Nada Filipović [1], Katarina Gerić [2], Stojan Sedmak [3]

UTICAJ USLOVA OPTEREĆENJA NA LOM ZAVARENOG TANKOZIDNOG REZERVOARA

LOADING CONDITION EFFECT ON THE FRACTURE OF WELDED THIN-WALLED STORAGE TANK

Stručni rad / Professional paper
UDK /UDC: 621.642-988-112.81:539.42
Rad primljen / Paper received: 17.01.2007.

Adresa autora / Author's address:
[1] Zavod za zavarivanje, Beograd, Srbija, zzz@bitsyu.net
[2] Fakultet tehničkih nauka, Novi Sad,Srbija
[3] Tehnološko-metalurški fakultet, Beograd, Srbija

Ključne reči
- krti lom
- žilavi lom
- posuda pod pritiskom
- zavareni spoj
- zona uticaja toplote
- uslovi opterećenja

Izvod

Uslovi opterećenja mogu bitno uticati na oblik loma rezervoara u eksploataciji. Prikazana su dva različita mehanizma loma tankozidnih zavarenih posuda pod pritiskom izrađenih od čelika iste debljine zida (8 mm). Do krtog loma je došlo pri prvom ispitivanju pritiskom gasovitim azotom rezervoara od konstrukcionog čelika S355J2G3 (EN 10025), čija je prelazna temperatura –20°C. Zbog preopterećenja i porasta temperature tokom vožnje mehanizmom žilavog loma je otkazala cisterna za prevoz amonijaka na vozilu, izrađena od finozrnog konstrukcionog čelika TSt 460 (DIN EN 10113-2), U oba slučaja, iako su ispoljeni različiti mehanizmi loma, početna prslina se pojavila u zoni uticaja toplote zavarenog spoja.

Keywords
- brittle fracture
- ductile fracture
- pressure vessel
- welded joint
- heat-affected-zone
- loading condition

Abstract

Loading conditions can affect significantly the fracture mode of storage tanks in service. Two different fracture mechanisms experienced in service of thin-walled pressure vessels of the same wall thickness (8 mm) are presented. Brittle fracture of the storage tank made of structural steel S355J2G3 (EN 10025) and transition temperature –20°C occurred during the first proof pressure test with nitrogen. Due to overloading and temperature increase, a mobile storage tank for ammonia transportation, made of microalloyed steel TSt 460 (DIN EN 10113-2), failed by a ductile mechanism. In both cases, although they exhibited different fracture mechanisms, the crack was initiated in the heat-affected-zone of the welded joint.

UVOD

Sigurnost opreme pod pritiskom je bitan uslov za njenu uspešnu eksploataciju. Zbog toga se preduzimaju stroge mere, počev od projektovanja, preko izrade i ispitivanja da bi se pre puštanja u rad opreme obezbedio i dokazao potreban nivo kvaliteta kao preduslov kontrolisane i pouzdane eksploatacije. Kako su najčešće u pitanju zavarene konstrukcije, posebna pažnja se posvećuje kvalitetu zavarenih spojeva. I pored svih preduzetih mera povremeno dolazi do otkaza opreme pod pritiskom u eksploataciji, što uslovljava proučavanje problema vezanih za te otkaze.

Predavanja Šeste međunarodne letnje škole mehanike loma (IFMASS 6) „Eksploatacijske prsline u posudama pod pritiskom i rezervoarima“ /1/, sa mnogim primerima prslina i obimnom literaturom su doprinela boljem razumevanju loma. Koliko se stanje u pogledu projektovanja izmenilo može se utvrditi poređenjem pristupa u predavanju S. Jukave, /2/, i novo uvedenih evropskih direktiva za opremu pod pritiskom, koje su prikazali Bređan i Kurai, /3/.

INTRODUCTION

The safety of pressurized equipment is a substantial requirement for its service. Accordingly, strict measures are taken, starting from design, through manufacture and testing, in order to assure and prove necessary quality level as a precondition of controlled and reliable service. Since welded structures are mostly in question, special attention is paid to the quality of welded joins. In spite of all measures undertaken, failure of pressurized equipment occurs occasionally, dictating the necessity to analyse problems connected with these failures.

Lectures of the Sixth International Fracture Mechanics Summer School (IFMASS 6) “Service cracks in pressure vessels and storage tanks” /1/, with many cracking examples and numerous references helped to better understand the fracture. How much the situation in design has changed one can conclude comparing the approach in S. Yukawa’s lecture, /2/, with established new European Directives for Pressurized Equipment, presented by Bređan and Kurai, /3/.

Iako je dala dobru sliku stanja u pogledu otkaza i lomova opreme pod pritiskom, IFMASS 6 nije u potpunosti pokrila sve uticajne faktore, od kojih su neki obrađeni u radovima M. Kirić i A. Sedmak /4/, J. Kurai i B. Aleksić /5/, G. Adžiev i A. Sedmak /6/, S. Sedmak i A. Sedmak /7/. Kao poseban literaturni doprinos u ovoj oblasti navodi se monografija „Prsline u zavarenim spojevima“ /8/, gde je kroz eksperimentalnu simulaciju zone uticaja toplote (ZUT) razjašnjeno ponašanje prslina u zavarenim spojevima, posebno u čelicima namenjenim za izradu opreme pod pritiskom.

U navedenoj literaturi nije u dovoljnoj meri istaknut uticaj uslova opterećenja. Koliko je ovaj uticaj značajan utvrđeno je u analizi otkaza dva rezervoara kod kojih je pri lomu ispoljen potpuno različit mehanizam zbog različitih uslova delovanja opterećenja, iako su ugrađeni čelici slične namene i iste debljine zida (8 mm), a uslovi izrade, uključujući zahtevanu plastičnost i žilavost, bili ispunjeni. U jednom slučaju lom je krt (posuda I), a drugom potpuno žilav (posuda II).

Do otkaza posude I – rezervoara zapremine 9,96 m^3 za prirodni utečnjen gas, izrađenog od konstrukcionog čelika, je došlo zbog krtog loma pri probnom ispitivanju pritiskom. Najniža radna temperatura rezervoara je –20°C, a najveći pritisak 16,7 bar. Zahtevi za prijem posude (osobine osnovnog metala, ultrazvučno ispitivanje i radiografska kontrola zavarenih spojeva) su bili zadovoljeni. Gasoviti azot za ispitivanje je uzet iz rezervoara, gde je držan u utečnjenom stanju na temperaturi –196°C. Pritisak za probno ispitivanje je bio 25 bar. Prilikom ispitivanja je došlo do eksplozije i rezervoar je potpuno razoren. Nema podataka o temperaturi i pritisku u trenutku loma.

Drugi otkaz se odnosi na cisternu zapremine 4 m^3 za prevoz tečnog amonijaka (NH_3), izrađenu od mikrolegiranog čelika. Cisterna je izrađena za radni pritisak p = 16 bar i temperaturu t = 5°C prema zahtevima za kvalitet za cisterne za transport opasnih fluida, u koje spada i amonijak. Posle 18 godina eksploatacije je došlo do otkaza cisterne. Posuda je u kritičnoj situaciji bila napunjena sa 320 kg amonijaka iznad dopuštenog punjenja od 2120 kg. Zbog porasta temperature u toku vožnje do 23,7°C pritisak gasa u cisterni je porastao, što je dovelo do plastične deformacije, pojave klobuka, smanjenja debljine zida i otkaza eksplozijom.

Rezultati izvedenih istraživanja su analizirani da bi se objasnili razlozi pojave ova dva otkaza.

OSOBINE MATERIJALA I ZAVARENIH SPOJEVA

Omotač rezervoara (posuda I) je izrađen od konstrukcionog čelika S355J2G3 EN 10025 debljine 8 mm. Hemijski sastav osnovnog metala omotača je dat u tab. 1, a mehaničke karakteristike u tab. 2. Izražena je trakavost mikrostrukture i neravnomerna raspodela perlita, uz sekundarnu strukturu, sulfidne uključke i segregacije. Feritno zrno je veličine 9–10 (×200), JUS C.A3.004 (sl. 1a).

Cisterna (posuda II), je izrađena od normalizovanog čelika klase TSt 460 (DIN) marke Nioval 470 (proizvodnje Železarna Jesenice), debljine 8 mm, hemijskog sastava datog u tab. 3, i mehaničkih karakteristika datih u tab. 4. Čelik je laminarne feritno-perlitne strukture finog zrna, veličine 12 (×400), JUS C.A3.004 (sl. 1b).

Although offered insight regarding failures and fractures of pressurized equipment, IFMASS 6 did not cover completely all influencing factors, some of them considered in papers of M. Kirić and A. Sedmak /4/, J. Kurai and B. Aleksić /5/, G. Adžiev and A. Sedmak /6/, S. Sedmak and A. Sedmak, /7/. As a special contribution in this field the monograph “Cracks in welded joints” /8/, is referred, in which crack behaviour in welded joints is clarified through experimental simulation of the heat-affected-zone (HAZ), especially in steels for pressurized equipment application.

In cited references the effect of loading condition is not underlined sufficiently. How much this effect is significant is established in failure analysis of two storage tanks exhibiting completely different fracture mechanisms due to different loading conditions, despite that used steels were assigned for similar application and of same thickness (8 mm), manufacturing requirements, including ductility and toughness. In the first case (vessel I) fracture was brittle, and fully ductile in the second case (vessel II).

Failure of vessel I – storage tank for liquefied natural gas, 9.96 m^3 in volume, made of structural steel, occurred due to brittle fracture at proof pressure test. Minimal operating temperature of storage tank is –20°C, and maximum pressure 16.7 bar. The requirements for vessel acceptance (parent metal properties, ultrasonic testing and radiographic examination of welded joints) had been met. Nitrogen gas for testing was brought from a tank where it was kept in a liquefied state, at –196°C. The pressure for proof test was 25 bar. An explosion occurred in this test, and the tank was completely destroyed. Data about temperature and pressure at fracture are not available.

The second failure refers to the mobile storage tank 4 m^3 in volume for transport of liquefied ammonia (NH_3), made of microalloyed steel. The tank’s designated operating pressure p = 16 bar and temperature t = 5°C, following requirements for dangerous fluid transport, where ammonia is classified. The tank failed after 18 years of service. In the critical situation the tank was charged with 320 kg of ammonia above the allowed 2120 kg. Due to temperature increase of 23.7°C during transport the gas pressure in the vessel increased, causing plastic deformation, bulging, wall thickness reduction, and the final failure by explosion.

The results of performed investigations were analysed for understanding the causes of these two failures.

PROPERTIES OF MATERIAL AND WELDED JOINTS

The storage tank mantle (vessel I) was produced of structural steel S355J2G3 EN 10025, 8 mm thick. Chemical composition of mantle parent metal is given in Table 1, and mechanical properties in Table 2. The microstructure banding is expressed and non-uniform pearlite distribution, with secondary structure, sulphide inclusions and segregations. Ferrite grain size is 9–10 (×200), JUS C.A3.004 (Fig. 1a).

Mobile storage tank (vessel II) was made of normalized steel of TSt 460 class (DIN) trade mark Nioval 470 (produced by Steelworks Jesenice), 8 mm thick, of chemical composition given in Table 3, and mechanical properties in Table 4. The steel is of fine grained laminated ferrite pearlite structure, size 12 (×400), JUS C.A3.004 (Fig. 1b).

Tabela 1. Hemijski sastav materijala omotača posude I (čelik S355J2G3)

C	Mn	Si	P	S
0,2	1,5	0,5	0,013	0,007

Table 1. Chemical composition of vessel I mantle material (steel S355J2G3).

C	Mn	Si	P	S
0.2	1.5	0.5	0.013	0.007

Tabela 2. Mehaničke osobine materijala omotača posude I (čelik S355J2G3)

Zatezna čvrstoća R_m, MPa	Napon tečenja R_{eH}, MPa	Izduženje A_5, %	Energija udara C_v, J
540	395	30	39

Table 2. Mechanical properties of vessel I mantle (S355J2G3 steel)

Tensile strength R_m, MPa	Yield strength R_{eH}, MPa	Elongation A_5, %	Impact energy C_v, J
540	395	30	39

Tabela 3. Hemijski sastav materijala omotača posude II (čelik Nioval 47)

C	Mn	Si	P	S	Cr	Ni	V	Al	Ti	Nb
0,16	1,52	0,41	0,006	0,006	0,11	0,12	0,07	0,06	0,001	0,035

Table 3. Chemical composition of vessel II mantle material (Nioval 47 steel).

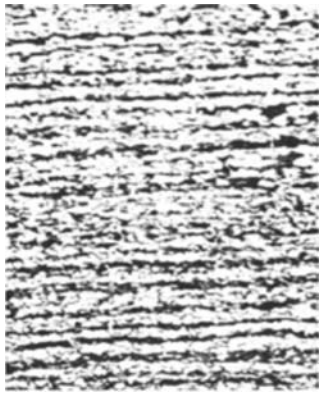
C	Mn	Si	P	S	Cr	Ni	V	Al	Ti	Nb
0.16	1.52	0.41	0.006	0.006	0.11	0.12	0.07	0.06	0.001	0.035

Tabela 4. Mehaničke osobine materijala omotača posude II (čelik Nioval 47)

Zatezna čvrstoća R_m, MPa	Napon tečenja R_{eH}, MPa	Izduženje A_5, %	Energija udara C_v, J
635	520	21	135

Table 4. Mechanical properties of vessel II mantle material (Nioval 47 steel).

Tensile strength R_m, MPa	Yield strength R_{eH}, MPa	Elongation A_5, %	Impact energy C_v, J
635	520	21	135

(a)  (b) 

Slika 1. Mikrostrukture ispitivanih čelika. (a) čelik S355J2G3 (posuda I), (b) čelik Nioval 47 (posuda II)
Figure 1. Microstructures of investigated steels. (a) steel S355J2G3 (vessel I), (b) Nioval 47 steel (vessel II).

Kružni i uzdužni zavareni spojevi omotača rezervoara (posuda I) su izvedeni kombinovanim zavarivanjem. Dva korena prolaza su zavarena u zaštitnoj atmosferi inertnog gasa volframovom elektrodom (TIG-141), prolazi ispune su izvedeni ručnim elektrolučnim zavarivanjem obloženom elektrodom (E-111). Udarna žilavost je ispitana na epruvetama smanjenih dimenzija (presek 5×10 mm). Prosečna energija udara je zadovoljavajuća: u grubozrnom području ZUT 23 J, a u metalu šava 27 J.

Mikrostruktura osnovnog metala je heterogena zbog laminarnog perlita (makro snimak zavarenog spoja, sl. 2). Mikrostruktura ZUT je grubi beinit sa acikularnim feritom unutar austenitnih zrna i mrežom proeutektoidnog ferita na granicama austenitnih zrna, sl. 3. Uključci i grubo austenitno zrno pogoduju pojavi acikularnog ferita. Proeutektoidni ferit je grub i krt, pa je sklon krtom lomu.

Kružni i uzdužni spojeva omotača cisterne su zavareni elektrolučnim postupkom pod prahom (EPP-12), po jednim prolazom sa svake strane. Ugaoni spojevi nosača cisterne sa omotačem su izvedeni E-111 zavarivanjem.

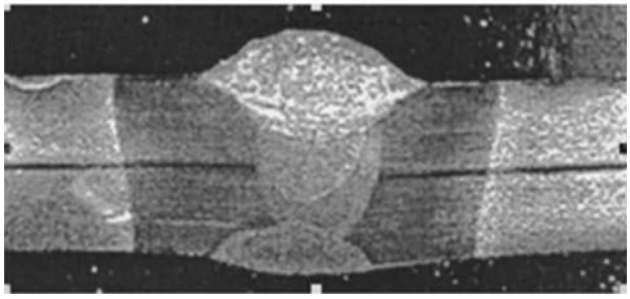
Metal šava kružnog zavarenog spoja je beinitno-feritne mikrostrukture sa grubom mrežom proeutektoidnog ferita na granicama austenitnih zrna.

Circumferential and longitudinal welded joints of storage tank mantle (vessel I) had been performed by combined welding. Two root passes were welded in inert gas shielding procedure with tungsten electrode (GTAW-141), filler passes were performed by metal manual arc welding with coated electrode (SMAW-111). Impact toughness was tested by sub-sized specimens (cross section 5×10 mm). The average impact energy is satisfactory: 23 J in the HAZ coarse grain region, and 27 J in the weld metal.

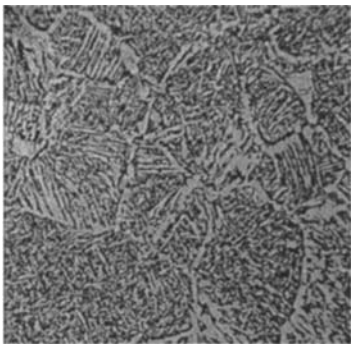
The parent metal microstructure is heterogeneous due to laminated pearlite (macrograph of welded joint, Fig. 2). The HAZ microstructure is coarse bainite with acicular ferrite inside austenite grains and proeutectoid ferrite mesh on austenite grain boundaries, Fig. 3. Inclusions and coarse austenite grains favoured the acicular ferrite occurrence. The proeutectoid ferrite is coarse and brittle, prone to brittle fracture.

Circumferential and longitudinal joints of mobile storage tank were welded by submerged arc welding (SAW-12), in one pass from each side. Fillet welds of tank supports to the mantle were welded by SMAW-111.

Weld metal of circumferential welded joint is of bainite ferrite microstructure with a coarse mesh of proeutectoid ferrite on austenite grain boundaries.



Slika 2. Makro snimak zavarenog spoja čelika S355J2G3
Figure 2. Macrograph of welded joint - S355J2G3 steel.



Slika 3. Grubozrno područje u zoni uticaja toplote (posuda I)
Figure 3. Coarse grain zone in the heat-affected-zone (vessel I).

ANALIZA LOMA

Izgled rezervoara (posuda I) posle krtog loma je prikazan na sl. 4. Plastični kolaps cisterne sa vidljivim klobukom je prikazan na sl. 5. Na obe posude inicijalna prslina se javila u ZUT. Na posudi I prslina se razvijala u uzdužnom pravcu, upravno na kružni zavareni spoj. Na posudi II prslina je krenula u uzdužnom pravcu iz ugaonog spoja, a posle je pratila kružni spoj.

Na posudi I prslina se javila u donjem delu omotača. Od donjeg dela parče materijala je odvaljeno, sl. 6. Prslina je inicirana u ZUT kružnog zavarenog spoja, sl. 7, u grubozrnoj mikrostrukturi poslednjeg prolaza, sl. 3, a zatim je na jednoj strani propagirala upravno na uzdužnu osu posude, duž ZUT kružnog spoja segmenta 2, sl. 8. Kada je dospela u područje veće žilavosti u zavarenom spoju, prslina je skrenula i zaustavila se u osnovnom metalu. Na drugoj strani prslina se razvijala uzdužno kroz osnovni metal. U segmentu 3, sl. 9, posle inicijacije prslina nije prolazila kroz ZUT, već se razvijala kroz osnovni metal, upravno na spoj, gde je i u ovom slučaju zaustavljena.

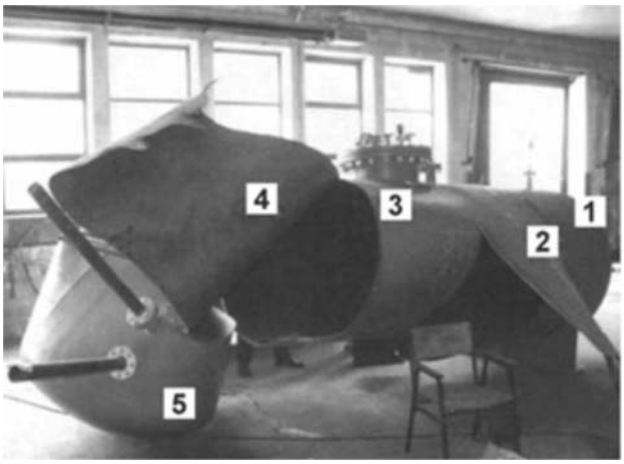
Analiza je pokazala da je površina preloma ravna i upravna na površinu lima na obe strane od tačke inicijacije duž ZUT, što je karakteristično za krti lom, bez plastične deformacije, sl. 10.

FRACTURE ANALYSIS

The appearance of storage tank (vessel I) after brittle fracture is shown in Fig. 4. Plastic collapse of the mobile tank with visible bulging is shown in Fig. 5. In both vessels the crack initiated in HAZ. In vessel I, the crack propagated in the longitudinal direction, perpendicular to the circumferential welded joint. In vessel II the crack initiated in fillet weld longitudinally and deviated to follow circumferential joint.

In vessel I, the crack occurred in the vessel mantle lower part. One piece of material was punched out from the lower part, Fig. 6. The crack initiated in circumferential weld HAZ, Fig. 7, in the final bead coarse microstructure, Fig. 3, then on one side propagated perpendicularly to the longitudinal vessel axis, along circumferential weld HAZ segment 2, Fig. 8. When the crack reached the region of higher toughness in welded joint, it deviated and arrested in the parent metal. On the other side, the crack propagated through parent metal longitudinally. In segment 3, Fig. 9, after initiation the crack did not follow HAZ, but developed through parent metal perpendicularly to weld, where it was again arrested.

Analysis revealed that the fracture surface is flat and perpendicular to the plate surface on both sides of the initiation point along HAZ which is typical for brittle fracture, without plastic deformation, Fig. 10.

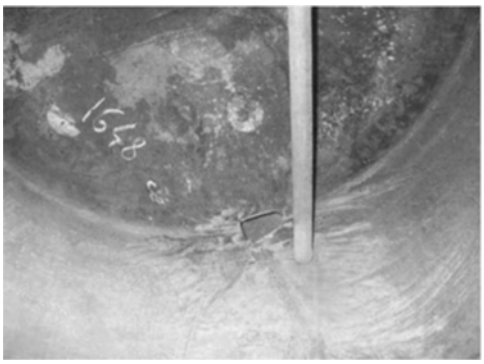


Slika 4. Krti lom podzemnog rezervoara (posuda I)
Figure 4. Brittle fracture of the underground storage (vessel I).

Slika 5. Žilavi lom cisterne (posuda II)
Figure 5. Ductile fracture of the storage tank (vessel II).

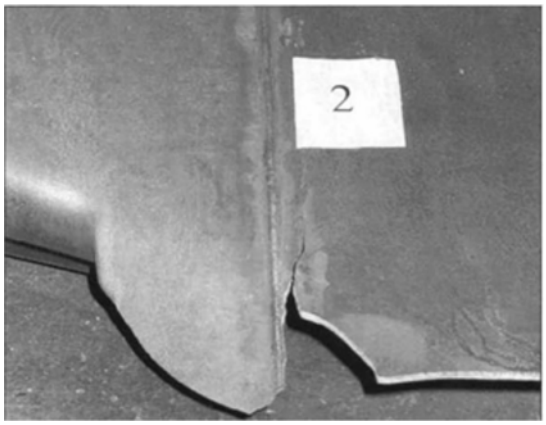
Strelasti prelom, vidljiv na sl. 10, može da se prati unazad do mesta inicijacije prsline. Posle ravne površine preloma, upravne na pravac dejstva sile, što odgovara krtom lomu, proces razdvajanja se završava mehanizmom klizanja u uslovima ravnog stanja napona, u pravcu maksimalnog napona smicanja pod uglom od 45°, sl. 10, za segment 2 na posudi i mnogo jasnije na sl. 11 za segment 3, sa tipičnim prelazom od krtog u žilavi lom, sa usnama klizanja.

Chevron patterns, easily found in Fig. 10, can be followed back to the crack initiation point. After the flat fractured surface, normal to loading direction, corresponding to brittle fracture, the separating process ends by shear mechanisms in plane stress condition in direction of maximal shear stress inclined 45°, Fig. 10, for vessel segment 2, and more clear in Fig. 11 for segment 3, with typical brittle to ductile transition fracture, with shear lips.

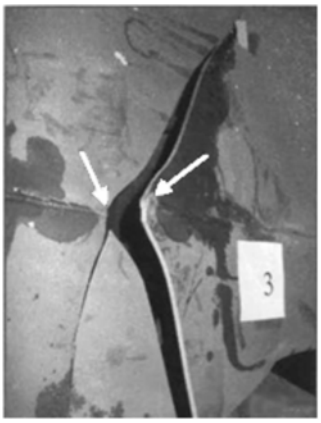


Slika 6. Lom donjeg dela rezervoar (posuda I)
Figure 6. Fracture on lower part of the storage tank (vessel I).

Slika 7. Prslina je inicirana i rasla kroz ZUT
Figure 7. Crack initiated and developed through HAZ.

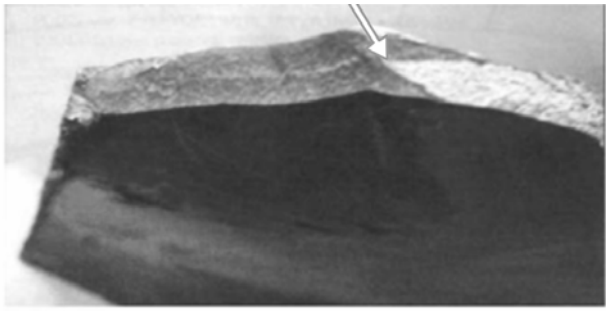


Slika 8. Prslina je skrenula u segmentu 2 iz zone uticaja toplote (ZUT) u osnovni metal
Figure 8. Crack deviated in the segment 2 from the heat-affected-zone (HAZ) into the parent metal.



Slika 9. Prslina je skrenula u segmentu 3 iz zone uticaja toplote (ZUT) u osnovni metal
Figure 9. Crack deviated in the segment 3 from the heat-affected-zone (HAZ) into the parent metal.

Slika 10. Površina preloma segmenta 2 sa strelastim tragom loma. Strelica označava prelaz iz krtog u plastični lom.
Figure 10. Fracture surface of segment 2 with chevron pattern. Arrow indicates transition from brittle to ductile fracture.



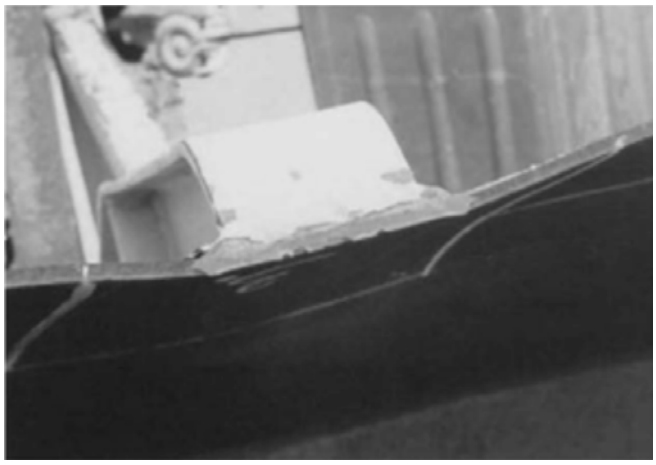
Slika 11. Površina preloma segmenta 3 sa strelastim tragom loma. Strelica označava prelaz iz krtog u plastični lom.
Figure 11. Fracture surface of segment 3 with chevron pattern. Arrow indicates transition from brittle to ductile fracture.

U cisterni za prevoz amonijaka (posuda II) prslina se inicirala u ZUT ugaonog šava između omotača i držača na osloncu, širila se prvo uzdužno, i konačno u pravcu upravnom na osu posude, sl. 5. Tačka inicijacije je utvrđena u području gde je plastična deformacija bila ometena, sl. 12, što odgovara uslovima ravne deformacije. Zajed dubine 1 mm je uočljiv na površini preloma, na početku ugaonog zavarenog spoja. Prslina je zatim rasla kroz osnovni metal u pravcu obimnog napona, sl. 13, mehanizmom smicanja, i dalje kroz ZUT kružnog zavarenog spoja.

Analiza površine preloma je ukazala na žilavi lom koji je sledio prethodnu plastičnu deformaciju. Skening elektronski mikroskop je otkrio vlaknasti žilavi lom, sl. 14, /9/, i razvoj loma po debljini u obliku polueliptične prsline. Usne klizanja su karakteristične za rast prsline u ovom slučaju, a površina preloma je nagnuta pod uglom 45°, u pravcu maksimalnih napona smicanja, sl. 15.

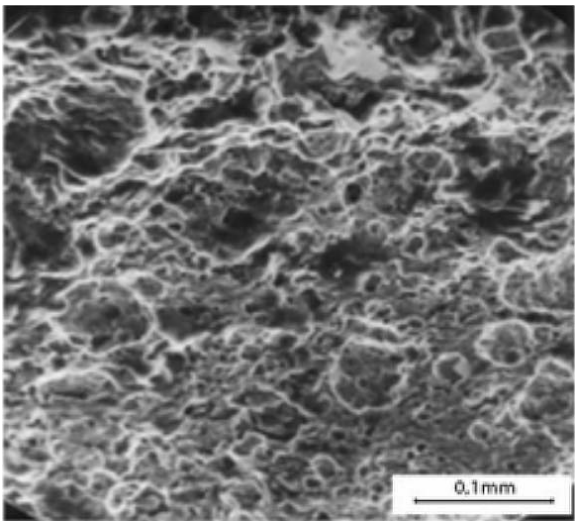
In the storage tank for ammonia transport (vessel II), the crack initiated in the HAZ of fillet weld between the mantle and support holder, grew longitudinally first, and finally in the direction perpendicular to the vessel axis, Fig. 5. The initiation point was located in the region of constrained plastic deformation, Fig. 12, corresponding to plane strain condition. An undercut 1 mm deep is visible on the fracture surface, where fillet weld starts. The crack then propagated through parent metal in the hoop stress direction, Fig. 13, by shear mechanisms, and further through HAZ of circumferential weld.

Analysis of the fractured surface has shown ductile fracture that followed prior plastic deformation. Scanning electron microscopy revealed fibrous ductile fracture, Fig. 14, /9/, and through thickness crack growth of semi-elliptic shape. Shear lips are typical for crack growth in this case, and the fracture surface is inclined by 45°, in direction of maximal shear stress, Fig. 15.

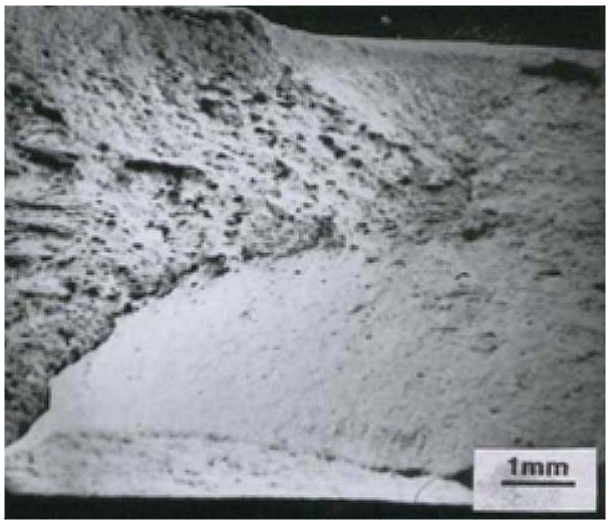


Slika 12. Položaj inicijacije prsline sa tragom rasta prsline
Figure 12. Crack initiation location and crack growth path.

Slika 13. Makro snimak ugaonog šava sa zajedom
Figure 13. Macrograph of fillet weld with undercut.



Slika 14. Površina žilavog loma cisterne za prevoz amonijaka
Figure 14. Ductile fracture surface of tank for ammonia transport.



Slika 15. Lom mehanizmom klizanja sa usnama klizanja
Figure 15. Fracture by shear mechanism with shear lips.

DISKUSIJA

Debljina zida obe posude je projektom određena prema naponu tečenja, čija je veličina za oba čelika u skladu sa standardom. I vrednosti izduženja posle prekida su odgovarale standardom propisanim vrednostima. Energija udara oba čelika je na zadovoljavajućem nivou, imajući u vidu veličinu epruvete (poprečni presek 5×10 mm).

Čvrstoća zavarenog spoja je prema projektu bila veća od čvrstoće osnovnog metala (overmečing), što je potvrđeno ispitivanjem na zatezanje epruveta zavarenog spoja. Udarna energija metala šava i ZUT je bila i granicama standarda, za 20 do 25% niža nego kod osnovnog metala, što je važno za grubozrno područje ZUT. Ovo područje je često najslabija tačka u zavarenom spoju, naročito kod čelika visoke čvrstoće, /8/. Gruba struktura i mala vrednost energije udara su verovatno razlog zbog čega se prslina inicijalno javlja u krupnozrnom području ZUT obe posude.

Uslovi ispitivanja pritiskom rezervoara (posuda I) propisuju da temperatura ispitivanja bude za najmanje 25°C viša od temperature nulte plastičnosti čelika, na kojoj je garantovana žilavost osnovnog metala i zavarenog spoja. Kako po standardu prelazna temperatura za čelik S355J2G3 iznosi –20°C, ispitivanje probnim pritiskom treba izvesti na temperaturi višoj od +5°C, da ni u kom slučaju zavarena konstrukcija ne bude izložena temperaturi nižoj od prelazne temperature. Za prvo ispitivanje rezervoara pritiskom korišćen je azot u gasovitom stanju, pod visokim pritiskom uzet iz posebnog rezervoara, pa je razlog nastanka krtog loma temperatura ispitivanja uspostavljena ekspanzijom gasa, koja je bila niža od prelazne temperature čelika. Treba imati u vidu da je mikrostruktura ZUT u grubozrnom području sklona krtom ponašanju, što uz očekivanu koncentraciju napona u zavarenom spoju omogućava iniciranje prsline i krti lom u uslovima ravne deformacije pri ovim uslovima ispitivanja. Lokacija inicijalne prsline je nađena u donjem delu rezervoara, što je očekivano jer tu temperatura niža. Prslina se nestabilno razvijala paralelno uzdužnoj osi posude, silom razvoja prsline uvedenom maksimalnim naponom, odnosno obimnim naponom. Posle izvesnog vremena temperatura posude je porasla i dalje se prslina razvijala stabilno, mehanizmom žilavog loma sa površinom preloma pod uglom 45°, u pravcu maksimalnih napona smicanja, sa izraženim usnama klizanja, odnosno u uslovima ravnog stanja napona. Lom posude ispitivanog rezervoara je tipičan primer kako se zavarena konstrukcija od koje se u eksploataciji očekuje duktilno ponašanje u datim uslovima opterećenja lomi nestabilno, tj. krto.

Lom pokretne cisterne za prevoz amonijaka (posuda II) je bio žilav. Debljina zida je smanjena na 5,3 mm u području inicijacije prsline. Izmerena tvrdoća ZUT na ploči omotača je bila 310–321 HV5, što je prema standardu EN288-3 prihvatljivo, ali je s obzirom na radni medijum (amonijak) preporučena maksimalna vrednost tvrdoće 250 HV zbog naponske korozije. Prslina se razvijala kroz grubozrno područje ZUT, gde je žilavost najmanja. Ovakvo ponašanje nije očekivano jer je kod čelika Nioval 47 utvrđena sklonost pojave područja visoke čvrstoće i male žilavosti ZUT u blizini linije stapanja, /8/.

DISCUSSION

Wall thickness for both vessels was determined based on yield strength in design, in both steels of value corresponding to specification. After fracture, values of elongation met the values prescribed by standard. Impact energy of both steels was at a satisfactory level, having in mind specimen size (cross section 5×10 mm).

According to the design, strength of the welded joint was higher than parent metal strength (overmatching), what is confirmed by tensile testing of welded joint specimens. Impact energy of weld metal and HAZ was in standard limits, 20 to 25% lower compared to the parent metal, what is important for coarse grain region in HAZ. This region is often the weakest point in a welded joint, especially in high strength steels, /8/. The coarse structure and low impact energy value are probably the reason why the crack initiated in the coarse grain region of HAZ in both vessels.

Pressure test conditions of storage tank (vessel I) require that test temperature must be at least 25°C higher than nil-ductility transition temperature, at which the toughness of parent metal and welded joint is guaranteed. Since according to standard the transition temperature of S355J2G3 steel is –20°C, proof pressure testing should be performed at a temperature above +5°C, in order to avoid exposure of the welded structure temperature bellow transition. Nitrogen gas was used for the first pressure test of storage tank, and is taken from a special storage tank under high pressure, and so brittle fracture is attributed to the temperature set by gas expansion which was lower than transition temperature. It is to bear in mind that HAZ microstructure in coarse grain region is prone to brittle behaviour that enabled, with expected stress concentration in welded joint, crack initiation and brittle fracture in plane strain in these testing conditions. The point of initiation is located in the lower part of storage tank, as expected, because the temperature there is lower. Crack propagated unstably, parallel to vessel longitudinal axis, by crack driving force of maximal stress, i.e. by hoop stress. After some time, the vessel temperature increased, and further crack propagation was stable, by a ductile fracturing mechanism with fracture surfaces at an angle of 45°, in the direction of maximal shear stress, with expressed shear lips, or meaning in plane stress condition. Fracture of the tested storage tank is a typical example how a welded structure of expected ductile behaviour in a given loading condition can be fractured in unstable manner, i.e. by brittle fracture.

Fracture of mobile storage tank (vessel II) for ammonia transport was ductile. Wall thickness was reduced to 5.3 mm at the point of crack initiation. The measured hardness of HAZ on mantle plate was from 310–321 HV5, acceptable by standard EN288-3, but regarding the working medium (ammonia), recommended maximal hardness value is 250 HV due to stress corrosion. The crack propagated through HAZ coarse grain region of the least toughness. Such behaviour is not expected having in mind that Nioval 47 steel is prone to the occurrence of a region of high strength and low toughness in HAZ close to fusion line, /8/.

Krti lom u toj oblasti je prirodan /5,6/, ali do njega u ovom slučaju nije došlo. Do loma cisterne je došlo na povišenoj temperaturi okoline, pa se i to kritično područje ponašalo duktilno. Zbog toga ni uticaj eventualne koncentracije napona zbog postojanja grešaka u zavarenom spoju nije došao do izražaja.

Brittle behaviour of this region is natural /5,6/, but this did not happen. The storage tank fractured at the elevated environmental temperature, so even this critical region behaved in a ductile manner. Hence, the effect of eventual stress concentration due to existing defects in welded joints had not been expressed.

ZAKLJUČAK

U opisanim primerima otkaza tankozidnih rezervoara osnovni razlog krtog i žilavog loma je povezan sa nepoštovanjem specificiranih radnih uslova, odnosno uslova opterećenja. Dokazano je da su osobine materijala i kvalitet zavarenih spojeva bili na zadovoljavajućem nivou i da nisu ni u jednom od prikazanih slučajeva uslovili otkaz konstrukcije. U slučaju rezervoara (posuda I) nije poštovan zahtev da temperatura ispitivanja probnim pritiskom bude dovoljno visoka u odnosu na prelaznu temperature nulte plastičnosti, pa su se osnovni metal i zavareni spojevi našli u situaciji neizbežnog krtog ponašanja, pri čemu i najmanja koncentracija napona dovodi od katastrofalnog loma. U slučaju pokretne cisterne je nepoštovanje propisa u količini punjenja uslovilo preopterećenje, koje u drugačijim uslovima spoljnje atmosfere (niža spoljnja temperatura) verovatno ne bi dovelo do katastrofalnog otkaza. Treba istaći da se u oba slučaja inicijalna prslina pojavila u ZUT zavarenog spoja na omotaču, kritičnoj lokaciji u pogledu krtog ponašanja zbog male žilavosti.

Iako su omotači posuda u oba slučaja bili iste i relativno male debljine i dovoljno velikog prečnika, što odgovara uslovima ravnog stanja napona, lom je u jednom slučaju bio krt, a u drugom žilav. Različiti oblici loma su posledica uspostavljenih različitih uslova opterećenja.

CONCLUSION

In the described cases of thin-walled storage tank failures the basic reason for brittle and ductile fracture is connected with disregarding specified operating conditions, i.e. loading conditions. It has been shown that material properties and welded joint quality are of satisfactory levels and did not cause failure of structures in no single of presented cases. In case of storage tank (vessel I) the condition that testing temperature in proof pressure test has to be sufficiently higher compared to the nil-ductility transition temperature has not been met, and parent metal and welded joints were inevitably exposed to the situation of brittle behaviour, when a small stress concentration can cause catastrophic failure. In case of mobile storage tank, disregarding the codes of the charge quantity had caused overloading which in different environment conditions (lower outer temperature) eventually would not cause catastrophic failure. It is to emphasize that in both cases initial crack occurred in HAZ of welded joint on the mantle, the critical location regarding brittle fracture due to low toughness.

Despite that mantles in both cases were of the same and relatively small thickness and of large diameters, convenient for plane stress conditions, the fracture was in one case brittle, and in the other ductile. Different fracture modes resulted from established different loading conditions.

LITERATURA – REFERENCES

1. *Eksploatacijske prsline u posudama pod pritiskom i rezervoarima*, Monograph of lectures held at IFMASS 6, Eds. S. Sedmak, A. Sedmak, TMF-ECPD-GOŠA, Beograd, 1994 (Service cracks in pressure vessels and storage tanks).
2. Jukava, S., *Preporuke za posude pod pritiskom – projektovanje, materijali i iskustvo*, kao pod (1), 1-26.
3. Bređan, A., Kurai, J., *Evropska direktiva za opremu pod pritiskom (PED) i integritet konstrukcija* – European pressure equipment directive (PED) and structural integrity, Integritet i vek konstrukcija (Structural integrity and life), Vol. 3, No1, 2003, 31-41.
4. Kirić, M., Sedmak, A., *Granične vrednosti unutrašnjeg pritiska za cilindre sa prslinom – The Boundary Pressure Values for Internally Pressurized Cracked Cylinders,* Integritet i vek konstrukcija (Structural integrity and life),Vol. 3, No1, 2003.
5. Kurai, J., Aleksić, B., *Ispitivanje pritiskom kao uzročnik pojave prslina kod opreme pod pritiskom u eksploataciji – Proof Pressure Test as a Cause of Crack Occurrence in Pressure Equipment in Service*, Integritet i vek konstrukcija (Structural integrity and life),Vol. 3, No 2, 2003.
6. Adžiev, G., Sedmak, A., *Ocena integriteta sfernog rezervoara – Integrity Assessment of Spherical Storage Tank*, Integritet i vek konstrukcija (Structural integrity and life),Vol. 3, No 2, 2003.
7. Sedmak, S., Sedmak, A., *Integritet cevovoda hidroelektrane – Integrity of Penstock of Hydroelectric Power plant,* Integritet i vek konstrukcija (Structural integrity and life),Vol. 5, No 2, 2005.
8. Gerić, K., Prsline u zavarenim spojevima – Monografija, (Cracks in welded joints – Monograph), FTN Izdavaštvo, Novi Sad, 2005.
9. Metals Handbook ASM, Vol.9, Metals Park Ohio.