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ANALIZA PARAMETARA PRSLINE ZAVARENOG SPOJA TOPLOOTPORNOG ČELIKA
ANALYSIS OF CRACK PARAMETERS OF WELDED JOINT OF HEAT RESISTANT STEEL

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.1:669.14, 621.791.05:669.14
Rad primljen / Paper received: 15.5.2008.

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Ključne reči
- legirani čelik
- zavareni spoj
- žilavost loma
- zamorna prslina
- prag zamora

Keywords
- alloyed steel
- welded joint
- fracture toughness
- fatigue crack
- fatigue threshold

Izvod

Dati su rezultati eksperimentalnih istraživanja izvedenih radi analize otpornosti prema prslinama pri statičkom i pri promenljivom opterećenju legiranog čelika A-387 (SRPS Č.7400) za rad na povišenoj temperaturi i njegovog zavarenog spoja. Ispitivanjem SEN-B, CT i Šarpi epruveta sa početnom prslinom je ocenjen značaj heterogenosti mikrostrukture i mehaničkih svojstava zavarenog spoja za žilavost loma i pojavu i rast zamorne prsline, na sobnoj i radnoj temperaturi.

Abstract

Results of experimental investigation are presented, performed for the analysis of crack resistance under static and under variable loading of alloyed steel A-387 (SRPS Č.7400) for elevated temperature application and its welded joint. Tests on SEN-B, CT and Charpy pre-cracked specimens have evaluated the significance that microstructural heterogeneity and mechanical properties of welded joints have on the fracture toughness and fatigue crack initiation and propagation, at room and working temperatures.

UVOD

Eksploatacijsko ponašanje legiranog čelika A-387 Gr 11 Class 1, namenjenog za izradu posuda pod pritiskom za visoke temperature, zavisi od svojstava njegovog zavarenog spoja, čiji su konstituenti osnovni metal (OM), zona uticaja toplote (ZUT) i metal šava (MŠ). Najčešće, kritična mesta po integritet zavarenog spoja i konstrukcije predstavljaju ZUT i MŠ, jer se u njima mogu obrazovati lokalne krte zone, osetljive na pojavu prslina, /1/.

Kvalifikacija propisane tehnologije zavarivanja ploča debljine 96 mm čelika A-387 je urađena u skladu sa standardom JUS EN 288-3, /2/. Ovaj standard ne propisuje ispitivanja na radnoj temperaturi (540°C), kao ni ispitivanja eksploatacijskih svojstava osnovnog materijala i konstituenata zavarenog spoja na sobnoj i radnoj temperaturi.

Pri određivanju žilavosti loma pri ravnoj deformaciji, K_{Ic}, konstituenata zavarenog spoja heterogene mikrostrukture, treba imati u vidu da je mehanika loma zasnovana na homogenosti materijala, uključujući područje vrha prsline, kako bi ostale u važnosti teorijske pretpostavke i značenja žilavosti loma kao izmerene osobine.

Bitna osobina zavarenog spoja je heterogenost mikrostrukture i mehaničkih osobina. Takođe je važna i neravnomerna raspodela napona, na koju utiču zaostali naponi od zavarivanja i koncentracija napona. Ovi značajni problemi ne isključili eksperimentalno određivanje žilavosti loma pri ravnoj deformaciji, K_{Ic}, zavarenog spoja i njegovih konstituenata, iako predstavljaju teškoće u tumačenju izmerenih vrednosti i dobijenih rezultata, /3–5/.

INTRODUCTION

Service behaviour of alloyed steel A-387 Gr 11 Class 1, aimed for manufacturing pressure vessels for high temperatures, depends on the properties of its welded joint, consisted of parent metal (BM), heat-affected-zone (HAZ) and weld metal (WM), as constituents. More often, critical locations regarding integrity of welded joint and structure correspond to HAZ and WM, since local brittle zones can be formed in them, sensitive to cracking, /1/.

Qualification of specified welding technology of plates, 96 mm thick, of steel A-387, is performed according to standard EN 288-3, /2/. This standard does not require testing at working temperature (540°C), and neither testing of in-service behaviour of parent metal and welded joint constituents at room and working temperatures.

While determining plane strain fracture toughness, K_{Ic}, of welded joint constituents of heterogeneous microstructure, one must bear in mind that fracture mechanics is based on material homogeneity, including region of crack tip, in order to hold the validity of theoretical assumptions and meanings of fracture toughness as measured property.

A substantial property of the welded joint is the heterogeneity of microstructure and mechanical properties. Irregular stress distribution is also important, affected by residual stresses after welding and stress concentration. These important problems do not exclude experimental determination of plane strain fracture toughness, K_{Ic}, of welded joint and its constituents, although they present difficulties in the interpretation of measured values and obtained results, /3–5/.

Radi boljeg razumevanja uticaja pojave i rasta prsline u zavarenim spojevima čelika za rad na povišenim temperaturama, ugrađenih u opremu za rad na visokim pritiscima, treba kvantitativno izraziti parametre koji kontrolišu deformacijsko ponašanje oko vrha prsline i otpornost prema prslinama. Zato je u ovom radu eksperimentalno ispitan uticaj heterogenosti mikrostrukture i mehaničkih osobina na žilavost loma, K_{Ic}, brzinu rasta zamorne prsline, *da/dN,* i na opseg faktora intenziteta napona praga zamora, ΔK_{th}, čelika A-387 i konstituenata njegovog zavarenog spoja na sobnoj temperaturi (20°C) i na radnoj temperaturi (540°C), /6/.

MATERIJAL ZA ISPITIVANJE

Uzorak zavarenog spoja dimenzija 350×500×96 mm od čelika A-387, sa dvostruko „U" metalom šava u sredini, je pripremljen za ova ispitivanja, /6/. Izgled zavarenog uzorka i raspored isecanja epruveta iz konstituenata zavarenog spoja (OM, ZUT i MŠ) su prikazani na sl. 1.

Hemijski sastav i mehaničke osobine čelika A-387 su dati u tabelama 1 i 2.

Primenjena su dva postupka zavarivanja ploča, /6/:
– ručno elektrolučno zavarivanje (SMAW) obloženom elektrodom LINCOLN Sl 19G (AWS: E8018-B2), za korene prolaze;
– elektrolučno zavarivanje pod praškom (SAW), korišćenjem dodatnog materijala žice LINCOLN LNS 150 i praška LINCOLN P230, za prolaze popune.

Hemijski sastav elektrode LINCOLN Sl 19G i žice LINCOLN LNS 150 prema atestnoj dokumentaciji su dati u tabeli 3. Mehaničke osobine prema atestnoj dokumentaciji su date u tabeli 4.

ISPITIVANJE ZATEZNIH OSOBINA

Zatezna ispitivanja epruveta uzetih iz osnovnog metala i iz metala šava, kao i iz sučeono zavarenog spoja, su izvedena na elektromehaničkoj kidalici u kontroli pomeranja, na sobnoj i na radnoj temperaturi.

Epruveta iz MŠ za ispitivanje na sobnoj temperaturi, prikazana na sl. 2a, je izrađena u skladu sa raspoloživim materijalom, a prema standardu EN 895, /7/. Radi lakšeg poređenja rezultata, epruveta iz OM je istih dimenzija (sl. 2a), a izrađena je prema standardu EN 10002-1. Epruveta zavarenog spoja (sl. 2b) je izrađena prema EN 895.

Za ispitivanje na temperaturi od 540°C korišćen je isti oblik epruveta (sl. 3) za sve konstituente zavarenog spoja, prema standardu ASTM E1475-00, /8/, sa dimenzijama usklađenim raspoloživoj opremi.

Tipične krive napon–deformacija za epruvete iz OM, MŠ i iz zavarenog spoja, dobijene ispitivanjem zatezanjem na sobnoj i radnoj temperaturi, date su na sl. 4.

Rezultati ispitivanja na sobnoj temperaturi i na radnoj temperaturi su dati u tabeli 5 za OM, u tabeli 6 za MŠ, i u tabeli 7 za epruvete zavarenog spoja.

Uticaj temperature ispitivanja na zatezne osobine je jasan. Na većoj temperaturi, vrednosti napona tečenja i zatezne čvrstoće su smanjene, a vrednosti izduženja povećane, kao što se može videti na sl. 4 i iz tabelarnih vrednosti u tabelama 5–7, /7/. Međutim, ovaj zaključak je vrlo uprošćen i u osnovi prividan, kao što će biti diskutovano.

For better understanding of crack occurrence and its growth effect in welded joints of steel for elevated temperatures, applied in equipment for high pressure, it is necessary to quantify the parameters controlling the strain behaviour in crack tip vicinity and crack resistance. Therefore, in this paper the effect of heterogeneity of microstructure and mechanical properties on fracture toughness, K_{Ic}, fatigue crack growth rate, *da/dN*, and fatigue threshold stress intensity factor range, ΔK_{th}, of A-387 steel and its welded joint constituents is experimentally investigated at room temperature (20°C) and at working temperature (540°C), /6/.

MATERIAL FOR TESTING

The steel A-387 welded joint sample 350×500×96 mm, with double "U" weld metal in the middle, had been prepared for this investigation, /6/. The welded sample and scheme for cutting out specimens from welded joint constituents (OM, HAZ and WM) are illustrated in Fig. 1.

The chemical composition and mechanical properties of A-387 1 steel are given in Tables 1 and 2.

Two welding procedures were applied, /6/:
– shielded metal manual arc welding (SMAW) with coated electrode LINCOLN Sl 19G (AWS: E8018-B2 for root weld passes;
– submerged arc welding (SAW) with consumable wire LINCOLN LNS 150 and flux LINCOLN P230, for filler passes.

Chemical composition of electrode LINCOLN Sl 19G and wire LINCOLN LNS 150 according to certificates is given in Table 3. Mechanical properties according to certificates are given in Table 4.

TESTING OF TENSILE PROPERTIES

Tensile tests of specimens taken from parent and weld metal, as well as from butt welded joint, had been performed on electrical mechanical testing machine with displacement control, at room and working temperatures.

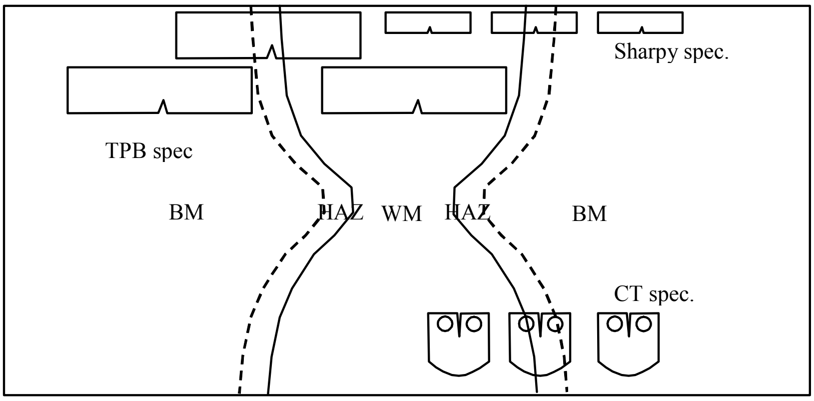
The WM specimen for room temperature tests, presented in Fig. 2a, is made according to available material, according to standard EN 895, /7/. The BM specimen is of the same dimensions for easier comparison of results (Fig. 2a), and made according to standard EN 10002-1. The welded joint specimen (Fig. 2b) is made according to EN 985.

For testing at 540°C the same specimen design is used (Fig. 3) for all welded joint constituents, according to standard ASTM E1475-00, /8/, with dimensions in compliance with the available equipment.

Typical stress–strain curves for BM, WM and welded joint specimens, obtained by tensile tests at room and working temperature, are given in Fig. 4.

Testing results at room and working temperatures are given in Table 5 for BM, in Table 6 for WM, and in Table 7 for welded joint specimens.

The effect of testing temperature on tensile properties is clear. At higher temperature the values of yield stress and tensile strength are reduced, and elongation values are increased, as can be seen in Fig. 4, and from values in Tables 5–7, /7/. However, this conclusion is very simplified and basically apparent, as it will be discussed.



Slika 1. Shema dvostrukog „U“ metala šava i mesta vađenja epruveta, /6/
Figure 1. Scheme of double "U" weld metal test sample and specimen sampling, /6/.

Tabela 1. Hemijski sastav ispitivanog čelika A-387
Table 1. Chemical composition of tested steel A-387.

Hemijski sastav, mas. %						
Chemical composition, mass %						
C	Si	Mn	P	S	Cr	Mo
0.15	0.29	0.54	0.022	0.011	0.93	0.47

Tabela 2. Zahtevane mehaničke osobine ispitivanog čelika A-387
Table 2. Required mechanical properties of tested steel A-387.

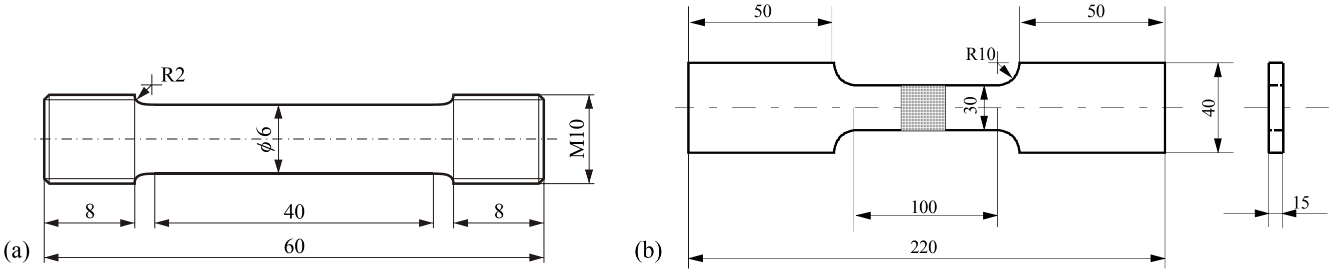
Napon tečenja,min.	Zatezna čvrstoća	Izduženje	Energija udara
Yield stress, min.	Tensile strength	Elongation	Impact energy
$R_{p0,2}$, MPa	R_m, MPa	A, %	KV, J
315	490–620	25	> 85

Tabela 3. Hemijski sastav dodatnog materijala, /6/
Table 3. Chemical composition of filler metal, /6/.

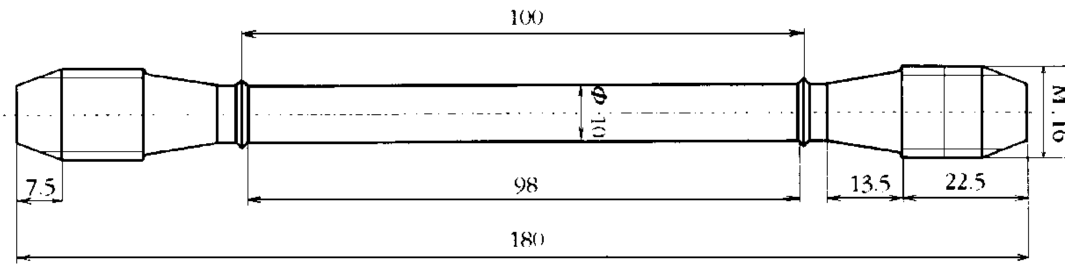
Dodatni materijal (Filler material)	Hemijski sastav, mas. % (Chemical composition, mass %)						
	C	Si	Mn	P	S	Cr	Mo
LINCOLN Sl 19G	0.08	0.045	0.35	0.025	0.025	1.10	0.50
LINCOLN LNS 150	0.11	0.18	0.37	0.020	0.020	1.04	0.47

Tabela 4. Mehaničke osobine dodatnog materijala, /6/
Table 4. Mechanical properties of filler metal, /6/

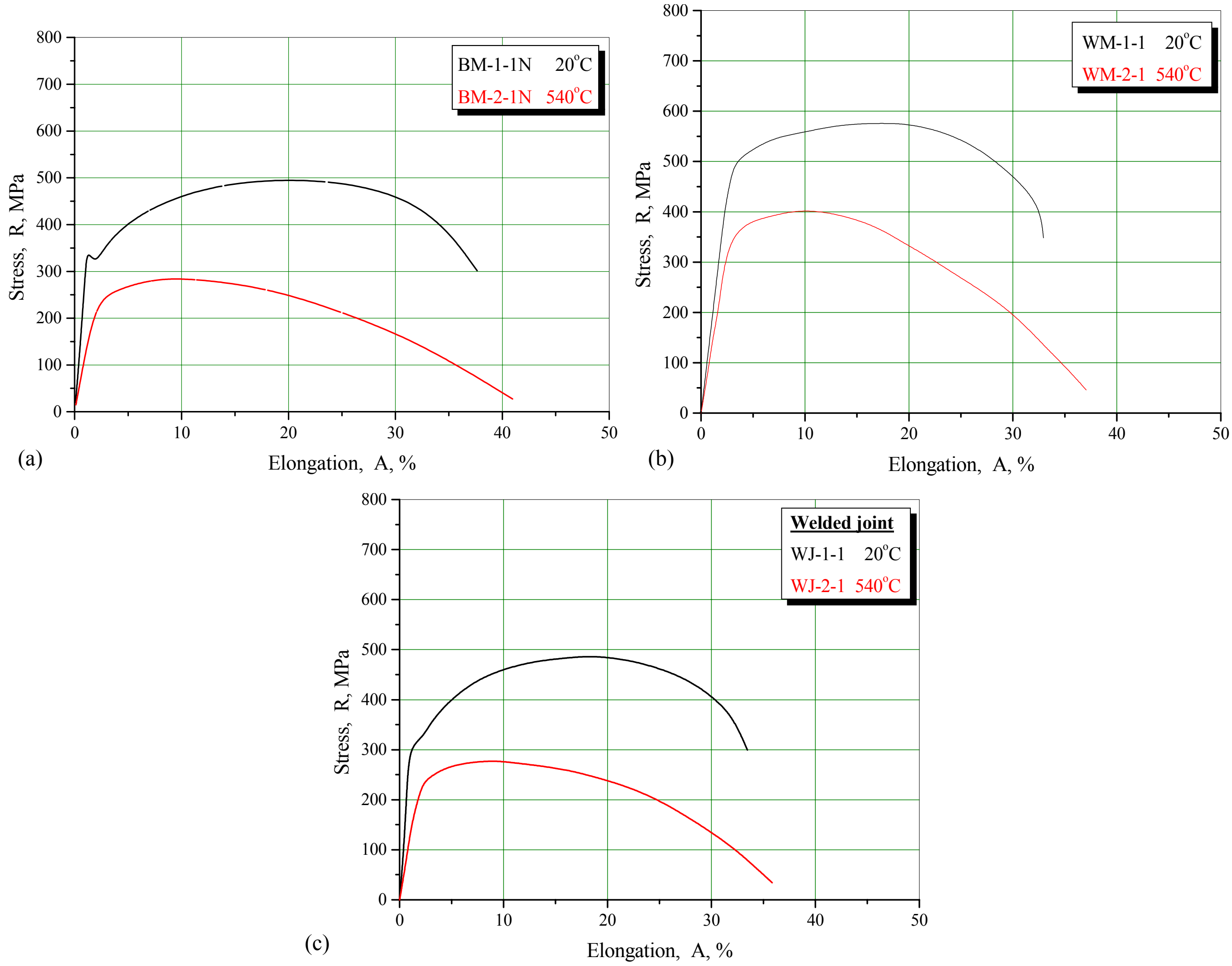
Dodatni materijal (Filler material)	Napon tečenja	Zatezna čvrstoća	Izduženje	Energija udara
	Yield stress	Tensile strength	Elongation	Impact energy
	$R_{p0,2}$, MPa	R_m, MPa	A, %	KV, J
LINCOLN Sl 19G	505	640	23	> 95
LINCOLN LNS 150	490	610	26	> 100



Slika 2. Epruvete za ispitivanja zatezanjem: a) OM i MŠ; b) sučeono zavareni spoj
Figure 2. Specimen for tensile testing: a) BM and WM; b) butt welded joint.



Slika 3. Epruvete za zatezna ispitivanja na povišenoj temperaturi, /8/
Figure 3. Specimen for tensile testing at elevated temperature, /8/.



Slika 4. Dijagram napon–izduženje: a) OM, b) MŠ, c) zavareni spoj
Figure 4. Diagrams stress–elongation: a) BM, b) WM, c) welded joint.

Tabela 5. Rezultati zateznih ispitivanja epruveta OM
Table 5. Results of tensile testing of BM specimens.

Epruvete	Temperatura ispitivanja	Napon tečenja	Zatezna čvrstoća	Izduženje*
Specimen	Testing temperature	Yield stress	Tensile strength	Elongation*
	°C	$R_{p0,2}$, MPa	R_m, MPa	A, %
OM-1-1N	20	330	495	37.6
OM-1-2N		318	479	36.1
OM-1-3N		324	488	38.7
OM-2-1N	540	219	284	40.1
OM-2-2N		212	279	39.6
OM-2-3N		226	303	39.9

* izmereno na L_0 = 100 mm, kao uporedna veličina (ne kao svojstvo materijala)
* measured on L_0 = 100 mm, as a comparative value (is not a material property)

Tabela 6. Rezultati zateznih ispitivanja epruveta MŠ
Table 6. Results of tensile testing of WM specimens.

Epruvete	Temperatura ispitivanja	Napon tečenja	Zatezna čvrstoća	Izduženje*
Specimen	Testing temperature	Yield stress	Tensile strength	Elongation*
	°C	$R_{p0,2}$, MPa	R_m, MPa	A, %
OM-1-1N	20	491	576	32.7
OM-1-2N		504	592	31.6
OM-1-3N		496	585	33.9
OM-2-1N	540	338	401	36.9
OM-2-2N		331	396	36.2
OM-2-3N		345	409	37.8

Tabela 7. Rezultati zateznih ispitivanja epruveta zavarenog spoja
Table 7. Results of tensile testing of welded joint specimens.

Epruvete	Temperatura ispitivanja	Napon tečenja	Zatezna čvrstoća	Izduženje*	Mesto loma
Specimen	Testing temperature	Yield stress	Tensile strength	Elongation*	Location of fracture
	°C	$R_{p0,2}$, MPa	R_m, MPa	A, %	
ZS - 1 - 1		322	488	33.5	BM
ZS - 1 - 2	20	319	497	32.2	BM
ZS - 1 - 3		315	491	31.9	BM
ZS - 2 - 1		221	278	35.8	BM
ZS - 2 - 2	540	224	285	34.6	BM
ZS - 2 - 3		217	277	37.9	BM

Osnovni zahtev pri projektovanju zavarenih konstrukcija je da se osigura čvrstoća. To se kod većine zavarenih konstrukcija postiže tako da MŠ ima veću čvrstoću nego OM (overmečing efekt). U ispitivanom slučaju je to ispunjeno i na sobnoj i na radnoj temperaturi (sl. 4a, b, tabele 5 i 6). Dodatni dokaz postignutog overmečing efekta je da su sve epruvete iz zavarenog spoja slomljene u OM i da se vrednosti napona tečenja i zatezne čvrstoće u tabelama 5 i 7 vrlo malo razlikuju, na nivou greške merenja. Treba istaći i dobru saglasnost vrednosti napona tečenja i zatezne čvrstoće iz ispitivanja (tabela 5) i specificiranih vrednosti (tabela 2).

Dobijeni rezultati zateznih osobina MŠ, tabela 6 i sl. 4b, potvrđuju da je tehnologija zavarivanja dobro specificirana (specifikacija postupka zavarivanja–WPS – je poseban dokument), uključujući predgrevanje i termičku obradu posle zavarivanja.

Posebnu pažnju u analizi zateznih osobina zahteva izduženje. U slučaju homogenog materijala, kakvim se u ovom slučaju mogu smatrati OM i MŠ, ova veličina ima smisla, ali samo za poređenje. Kod epruveta iz zavarenog spoja, sl. 2b, sl. 3, vrednost izduženja nema značenje, jer u mernu dužinu od 100 mm ulaze OM i MŠ, različitih zateznih osobina, a zahvaćen je i deo ZUT u kome zatezne osobine nisu poznate. Ipak, karakter dobijenih krivih zatezanja pokazuje da je u pitanju duktilni materijal sa približnim učešćem ravnomernog i neravnomernog izduženja u odnosu 1:2 (sl. 4).

Iz aspekta ponašanja zavarene konstrukcije u eksploataciji treba podvući da je pri realnoj veličini izduženje elastično, a samo lokalno i sa ograničenom veličinom i plastično, pa vrednosti izduženja sa sl. 4 i iz tabela 5–7 mogu da služe samo za poređenje i na osnovu njih se ne može ocenjivati ponašanje materijala, naročito kada se razmatra ZUT, pojava i rast prslina.

Za izvedena ispitivanja je od posebnog značaja što su dobijene vrednosti čvrstoće na radnoj temperaturi na nivou specificiranih. To će značajno doprineti oceni otpornosti prema prslina pri statičkom i pri promenljivom opterećenju heterogene strukture, kakvu predstavlja zavareni spoj, a naročito zona uticaja toplote.

ISPITIVANJE STRUKTURE

Makro snimak sučeono zavarenog spoja čelika A-387 je dat na sl. 5. Jasno se razlikuju: osnovni metal (OM) i metal šava (MŠ), i zona uticaja toplote (ZUT) između njih, /6/.

Osnovni metal je ravnomerne mikrostrukture koja, pored svetlih poligonalnih kristala ferita, sadrži i transformisane oblasti perlita u vidu kompaktnog tamnog mikrokonstituenta.

A basic requirement in the design of welded structures is to assure the strength. In most welded structures this is achieved by superior strength of WM compared to BM (overmatching effect). In the tested case this is achieved at room and working temperatures (Fig. 4a–b, Tables 5–6). Additional proof of realized overmatching is that all specimens from welded joint fractured in BM and the difference in yield stress and tensile strength in Tables 5 and 7 is minor, at measurement error level. It is to notice good agreement between yield stress and tensile strength values from test (Table 5) and specified values (Table 2).

Obtained results of tensile properties of WM, Table 6 and Fig. 4b, confirmed a properly specified welding technology (welding procedure specification–WPS – is a separate document), including preheating and post-weld heat treatment.

Special attention in tensile properties should be paid to elongation. When material is homogeneous, as BM and WM should be considered here, this value is reasonable, but only for comparison. For welded joint specimens, Fig. 2b, Fig. 3, the elongation value is meaningless, since the measuring length of 100 mm includes BM and WM of different tensile properties, but also a part of HAZ is included, where tensile properties are unknown. Nevertheless, the character of obtained tensile curves shows that the material in question is ductile, with an approximate ratio of uniform and non-uniform elongation of 1:2 (Fig. 4).

From the aspect of in-service behaviour of the welded structure it is to underline that elongation is elastic for real values, and only locally plastic of limited value, so elongation values from Fig. 4 and Tables 5–7 can serve only for comparison and cannot serve as basis for material behaviour assessment, especially when considering the HAZ and the occurrence and propagation of cracks.

In the performed tests, of special importance is that the obtained strength values at the working temperature are within specified levels. This will significantly contribute to crack resistance evaluation of the statically and variably loaded heterogeneous structure, such as the welded joint, and the heat-affected-zone itself.

EXAMINATION OF STRUCTURE

A macrograph of butt welded joint of A-387 steel is given in Fig. 5. Clearly recognized are: parent (BM) and weld metal (WM), and heat-affected-zone (HAZ), in between, /6/.

The uniform microstructure of parent metal in addition to light polygonal ferritic crystals contains transformed regions of pearlite in the form of compact dark micro-constituent.

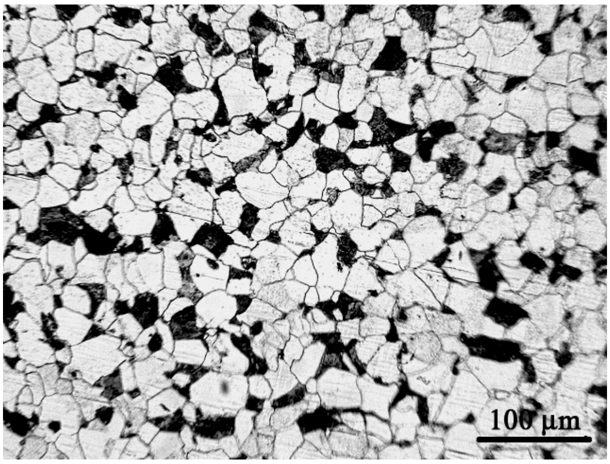
Mikrostruktura OM je prikazana na sl. 6, sa veličinom zrna 5, prema ASTM, /6/.

Metal šava ima strukturu ferita i lamelarnog perlita, sl. 7, /6/. Krupni dendriti su posledica veličine zavarivačkog kupatila zbog dimenzija zavarenih ploča. Zona uticaja toplote takođe ima feritno-perlitnu mikrostrukturu, sl. 8, /6/. Treba imati na umu da se ta lokalna mikrostruktura može bitno razlikovati od mikrostrukture na drugim mestima ZUT.

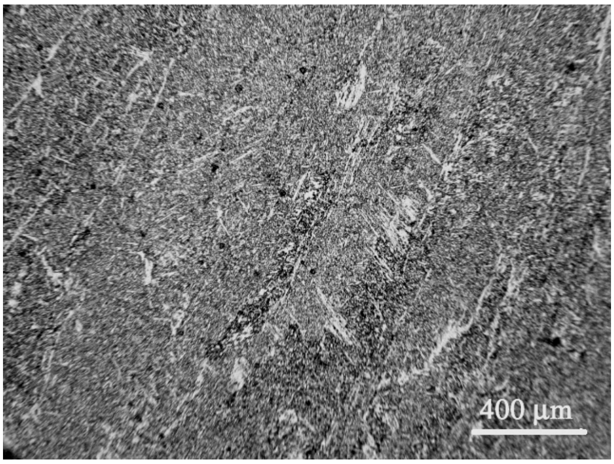
The BM microstructure is presented in Fig. 6, with grain size 5, according to ASTM, /6/.

The weld metal microstructure is ferrite and lamellar pearlite, Fig. 7, /6/. Coarse dendrites are the consequence of welding pool size due from the size of welded plates. The heat-affected-zone is also of ferritic-pearlitic microstructure, Fig. 8, /6/. One has to have in mind that this local microstructure can significantly differ from microstructures at other HAZ locations.

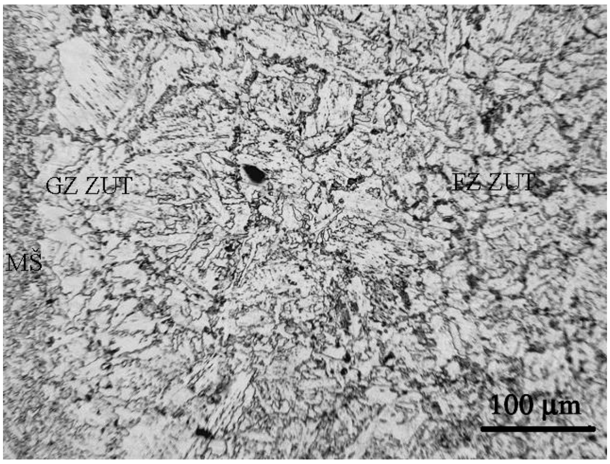
Slika 5. Makrosnimak zavarenog spoja
Figure 5. Macrograph of welded joint.



Slika 6. Mikrostruktura osnovnog metala (OM)
Figure 6. Microstructure of parent metal (BM).



Slika 7. Mikrostruktura metala šava (MŠ)
Figure 7. Microstructure of weld metal (WM) .



Slika 8. Mikrostruktura zone uticaja toplote (ZUT)
Figure 8. Microstructure of the heat-affected-zone (HAZ).

ISPITIVANJA ŽILAVOSTI LOMA

Uticaj heterogenosti mikrostrukture i mehaničkih osobina konstituenata zavarenog spoja na žilavost loma pri ravnoj deformaciji, K_{Ic}, se može utvrditi postavljanjem vrha zamorne prsline na epruveti u različita područja i praćenjem kroz koje se područje lom razvija.

Postupak i rezultati ispitivanja

Ispitivanje žilavosti loma je izvedeno epruvetama za savijanje u tri tačke (SEN-B), debljine 17,5 mm, sl. 9a, i kompaktnih epruveta za zatezanje (CT), debljine 8 mm, sl. 9b, prema standardu ASTM E1820, /9/.

Epruvete za savijanje SEN-B su ispitivane na sobnoj temperaturi. Na radnoj temperaturi su, zbog dimenzija opreme, mogle da se ispituju samo CT epruvete.

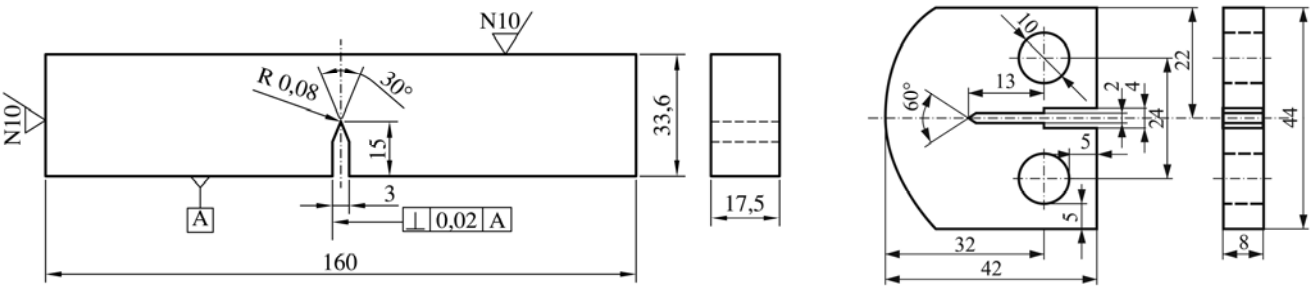
FRACTURE TOUGHNESS TESTING

The effect of microstructural heterogeneity and mechanical properties of welded joint constituents on the plane strain fracture toughness, K_{Ic}, can be assessed by placing a fatigue pre-crack tip on the specimen in different regions and monitoring the regions of fracture growth.

Procedure and testing results

Fracture toughness tests were performed using three-point bend specimens (SEN-B), 17.5 mm thick, Fig. 9a, and compact tension specimens (CT), 8 mm thick, Fig. 9b, according to the standard ASTM E1820, /9/.

Three-point bend (SEN-B) specimens were tested at room temperature. Due to equipment dimensions, only CT specimens could be tested at working temperature.



(a) (b)

Slika 9. Epruvete za ispitivanje mehanike loma: a) SEN-B epruveta, b) CT epruveta

Figure 9. Fracture mechanics test specimens: a) SEN-B specimen, b) CT specimen.

Žilavost loma, K_{Ic}, je određena na osnovu kritične vrednosti J integrala, mere žilavosti loma, J_{Ic}, ispitivanjem prema standardu ASTM E813-89, /10/:

$$K_{Ic} = \sqrt{\frac{J_{Ic}E}{1-\nu^2}} \tag{1}$$

gde je: E–modul elastičnosti, a ν–koeficijent Poasona.

Za određivanje J integrala primenjena je metoda ispitivanja jedne epruvete uzastopnim delimičnim rasterećivanjem. Parom podataka delujuća sila, F, otvaranje prsline, δ, dobijaju se tačke krive osnovne zavisnosti (sl. 10, levo). Postupkom za određivanje kritične vrednosti, mere žilavosti loma, J_{Ic}, zahteva se konstrukcija krive otpornosti (J-R kriva), prikazana na sl. 10, desno, u kojoj se priraštaj prsline određuje na osnovu promene popustljivosti. Osnovni, ali osetno skuplji, postupak u standardu ASTM E813, je metoda više istovetnih epruveta, različitih dužina početne zamorne prsline, i time različite popustljivosti.

Pri ispitivanju jedne epruvete, ona se intervalno rasterećuje do oko 30% trenutno dostignutog nivoa sile, iskustveno odabranog prema tipu materijala. Na osnovu promene nagiba linije popustljivosti, C, sa rastom prsline, određuje se priraštaj prsline, Δa, između dva uzastopna rasterećenja, koji odgovara dostignutoj veličini sile:

$$\Delta a_i = \Delta a_{i-1} + \left(\frac{b_{i-1}}{\eta_{i-1}}\right)\cdot\left(\frac{C_i - C_{i-1}}{C_{i-1}}\right) \tag{2}$$

b i η su konstante, definisane u standardu ASTM E813.

Naredne faze su određivanje kritične veličine, J_{Ic}, i primena te veličine u jed. (1) radi proračuna žilavost loma, K_{Ic}, metodom popustljivosti jedne epruvete.

Diskusija rezultata ispitivanja žilavosti loma

Dobijeni dijagrami su prikazani na sl. 10 za epruvete iz OM ispitane na sobnoj temperaturi, a na sl. 11 za epruvete ispitane na 540°C. Odgovarajuće krive za MŠ su date na sl. 12 i 13, a za ZUT na sl. 14 i 15, /6, 11/.

Izračunate vrednosti žilavosti loma, K_{Ic}, su date u tabeli 8, za epruvete sa zarezom u OM, MŠ i ZUT.

Primetno je da strukturna i mehanička heterogenost zavarenog spoja utiče na njegovu otpornost prema razvoju prsline. Zbog toga je potrebno pri propisivanju uslova za ispitivanje mehanike loma definisati ne samo postupak ispitivanja i položaj zamorne prsline, već i način tumačenja i značenje dobijenih rezultata, /6/.

Fracture toughness, K_{Ic}, is determined based on J integral critical value, a measure of fracture toughness, J_{Ic}, by tests according to the ASTM E813-89 standard, /10/:

$$K_{Ic} = \sqrt{\frac{J_{Ic}E}{1-\nu^2}} \tag{1}$$

where: E–elasticity modulus, and ν–Poisson's ratio.

For determining the J integral, a single specimen test method by successive partial unloading is applied. Data pairs: applied force, F, crack opening displacement, δ, are points of the basic relationship curve (Fig. 10, left). The procedure for determining the critical value, a measure of fracture toughness, J_{Ic}, requires the design of the resistance curve (J-R curve), shown in Fig. 10, right, where the crack increase is determined based on compliance change. Basic, but more expensive, procedure in ASTM E813 standard is the multi-specimen (same size) method, but with different length of fatigue pre-cracks, having different compliance.

In a single specimen test the specimen is unloaded in intervals to about 30% of actually attained force level, chosen by experience with material type. Based on the change of compliance line slope, C, with crack extension, the crack increase, Δa, between two successive unloadings, corresponding to attained force value, is determined as:

$$\Delta a_i = \Delta a_{i-1} + \left(\frac{b_{i-1}}{\eta_{i-1}}\right)\cdot\left(\frac{C_i - C_{i-1}}{C_{i-1}}\right) \tag{2}$$

b and η are constants, defined in standard ASTM E813.

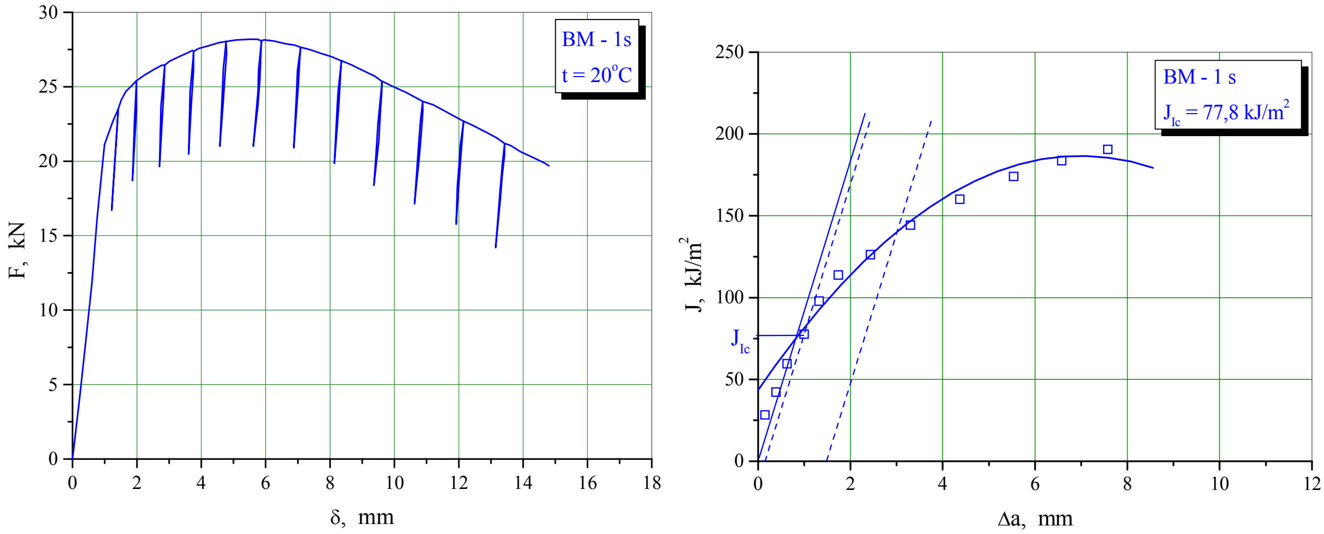
Next steps are determination of critical value, J_{Ic}, and use of this value in Eq. (1) for fracture toughness, K_{Ic}, calculation by single specimen compliance method.

Discussion of fracture toughness testing results

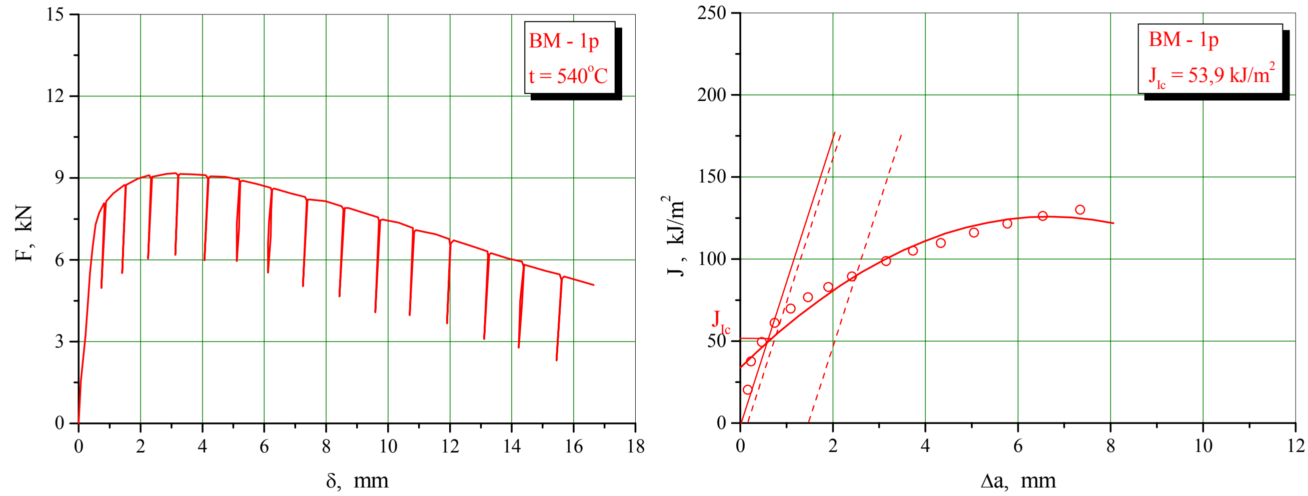
Obtained diagrams are presented in Fig. 10 for BM specimens tested at room temperature, and in Fig. 11 for specimens tested at 540°C. Corresponding curves for WM are given in Figs. 12 and 13, and for HAZ in Figs. 14 and 15, /6, 11/.

Calculated values of fracture toughness, K_{Ic}, are given in Table 8 for the specimens notched in BM, WM and HAZ.

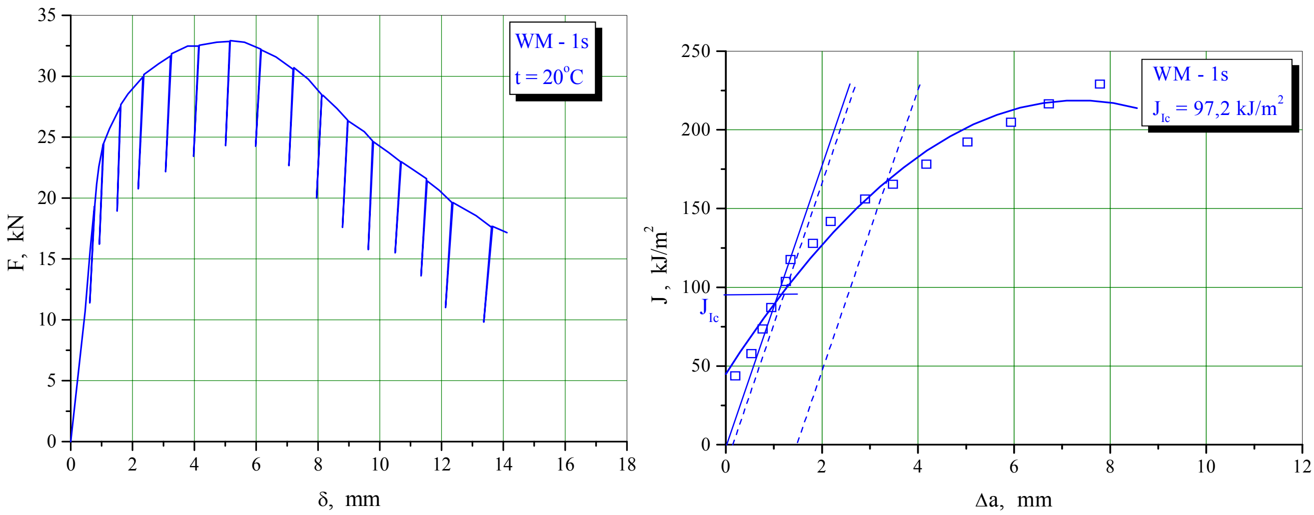
It can be seen that structural and mechanical heterogeneities of a welded joint affect its resistance to crack propagation. Therefore, specifications for fracture mechanics testing conditions should prescribe not only the test procedure and location of a fatigue crack, but also the method of interpretation and meaning of the obtained results, /6/.



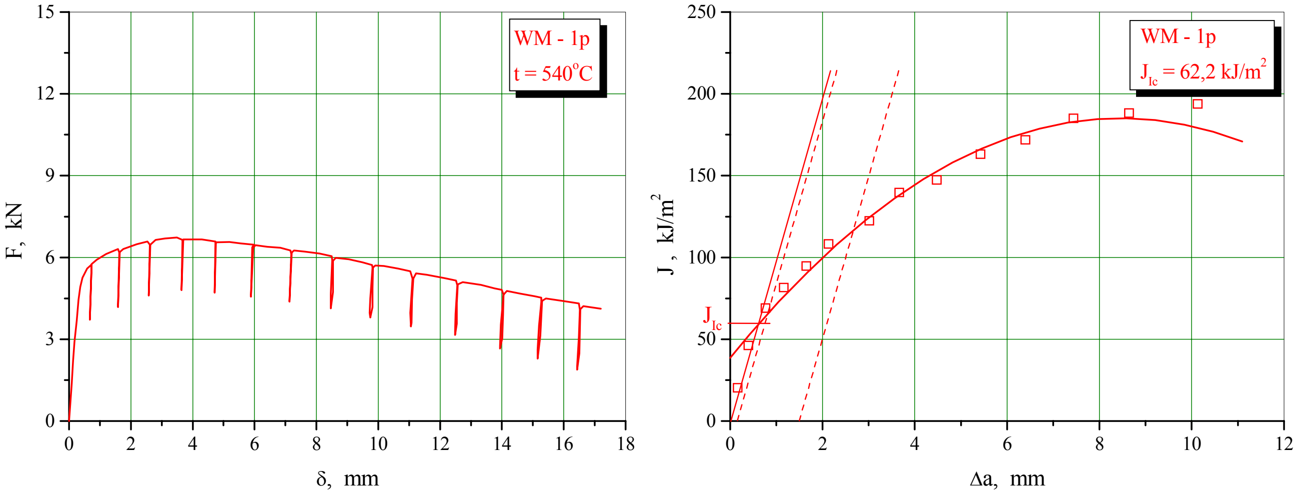
Slika 10. Dijagrami F–δ i J–Δa za epruvetu sa zarezom u OM i ispitanu na sobnoj temperaturi
Figure 10. Diagrams F–δ and J–Δa for specimen notched in BM at room temperature.



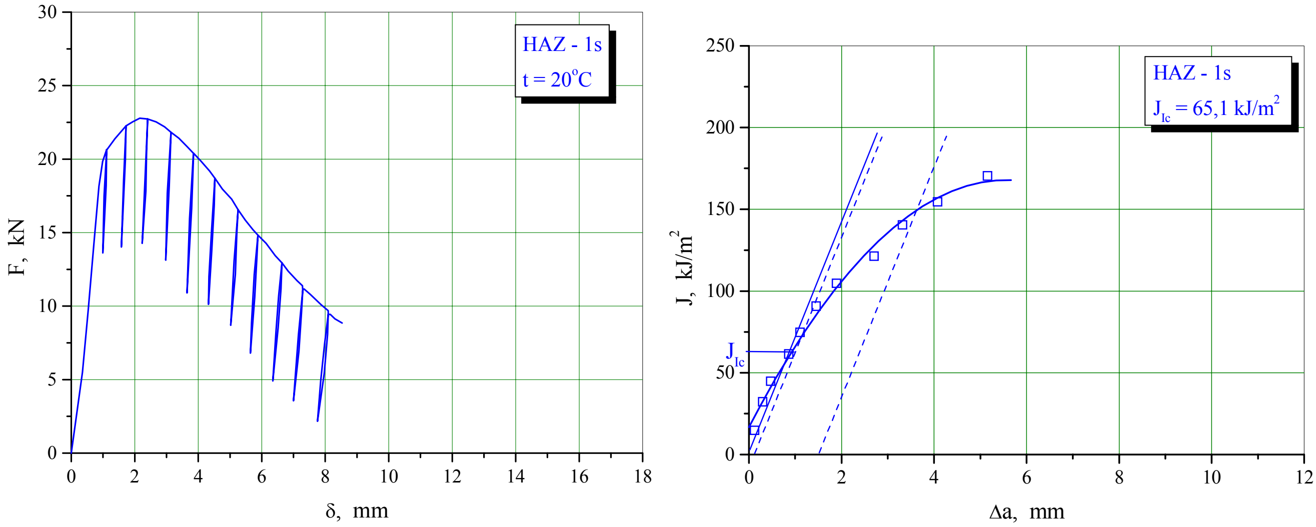
Slika 11. Dijagrami F–δ i J–Δa za epruvetu s zarezom u OM i ispitanu na radnoj temperaturi
Figure 11. Diagrams F–δ and J–Δa for specimen notched in BM at operating temperature.



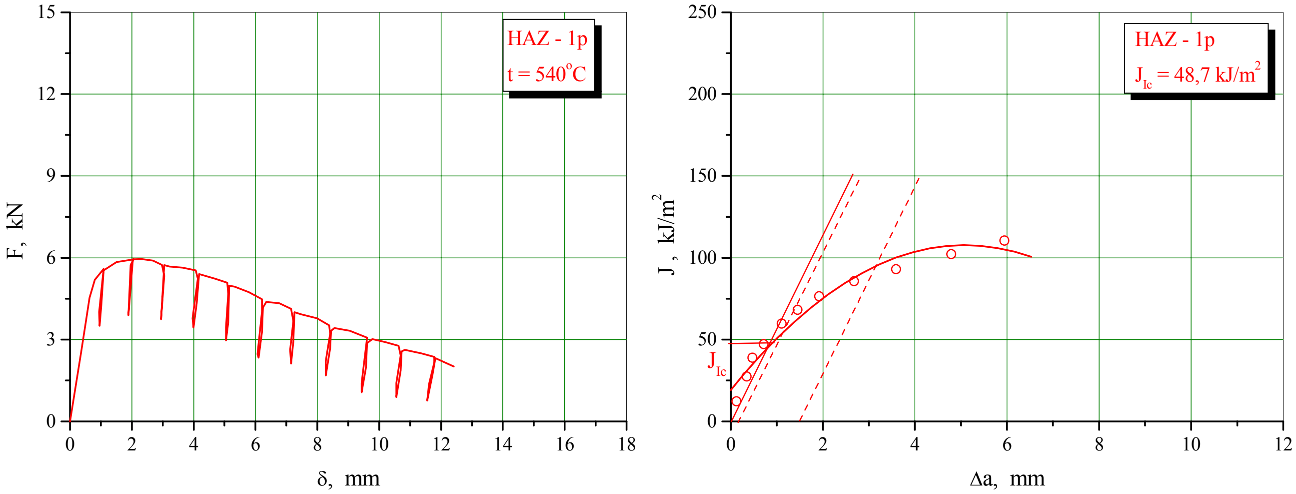
Slika 12. Dijagrami F–δ i J–Δa za epruvetu sa zarezom u MŠ i ispitanu na sobnoj temperaturi
Figure 12. Diagrams F–δ and J–Δa for specimen notched in WM at room temperature.



Slika 13. Dijagrami *F–δ* i *J–Δa* za epruvetu sa zarezom u MŠ i ispitanu na radnoj temperaturi
Figure 13. Diagrams *F–δ* and *J–Δa* for specimen notched in WM at operating temperature.



Slika 14. Dijagrami *F–δ* i *J–Δa* za epruvetu sa zarezom u ZUT i ispitanu na sobnoj temperaturi
Figure 14. Diagrams *F–δ* and *J–Δa* for specimen notched in HAZ at room temperature.



Slika 15. Dijagrami *F–δ* i *J–Δa* za epruvetu sa zarezom u ZUT i ispitanu na radnoj temperaturi
Figure 15. Diagrams *F–δ* and *J–Δa* for specimen notched in HAZ at operating temperature.

Karakter krivih se menja u zavisnosti od položaja vrha zareza, odnosno, zamorne prsline, i temperature ispitivanja. Može se uočiti gotovo identični karakter pojedinačnih krivih u svakoj grupi, s tim što je razlika u dijagramima za pojedine epruvete isključivo u veličini maksimalne sile, F_{max}, što direktno zavisi od dužine zamorne prsline, a, i temperature ispitivanja, /6/.

Najveću vrednost K_{Ic} na sobnoj temperaturi imaju epruvete sa zarezom u MŠ (srednja vrednost K_{Ic} ~145 MPa·m$^{1/2}$). Nešto niže vrednosti K_{Ic} imaju epruvete sa zarezom u BM (srednja vrednost K_{Ic} ~130 MPa·m$^{1/2}$). Rasipanje rezultata je malo, 10–15 MPa·m$^{1/2}$ u odnosu na minimalnu i maksimalnu vrednost. Niže vrednosti K_{Ic} imaju epruvete sa zarezom ZUT. Međutim, razlika u odnosu na OM nije tolika da upućuje na značajnije smanjenje osobina, /6/. Bliske vrednosti K_{Ic} za OM i ZUT mogu se dovesti u vezu sa mikrostrukturom. Naime, oba konstituenta imaju feritno perlitnu mikrostrukturu, slične otpornosti prema prslinama pri statičkom opterećenju. Treba ipak imati u vidu da je u ovom ispitivanju položaj vrha zamorne prsline slučajno odabran i da u ZUT mogu postojati područja drugačije mikrostrukture i manje žilavosti loma.

Primenom osnovne formule mehanike loma:

$$K_{Ic} = \sigma\sqrt{\pi \cdot a_c} \quad (3)$$

i unošenjem vrednosti dozvoljenog napona, $\sigma_{doz} = \sigma$, za faktor oblika jednak jedinici, mogu se izračunati približne vrednosti za kritičnu dužinu prsline, a_c, (tabela 8).

Prslina najveće dužine, a_c,, može se pojaviti pri statičkom opterećenju u MŠ, ali bez pojave krtog loma.

Pri statičkom opterećenju, navedene razlike u veličini K_{Ic} ne moraju da imaju značajnijeg uticaja na sigurnost konstrukcija. Očigledno da će dozvoljeni napon, manji od napona tečenja, dati veće vrednosti za kritičnu dužinu prsline, i ako u ispitivanom materijal postoji prslina dužine manje od kritične, nema opasnosti od krtog loma. Takvu prslinu treba otkriti i oceniti njenu dužinu pogodnim postupkom ispitivanja bez razaranja. Posle analize integriteta, može se, pod određenim uslovima, dopustiti eksploatacija konstrukcije i u periodu rasta prsline. Bitni podaci za odluku o daljoj eksploataciji komponente sa prslinom su brzina rasta prsline i njena zavisnosti od delujućeg opterećenja. Promene u vrednosti K_{Ic} su tada značajne, jer kritična dužina prsline, a_c, direktno zavisi od vrednosti K_{Ic}.

Uticaj temperature na žilavosti loma K_{Ic}, je dat u tabeli 8. Smanjenje žilavosti loma za 35–45% na radnoj temperaturi u odnosu na sobnu temperaturu zavisi od položaja vrha zamorne prsline (OM, MŠ, ZUT), sa najvećom vrednošću K_{Ic} kod epruvete sa zarezom u MŠ. Dobijene krive J–Δa imaju gotovo identičan karakter, samo se veličina maksimalne sile, F_{max}, razlikuje, što je u direktnoj zavisnosti od dužine zamorne prsline a.

ANALIZA ZAMORA PRIMENOM MEHANIKE LOMA

Ako je konstrukcijska komponenta neprekidno izložena promenljivom opterećenju, iz koncentratora napona može doći do inicijacije zamorne prsline i do njenog rasta ako je prekoračen opseg faktora intenziteta na pragu zamora, ΔK_{th}.

The character of curves varies depending on the notch, i.e. fatigue crack, tip location, and testing temperature. It is possible to observe an almost identical character of the individual curves in each group, the difference between the diagrams for individual specimens is exclusively in the maximal force value, F_{max}, directly dependent on fatigue crack length, a, and on the testing temperature, /6/.

The maximum value of K_{Ic} at room temperature have the specimens notched in WM (mean K_{Ic} ~145 MPa·m$^{1/2}$). Somewhat lower K_{Ic} values exhibited specimens notched in BM (mean value K_{Ic} ~ 130 MPa·m$^{1/2}$). The scatter of results is small, 10–15 MPa·m$^{1/2}$ in terms of minimal and maximal values. Lower K_{Ic} values belong to specimens notched in HAZ. However, the difference does not indicate an important reduction of properties, /6/. Close K_{Ic} values for BM and HAZ can be connected to microstructures. Namely, both constituents have ferritic–pearlitic microstructures of similar crack resistance at static loading. However, one should have in mind that the location of fatigue crack tip is random in the performed tests, and regions of different microstructures and lower fracture toughness can exist in the HAZ.

By applying the fracture mechanics fundamental formula:

$$K_{Ic} = \sigma\sqrt{\pi \cdot a_c} \quad (3)$$

and introducing the value of allowable stress, $\sigma_{doz} = \sigma$, for a shape factor equalling unity, approximate values of critical crack length, a_c, can be calculated, (Table 8).

Largest crack length, a_c,, can occur under static load in WM, but without brittle fracture occurrence.

Under static loading, the given differences in K_{Ic} value must not have significant effect on structural safety. It is obvious that allowable stress, lower than yield stress, will produce higher values for critical crack length, and if there is a crack of length less than critical in the tested material, there is no danger of brittle fracture. Such a crack has to be detected and its length assessed by convenient non-destructive testing method. Following the integrity analysis, under defined conditions it is possible to allow the operation of the structure even in the crack growth period. Important data for decision on extended operation of cracked component are crack growth rate and its dependence on applied load. The changes in K_{Ic} value are then important, since critical crack length, a_c, is directly depended on K_{Ic} value.

The effect of temperature on fracture toughness, K_{Ic}, is given in Table 8. Reduction in fracture toughness of 35–45% at working temperature compared to room temperature depends on fatigue crack tip location (BM, WM, HAZ), with maximal value of K_{Ic} in the specimen notched in WM. Obtained J–Δa curves are of almost identical character, only the value of maximal force F_{max} is different, directly related to fatigue crack length a.

FATIGUE.ANALYSIS BY FRACTURE MECHANICS

If the structural component is continuously exposed to variable loads, fatigue crack may initiate and propagate from severe stress raisers if the stress intensity factor range at fatigue threshold, ΔK_{th}, is exceeded.

Tabela 8. Rezultati ispitivanja kritičnog J integrala, J_{Ic}, i kritičnog faktora intenziteta napona, K_{Ic}
Table 8. Test results of critical J integral, J_{Ic}, and critical stress intensity factor, K_{Ic}.

Oznaka	Temperatura ispitivanja	Kritični J integral	Kritični faktor intenziteta napona	Kritična dužina prsline
Designation	Testing temperature	Critical J-integral	Critical stress intensity factor	Critical crack length
	°C	J_{Ic}, kJ/m^2	K_{Ic}, MPa m$^{1/2}$	a_c, mm
BM-1s	20	77,8	132,4	52,8
BM-2s		75,2	130,3	51,1
BM-3s		73,2	128,4	49,7
WM-1s	20	97,2	148,0	66,0
WM -2s		93,7	145,3	63,6
WM -3s		92,2	143,1	61,7
HAZ-1s	20	65,1	121,1	44,2
HAZ -2s		70,2	125,2	47,4
HAZ -3s		71,3	125,6	47,9
BM-1p	540	53,9	90,2	46,1
BM-2p		49,7	87,4	43,4
BM-3p		55,1	92,1	48,1
WM -1p	540	62,2	97,8	54,3
WM -2p		60,3	96,3	52,6
WM -3p		55,6	92,5	48,5
HAZ -1p	540	48,7	86,6	42,5
HAZ -2p		46,8	85,2	41,6
HAZ -3p		47,3	85,9	42,2

Osnovni doprinos mehanike loma u analizi zamora je podela procesa loma na period inicijacije prsline i na period njenog razvoja do kritične veličine za brzi lom. Ukupan broj ciklusa do loma, N_u, podeljen na broj ciklusa za nastanak zamorne prsline, N_i, i za njen rast do kritične veličine za lom, N_p: ($N_u = N_i + N_p$).

Razvoj u proučavanju ponašanja materijala pri promenljivom opterećenju je ostvaren primenom eksperimentalnog i teorijskog pristupa. Analiza stanja napona i deformacija na vrhu rastuće zamorne prsline primenom linearno elastične mehanike loma (LEML) je omogućila razvoj Parisove jednačine za metale i legure, koja preko koeficijenta C i eksponenta m povezuje brzinu rasta zamorne prsline da/dN i opsegom faktora intenziteta napona ΔK, /12/:

$$\frac{da}{dN} = C\,(\Delta K)^m \tag{4}$$

Standard ASTM E647, /13/, propisuje ispitivanje prsline sa zamorom za merenje brzine rasta zamorne prsline, da/dN, i proračun opsega faktora intenziteta napona, ΔK.

Dva su zahteva osnovna u ASTM E647: brzina rasta treba da je veća od 10^{-8} m/ciklus da se izbegne područje praga zamora, a amplituda opterećenja treba da je konstantna.

Standardne Šarpi epruvete, sa zamornom prslinom u različitim konstituentima zavarenog spoja, opremljene folijom RUMUL RMF A-5 merne dužine 5 mm (sl. 16) za kontinualno praćenje dužine prsline, su ispitane na sobnoj temperaturi promenljivom silom, radi određivanja brzine rasta zamorne prsline, da/dN, i opsega faktora intenziteta napona na pragu zamora, ΔK_{th}. Ispitivanje je izvedeno u kontroli sile, savijanjem u tri tačke, na rezonantnom visokofrekventnom pulzatoru FRACTOMAT.

Ispitivanja na radnoj temperaturi su izvedena na CT epruvetama, jer se na 540°C ne mogu koristiti merne folije, pa se meri pomeranje napadne tačke sile.

A basic contribution of fracture mechanics in the fatigue analysis is the division of fracture process to the period of crack initiation and period of growth to critical size for fast fracture. Total number of cycles to fracture, N_u, is divided into number of cycles for fatigue crack initiation, N_i, and its growth to the value critical for fracture, N_p: ($N_u = N_i + N_p$).

Development in the research of material behaviour under variable loading is achieved by applying experimental and theoretical approaches. Analysis of stress and strain state at growing fatigue crack tip by applying linear elastic fracture mechanics (LEFM) enabled to develop the Paris equation for metals and alloys that relates fatigue crack growth rate, da/dN, to the stress intensity factor range, ΔK, through coefficient C and exponent m, /12/:

$$\frac{da}{dN} = C\,(\Delta K)^m \tag{4}$$

The standard ASTM E647, /13/, defines testing of pre-cracked specimen for fatigue crack growth rate measurement, da/dN, and calculation of stress intensity factor range, ΔK.

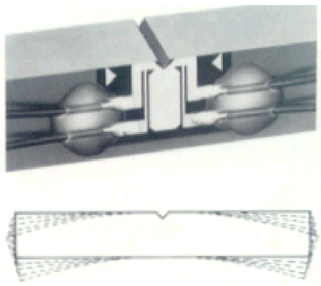
Two basic requirements in ASTM E647 are: the crack growth rate should be above 10^{-8} m/cycle to avoid fatigue threshold region and load should be of constant amplitude.

Standard Charpy specimens, fatigue pre-cracked in different welded joint constituents, and instrumented by foil RUMUL RMF A-5, of measuring length 5 mm (Fig. 16) for continuous monitoring of crack length, were tested at room temperature under variable loading for determination of fatigue crack growth rate, da/dN, and stress intensity factor range at fatigue threshold, ΔK_{th}. Testing was performed by controlled load in three-point bending on the FRACTOMAT high frequency resonant pulsator.

CT specimens were tested on working temperature, since at 540°C the measuring foils can not be used, and load line displacement is measured instead.

Zavisnosti *da*/*dN*–Δ*K* dobijene ispitivanjem epruveta sa prslinom u OM, MŠ i ZUT na sobnoj temperaturi i na 540°C date su na sl. 17, /6/. Vrednosti koeficijenta *C* i eksponenta *m*, i opsega faktora intenziteta na pragu zamora, ΔK_{th}, su date u tabeli 9.

Relations *da*/*dN*–Δ*K* for specimens pre-cracked in BM, WM, and HAZ, tested at room temperature and at 540°C, are given in Fig. 17, /6/. The values of coefficient *C* and exponent *m*, with values of stress intensity factor range at fatigue threshold, ΔK_{th}, are given in Table 9.



Slika 16. Šarpi epruveta opremljena folijom RUMUL RMF A-5 za kontinualno praćenje dužine prsline

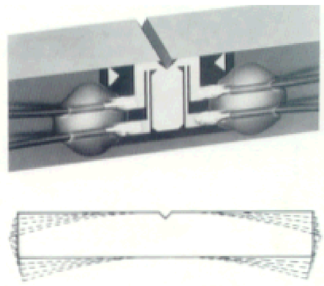
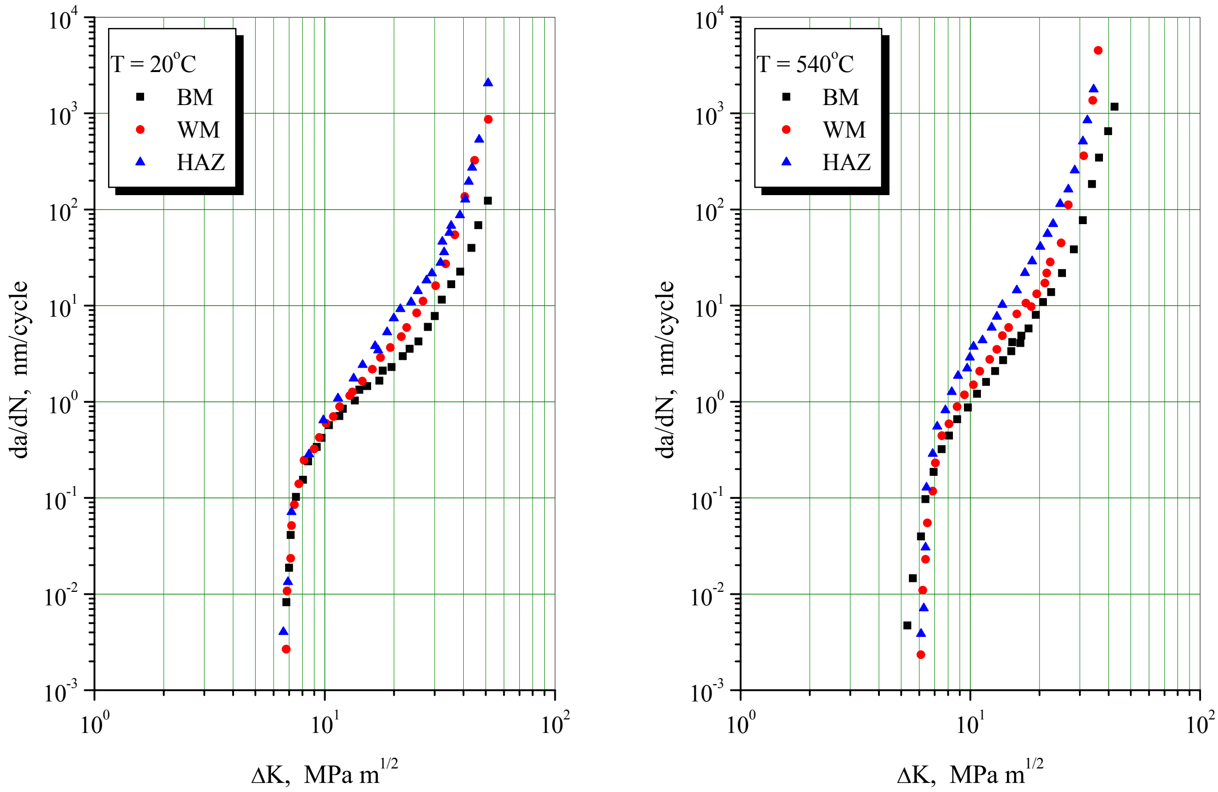


Figure 16. Charpy specimen instrumented by foil RUMUL RMF A-5 for continuous monitoring of crack length.



Slika 17. Zavisnost *da*/*dN*–Δ*K* za epruvete sa prslinom u BM, WM i HAZ, ispitane na sobnoj temperaturi (levo) i na 540°C (desno)
Figure 17. Relation *da*/*dN*–Δ*K* for specimens pre-cracked in BM, WM and HAZ, tested at room temperature (left) and at 540°C (right).

Tabela 9. Parametri Parisove jednačine
Table 9. Parameters of Paris equation.

Oznaka epruvete	Temperatura ispitivanja	Opseg faktora intenziteta napona na pragu zamora	Koeficijent *C*	Eksponent *m*	Brzina rasta prsline *da/dN* za Δ*K* = 10 MPa m$^{1/2}$
Specimen designation	Test temperature	Stress intensity factor range at fatigue threshold	Coefficient *C*	Exponent *m*	Crack growth rate *da/dN* at Δ*K* = 10 MPa m$^{1/2}$
	°C	ΔK_{th}, MPa m$^{1/2}$			nm/cycle
BM–1s	20	6.8	$2.98 \cdot 10^{-13}$	3.62	$1.24 \cdot 10^{-09}$
WM–1s		6.8	$3.88 \cdot 10^{-13}$	3.82	$2.56 \cdot 10^{-09}$
HAZ–1s		6.7	$3.05 \cdot 10^{-13}$	4.01	$3.12 \cdot 10^{-09}$
BM–1p	540	5.9	$3.11 \cdot 10^{-13}$	4.08	$3.74 \cdot 10^{-09}$
WM–1p		6.2	$3.27 \cdot 10^{-13}$	4.14	$4.51 \cdot 10^{-09}$
HAZ–1p		6.1	$3.38 \cdot 10^{-12}$	3.17	$5.00 \cdot 10^{-09}$

Veliki gotovo linearni srednji deo krive na sl. 17 je pokriven Parisovim zakonom i praktično je najvažniji, jer dopušta da se napravi razlika između malih brzina rasta zamorne prsline (inicijacija) u blizini praga zamora, i visokih brzina (K_{Ic}), kada dolazi do loma. Primena Parisove jednačine je naročito pogodna za zamor konstrukcija izrađenih od materijala povišene i visoke čvrstoće.

Kako se iz tabele 9 vidi, položaj zamorne prsline i temperatura ispitivanja imaju značajan uticaj na vrednosti ΔK_{th} i na rast zamorne prsline, /6/.

Radi poređenja osobina konstituenata zavarenog spoja, za različite vrednosti opsega faktora intenziteta napona ΔK su izračunate brzine rasta zamorne prsline. Kao referentna je uzeta vrednost $\Delta K = 10$ MPa√m, koja se nalazi u srednjem delu dijagrama, u kome važi Parisov zakon, sl. 17.

Brzina rasta zamorne prsline na sobnoj temperaturi, da/dN, je $1{,}24\cdot10^{-9}$ μm/ciklus za epruvetu iz OM, $2{,}56\cdot10^{-9}$ μm/ciklus za epruvetu iz MŠ i $3{,}12\cdot10^{-9}$ μm/ciklus za epruvetu ZUT. Na temperaturi 540°C odgovarajuće vrednosti su veće ($3{,}74\cdot10^{-9}$; $4{,}51\cdot10^{-9}$; $5{,}00\cdot10^{-9}$ za OM, MŠ i ZUT, redom), /6/.

Ponašanje zavarenog spoja i njegovih konstituenata treba povezati sa promenom nagiba krive u delu važenja Parisovog zakona. Materijali manje brzine rasta zamorne prsline imaju na dijagramu da/dN–ΔK manji nagib, /6/.

Usporen rast je utvrđen kod uzoraka sa prslinom u OM i MŠ, jer je za istu brzinu rasta potreban veći opseg faktora intenziteta napona. Maksimalna brzina rasta zamorne prsline se očekuje kada se opseg faktora intenziteta napona približava žilavosti loma pri ravnoj deformaciji, pri kojoj je moguć krti lom, /14/.

I pored znatnih razlika u brzinama rasta zamorne prsline, dobijene vrednosti su još uvek male i prihvatljive. To znači da nivo otpornosti prema rastu zamorne prsline ispitivanog čelika i njegovog zavarenog spoja prihvatljiv i da se može uspešno koristiti u slučaju otkrivenih grešaka tipa prsline, prvenstveno pri niskocikličnom zamoru.

ZAKLJUČAK

Sledeći zaključci mogu da se izvuku:

– Strukturna i mehanička heterogenost zavarenog spoja i temperatura ispitivanja, utiču na njegovu otpornost prema razvoju prsline i na dobijene vrednosti K_{Ic} i a_c. Feritno-lamelarno perlitna struktura OM je bolje otpornosti prema rastu prsline u uslovima statičkog opterećenja nego feritno perlitna struktura OM ujednačene veličine zrna i feritno perlitna struktura ZUT različite veličine zrna. Bliskost dobijenih vrednosti K_{Ic} za OM i ZUT se objašnjava položajem vrha zamorne prsline u području ZUT čija je struktura slična strukturi OM.
– Temperatura ispitivanja ima uticaja na vrednosti žilavosti loma K_{Ic} i kritične dužine prsline a_{cr}. Smanjenje žilavosti loma je 35–45%, zavisno od položaja vrha zamorne prsline (OM, MŠ i ZUT). Najveću vrednost K_{Ic} imaju epruvete sa zarezom u MŠ, dok su kod OM i ZUT dobijene niže vrednosti K_{Ic}. Dobijeni rezultati na radnoj temperaturi su srazmerno niži u odnosu na rezultate dobijene na sobnoj temperaturi, i posledica su slabljenja osobina materijala na povišenoj temperaturi.

The dominant, almost linear central part of curve in Fig. 17 is covered by the Paris law and is practically most important, since it allows to make a difference between low fatigue crack growth rates (initiation), close to the fatigue threshold, and high rates (K_{Ic}), when fracture occurs. The application of Paris equation is very convenient for fatigue of structures produced of elevated and high strength materials.

As it can be seen from Table 9, fatigue crack-tip position and testing temperature significantly affect ΔK_{th} values and fatigue crack growth, /6/.

For comparison of welded joint constituent properties, different values of the stress intensity factor range ΔK crack growth rates are calculated. As a referent value, $\Delta K =$ 10 MPa√m is accepted, within a middle part of the diagram, where Paris law is valid, Fig. 17.

Fatigue crack growth rate at room temperature, da/dN, is $1.24\cdot10^{-9}$ μm/cycle for the BM specimen, $2.56\cdot10^{-9}$ μm/cycle for the WM specimen and $3.12\cdot10^{-9}$ μm/cycle for specimen of HAZ. At 540°C, the corresponding values are higher: ($3.74\cdot10^{-9}$; $4.51\cdot10^{-9}$; $5.00\cdot10^{-9}$ for BM, WM and HAZ, in respect, /6/.

The behaviour of welded joint and its constituents is to be connected to the change of curve slope at the part of Paris law validity. Materials of lower fatigue crack growth rate have a lower slope in the diagram da/dN–ΔK, /6/.

Slow growth is confirmed for specimens cracked in BM and WM, since a larger stress intensity factor range is required for the same growth rate. Maximal fatigue crack growth rate is expected when the stress intensity factor range approaches to plane strain fracture toughness, whereupon brittle fracture is possible, /14/.

In spite of significant differences in fatigue crack growth rates, the obtained values are yet small and acceptable. This means that the level of fatigue crack growth resistance of the tested steel and its welded joint is acceptable and may be successfully applied in cases of detected crack-like defects, primarily for low-cycle fatigue.

CONCLUSIONS

Following conclusions can be derived:

– The resistance to crack growth and obtained values of K_{Ic} and a_c of the welded joint are affected by its structural and mechanical heterogeneity and by the testing temperature. Ferritic-lamellar pearlitic structure of WM is of better resistance to crack growth in static loading condition than the ferritic-pearlitic structure of BM of uniform grain size, and the ferritic-pearlitic structure of HAZ of different grain size. Obtained close K_{Ic} values of BM and HAZ are explained by the location of fatigue crack tip in HAZ region of structure, similar to BM structure.
– The testing temperature influences fracture toughness K_{Ic} and critical crack length a_{cr} values. Reduction of fracture toughness is 35–45%, depending on fatigue crack tip location (BM, WM, or HAZ). Specimens notched in WM have the highest value K_{Ic}, whereas for BM and HAZ obtained K_{Ic} values are lower. Results obtained at working temperature are proportionally lower compared to results at room temperature, and are a consequence of reduced material properties at elevated temperature.

– Mesto postavljanja zareza i inicijacija prsline, kao i temperatura ispitivanja, imaju uticaj na vrednosti praga zamora ΔK_{th} i parametre rasta zamorne prsline.
– Najmanju brzinu rasta zamorne prsline imaju uzorci sa zarezom i iniciranom prslinom u OM, dok je najveća brzina rasta zamorne prsline kod uzoraka sa zarezom u ZUT. Ovo je u direktnoj vezi sa uticajem heterogenosti mikrostrukture područja ZUT na brzinu rasta zamorne prsline, *da/dN*.
– Epruvete konstituenata zavarenog spoja na radnoj temperaturi (540°C), pri promenljivom opterećenju, pri ispitivanju praga zamora i parametara rasta zamorne prsline, pokazale su povećanje brzine rasta dva do četiri puta u odnosu na sobnu temperaturu, što može da se objasni slabljenjem osobina materijala na povišenoj temperaturi.

– Notch location and crack initiation, as well as testing temperature, influence values of fatigue threshold ΔK_{th} and fatigue crack growth parameters.
– The minimum fatigue crack growth rate is exhibited on specimens pre-cracked in BM, and the maximum fatigue crack growth rate in specimens pre-cracked in HAZ. This is directly connected to the effects that microstructural heterogeneity in HAZ regions has on the fatigue crack growth rate, *da/dN*.
– Specimens of welded joint constituents at working temperature (540°C) exhibited two to four-fold higher crack growth rates when compared to room temperature under variable loads in tests of the fatigue threshold and fatigue crack growth parameters, which can be explained by reduced material properties at elevated temperature.

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