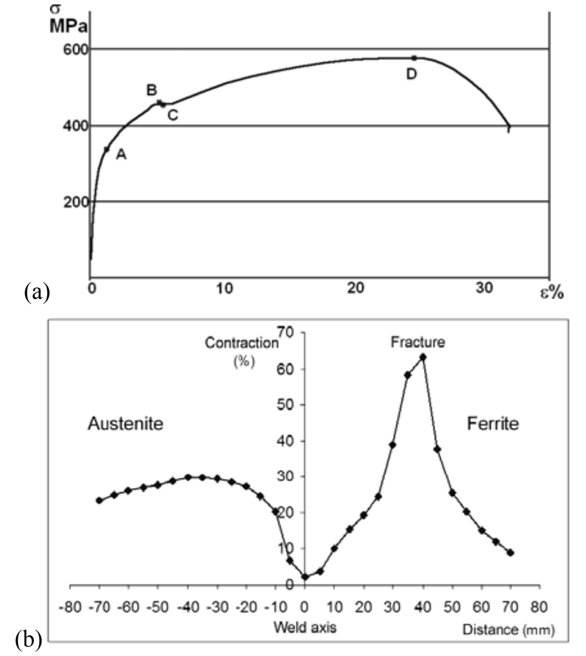
Figure 9. Stress vs. strain, a) austenitic parent metal, steel X; b) all weld metal INOX 29/9 (WM); c) ferritic parent metal, steel M.
Slika 9. Napon-deformacija , a) austenitni osnovni metal, čelik X; b) metal šava INOX 29/9 (WM); c) feritni osnovni metal, čelik M

Distribution of strains in loaded welded joint

Highest tensile strength is found for all WM produced by INOX 29/9 electrode (755 MPa), for PM steel X it is only 600 MPa, while PM steel M exhibited the lowest tensile strength (555 MPa). The highest value of yield strength is for all WM (545 MPa), the lowest for steel X (315 MPa), and for steel M it is in-between, (435 MPa). These values determined the behaviour of welded joint constituents, also influenced by elongation properties and strain hardening.

Elongation at fracture A_5 is highest for steel X (specified 36%, measured value 27%), somewhat lower for WM (specified 35%, measured 30%) and the lowest for steel M (specified 25%, measured 12.5%). From Figure 9, strengthening coefficient *H'* is determined to be 1055 MPa for steel X, 960 MPa for steel M and 700 MPa for INOX 29/9 all WM, which governed post yield behaviour of the individual constituents.

To understand the behaviour of the stressed pressure vessel, it is necessary to explain the tensile behaviour of the three-material body (Fig. 10). Yielding will initiate (point A, Fig. 10a) and develop only in austenitic steel X of lowest yield strength, with expressed ductility and strain hardening, to point B, when yield strength level of steel M is achieved. At point B, deformation is redistributed, developing in both steels M and X (faster in steel X), up to point D, at the level of steel M tensile strength. Plastic strain started in WM at a neglected level (Fig. 10b), since post yielding strength of steel X is higher than tensile strength of steel M (Fig. 9). Hence, final fracture of specimen occurred in the ferritic steel M, (σ_m = 555 MPa, Fig. 10b).



(a)

(b)

Figure 10. Behaviour of welded joint specimen in tensile test, a) stress–strain curve; b) distribution of contraction.
Slika 10. Ponašanje epruvete zavarenog spoj pri zatezanju, a) kriva napon–deformacija; b) raspodela kontrakcije

In tested cases (different heat input, room and low temperature to –60°C), WM had the lowest toughness, due to the presence of δ ferrite. The HAZ of steel M exhibited high impact toughness, for both crack initiation and growth. This was attributed to the crack tip location in the region of higher toughness in HAZ. In combination with the overmatching effect, this provided the basis for structural integrity improvement, /3/. To verify this, fracture mechanics tests of critical regions were performed using J-integral.

Assessment of crack significance by fracture mechanics parameters

Charpy type specimens with V notch were used, produced from samples 2 and 4, fatigue pre-cracked to crack length 5 mm in the HAZ of steel NIOVAL 47, and in weld metal. Standard ASTM E1820 was used, SEN(B) specimen had been tested as a relationship *J* vs. crack opening displacement, δ, by unloading compliance method, at 20°C and at –60°C. Two diagrams, typical for the HAZ behaviour are presented in Fig. 11, indicating that HAZ specimens saved sufficient toughness even at –60°C.

The goal of testing was to define crack resistance curve (*J-R* curve). From this curve it is possible to determine critical J_{Ic}, a measure of fracture toughness, convert it to plane strain fracture toughness K_{Ic} and verify crack significance in regard to brittle fracture. The complete *J-R* curve is more useful, enabling the determination of the stress level for initiation of stable crack growth.

For the same specimens, 2 and 4, *J-R* curves are presented in Fig. 12, and structural integrity assessment for the cracked storage tank is shown in Fig. 13.

Obtained values of K_{Ic} show the effects of testing temperature on welded joint components. Highest K_{Ic} values belong to specimens notched in HAZ, and notched in WM have 50% lower values. This is not important for static loading, but can be critical at variable loading, and when the crack size, a_c, critical for brittle fracture is reached.

Presented data enabled to analyse structural integrity of the damaged dissimilar welded joint. In a welded structure crack-like defects are probable, and in vessels they are often surface cracks in HAZ or in WM, close to the fusion region. Frequently, the shallow crack cannot be detected by available devices for non-destructive testing, and the vessel might be used eventually with cracks from the beginning.

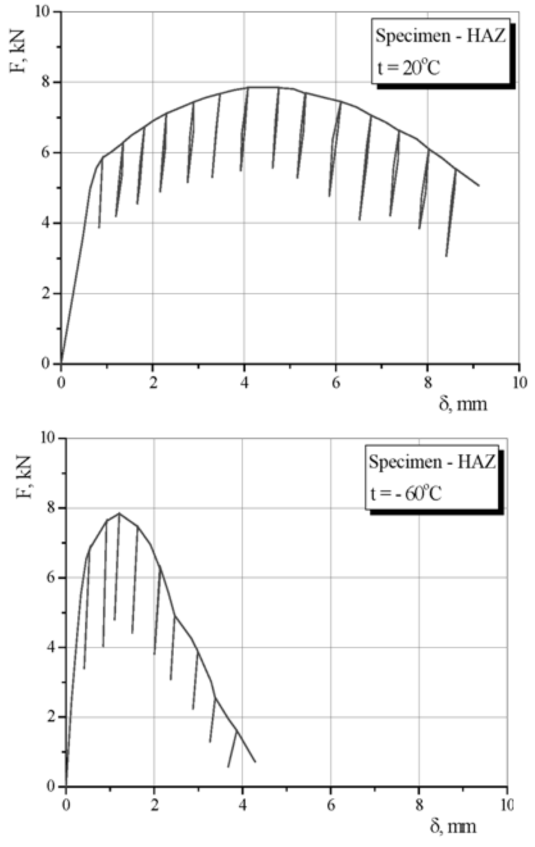


Figure 11. Relationship *J* vs. COD, δ, for HAZ specimens.
Slika 11. Zavisnost *J*–COD, δ, za epruvete iz ZUT

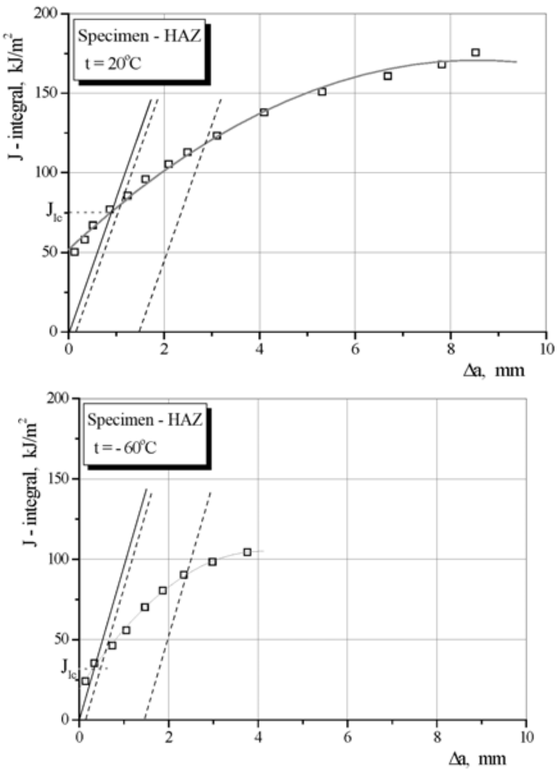
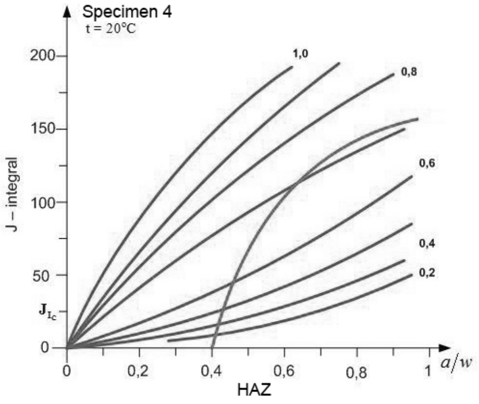
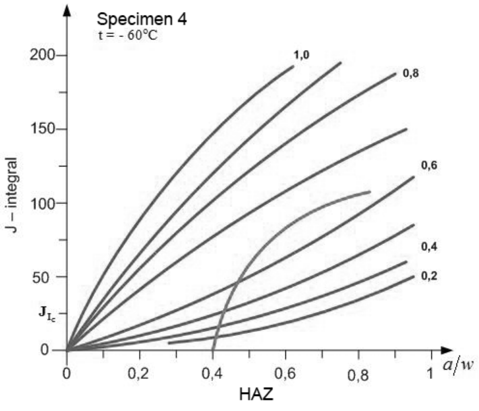


Figure 12. *J-R* curve and J_{Ic} value, for HAZ specimens.
Slika 12. *J-R* kriva i vrednost J_{Ic}, za epruvete iz ZUT



HAZ, heat input 10.03 kJ, 20°C.
ZUT, uneta toplota 10,03 kJ, 20°C



HAZ, heat input 10.03 kJ, 20°C.
ZUT, uneta toplota 10.03 kJ, 20°C

Figure 13. Structural integrity assessment of storage tank.
Slika 13. Ocena integriteta rezervoara sa prslinom

Obtained values of K_{Ic} show effects of testing temperature on welded joint components. Highest K_{Ic} values belong to specimens notched in HAZ, and notched in WM have 50% lower values. This is not important for static loading, but can be critical at variable loading, and when the crack size value, a_c, critical for brittle fracture is reached.

DISCUSSION

The aim of this paper is to present and discuss the significance and complexity of quality assurance of storage tanks during exploitations. Inspections, followed by maintenance and repair are involved as regular actions for secure use of pressure equipment in service. Welding procedure and welded joint properties are of vital importance for quality assurance, at least as in the manufacture of new equipment. Permanent joining of components responsible for their resistance must be in both cases carried out by suitably educated and qualified personnel (EN 287), according to suitable operating procedures (EN 288).

However, the conditions imposed for welding in manufacture and repair may differ significantly. Hence, the requirements in the developed and introduced quality assurance system for new products based on ISO 9000 and PED 97/23/EC are not fully applicable for repair welding, better say they are not sufficient. Directives and WPS for repair have to be evolved for each individual case, when this is required in the user company or by national authority.

Quality is a global property of a structure. To assure the quality required by design, a series of testing should be performed before, during and after manufacture, /1/, in order to verify input data regarding the material, manufacture (also with reference to welding) and functionality. In the procedure of the quality assessment it is necessary to check if relevant properties, obtained by tests, satisfy the values specified in standards, codes and recommendations.

According to the scheme given in Fig. 1, in the case of new equipment, the final step for acceptance of components should be the quality assurance level, so fitness-for-purpose after repair, or further evaluation can be applied only exceptionally. On the other hand, for further use of components during exploitation, the acceptance level in general is based on fitness-for-purpose. The reason is a great number of influencing factors which are not present in the case of new equipment. This means, essential safety requirements from Annex I of PED 97/23/EC must be fulfilled and evidenced with more data for re-design and re-construction, considering the previous solution, as it is shown in Ref. /19, 20/. An important problem is connected with the applied material. For relatively new equipment, the specification for material is generally available and valid, or at least similar steels can be found. It is to have in mind that many storage tanks are in service for a long time, sometimes for many decades. So, many necessary data about the material (already specified in the text), technology and manufacture, operating and loading conditions, inspection, maintenance and retrofits might not be available, and have to be assumed. In that case the applied steel can be verified only partly, no specification is available, and in some cases it is not possible to get a similar material. Also samples for experimental tests can not be prepared due to the shortage of the material. Evaluation of quality assurance in this situation is uncertain. Some assumptions about steel characteristics have to be induced in that case, and verified in the best possible way, as it is applied in Ref. /21/.

It is also to note that quality, although a global property, is related with and depends on local material properties. Most important local properties that affect the quality, are connected with detection, properties and the behaviour of a crack, with the microstructure and its heterogeneity, mechanical properties (as tensile, impact, toughness, hardness) corresponding to microstructure, what is of special importance in the case of the welded joint.

Microstructural analysis of materials and welded joint constituents can help to decide on further use of damaged storage tanks. Because mechanical properties are related to microstructure, the heterogeneity of the welded structure has to be determined. The procedure of simulation, /11/, enables to obtain a sufficient volume of material for testing properties of different regions within the HAZ. On the other hand it is possible by HAZ simulation to identify important phase transformations during welding and to assess the characteristics of the critical region in the fusion zone. It has helped to determine weak points of steel NIOVAL 47 in HAZ region close to the fusion line, regarding brittle fracture, and enabled to understand the failures of pressure equipment produced of this steel /5, 11, 13/. Due to experienced problems in welding and service of this steel, it has been excluded from further use in new equipment, in spite the fact that it is possible to obtain a welded joint of the requested quality by proper WPS and its strict application, as it is achieved in the repair welding of the presented spherical and cylindrical vessels /15, 16, 17, 22, 23/. Anyhow, normalised steel NIOVAL 47 in steelworks “Jesenice” was successfully replaced by quenched and tempered steel NIOMOL 490 of the same strength class and applied for spherical storage tanks, /11/.

A next important aspect for quality assurance is the crack significance and behaviour in the welded structure. A first important step is to detect the crack in a structure, what is possible by applying new developed sophisticated NDT equipment and by regular inspection and monitoring of cracks, today a normal procedure for pressure equipment. Anyhow, fracture mechanics has enabled to assess the significance of detected crack /24-28/, but also to predict the crack behaviour in the elastic and elastic-plastic range, /29/.

Numerical methods and modelling are powerful tools for extended analysis, also for repair, as presented in /20, 30/. Their application can significantly improve the quality level of the structure after repair.

More evidence for the quality level has to be supplied for the repairing procedure and inspection. It is important to avoid failures in further service, and both parts, the user and the national authority are interested for complete verification of presented evidences with high accuracy. Criteria for the quality level have to be defined separately for each case and have to be verified in a proper way, as this is done in the presented examples. However, there is no general rule, similar to that accepted in PED, for the acceptance of the equipment.

Three different approaches are explicitly presented in order to constitute the acceptance criteria.

In the first example of the spherical storage tank, it was important to eliminate the possibility of crack existence in vessels accepted for further service. The former procedure allowed to apply proof tests under pressure, higher than the operating pressure as the final step in acceptance procedure, according to valid regulations. After extended experience and investigation, it has been established that due to the existence of the M-A constituent in HAZ in tanks produced of NIOVAL 47 steel, the subcritical crack indications during proof test initiated as microcracks. In regular service these microcracks developed, by stress corrosion in the aggressive environment, sometimes supported by variable loads, into through cracks, producing leakage. The solution is found in proof pressure reduction to operating level, but this was not sufficient. Additional inspections and tests were required for repaired tanks during service.

The second example of temporary fixtures welded in spherical tanks indicated two interesting aspects. The first revealed that WPS requirements must be obeyed also for auxiliary weldments. The second aspect is that initiated cracks had been arrested in the region of parent metal not affected by welding. Hence, the presented analysis based on fracture mechanics using the J-integral as a parameter, was sufficient for decisions on necessary actions in the process of tank acceptance.

CONCLUSION

Generally, it is possible to apply the principles of quality assurance approach, developed for new products manufactured according to the directive PED 97/23/EC, also for pressure components repaired during service.

To achieve a similar level of quality for new and for used equipment, following differences between new and repaired components should be respected:

- Interested litigants for new equipment are manufacturer and customer, for repaired components user and national authority for safety.
- Manufacturing and repairing procedures are different, although it is reasonable to apply qualified WPS for new equipment also in repair. It is not always possible.
- Available materials and relevant input WPS data for repairing are limited. Since the damaged component might be old, similar materials can be used with assumed weldability and characteristics.
- More evidence for the quality level should be supplied for the repair procedure and inspection. Criteria for the quality level have to be defined separately for each component and have to be verified in a proper way, as this is done in the presented examples.
- Introduction of numerical modelling can extend the applicability of the quality assurance approach, especially for repaired equipment.

REFERENCES

1. ISO 9000 http://en.wikipedia.org/wiki/ISO_9000
2. Milović, Lj., Vuherer, T., Zrilić, M., Momčilović, D., Jaković, D., *Structural Integrity Assessment of Welded Pressure Vessel Produced of HSLA Steel*, Journal of Iron and Steel Research International, 18 (1-2) : 888-892, 2011.
3. Jovičić, R., *Analysis of cracks effect on integrity of ferrite-austenite welded joints*, (in Serbian), PhD Thesis, University of Belgrade, Faculty of Mechanical Engineering, 2007.
4. The Pressure Equipment Directive (97/23/EC), on Internet
5. Bređan, A., Kurai, J., *European Pressure Equipment Directive (PED) and Structural Integrity*, (in Serbian), Structural Integrity and Life (IVK), 3 (1): 31-42, 2003.
6. King, R.T., *Failures of pressure vessels*, Metals Handbook Ninth Edition, Vol.11, Failure Analysis and Prevention, ASM, Metals Park, Ohio, 1986, pp. 650-652.
7. Reed, R.P., McHenry, H.I., Kasen, M.B., *A fracture mechanics evaluation of flaws in pipeline girth welds*, Weld. Res. Counc. Bull. 245, 1979.
8. Reed, R.P., Schramm, R.E., *Acceptance inspection of circular welds in pipelines, with reference to non-destructive testing*, Fracture Mechanics of Weldments, Ed. S. Sedmak, TMF, GOŠA Institute, Belgrade, (in Serbian), pp.307-317, 1985.
9. Sedmak, T., Sedmak, S., Milović, Lj., *The applicability of strategy for risk based maintenance to a penstock*, Structural Integrity and Life (IVK), 12 (3): 191-197, 2012.
10. Kirin, S., Jovanović, A., Stanojević, P., Sedmak, A., Džindo, E., *Risk Analysis in Structural Integrity – Application to a Large Company*, Structural Integrity and Life (IVK), 11 (3): 209-212, 2012.
11. Gerić, K., *Cracks in Welded Joints*, (in Serbian), FTN Izdavaštvo, Novi Sad, 2005.
12. Hrivnak, I., *Breakdown and repair of large spherical containers for liquefied hydrocarbon gases*, IIW Doc. IX-1516-88, Bratislava, 1988.
13. Kurai, J., Aleksić, B., *Proof pressure test cause cracks in pressure equipment in service*, (in Serbian), Structural Integrity and Life (IVK), 3 (2): 65-71, 2003.
14. Hrivnak, I., *Repair welding of huge spherical storage tanks*, Service Cracks in Pressure Vessels and Storage Tanks, (in Serbian), Eds. S. Sedmak, A. Sedmak, TMF, ECPD, GOŠA Institute, Belgrade, pp.328-351, 1994.
15. Aleksić, B., Fertilio, A., *Repair of spherical tank for storage VCM in volume of 2000 m^3*, in Service Cracks in Pressure Vessels and Storage Tanks, (in Serbian), Eds. S. Sedmak, A. Sedmak, TMF, ECPD, GOŠA Institute, Belgrade, pp.255-261, 1994.
16. Sedmak, S., Petrovski, B., Sedmak, A., Lukačević, Z., *The study of crack significance in spherical storage tanks by J resistance curve*, Conference on Weld Failures, TWI, Welding Institute, London, 1988.
17. Gnirss, G., Hrivnak, I., Lukačević, Z., *Recommendations for reliable operation of pressure vessels exposed to aggressive media like ammonia and sour gas*, IIS/IIW Doc. IX-1711-93/XI-609-93. 1993.
18. Berković, M., *Problems of Plane and Triaxial Stress States in Pressure Vessels and Pipelines*, Structural Integrity and Life (IVK), 4 (2): 67-74, 2004.
19. Fertilio, A., Janković, T., Kovačević, I., Salamić, D., *Sanacija oštećenja u cilju postizanja integriteta reaktora i produžetka veka eksploatacije*, *Reactor Damage Overhaul in the Course of Integrity Achievement and Service Life Extension*, Structural Integrity and Life (IVK), 4 (3): 129-136, 2004.
20. Maneski, T., Sedmak, A., Milović, Lj., Fertilio, A., Sedmak, S., *Fitness-for-Purpose Assessment of Repaired Feedwater Heater*, Structural Integrity and Life (IVK), 6 (3): 111-120, 2006.
21. Sedmak, A., *The Application of Fracture Mechanics to Structural Integrity* (in Serbian), University of Belgrade, Faculty of Mechanical Engineering, Belgrade, 2003.
22. Adžiev, T., Sedmak, A., Adžiev, G., Arsić, M., *Residual strength assessment of cracked welded spherical storage tank*, Structural Integrity and Life (IVK), (in Serbian), 2 (1-2): 20-22, 2002.
23. Adžiev, G., Sedmak, A., *Integrity assessment of spherical storage tank*, Structural Integrity and Life (IVK), 3 (2): 93-98, 2003.
24. Fracture mechanics of weldments, US-Yu joint project, Principal investigator S. Sedmak, Annual reports, University of Belgrade, Faculty of Technology and Metallurgy (TMF), 1982-1991.
25. Sedmak, S., Sedmak, A., *The experimental analysis of crack behavior in welded pressure vessels*, IIW Doc. X-1447, 1998.
26. Sedmak, S., Petrovski, B., Sedmak, A., *The Resistance to Crack Growth of Different Regions of Weldments in a Real Structure*, Int. J of Pres Ves and Piping, 52: 313-335, 1992.
27. Ratwani, M., Sedmak, S., Petrovski, B., *The assessment of residual strength of pressure vessel with surface crack by resistance curve*, in Fracture Mechanics of Weldments (in Serbian), Ed. S. Sedmak, GOŠA, TMF, Belgrade, 1985, p.131-162.
28. Sedmak, S., Sedmak, A., *Welded penstock produced of high-strength steel and application of fracture mechanics parameters to structural integrity assessment*, in Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines, Eds. G. Pluvinage, M.H. Elwany, Springer, pp.271-286, 2008.
29. Sedmak, A., Sedmak, S., Milović, Lj., Pressure Equipment Integrity Assessment by Elastic-Plastic Fracture Mechanics Methods, monograph, Society for Structural Integrity and Life (DIVK), Belgrade, 2011.
30. Berković, M., Maksimović, S., Sedmak, A., *Analysis of Welded Joints by Applying the Finite Element Method*, Structural Integrity and Life (IVK), 4 (2): 75-84, 2004.