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PONAŠANJE PRI ZAMORU I LOMU ZAVARENIH SPOJEVA ČELIKA NIOMOL 490K

FRACTURE AND FATIGUE BEHAVIOUR OF NIOMOL 490K WELDED JOINT

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Ključne reči
- zavareni spoj
- čelik viske čvrstoće
- brzina rasta prsline
- prag zamora
- integritet konstrukcije

Izvod

Cilj rada je ispitivanje epruveta radi analize ponašanja prslina u zavarenim spojevima posuda pod pritiskom izrađenim od mikrolegiranog čelika, primenom parametara mehanike loma. Čelik NIOMOL 490K je namenjen za izradu zavarenih konstrukcija izloženih dinamičkom opterećenju i niskoj temperaturi, zbog čega, osim dovoljne čvrstoće, mora imati i prihvatljivu žilavost. U cilju razumevanja uzroka i načina pojave i rasta prslina u zavarenim spojevima čelika povišene čvrstoće potrebno je da se utvrdi kako heterogenost mikrostrukture i mehaničkih svojstava zavarenog spoja, a pre svega HAZ, utiču na pojavu i rast prsline kao i na parametre rasta zamorne prsline. Ovaj rad treba da doprinese razvoju osnovnih parametara i kriterijuma prihvatljivosti grešaka tipa prslina kod posuda pod pritiskom namenjenih za rad u uslovima niskih temperatura i agresivnih sredina.

UVOD

Osnovni zahtev koji mora zadovoljiti svaka zavarena konstrukcija je sigurnost i pouzdanost u uslovima eksploatacije. Da bi taj zahtev bio zadovoljen presudne su osobine zavarenog spoja, /1/.

Kako su u pitanju složene konstrukcije, za detaljno poznavanje osobina zavarenih spojeva neophodna su eksperimentalna istraživanja, kao i tumačenje dobijenih rezultata.

Čelik NIOMOL 490K, koji spada u grupu mikrolegiranih čelika sa molibdenom, napona tečenja min. 490 MPa, namenjen za izradu zavarenih konstrukcija izloženih dinamičkom opterećenju i dejstvu niske temperature, zbog čega, sem dovoljne čvrstoće, mora imati i dobru žilavost. Uspešna primena ovog čelika zavisi od stepena pogoršavanja svojstava osnovnog metala (PM) zavarivanjem. Zona uticaja toplote (HAZ) i metal šava (WM) mogu biti mesta smanjene žilavosti sa prelaznom temperaturom krtosti pomerenom ka višim temperaturama, /2/.

Keywords
- welded joint
- high strength steel
- crack growth rate
- fatigue threshold
- structural integrity

Abstract

The aim of this paper is testing specimens for analysing crack behaviour in welded joints of pressure vessels, made of microalloyed steel, by applying fracture mechanics parameters. Steel NIOMOL 490 K is designed for welded structures exposed to dynamic loads and low temperature, and in respect to this, apart to sufficient strength, it must also have acceptable toughness. In the course of understanding causes and modes of crack initiation and growth in welded joints of high strength steels, it is necessary to establish how the heterogeneity of microstructure and mechanical properties, primarily in HAZ, affect crack initiation and growth, as well as fatigue crack growth parameters. This paper should contribute to the development of basic parameters and criteria for the acceptance of crack-like defects in pressure vessels aimed to operate at conditions of low temperature and aggressive environment.

INTRODUCTION

The basic requirements each welded structure has to satisfy are safety and reliability in operating conditions. In order to fulfil this requirement welded joint properties are of crucial importance, /1/.

Since complex structures are in question, detailed description of welded joint properties require experimental investigations, and interpretation of obtained results.

NIOMOL 490K belongs to the class of molybdenum microalloyed steels, of yield strength min. 490 MPa, aimed for manufacturing welded structures exposed to dynamic loads and low temperature effects, and in respect to this, with sufficient strength, it must also possess acceptable toughness. Successful use of this steel depends on the deterioration level of properties of the parent metal (PM) by welding. Heat-affected-zone (HAZ) and weld metal (WM) can be locations of reduced toughness with nil-ductility transition temperature shifted to higher temperatures, /2/.

Kako se problem postojanja prslina u odgovornim zavarenim konstrukcijama koje se izrađuju od mikrolegiranih čelika često javlja, kao što je to slučaj kod posuda pod pritiskom, jasna je potreba ispitivanja da li su zavareni spojevi skloni stvaranju i rastu prslina.

Za eksploatacijsku sigurnost zavarenih konstrukcija najvažnije su karakteristike koje opisuju pojavu i rast prslina pod uticajem promenljivog opterećenja. Pojavu zamornih prslina na konstrukcijski glatkim i homogenim oblicima, zbog lokalne koncentracije napona na konstrukcijski neizbežnim geometrijskim prelazima i promenama poprečnih preseka još uvek nije moguće opisati nekim jednostavnim zavisnostima opterećenja, napona, karakteristika materijala i veličine površine poprečnog preseka, pa se koriste empirijski izvedene zavisnosti, po pravilu uslovljene obimnim eksperimentalnim ispitivanjima.

Inicijacija i rast prsline izazvane promenljivim opterećenjem predmet su mnogih istraživanja. Parisov zakon rasta prsline, koji uspostavlja zavisnost veličine delujućeg promenljivog opterećenja, odnosno, odgovarajućeg opsega faktora intenziteta napona i rasta prsline po ciklusu, je danas opšte prihvaćen, jer načelno opisuje mikromehaničko ponašanje rastuće prsline. Radi potpunijeg razumevanja uzroka i načina pojave i rasta prslina u zavarenim spojevima čelika povišene čvrstoće potrebno je da se utvrdi kako heterogenost strukture i mehaničkih svojstava zavarenog spoja, a pre svega HAZ, utiče na pojavu i rast prsline kao i na parametre rasta zamorne prsline, /3/.

OSNOVNI MATERIJAL I TEHNOLOGIJA ZAVARIVANJA

Osnovni materijal

Za eksperimentalna ispitivanja korišćen je čelik NIOMOL 490K iz grupe mikrolegiranih čelika sa molibdenom, naponom tečenja min. 490 MPa i garantovanom prelaznom temperaturom krtosti od –60°C, proizveden u „Železarni ACRONI“, Jesenice. Namenjen je pre svega za rad u uslovima dinamičkog opterećenja i na niskim temperaturama. Hemijski sastav ispitivanog čelika je dat u tab. 1, a osnovna mehanička svojstva u tab. 2.

Tabela 1. Hemijski sastav čelika NIOMOL 490K, tež. %

C	Si	Mn	P	S	Al	Cr
0,10	0,41	0,57	0,008	0,002	0,042	0,53

Tabela 2. Mehanička svojstva čelika NIOMOL 490 K

Pravac	Napon tečenja	Zatezna čvrstoća	Izduženje	Energija udara
	$R_{p0,2}$ (MPa)	R_m (MPa)	A (%)	ISO-V (J)
L–T	576	694	28,1	242,248,263
T–L	571	699	22,8	245,248,255

L–uzdužni pravac (valjanja), T–poprečni pravac

Tehnologija zavarivanja

Za zavarivanje mikrolegiranih čelika NIOMOL 490K važno je odabrati prikladne parametre režima postupka da se izbegne pogoršanje osobine čelika. Termički ciklus zavarivanja zavisi od:

- unete energije,
- debljine materijala,
- temperature osnovnog materijala i temperature predgrevanja,
- oblika zavarenog spoja i dimenzija,

Since the problem of crack existence in responsible welded structures, made of microalloyed steels, frequently occurs, as is the case with pressure vessels, the necessity to test whether welded joints are prone to crack initiation and growth is clear.

The most important characteristics for service safety of welded joints are those describing crack initiation and growth caused by variable loading. The occurrence of fatigue cracks on smooth and homogeneous designed shapes due to local stress concentration at inevitable transitions in design geometry and at cross section changes still can not be described by simple relations between load, stress, material characteristics and cross section area size, and empirically derived dependencies are used, generally requiring extended experimental testing.

Crack initiation and growth caused by variable loading is the subject of numerous investigations. The crack growth law of Paris that had established the relation between the applied variable load quantity, or the corresponding stress intensity factor range and crack growth per cycle, is today commonly accepted, because it basically describes micromechanical behaviour of the growing crack. In order to understand as much as possible the causes and modes of crack occurrence and growth in welded joints of high strength steels it is necessary to determine how the heterogeneity of microstructure and mechanical properties of welded joints, primarily of HAZ, affect crack initiation and growth, as well as fatigue crack growth parameters, /3/.

PARENT MATERIAL AND WELDING TECHNOLOGY

Parent material

Experimental testing is performed with NIOMOL 490K steel of a molybdenum microalloyed steel group, of yield strength min. 490 MPa and specified nil-ductility transition temperature of –60°C, produced in “Steelworks ACRONI”, Jesenice. It is primarily applied for dynamic loading conditions and at low temperatures. Chemical composition of the tested steel is given in Table 1, and basic mechanical properties in Table 2.

Table 1. Chemical composition of NIOMOL 490K, wt. %.

C	Si	Mn	P	S	Al	Cr
0.10	0.41	0.57	0.008	0.002	0.042	0.53

Table 2. Mechanical properties of NIOMOL 490K.

Direction	Yield strength	Ultimate strength	Elong.	Impact energy
	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)	ISO-V (J)
L–T	576	694	28,1	242,248,263
T–L	571	699	22,8	245,248,255

L–longitudinal (rolling) direction, T–transverse direction

Welding technology

The welding regime of microalloyed steel NIOMOL 490K requires a selection of proper parameters in order to avoid deterioration of properties. The welding thermal cycle depends on:

- heat input,
- material thickness,
- temperature of parent metal and preheating temperature,
- welded joint shape and size,

– broja prolaza.

S obzirom na vrstu čelika i zahteve tehničkih propisa, zavarivanje uzoraka je izvedeno sa dva tehnološka postupka, /1/:

– ručno-elektrolučno zavarivanje (E postupak) elektrodom EVB Ni Mo, ACRONI, Jesenice, i
– zavarivanje u zaštiti CO_2 (MAG) žicom VAC 60 Ni, ACRONI, Jesenice.

Propisani hemijski sastav dodatnog materijala dat je u tab. 3, a mehanička svojstva u tab. 4.

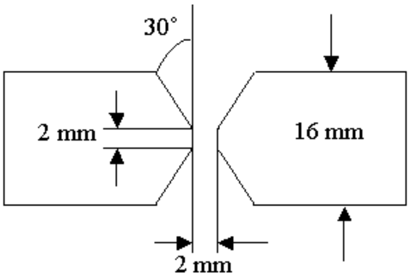
Tabela 3. Hemijski sastav dodatnog materijala, tež. %

Dodatni materijal	C	Si	Mn	Ni	Mo	S	P
VAC 60 Ni	0,08	0,80	1,5	1,10		<0,025	<0,025
EVB NiMo	0,06	0,45	1,15	2,5	0,4		

Tabela 4. Mehanička svojstva čistog metala šava

Dodatni materijal	Napon tečenja (MPa)	Zatezna čvrstoća (MPa)	Izduženje (%)	Energija udara (J)	
				–20°C	–40°C
VAC 60 Ni	440–510	560–630	22–30		> 47
EVB NiMo	> 510	580–710	> 22	> 47	> 47

Sučeoni zavareni spoj je izveden sa simetričnom X pripremom ivica, JUS C.T3.030, sl. 1. Redosled prolaza pri zavarivanju dat je na sl. 2.



Slika 1. Priprema ivica zavarenog uzorka
Figure 1. Edge preparation of welding sample.

Izabrani parametri režima zavarivanja za E i MAG postupke su prikazani u tab. 5.

Tabela 5. Parametri zavarivanja

Postupak zavarivanja	Napon (V)	Jačina struje (A)	Brzina zavariv. (cm/min)	Uneta toplota (kJ/cm)
E	24	280	20	12–15
MAG	28	300	32	15–17

ODREĐIVANJE ŽILAVOSTI LOMA PRI RAVNOJ DEFORMACIJI K_{Ic}

Uticaj heterogenosti mikrostrukture i mehaničkih osobina zavarenog spoja se pre svega odražava kroz položaj vrha zamorne prsline na epruveti i osobine područja kroz koje se lom razvija. Žilavost loma pri ravnoj deformaciji, K_{Ic}, epruveta izrađenih iz zavarenih ploča čelika NIOMOL 490K je ispitana radi ocene ponašanja osnovnog metala (PM), metala šava (WM) i zone uticaja toplote (HAZ) u prisustvu greške tipa prsline, koja je u zavarenim spojevima najopasnija greška.

Ispitivanje je izvedeno korišćenjem epruvete za savijanje u tri tačke SEN(B), definisane standardom ASTM E399, /4/, i prikazane na sl. 3, jer je veoma prikladna za ispitivanje. Zarez i vrh zamorne prsline su postavljeni u PM, WM i HAZ.

– number of passes.

According to steel type and technical code requirements, two welding processes were applied for welding samples, /1/:

– metal manual arc welding (MMA process) with electrode EVB Ni Mo, ACRONI, Jesenice, and
– CO_2 gas shielded arc welding (MAG) with wire VAC 60 Ni, ACRONI, Jesenice.

The specified chemical composition of consumables is given in Table 3, and mechanical properties in Table 4.

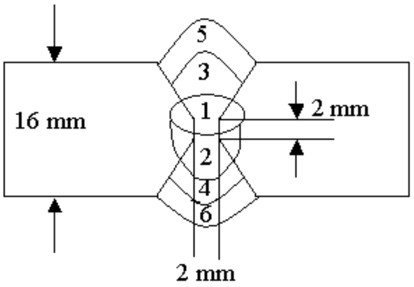
Table 3. Chemical composition of consumable, wt. %.

Consumable	C	Si	Mn	Ni	Mo	S	P
VAC 60 Ni	0.08	0.80	1.5	1.10		<0.025	<0.025
EVB NiMo	0.06	0.45	1.15	2.5	0.4		

Table 4. Mechanical properties of pure weld metal.

Consumable	Yield strength (MPa)	Ultimate strength (MPa)	Elong. (%)	Impact energy (J)	
				–20°C	–40°C
VAC 60 Ni	440–510	560–630	22–30		> 47
EVB NiMo	> 510	580–710	> 22	> 47	> 47

Butt welded joint is performed with symmetrical X groove preparation, JUS C.T3.030, Fig. 1. The sequence of welding passes is given in Fig. 2.



Slika 2. Redosled zavarivanja prolaza
Figure 2. Sequence of welding passes.

Selected welding regime parameters for MMA and MAG processes are presented in Table 5.

Table 5. Welding parameters.

Welding process	Voltage (V)	Current (A)	Welding rate (cm/min)	Heat input (kJ/cm)
E	24	280	20	12–15
MAG	28	300	32	15–17

DETERMINATION OF PLANE STRAIN FRACTURE TOUGHNESS K_{Ic}

The effect of the heterogeneity in the welded joint microstructure and its mechanical properties primarily reflect on the location of fatigue pre-crack on the specimen and on properties of regions through which fracture develops. Plane strain fracture toughness, K_{Ic}, of specimens produced of NIOMOL 490K steel welded plates is tested for evaluating the behaviour of parent metal (PM), weld metal (WM) and heat-affected-zone (HAZ) in the presence of a crack-like defect, as the most threatening defect in the welded joint.

Tests are performed using three-point bend specimen SEN(B), defined in standard ASTM E399, /4/, and shown in Fig. 3, as very convenient for testing. The notch and fatigue crack tip are located in the PM, the WM and in the HAZ.

Osnovi uslov debljine epruvete, potreban za uspostavljanje ravnog stanja deformacije, prema ASTM E399:

$$B \geq 2,5\left(\frac{K_{Ic}}{R_{p0,2}}\right)^2 \qquad (1)$$

nije ispunjen debljinom epruvete od 12 mm za napon tečenja čelika NIOMOL 490K (tab. 2), pa je umesto linearno-elastične mehanike loma (standard ASTM E399) korišćena elasto-plastična mehanike loma prema standardima ASTM E813, /5/, i ASTM E1152, /6/, ASTM E1820 i BS 7448. Primenjeni postupak omogućava da se vrednost kritičnog faktora intenziteta napona, K_{Ic}, odredi posredno, preko kritičnog J integrala, mere žilavosti loma, J_{Ic}, praćenjem razvoja prsline u plastičnom području.

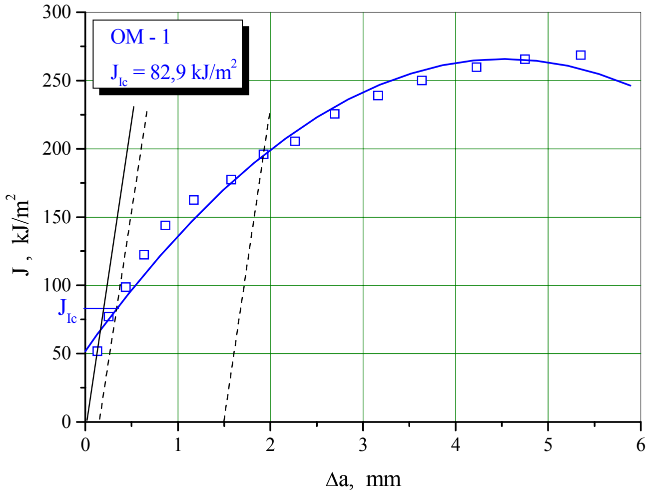
Prema tome, cilj ovog eksperimenta je određivanje kritične vrednosti J integrala, J_{Ic}, a postupak ispitivanja se ogleda u dobijanju krive otpornosti prema prslini, R–krive, odnosno, J–Δa zavisnosti, koja predstavlja vrednosti J integrala za ravnomerne priraštaje prsline Δa.

Eksperimenti u ovom istraživanju su izvedeni metodom ispitivanja jedne epruvete sukcesivnim parcijalnim rasterećenjem, odnosno, metodom popustljivosti jedne epruvete, kako je to definisano standardom ASTM E1152. Cilj metode popustljivosti je da se registruje veličina razvoja prsline, Δa, iz zapisa koji se dobija tokom ispitivanja.

Na osnovu podataka prikupljenih sa kidalice i merenja otvora prsline (COD davač), konstruisani su dijagrami sila F–otvaranje usana vrha prsline δ (CMOD).

Korišćenjem dobijenih podataka konstruiše se J–Δa kriva u vidu regresione linije, prema ASTM E813. Iz regresione linije dobijene na taj način određuje se kritična vrednost J integrala, J_{Ic}. Prikazani su tipični primeri krivih J–Δa dobijenih ispitivanjem epruveta sa zarezom u:

- osnovnom metalu (PM) (sl. 4),
- metalu šava (WM), na sl. 5, dobijen elektrodom EVB NiMo i na sl. 6, dobijen žicom VAC 60Ni, i
- zoni uticaja toplote (HAZ), na sl. 7, za E postupkom zavareni spoj, i na sl. 8, za spoj zavaren MAG postupkom u zaštitnom gasu CO_2 i dodatnim materijalom VAC 60Ni.



Slika 4. Dijagram J–Δa epruvete sa zarezom u PM
Figure 4. J–Δa diagram for specimen with notch in PM.

Basic specimen thickness requirements for establishing the plane strain condition, according to ASTM E399:

$$B \geq 2.5\left(\frac{K_{Ic}}{R_{p0.2}}\right)^2 \qquad (1)$$

is not fulfilled by specimen thickness of 12 mm for yield strength of NIOMOL 490K steel (Table 2), so instead of linear-elastic fracture mechanics (ASTM E399 standard) elastic-plastic fracture mechanics is used according to standards ASTM E813, /5/, and ASTM E1152, /6/, ASTM E1820, and BS 7448. The applied procedure allowed to determine the critical stress intensity value, K_{Ic}, indirectly, via critical J integral, a measure of fracture toughness, J_{Ic}, considering crack development in the plastic region.

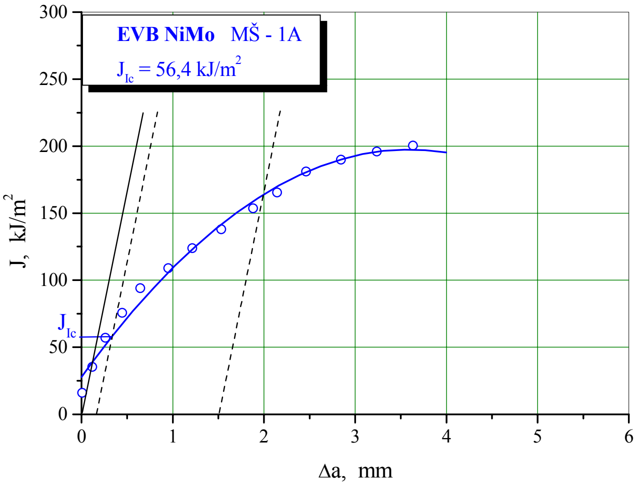
Accordingly, the goal of this experiment is determination of J integral critical value, J_{Ic}, and the testing procedure reflects in obtaining the crack resistance curve, the R-curve, or J–Δa dependence, representing J integral values for uniform crack extension Δa.

Experiments in the investigation were performed by successive partial unloading, that is to say by the single specimen compliance method, as defined in ASTM E1152. The objective of the compliance method is to register the crack extension value, Δa, from the record obtained in the test.

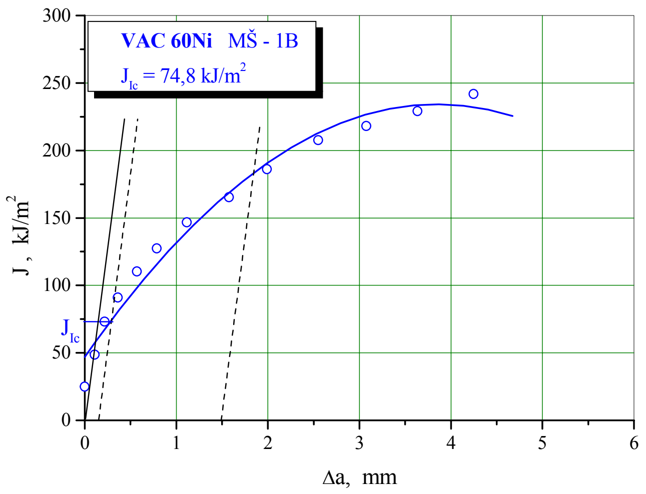
Based on data acquired from the test machine and crack opening displacement measurement (COD gauge), load F vs. crack mouth opening displacement δ (CMOD) diagrams are plotted.

Based on acquired data, the J–Δa curve is plotted in the form of a regression line, according to ASTM E813. The regression line obtained in this way serves for determining the critical value of J integral, J_{Ic}. Typical J–Δa curve examples are presented, obtained from specimens notched in:

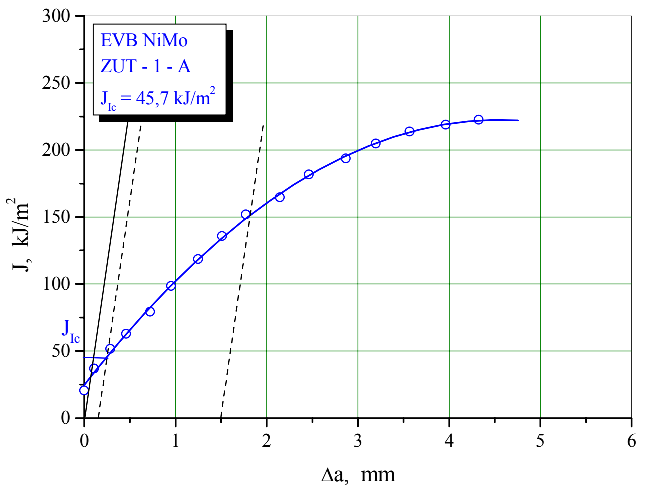
- parent metal (PM) (Fig. 4),
- weld metal (WM), in Fig. 5, obtained by electrode EVB NiMo, and in Fig. 6 by wire VAC 60Ni, and
- heat-affected-zone (HAZ), in Fig. 7, for a MMA welded joint, and in Fig. 8 for CO_2 gas shielded welding process using consumable VAC 60Ni.



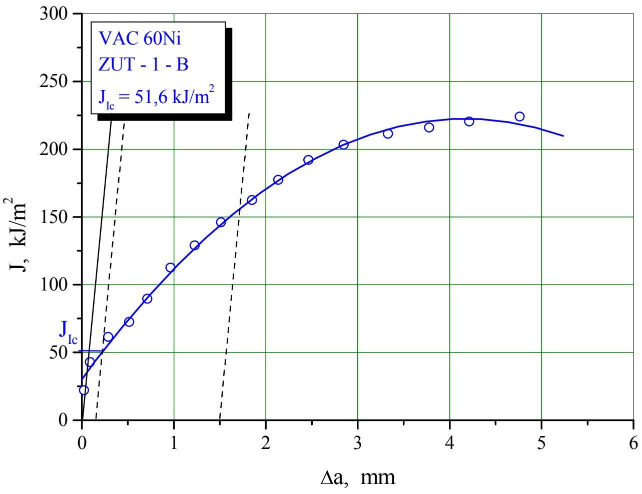
Slika 5. Dijagram J–Δa (zarez u WM, dodatni materijal EVB NiMo)
Figure 5. J–Δa diagram (notch in WM, consumable EVB NiMo).



Slika 6. Dijagram *J*–Δ*a* (notch in WM, dodatni materijal VAC 60Ni)
Figure 6. *J*–Δ*a* diagram (notch in WM, consumable VAC 60Ni).



Slika 7. Dijagram *J*–Δ*a* (notch in HAZ, dodatni mat. EVB NiMo)
Figure 7. *J*–Δ*a* diagram (notch in HAZ, consumable EVB NiMo).



Slika 8. Dijagram *J*–Δ*a* za epruvetu sa zarezom u HAZ (dodatni materijal VAC 60Ni)
Figure 8. *J*–Δ*a* diagram for specimen with notch in HAZ (consumable VAC 60Ni).

Poznavajući kritičnu vrednost *J* integrala, J_{Ic}, može se izračunati kritična vrednost faktora intenziteta napona ili žilavost loma pri ravnoj deformaciji, K_{Ic}, pomoću zavisnosti:

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

Ovde je E–modul elastičnosti, a ν–koeficijent Poasona. Izračunate vrednosti žilavosti loma pri ravnoj deformaciji, K_{Ic}, su date u tab. 6 za epruvete sa zarezom u PM, tab. 7 za epruvete sa zarezom u WM, i u tab. 8 za epruvete sa zarezom u HAZ.

Knowing the critical value of *J* integral, J_{Ic}, it is possible to calculate the critical value of stress intensity factor or plane strain fracture toughness, K_{Ic}, by applying the relationship:

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

Here, E is elasticity modulus, and ν is Poisson’s ratio. Calculated values of plane strain fracture toughness, K_{Ic}, are given in Table 6 for specimen notched in PM, in Table 7 for specimens notched in WM, and in Table 8 for specimens notched in HAZ.

Tabela 6. Vrednosti parametara mehanike loma za epruvete sa zarezom u osnovnom materijalu
Table 6. Fracture mechanics parameters values for specimens notched in the parent metal.

Oznaka epruvete	Kritični *J* integral, J_{Ic} (kJ/m^2)	Kritični faktor intenziteta napona, K_{Ic} (MPa·m$^{1/2}$)
Specimen no.	Critical *J* integral, J_{Ic} (kJ/m^2)	Critical stress intensity factor, K_{Ic} (MPa·m$^{1/2}$)
OM-1	82.9	138.5
OM-2	79.3	135.3
OM-3	80.0	135.9

Tabela 7. Vrednosti parametara mehanike loma za epruvete sa zarezom u metalu šava
Table 7. Fracture mechanics parameters values for specimens notched in the weld metal.

Oznaka epruvete	Korišćena elektroda	Kritični *J* integral, J_{Ic} (kJ/m^2)	Kritični faktor intenziteta napona, K_{Ic} (MPa·m$^{1/2}$)
Specimen no.	Consumable	Critical *J* integral, J_{Ic} (kJ/m^2)	Critical stress intensity factor, K_{Ic} (MPa·m$^{1/2}$)
MŠ-1A	EVB NiMo	56.4	113.6
MŠ-2A		57.0	112.8
MŠ-3A		61.4	117.0
MŠ-1B	VAC 60Ni	74.8	128.4
MŠ-2B		71.7	127.1
MŠ-3B		69.5	125.1

Tabela 8. Vrednosti parametara mehanike loma za epruvete sa zarezom u HAZ
Table 8. Fracture mechanics parameters values for specimens notched in the HAZ.

Oznaka epruvete	Korišćena elektroda	Kritični *J* integral, J_{Ic} (kJ/m^2)	Kritični faktor intenziteta napona, K_{Ic} (MPa·m$^{1/2}$)
Specimen no.	Consumable	Critical *J* integral, J_{Ic} (kJ/m^2)	Critical stress intensity factor, K_{Ic} (MPa·m$^{1/2}$)
ZUT-1-A	A-EVB NiMo	45.7	100.1
ZUT-2-A		47.3	102.5
ZUT-3-A		45.8	100.8
ZUT-1-B	B-VAC 60Ni	51.6	107.6
ZUT-2-B		53.9	110.7
ZUT-3-B		57.8	114.7

Primetno je da strukturne i mehaničke heterogenosti zavarenog spoja imaju značajan uticaj na njegovu otpornost prema razvoju prsline, kako u elastičnom, tako i u plastičnom području. 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 rezultata.

Heterogenost mehaničkih svojstava zavarenog spoja, odnosno, konstituenata zavarenog spoja, se jasno razaznaje kroz dobijene vrednosti žilavosti loma pri ravnoj deformaciji, K_{Ic}, određenoj posredno preko kritične vrednosti *J* integrala, J_{Ic}. Najveću izmerenu vrednost K_{Ic} imaju epruvete sa zarezom u osnovnom metalu. Dobijene vrednosti K_{Ic} od prosečno 136,6 MPa·m$^{1/2}$ su u granicama literaturnih vrednosti za ovu grupu mikrolegiranih čelika, /3/. Nešto niže vrednosti K_{Ic} imaju epruvete sa zarezom u WM, od kojih dodatni materijal EVB NiMo, sa srednjom vrednosti K_{Ic} = 126,9 MPa·m$^{1/2}$ pokazuje veću otpornost prema lomu nego dodatni materijal VAC 60Ni, sa srednjom vrednosti K_{Ic} = 114,5 MPa·m$^{1/2}$. Međutim, u razmatranom slučaju su razlike relativno male i kreću se približno 10–15 MPa·m$^{1/2}$ u odnosu na minimalnu i maksimalnu vrednost. Najmanje vrednosti ima HAZ, koji inače predstavlja kritično mesto u zavarenom spoju.

ODREĐIVANJE BRZINE RASTA ZAMORNE PRSLINE

U slučaju umerenih opterećenja, odnosno, pri ravnomernom zamoru, brzina rasta zamorne prsline je definisana prema Parisovom zakonu data u zavisnosti od raspona faktora intenziteta napona ΔK_I:

$$\frac{da}{dt} = C\left(\Delta K_I\right)^m \tag{3}$$

gde su *C* i *m* konstante materijala, a konstanta *n* obično ima vrednosti između 2 i 4.

Iz oštrih koncentratora napona će u uslovima promenljivog opterećenja posle određenog broja ciklusa doći do inicijacije prsline i do njenog rasta ako je prekoračen prag

It is noticeable that structural and mechanical heterogeneities of welded joints have significant effect on its resistance to crack growth, both in elastic and in plastic regions. This is why it is important when prescribing requirements for fracture mechanics tests to define not only the testing procedure and fatigue crack location, but also how to interpret and qualify the results.

Heterogeneity of mechanical properties in the welded joint, or in other words the welded joint constituents, can be clearly recognised through obtained values of plane strain fracture toughness, K_{Ic}, determined indirectly via critical *J* integral value, J_{Ic}. The highest measured K_{Ic} values belong to specimens notched in the parent metal. Obtained values of 136.6 MPa·m$^{1/2}$ in average are within limits of reported values for this class of microalloyed steel in references, /4/. Somewhat lower K_{Ic} values exhibited specimens notched in WM, of which consumable EVB NiMo with average value K_{Ic} = 126.9 MPa·m$^{1/2}$ has demonstrated higher fracture resistance than VAC 60Ni with K_{Ic} = 114.5 MPa·m$^{1/2}$ as average value. However, in the considered case the differences are relatively small and amount to 10–15 MPa·m$^{1/2}$ related to minimum and maximum values. The lowest values belong to HAZ, representing the critical part of welded joint.

DETERMINING FATIGUE CRACK GROWTH RATE

In the case of modest loads, or at steady fatigue, the fatigue crack growth rate is defined as a function of the stress intensity factor range ΔK_I, according to the power law relationship, commonly known as Paris law:

$$\frac{da}{dt} = C\left(\Delta K_I\right)^m \tag{3}$$

where *C* and *m* are material constants, and the constant *n* is usually between 2 and 4.

At locations of severe stress raisers in variable loading condition after a determined number of cycles the crack will initiate and propagate if the fatigue threshold, ΔK_{th}, is exceeded. Since the structure under determined conditions zamora ΔK_{th}. Kako konstrukcija pod određenim uslovima neće biti ugrožena dok prslina ne dostigne kritičnu veličinu, može se, uz prethodne analize, dopustiti eksploatacija konstrukcije sa prslinom i u periodu rasta prsline. Bitan podatak za odluku o daljoj eksploataciji je poznavanje brzine rasta prsline i njene zavisnosti od delujućeg opterećenja. Standard ASTM E647, /7/, propisuje merenje brzine rasta zamorne prsline *da/dN* (*a* je dužina prsline, *N* broj ciklusa), koja se razvija iz postojeće prsline i proračun opsega faktora intenziteta napona, ΔK. To znači da epruveta treba da ima zamornu prslinu. Dva su bitna ograničenja u standardu ASTM E647: brzina rasta mora da je veća od 10^{-8} m/ciklus da bi se izbeglo područje praga zamora, ΔK_{th}, a opterećenje treba da bude konstantne amplitude.

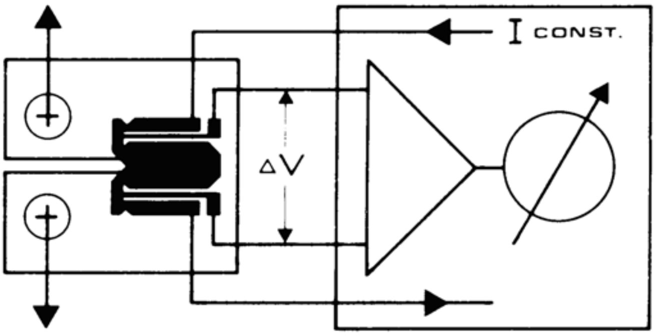
Ispitivanje u cilju određivanja brzine rasta zamorne prsline *da/dN* i praga zamora ΔK_{th} izvedeno je na standardnim Šarpi V epruvetama metodom savijanja epruvete u tri tačke na rezonantnom visokofrekventnom pulzatoru CRACKTRONIC.

Ispitivanje je izvedeno u kontroli sile. Na mehanički pripremljenim epruvetama su zalepljene merne trake RUMUL RMF A-5, merne dužine 5 mm, pomoću kojih je praćen rast prsline, sl. 9, uređajem FRACTOMAT, baziranim na električnom potencijalu trake i povezanim sa instrumentima. Merna traka, tanka otporna merna folija, zalepljena na epruvetu na isti način kao i klasične merne trake za merenje deformacija. Kako zamorna prslina raste ispod merne folije, ova se cepa, prateći vrh zamorne prsline, čime se električni otpor folije menja linearno sa promenom dužine prsline.

will not be endangered until the crack reaches critical value, it is possible, following preliminary analysis, to allow the operation of the structure containing the crack also in the time period of crack growth. Knowledge of crack growth rate and its dependence on applied load is substantial information for deciding on further exploitation. Standard ASTM E647, /7/, defines the procedure of measuring fatigue crack growth rate *da/dN* (*a*–crack length, *N*–number of cycles) that develops from an existing crack, and also calculates the stress intensity factor range, ΔK. This means the specimen should have a fatigue pre-crack. There are two basic limitations in ASTM E647: crack growth rate should be higher than 10^{-8} m/cycle in order to avoid fatigue threshold region, ΔK_{th}, and the load should be of constant amplitude.

Tests for determining the fatigue crack growth rate *da/dN* and fatigue threshold ΔK_{th} are performed with standard Charpy V specimens by applying the three point bend specimens on resonant high frequency CRACKTRONIC pulsator.

Tests are performed in load control conditions. Strain gauges RUMUL RMF A-5 of 5 mm length are cemented on machined specimens, allowing crack growth monitoring by FRACTOMAT device, based on electrical potential of gauge and connected with instrumentation Fig. 9. The measuring gauge, a thin resistant measuring foil, is cemented on the specimen in the same way as classical strain gauges. As the crack grows under the measuring foil causing it to rip, it traces the fatigue crack tip, changing foil electrical resistance linearly with the crack length.



Slika 9. Šema merne folije i načina registrovanja rasta prsline
Figure 9. Scheme of measurement foil and crack growth detection.

Brzina rasta zamorne prsline je određena na osnovu dobijenih zavisnosti dužina prsline *a*–broj ciklusa *N*. Naime, u toku eksperimenta je automatski zapisivan broj ciklusa za svakih 0,05 mm rasta prsline. Dobijene zavisnosti *a–N*, su korišćene kao podloga za određivanje brzine rasta zamorne prsline, *da/dN*.

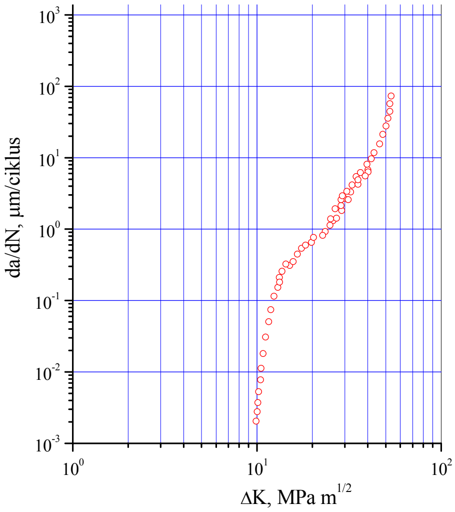
Na osnovu toka ispitivanja izračunate su i nacrtane zavisnosti log *da/dN*–log ΔK. Tipični dijagrami zavisnosti *da/dN* od ΔK su dati na sl. 10 za epruvetu sa zarezom u PM, sl. 11, za epruvete sa zarezom u WM i HAZ za E postupak, i na sl. 12 za epruvete sa zarezom u WM i HAZ za postupak MAG.

Radi lakšeg poređenja dobijenih rezultata ispitivanja, u tab. 9 su date vrednosti praga zamora ΔK_{th}, koeficijenta *C* i eksponenta *m* zamornog rasta prsline.

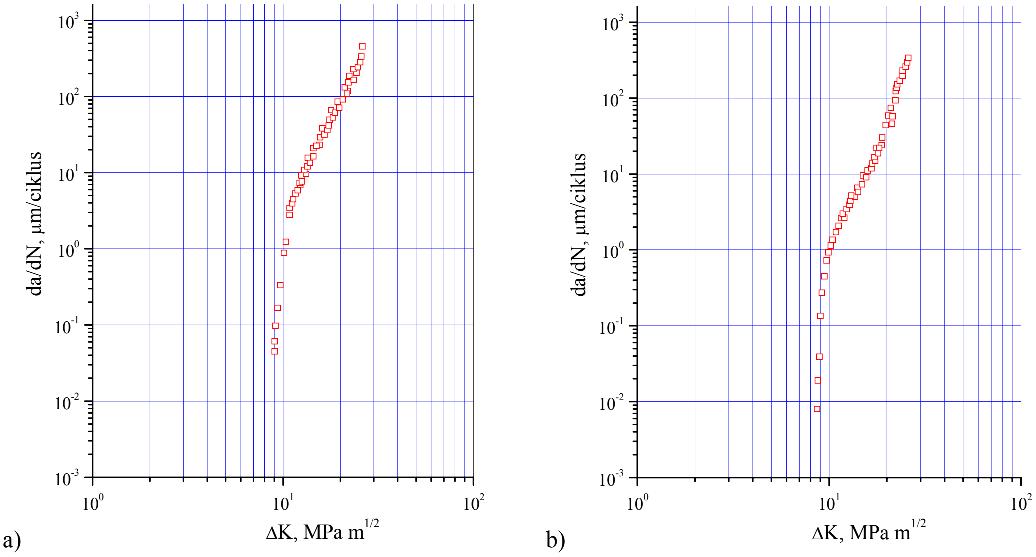
Fatigue crack growth rate is determined based on obtained relationships of crack length *a*–number of cycles *N*. In fact, in the experiment the number of cycles is continuously registered for each 0.05 mm of crack growth. Obtained dependence curves *a–N* are used as the basis for determining fatigue crack growth rate, *da/dN*.

Based on the course of the test the relations log *da/dN*–log ΔK are calculated and plotted. Typical diagrams relating *da/dN* to ΔK are given in Fig. 10 for specimen notched in PM, in Fig. 11 for the specimen of the MMA welded joint notched in WM and HAZ and in Fig. 12 for the specimen of MAG welded joint notched in WM and HAZ.

For sake of easier comparison the results in Table 9 also show values of the fatigue threshold ΔK_{th}, coefficient *C* and exponent *m* for fatigue crack growth.

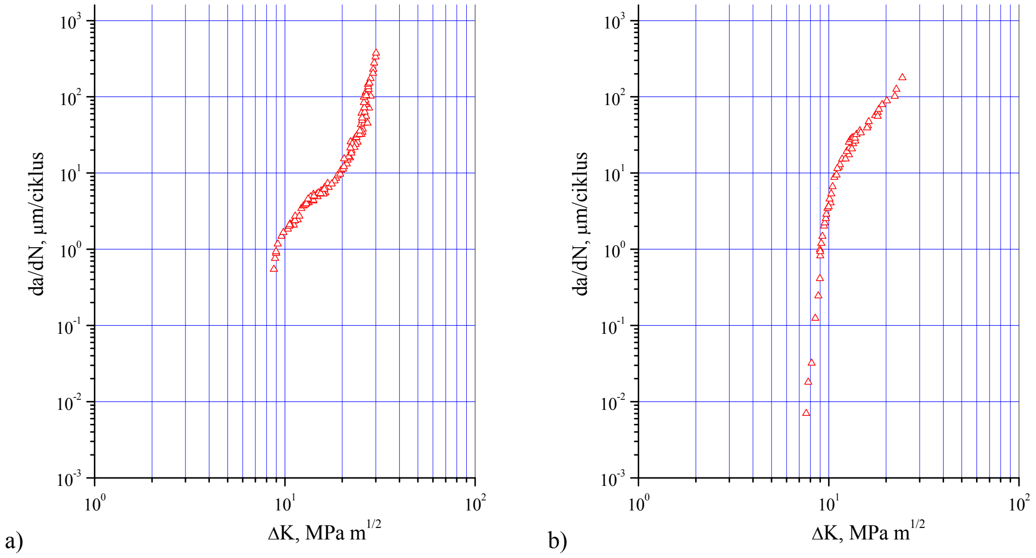


Slika 10. Dijagram zavisnosti *da/dN*–Δ*K* za PM NIOMOL 490K
Figure 10. Dependence *da*–Δ*K* for PM NIOMOL 490K.



a) b)

Slika 11. Dijagram zavisnosti *da/dN*–Δ*K* za E postupak: a) WM, b) HAZ
Figure 11. Dependence *da/dN*–Δ*K* for MMA welding: a) WM, b) HAZ.



a) b)

Slika 12. Dijagram zavisnosti *da/dN*–Δ*K* za MAG postupak: a) WM, b) HAZ
Figure 12. Dependence *da/dN*–Δ*K* for MAG procedure: a) WM, b) HAZ.

Tabela 9. Rezultati određivanja parametara rasta zamorne prsline
Table 9. Results of determined fatigue crack growth parameters.

Mesto zareza	Primenjena tehnologija	Prag zamora, ΔK_{th} (MPa·m$^{1/2}$)	Koeficijent C	Eksponent m
Location of notch	Applied welding	Fatigue threshold, ΔK_{th} (MPa·m$^{1/2}$)	Coefficient C	Exponent m
OM		9.4	$3.3\cdot10^{-10}$	3.81
MŠ	REL	9.1	$3.6\cdot10^{-10}$	3.39
ZUT		8.7	$3.1\cdot10^{-10}$	3.88
MŠ	MAG	8.8	$4.2\cdot10^{-10}$	3.31
ZUT		7.6	$3.8\cdot10^{-10}$	3.65

Ispitivanja su izvedena pri rastućem opsegu faktora intenziteta napona i konstantnom odnosu $R = \sigma_{\min}/\sigma_{\max} = 0{,}1$, gde je $\sigma_{\min}$ najniži, a $\sigma_{\max}$ najviši nivo napona u ciklusu. To znači da amplituda dinamičkog opterećenja u toku priraštaja prsline treba da se smanjuje, isto kao i frekvencija, što je tok ispitivanja i potvrdio. Prikazani dijagrami takođe ukazuju i na uticaj veličine maksimalne sile u procesu ispitivanja. Nagib krivih u oblasti II (zona važenja Parisovog zakona) je po pravilu manji ako je opseg sile veći. Postoje područja u kojima su dijagrami slični, odnosno, u kojima je zavisnost da/dN i ΔK približno ista za svaku grupu epruveta.

Prikazani dijagrami ukazuju da mesto postavljanja V-2 zareza i inicijacije prsline (zarezi u WM i HAZ) ima uticaja na veličinu praga zamora, kao i na vrednosti koeficijenta C i eksponenta m u Parisovoj jednačini. Dobijene vrednosti praga zamora su veće kod E postupka zavarivanja nego kod MAG postupka. Znači da je potreban veći opseg faktora intenziteta napona ΔK da dođe do rasta postojeće prsline u spoju zavarenom E postupkom nego u spoju zavarenom MAG postupkom. Međutim, dobijene vrednosti brzine rasta zamorne prsline da/dN u zoni važenja Parisovog zakona su nešto više kod E postupka nego kod MAG postupka, pokazujući veću otpornost na propagaciju prsline u drugom slučaju. Ovaj podatak je vrlo važan kod izbora tehnologija zavarivanja za konstrukcije koje su u eksploataciji izložene dugotrajnom promenljivom opterećenju, i gde je verovatnoća pojave greške tipa prsline realna.

Vrednosti praga zamora ΔK_{th}, dobijene kod osnovnog materijala ($\Delta K_{th} = 9{,}4$ MPa·m$^{1/2}$) su više od odgovarajućih vrednosti ispitivanja epruveta sa zarezom u WM i HAZ za obe tehnologije zavarivanja.

Uticaj mesta postavljanja zareza i pravca propagacije prsline, odnosno, heterogenosti strukture konstituenata zavarenog spoja, na brzinu rasta zamorne prsline da/dN, je u direktnoj vezi sa određenim parametrima Parisove jednačine, koeficijentom C i eksponentom m. Za analizu je uzeta vrednost opsega faktora intenziteta napona $\Delta K = 15$ MPa·m$^{1/2}$, jer se ova vrednost na dijagramima zavisnosti da/dN–ΔK nalazi u delu stabilnog rasta prsline u kojem važi Parisov zakon. Iz dobijenih rezultata se vidi da najmanju brzinu rasta zamorne prsline, da/dN, imaju uzorci sa prslinom u PM, zatim u WM MAG postupka. Najveća brzina rasta zamorne prsline je nađena kod uzoraka sa vrhom zamorne prsline u ZUT. To znači da je, pri istom opsegu faktora intenziteta napona ΔK (pri istom nivou opterećenju) za epruvete sa vrhom zamorne prsline u PM i WM MAG postupka zavarivanja, potrebno više ciklusa promenljivog opterećenja za isti priraštaj prsline nego za epruvete sa vrhom zamorne prsline u spoju zavarenom E postupkom.

Tests are performed at increasing stress intensity factor range ΔK and constant ratio $R = \sigma_{\min}/\sigma_{\max} = 0.1$, where $\sigma_{\min}$ is the lowest, and $\sigma_{\max}$ the highest stress level in a cycle. This means that the amplitude of dynamic loading should decrease with crack extension, as well as frequency, what is confirmed in the testing process. Presented diagrams also indicate the effect of the maximal load magnitude in the test process. The curve slope in range II (Paris law validity region) is generally lower when the load range is higher. There are regions with similar diagrams, or regions where the dependence da/dN–ΔK is almost the same for each specimen group.

Presented diagrams show that location of V-2 notch and crack initiation positioning (notches in WM and HAZ) have the effect on fatigue threshold value, as well as on coefficient C and exponent m in the Paris equation. Obtained fatigue threshold values are higher at MMA welding than at MAG. This means that a higher stress intensity factor range ΔK is necessary for the initiation of existing crack in joint welded by MMA then in the MAG welded joint. However, obtained fatigue crack growth rate values da/dN are slightly higher in the MMA welded joint than in the MAG welded joint, indicating higher crack propagation resistance in the second case. This information is of special importance for selecting the welding technology of structures exposed in service to long lasting variable loads, and where the probability of occurrence of crack-like defects is real.

Values of fatigue threshold ΔK_{th} obtained for parent metal ($\Delta K_{th} = 9.4$ MPa·m$^{1/2}$) are higher than corresponding test values for specimens notched in WM and HAZ for both welding processes.

The influence of notch location and crack propagation direction, or the structural heterogeneity of welded joint constituents on fatigue crack growth rate da/dN is directly connected to the obtained parameters of the Paris law, coefficient C and exponent m. In the analysis, the accepted value of stress intensity factor range is $\Delta K = 15$ MPa·m$^{1/2}$, since this value in da/dN–ΔK diagrams is within the part of stable crack growth where Paris law is valid. Obtained results show that the lowest fatigue crack growth rate, da/dN, is exhibited in specimens notched in PM, and then in WM of the MAG process. The highest fatigue crack growth rate is found in samples with the fatigue crack tip in HAZ. This means that for the same stress intensity factor range ΔK (at the same load level) for MAG welded specimens notched in PM and WM, much more variable load cycles are required for reaching the same crack extension than for specimens with the fatigue crack tip in the MMA welded joint.

Maksimalna brzina rasta prsline se može očekivati na nivou opsega faktora intenziteta napona koji se približava vrednosti žilavosti loma pri ravnoj deformaciji ΔK_{Ic}, jer na tom nivou dolazi do krtog loma. To znači da, ako te vrednosti unesemo u dobijene dijagrame da/dN–ΔK, moguće je proceniti brzine rasta prsline pri kojima će proces zamora ustupiti mesto razvoju krtog loma pri različitim nivoima opterećenja. Pri većem opterećenju će nastupiti i nepovoljnija situacija, jer mala opterećenja ne mogu izazvati toliko velike brzine rasta zamorne prsline da se približe nivou faktora intenziteta napona koji je potreban za pojavu krtog loma.

Generalno, ponašanje konstituenata zavarenog spoja, kao i zavarenog spoja u celini treba povezati sa promenom nagiba dela krive u zoni važenja Parisovog zakona. Po pravilu, materijali koji imaju manju brzinu rasta zamorne prsline, imaju na dijagramu da/dN–ΔK manji nagib. U razmatranom slučaju, sporiji rast je potvrđen kod uzoraka sa prslinom u PM i WM, jer za istu brzinu rasta zahteva veći opseg faktora intenziteta napona.

Ovakav zaključak je zasnovan prvenstveno na uporednoj analizi rezultata ispitivanja zavarenih spojeva čelika NIOMOL 490, dobijenih E i MAG postupkom, dakle komercijalno dostupnim tehnikama, bez posebnih mera kontrole. Sva ispitana svojstva su pokazala dovoljan stepen sličnosti, odnosno, ni u jednom slučaju nije dobijena razlika u HAZ ili WM u odnosu na PM koja bi bila od značaja za procenu integriteta konstrukcije. To se najbolje vidi u ispitivanju otpornosti na prsline (žilavost, žilavost loma, J_R krive, Parisove krive), odnosno, kod procene integriteta sferne posude pod pritiskom, gde su razlike u nivou napona potrebnog za rast prsline u PM, WM i HAZ svega 2% za oba postupka zavarivanja.

Dobijeni parametri rasta zamorne prsline pokazuju određene razlike za različite tehnologije zavarivanja. Dobijene vrednosti praga zamora ΔK_{th} su veće kod E postupka zavarivanja nego kod MAG postupka. Međutim, dobijene vrednosti brzine rasta zamorne prsline da/dN u zoni važenja Parisovog zakona su nešto više kod E postupka nego kod MAG postupka, odnosno, veću otpornost na propagaciju prsline ima zavareni spoj dobijen MAG postupkom, nego E postupkom zavarivanja.

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7. ASTM E647

Maximum crack growth rate can be expected at the stress intensity factor range level approaching plane strain fracture toughness value ΔK_{Ic}, since at this level, brittle fracture would occur. This means, if these values are introduced in the obtained da/dN–ΔK diagrams it is possible to assess crack growth rates at which the fatigue process will be replaced by brittle fracture at different load levels. At a higher load the situation will be unfavourable, since low loads cannot produce fatigue crack growth rates of so great magnitude to approach the stress intensity factor range required for brittle fracture occurrence.

In general, welded joint constituent behaviour, and also of the entire welded joint should be connected to the change in curve slope in the region of Paris law validity. As a rule, materials exhibiting lower fatigue crack growth rate have a lower slope on the da/dN–ΔK diagram. In the considered case, slower growth is confirmed with samples cracked in PM and WM, since the same growth rate requires a higher stress intensity factor range.

Such a conclusion is based primarily on the comparative results analysis of tested NIOMOL 490 K steel welded joints, produced by MMA and MAG welding processes, apparently for commercially available techniques without special inspection measures. All tested properties have shown a sufficient degree of similarity, and in no single case the obtained difference in HAZ or in WM relative to PM was not significant for structural integrity assessment. This is most clearly visible in crack resistance tests (toughness, fracture toughness, J_R curves, Paris curves), or e.g. in the structural integrity assessment of spherical pressure vessel, where differences in the stress level required for crack growth in PM, WM and HAZ are only 2% for both welding processes.

Obtained parameter for fatigue crack growth have shown certain differences for different welding technologies. Obtained values of the fatigue threshold ΔK_{th} are higher for MMA than for the MAG process. However, the obtained fatigue crack growth rates da/dN in the region of Paris law validity are somewhat higher for MMA than for the MAG welding process, indicating a higher crack propagation resistance of the MAG welded joint than the MMA welded joint.