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## Mismatch effect on fatigue crack propagation limit curves of S690QL, S960QL and S960TM type base materials and their gas metal arc welded joints

### Uticaj neusklađenosti na granične krive širenja zamornih prslina osnovnih materijala tipa S690KL, S960KL i S960TM i njihovih, elektrolučno u zaštiti gasa, zavarenih spojeva

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**Ključne reči:** Čelici povišene čvrstoće, elektrolučno zavarivanje u zaštiti gasa, efekat neusklađenosti, rast zamornih prslina, dizajna ili granične krive

#### Abstract

Nowadays, one of the basic trends in the industry is the environmental impact reduction, in other words the weight decreasing of structural elements and structures, which can be approached by applying different high strength steels. In case of different steel structures, the main manufacturing and joining technology is the welding, the conventional and advanced methods of fusion and pressure welding processes. Beside the weight decreasing, the reliability and safety requirements according to steel structures have significant grown. During the welding process, the welded parts are affected with heat-effect and mechanical loads, which result in inhomogeneous welded joint. The inhomogeneity of the welded joints appears both in microstructural (local) and in geometrical (both local and global) aspects. The changes in microstructure and geometry appear in deflections (basically acceptable), or rather in failures (basically unacceptable); and these influence both the behaviour and the loadability of welded joints. Discontinuities in base materials and their welded joints have especially high danger in case of cyclic loading conditions, which are typical for different structures and structural elements (e.g. bridges, vehicles).

There are different standards and prescriptions containing fatigue crack propagation limit curves and rules for the prediction of the crack growth; simple and two-stage crack growth relationships can be found in the literature, most frequently based on the Paris-Erdogan law. The paper summarizes and presents the results according to our fatigue crack growth investigations on Weldox 700E and Weldox 960E quenched and tempered

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#### Rezime

Danas je jedan od osnovnih trendova u industriji, smanjenje uticaja na životnu sredinu, drugim rečima smanjenje težine konstrukcijskih elemenata i konstrukcija kojima se može pristupiti primenom različitih čelika velike čvrstoće. U slučaju različitih čeličnih konstrukcija, glavna tehnologija proizvodnje i spajanja je zavarivanje, konvencionalnim i naprednim postupcima zavarivanja topljenjem i pritiskom. Pored smanjenja težine, zahtevi za pouzdanost i sigurnost čeličnih konstrukcija su značajno porasli. Tokom procesa zavarivanja, na zavarene delove utiču toplotna i mehanička opterećenja, što rezultira nehomogenim zavarenim spojem. Nehomogenost zavarenih spojeva pojavljuje se i u mikr strukturi (lokalni) i u geometrijskim (i lokalnim i globalnim) aspektima. Promene mikrostrukture i geometrije pojavljuju se u odstupanjima (u osnovi prihvatljivo), ili bolje rečeno u lomovima (u osnovi neprihvatljivo); a oni utiču i na ponašanje i na nosivost zavarenih spojeva. Prekidi u osnovnim materijalima i njihovim zavarenim spojevima imaju posebno veliku opasnost u slučaju cikličnih opterećenja, koji su tipični za različite konstrukcije i konstrukcijske elemente (npr. mostovi, vozila).

Postoje različiti standardi i preporuke koji sadrže granične krive širenja zamorne prslina i pravila za predviđanje rasta prslina; u literaturi se mogu naći jednostavni i dvostepeni odnosi rasta prslina, koji se najčešće zasnivaju na Paris-Erdogan-ovom zakonu. Rad rezimira i prikazuje rezultate prema našim istraživanjima rasta prslina na Weldox 700E i Weldox 960E kaljeni i otpušteni (Q + T) i na Alform 960M termomehanički obrađenom (TM) čeliku



(Q+T) and on Alform 960M thermomechanically treated (TM) high strength steel base materials and their gas metal arc welded joints. The mismatch effect has also been studied; matched, overmatched, undermatched and matched/overmatched (mixed-matched) welded joints were investigated. 15 mm thick plates were used for the investigations, statistical aspects were applied both for presenting the possible crack locations in the real plates, as well as for processing the measured data. Furthermore, the results will be compared with each other, and fatigue crack propagation limit curves will be derived using simple crack growth relationship.

### 1. Introduction

Reliability of a structural element having crack or cracklike defect under cyclic loading conditions is determined by the geometrical features of the structural element and the flaws, the loading conditions, as well as the material resistance to fatigue crack propagation. There are different documents [1-3], standards and recommendations [4-6] containing fatigue crack propagation limit or design curves and rules for the prediction of the crack growth [6, 7]. The background of the fatigue crack propagation limit curves and the calculations consist of two basic parts: statistical analysis of numerous investigations (fatigue crack propagation tests) and fatigue crack propagation law, frequently the Paris- Erdogan law [8],

$$\frac{da}{dN} = C\Delta K^n, \quad (1)$$

where  $da/dN$  is the fatigue crack growth rate,  $\Delta K$  is the stress intensity factor range, furthermore  $C$  and  $n$  are material constants.

The research work and this paper aimed to characterise the fatigue crack propagation resistance of different high strength structural steels and their welded joints using limit curves [9, 10], based on statistical analysis of test results and the Paris-Erdogan law;

determination of limit curves for different high strength structural steels and their gas metal arc welded joints, under mode I (tension) loading condition.

## 2. Testing circumstances

### 2.1 Materials

15 mm thick plates were used for the welding and the base materials and welded joints investigations of SSAB Weldox 700E (abbreviated: W700E) and VOESTALPINE Alform 960M (abbreviated: A960M) material grades. 15 mm thick SSAB Weldox 960E (abbreviated W960E) plate was tested during the

visoke čvrstoće osnovni materijali i njihovi spojevi zavareni elektrolučno u zaštiti gasa. Efekat neusklađenosti je takođe proučen; ispitivani su podudarni, jači (overmatched), slabiji (undermatched), podudarni i podudarni / jači (mešani) zavareni spojevi. Korišćene su ploče debljine 15 mm za istraživanja, primenjeni su statistički aspekti i za predstavljanje mogućih lokacija prslina u stvarnim pločama, kao i za obradu izmerenih podataka. Pored toga, rezultati će se upoređivati jedan sa drugim i sa graničnom krivom širenja zamorne prslina će se izvesti pomoću jednostavnog odnosa rasta prslina.

### 1. Uvod

Pouzdanost konstrukcijskog elementa koji ima prslinu ili defekt koji liči na prslinu u uslovima cikličnog opterećenja, određuje se pomoću geometrijskih karakteristika konstrukcijskog elementa i nedostaci, uslovi opterećenja, kao i otpornost materijala na širenje prslina. Postoje različiti dokumenti [1-3], standardi i preporuke [4-6] koji sadrže granicu širenja zamorne prslina ili konstrukcijske krive i pravila za predviđanje rasta prslina [6, 7]. Pozadina granične krive širenja zamorne prslina i proračuni se sastoje od dva osnovna dela: statistička analiza brojnih istraživanja (testovi širenja zamorne prslina) i zakon o širenju zamorne prslina, poznat kao Paris- Erdogan-ov zakon [8],

$$\frac{da}{dN} = C\Delta K^n, \quad (1)$$

gdje je  $da/dN$  stopa rasta zamorne prslina,  $\Delta K$  je raspon faktora intenziteta napona, dalje su  $C$  i  $n$  materijalne konstante materijala.

Istraživački rad i ovaj rad imaju za cilj

- okarakterisati otpornost na širenje prslina kod različitih konstrukcionih čelika visoke čvrstoće i njihovih zavarenih spojeva koristeći granične krive [9, 10], zasnovane na statističkoj analizi rezultata ispitivanja i Paris-Erdogan-ovom zakonu;

- određivanje graničnih krivih za različite konstrukcione čelike visoke čvrstoće i njihove spojeve elektrolučno zavarene u zaštiti gasa, pod režimom opterećenja I (zatezanje)

## 2. Podaci o ispitivanju

### 2.1 Materijali

Ploče debljine 15 mm korišćene su za ispitivanje zavarivanja, osnovnih materijala i zavarenih spojeva SSAB Weldox 700E (skraćeno: W700E) i VOESTALPINE Alform 960M (skraćeno: A960M). 15 mm debljina SSAB Weldox 960E (skraćeno



base material examinations, too (designated Weldox 960E-BM and abbreviated W960E); furthermore, 20 mm thick plates were welded and investigated (designated Weldox 960E-WJ and abbreviated W960E). Böhler UNION X85, UNION X90 and UNION X96 (abbreviated X85, X90 and X96, respectively) filler metal were used for the production of welded joints. The chemical composition of the base materials and the filler metals, and the mechanical properties can be seen based on quality certificates in Tab. 1 and Tab. 2, respectively. Based on the data given in Tab. 1 and Tab. 2, it can be found that the two Weldox 960E base materials are the same.

W960E) ploča testirana je i tokom ispitivanja osnovnog materijala (označena Weldox 960E-BM i skraćeno W960E); dalje su zavarene i istražene ploče debljine 20 mm (označene sa Weldox 960E-WJ i skraćeno W960E). Za izradu zavarenih spojeva korišćeni su Bohler UNION X85, UNION X90 i UNION X96 (skraćeno X85, X90 i X96) dodatni materijali. Hemijski sastav osnovnih i dodatnih materijala i mehanička svojstva mogu se videti na osnovu potvrda kvaliteta u Tab. 1 i Tab. 2, respektivno. Na osnovu podataka datih u Tab. 1 i Tab. 2, može se utvrditi da su dva osnovna materijala Weldox 960E ista.

| Material Designation | C     | Si    | Mn    | P      | S      |
|----------------------|-------|-------|-------|--------|--------|
| Weldox 700E          | 0.14  | 0.30  | 1.13  | 0.007  | 0.001  |
| Union X85            | 0.07  | 0.68  | 1.62  | 0.010  | 0.010  |
| Union X90            | 0.10  | 0.8   | 1.8   | N/A    | N/A    |
| Weldox 960E-BM       | 0.16  | 0.22  | 1.24  | 0.009  | 0.001  |
| Weldox 960E-WJ       | 0.16  | 0.23  | 1.25  | 0.008  | 0.001  |
| Alform 960M          | 0.084 | 0.329 | 1.65  | 0.011  | 0.0005 |
| Union X96            | 0.1   | 0.81  | 1.94  | 0.015  | 0.011  |
| Material Designation | Cr    | Ni    | Mo    | V      | Ti     |
| Weldox 700E          | 0.30  | 0.04  | 0.167 | 0.011  | 0.009  |
| Union X85            | 0.29  | 1.73  | 0.61  | <0.01  | 0.08   |
| Union X90            | 0.35  | 2.3   | 0.6   | N/A    | N/A    |
| Weldox 960E-BM       | 0.19  | 0.05  | 0.581 | 0.041  | 0.004  |
| Weldox 960E-WJ       | 0.20  | 0.04  | 0.605 | 0.04   | 0.004  |
| Alform 960M          | 0.61  | 0.026 | 0.29  | 0.078  | 0.014  |
| Union X96            | 0.52  | 2.28  | 0.53  | <0.01  | 0.06   |
| Material Designation | Cu    | Al    | Nb    | B      | N      |
| Weldox 700E          | 0.01  | 0.34  | 0.001 | 0.002  | 0.003  |
| Union X85            | 0.06  | <0.01 | N/A   | N/A    | N/A    |
| Union X90            | N/A   | N/A   | N/A   | N/A    | N/A    |
| Weldox 960E-BM       | 0.01  | 0.056 | 0.016 | 0.001  | 0.003  |
| Weldox 960E-WJ       | 0.01  | 0.06  | 0.016 | 0.001  | 0.003  |
| Alform 960M          | 0.016 | 0.038 | 0.035 | 0.0015 | 0.006  |
| Union X96            | 0.06  | <0.01 | N/A   | N/A    | N/A    |

**Tab. 1** The chemical composition of the examined base materials and filler metals [weight %]

**Tab. 1** Hemijski sastav ispitivanih osnovnih i dodatnih materijala [težinski %]

| Material Designation | $R_{p0.2}$ [MPa] | $R_m$ [MPa] | A [%]  | CVN impact energy [J]   |
|----------------------|------------------|-------------|--------|-------------------------|
| Weldox 700E          | 791              | 836         | 17.0   | -40°C: 165              |
| UNION X85            | ≥ 790            | ≥ 880       | ≥ 16.0 | -50°C: ≥ 47; 20°C: ≥ 90 |
| UNION X90            | ≥ 890            | ≥ 950       | ≥ 15.0 | -50°C: ≥ 47; 20°C: ≥ 90 |
| Weldox 960E-BM       | 1007             | 1045        | 16.0   | -40°C: 141              |
| Weldox 960E-WJ       | 1007             | 1053        | 16.0   | -40°C: 105              |
| Alform 960M          | 1051             | 1058        | 16.9   | -40°C: 40               |
| UNION X96            | ≥ 930            | ≥ 980       | ≥ 14.0 | -50°C: ≥ 47; 20°C: ≥ 80 |

**Tab. 2** The mechanical properties of the examined base materials and filler metals

**Tab. 2** Mehanička svojstva ispitivanih osnovnih i dodatnih materijala

## 2.2 Welding circumstances

The dimensions of the welded workpieces were 300 mm x 125 mm. For the equal stress distribution X-grooved (double V-grooved) welding joints were used, with 80° opening angle and with 2 mm gap between the two plates. The welding equipment was a Daihen Varstroj Welbee Inverter P500L (WB-P500L) MIG/MAG power source; 1.2 mm diameter solid wires and 18% CO<sub>2</sub> + 82% Ar gas mixture (M21) were applied. The root layers (2 layers) were made by a qualified welder, while the filler layers (6

## 2.2 Podaci o zavarivanju

Dimenzije zavarenih komada su bile 300 mm k 125 mm. Za jednaku raspodelu naprezanja korišćeni su X žljebovi (dvostruki V žljebovi), sa uglom otvora 80 ° i zazorom od 2 mm između dve ploče. Oprema za zavarivanje je bio Daihen Varstroj Velbee Inverter P500L (VB-P500L) MIG / MAG izvor napajanja; Primenjene su pune žice prečnika 1,2 mm i gasna smeša 18% CO<sub>2</sub> + 82% Ar (M21). Korenske slojeve (2 sloja) napravio je kvalifikovani zavarivač, dok su slojevi ispune (6 slojeva za ploče debljine 15 mm ili



layers for 15 mm thick plates or 10 layers for 20 mm thick plates) by an automated welding car, in all cases. During the welding process, the workpieces were rotated systematically, after each layer. The applied mismatch characteristics (base materials and filler metals pairing) can be found in Tab. 3.

10 slojeva za ploče debljine 20 mm) izvedeni automatskim zavarivačkim vozilom. Tokom procesa zavarivanja, radni komadi se sistematski rotiraju, nakon svakog sloja. Primenjene karakteristike neusklađenosti (uparivanje osnovnih materijala i dodatnih materijala) mogu se naći u Tab. 3.

| Base material | Mismatch type  | Filler metal  |
|---------------|--|---------------|
| Weldox 700E   | matching (M)   | UNION X85     |
| Weldox 700E   | overmatching (OM)  | UNION X90     |
| Weldox 700E   | root layers: matching / filler layers: overmatching (M/OM) | UNION X85/X90 |
| Weldox 960E   | matching (M)   | UNION X96     |
| Aiform 960M   | undermatching (UM)   | UNION X90     |
| Aiform 960M   | matching (M)   | UNION X96     |

**Tab. 3** Mismatch characteristics: the applied base materials and filler metals pairing

**Tab. 3** Karakteristike neusklađenosti: uparivanje osnovnih i dodatnih materijala

The welding parameters were selected based on both theoretical considerations [11-15] and real industrial applications. A welding monitoring system (WeldQAS, developed and delivered by HKS-Prozesstechnik GmbH [16]) was used for the registration of the welding parameters. Based on the registered data, the applied welding parameters (average or range values) were summarized in Tab. 4. The table shows the welding current (I), the voltage (U) and the welding speed (vw) values, also the preheating (T<sub>pre</sub>) and the interpass (T<sub>ip</sub>) temperatures, with the linear energy (E<sub>v</sub>) and the calculated critical cooling time (t<sub>8.5/5</sub>) values. The parameters of the root and the filler layers were summarized separately

Parametri zavarivanja su odabrani na osnovu teorijskih razmatranja [11-15] i stvarnih industrijskih primena. Za registraciju parametara zavarivanja korišćen je sistem za nadgledanje zavarivanja (WeldQAS, koji je razvio i isporučio HKS-Prozesstechnik GmbH [16]). Na osnovu registrovanih podataka, primenjeni parametri zavarivanja (prosečne ili raspon vrednosti) sumirani su u Tab. 4. U tabeli su prikazane vrednosti struje zavarivanja (I), napona (U) i brzine zavarivanja (vw), takođe temperature predgrevanja (T<sub>pre</sub>) i međuslojne temperature (T<sub>ip</sub>), sa linearnom energijom (E<sub>v</sub>) i izračunatom vrednosti kritičnog vremena hlađenja (t<sub>8.5 / 5</sub>). Parametri za sloja korena i slojeve ispune su sažeti odvojeno.

| Base material / filler metal                   | Layer       | T <sub>pre</sub> , T <sub>ip</sub> [°C] | I [A]                 | U [V]                  |
|--|-------------|---|-----------------------|------------------------|
| W700E / X85<br>W700E / X 90<br>W700E / X85/X90 | 1-2 root    | 150                                     | 130-140               | 19.0-20.5              |
|  | 3-8 filler  | 180                                     | 280-300               | 28.5-29.5              |
| W960E / X96                                    | 1 root      | 200                                     | 96                    | 17.3                   |
|  | 2 root      | 180                                     | 194                   | 22.0                   |
|  | 3-12 filler | 150                                     | 298-308               | 29.0-31.0              |
| W960M / X90<br>W960M / X96                     | 1-2 root    | 60                                      | 130-140               | 19.0-20.5              |
|  | 3-8 filler  | 150                                     | 270-300               | 27.0-28.0              |
| Base material / filler metal                   | Layer       | v <sub>w</sub> [cm/min]                 | E <sub>v</sub> [J/mm] | t <sub>8.5/5</sub> [s] |
| W700E / X85<br>W700E / X 90<br>W700E / X85/X90 | 1-2 root    | 20                                      | 700-750               | 7-8                    |
|  | 3-8 filler  | 40                                      | 1000-1100             | 9-11                   |
| W960E / X96                                    | 1 root      | 11                                      | 727                   | 6.7                    |
|  | 2 root      | 27                                      | 764                   | 6.5                    |
|  | 3-12 filler | 45                                      | 940-1000              | 7-8                    |
| W960M / X90<br>W960M / X96                     | 1-2 root    | 20                                      | 700-750               | 7-8                    |
|  | 3-8 filler  | 30-45                                   | 900-1400              | 7-15                   |

**Tab. 4** Applied welding parameters

**Tab.4** Primenjeni parametri zavarivanja

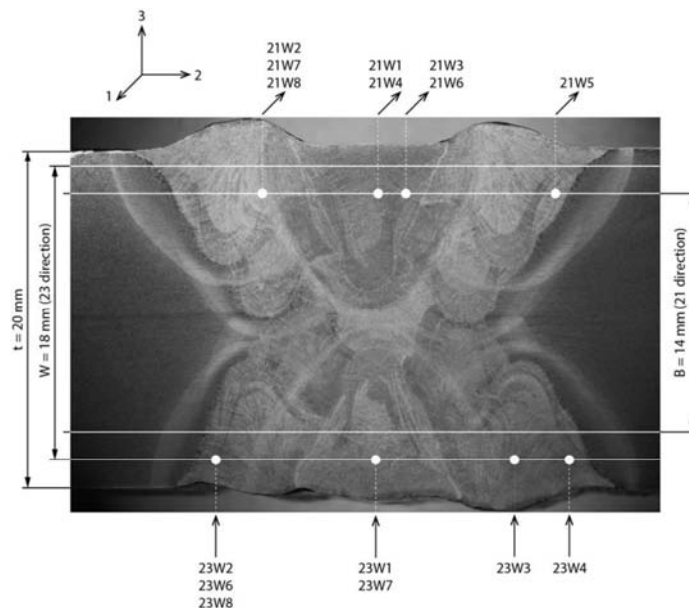


**2.3 Fatigue crack growth tests**

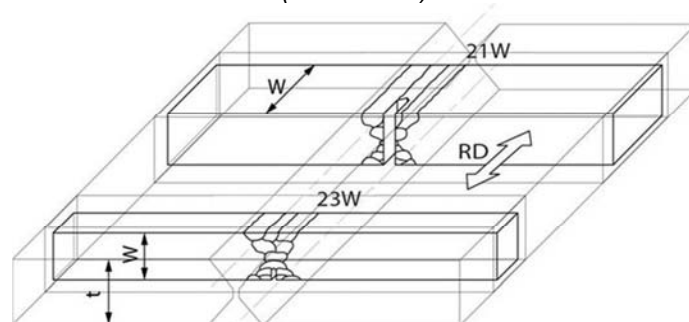
The FCG tests were executed on three-point bending (TPB) specimens, nominal W values were 26 mm (t = 15 mm) and 28 mm (t = 20 mm), and 13 mm (t = 15 mm) and 18 mm (t = 20 mm) for the base materials and the welded joints, in the 21 and 23 directions, respectively. The position of the notches correlated with the rolling direction (T-L, L-T, T-S and L-S). The positions of the cut specimens from the and 23W) were used (Fig. 2). Fig. 3 shows one possible location of the notch in the thickness direction (23W). welded joints is shown in Fig. 1, 21 and 23 directions (21W).

**2.3 Testovi rasta zamorne prsline**

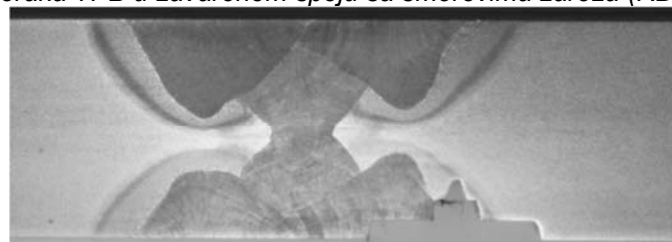
Testovi rasta zamorne prsline (FCG) su izvedeni na uzorcima savijanjem u tri tačke (TPB), nominalne vrednosti W su bile 26 mm (t = 15 mm) i 28 mm (t = 20 mm), a 13 mm (t = 15 mm) i 18 mm (t = 20 mm) za osnovne materijale i zavarene spojeve, u smeru 21 i 23, respektivno. Položaj zarezu je u korelaciji sa pravcem valjanja (T-L, L-T, T-S i L-S). Korišćeni su položaji isečenih uzoraka od i 23W) (Sl. 2). Sl. 3 prikazuje jednu moguću lokaciju zarezu u pravcu debljine (23W). zavareni spojevi prikazani su na slikama 1, 21 i 23 smeru (21W).



**Fig. 1** TPB specimen locations in the Weldox 960E / UNION X96 welded joints with the crack paths (21W and 23W)  
**Sl. 1** Lokacije uzoraka za savijanje u tri tačke (TPB) Weldox 960E / UNION X96 zavarenim spojevima sa prslinama (21W i 23W)



**Fig. 2** TPB specimen locations in the welded joint with the notch directions (RD = rolling directions)  
**Sl. 2** Položaji uzoraka TPB u zavarenom spoju sa smerovima zarezu (RD = pravci valjanja)



**Fig. 3** One possible location of the notch in the thickness direction  
**Sl. 3** Jedno moguće mesto zarezu u smeru debljine



The notch locations, the notch distances from the centreline of the welded joints, were different, therefore the positions of the notches and the crack paths represent the most important and the most typical crack directions in a real welded joints. Post-weld heat treating was not applied after welding on GMAW joints (investigations in as-welded condition).

The FCG examinations were performed with tensile stress,  $R = 0.1$  stress ratio, sinusoidal loading wave form, at room temperature, and on laboratory air, using MTS type electro-hydraulic testing equipment. The loading frequency was  $f = 20$  Hz for two-thirds of the growing crack's length, approximately, and it was  $f = 5$  Hz for the last third. The propagating crack was registered with optical method, using video camera and hundredfold magnification ( $N = 100x$ ).

### 3. Results of examinations

#### 3.1 Hardness distribution

HV10 hardness values were measured along two lines, as it can be seen in Fig. 4, furthermore Fig. 5 shows the hardness distributions (Weldox 700E / UNIONX85/UNION X90).

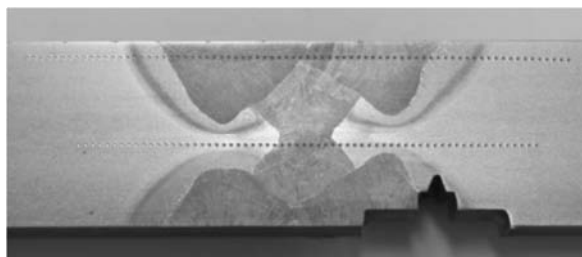
Lokacije zarez, udaljenosti zarez od središnje linije zavarenih spojeva, bili su različiti, pa su položaji zarez i prslina najvažniji i najtipičniji pravci prslina u stvarnim zavarenim spojevima. Termička obrada posle zavarivanja na zavarenim spojevima GMAW-MIG/MAG (ispitivanja u stanju zavarivanja) nije primenjena.

FCG ispitivanja izvedena su sa zateznim naponom, odnosom napona  $R = 0,1$ , sinusoidnim talasnim opterećenjem, na sobnoj temperaturi i na laboratorijskom vazduhu, koristeći elektrohidrauličku opremu za ispitivanje tipa MTS. Frekvencija opterećenja bila je  $f = 20$  Hz za dve trećine rastuće dužine prslina, otprilike, i bila je  $f = 5$  Hz za poslednju trećinu. Propagirajuća prslina registrovana je optičkim metodama, korišćenjem video kamere i uvećanjem od 100 puta ( $N = 100x$ ).

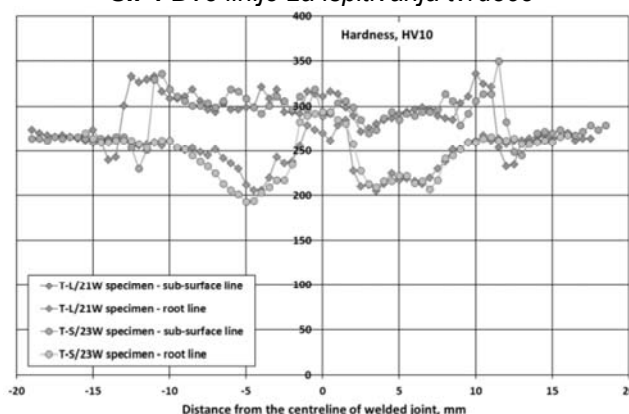
### 3. Rezultati ispitivanja

#### 3.1 Raspodela tvrdoće

Vrednosti tvrdoće HV10 merene su duž dve linije, kao što se može videti na slici 4, a na slici 5 prikazane su distribucije tvrdoće (Weldox 700E / UNIONKS85 / UNION X90).



**Fig. 4** Two lines for hardness tests  
**Sl. 4** Dve linije za ispitivanja tvrdoće



**Fig. 5** Hardness distributions measured on Weldox 700E / UNIONX85/UNION X90 specimen  
**Sl. 5** Raspodela tvrdoće merena na uzorku Weldox 700E / UNIONX85/UNION X90

#### 3.2 Fatigue crack growth tests

The next figures and Table 5 show selected experimental results on Weldox 700E / UNIONX85/UNION X90 welded joints. The crack length vs. number of cycles curves can be seen in different orientation in Fig. 6 and Fig. 7, and the

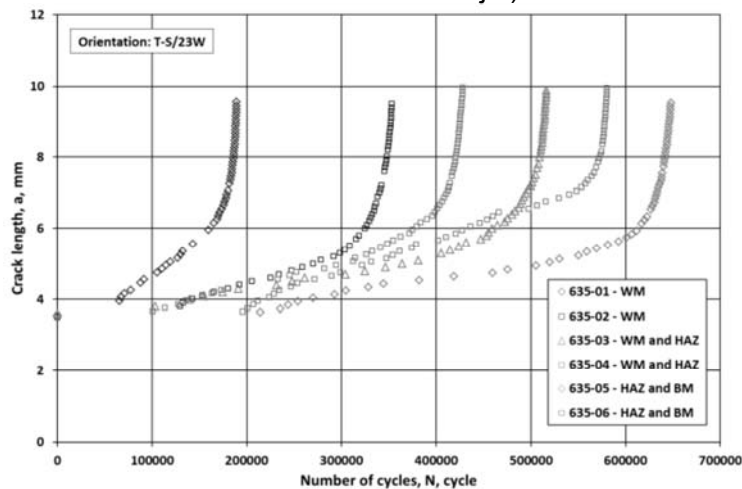
#### 3.2 Testovi rasta zamorne prsline

Sledeće slike i tabela 5 prikazuju odabrane eksperimentalne rezultate na Weldox 700E / UNIONKS85 / UNION Ks90 zavarenim spojevima. Dužina prslina naspram krivih broja ciklusa može se videti u različitoj orijentaciji na Sl. 6 i Sl. 7, a

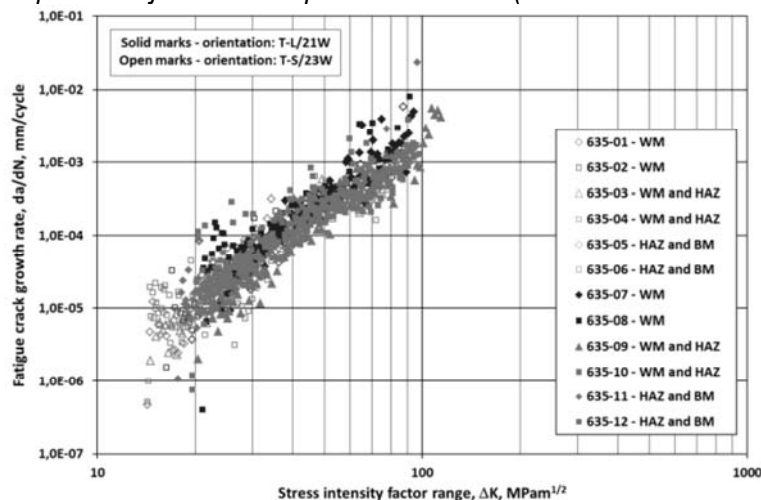


calculated stress intensity factor range vs. fatigue crack growth rate values are shown in Fig. 8 (WM = weld metal, HAZ = heat affected zone, BM = base material).

izračunati raspon faktora intenziteta napona u odnosu na vrednosti brzine rasta zamorne prsline, prikazan je na Sl. 8 (WM = metal šava, HAZ = zona pod uticajem toplote, BM = osnovni materijal).



**Fig. 6** Crack length vs. number of cycles curves in T-S/23W orientation (Weldox 700E / UNIONX85/UNION X90)  
**Sl. 6** Dužina prsline naspram broja ciklusa na pravcu T-S/23W (Weldox 700E / UNIONX85/UNION X90)



**Fig. 8** Results of FCG tests on Weldox 700E / UNIONX85/UNION X90 welded joints (altogether 12 specimens)  
**Sl. 8** Rezultati FCG testova na zavarenim spojevima Weldox 700E / UNIONKS85 / UNION X90 (ukupno 12 uzoraka)

Secant method [17] was used to evaluate the fatigue crack growth data. The constants (C and n) of the Paris-Erdogan relationship [8] were calculated using the least squares regression method, and the fatigue fracture toughness ( $\Delta K_{fc}$ ) values were determined using the crack length on the crack front measured by stereo microscope. The data belonging to stage II of the kinetic diagram of fatigue crack propagation have been eliminated during the least square regression analysis, for each specimen, systematically.

Tab. 5 summarizes the FCG test results executed on specimens cut from Weldox 700E / UNIONX85/UNION X90 welded joints (Sp ID = specimen ID, Co coe = correlation coefficient).

Za procenu podataka rasta prsline usled zamora korišćena je metoda sekante [17]. Konstante (C i n) Paris-Erdogan-ovog odnosa [8] izračunate su korišćenjem metode najmanje kvadratne regresije, a vrednosti žilavosti preloma usled zamora ( $\Delta K_{fc}$ ) određene su korišćenjem dužine prsline na prednjoj strani merene stereo mikroskopom. Podaci koji pripadaju II stadijumu kinetičkog dijagrama širenja prsline usled zamora eliminisani su tokom analize najmanje kvadratne regresije, za svaki uzorak, sistematski.

Tabela. 5 rezimira rezultate FCG ispitivanja izvršenih na uzorcima iz Weldox 700E / UNIONKS85 / UNION X90 zavarenih spojeva (Sp ID = ID uzorak, Co koeficijent korelacije).



| Sp ID  | Crack path | C                                |      | Co-coe [-] | $\Delta K_c$ [MPam <sup>3/2</sup> ] |
|--------|------------|----------------------------------|------|------------|-------------------------------------|
|        |            | [MPam <sup>3/2</sup> , mm/cycle] | n    |            |                                     |
| 635-01 | WM         | 5.23E-10                         | 3.30 | 0.9549     | 91.3                                |
| 635-02 | WM         | 8.03E-10                         | 3.21 | 0.9496     | 76.2                                |
| 635-03 | WM / HAZ   | 3.45E-10                         | 3.43 | 0.9632     | 80.1                                |
| 635-04 | WM / HAZ   | 4.62E-10                         | 3.27 | 0.9205     | 82.1                                |
| 635-05 | HAZ / BM   | 2.20E-10                         | 3.61 | 0.9372     | 68.1                                |
| 635-06 | HAZ / BM   | 2.13E-09                         | 2.94 | 0.9309     | 82.9                                |
| 635-07 | WM         | 4.42E-10                         | 3.44 | 0.9454     | 95.7                                |
| 635-08 | WM         | 2.72E-09                         | 2.97 | 0.9274     | 96.0                                |
| 635-09 | WM / HAZ   | 2.88E-10                         | 3.36 | 0.9599     | 117.0                               |
| 635-10 | WM / HAZ   | 5.07E-09                         | 2.76 | 0.9285     | 98.8                                |
| 635-11 | HAZ / BM   | 8.64E-10                         | 3.20 | 0.9613     | 102.9                               |
| 635-12 | HAZ / BM   | 2.23E-09                         | 2.94 | 0.9354     | 100.0                               |

**Tab. 5** Fatigue crack propagation test results executed on specimens cut from Weldox 700E / UNIONX85/UNION X90 welded joints

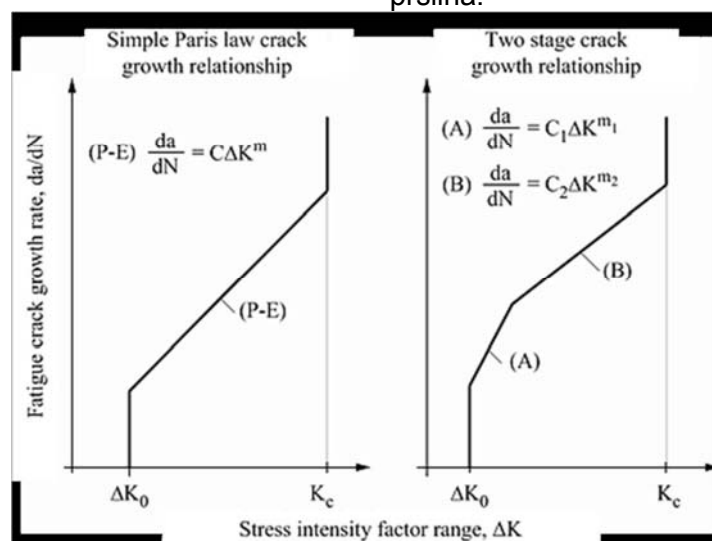
**Tab. 5.** Rezultati ispitivanja širenja prslina na uzorcima od Weldox 700E / UNION X85 / UNION X90 zavarenih spojeva

#### 4. Determination of fatigue crack propagation limit curves

Kinetic diagrams of fatigue crack growth can be simplified and described using both simple and two-stage crack growth relationships, as it can be seen in Fig. 9, based on [6]. (In BS 7910 m is used as Paris-Erdogan exponent, instead of n.) According to the main aim of our research work and the paper, the simple crack growth relationship was selected and used.

#### 4. Određivanje graničnih kriva širenja prslina zamora

Kinetički dijagrami rasta prslina usled zamora mogu se pojednostaviti i opisati upotrebom jednostavnih i dvostepenih odnosa rasta prslina, kao što se može videti na slici 9, na osnovu [6]. (U BS 7910 m koristi se kao eksponent Paris-Erdogan, umesto n..) Prema glavnom cilju našeg istraživačkog rada i rada odabran je i korišćen jednostavan odnos rasta prslina.



**Fig. 9** Simple and two-stage fatigue crack growth relationships, based on [6]

**Sl. 9** Jednostavni i dvostepeni rast zamorne prslina, zasnovan na [6]

Based on the experimental data and results, fatigue crack propagation limit curves can be determined. Generally, the determination of the fatigue design curves consists of six steps, as follows [10]. First step: determination of measuring values, the threshold stress intensity factor range ( $\Delta K_{th}$ ), if available, the two parameters of the Paris-Erdogan law (in our case C and n) and the fatigue fracture toughness ( $\Delta K_{fc}$ ). Second step: classification of measured values into statistical samples, on the basis of calculated test results, applying Wilcoxon matched pairs test. Third step: selection of the distribution function type using Shapiro-Wilk, Kolmogorov-Smirnov and chi square

Na osnovu eksperimentalnih podataka i rezultata mogu se odrediti granične krive širenja prslina usled zamora. Uopšteno, utvrđivanje krivih zamora sastoji se od šest koraka, kako sledi [10]. Prvi korak: određivanje mernih vrednosti, raspon faktora intenziteta praga napona ( $\Delta K_{th}$ ), ako su dostupni, dva parametra Paris-Erdoganovog zakona (u našem slučaju C i n) i žilavost preloma usled zamora ( $\Delta K_{fc}$ ). Drugi korak: klasifikacija izmerenih vrednosti u statističke uzorke, na osnovu izračunatih rezultata ispitivanja, primenom testa Wilcoxon-ovih podudarnih parova. Treći korak: izbor vrste funkcije distribucije korišćenjem Shapiro-Wilk, Kolmogorov-Smirnov i kvadrata chi





( $\chi^2$ ) goodness of fit tests (testing if sample data fits a distribution from a certain population, i.e. a population with a normal or a Weibull distribution), at a level of significance  $\varepsilon = 0.05$ . After the analysis, it was concluded, that only the three parameter Weibull-distribution function is suitable for describing all the configured samples. Fourth step: calculation of the parameters of the three parameter Weibull-distribution functions. The parameters of the distribution functions were calculated for all the configured samples using the

$$F(x) = 1 - \exp\left[-\left(\frac{x - N_0}{\beta}\right)^{1/\alpha}\right] \quad (2)$$

equation, where  $N_0$  is the threshold parameter,  $\alpha$  is the shape parameter and  $\beta$  is the scale parameter. Fifth step: selection of the characteristic values of the distribution functions. Considering the influencing effects of the material parameters on the life-time estimation, characteristic values of  $\Delta K_{th}$ ,  $n$  and  $\Delta K_{fc}$  were selected. The threshold stress intensity factor range ( $\Delta K_{th}$ ) is that value which belongs to the 95% probability, the exponent of the Paris-Erdogan law ( $n$ ) is that value which belongs to the 5% probability and the fatigue fracture toughness ( $\Delta K_{fc}$ ) is that value which belongs to the 5% probability of the relevant Weibull-distribution function. The Paris-Erdogan constant ( $C$ ) can be calculated on the material group (in our case steels) dependent correlation between  $C$  and  $n$ . The described fifth step can be seen in Fig. 10, schematically. Sixth step: calculation of the parameters of the limit curves.

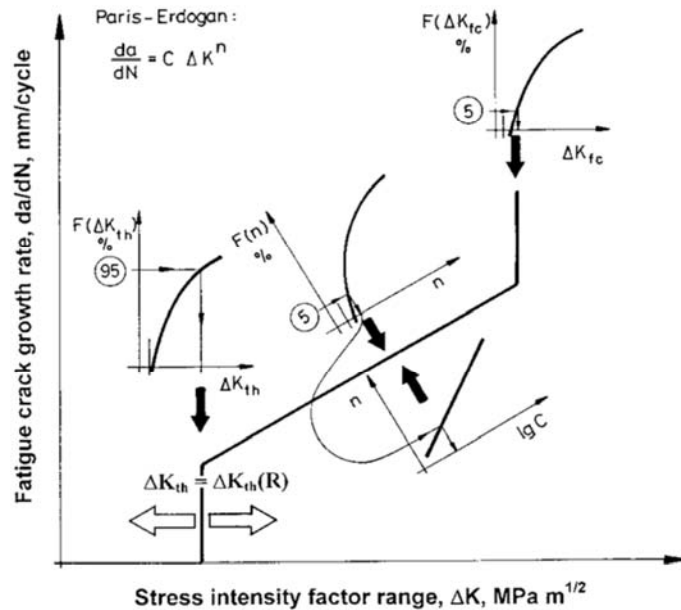
The main characteristics of the determined limit curves can be found in Tab. 6 ( $M_t$  = Mismatch type, Ref = reference). In those cases, when the orientation and/or the path of the propagating crack is known, the values in Tab. 6 can be directly used. In those cases, when  $n$  and  $\Delta K_{fc}$  values calculated in different directions (T-L and L-T vs. T-S, or 21W vs. 23W) are significantly different, and the orientation and/or the growing crack path is not known, the lowest value should be considered from the related ones. The unambiguous determination of the design curves in the near threshold region (near  $\Delta K_{th}$ ) is difficult. On the one hand, if the threshold stress intensity factor range value ( $\Delta K_{th}$ ) is not known, values can be found in the literature (e.g. [21-23]) are usable; furthermore, in special or particular cases, results of virtual testing [24] can be applied, too. On the other hand, the threshold stress intensity factor range value ( $\Delta K_{th}$ ), must be reduced by tensile residual stress field and may be increased by compressive residual stress field (e.g. welding residual stresses).

$\chi^2$  ispravnosti testova (ispitivanje da li uzorak podataka odgovara distribuciji iz određene zastupljenosti, tj. zastupljenosti sa normalnom ili Weibull funkcija distribucije), na nivou značajnosti  $\varepsilon = 0,05$ . Nakon analize zaključeno je da su samo tri parametra Weibull funkcije distribucije pogodno za opisivanje svih konfigurisanih uzoraka. Četvrti korak: izračunavanje parametara tri parametrske funkcije Weibull-distribucije. Parametri distribucijskih funkcija su izračunati za sve konfigurisane uzorke koristeći

$$F(x) = 1 - \exp\left[-\left(\frac{x - N_0}{\beta}\right)^{1/\alpha}\right] \quad (2)$$

jednačinu, gde je  $N_0$  parametar praga,  $\sigma$  je parametar oblika, a  $\beta$  je parametar skale. Peti korak: izbor karakterističnih vrednosti distributivnih funkcija. S obzirom na uticaj parametara materijala na procenu životnog veka, odabrane su karakteristične vrednosti  $\Delta K_{th}$ ,  $n$  i  $\Delta K_{fc}$ . Raspon faktora intenziteta graničnog naprežanja ( $\Delta K_{th}$ ) je vrednost koja pripada verovatnoći od 95%, eksponent Paris-Erdogan-ovog zakona ( $n$ ) je ta vrednost koja pripada verovatnoći od 5%, a žilavost loma zamora ( $\Delta K_{fc}$ ) je ta vrednost koja pripada verovatnoći od 5% za relevantnu funkciju distribucije Weibull-a. Konstanta Paris-Erdogan-a ( $C$ ) može se izračunati na osnovu grupe materijala (u našem slučaju čelika) zavisne korelacije između  $C$  i  $n$ . Opisani korak može se šematski videti na slici 10. Šesti korak: izračunavanje parametara granične krive.

Glavne karakteristike utvrđenih graničnih krivih mogu se naći u Tab. 6 ( $M_t$  = Tip neusklađenosti, Ref = referenca). U onim slučajevima, kada je poznata orijentacija i / ili putanja širenja prslina, vrednosti u Tab. 6 se mogu direktno koristiti. U onim slučajevima, kada su  $n$  i  $\Delta K_{fc}$  vrednosti izračunate u različitim smerovima (TL i LT u odnosu na TS, ili 21W u odnosu na 23W) značajno se razlikuju, a orijentacija i / ili put rastuće prslina nije poznat, najniža vrednost treba da bude uzeta u obzir. Teško je nedvosmisleno odrediti dizajn krive u blizini praga (blizu  $\Delta K_{th}$ ). S jedne strane, ako vrednost raspona faktora intenziteta praga naprežanja ( $\Delta K_{th}$ ) nije poznata, vrednosti se mogu naći u literaturi (npr. [21-23]) koje su upotrebljive; Nadalje, u specijalnim ili posebnim slučajevima, mogu se primeniti i rezultati virtualnog testiranja [24]. S druge strane, vrednost raspona faktora intenziteta napona ( $\Delta K_{th}$ ) mora se smanjiti zateznim zaostalim poljem i može povećati pritiskim poljem zaostalih napona (npr. zaostali naponi usled zavarivanja).



**Fig. 10** The proposed method for determination of fatigue crack propagation limit curves  
**Sl. 10** Predloženi postupak za određivanje graničnih krivih širenja prslina usled zamora

| BM    | M t  | Orientation      | n                                | C        | ΔK <sub>fc</sub> | Ref        |
|-------|------|------------------|----------------------------------|----------|------------------|------------|
|       |      |                  | [MPam <sup>1/2</sup> , mm/cycle] |          |                  |            |
| W700E | BM   | T-L, L-T         | 1,70                             | 8,09E-07 | 101              | [18]       |
|       |      | T-S              | 1,50                             | 2,06E-06 | 75               |            |
| W700E | M    | T-L/21W          | 4,10                             | 1,12E-11 | 105              | [18]       |
|       |      | T-S/23W          | 2,30                             | 4,93E-08 | 80               |            |
| W700E | OM   | T-L/21W          | 1,85                             | 4,02E-07 | 96               | [18]       |
|       |      | T-S/23W          | 1,90                             | 3,19E-07 | 61               |            |
| W700E | M/OM | T-L/21W          | 2,67                             | 8,88E-09 | 90               | this study |
|       |      | T-S/23W          | 2,85                             | 3,87E-09 | 67               |            |
| W960E | BM   | T-S, L-S, T-L    | 1,80                             | 3,50E-07 | 94               | [19]       |
| W960E | M    | T-L/21W, T-S/23W | 2,75                             | 1,03E-08 | 93               | [20]       |
| A960M | BM   | T-L, L-T         | 1,82                             | 4,63E-07 | 116              | [18]       |
|       |      | T-S              | 1,75                             | 6,41E-07 | 87               |            |
| A960M | UM   | T-L/21W          | 2,40                             | 3,10E-08 | 115              | [18]       |
|       |      | T-S/23W          | 2,15                             | 9,93E-08 | 67               |            |
| A960M | M    | T-L/21W          | 1,90                             | 3,19E-07 | 114              | [18]       |
|       |      | T-S/23W          | 2,75                             | 6,06E-09 | 82               |            |

**Tab. 6** Characteristics of the determined fatigue crack propagation limit curves  
**Tab. 6.** Karakteristike utvrđenih graničnih krivih širenja prslina usled zamora

**5. Summary and conclusions**

Based on our investigations and their results the following conclusions can be drawn. The results of the executed investigations justified the necessity of statistical approaches, especially referring to the directions of the base materials and the welded joints, and the determination of the number of the tested specimens. The applied gas metal arc welding process and the used technological parameters are suitable for production welded joints with appropriate quality,

**5. Rezime i zaključci**

Na osnovu naših istraživanja i njihovih rezultata mogu se doneti sledeći zaključci. Rezultati izvršenih istraživanja opravdali su neophodnost statističkih pristupa, posebno se odnose na smer osnovnog materijala i zavarene spojeve, kao i određivanje broja ispitivanih uzoraka. Primenjeni postupak elektrolučnog zavarivanja u zaštiti gasa i korišćeni tehnološki parametri pogodni su za izradu zavarenih spojeva odgovarajućeg kvaliteta, pri čemu odgovarajući kvalitet sadrži



where the appropriate quality contains the eligible resistance to fatigue crack propagation.

The welding causes unfavourable effects both on the mechanical properties and the fatigue crack growth resistance of the high strength steels.

The average values of the Paris-Erdogan exponents ( $n$ ) of Weldox 700E and Alform 960M base materials in the T-L and L-T directions and of the Weldox 960Q base material in the T-S and L-S directions are significantly not different, which means equal fatigue crack growth resistance in these orientations. The average values of the Paris-Erdogan exponent ( $n$ ) of Weldox 700E and Alform 960M base materials in the T-S orientation and of the Weldox 960Q base material in the T-L orientation are significantly different. The fatigue crack growth resistance of the Weldox 700E material is more unfavourable in T-S direction. The material strength category (in our case 690 MPa or 960 MPa) and the production condition (in our case quenching and tempering or thermomechanically treating) cause significant effect on the fatigue crack growth resistance, too.

The average values of the Paris-Erdogan exponents ( $n$ ) of the matching (M), overmatching (OM), matching / overmatching (M/OM) and undermatching (UM) conditions of the investigated welded joints were statistically higher than the exponents of the concerning base materials.

The average value of the Paris-Erdogan exponent ( $n$ ) of the overmatching (OM) welded joint of the Weldox 700E is lower than the exponent of both the matching (M) and the matching/overmatching (M/OM) conditions. The fatigue crack growth resistance under overmatching (OM) condition is lower than both matching (M) and matching/overmatching (M/OM) conditions. It means that the matching/overmatching (M/OM) mismatch type is more beneficial than the overmatching (OM) type.

The average value of the Paris-Erdogan exponent ( $n$ ) of the matching (M) welded joint of the Alform 960M is lower than the exponent of the undermatching (UM) condition. The fatigue crack growth resistance under matching (M) condition is lower than undermatching (UM) condition.

The determined results fundamentally refer to reliable and reproducible examinations. Unfortunately, the standard deviation coefficients are in some cases too high (Paris-Erdogan exponent ( $n$ ), T-S, 21W and 23W orientations).

Based on these results and the used methods fatigue crack propagation limit curves can be determined for the investigated high strength base materials and their gas metal arc welded joints,

prihvatljivi otpor protiv širenja prslina.

Zavarivanje izaziva nepovoljne efekte i na mehanička svojstva i na otpornost na rast prslina kod čelika visoke čvrstoće.

Prosečne vrednosti Paris-Erdogan-ovih eksponenata ( $n$ ) Weldox 700E i Alform 960M osnovnih materijala u pravcima TL i LT i materijala Weldox 960K u pravcu TS i LS značajno se ne razlikuju, što znači jednak otpor rastu prslina usled zamora u ovim orijentacijama. Prosečne vrednosti Paris-Erdogan-ovih eksponenata ( $n$ ) Weldox 700E i Alform 960M osnovnih materijala u T-S orijentaciji i Weldox 960K osnovnog materijala u T-L orijentaciji su značajno različite. Otpor na rast prslina usled zamora materijala Weldox 700E je nepovoljniji u T-S smeru. Kategorija čvrstoće materijala (u našem slučaju 690 MPa ili 960 MPa) i stanje proizvodnje (u našem slučaju kaljenje i otpuštanje ili termomehanička obrada) takođe imaju značajan uticaj na otpornost na rast prslina.

Prosečne vrednosti Paris-Erdogan-ovih eksponenata ( $n$ ) kod uslova podudaranja (M), jačeg (OM), podudaranja / jačeg (M / OM) i slabijeg (UM) ispitivanih zavarenih spojeva su statistički veće od eksponenata za osnovne materijale.

Prosečna vrednost Paris-Erdogan eksponenta ( $n$ ) jačeg (OM) zavarenog spoja Weldox 700E je niža od eksponenta i uslova podudaranja (M) i podudaranja / jačeg (M / OM) uslova. Otpor rasta prslina usled zamora pod uslovima jačeg (OM) je niži od uslova podudaranja (M) i uslova podudaranja / jačeg (M / OM). To znači da je tip neusklađenosti, podudaranje / jači (M / OM), povoljniji od tipa jačeg (OM).

Prosečna vrednost Paris-Erdogan eksponente ( $n$ ) podudarajućeg (M) zavarenog spoja Alform 960M je niža od eksponenta za uslov slabijeg (UM). Otpor na rast prslina usled zamora pod podudarajućim (M) uslovima je niži od uslova slabijeg (UM).

Utvrđeni rezultati se u osnovi odnose na pouzdana i ponovljiva ispitivanja. Nažalost, standardni koeficijenti devijacije su u nekim slučajevima previsoki (Paris-Erdogan eksponent ( $n$ ), T-S, 21W i 23W orijentacije).

Na osnovu ovih rezultata i korišćenim metodama mogu se utvrditi granične krive širenja prslina za ispitivane osnovne materijale i njihove zavarene spojeve postupkom elektročućnog zavarivanja u zaštiti gasa, upotrebom pojednostavljene metode [6]. Granične krive s jedne strane tačno odražavaju karakteristike rasta prslina usled zamora i osnovnih materijala i zavarenih spojeva, s druge strane se mogu koristiti za kritičku procenu inženjerskih analiza (ECA) i proračune strukturnog integriteta:



using simplified method [6]. The limit curves on the one hand correctly reflect the fatigue crack growth characteristics of both the base materials and the welded joints, on the other hand are usable for engineering critical assessment (ECA) and structural integrity calculations:

- determination of propagable and critical crack sizes;
- calculation of lifetime determined by the propagable crack size;
- calculations of remaining lifetime functions, influences on the lifetime values and lifetime function (in other words parameter study);
- reliability of remaining lifetime estimation;
- calculation of damage parameter and damage function [25].

Further examinations required in order to draw statistically better established conclusions, to measure threshold stress intensity factor range ( $\Delta K_{th}$ ) values for base materials and welded joints, and finally, to study the effects of the welding residual stress fields.

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- određivanje kritične veličine prsline koje se može proširiti;
- izračunavanje životnog veka utvrđenog veličinom prsline koja se širi;
- proračun preostalih radnih funkcija, uticaj na vrednosti radnog veka i funkciju radnog veka (drugim rečima, studija parametara);
- pouzdanost procene preostalog radnog veka;
- proračun parametra oštećenja i funkcije oštećenja [25].

Potrebna su dalja ispitivanja kako bi se izvukli statistički bolje utvrđeni zaključci, izmerili vrednosti praga faktora intenziteta napona ( $\Delta K_{th}$ ) za osnovne materijale i zavarene spojeve i, na kraju, da bi se proučio efekat zaostalih polja zaostalih napona usled zavarivanja.

#### Priznanja

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