Miodrag Arsić, Vujadin Aleksić, Nenad Hut [1]

ANALIZA STANJA I OCENA INTEGRITETA KOTLOVA
ANALYSIS OF STATE AND INTEGRITY ASSESSMENT OF BOILERS

Originalni naučni rad / Original scientific paper
UDK / UDC: 621.791
Rad primljen / Paper received: 20.11.2004.

Adresa autora / Authors' address:
[1] Institut IMS AD, Bulevar vojvode Mišića 43, Beograd

Ključne reči
- kotlovsko postrojenje
- analiza stanja
- zavareni spoj
- ocena integriteta

Izvod

Prevremeni otkaz kotlovskih postrojenja može biti izazvan istovremenim uticajem većeg broja tehnološko-metalurških, konstrukcijskih i eksploatacijskih faktora. Zato se povoljna konstrukcijska rešenja, koja obezbeđuju sigurnost i integritet u uslovima eksploatacije, mogu ostvariti samo pravilnim izborom materijala i potpunim poznavanjem ponašanja osnovnog materijala i zavarenih spojeva u različitim radnim uslovima.

U radu je prikazan metodološki pristup za analizi stanja cevnog sistema kotla, na primeru vrelovodnog kotla VKL-50 (kapacitet proizvodnje pare 50 m^3/h). Opisane su primenjene metode ispitivanja svojstava osnovnog materijala i zavarenih spojeva i izloženi su rezultati ispitivanja. Prikazani pristup je omogućio ocenu integriteta kotla u različitim režimima rada.

Keywords
- boiler
- state analysis
- welded joint
- integrity assessment

Abstract

A premature failure of boilers can be caused by simultaneous effects of a number of technological and metallurgical, design and service factors. Hence, satisfying design solution, which would ensure security and integrity in service states, can be achieved only by a proper choice of materials and a complete knowledge of the behaviour of parent material and welded joints in various operating conditions.

In the paper, the methodological approach has been presented for the state analysis of the boiler pipe system in the case of a hot-water boiler VKL-50 (steam production capacity 50 m^3/h). The applied methods for testing the parent metal and welded joints and the test results are presented. The described approach enabled to assess the integrity of boiler in different operation regime.

UVOD

U mnogim slučajevima se zahteva, posle perioda eksploatacije, koji se približava projektnom veku, donošenje odluke o daljoj eksploataciji i oceni pouzdanosti kotlovskog postrojenja. Za donošenja takve odluke neophodni su podaci o trenutnom stanju postrojenja. Pri oceni trenutnog stanja analizom izvedenih rešenja se može doći do važnih informacija i za poboljšavanje metoda projektovanja kotlovskih postrojenja, za razvoj novih tehničkih rešenja i metoda ispitivanja, za poboljšanje postupka održavanja, kao i za razvoj i izbor materijala poboljšanih svojstava i tehnologija njihove obrade.

Konstrukcije izrađene zavarivanjem, kao što su posude pod pritiskom i cevni sistemi, su izložene različitim vidovima opterećenja u eksploataciji, pa su potrebna detaljna ispitivanjem ugrađenih materijala u konstrukciju i njenih zavarenih spojeva. Takva ispitivanja su skupa, pa bi bilo korisno napraviti analitičku standardnu proceduru koja će na osnovu mehaničkih karakteristika materijala i zavarenih spojeva, kao i oštećenja i geometrije otkrivenih grešaka u materijalu i zavarenom spoju, dati brz odgovor o trenutnom stanju konstrukcije. Prvi koraci su ostvareni primenom inženjerskih metoda u proceni integriteta konstrukcije /1/.

INTRODUCTION

In many cases after a certain period of exploitation, approaching the designed life, it is required to make a decision on further service and reliability assessment of the boiler system. In order to make such a decision, current boiler state data are necessary. Through the benefits of performed solution analysis, current condition assessment has acquired important information considering improvement in design methods of boiler components, development of new technical solutions and testing techniques, all for improving maintenance procedures, as well as development and choice of materials with improved characteristics and their processing technology.

Structures produced by welding, such as pressure vessels and pipelines are exposed to different modes of loading in service, and detailed testing of materials implemented in structures and their welded joints are necessary. Such tests are expensive, and it is reasonable to develop standard procedures for analysis, which can produce fast response of the current state of the structure, based on mechanical properties of material and welded joints, and the damage and geometry of detected defects in the material and welded joints. First steps are achieved by introduction of engineering methods in structural integrity assessment /1/.

Primena mehanike loma je donela značajne promene u inženjerskoj praksi, jer je potvrđeno da je analiza mehanike loma prihvatljiva osnova ako je ocena integriteta konstrukcije konzervativna /2/.

ANALIZA STANJA KOTLOVSKOG POSTROJENJA

Na sl. 1. data je shema kotlovskog postrojenja.

Analiza stanja kotlovskog postrojenja polazi od baze podataka, kada ona postoji, sl. 2, ili se mora primeniti procedura, koja zahteva sistematizovan prilaz problemu, sl. 3. Ovi procesi se mogu smatrati osnovnim metodološkim pristupima za analizu trenutnog stanja konstrukcija i ocenu integriteta kotlovskog postrojenja u daljoj eksploataciji.

Pri analizi stanja treba uzeti obzir i uticajne faktore, koji mogu dovesti do prevremenog otkaza. Oni mogu biti tehnološko-metalurški, projektni i eksploatacijski, sl. 4.

Metodološki pristup analizi stanja i oceni integriteta kotlovskog postrojenja je prikazan kroz primenu na cevni sistem vrelovodnog kotla VKL-50.

Application of fracture mechanics introduced important changes in engineering practice since it is confirmed that fracture mechanics analysis is an acceptable basis if the structural integrity assessment is conservative /2/.

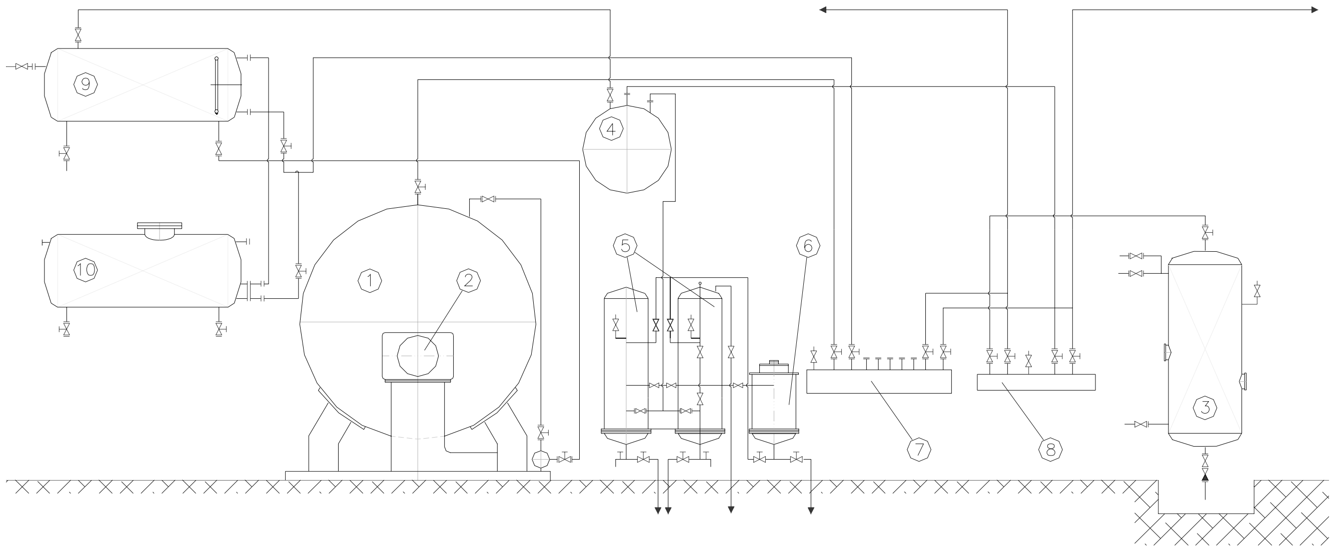
ANALYSIS OF STATE OF THE BOILER SYSTEM

Figure 1 shows a boiler system scheme.

Boiler system state analysis relies on a database, if available, Fig. 2, otherwise a procedure requiring a systematical approach to the problem has to be applied, Fig. 3. These processes can be assumed as basic methodological approaches in the analysis of current structural state and integrity assessment of boilers in further service.

State analysis must include affecting factors which can lead to premature failure. Their nature can be technological and metallurgical, and of design and service, Fig. 4.

The methodological approach in state analysis and integrity assessment of boilers is presented as applied to hot water boiler VKL-50 tube system.



1 - Horizontalni blok kotao (Horizontal boiler block)
2 - Automatski gorionik za mazut (Automated oil burner)
3 - Elektrogenerator pare EGP-1000 (Electrical steam generator)
4 - Napojni rezervoar (Inlet storage tank)
5 - Jonski filteri (Ion filters)
6 - Posuda za so (Salt pot)
7 - Razdelnik pare za kotao (Steam boiler distributor)
8 - Razdelnik pare za elektrogenerator (Steam generator distributor)
9 - Rezervoar za vodu (Water reservoir)
10 - Rezervoar za mazut (Oil reservoir)

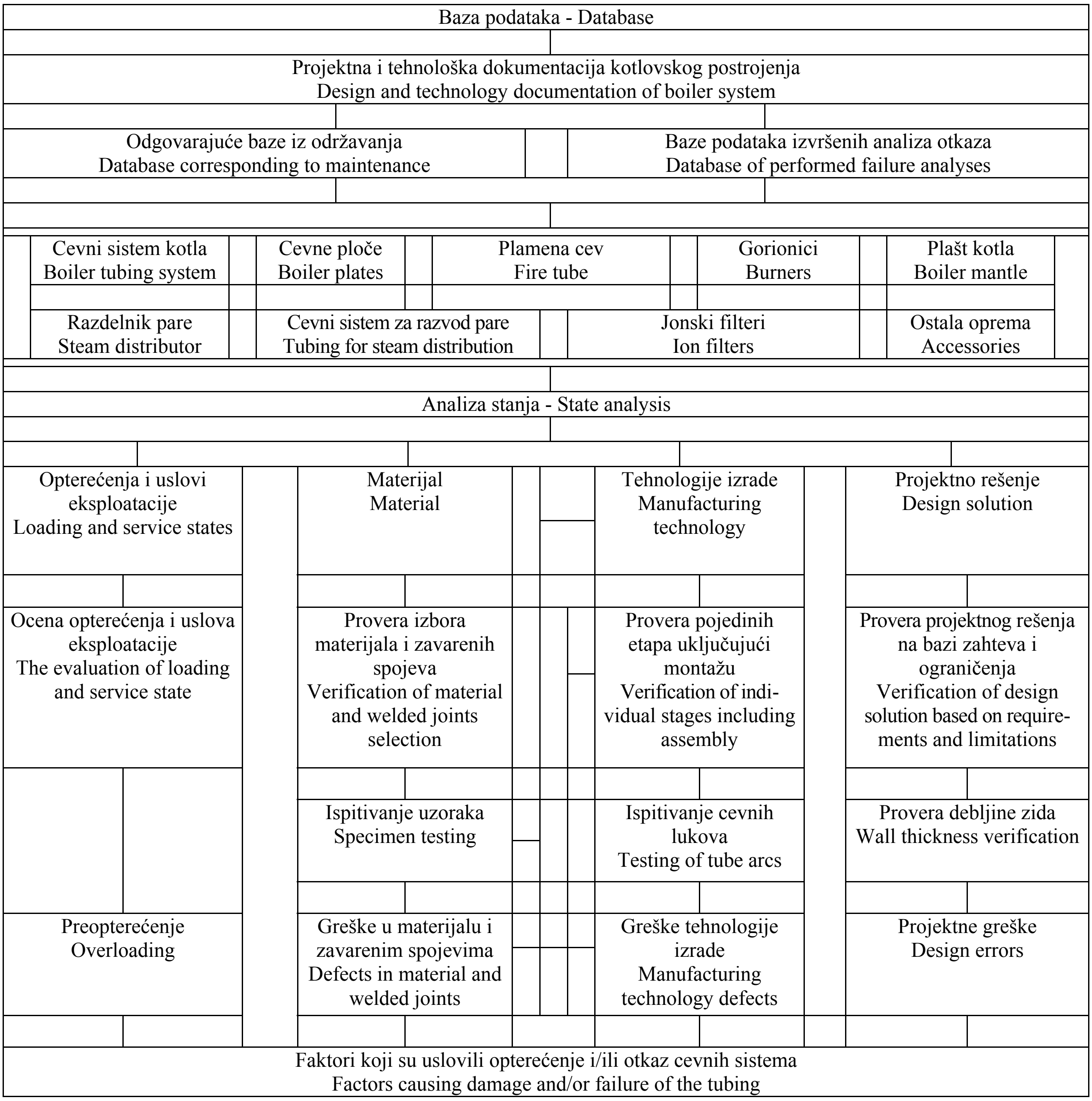
Slika 1. Shema kotlovskog postrojenja
Figure 1. Boiler system scheme.

Projekt izvedenog stanja kotlovskog postrojenja je osnova dalje analize koja se izvodi na osnovu postojeće projektne i tehnološke dokumentacije. Kada za kotlovsko postrojenje iz ma kog razloga takva dokumentacija ne postoji, zadatak analize stanja je i izrada projekta izvedenog stanja, koji obuhvata:

- Osnovne tehničke podatke
- Podatke o sigurnosnoj i pratećoj opremi
- Plan i program ispitivanja
- Rezultate izvršenih ispitivanja
- Potrebne proračune
- Analizu tehnologije izrade
- Grafičku dokumentaciju
- Uputstva za rukovanje i održavanje

The design of performed state of the boiler system is the basis for next analysis, which is based on the existing design and technological documentation. If for any reason such documentation does not exist, the state analysis also requires the design of the performed state, including:

- Basic technical data
- Safety equipment and accessories data
- Inspection plan and program
- The results of performed inspection
- Necessary calculations
- Manufacturing technology analysis
- Graphic documentation
- Handling and maintenance manual



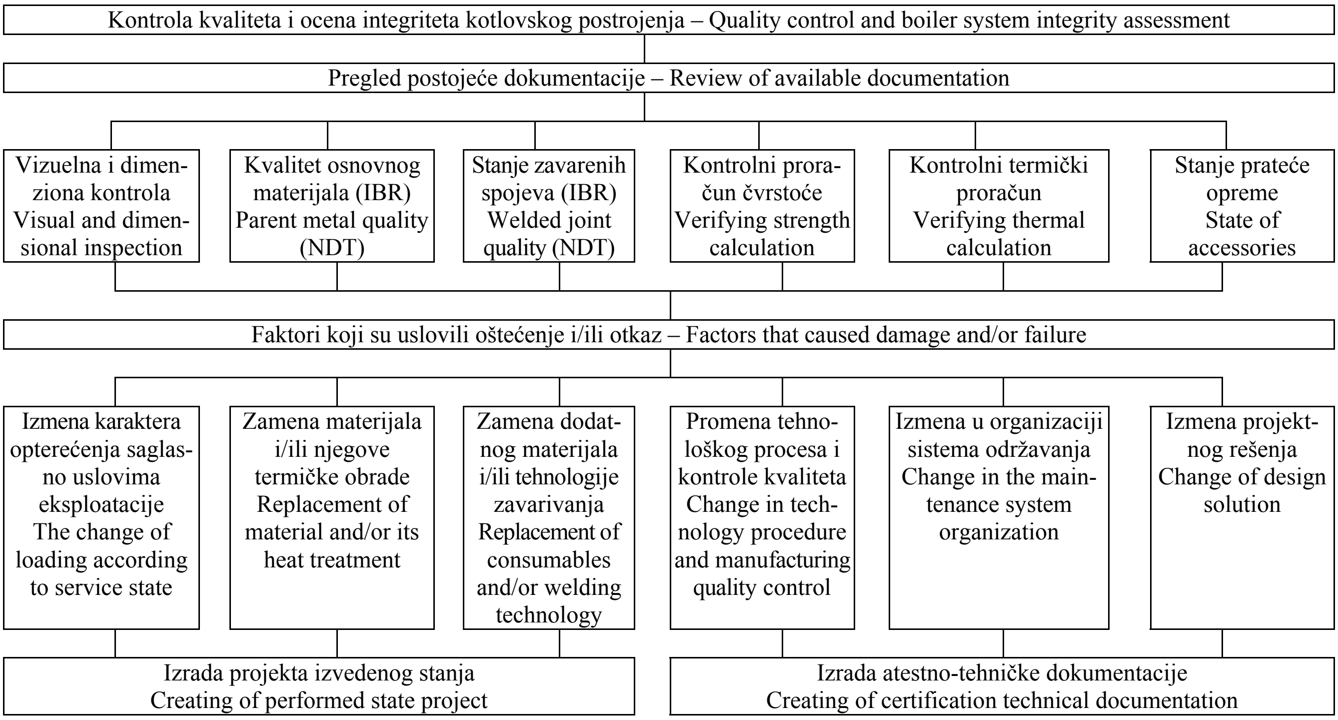
Slika 2. Procedura analize stanja kotlovskog postrojenja korišćenjem baze podataka
Figure 2. The analysis procedure of boiler system state by using a database.

ANALIZA STANJA CEVNOG SISTEMA KOTLA

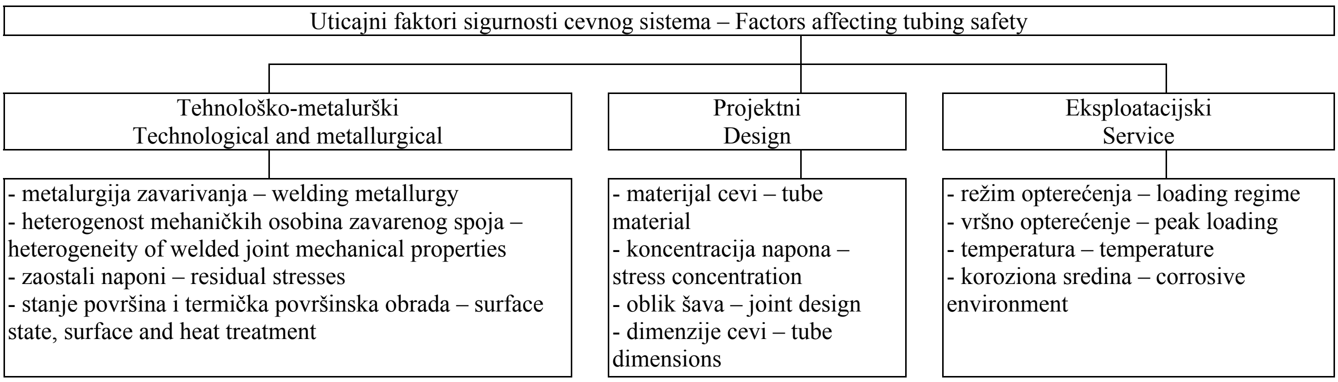
Osnovne karakteristike cevnog sistema vrelovodnog kotla VKL-50 (sl. 1), koji služi za toplifikaciju, su sledeće:
- Prečnik bešavnih cevi cevnog snopa – 57 mm
- Debljina zida cevi – 4 mm
- Pritisak vrele vode na izlazu – 13 bar
- Temperatura vrele vode na izlazu – 170°C
- Šavne cevi zavarene TIG postupkom
- Zavareni spojevi izvedeni u dva prolaza, koreni i završni
- Dodatni materijal – žica SGMo (DIN 8578)–∅2,4 mm
- Zavarivanje izvedeno strujom direktnog polariteta
- Jačina struje zavarivanja – 200 A
- Napon luka – 16 V
- Zaštitni gas argon; protok – 12 l/min

STATE ANALYSIS OF BOILER SYSTEM TUBING

The basic characteristics of a tubing system of hot water boiler VKL-50 (Fig. 1) for remote heating are:
- Diameter of seamless bundled tubes – 57 mm
- Tube wall thickness – 4 mm
- Hot water pressure on exit – 13 bar
- Hot water temperature on exit – 170°C
- Welded tubes welded by TIG procedure
- Welded joints performed in two passes, root and cover
- Consumable – SGMo wire (DIN 8578)–∅2.4 mm
- Welding performed by direct polarity current
- Current amperage – 200 A
- Arc voltage – 16 V
- Shielding gas argon; flow – 12 l/min



Slika 3. Procedura analize stanja kotlovskog postrojenja kada ne postoji baza podataka
Figure 3. The procedure of boiler state analysis in case of non-existing database.



Slika 4. Pregled uticaja na integritet cevnog sistema
Figure 4. A review of factors affecting tube safety.

Analiza hemijskog sastava cevi

Analiza hemijskog sastava materijala datog u tabeli 1, izvedena je na uzorku cevi iz eksploatacije.

The analysis of chemical composition of tubes

The analysis of chemical composition of tubes given in Table 1 was performed on a sample taken from service.

Tabela 1. Hemijski sastav materijala cevi, %
Table 1. Chemical composition of tube material, %.

Element	C	Si	Mn	P	S	Al	Cu	Cr	Ni	Nb
Sadržaj – Contents, %	0.12	0.27	0.43	0.006	0.006	0.018	0.225	0.051	0.01	0.011

Čelik je garantovane čistoće, P + S < 0,012, a Cu i Nb su nečistoće (tab. 1) i odgovara Č.1214 JUS C.B5.022.

Sadržaj bakra iznad 0,2% povećava otpornost čelika prema atmosferskoj koroziji, ali na povišenim temperaturama bakar izaziva interkristalnu krtost ako se po granicama zrna izluči interkristalni krti sloj CuFe - (prsline usled zagađenja bakrom - *Copper Contamination Cracking* - CCC).

Steel has garantied purity, P + S < 0.012, Cu and Nb are impurities (Table 1), and it corresponds to Č.1214 JUS C. B5.022.

Copper content above 0.2% improves resistance to atmospheric corrosion, but at elevated temperatures copper can cause intercrystalline brittleness if an intercrystalline brittle layer of CuFe is precipitated along grain boundaries (Copper Contamination Cracking - CCC).

Sadržaj Nb je takođe visok. Niobijum već pri malim sadržajima (0,005-0,008) gradi karbonitride koji posle valjanja daju vrlo sitno zrno, čime se postiže povećanje napona tečenja, ali se smanjuje udarna žilavost.

Ispitivanje zavarenih spojeva zatezanjem

Ispitivanja zatezanjem zavarenih spojeva izvedena su na sobnoj temperaturi i na povišenoj temperaturi (200°C) na epruvetama sa nadvišenjem i na standardnim epruvetama sa paralelno obrađenim bokovima prema JUS ISO 3834-1051. Crteži epruveta i rezultati ispitivanja su dati u tab. 2.

Ispitivanja zavarenih spojeva zatezanjem ukazuju na zadovoljavajuću čvrstoću uz izraženu plastičnost.

Ispitivanje tvrdoće zavarenih spojeva

Na uzorku pripremljenom prema JUS ISO 3834-1 ispitana je tvrdoća kroz zavareni spoj po Vikersu (HV 30), tab. 3, saglasno JUS C.A4.030.

Iz rezultata ispitivanja se vidi da je tvrdoća zone uticaja toplote (merna mesta 2; 7; 10; 5; 8; 13) veća za oko 20% od tvrdoće osnovnog metala, što je prihvatljivo. Tvrdoća metala šava (merna mesta 3; 4; 11; 12) veća su za oko 48% od tvrdoće osnovnog metala, što za posledicu ima povećanu krtost metala šava.

Iz rezultata ispitivanja se vidi da je tvrdoća zone uticaja toplote (merna mesta 2; 7; 10; 5; 8; 13) veća za oko 20% od tvrdoće osnovnog metala, što je prihvatljivo. Tvrdoća metala šava (merna mesta 3; 4; 11; 12) veća su za oko 48% od tvrdoće osnovnog metala, što za posledicu ima povećanu krtost metala šava.

The percentage of Nb is also high. Even in smaller amounts (0.005-0.008), niobium creates carbon-nitrides which give fine grain after rolling, producing an increased yield stress, but also a decreased impact toughness.

Tensile testing of welded joints

Welded joint tensile tests were preformed at room and elevated temperature (200°C) on specimens with reinforcement and on standard specimens with parallel machined sides according to JUS ISO 3834-1051. Specimen drawings and test results are given in Table 2.

Tensile tests of welded joints indicated satisfying strength, with expressed ductility.

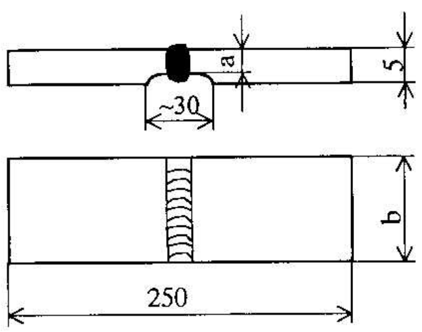
Hardness testing of welded joints

Hardness has been tested on a specimen prepared in accordance to JUS ISO 3834-1 through welded joint by Vickers (HV 30), Table 3, according to JUS C.A4.030.

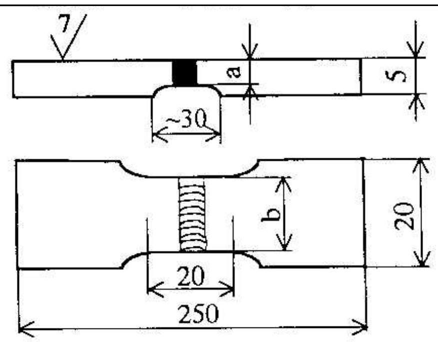
It can be seen from the test results that the hardness of the heat-affected zone (measuring points 2; 7; 10; 5; 8; 13) is about 20% greater than the hardness of the parent metal which is acceptable. Weld metal hardness (points 3; 4; 11; 12) is about 48% greater than that of the parent metal which results in increased brittleness of the weld metal.

It can be seen from the test results that the hardness of the heat-affected zone (points 2; 7; 10; 5; 8; 13) is about 20% greater than the hardness of base metal which is acceptable. Weld metal hardness (points 3; 4; 11; 12) is about 48% greater than that of base metal which results in increased brittleness of the weld metal.

Tabela 2. Epruvete i rezultati ispitivanja zatezanjem
Table 2. Specimens and results of tensile tests.



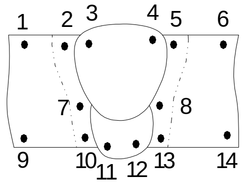
Oblik i dimenzije epruvete sa nadvišenjem
Shape and dimensions of specimen with reinforcement.



Oblik i dimenzije standardne epruvete
Shape and dimensions of standard specimen.

Epruveta Specimen	Dimenzije epruvete Specimen dimensions		Sila tečenja Yield load	Napon tečenja Yield stress	Sila loma Load at fracture	Zatezna čvrstoća Tensile strength	Izduženje Elongation	Suženje preseka Cross-section contraction
	a [mm]	b [mm]	F_e [N]	R_{eH} [MPa]	F_m [N]	R_m [MPa]	A_5 [%]	Z [%]
tech. 1	3.6	17.5	22563	358	28449	452	24.5	51.1
tech. 2	3.6	17.8	23544	367	29430	459	25.5	53.5
Srednja vrednost za tehničku epruvetu Technical specimen average value				363		456	25	52.3
stand. 3	3.6	15.4	17168	301	22563	396	24.5	53.3
stand. 4	3.6	15.2	17658	323	22073	403	18.0	45.8
Srednja vrednost za standardnu epruvetu Standard specimen average value				312		400	21.3	49.6

Tabela 3. Skica i rezultati ispitivanja tvrdoće zavarenog spoja
Table 3. Scheme and hardness test results for welded joint.

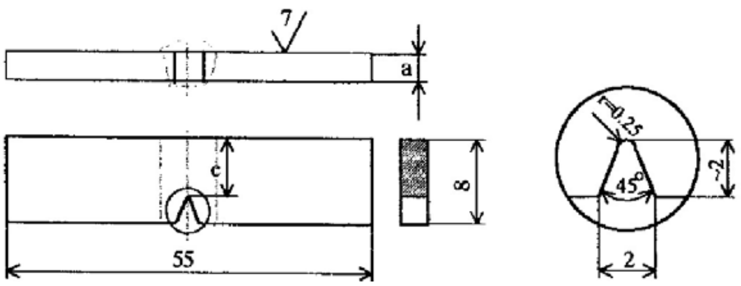
Presek zavarenog mesta i merna mesta Welded joint cross-section and measuring points	Tvrdoća na mernom mestu, HV 30 Hardness at measuring points, HV 30													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	155	155	223	223	152	155	145	145	168	163	227	223	155	145

Ispitivanje udarne žilavosti metala šava

Ispitivanje udarne žilavosti obavljeno je na sobnoj temperaturi (20°C) prema EN 10045-1, na epruvetama manjih dimenzija od standardne epruvete (sl. 5), zbog dimenzija raspoloživog materijala cevi. Zarez je napravljen u metalu šava. Rezultati ispitivanja, prikazani u tab. 4, pokazuju da je udarna žilavost metala šava zadovoljavajuća.

Impact toughness testing of weld metal

Impact testing was performed at room temperature (20°C), according to EN 10045-1, on sub-sized specimens (Fig. 5), due to the dimensions of the available tube material. The notch is made in the weld metal. Results of this test, given in Table 4, show that the impact toughness of the weld metal is satisfactory.



Slika 5. Oblik i dimenzije epruvete za ispitivanje žilavosti metala šava
Figure 5. Shape and dimensions of specimen for impact toughness testing of weld metal.

Tabela 4. Rezultati ispitivanja žilavosti metala šava
Table 4. Impact toughness testing results of welded joint.

Epruveta Specimen	Dimenzije – Dimensions, [mm]		Površina A, [cm^2] Area A, [cm^2]	Energija loma KV, [J] Fracture energy KV, [J]	Žilavost, [J/cm^2] Toughness, [J/cm^2]
	a	c			
1	3.7	6.53	0.242	46.1	191
2	3.8	6.27	0.238	47.1	198
3	3.7	6.19	0.229	42.2	184
4	3.7	6.45	0.238	47.2	198
5	3.8	6.35	0.241	46.2	192
Srednja vrednost – Average value				45.76	193

Metalografska ispitivanja zavarenog spoja

Na posebno pripremljenom izbrusku izvedena su makroskopska i mikroskopska ispitivanja (sl. 6). Makroskopskim ispitivanjima je nađeno da je penetracija zadovoljavajuća i da nema prslina. Mikroskopskim ispitivanjima je utvrđeno da je struktura osnovnog metala feritno-perlitna (odnos ferita i perlita 80:20), da je veličina zrna ASTM 5-7, a u korenom prolazu šava je prisutna Vidmanštetenova struktura.

Metalografska ispitivanja cevnih lukova

Metalografska ispitivanja su izvedena u cilju analize deformacije zrna u spoljnjoj i unutrašnjoj zoni cevnih lukova. Analiziran je uzorak u kritičnoj zoni (zona sa najvećim zatezanjem u spoljnjem delu luka). Na sl. 7 prikazane su mikrostrukture u pojedinim zonama cevnog luka.

Na sl. 7a je uočljiva velika deformacija zrna u pravcu zatezanja (zrno je izduženo), što je prihvatljivo samo ako opterećenje deluje u pravcu zrna. Mikrostruktura unutrašnje

Metallographic welded joint testing

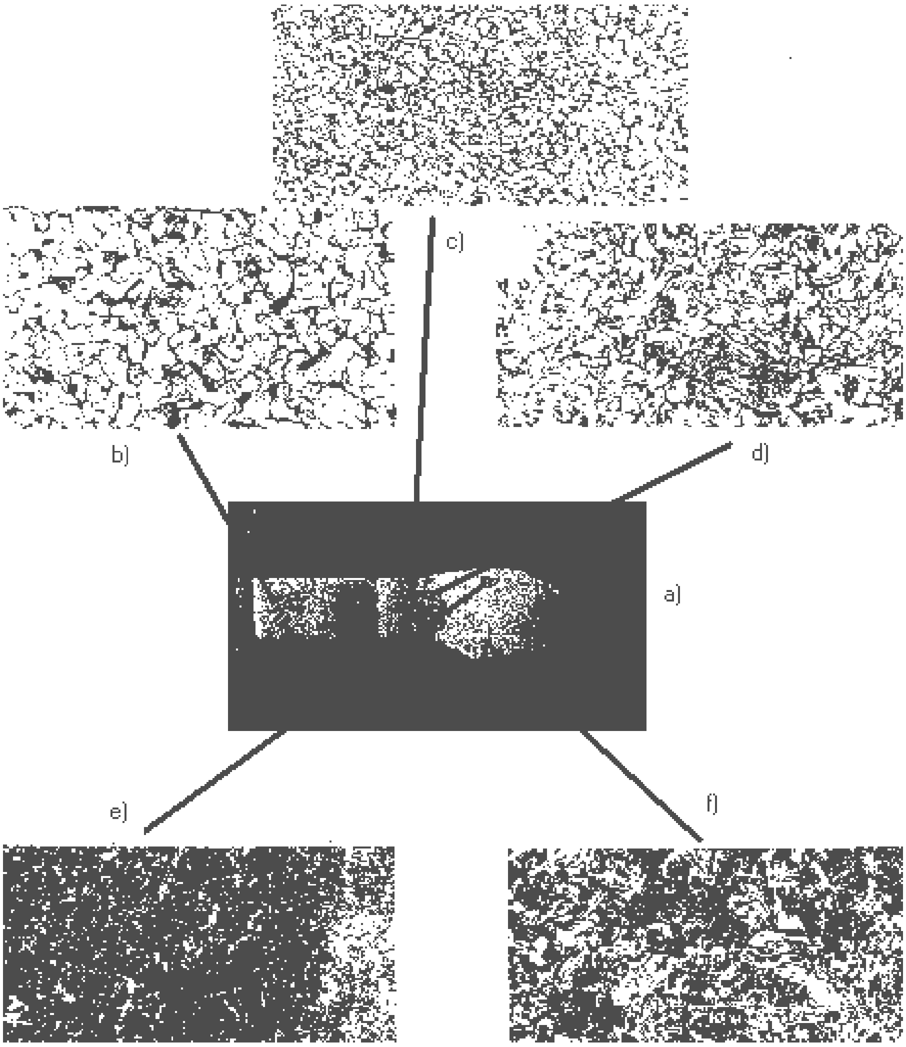
Macroscopic and microscopic tests (Fig. 6) were performed on specially prepared samples. Macroscopic tests determined that the penetration is satisfying and that there are no cracks. Microscopic tests showed that the parent metal structure is ferrite-pearlite (with a ferrite to pearlite ratio 80:20), the grain size is ASTM 5-7, and that a Widmannstätten structure is present.

Metallographic testing of tube arcs

Metallographic testing was performed in order to analyse grain deformation in the inner and outer zones of tube arcs. The sample was analysed in its critical zone (the zone with greatest elongation in the outer part of the arc). Figure 7 shows the microstructure of selected tube arc zones.

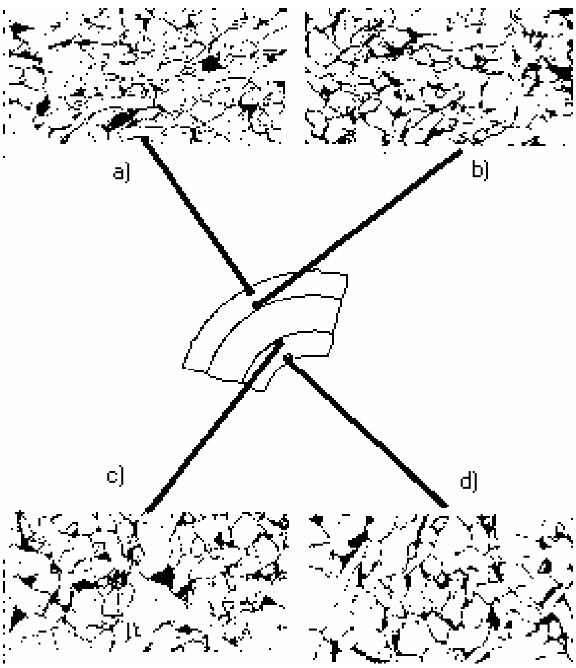
Figure 7a shows significant grain deformation in tensile direction (the grain is elongated), which is acceptable only if the loading is applied in the direction of the grain. The zone na prednjem luku, sl. 7b, takođe je izdužena, ali manje od strukture u spoljnjoj zoni. Na unutrašnjem luku u obe zone zrno je pretrpelo deformaciju sabijanja, pa je došlo do njegovog zadebljanja, sl. 7c, d.

inner zone microstructure on the front arc, Fig. 7b, is also elongated, but not as much as the outer zone structure. The grain in both zones of the inner arc has suffered a compressive deformation which led to its thickening, Fig. 7c, d.



Slika 6. Snimci mikrostrukture zavarenog spoja (×100): a) makrosnimak zavarenog spoja; b) osnovni metal; c) ZUT (zona normalizacije); d) ZUT (zona pregrevanja); e) metal šava završnog zavara; f) metal šava korenog zavara

Figure 6. Welded joint microstructures (×100). a) macro image of welded joint; b) parent metal; c) HAZ (normalization region); d) HAZ (overheating region); e) weld metal cover; f) weld metal root.



Slika 7. Mikrostrukture pojedinih zona cevnog luka (×100): a) spoljnje zone na spoljnjem luku; b) unutrašnje zone na spoljnjem luku; c) spoljnje zone na unutrašnjem luku; d) unutrašnje zone na unutrašnjem luku

Figure 7. Microstructures of tube arc zones (×100): a) outer arc outer zone; b) inner arc outer zone; c) outer arc inner zone; d) inner arc inner zone.

Provera debljine zida cevnog sistema ultrazvukom

Radi provere stanja cevnog sistema kotla potrebno je izmeriti debljine zida. Debljine zida cevi izmerena je na 10% cevi prema standardu ISO 200.95.055, ultrazvučnim aparatom KRAUT-KRAMER DM-4, prema prihvaćenoj shemi. Minimalna izmerena debljina zida cevi je $s_{\min}$ = 2,6 mm, što je prihvatljivo.

Kontrolni proračun čvrstoće materijala cevi

Proračun debljine tankozidne cevi pod unutrašnjim pritiskom izveden je prema JUS M.E2.260, za podatke:

Materijal cevi Č.1214 JUS C.B5.022.
Proračunski pritisak p = 13 bar
Proračunska temperatura t = 170°C
Proračunska čvrstoća za t K = 220 MPa
Spoljni prečnik cevi d_s = 57 mm
Stepen sigurnosti S = 1,5
Dodatak za netačnost u izradi c_1 = 0,3
Dodatak na koroziju i habanje c_2 = 1,0
Koeficijent valjanosti zavarenog spoja ν = 0,8

Ovaj standard za cevi izložene unutrašnjem ili spoljnjem pritisku važi pod uslovom da je $d_s \leq 200$ mm i $d_s/d_u < 1{,}7$, što je ispunjeno.

Potrebna debljina zida cevi je:

$$s = \frac{d_s \cdot p}{20 \cdot \frac{K}{S} \cdot \nu + p} + c_1 + c_2 \leq s_{\min} \qquad (1)$$

Za date podatke potrebna debljina zida cevi je s = 1,6 mm. Izmerene debljine zida cevi su $s_{\min}$ = 2,6 mm, znatno veće od potrebne vrednosti, pa se cevi mogu i dalje koristiti u predviđenim uslovima eksploatacije.

Proračun čvrstoće cevnih lukova

Srednji obimni napon u zidovima cevnog luka, izloženog unutrašnjem pritisku, izračunava se na osnovu ravnoteže sila u području pod dejstvom pritiska i napona u materijalu poprečnog preseka na strani krivine kolena /3/, sl. 8.

Na sl. 8a prikazane su površine poprečnog preseka cevnog luka ($F_{\sigma u}$ i $F_{\sigma s}$) i površine izložene pritisku (F_{pu} i F_{ps}). Odgovarajuće sile u materijalu su: $\sigma_{uu} \cdot F_{\sigma u}$ i $\sigma_{us} \cdot F_{\sigma s}$, a sile u prostoru izloženom pritisku su: $p \cdot F_{pu}$ i $p \cdot F_{ps}$, sl. 8b.

Na sl. 8c prikazan je dijagram korekcionih faktora A_u i A_s za određivanje minimalne debljine zida cevnog kolena pod dejstvom unutrašnjeg pritiska. Minimalno potrebna debljina spoljnjeg i unutrašnjeg zida cevnog kolena (luka) određuje se iz odnosa R/d i krivih A_s za spoljnji, i R/d i krivih A_u za unutrašnji zid luka.

Na taj način se dobija:

$$\sigma_{uu} \cdot \left(R - \frac{d}{2} - \frac{s_u}{2}\right) \cdot \pi \cdot s_u = p \cdot \left(R - \frac{d}{4}\right) \cdot \pi \cdot \frac{d}{2} \qquad (2)$$

$$\sigma_{uu} = p \cdot \frac{d}{2 \cdot s_u} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} \qquad (3)$$

$$\sigma_{us} \cdot \left(R + \frac{d}{2} + \frac{s_s}{2}\right) \cdot \pi \cdot s_s = p \cdot \left(R + \frac{d}{4}\right) \cdot \pi \cdot \frac{d}{2} \qquad (4)$$

Tube system wall thickness verification by ultrasound

In order to verify the state of the hot water boiler tube system, it is necessary to measure wall thickness. This was performed on 10% of tubes according to ISO 200.95.055 standard using an ultrasound device KRAUT-KRAMER DM-4 according to the accepted scheme. Minimal wall thickness measured is $s_{\min}$ = 2.6 mm, what is acceptable.

Reference calculation of tube material strength

The calculation of thin-walled tubes under inner pressure is performed according to JUS M.E2.260, for the data:

Tube material Č.1214 JUS C.B5.022.
Design pressure p = 13 bar
Design temperature t = 170°C
Design strength for t K = 220 MPa
Outer tube diameter d_s = 57 mm
Safety margin S = 1.5
Addition for manufacturing inaccuracy c_1 = 0.3
Addition for corrosion and wear c_2 = 1.0
Coefficient of welded joint quality ν = 0.8

This standard for tubes exposed to inner or outer pressure is valid under condition that $d_s \leq 200$ mm and $ds/d_u < 1.7$, what is satisfied.

The necessary wall thickness is:

$$s = \frac{d_s \cdot p}{20 \cdot \frac{K}{S} \cdot \nu + p} + c_1 + c_2 \leq s_{\min} \qquad (1)$$

For specified data the necessary tube wall thickness is s = 1.6 mm. Thickness measured values are $s_{\min}$ = 2.6 mm, significantly greater than the necessary value, hence these tubes can be used in predicted service conditions.

Tube arc strength calculation

The average hoop stress in tube arc wall exposed to inner pressure is calculated as based on equilibrium of forces in region under pressure effect and stress acting in material of cross-section on the side of knee curvature /3/, Fig. 8.

Figure 8a shows the tube arc cross-section areas ($F_{\sigma u}$ and $F_{\sigma s}$) and areas exposed to pressure (F_{pu} and F_{ps}). Corresponding forces in material are: $\sigma_{uu} \cdot F_{\sigma u}$ and $\sigma_{us} \cdot F_{\sigma s}$, and forces in region exposed to pressure are: $p \cdot F_{pu}$ and $p \cdot F_{ps}$, Fig. 8b.

In Fig. 8c the diagram presents correction factors A_u and A_s for determination of tube arc minimal wall thickness under action of inner pressure. Minimal necessary thickness of outer and inner wall of tube arc can be determined from ratio R/d and A_s curves for outer, and R/d and A_u curves for inner arc wall.

In this way it is possible to obtain:

$$\sigma_{uu} \cdot \left(R - \frac{d}{2} - \frac{s_u}{2}\right) \cdot \pi \cdot s_u = p \cdot \left(R - \frac{d}{4}\right) \cdot \pi \cdot \frac{d}{2} \qquad (2)$$

$$\sigma_{uu} = p \cdot \frac{d}{2 \cdot s_u} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} \qquad (3)$$

$$\sigma_{us} \cdot \left(R + \frac{d}{2} + \frac{s_s}{2}\right) \cdot \pi \cdot s_s = p \cdot \left(R + \frac{d}{4}\right) \cdot \pi \cdot \frac{d}{2} \qquad (4)$$

$$\sigma_{us} = p \cdot \frac{d}{2 \cdot s_s} \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} \qquad (5)$$

gde je:
σ_{uu} – naponi u zidu na unutrašnjoj krivini cevnog kolena
σ_{us} – naponi u zidu na spoljnjoj krivini cevnog kolena
p – proračunski pritisak
R – poluprečnik cevnog kolena
d – unutrašnji prečnik cevnog kolena
s_u – debljina zida cevnog kolena na unutrašnjoj krivini
s_s – debljina zida cevnog kolena na spoljnjoj krivini

Prema hipotezi o složenom naponu tankozidnih omotača i cevi (ljuske) /4/ može se uzeti da je raspodela napona σ po debljini zida ravnomerna $\sigma_r = -p$, odnosno na unutrašnjoj krivini $\sigma_{ru} = -p/2$ i na spoljnjoj krivini $\sigma_{rs} = -p/2$:

na unutrašnjoj krivini

$$\sigma_{vu} = \sigma_{uu} - \sigma_{ru} = p \cdot \frac{d}{2 \cdot s_u} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} + \frac{p}{2} = \frac{K}{S} \qquad (6)$$

a na spoljnjoj krivini

$$\sigma_{vs} = \sigma_{us} - \sigma_{rs} = p \cdot \frac{d}{2 \cdot s_s} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R + d + s_s} + \frac{p}{2} = \frac{K}{S} \qquad (7)$$

gde je:
K [MPa] – proračunska čvrstoća materijala (napon tečenja)
S – stepen sigurnosti.

Za $\sigma_v = K/S$, dobija se izraz za najmanju debljinu zida

$$s_u = \frac{d \cdot p}{2 \cdot \left(\frac{K}{S}\right) - p} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} = s_o \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} \qquad (8)$$

odnosno

$$s_s = \frac{d \cdot p}{2 \cdot \left(\frac{K}{S}\right) - p} \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} = s_o \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} \qquad (9)$$

gde je najmanja debljina zida prave cevi:

$$s_o = \frac{d \cdot p}{2 \cdot \left(\frac{K}{S}\right) - p} \qquad (10)$$

Za geometrijske karakteristike cevnih lukova, uslove eksploatacije i čelik Č.1214, minimalne debljine zida su s_s = 2,4 mm (za poluprečnik luka R = 200 mm) i s_s = 2,3 mm (za poluprečnik luka R = 90 mm).

Ultrazvučna provera debljine zida cevnih lukova

Najosetljiviji delovi cevnog sistema su lukovi čija je otpornost manja od otpornosti pravih delova, zbog izraženih zateznih i pritisnih zona. Oštećenja se najviše koncentrišu u zoni zatezanja lukova (spoljnji luk cevi) i u neutralnoj zoni, zbog smanjene debljine zida. Ubrzanom oštećenju doprinose korozija, erozija i zamor. Zato je ultrazvučnim meračem proverena debljina zida na tri luka i utvrđena njihova promena u odnosu na pravi deo. Za luk od 90° sa

$$\sigma_{us} = p \cdot \frac{d}{2 \cdot s_s} \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} \qquad (5)$$

where:
σ_{uu} – stresses in inner wall of tube arc curvature
σ_{us} – stresses in outer wall of tube arc curvature
p – design pressure (for calculation)
R – tube arc radius
d – tube arc inner diameter
s_u – tube arc wall thickness on inner curvature
s_s – tube arc wall thickness on outer curvature

According to hypothesis of complex stress in thin-walled envelopes and tubes (shells) /4/, it is assumed that distribution of stress σ across the wall is uniform $\sigma_r = -p$, on inner curvature $\sigma_{ru} = -p/2$ and on outer curvature $\sigma_{rs} = -p/2$:

on inner curvature

$$\sigma_{vu} = \sigma_{uu} - \sigma_{ru} = p \cdot \frac{d}{2 \cdot s_u} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} + \frac{p}{2} = \frac{K}{S} \qquad (6)$$

on outer curvature

$$\sigma_{vs} = \sigma_{us} - \sigma_{rs} = p \cdot \frac{d}{2 \cdot s_s} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R + d + s_s} + \frac{p}{2} = \frac{K}{S} \qquad (7)$$

where:
K [MPa] – design material strength (yield strength)
S – safety factor.

For $\sigma_v = K/S$, relation for minimal wall thickness is:

$$s_u = \frac{d \cdot p}{2 \cdot \left(\frac{K}{S}\right) - p} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} = s_o \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} \qquad (8)$$

and

$$s_s = \frac{d \cdot p}{2 \cdot \left(\frac{K}{S}\right) - p} \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} = s_o \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} \qquad (9)$$

where the minimal wall thickness of straight tube is:

$$s_o = \frac{d \cdot p}{2 \cdot \left(\frac{K}{S}\right) - p} \qquad (10)$$

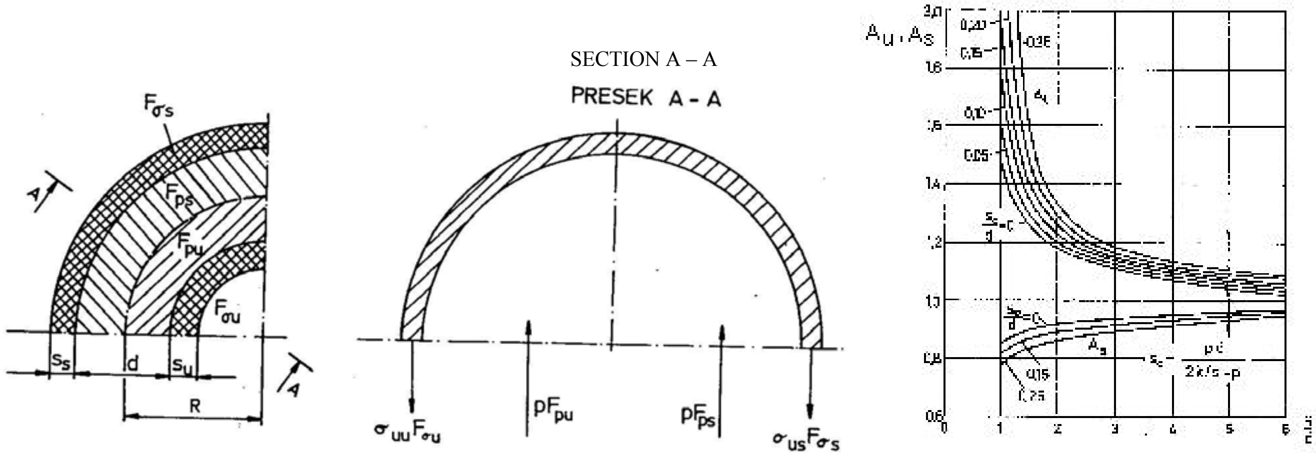
For geometry characteristics of tube arcs, service condition and steel Č.1214, the minimal wall thicknesses are s_s = 2.4 mm (for arc radius R = 200 mm) and s_s = 2.3 mm (for arc radius R = 90 mm).

Ultrasound verification of tube arc wall thickness

The most sensitive parts of a tubing system are the arcs whose resistance is smaller than that of straight parts due to pronounced tension and compression zones. Damages are mostly concentrated in the arc tension zone and the neutral zone, due to reduced wall thickness. Corrosion, erosion and fatigue contribute to rapid damaging. Hence, the wall thickness is measuring by an ultrasound device on three arcs and their variations are compared to the straight part.

osnim rastojanjem 200 mm merna mesta su data na sl. 9a. Merna mesta na spoljnjem luku su na rastojanju 30 mm, a na unutrašnjem 25 mm.

Measuring points for a 90° arc and 200 mm axial distance are given in Fig. 9a. The outer arc measuring point distance is 30 mm, and 25 mm on inner arc.

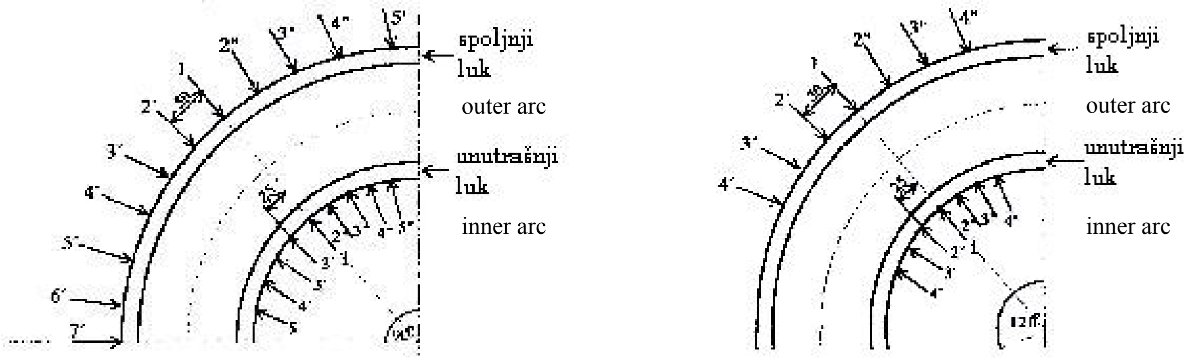


a) b) c)

a) Površine preseka cevnog luka i područja izloženog pritisku b) Ravnoteža sila c) Korekcijski faktori

a) Cross section areas of tube arc and zone under pressure b) Force equilibrium c) Correction factors

Slika 8. Određivanje debljine zida cevnog luka pod dejstvom unutrašnjeg pritiska
Figure 8. Determining of tube arc wall thickness under the effect of inner pressure



a) ∅57/90°–200 mm b) ∅57/120°–90 mm

Slika 9. Merna mesta na cevnim lukovima
Figure 9. Measuring points on tube arcs.

Najmanja izmerena debljina zida spoljnjeg cevnog luka je 3,7 mm, što je za 7,5% manje od nominalne debljine, a najveće zadebljanje na unutrašnjem cevnom luku je 4,7 mm i to u zonama označenim sa 2” i 3’, sl. 9a, što je 17,5% veće od osnovne debljine zida cevi.

Merna mesta na cevnom luku ∅57/120°–90 mm prikazana su na sl. 9b. Najmanja debljina zida spoljnjeg cevnog luka je 3,7 mm što je za 7,5% manje od osnovne debljine, a najveće zadebljanje na unutrašnjem cevnom luku je 5,0 mm i to u osi simetrije luka, što je za 25% veće od osnovne debljine zida cevi.

Treći cevni luk je isti kao i drugi po dimenzijama i obliku. Merna mesta su kao na sl. 9b. Najmanja debljina spoljnjeg cevnog luka je u zoni maksimalnog zatezanja i iznosi 3,5 mm što je 12,5% manje od osnovne debljine, a najveća debljina je 4,7 mm što je 17,5% veće od osnovne debljine.

S obzirom da je dozvoljeno stanjenje zida cevnog luka prema standardu JUS M.E2.012 do 15%, a najmanje izmerena debljina zida je u tim granicama, može se zaključiti da debljine zida cevnih lukova zadovoljavaju.

The minimal measured wall thickness of the outer tube arc is 3.7 mm, which is 7.5% less than nominal thickness, and the largest thickening on the inner tube arc is 4.7 mm, within zones depicted as 2” and 3', Fig. 9a, which is 17.5% larger than the basic wall thickness.

Measuring points on a tube arc ∅57/120°–90 mm are shown in Fig. 9b. The minimal wall thickness of the outer tube arc is 3.7 mm, which is 7.5% less than the basic thickness and the largest thickening on the inner tube arc is 5.0 mm along the arc's symmetry axis which is 25% larger than the basic wall thickness.

The third tube arc is similar in shape and dimensions as the second arc. Measuring points are shown in Fig. 9b. The minimal outer thickness 3.5 mm is in zone of maximal tension and 12.5% lesser than–, while maximal thickness is 4.7 mm and 17.5% larger than basic thickness.

Since the reduction in wall thickness of 15% is allowed by JUS M.E2.012 standard, and minimal measured wall thickness is within this limit, one may conclude that tube arc wall thicknesses are satisfactory.

ANALIZA UTICAJA KOROZIONOG OŠTEĆENJA NA ČVRSTOĆU I PREOSTALI VEK CEVI

Postupak utvrđivanja čvrstoće i preostalog veka cevi sa eroziono - korozivnim (EK) oštećenjima zasniva se na sledećim principima:
– čvrstoća cevi sa EK oštećenjima u toku eksploatacijskog perioda do donošenja odluke o zameni ili popravci ne sme da bude manja od projektne čvrstoće;
– čvrstoću cevi sa EK oštećenjima ne treba određivati samo u trenutku redovnog pregleda, već je treba proceniti i za period do narednog redovnog pregleda;
– predistoriju razvoja svakog pojedinačnog oštećenja izazvanog EK dejstvom treba uzeti u obzir prilikom proračuna, tj. vreme korišćenja cevnog sistema sa EK oštećenjima i kinetiku rasta oštećenja;
– uprošćenja se mogu koristiti samo ako daju konzervativne rezultate.

Oslabljena oblast usled oštećenja utvrđuje se na osnovu rezultata pojedinačnih ispitivanja stanja cevnih elemenata. U cilju pojednostavljenja postupka, oblast oštećenja, sl. 10, se određuje kao površina pravougaonika:

$$A_i = L_i\,(s - s_i) \quad (11)$$

gde je L_i ukupna dužina korozivnog oštećenja u pravcu cevi, s je nominalna debljina zida cevi, s_{pr} je projektna debljina cevi i s_i je minimalna debljina zida cevi.

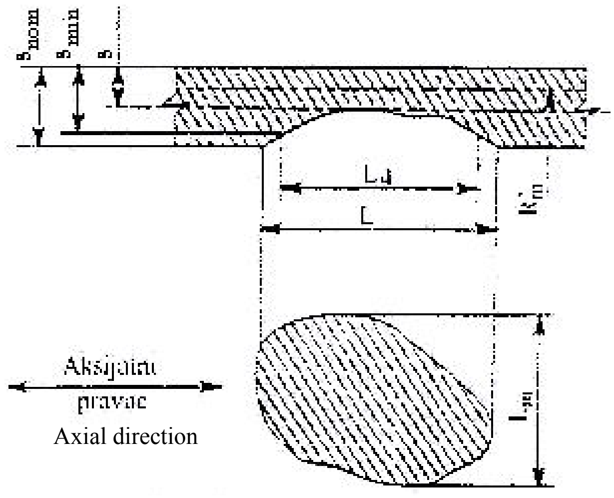
ANALYSIS OF CORROSION DEFECTS INFLUENCING TUBE STRENGTH AND REMAINING LIFETIME

The procedure of determining strength and remaining life of tubes with erosion - corrosion (EC) damages is based on the following principles:
– tube strength with EC damages during service period up to the time when decision about replacement or repair is made must not be lower than the designed strength;
– tube strength with EC damages should not be determined only during regular inspection, but it should also be assessed up to the period of next regular inspection;
– the history of every single damage caused by EC effect should be taken into account during calculation, i.e. the service time of the tube system with EC damages and defect growth kinetics;
– simplifications may be used only if they give conservative results.

The area weakened due to corrosion is determined from results of particular tests of the state of tube elements. In order to make the procedure simpler, the defect area, Fig. 10, is calculated as the area of a rectangle:

$$A_i = L_i\,(s - s_i) \quad (11)$$

where L_i is the corrosion damage length in the tube direction, s is nominal tube wall thickness, s_{pr} is the designed wall thickness, and s_i is the minimal wall thickness.



Slika 10. Skica segmenta cevi sa eroziono-korozivnim oštećenjem
Figure 10. Sketch of a tube segment with erosion-corrosion damage.

Granična vrednost dopuštene dužine korozionog oštećenja, za koju se ne smanjuje nosivost, određuje se kao /5/:

$$L_{dop} = 8 \cdot \sqrt{R \cdot s_{\min}} \quad (12)$$

gde je R poluprečnik cevi.

Kod razmatranih cevi dopuštena dužina EK oštećenja cevi za poluprečnik cevi R = 28,5 mm i minimalnu izmerenu debljinu zida ($s_{\min}$ = 2,6 mm) iznosi L_{dop} = 97,4 mm. Kod ispitanih cevi nije uočeno neprekidno EK oštećenje na dužini većoj od dopuštene.

Vreme sigurne eksploatacije T, ako je zadovoljen uslov iz jedn. (12), procenjuje se korišćenjem sledeće zavisnosti:

$$T = \frac{s - s_{pr}}{s - s_i} \cdot \frac{T_i}{K};\; K = (i_u + 1{,}4)/(i_u + 1) \quad (13)$$

The allowed corrosion damage length, for which there is no decrease in loading capacity, is determined as /5/:

$$L_{dop} = 8 \cdot \sqrt{R \cdot s_{\min}} \quad (12)$$

where R represents the tube radius.

The allowed EC damage length of the considered tubes, for tube radius R = 28.5 mm and minimal measured wall thickness ($s_{\min}$ = 2.6 mm) is L_{dop} = 97.4 mm. No continuous corrosion damage of a length greater than the allowed has been observed in the examined tubes.

If the condition in Eq. (12) is fulfilled, safe service time T can be evaluated using the following relation:

$$T = \frac{s - s_{pr}}{s - s_i} \cdot \frac{T_i}{K};\; K = (i_u + 1.4)/(i_u + 1) \quad (13)$$

gde je T_i period eksploatacije segmenta cevi pre poslednjeg pregleda, K je korekcioni faktor greške, i_u je ukupan broj pregleda korozionog oštećenja u toku eksploatacije cevi.

Interval pouzdane eksploatacije ΔT cevnog sistema sa EK oštećenjima određuje se iz izraza:

$$\Delta T = T - T_i \quad (14)$$

Navedeni postupak ima praktičan značaj, jer omogućava da se utvrdi period sigurnog rada cevnog sistema i proceni vreme do narednog pregleda na bazi ispitivanja bez razaranja. Međutim, za njegovu primenu neophodno je postojanje aktivne baze podataka. Za razmatrano kotlovsko postrojenje VKL-50 korisnik nije raspolagao bazom podataka, pa se navedeni postupak nije mogao primeniti u potpunosti, odnosno, nije moglo da se predvidi vreme razvoja EK oštećenja T prema jedn. (13), već samo dopuštena dužina EK oštećenja R. Postupak je prikazan, pre svega, kao jedan od mogućih pristupa u oceni integriteta cevnog sistema kotlovskog postrojenja.

PROCENA INTEGRITETA ZAVARENIH CEVI

Za procenu integriteta zavarenih spojeva na cevima vrelovodnog kotla VKL-50, s obzirom da ne postoji baza podataka, primenjen je probabilistički model tipa "čvrstoća-naprezanje" /6/, koji se zasniva na predstavljanju karaktera promene čvrstoće zavarenih spojeva i promeni naprezanja koja deluju u vidu slučajnih veličina ili slučajnih funkcija vremena. Pri tome se pod *naprezanjem* podrazumevaju svi spoljnji uticajni faktori, a pod *čvrstoćom* zbir unutrašnjih osobina zavarenog spoja koje kvantitativno karakterišu njegov stepen zaštićenosti od svakog spoljnjeg faktora. Otkaz predstavlja slučajno stanje koje odgovara definisanom stepenu prekoračenja naprezanja u odnosu na čvrstoću.

Kao osnova upotrebljen je uslov $R_{ZS} > \sigma$, tj. $R_{ZS} - \sigma > 0$, za pouzdanost zavarenog spoja. Nova slučajna promenljiva U

$$U = R_{ZS} - \sigma \quad (15)$$

omogućava određivanje pouzdanosti izrazom:

$$R = \int_0^{\infty} f(U)du \quad (16)$$

Površina koja odgovara "preklopu" F raspodela $f(\sigma)$ i $f(R_{ZS})$, sl. 11, predstavlja meru verovatnoće otkaza. Pouzdanost je veća ukoliko je ova površina manja.

Radi korišćenja tabličnih vrednosti uvodi se smena:

$$X = \frac{U - \bar{U}}{S_U} \quad (17)$$

Granična vrednost promenljive X uz $U = 0$, će biti:

$$X = m = \frac{0 - \bar{U}}{S_U} = -\frac{\bar{U}}{S_U} = \frac{\bar{R}_{ZS} - \bar{\sigma}}{\sqrt{S_{R_{ZS}}^2 + S_\sigma^2 - 2\cdot\rho\cdot S_{R_{ZS}}^2 \cdot S_\sigma}} \quad (18)$$

gde su srednje vrednosti veličina U, R_{ZS}, σ, označene sa crtom iznad, a S_{Rzs} i S_σ su varijance promenljivih.

where T_i is the tube segment service period prior to its last inspection, K is the error correction factor; i_u is the total number of corrosion damage inspections of tube in service.

The time interval of reliable service ΔT of tube system with corrosion damage can be determined from:

$$\Delta T = T - T_i \quad (14)$$

This procedure has practical significance, for it allows to determine the safe service period of tube systems and to evaluate the amount of time remaining until the next inspection based on non-destructive testing. However, its application requires an active database. The owner of the considered boiler system VKL-50 did not have an available database, and the presented procedure could not be applied, i.e. it was not possible to predict the time for EC damage development according to Eq. (13), but only the allowed EK damage length R. The procedure is presented, above all, as one possible approach in the integrity assessment of the boiler tubing system.

INTEGRITY ASSESSMENT OF WELDED TUBES

In order to assess the integrity of welded joints on hot water boiler VKL-50 tubes, having in mind that no database is available, the probabilistic "strength-stress" model /6/ is applied, and is based on presenting the character of strength variations in welded joints and on stress variations which act as random values or random time functions. Here, by *stress* - all external influencing factors are included, and *strength* represents the sum of the welded joint's internal properties, that characterize its level of protection against every external factor in a quantitative way. Failure represents a random state that corresponds to a defined level of overstressing compared to strength.

The condition $R_{ZS} > \sigma$, i.e. $R_{ZS} - \sigma > 0$, is used as welded joint reliability. The new random variable U

$$U = R_{ZS} - \sigma \quad (15)$$

enables reliability determination from the expression:

$$R = \int_0^{\infty} f(U)du \quad (16)$$

The area corresponding to "overlapping" F of distributions $f(\sigma)$ and $f(R_{ZS})$, Fig. 11, represents a measure of failure probability. Reliability is higher if the area is smaller.

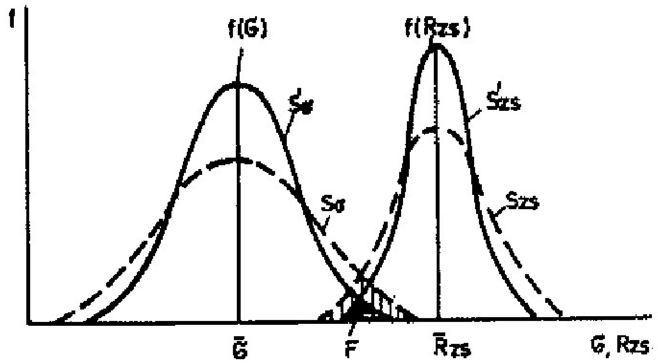
A substitution is introduced for the use of tabular values:

$$X = \frac{U - \bar{U}}{S_U} \quad (17)$$

Limit values of variable X with $U = 0$ will become:

$$X = m = \frac{0 - \bar{U}}{S_U} = -\frac{\bar{U}}{S_U} = \frac{\bar{R}_{ZS} - \bar{\sigma}}{\sqrt{S_{R_{ZS}}^2 + S_\sigma^2 - 2\cdot\rho\cdot S_{R_{ZS}}^2 \cdot S_\sigma}} \quad (18)$$

where the average values of U, R_{ZS}, σ, are designated by the macron symbol, and S_{Rzs} and S_σ are variances of variables.



Slika 11. Uticaj promene disperzije čvrstoće i naprezanja na pouzdanost
Figure 11. The effect of strength and stress dispersion variation on reliability.

Ako su R_{ZS} i σ međusobno nezavisne promenljive, što je obično slučaj, koeficijent korelacije je $r = 0$, pa se izraz pojednostavljuje:

$$m = \frac{\bar{R}_{ZS} - \bar{\sigma}}{\sqrt{S_{Rzs}^2 + S_\sigma^2}} \quad (19)$$

Ovde je m argument tablične vrednosti ili indeks pouzdanosti. Tada se pouzdanost izračunava kao:

$$R = \int_m^\infty f(X)dX = \frac{1}{\sqrt{2\cdot\pi}} \cdot \int_m^\infty e^{-X^2/2} dX = \Phi(m) \quad (20)$$

gde je $\Phi(m)$ funkcija Laplasa.

Iz izraza (19) i (20) jasno se uočavaju bitni uticaji na pouzdanost:

$$R = R(\bar{R}_{zs}, S_{Rzs}, \bar{\sigma}, S_\sigma) \quad (21)$$

Srednje vrednosti i varijabilnosti osobina zavarenog spoja i naprezanja određuju pouzdanost, i njihovim upravljanjem može da se upravlja pouzdanošću. Pouzdanost može da se poveća povećanjem čvrstoće zavarenog spoja i smanjenjem naprezanja i njihovih disperzija, šrafirana površina na sl. 11.

Kada postoji više mogućih načina otkaza i ako svaki počinje i širi se nezavisno jedan od drugog, mora da bude zadovoljen sistem zavisnosti:

$$R_{ZS1} > \sigma_1; R_{ZS2} > \sigma_2; ......R_{ZSn} > \sigma_n \quad (22)$$

odnosno, pouzdanost je jednaka:

$$R = \prod_{i=1}^n R_i \quad (23)$$

Kako je zavarena konstrukcija složeni sistem od više različito opterećenih zavarenih spojeva, pouzdanost treba tražiti za najopterećeniji ili za skup zavarenih spojeva /7/.

Pri proceni pouzdanosti zavarenih spojeva na ekranskim cevima i na cevima zagrejača vode-ekonomajzera razmotrene su tri promenljive: unutrašnji prečnik D_u = 49,8 ± 0,15 mm za neoštećene cevi i D_u = 49,8 + 2,0 mm za najoštećenije cevi, pritisak radnog fluida u cevi p = 1,3 ± 0,1 MPa i debljina zida cevi u zoni zavarenih spojeva, s = 3,6 ± 0,1 mm za neoštećene cevi i s = 3,6 – 1,0 mm za najoštećenije cevi.

Srednje naprezanje u zidu cevi se izračunava izrazom:

If R_{ZS} and σ are mutually independent variables, which is generally the case, the correlation coefficient is $r = 0$, and the expression is simplified:

$$m = \frac{\bar{R}_{ZS} - \bar{\sigma}}{\sqrt{S_{Rzs}^2 + S_\sigma^2}} \quad (19)$$

Here, m is an argument of tabular values or a reliability index. Then the reliability is calculated as:

$$R = \int_m^\infty f(X)dX = \frac{1}{\sqrt{2\cdot\pi}} \cdot \int_m^\infty e^{-X^2/2} dX = \Phi(m) \quad (20)$$

where $\Phi(m)$ is the Laplace function.

From expressions (19) and (20) substantial effects on reliability are clearly recognized:

$$R = R(\bar{R}_{zs}, S_{Rzs}, \bar{\sigma}, S_\sigma) \quad (21)$$

Average values and variability of welded joint properties and stresses determine reliability, and by controlling them it is possible to control the reliability. The reliability can be increased by increasing welded joint strength and by decreasing stress and their dispersions, shaded area in Fig. 11.

If several possibility modes for failure exist and if they begin and develop independently, a relation system must be satisfied:

$$R_{ZS1} > \sigma_1; R_{ZS2} > \sigma_2; ......R_{ZSn} > \sigma_n \quad (22)$$

that means the reliability is equal to:

$$R = \prod_{i=1}^n R_i \quad (23)$$

The welded structure is a complex system of several differently loaded welded joints and the reliability should be determined for the highly stressed welded joint, or for a set of welded joints /7/.

The reliability assessment of welded joints on screen tubes and water heater–economizer tubes had considered three variables: inner diameter D_u = 49.8 ± 0.15 mm for undamaged tubes and D_u = 49.8 + 2.0 mm for the most damaged tubes, fluid pressure p = 1.3 ± 0.1 MPa, and tube wall thickness s = 3.6 ± 0.1 mm for undamaged tubes and s = 3.6 – 1.0 mm for the most damaged tubes.

Average stress in tube wall is given by the expression:

$$\overline{\sigma} = \frac{\overline{D}_u \cdot \overline{p}}{2 \cdot \overline{s}} \tag{24}$$

Varijanca naprezanja zavisi od varijance promenljivih:

$$\sigma = f(\overline{D}, \overline{p}, s) = f(x_1, x_2, x_3) \tag{25}$$

Uopšteno se varijanca može izračunati kao /7/:

$$S_y^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2_{x_i = x} -S_{x_i}^2 + 2 \cdot \sum_{i<j}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2_{x_i = x_i} - \\ -\left(\frac{\partial f}{\partial x_j}\right)^2_{x_j = x_j} - K_{ij} \tag{26}$$

Kada nema korelacije, $K_{ij} = 0$, izraz se pojednostavljuje:

$$S_y^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2_{x_i = \overline{x}} - S_{x_i}^2 \tag{27}$$

Za argument tablične vrednosti, tj. za indeks pouzdanosti iz tabela /6,7/, m = 3,5, dobija se za neoštećene cevi (debljina zida s = 3,6 mm) vrlo visoka pouzdanost zavarenih spojeva R = 0,99, a za oštećene cevi (s = 2,6 mm) m = 0,96, pouzdanost zavarenih spojeva R = 0,66.

Na osnovu analiza i pokazatelja o ugroženosti zavarenih spojeva cevnog sistema vrelovodnih kotlova za daljinsko grejanje, utvrđena pouzdanost za jedan od kritičnih zavarenih spojeva može se smatrati prihvatljivom za period jedne grejne sezone, nakon čega treba ponovo izvršiti propisana ispitivanja.

ZAKLJUČAK

1. Dug radni vek, produženje operativnog ciklusa, sigurnost i pouzdanost u radu su ciljevi, kojima su namenjena istraživanja postupka za određivanje stanja cevnog sistema vrelovodnog kotla. U tu svrhu su izvršena ispitivanja hemijskog sastava materijala cevi, ispitivanja mehaničkih osobina i strukture zavarenih spojeva, provera geometrije cevnih lukova i kontrola (10%) debljine zida cevi i proračun čvrstoće cevi i cevnih lukova.
2. Postojeće procedure primenjene na cevnim segmentima u oblasti termoenergetike, oštećene eroziono-koroziono, ne pružaju zahtevani nivo pouzdanosti u eksploataciji i ne omogućuju korišćenje ocenjenog preostalog veka ukoliko ne postoje odgovarajuće baze podataka.
3. Probabilistička analiza pouzdanosti kritičnih zavarenih spojeva omogućava da se proceni kojom se verovatnoćom inženjerska procena približava stvarnom stanju. Rezultati probabilističke ocene potvrđuju važnost:
   - određivanja tačnih ulaznih podataka;
   - primene analitičkih modela koji minimalno odstupaju od realnog stanja;
   - određivanja pouzdanosti kritičnih zavarenih spojeva na osnovu realne analize.
4. Uvođenje informacionog sistema i formiranje odgovarajućih baza podataka od izuzetnog je značaja za preventivno održavanje i ocenu kvaliteta i pouzdanosti cevnih sistema, kao i kotlovskih postrojenja.
5. Metodološki pristup za analizu stanja cevnog sistema kotlova, prikazan na primeru vrelovodnog kotla VKL-50, može biti upotrebljen za izradu nove ili za modernizaciju

$$\overline{\sigma} = \frac{\overline{D}_u \cdot \overline{p}}{2 \cdot \overline{s}} \tag{24}$$

Stress variance depends on variable variances:

$$\sigma = f(\overline{D}, \overline{p}, s) = f(x_1, x_2, x_3) \tag{25}$$

In general, the variance can be calculated as /7/:

$$S_y^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2_{x_i = x} -S_{x_i}^2 + 2 \cdot \sum_{i<j}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2_{x_i = x_i} - \\ -\left(\frac{\partial f}{\partial x_j}\right)^2_{x_j = x_j} - K_{ij} \tag{26}$$

If there is no correlation, $K_{ij} = 0$, the relation is simplified:

$$S_y^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2_{x_i = \overline{x}} - S_{x_i}^2 \tag{27}$$

For argument tabular values, i.e. reliability index from tables, /6,7/, m = 3.5, very high welded joint reliability is obtained R = 0.99 for undamaged tubes (wall thickness s = 3.6 mm), and for damaged tubes (s = 2.6 mm) m = 0.96, welded joint reliability is R = 0.66.

Based on analysis and on indications of poor integrity of welded joints in the hot-water boiler tubing system for remote heating, the reliability established for one critical welded joint may be considered as acceptable for the period of one heating season, after which it will be necessary to repeat the specified inspection.

CONCLUSION

1. Long service life, operating cycle extension, service safety and reliability, are goals that require research of the procedure for determining the state of a hot-water boiler tubing system. Thus, the tube material chemical composition, mechanical properties and welded joint structural tests are performed, which also include tube arc geometry assessment and tube wall thickness measurements (10%) and strength calculation of tubes and tube arcs.
2. Existing procedures applied to tubing segments in the thermal energy domain, damaged by erosion-corrosion, do not offer the required reliability level in service and do not allow the use of assessed remnant life if corresponding databases are not available.
3. The probabilistic analysis of critical welded joint reliability enables to assess the probability the engineering assessment reaches the real state. Results of this probabilistic assessment confirm the importance of:
   - determining the correct input data;
   - applying analytical models with minimal deviations compared to the real state;
   - determining critical welded joint reliability based on real analysis.
4. Introducing an information system and forming adequate databases is of great significance for preventive maintenance and assessment of quality and reliability of the tubing system, as well as boiler components.
5. The methodological approach in the analysis of boiler tubing system state, illustrated by hot-water boiler VKL-50, may be used for creating a new or for modernizing

postojeće konstrukcije, za planiranje obima i termina izvođenja remonta, i količine rezervnih delova i materijala.

6. Integritet konstrukcija je nova naučna i inženjerska disciplina koja obuhvata analizu stanja napona i deformacija i dijagnostiku ponašanja i promena, procenu veka i revitalizaciju konstrukcija. To znači da ova disciplina omogućava da se utvrde “slaba” mesta u konstrukciji. Ovaj pristup je posebno važan za konstrukcije koje su izložene radnim uslovima tipičnim za nastanak prslina, kao što su zamor, puzanje i korozija. Tipičan primer takvih konstrukcija su upravo kotlovska postrojenja.

existing structures, and for planning the repair scope and deadlines, and the required amounts of spare parts and materials.

6. Structural integrity is a new scientific and engineering discipline which includes stress and strain state analysis and diagnostics of structural behaviour and changes, life assessment and structural retrofitting. This discipline enables to determined “weak” points in the structure. This approach is of special importance for structures exposed to operating conditions typical for crack occurrence, such as fatigue, creep and corrosion. Typical examples of such structures are boiler systems.

LITERATURA - REFERENCES

1. Aleksić V., Arsić M., Sedmak A., *Primena inženjerskih metoda kod procene integriteta zavarenih konstrukcija*, Savetovanje sa međunarodnim učešćem "IBR 2002", Tara, 2002, str. 45–51.
2. Sedmak A., *Primena mehanike loma na integritet konstrukcija*, Mašinski fakultet, Beograd, 2003.
3. Propisi TRD-301 (Technische Regeln für Dampfkessel): Proračun cevnih lukova, Nemačka.
4. Timošenko S., Vojnovski-Kriger S., *Teorija ploča i ljuski*, Građevinska knjiga, Beograd, 1962.
5. Korhonen. R., O. Hietanen, *Erosion-corrosion at parallel feed water discharge lines in Loviisa WWR 440*, ibid. 1994.
6. Ivanović G., D. Stanivuković, *Pouzdanost tehničkih sistema*, Zbirka rešenih zadataka, Mašinski fakultet, Beograd, 1987.
7. Kocecioglu D., Mechanical reliability and probabilistic design for reliability, The George Washington University, 1978.