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ISPITIVANJA METODAMA BEZ RAZARANJA FERITNO-AUSTENITNIH ZAVARENIH SPOJEVA

NON-DESTRUCTIVE TESTING OF FERRITIC-AUSTENITIC WELDED JOINTS

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Ključne reči
- ispitivanja bez razaranja
- zavareni spoj
- prslina
- rezervoar

Izvod

U radu je dat prikaz postupka ispitivanja celog rezervoara za tečni CO_2 i praćenja stanja zavarenih spojeva novih priključaka tokom eksploatacije. Rezervoar je izrađen od mikrolegiranog čelika povišene čvrstoće NIOVAL 47, a priključci od visokolegiranog austenitnog čelika. Novougrađeni zavareni spojevi su ispitani metodama bez razaranja u cilju utvrđivanja njihove eksploatacijske sigurnosti. Svojstva materijala feritno-austenitnog spoja nameću ograničenja u primeni ovih ispitivanja, pa je neophodno korišćenje dopunskih metoda (replika, merenja tvrdoća). Pokazano je da je samo tako moguće dobiti dovoljno podataka za pouzdanu procenu sigurnosti spojeva u eksploataciji.

Keywords
- non-destructive testing
- welded joint
- crack
- storage tank

Abstract

The paper presents procedures for a complete test of the liquid CO_2 storage tank and monitoring of welded joints on new connections. The storage tank is produced of high strength microalloyed steel NIOVAL 47, and connections are of high-alloyed austenitic steel. Newly introduced welded joints are tested by non-destructive methods for safety verification. Ferritic-austenitic welded joint properties impose limitations in applying these tests, so an application of additional methods is necessary (replicas, hardness test). It is shown that only in this way is it possible to obtain sufficient data for reliable assessment of joint safety.

UVOD

Tokom eksploatacije rezervoara za skladištenje tečnog ugljendioksida ukazala se potreba za ugradnjom dva nova priključka u gornje dance, preko kojih bi se povezala spoljna freonska jedinica i unutrašnji, u rezervoar ugrađeni, toplotni izmenjivač. Ugljendioksid se u ovom rezervoaru skladišti na temperaturama od -30 do -50°C. I pored spoljne toplotne izolacije, dolazi do zagrevanja ugljendioksida u rezervoaru, usled čega raste isparljivost tečne faze, što dovodi do porasta pritiska gasne faze ugljendioksida koja dostiže pritisak otvaranja ventila sigurnosti i ugljendioksid se ispušta u atmosferu, tj. javljaju se gubici. Što je viša temperatura u rezervoaru češće je ispuštanje ugljendioksida u atmosferu, odnosno, veći su gubici. Ovi gubici se mogu smanjiti sniženjem temperature u rezervoaru, tj. poboljšanjem toplotne izolacije ili hlađenjem gasne faze ugljendioksida u toplotnom izmenjivaču koji je povezan sa spoljnom rashladnom freonskom jedinicom.

IZRADA I ZAVARIVANJE PRIKLJUČAKA

Rezervoar za skladištenje tečnog CO2 je vertikalna, cilindrična, toplotno izolovana posuda pod pritiskom, izrađena od mikrolegiranog čelika povišene čvrstoće ČRN 460 (JUS C.B0.502), tj. NIOVAL 47 (oznaka proizvođača Železarna Jesenice), debljine 12 mm. Osnovni podaci su: spoljni prečnik 2000 mm, ukupna visina 10080 mm, zapremina 25 m^3, maksimalni radni pritisak 25 bar, ispitni pritisak 32,5 bar, klasa posude II i najniža radna temperatura -50°C, /1/.

INTRODUCTION

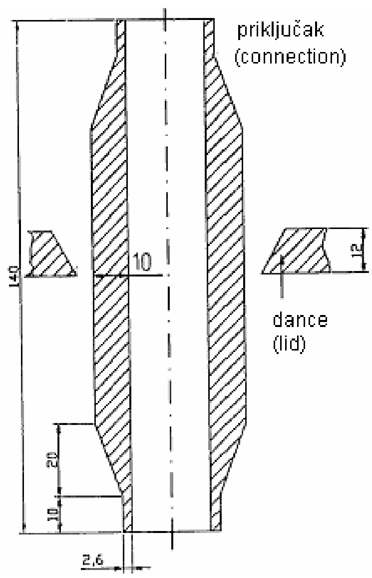
In-service operation of the liquid carbon dioxide storage tank has indicated a necessity for introducing two new connections at the upper lid in order to connect the outer freon unit to the inner built-in heat exchanger. Carbon dioxide is stored at temperatures from -30 to -50°C. In spite of outer thermal insulation, the carbon dioxide in the tank is heated and evaporation of its liquid phase increases. This results in higher gas phase pressure, which reaches critical safety valve release pressure. The carbon dioxide then leaks into the atmosphere, thus contributing to an increased loss of carbon dioxide. Higher temperatures in the storage tank will cause frequent leaks and much greater loss of carbon dioxide. These losses may be reduced by lowering the temperature inside the tank, i.e. by improving thermal insulation, or by cooling the carbon dioxide gas phase inside the heat exchanger – which is connected to the outer freon cooling unit.

MANUFACTURING AND WELDING CONNECTIONS

The CO_2 storage tank is a vertical cylindrical, thermally insulated pressure vessel produced of high strength microalloyed steel ČRN 460 (JUS C.B0.502), or NIOVAL 47 (Steelworks Jesenice trade mark), 12 mm thick. Basic data are: outer diameter 2000 mm, total height 10080 mm, volume 25 m^3, maximal operating pressure 25 bar, proof test pressure 32.5 bar, vessel class II and minimal operating temperature -50°C, /1/.

S obzirom da je najniža radna temperatura rezervoara -50°C, za njegovu izradu su upotrebljeni čelici sa garantovanom žilavošću na ovoj temperaturi. Pošto čelik NIOVAL 47 zadovoljava ovaj uslov, upotrebljen je za izradu plašta i danaca. Međutim, zbog specifičnog postupka proizvodnje mikrolegiranih čelika, pa i čelika NIOVAL 47, od njih se ne proizvode cevi, pa je proizvođač rezervoara za izradu priključaka upotrebio cevi i prirubnice od austenitnog čelika Č.4572 (JUS C.B0.600), /1/. Za izradu dva nova priključka, takođe je izabran čelik Č.4572 i prema proračunu /2/ priključci su prečnika 26,9 mm i debljine zida 2,6 mm. S obzirom da je izmenjivač predviđen za pothlađivanje gasne faze, smešten je u gornji deo rezervoara, pa su novougrađeni priključci postavljeni u gornje dance, sl. 1, /2/. Međutim, pošto je teško ostvariti kvalitetan zavareni spoj između materijala sa ovolikim razlikama u debljinama, usvojeno je da se za dance zavaruju ojačanja debljine približne debljini danca i da se onda za ojačanja zavaruju priključne cevi, sl. 1. U daljem tekstu će biti reči samo o zavarenim spojevima ojačanja i danca. Ojačanja su izrađena mašinskom obradom iz tuljka, prema dimenzijama datim na sl. 1. Ojačanja su zavarena za dance E postupkom, rutilno obloženom elektrodom legiranom sa 29% Cr i 9% Ni (oznaka E 29 9 R 12 prema standardu EN 1600). Oblik i dimenzije žlebova su prikazani na sl. 1. Žlebljenje je izvedeno gasnim rezanjem tako što su u dancu prosečeni otvori prečnika jednakog prečniku priključaka, a zatim su brušenjem obrađene ivice na zadate mere, sl. 1, /3/.

Since the lowest operating temperature of storage tank is -50°C, it is made of steels with guaranteed toughness at this temperature. The steel NIOVAL 47 fulfils this condition and is selected for manufacturing mantle and lids. Anyhow, due to specific procedure of microalloyed steel production, including NIOVAL 47, it is not used for making tubes, and so the storage tank manufacturer applied tubes and flanges of austenitic steel Č.4572 (JUS C.B0.600), /1/. Steel Č.4572 is also used for making two new connections. Since the exchanger cools the gas phase, it is located in the upper tank with new built-in connections positioned in the upper lid, Fig. 1, /2/. According to calculation in /2/, concerning operating pressures in the tank and exchanger, the connections with 26.9 mm–diameter and 2.6 mm–wall thickness, made of Č.4572, are satisfactory. However, it is difficult to achieve a quality welded joint with such large differences in thickness and is decided reinforcements are to be welded to the lid with thicknesses similar to that of lid, and afterwards the connecting tubes are welded to the reinforcement, Fig. 1. Hereupon, only welded joints of reinforcements and lid are considered. Reinforcements are machined from a tube, according to dimensions in Fig. 1. Reinforcements are welded to lid by MAW procedure using rutile electrode, alloyed with 29% Cr and 9% Ni (designation E 29 9 R 12 according to EN 1600). Groove shape and dimensions are given in Fig. 1. Grooves on lid are produced as oxy-acetylene cut holes of diameter corresponding to connection diameter, and ground at the edges to specified dimensions, Fig. 1, /3/.



Slika 1. Izgled i dimenzije ojačanja priključka i žleba spoja.
Figure 1. Design and dimensions of connection and joint groove.

Pre početka zavarivanja elektrode su osušene na 300°C za 2h. Čelik NIOVAL 47 je predgrejan na 230°C (izračunato prema metodi Ito-Besio). Tokom zavarivanja održavana je međuprolazna temperatura 200-220°C. Zavarivanje je izvedeno sa spoljne strane rezervoara, nakon čega su sa korene strane spojeva brušenjem odstranjene greške i zavarena su dva korena prolaza. Nakon završenog zavarivanja spojevi su držani na 150°C za 1h u cilju smanjenja koncentracije vodonika u zavarenim spojevima.

Prior to welding, the electrodes are dried at 300°C during 2 hours. Steel NIOVAL 47 is preheated at 230°C (calculated by Itto-Bessyo method). Interpass temperature is held within 200-220°C during welding. Welding is performed on outer tank side, followed by removal of defects by grinding and an additional welding two root passes. After completion of the welding process, joints are held at 150°C for 1 hour, for reducing hydrogen concentration in welded joints.

OGRANIČENJA U PRIMENI ISPITIVANJA METODAMA BEZ RAZARANJA ZAVARENIH PRIKLJUČAKA

Potrebni nivo kvaliteta zavarenih spojeva, vrste i obim primene pojedinih metoda ispitivanja bez razaranja (IBR) i kriterijum prihvatljivosti za otkrivene greške su definisani Pravilnikom o tehničkim normativima za stabilne posude pod pritiskom /4/ i odgovarajućim jugoslovenskim standardima.

Procedura definisanja potrebnog nivoa kvaliteta zavarenih spojeva na posudama pod pritiskom (PPP) je data u: standardu JUS M.E2.151 – Određivanje klase posude, Pravilniku o tehničkim normativima za stabilne posude pod pritiskom i standardima JUS C.T3.010 (1984) – Klase kvaliteta zavarenih spojeva izvedenih topljenjem na čeliku i JUS C.T3.010 (1995) – Tehnički uslovi za zavarene spojeve izvedene topljenjem na čeliku. Na taj način je određeno da je potrebni nivo kvaliteta predmetnih zavarenih spojeva definisan klasom II prema standardu JUS C.T3.010/84, odnosno nivoom kvaliteta C prema standardu JUS C.T3.010/95.

Dalji postupak utvrđivanja potrebnog, a i izvedenog kvaliteta zavarenih spojeva na PPP je definisan u standardu JUS M.E2.159 – Kontrola i ispitivanje zavarenih spojeva. Po ovom standardu zahtevi za vrste i obim IBR za spoj koji je veza priključka i plašta/danca, klase kvaliteta II su sledeći: vizuelni pregled i dimenziona kontrola 100%, ispitivanje magnetima ili penetrantima 100% i ultrazvučno ispitivanje 70%. Kriterijumi prihvatljivosti za otkrivene greške su dati u standardu JUS ISO 5817.

Metodama IBR se, pre svega, utvrđuje homogenost, odnosno prisustvo grešaka u materijalu (vizuelni pregled, dimenziona kontrola, ispitivanja penetrantima i magnetima, radiografsko ispitivanje i ispitivanje ultrazvukom). Metodama IBR je moguće utvrditi i neke osobine materijala (hemijski sastav, mikrostruktura i tvrdoća). Svaka od metoda IBR ima prednosti i nedostatke, tako da se pouzdana ocena značaja greške za sigurnost zavarene posude pod pritiskom ne može doneti na osnovu rezultata ispitivanja samo jednom metodom.

Vizuelni pregled je osnovna metoda ispitivanja PPP kojom se mogu otkriti greške veličine do 0,01 mm, /5/. Svi standardi za ispitivanje PPP i zavarenih spojeva na njima propisuju 100% vizuelni pregled.

Dimenziona kontrola PPP se izvodi da bi se ustanovilo da li se dimenzije nalaze u propisanim granicama.

Radiografska ispitivanja ovde razmatranog spoja su ograničena prirodom materijala u spoju i geometrijom spoja. S obzirom da su pored grešaka u metalu šava moguće i prsline u zoni uticaja toplote (ZUT) čelika NIOVAL 47 (čelik je sklon pojavi hladnih prslina u ZUT) jasno je da se moraju ispitati obe zone. Međutim, austenitni i feritni ili feritno perlitni čelici imaju različite stepene apsorpcije zračenja. Zbog toga je svaku zonu ovih spojeva potrebno prozračiti posebno, jedanput sa parametrima prozračivanja prilagođenim austenitnom, a drugi put sa parametrima prozračivanja prilagođenim feritnom, odnosno, feritno perlitnom čeliku.

Da bi se dobio upotrebljiv radiogram tj. film na kome se greške u zavarenom spoju mogu videti jasno, u svojoj prirodnoj veličini i na svojim stvarnim pozicijama, potrebno je da film leži na površini ispitivanog materijala sa suprotne

LIMITATIONS OF APPLYING NON-DESTRUCTIVE TEST PROCEDURES TO WELDED CONNECTIONS

Required quality level of welded joints, types and scope of applied non-destructive testing method (NDT) together with acceptance criteria for detected defects are defined by Regulation of technical norms for stable pressure vessels /4/ and corresponding Yugoslav standards.

The procedure for defining the necessary quality level of welded joints in pressure vessels (PPP) is given in standard JUS M.E2.151 – Determination of vessel class, Regulation of technical norms for stable pressure vessels, and standards JUS C.T3.010 (1984) – Quality classes of welded joints obtained by melting on steel, and JUS C.T3.010 (1995) – Technical requirements for welded joints performed by melting on steel. In this way it is defined that the required quality level of considered welded joints corresponds to class II according to standard JUS C.T3.010/84, and respectively by quality level C according to standard JUS C.T3. 010/95.

Next procedure for determination of required, but also of performed quality of welded joints on PPP is defined by standard JUS M.E2.159 – Inspection and testing of welded joints. According to this standard, NDT requirements for types and scopes for a joint linking the connection and mantle/lid, of quality class II, are as follows: visual and dimensional inspection 100%, testing by magnets or dye penetrants 100%, and ultrasonic testing 70%. The acceptance criteria for detected defects are given in standard JUS ISO 5817.

The use of NDT methods primarily determines the homogeneity, i.e. presence of defects in the material (visual and dimensional inspection, testing by penetrants and by magnets, radiography and ultrasonic testing). It is possible to determine also some material properties (chemical composition, microstructure and hardness). Each NDT method is characterized by its advantages and disadvantages, and reliable defect evaluation of importance for the integrity of welded pressure vessels cannot be obtained from the results of only one particular method.

Visual examination is the basic method for testing pressure vessels and allows detection of defects up to 0.01 mm, /5/. All standards for pressure vessel testing and their welded joints specify a 100% visual examination.

Dimensional inspection of pressure vessels is aimed to determine whether the dimensions are within specified limits.

Radiographic examination in the case of the discussed joint is limited due to the nature of the material and joint geometry. In addition to defects in the weld metal, there are also cracks in the heat-affected-zone (HAZ) of NIOVAL 47 steel (this steel is prone to cold cracking in HAZ), it is clear that both zones must be examined. Anyhow, austenitic and ferritic or ferritic-bainitic steels have different radiation absorption levels. Hence, each of these zones should be irradiated separately, one with radiation parameters convenient for austenitic, and the other with radiation parameters convenient for ferritic, i.e. ferritic-bainitic steel.

In order to obtain a usable radiograph, the film on which defects in the welded joint are clearly visible in their full scale and at original locations, it is necessary for the film to strane od izvora zračenja. Svako udaljavanje filma od površine materijala izaziva rasipanje zraka i slabljenje njihovog intenziteta, zbog čega se smanjuje mogućnost otkrivanja manjih grešaka i deformiše se izgled i položaj greške. S obzirom na geometriju ovog priključka, film nije moguće postaviti tako da leži na površini ispitivanog materijala, zbog čega metoda nije primenljiva u ovom slučaju. Međutim, treba napomenuti da je u slučaju priključaka čiji je jedan kraj ravan sa površinom lima kroz koji priključak prodire, moguće film postaviti na površinu lima i uz snimanje iz više pozicija dobiti dobru sliku o greškama u zavarenom spoju.

Ispitivanja ultrazvukom ovde razmatranog spoja su uslovljena geometrijom spoja i prirodom materijala u spoju. S obzirom na mali unutrašnji prečnik priključka nije moguće skeniranje zavarenog spoja iz unutrašnjosti priključka tj. sa austenitnog materijala. Zato se skeniranje izvodi sa feritnog materijala sa spoljne i unutrašnje strane rezervoara. Austenitna struktura i krupno zrno prigušuju ultrazvuk, zbog čega prelaz iz feritne (osnovni materijal–OM) u austenitnu (metal šava–MŠ) i prelaz iz sitnozrne (OM) u krupnozrnu strukturu (MŠ) mogu delovati kao granične površine tj. mogu reflektovati ultrazvuk kao greške. Zato ispitivanje predmetnih spojeva samo sa feritnog materijala može da "zakloni" greške koje se nalaze u metalu šava i da one zato ne budu otkrivene. S obzirom na prigušenje ultrazvuka i u austenitu i u krupnozrnoj strukturi, pri ispitivanju ovih spojeva, upadni ugao ultrazvučnih glava treba birati tako da ultrazvučni put bude što kraći. Takođe treba imati u vidu da je eho greške u austenitnom materijalu na ekranu defektoskopa pomeren, što je bitno zbog određivanja položaja greške, pa prigušenje zvuka manje utiče na tačnost određivanja položaja greške, a više na tačnost određivanja veličine greške. Korišćenjem sondi niže frekvencije potiskuju se šumovi, pa se preciznost ispitivanja povećava kada je snop ultrazvučnih talasa uži, jer se kod širokog snopa javlja veći eho uslovljen većim spektrom brzina zvuka.

Ispitivanje penetrantima je uslovljeno:
– neravninama na licu šava (šav se ispituje bez uklanjanja ovih neravnina, jer bi se brušenjem smanjila njegova visina),
– tragovima brušenja (nastalim tokom pripreme žleba za zavarivanje priključaka),
– zahtevom čistoće ispitne površine koji uslovljava da se ispitivanje penetrantima mora primeniti pre ispitivanja magnetima i ultrazvukom (kod ovih metoda na ispitnu površinu se nanose emulzije i kontaktni medijum),
– mogućom oksidacijom površine prsline, što smanjuje sposobnost kvašenja, penetracije i otkrivanja prsline, pa ispitivanje treba obaviti u što kraćem roku.

Ispitivanje magnetima razmatranog spoja je ograničeno zbog nemagnetičnih osobina austenitnog materijala u spoju tj. može se očekivati da se magnetne linije pri nailasku na nemagnetični austenitni materijal prekidaju, što treba da rezultuje gubitkom magnetnog polja, sl. 5. Međutim, praktična iskustva pokazuju da se magnetno polje uspostavlja i kada se polovi magnetnog jarma postave u feritni magnetični materijal, uz samu ivicu austenitnog nemagnetičnog metala šava ili se postave tako da austenitni priključak bude između polova. Prema tome, austenitni materijal vrlo vero-

cover the surface of tested material opposite to the side of the radiating source. Any distancing of the film from the material surface contributes to dissipation of rays and weakening of intensity, reducing the possibility of detecting small defects and resulting in a deformed picture and location of defects. Due to the geometry of this connection it is not possible to position the film to properly cover the surface of the tested material, thus inhibiting use of the method in this case. However, it is to mention that a connection having one end co-planar with the plate surface through which the connection penetrates, it is possible to position the film on the plate surface with several exposures at various positions to obtain a satisfactory image of the defects in welded joint.

Ultrasonic testing of the considered joint is limited due to joint geometry and type of material. Having in mind the small inner diameter of the connection, it is not possible to scan the welded joint from the inside of the connection, i.e. the austenitic material. Thus, scanning is performed on ferritic material at outer and inner sides of vessel. Austenitic structure and coarse grain interfere the ultrasound, and the transition from ferrite (parent metal–PM) to austenitic metal (weld metal–WM), and also from the fine-grained (PM) to coarse-grained structure (WM) can act as boundary surfaces, i.e. can reflect ultrasound as defects. Hence, examination of considered joints on ferritic material in particular can “shield” defects in weld metal and leave them undetected. Due to ultrasound attenuation in austenite and in coarse grain structure, tests on these joints require that impact angles on ultrasonic sensors should be such so that minimal ultrasonic path is established. In addition, the echo of the defect in the austenitic material shifts on the defectoscope, and is important for determining defect location, so sound attenuation has less influence on precision location, and is more expressed in defect size determination. Lower frequency sensors suppress noise, and testing is more precise with narrower ultrasonic beam, since a broader beam produces a larger echo due to higher sonic speed spectrum.

Dye penetrant testing is limited to:
– roughness on weld face (welds are tested with existing surface roughness, since grinding may reduce its height),
– grinding paths (involved during groove preparation for welding of connections),
– requirement for cleanliness of the test surface that stipulates the dye penetrant test before magnetic and ultrasonic tests (these methods require emulsions and contact media to be applied over the test surface),
– possible oxidation of crack surface, reducing moistening capacity, penetration and crack detection, so tests should be performed in the shortest time possible.

Magnetic tests have limitations to the welded joint that emerge from non-magnetic properties of austenitic material in the joint, so it can be expected that magnetic lines will be disrupted when entering the austenitic material, resulting in loss of magnetic field, Fig. 5. Anyhow, practical experience shows that magnetic field is restored also when the poles of magnetic core are positioned in ferritic magnetic material, close to the edge of austenitic non-magnetic weld metal or, positioned so that the austenitic connection is between poles.

vatno menja tok i intenzitet magnetnih linija sile. Da bi ispitivanje bilo pouzdano mora se znati pravac i jačina magnetnog polja (mogućnost otkrivanja prslina zavisi od njihove orijentacije u odnosu na magnetne linije i od jačine magnetnog polja), što ovde nije slučaj. Praktično iskustvo ispitivanja velikog broja ovakvih spojeva pokazuje da se mogu otkriti veće prsline (dužina preko 30 mm) koje su na rastojanju 10 mm i više, od ivice austenitnog spoja. Nikada, međutim, nisu otkrivene prsline u ZUT, tj. u zoni širine 3–5 mm od linije stapanja.

Ispitivanjem tvrdoće Poldi metodom dobija se veliki otisak, često veći od ZUT, zbog čega nije moguće selektivno ispitivanje delova zavarenog spoja pa metoda nije pogodna za njihovo ispitivanje.

Veće mogućnosti za ispitivanje tvrdoće zavarenih spojeva pruža prenosni uređaj MikroDur proizvođača "Krautkramer", /5/. Ispitivanje daje otisak oblika piramide, dovoljno malih dimenzija da se mogu selektivno ispitivati pojedini delovi metala šava i ZUT. Za ispitivanje se zahteva polirana površina.

Ispitivanje mikrostrukture metodom replike je ograničene primene zbog nemogućnosti nagrizanja različitim reagensima i posmatranja pod uslovima koje omogućava laboratorijski metalografski mikroskop (npr. polarizovano svetlo). Međutim, metodom se mogu dobiti značajni podaci o mikrostrukturi. Metoda je posebno pogodna za otkrivanje mikroprslina.

REZULTATI ISPITIVANJA ZAVARENIH SPOJEVA PRIKLJUČAKA METODAMA BEZ RAZARANJA

Zavareni spojevi priključaka su ispitani metodama bez razaranja u dva navrata, jednom pre, a drugi put posle ispitivanja rezervoara unutrašnjim pritiskom, /3/.

Vizuelni pregled i dimenziona kontrola su izvedeni tokom pripreme za zavarivanje, tokom zavarivanja i nakon zavarivanja. Pre zavarivanja kontrolisani su: dimenzije i materijal priključka, oblik i dimenzije žleba, čistoća površina, postupak i temperatura predgrevanja, kvalitet i dimenzije dodatnog materijala. U toku zavarivanja kontrolisani su: parametri režima zavarivanja, tehnika rada i raspored zavara, čišćenje šljake i prisustvo površinskih grešaka u pojedinim zavarima, a nakon zavarivanja geometrija i izgled šava i prisustvo površinskih grešaka. Obim ispitivanja je 100% za lica i naličja spojeva. Tokom rada sve navedene veličine su usaglašene sa zahtevima datim u literaturi, /6/. Ispitivanjem su otkriveni pojedinačni ivični zajedi dozvoljene veličine za nivo kvaliteta C.

Ispitivanje penetrantima je urađeno obojenim penetrantom sa spoljne i unutrašnje strane rezervoara, pre ispitivanja magnetima i ultrazvukom. Ispitne površine su očišćene čeličnom četkom (na ispitnim površinama su prisutne neravnine na licu šava i tragovi brušenja u ZUT feritnog čelika). Ispitani su metal šava, ZUT priključka i danca i zone širine oko 20 mm od linije stapanja u oba osnovna metala. Iskustveno je utvrđeno da se u opisanim uslovima ispitivanja mogu otkriti prsline duže od 1,5–2,0 mm i pore prečnika većeg od 0,5 mm. Ispitivanjem, osim pojedinačnih manjih ivičnih zajeda prihvatljive veličine, nisu otkrivene druge greške.

Accordingly, austenitic material most probably changes the direction and intensity of magnetic force lines. Reliable tests require that the direction and intensity of magnetic field must be known (possibility of detecting cracks depends on crack orientation in regard to magnetic lines, and on magnetic field intensity), not being the case here. Practical experience in testing a significant number of such joints indicates that larger cracks can be detected (lengths over 30 mm) at distances of 10 mm (or more) from the edge of austenitic joint. However, cracks in HAZ had never been detected, i.e. in 3–5 mm wide zone from the fusion line.

Hardness tests by Poldi method result in a large indent, usually larger than the HAZ, that prohibits selective testing of welded joint zones, and so the method is not convenient.

More possibilities for hardness tests of welded joints are featured with the MicroDur portable device, produced by "Krautkramer", /5/. The test produces an indent the shape of a pyramid, sufficiently small in size to allow selective testing of individual zones of the weld metal and HAZ. A polished surface is a prerequisite for this test.

Microstructural tests on pressure vessels by replication are of limited application due to the impossibility of etching by different reagents and observation in conditions allowed by laboratory metallographic microscopes (i.e. polarized light). Anyhow, the method enables obtaining important data about microstructure. The method is very convenient in revealing microcracks.

RESULTS OF CONNECTION WELDED JOINT TESTS BY NON-DESTRUCTIVE METHODS

Welded joints on the connection were tested by non-destructive tests two times, once before, and another time – after the proof pressure test. Results of NDT before proof pressure vessel test are given elsewhere, /3/.

Visual and dimensional inspections are performed: during welding preparation; during; and after welding. Prior to welding, inspections included: dimensions and material of connection; groove shape and dimensions; surface cleanliness; procedure and temperature of preheating; consumable quality and dimensions. During welding inspection included: welding regime parameters; work techniques and disposition of passes; slag removal and presence of surface cracks in individual welds; and post-welding included: weld geometry and appearance; presence of surface defects. Scope of tests was 100% on both weld face and toe. All values conform to requirements given in /6/. Tests reveal individual edge undercuts of acceptable size for quality level C.

Dye penetrant tests are performed with colour penetrants on both outer and inner vessel surfaces, before magnetic and ultrasonic tests. Tested areas were cleaned with steel brush (tested surfaces had a roughness on weld face, and traces of grinding in the HAZ of ferritic steel). Weld metal, HAZ in the connection and lid, and 20 mm zones from fusion lines in both parent metals were tested. Experience confirms that in the described test conditions, cracks longer than 1.5–2 mm and pores of diameters larger than 0.5 mm may be detected. Apart from individual small edge undercuts of acceptable size, other defects had not been detected.

Ispitivanje magnetima je urađeno sa fluorescentnom emulzijom magnetnog praha, krupnoće 3 μm sa spoljne i unutrašnje strane rezervoara u zoni širine oko 30 mm od linije stapanja u feritnom osnovnom metalu, i to pre ispitivanja ultrazvukom. Kvalitet pripreme ispitne površine je kao i u prethodnom slučaju. Spojevi su namagnetisani iz većeg broja pozicija po obimu spoja sa rastojanjem polova magneta od ivice spoja oko 30 mm. Iskustveno je utvrđeno da se u slučajevima zavarenih spojeva priključka, gde su svi elementi u spoju od feritnih, odnosno, feritno perlitnih čelika, u ovakvim uslovima ispitivanja mogu otkriti prsline duže od 1,5 mm. U slučaju pripreme ispitne površine finim brušenjem, mogu se otkriti prsline duže od 0,5 mm. Ispitivanjem nisu otkrivene nikakve greške.

Za ispitivanje ultrazvukom korišćena je eho metoda i kose ultrazvučne sonde (sa upadnim uglovima 45° i 70°) i sa nižom frekvencijom. Sa spoljne i unutrašnje strane rezervoara ispitani su metal šava, ZUT priključka i danca i zone uz linije stapanja u oba osnovna metala. Ispitivanjem u ovim uslovima mogu se otkriti greške koje imaju ekvivalentnu površinu jednaku ili veću od površine kružne greške prečnika 1,5 mm. Ispitivanjem nisu otkrivene nikakve greške.

Na oba priključka urađeno je po jedno ispitivanje mikrostrukture metodom replike i to sa spoljne strane rezervoara, tako da su obuhvaćeni osnovni metal čelik NIOVAL 47, njegov ZUT i metal šava. Ispitivanjima je utvrđeno da su mikrostrukture zone pregrevanja ZUT, u oba priključka, beinitnog tipa sa relativno finim zrnom. Nije konstatovana pojava martenzita. Na obe replike u grubozrnim područjima ZUT su uočene mikroprsline. Na sl. 2 su prikazane tri mikroprsline koje su blizu jedna drugoj tako da se može pretpostaviti da su ostatak veće mikroprsline koja je delimično uklonjena brušenjem prilikom metalografske pripreme. Mikrostrukture oba metala šava su austenitne sa oko 25% δ-ferita.

Tvrdoće su izmerene na osnovnom metalu čelika NIOVAL 47 i njegovom ZUT, na mestima ispitivanja mikrostruktura, na poliranoj i nagriženoj površini nakon uklanjanja replika. Za merenje je korišćen uređaj MikroDur "Krautkramera". Na osnovu razlike u obojenju osnovnog metala, ZUT i metala šava, tačno su određene lokacije mesta merenja. U osnovnom metalu su izmerene tvrdoće 166–190 HV, /3/, a u ZUT 210–260 HV. Ove vrednosti ne ukazuju na prisustvo krtih struktura i prihvatljive su.

Ispitivanja penetrantima su ponovljena na mestima uzimanja replika. Može se pretpostaviti znatno veća osetljivost metode na ovim mestima, zbog izuzetno kvalitetne pripreme ispitnih površina (polirane površine). Korišćene su napred navedene tehnike i parametri ispitivanja. Ovim ispitivanjima nisu otkrivene nikakve greške, /3/.

Nakon ispitivanja rezervoara unutrašnjim pritiskom ponovljena su IBR, osim merenja tvrdoće i ispitivanja mikrostrukture, /7/. Vizuelnim pregledom i ispitivanjem penetrantima su otkriveni ivični zajedi dozvoljene veličine. Ispitivanjima magnetima i ultrazvukom nisu otkrivene greške u zavarenim spojevima.

Magnetic tests are performed with fluorescent emulsion of magnetic powder, with particles of 3 μm, on both outer and inner tank surfaces within the 30 mm zone from the fusion line in the ferritic parent metal, all before ultrasonic tests. The prepared test surface quality is the same as in the previous case. The joints are magnetized at several positions along the weld circumference with about 30 mm distance of magnetic poles from weld edge. As confirmed by experience, in case of welded joints on connections, where all joint elements are of ferritic, i.e. ferritic-pearlitic steels, cracks longer than 1.5 mm may be detected in described testing conditions. If the test surface is prepared by fine grinding, cracks longer than 0.5 mm can be detected. No defects were detected by performed tests.

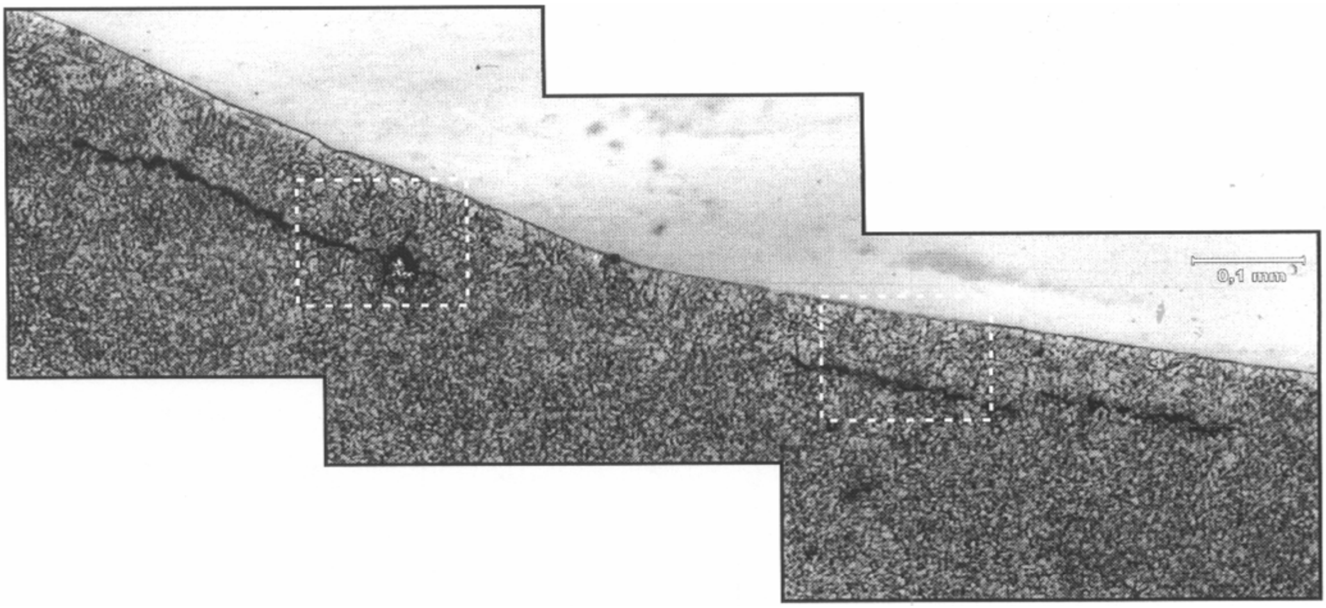
The ultrasonic echo test method was used, and slant ultrasonic sensors (with impact angles of 45° and 70°) and with lower frequency. The weld metal, HAZ in the connection and lid, and zones close to fusion lines in both parent metals were tested on both outer and inner tank surfaces. Cracks of equivalent area equal to or greater than the area of a circular defect 1.5 mm in diameter may be detected in the described test conditions. No defects were detected in the performed tests.

A single microstructural test method by replicas is performed on both connections on the outer tank surface side, and it included the parent metal NIOVAL 47 steel, and its HAZ and weld metal. Tests revealed that overheated HAZ microstructures in both connections are of the bainitic type with relatively fine grains. Presence of martensite is not determined. Microcracks were noticed in both replicas in coarse grain regions of the HAZ. Three microcracks close to each other are presented in Fig. 2, apparently they are the remains of a greater microcrack that had been partly removed by grinding during the metallographic preparation. Microstructures of the two weld metals are austenitic with about 25% of δ-ferrite.

Hardness was measured on parent metal of NIOVAL 47 steel and it's HAZ, at locations of microstructural tests, on polished and etched areas after removing replicas. Tests are performed by using the "Krautkramer" MicroDur device. According to colour differences between the parent metal, HAZ, and weld metal, the measuring locations are accurately determined. Hardness of 166–190 HV was measured in the parent metal, /3/, and 210–260 HV in HAZ. These values do not indicate existence of brittle structures and they are acceptable.

Dye penetrant tests were repeated at replication locations. A much higher sensitivity of the method on these locations is supposed due to the extreme quality preparation of test surfaces (polished). Methods and test parameters described above are applied. No defects were detected by these tests /3/.

NDT is repeated after proof pressure test of the tank, except for hardness tests and microstructural analysis, /7/. Edge undercuts of acceptable size have been detected by visual inspection and dye penetrant test. No defects were detected in welded joints by magnetic and ultrasonic tests.



Slika 2. Mikroprsline u zoni pregrevanja u čeliku NIOVAL 47 zavarenog spoja priključka
Figure 2. Microcracks in coarse grains region of HAZ in NIOVAL 47 steel welded joint of connection.

ANALIZA I DISKUSIJA REZULTATA

Upotrebljeni materijali imaju različitu zavarljivost. Austenitni čelik priključka ima vrlo dobru zavarljivost, zbog čega se u njegovoj ZUT ne očekuju greške. Metal šava je takođe austenitne strukture i u njemu se pored uobičajenih greška formiranja šava (poroznost, uključci šljake, nalepljivanje, neprovar) mogu pojaviti i tople prsline. Tokom zavarivanja vođen je neprekidni vizuelni nadzor rada zavarivača i sve uočene greške su odmah odstranjene brušenjem. Jedino je moguća pojava manjih podpovršinskih grešaka koje se ne mogu otkriti vizuelnim putem, kao što su uključci šljake, poroznost i nalepljivanje. Austenitni metal šava ima jako dobru žilavost, zbog čega je kritična dužina prsline (dužina koja dovodi do loma) u njemu velika, veća od praga osetljivosti penetrantske i ultrazvučne metode, pa se prsline u metalu šava lako otkrivaju ovim metodama. Uticaj ostalih grešaka na pojavu loma je daleko manji od uticaja prslina.

Čelik NIOVAL 47 je sklon pojavi hladnih prslina u ZUT zbog sklonosti ka obrazovanju krtih struktura. Pojavi krtih struktura u ovoj zoni pogoduje još i mešanje visokolegiranog dodatnog materijala, /6/, i OM sa relativno visokim sadržajem ugljenika, /6/, što za posledicu ima pojavu zakaljene zone po liniji stapanja, koja se ne može izbeći. Kritična dužina prsline u ovoj krtoj strukturi je mala, zbog čega se one teško otkrivaju. U OM čelika NIOVAL 47 (na rastojanju do 30 mm od linije stapanja) ne očekuje se pojava nikakvih greška. Praktično iskustvo pokazuje da su u ovoj zoni prsline moguće jedino u slučaju prisustva izuzetno velikih grešaka u MŠ, što ovde nije slučaj. Osnovni metal ima visoku žilavost pa je kritična dužina prslina u njemu velika, daleko veća od praga osetljivosti metoda IBR, zbog čega se ove prsline lako otkrivaju.

Rezultati IBR pokazuju da su otkrivene samo hladne prsline u ZUT čelika NIOVAL 47, neposredno uz liniju stapanja. Druge greške nisu otkrivene. Da bi ove prsline nastale

ANALYSIS OF TEST RESULTS AND DISCUSSION

The applied materials possess different weldability. Austenitic steel in the connection has good weldability and no defects are expected in its HAZ. The weld metal has also the austenitic structure, and crystallization cracks can occur in addition to usual defects of weld formation (porosity, slag inclusion, lack of fusion/penetration). Continuous visual supervision of welding is performed on the spot and all noticed defects are removed instantly by grinding. Only smaller subsurface defects may possibly occur that can not be detected by visual inspection, such as slag inclusions, porosity and overlapping. Austenitic weld metal has very good toughness, and apparently critical crack length (the length which may cause fracture) is large, even larger than the sensitivity threshold of both penetrant and ultrasonic tests, so that cracks in weld metal are easily detected by these methods. The effects of other defects on fracture occurrence are significantly lower than the effects of cracks.

Steel NIOVAL 47 is prone to cold cracking in the HAZ because of its tendency to form brittle structures. Appearance of brittle structures in this zone is also instigated by high-alloyed consumables, /6/, and from BM with relatively high levels of carbon content, /6/, that as a consequence leads to appearance of quenched zone on fusion lines, and can not be avoided. The critical crack length in this brittle structure is small, making them hard to detect. No defects are expected in the BM of steel NIOVAL 47 (at 30 mm distance from the fusion line). Practical experience shows that cracks in this zone are possible only in the presence of extremely large defects in the WM, which is not the case here. Base metal has a high toughness and its critical crack length is large, larger than the sensitivity threshold of NDT methods, enabling easy detection of these cracks.

NDT results show detection of only cold cracks in HAZ of NIOVAL 47, in the proximity of the fusion line. Other defects have not been detected. These cracks may appear moraju da se steknu sledeći uslovi: krta mikrostruktura, kritična koncentracija rastvorenog vodonika i dovoljno visoki naponi.

Mikrostruktura ZUT je ocenjena kao beinitna bez tragova martenzita. Prisustvo igličastih mikrokonstituenata, sl. 2, ukazuje na neotpušteni beinit koji je blizak strukturi martenzita. Pojavi ove strukture pogodovalo je zavarivanje na otvorenom, gde, i pored mera zaštite zone zavarivanja, nije bilo moguće sprečiti povremeno ubrzano hlađenje pod uticajem strujanja vazduha. Rezultati merenje tvrdoća ZUT ukazuju da u mikrostrukturi nema martenzitnog konstituenta.

Može se proceniti da je sadržaj vodonika u zavarenom spoju mali. Zavarivanje je izvedeno elektrodom sa rutilnom oblogom, koja u zavareni spoj unosi više vodonika od elektroda sa bazičnom oblogom. Izbor elektrode uslovljen je njenim hemijskim sastavom, koji je opet uslovljen hemijskim sastavima materijala priključaka i danca. Elektrode takvog hemijskog sastava (29% Cr i 9% Ni) se ne proizvode sa bazičnom oblogom. Zbog toga su tehnologijom zavarivanja predviđene mere predgrevanja, održavanja međuprolazne temperature i progrevanje kojima se smanjuje koncentracija vodonika u zavarenom spoju.

Iz rezultata ispitivanja je jasno da su prsline nastale samo pod uticajem zaostalih napona (nastale i otkrivene pre izlaganja rezervoara bilo kakvom unutrašnjem pritisku). Tehnologijom zavarivanja su predviđene i primenjene mere predgrevanja, održavanja međuprolazne temperature i progrevanje, kao i određeni redosled zavarivanja, koje utiču na smanjenje zaostalih napona u zavarenom spoju. Očigledno je, međutim, da te mere u ovom slučaju nisu dovoljne i da je potrebno dalje smanjenje zaostalih napona, što je moguće postići smanjenjem debljine zida priključka i upotrebom dodatnog materijala manje čvrstoće. Smanjenjem debljine zida priključka olakšava se njegova plastična deformacija u zoni zavarenog spoja u radijalnom pravcu, a upotreba dodatnog materijala niže čvrstoće omogućava plastičnu deformaciju metala šava tokom zavarivanja. U oba slučaja zaostali naponi se smanjuju na račun plastične deformacije.

S obzirom da su preduzete sve mere za sprečavanje pojave prslina, a da su se one ipak pojavile, verovatno je da se isecanjem i ponovnim zavarivanjem ne bi njihova ponovna pojava izbegla. Zato se postavilo pitanje procene prihvatljivosti otkrivenih prslina. Ova procena je urađena primenom postupka koji je prikazan u standardu BSI PD 6493 "Uputstvo za ocenu prihvatljivosti grešaka u zavarenim spojevima", /8/. Ocenjeno je da su prsline sa sl. 2 ustvari delovi jedne veće polueliptične prsline koja leži u ravni skoro upravnoj na površinu lima i koja ima početnu dužinu 2,1 mm i dubinu 0,7 mm. Naime, tokom pripreme površine za ispitivanje mikrostrukture, brušenjem i poliranjem je odstranjen sloj čelika debljine oko 0,5 mm na mestu prsline. Time su i dužina i dubina prsline smanjene i dovedene na one vidljive na sl. 2. Isprekidane su zbog nepravilnog polueliptičnog oblika početne prsline. Prslina je ocenjena kao prihvatljiva, odnosno, konstatovano je da se rezervoar može pustiti u rad sa prslinom.

Prvo IBR (pre uzimanja replika) izvedeno je na brušenoj ispitnoj površini. Može se pretpostaviti da prsline otkrivene metodom replike nisu otkrivene ispitivanjem penetrantima

when the following conditions are fulfilled: brittle microstructure, critical concentration of dissolved hydrogen and sufficiently high stresses.

The HAZ microstructure is accounted as bainitic without traces of martensite. Presence of acicular microconstituents, Fig. 2, indicates untempered bainite that is similar to martensite. Welding in the open environment has tempted the appearance of this structure, where, in despite of applied shielding measures, occasional accelerated cooling in the air stream could not be detained. Results of HAZ hardness measurements indicate no presence of the martensitic constituent in the structure.

Hydrogen content in the welded joint is estimated to be low. Welding is performed by rutile coated electrode that deploys more hydrogen into the weld than basic coated electrodes. Chemical composition of an electrode is a prerequisite for choosing electrodes, which is also predetermined from chemical compositions of connection and lid materials. Electrodes of such chemical contents (29% Cr and 9% Ni) are not produced with basic coating. Hence, welding technology requires preheating measures, maintaining interpass temperature, all for reducing concentrations of hydrogen in the weld.

Test results clearly show that cracks have appeared only from residual stresses (initiated and detected before applying any internal pressure to the tank). Welding technology defines and applies measures for preheating, maintaining interpass temperatures, as well as a specific welding schedule, that influence reduction of residual stresses in the weld. Obviously, these measures had not been sufficient, and further reduction of residual stresses is necessary, and can be accomplished by reducing the connection wall thickness and by using consumables of lower strength. Smaller wall thickness on the connection allows more plastic strain of the welded joint region in the radial direction, and use of lower strength consumables enables plastic deformation of the weld metal during welding. In both cases residual stresses decrease at the expense of plastic deformation.

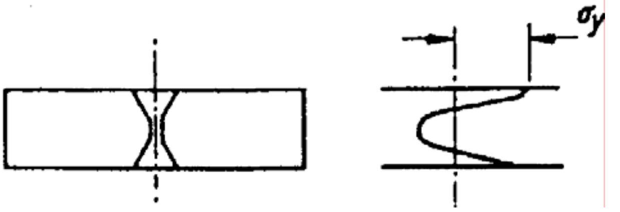
Since all measures were taken to prevent cracking, and yet cracks did appear, subsequent cutting out and repeated welding most likely would not have prevented their reappearance. Therefore, evaluating the acceptability of detected cracks is now the question. They are evaluated by applying the procedure outlined in BSI PD 6493 "Guidance on methods for assessing the acceptability of flaws in fusion welded structures", /8/. Assessments show that cracks in Fig. 2 are in fact, parts of a large semi-elliptical crack, positioned on a plane almost perpendicular to the plate surface, with initial length of 2.1 mm and depth of 0.7 mm. Thus, microstructural test-surface preparation, by grinding and polishing, has removed a 0.5 mm layer of steel at the crack location. This reduced crack length and depth to the extent visible in Fig. 2. The paths are interrupted because of irregular semi-elliptical shape of the original crack. The crack is assessed as acceptable, and the tank containing the crack may continue operation, as is concluded.

The first NDT (before making replicas) is performed on the ground test surface. Supposedly, the cracks detected by replication method may not be detected by dye penetrants, zato što im je veličina bliska pragu osetljivosti metode. Iz rezultata ispitivanja penetrantima se može zaključiti da u ZUT čelika NIOVAL 47 nema prslina dužih od oko 2 mm. Konstatovano je da ispitivanje magnetima nije pouzdano u ovoj zoni. Ultrazvučnim ispitivanjem greška nije otkrivena jer se nalazi ispod praga osetljivosti metode.

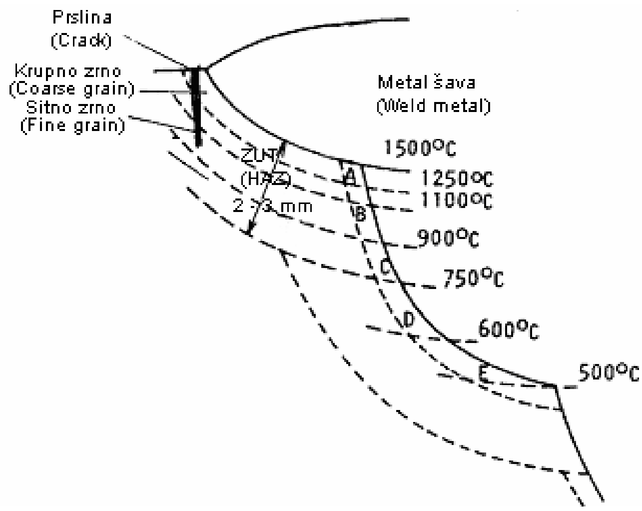
Odgovor na pitanje da li ovolikih ili većih prslina ima u unutrašnjosti ZUT čelika NIOVAL 47, može se dobiti analizom potrebnih uslova za nastanak hladnih prslina. Za ovu analizu se može usvojiti da su koncentracija vodonika i mikrostruktura jednake po celoj zapremini ZUT. Raspored zaostalih napona po debljini ukrućenog zavarenog spoja je prikazan na sl. 3, /5/. Sa slike se vidi da se zaostali naponi smanjuju i da iz zateznih prelaze u pritisne sa udaljavanjem od površine. Prema tome uslovi za nastanak prslina su najpovoljniji na površini zbog najvećih zaostalih napona. Zato je logično da u dubini materijala prsline budu manje i ređe. Pošto površinska prslina ima ekvivalentnu površinu manju od praga osetljivosti ultrazvučne metode, za očekivati je da i eventualne podpovršinske prsline budu ispod praga osetljivosti, odnosno, da ne budu otkrivene.

because their size is close to the threshold value. Results of dye penetrant tests lead to the conclusion that there are no cracks longer than 2 mm in the HAZ of steel NIOVAL 47. Magnetic tests have shown to be unreliable in this zone. Ultrasonic testing did not detect the crack since it is also below the threshold value.

The question - are there cracks of these or larger sizes in HAZ of steel NIOVAL 47, can be answered by analysing required conditions for the appearance of cold cracks. This analysis assumes that both concentration level of hydrogen and microstructures are equally distributed in HAZ. The disposition of residual stresses over thickness of the rigid welded joint is shown in Fig. 3, /5/. As illustrated, residual stresses decrease and transform from tensile to compressive state when distancing from the surface. Accordingly, conditions for crack initiation are most probable on the surface, due to the highest level of residual stresses. It is logical for cracks to become smaller and less distributed deeper within the material. The surface crack has an equivalent surface area that is smaller than the threshold value of ultrasonic test and so it is expected that eventual subsurface cracks will also have values below this response level, and therefore, will not be detected.



Slika 3. Promena zaostalih napona, koji deluju u radijalnom pravcu priključka po debljini materijala.
Figure 3. Transformation of residual stresses, acting in the radial direction of the connection, through material thickness.



Slika 4. Presek kroz zavareni spoj sa prslinom.
Figure 4. Cross section of welded joint with crack.

Drugo IBR (nakon uzimanja replika) urađeno je penetrantima na poliranoj površini. Osetljivost metode je u ovom slučaju veća, ali su prsline daleko manje dužine 0,16–0,35 mm, sl. 2, tj. ispod praga osetljivosti metode zbog čega nisu otkrivene. Može se reći da u ovoj zoni nema prslina dužih od oko 1,5 mm.

Treće IBR je urađeno nakon ispitivanja rezervoara unutrašnjim pritiskom. Ispitna površina je bila pripremljena većim delom kao kod prvog IBR, a na mestu drugog IBR je pripremljena brusnim papirom. S obzirom da je iz prethodnih razmatranja očigledno da u ZUT NIOVALA 47 postoje uslovi za nastanak i rast hladnih prslina, logično je očekivati da će dalji rast napona u ovoj zoni, izazvan unutrašnjim ispitnim pritiskom u rezervoaru, pogodovati nastanku novih i rastu postojećih prslina. Iz rezultata IBR se, međutim, vidi da ovim ispitivanjima nisu otkrivene nikakve greške. Ovo dokazuje da nema prslina koje su veće od praga osetljivosti

The second NDT (after making replicas) is performed by penetrants on the polished surface. The sensitivity of the method is higher in this case, but cracks are shorter 0.16–0.35 mm, Fig. 2, and below the threshold for this technique which made them undetectable. Apparently, this zone does not contain cracks longer than about 1.5 mm.

The third NDT test is performed after testing the tank by internal pressure. The test surface is prepared, in most part, as in the first NDT test, and abrasive paper was used in the second NDT. Since previous considerations made obvious that conditions are fulfilled for cold crack initiation and growth to occur in the HAZ of NIOVAL 47, it is logical that further increase of stresses in this zone, caused by inner test pressure, will contribute the initiation of new and growth of existing cracks. However, NDT results show that no such defects were detected. This proves that there are no cracks of sizes within threshold limits of NDT techniques, metoda IBR, ali ne dokazuje da nove prsline nisu stvorene ili da nije došlo do rasta prslina do veličine manje od praga osetljivosti metoda IBR.

Pri rastu površinske prsline njen vrh dospeva u oblast smanjenih zaostalih napona. S druge strane, u pravcu rasta prsline se nalazi finozrna struktura OM sl. 4, daleko veće žilavosti. Ako prslina raste u ravni prostiranja ZUT, sl. 4, onda se ugao između ravni prostiranja prsline i pravca glavnog napona smanjuje zbog čega se smanjuju i delujući naponi. Na taj način može se očekivati da će, ako dođe do rasta mikroprslina, na određenoj dubini ovaj rast prestati ili zbog porasta žilavosti materijala ili zbog smanjenja delujućih napona. Povoljni uslovi za rast ostaju u bočnom pravcu. Isto razmatranje se može primeniti na rast podpovršinskih prslina.

ZAKLJUČCI

Na osnovu sprovedenih ispitivanja metodama bez razaranja na spojevima novih priključaka ugrađenih u rezervoar za tečni CO_2 može se zaključiti:

1. Uvek treba poći od pretpostavke da zavareni spojevi sadrže greške, među njima i prsline kao najopasniji vid grešaka. Stoga je potrebno definisati mesta najveće verovatnoće pojave grešaka.
2. Potreban je neposredan vizuelni nadzor nad radom zavarivača, koji se u praksi kao metoda za obezbeđenje kvaliteta zavarenih spojeva nedovoljno koristi. Ovim nadzorom se mogu eliminisati greške koje se kasnije metodama IBR teško otkrivaju.
3. Propisane metode IBR imaju ograničenja u primeni, koja su više uslovljena svojstvima austenitnog i feritnog čelika u spoju, a manje geometrijom spojeva priključka. Zbog toga se greške u ovakvim zavarenim spojevima mogu otkriti samo kombinacijom više metoda IBR, odnosno, pored standardom propisanih metoda IBR potrebne su i dopunske metode.
4. Mikroprsline koje su se pojavile u ZUT su identifikovane jedino metodom replika, što ukazuje na značaj primene ove metode.
5. Radiografska metoda nije standardom propisana za ispitivanje zavarenih spojeva priključaka. Ova metoda se uz određena ograničenja može primeniti za ispitivanje ovih spojeva i svakako treba koristiti jer može da da i više podataka od nekih od propisanih metoda.

but also it does not prove whether new cracks have been created, or perhaps had extended to lengths below the NDT technique threshold limit.

While a surface crack grows, its tip enters the region of decreased residual stresses. Alternately, a fine-grained BM structure of much higher toughness is located in the direction of crack growth, Fig. 4. If the crack propagates in the plane of the developing HAZ, Fig. 4, then the angle between the crack propagation plane and the direction of principal stress diminishes, causing acting stresses also to decrease. It can be expected that, if microcracks start to propagate, this growth may stop at a certain depth due to the increase in material toughness or due to the decrease of acting stresses. Favourable conditions for growth remain in the lateral direction. A similar analysis may hold for the growth of subsurface cracks.

CONCLUSIONS

Based on non-destructive testing techniques performed on new connection joints in the CO_2 tank, the following is concluded:

1. Welded joints should always be assumed to contain defects, among them cracks as the most threatening type of defect. Hence, locations of defects that are most probable should be defined.
2. Immediate supervision of the welder's performance is a prerequisite, which is insufficiently used in practice as a method for quality assurance of welded joints. Supervision can eliminate defects that are later hard to detect by means of NDT.
3. Prescribed NDT methods have limitations in practice, that mainly depend on the characteristics of austenitic or ferritic steel in the joint, and less on connection joint geometry. This is why defects in welded joints of this type can be detected only by a combination of multiple NDT methods, namely, additional methods are necessary apart from the NDT methods prescribed by standard.
4. Microcracks that appeared in HAZ are identified only by the replication method, indicating the relevance of this method.
5. The radiographic technique is not prescribed by standard for testing welded joints on connections. This method may be applied in testing these joints with certain limitations, and should certainly be used because it may offer more results than particular prescribed methods.

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