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CRACK INITIATION AND GROWTH IN WELDED JOINT OF STEEL FOR OPERATION AT ELEVATED TEMPERATURE

INICIJACIJA I RAST PRSLINE U ZAVARENOM SPOJU ČELIKA ZA RAD NA POVIŠENIM TEMPERATURAMA

Original scientific paper / Originalni naučni rad
The paper was published in its original form in the Proceedings of the 31st Conference with international participation "Welding 2020" held in Kladovo, Serbia from 13 to 16 October 2021.
Paper received / Rad primljen:
September 2021.
Paper accepted / Rad prihvaćen:
January 2022.

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Keywords: *Weld joint, fracture toughness, fatigue crack initiation, fatigue crack growth, fatigue threshold*

Ključne reči: *Zavareni spoj, žilavost loma, stvarenje zamorne prsline, rast zamorne prsline, prag zamora*

Abstract

In a paper given, experimental investigations have included the analysis of crack initiation and growth in welded joint of steel for operation at elevated temperatures. For better understanding of the phenomenon of crack initiation and propagation in welded joints of A-204 Gr. A steel, designed for high-temperature and high-pressure application, it is necessary to determine the effect of heterogeneity of microstructural and mechanical properties on fracture toughness and fatigue crack initiation and propagation in welded components. Based on the tests conducted with pre-cracked CT and Charpy size specimens, the effect of heterogeneity of microstructural and mechanical properties of welded joints on fracture toughness and fatigue-crack growth parameters was determined.

Rezime

U radu su prikazana eksperimentalna istraživanja koja uključuju analizu stvaranja i rasta prsline u zavarenom spoju čelika za rad na povišenim temperaturama. Za bolje razumevanje fenomena stvaranja i rasta prsline u zavarenim spojevima čelika A-204 Gr. A, namenjenog za rad na visokim temperaturama i pritiscima, potrebno je utvrditi uticaj heterogenosti mikrostrukturnih i mehaničkih svojstava na žilavost loma i stvaranje i rast zamorne prsline u komponentama zavarenog spoja. Na osnovu ispitivanja provedenih na CT i Charpy epruvetama na kojima su prethodno inicirane prsline utvrđen je uticaj heterogenosti mikrostrukturnih i mehaničkih svojstava zavarenog spojeva na žilavost loma i parametre rasta zamorne prsline.

1. Introduction

Service behaviour of alloyed steel A-204 Gr. A, designed for manufacture of pressure vessels operating at high temperature and exposed to high pressure, is highly dependent on the properties of critical regions of welded-joint, heat-affected-zone (HAZ) and weld metal (WM), primarily due to their high sensitivity to brittle fracture. Heat affected zone (HAZ) and weld metal (WM) are potential locations of crack initiation, i.e. the locations where local brittle zones may form to whom crack initiation is ascribed [1].

Qualification of specified welding technology of plates, 50mm thick, of steel A-20B Gr. A, is performed according to standard SRPS EN ISO 15614-1 [2].

However, this standard requires neither testing of operating temperature (325°C) nor testing of in-service behaviour of basic metal and welded joint constituents at room and operating temperatures.

The problem of determination of fracture toughness, K_{Ic}, is treated as a problem of principle, as fracture mechanics assumes homogeneous material not only near the crack tip but at some distance from it as well, in order to make theoretical assumptions and meanings of fracture toughness as a property measured using some of the methods of fracture mechanics still valid. Welded joint, as an integral part of a structure, has inhomogeneous microstructure and mechanical properties, very often geometry too, and stress field as well, affected by various factors such as residual stresses after welding. However, these fundamental difficulties do not make experimental determination of fracture mechanics, K_{Ic}, impossible under plane strain conditions, either in certain critical regions of a welded joint or a welded joint as a whole, but they do make interpretation of the measured values difficult. Therefore, great interest in application of investigations of fracture mechanics in case of welded joints is natural [3].

For better understanding of the cause and mechanism of crack initiation and growth in welded joints of steel designed for operation at elevated temperatures and under high pressures, it is necessary to establish the effect of heterogeneity of the structure and mechanical properties of a welded joint on crack initiation and growth and to quantify the parameters affecting the local strain behaviour and crack growth. The aim of this experiment is to study the effect of heterogeneity of microstructure and mechanical properties on fracture toughness, K_{Ic}, and fatigue crack growth parameters da/dN and ΔK_{th} of A-204 Gr. A steel welded joint constituents at room temperature and at 325°C [4].

2. Experimental

For assessment of the effect of operating temperature on fracture toughness, KIc, and fatigue-crack growth parameters of A-204 Gr. A steel, sample of 500x200x50 mm with U weld metal in the centre were available. The specimens for qualification of the welded joint, WM and HAZ were machined from a welded sample plate [5]. The standard values and test values chemical composition and mechanical properties of A-204 Gr. A steel are shown in Tables 1 and 2, respectively.

Table 1. *Chemical composition of tested material [5]*

Tabela 1. *Hemijski sastav ispitivanog materijala [5]*

Material		Chemical composition, [mass %]						
		C	Si	Mn	P	S	Mo	Fe
A-204 Gr. A	Standard values	≤0.18	0.15-0.40	≤0.90	≤0.035	≤0.035	0.45-0.60	rest
	Test values	0.15	0.33	0.71	0.012	0.009	0.51	rest

Table 2. *Mechanical properties of tested material [5]*

Tabela 2. *Mehaničke osobine ispitivanog materijala [5]*

Material		Yield strength $R_{p0,2}$, [MPa], min.	Tensile strength, R_m, [MPa]	Elongation, A, [%]	Impact energy, [J]
A-204 Gr. A	Standard values	255, min.	450-585	23, min.	40, min.
	Test values	319	491	32	155

The plates were welded by two procedures [5]:

- root passes – by metal manual arc welding (MMA) with coated electrode LINCOLN SI 12G (AWS A5.5: E7018-A1-H4R), ∅3.25mm diameter, and
- filler metal passes – by metal manual arc welding (MMA) with coated electrode LINCOLN SI 12G (AWS A5.5: E7018-A1-H4R), ∅3.25 mm diameter.

Chemical composition of coated electrode LINCOLN SI 12G according to certificates is given in Tab. 3. Main mechanical properties according to certificates are given in Tab. 4.

Table 3. *Chemical composition of filler metal [5]*

Tabela 3. *Hemijski sastav dodatnog metala [5]*

Filler metal	Chemical composition, [mass %]					
	C, min.	Si, max.	Mn, max.	P, max.	S, max.	Mo, max.
LINCOLN SL 12G	0.12	0.60	0.80	0.020	0.020	0.55

Table 4. *Mechanical properties of filler metal [5]*

Tabela 4. *Mehanička svojstva dodatnog metala [5]*

Filler metal	Yield strength $R_{p0,2}$, [MPa], min.	Tensile strength, R_m, [MPa], min.	Elongation, A, [%], min.	Impact energy,[J], min.
LINCOLN SL 12G	355	510	22	47

3. Results and discussion

3.1. Fracture toughness K_{Ic}

The effect of heterogeneity of structure and mechanical properties of welded joint constituents in location of a fatigue-crack tip in the first place, and in properties of the region where fracture develops. Testing of plane-strain fracture toughness of the specimens taken from the welded plate made of steel A-204 Gr. A was conducted. The aim was to determine critical stress-intensity factor, K_{Ic}, i.e. to estimate the behaviour of basic metal (BM) and components of the welded joint, weld metal (WM) and heat-affected zone (HAZ) in presence of a crack-type defect as the most jeopardizing defect in structural materials, especially in welded joints. The tests were conducted using the three-point bend (TPB) and CT specimens, geometry of which is defined by the ASTM E1820 standard [6]. Three-point bend (TPB) specimens were used for testing at room temperature. Due to specific design of the chamber, CT specimens were used for testing at operating temperature of 325°C.

The experiments were conducted using the single-specimen method with successive partial unloading, i.e. the method of single-specimen relaxation. The aim of relaxation with unloading was to register the value of crack propagation, Δa, occurring during testing.

Based on the data collected from tearing machine and COD indicator, the diagrams force, F – crack mouth opening displacement (CMOD), δ, were plotted that are the foundation for plotting the diagram J – Δa, where regressive line is plotted according to ASTM E1820 [6]. Critical J-integral, J_{Ic}, is obtained from the regressive line obtained. The typical diagrams F – δ and J – Δa for the specimen with a notch in BM, weld metal WM and HAZ is given in Figures 1, 3 and 5 for room temperature, and Figures 2, 4 and 6 for operating temperature respectively. From the very appearance of the diagrams, the effect of structural heterogeneity on toughness of basic metal and welded joint components is obvious [7].

The value of critical stress-intensity factor or plane-strain fracture toughness, K_{Ic}, can be computed when the values of critical J_{Ic} integral are known, using the dependences:

$$K_{Ic} = \sqrt{\frac{J_{Ic} \cdot E}{1-\nu^2}} \qquad (1)$$

One can observe that structural and mechanical heterogeneities of a welded joint significantly affect its resistance to crack propagation, both in elastic and in plastic regions. Heterogeneity of mechanical properties of a welded joint, i.e. the welded-joint components, is obvious from the obtained value of plane-strain fracture toughness, K_{Ic}, determined indirectly through critical J_{Ic} integral.

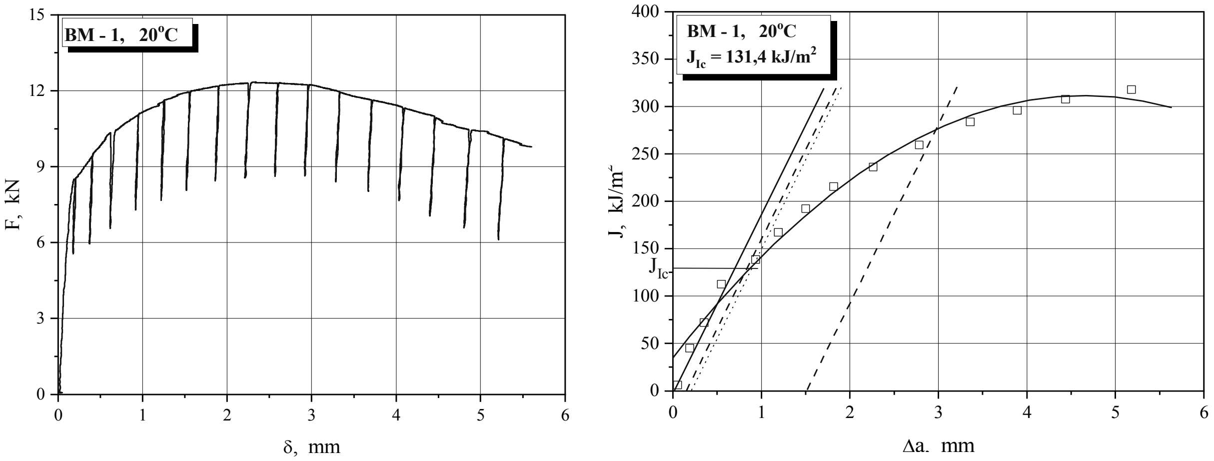


Figure 1. *Diagrams F – δ and J – Δa for the specimen with a notch in BM for room temperature*

Slika 1. *Dijagrami F – δ i J – Δa za uzorak sa zarezom u OM na sobnoj temperaturi*

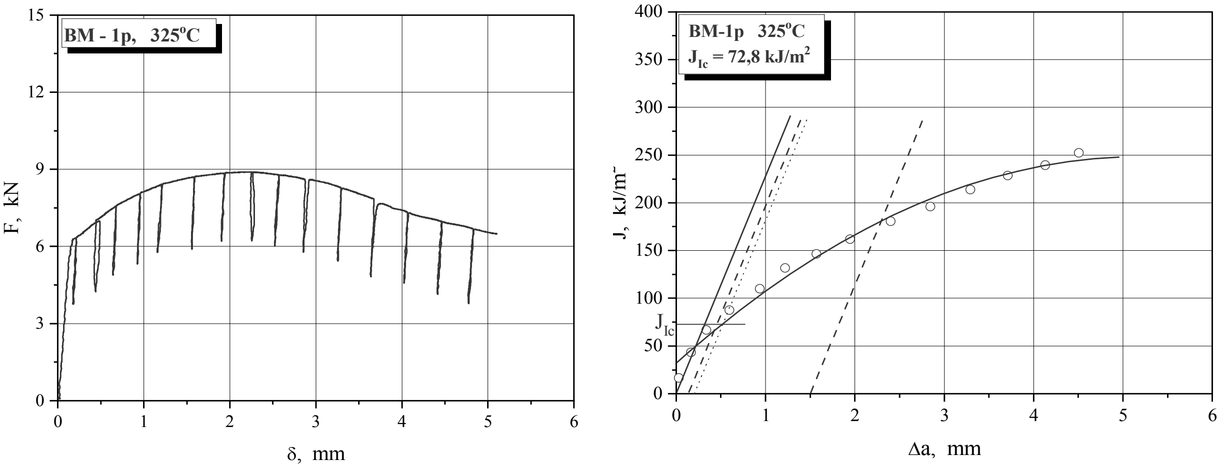


Figure 2. *Diagrams F – δ and J – Δa for the specimen with a notch in BM for operating temperature*

Slika 2. *Dijagrami F – δ i J – Δa za uzorak sa zarezom u OM na radnoj temperaturi*

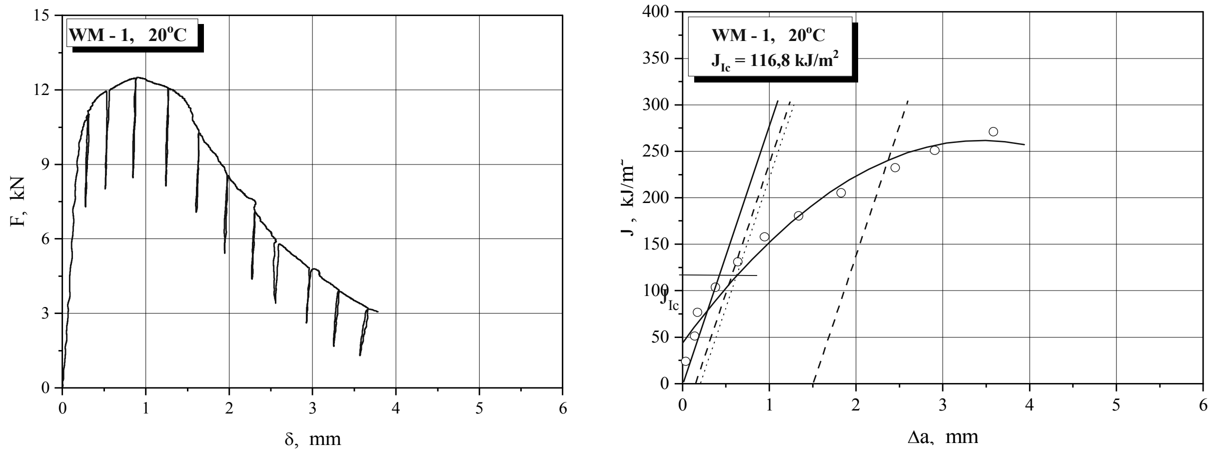


Figure 3. *Diagrams F – δ and J – Δa for the specimen with a notch in WM for room temperature*

Slika 3. *Dijagrami F – δ i J – Δa za uzorak sa zarezom u MV na sobnoj temperaturi*

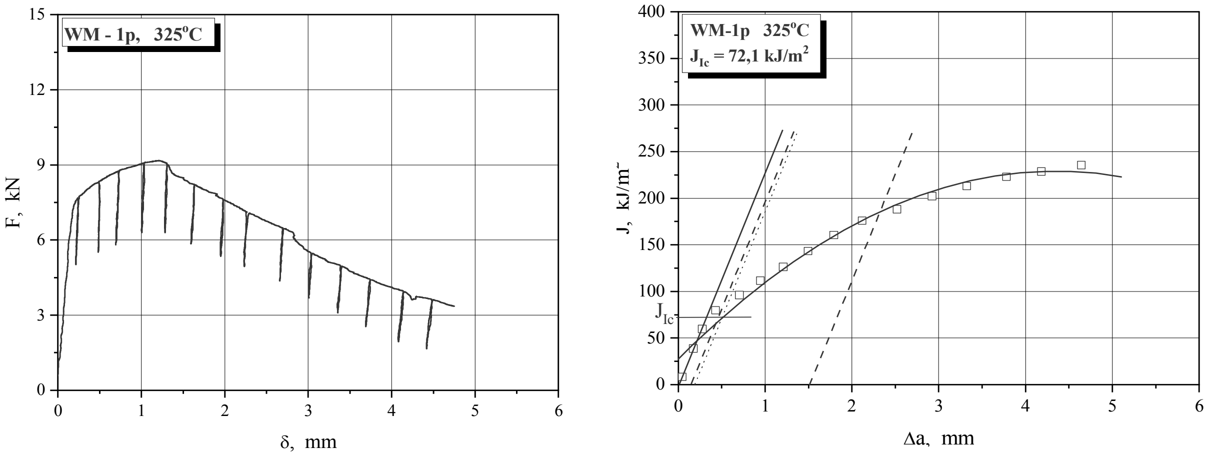


Figure 4. *Diagrams F – δ and J – Δa for the specimen with a notch in WM for operating temperature*

Slika 4. *Dijagrami F – δ i J – Δa za uzorak sa zarezom u MV na radnoj temperaturi*

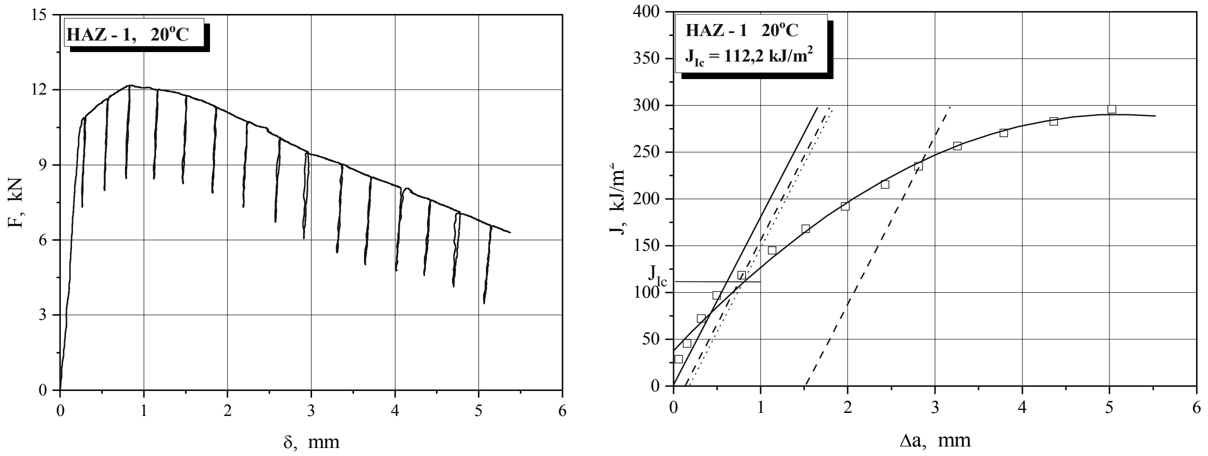


Figure 5. *Diagrams F – δ and J – Δa for the specimen with a notch in HAZ for room temperature*

Slika 5. *Dijagrami F – δ i J – Δa za uzorak sa zarezom u ZUT-u na sobnoj temperaturi*

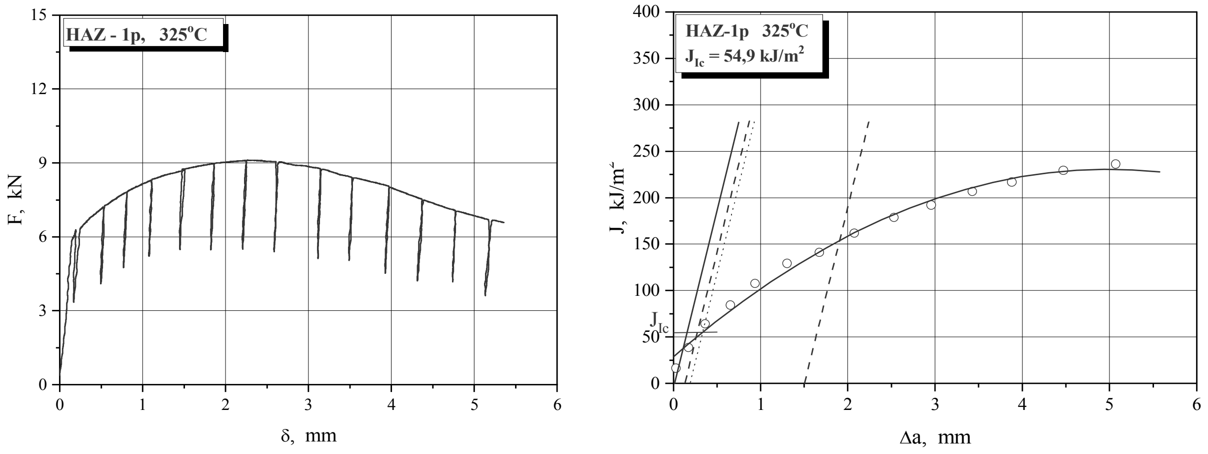


Figure 6. *Diagrams F – δ and J – Δa for the specimen with a notch in HAZ for operating temperature*

Slika 6. *Dijagrami F – δ i J – Δa za uzorak sa zarezom u ZUT-u na radnoj temperaturi*

The specimens with a notch in BM have the largest measured value of K_{Ic}. Average K_{Ic} values of ~174 MPa $m^{1/2}$ that were obtained are within the limits of the values in literature for this group of general structural steels. Somewhat lower K_{Ic} values were obtained for the specimens with a notch in WM, (mean value of K_{Ic} was ~151MPa $m^{1/2}$). However, in this particular case the differences are relatively small, ranging from 10 to 15MPa $m^{1/2}$ in terms of minimum and maximum value.

These differences do not necessarily affect significantly the structures exposed to static loading in service. However, under conditions where the structural components are permanently exposed to variable loading, the variations in the K_{Ic} values are very important, as the critical crack length, a_c, i.e. resistance to crack propagation, directly depends on the K_{Ic} value. By applying the fundamental formula of fracture mechanics

$$K_{Ic} = \sigma \cdot \sqrt{\pi \cdot a_c} \qquad (2)$$

and introducing the value of allowable stress $\sigma_{doz} = \sigma$, assuming that the shape factor equals to one, approximate values of critical crack length, a_{cr}, can be computed.

3.2. Application of fracture mechanics in study of fatigue

Fatigue crack will initiate and propagate from severe stress raisers under variable loading after determined cycle number if the stress-intensity factor range, ΔK_{th}, for fatigue threshold is achieved. The structure can be used before growing crack reaches critical value, based on performed structural integrity analysis. Substantial data for the decision about extended service of cracked component is crack growth rate and its dependence on acting load. Standard ASTM E647 [8] 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 standard ASTM E647 are crack growth rate above 10^{-8} m/cycle to avoid threshold ΔK_{th} regime, and testing with constant amplitude loading.

Standard Charpy size specimens, pre-cracked in different welded joint regions, were tested under variable loading for determination of stress-intensity factor range at fatigue threshold, ΔK_{th}, and fatigue crack growth rate da/dN. Testing was performed in load control, by three-points bending on high-frequency resonant pulsator CRACKTRONIC, Figure 7.

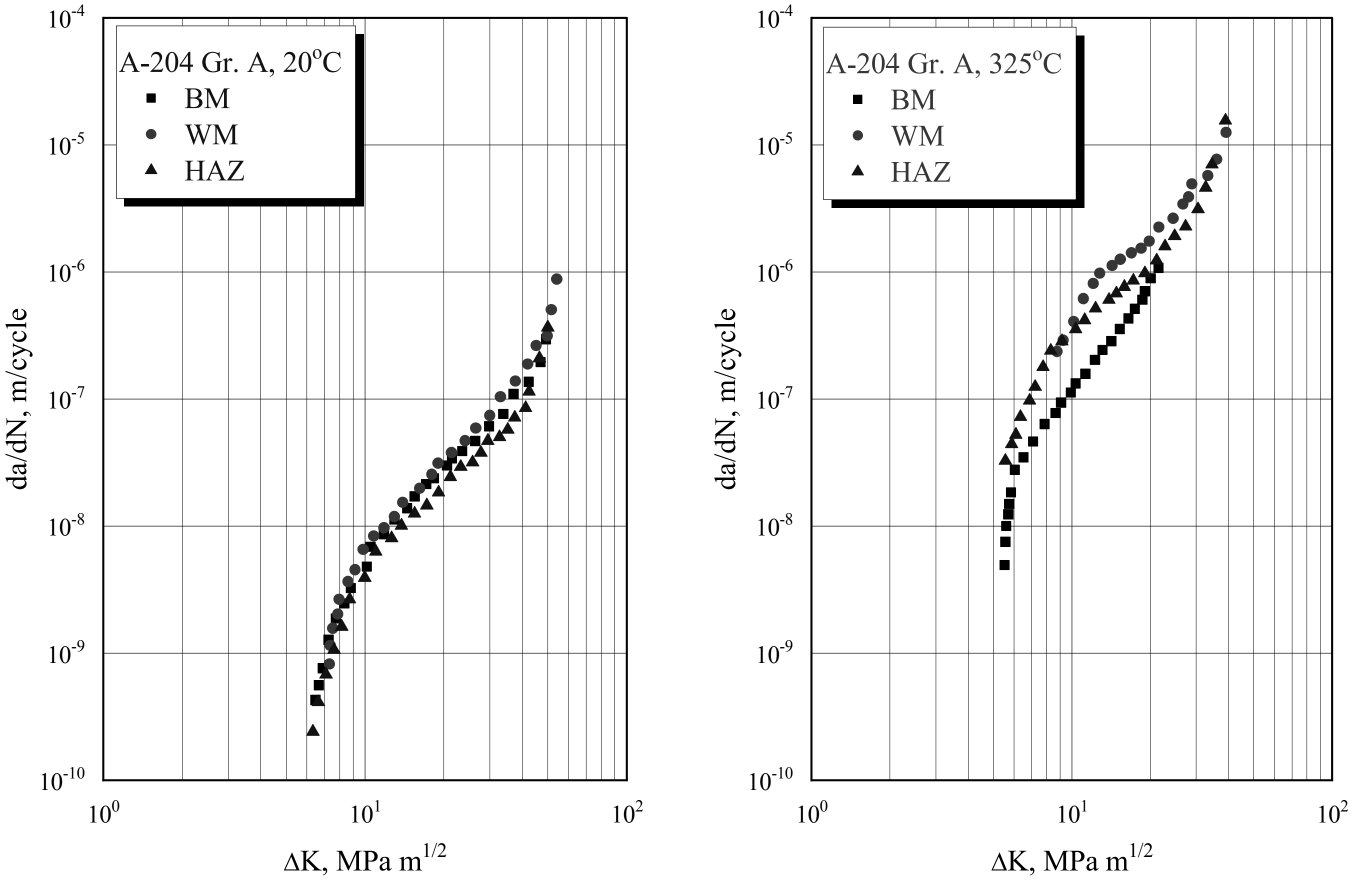
***Figure 7.** View of specimen with cemented-foil crack gauge-foil with variable loading bending scheme*

***Slika 7.** Izgled uzoraka sa cementiranom folijom za merenje prslina sa šemom savijanja sa promenljivim opterećenjem*

This FRACTOMAT device is based on electrical potential measurement, connected with corresponding instruments. For monitoring of crack growth, foil crack gauges RUMUL RMF A-5, 5 mm long, were cemented on the machined specimens, applying the same procedure as for classical strain gauges.

Both fatigue-crack growth parameters at operating temperature of 325°C and fracture toughness were determined on CT specimens, whose geometry is defined by ASTM E1820. The dependence fatigue-crack growth rate per cycle, da/dN, vs. stress-intensity factor range, ΔK, is determined by the coefficient C and exponent m in the equation of Paris [9]. This relation can be calculated and drawn in a form log da/dN - log (ΔK), based on the results of tests conducted at room and operating temperature (325°C). Obtained relations are presented in Figure 8. for the specimens pre-cracked in base metal (BM); weld metal (WM) and heat-affected-zone (HAZ).

For comparison, the value of the stress-intensity factor range ΔK = 15MPa√m is located in the portion of the curve where Paris law applies, as shown in Fig. 8. Corresponding crack-growth rates at room temperature ranged from 4.25·10-09 m/cycle for base metal to 7.18·10-09 m/cycle for weld metal and 6.11·10-09 m/cycle in HAZ, indicating that WM is critical constituent in welded joint. At 325°C, crack-growth rates are significantly higher when compared to room temperature (1.37·10-07; 4.28·10-07; 3.11 10-7 for base metal, weld metal and HAZ, respectively), but with smaller differences in constituents that can be explained by better ductility at elevated temperature. Again, WM is most critical constituent in welded joint.



a) b)

Figure 8. *Fatigue-crack growth rate per cycle, da/dN, vs. stress-intensity factor range, ΔK, specimens pre cracked in BM, WM, and HAZ tested: a) at room temperature and b) at 325°C*

Slika 8. *Brzina rasta zamorne prsline po ciklusu, da/dN, u odnosu na opseg faktora intenziteta napona, ΔK, uzorci sa prethodno nanešenom prslinom u OM, MV i ZUTu testirani: a) na sobnoj temperaturi i b) na 325°C*

In spite of significant differences in fatigue-crack growth rates, obtained values are still low and acceptable. That means that tested steel and its welded joint exhibited acceptable level of fatigue-crack growth resistance and can be successfully applied for variable loading in case of detected crack-like defects, primarily for low-cycle fatigue.

The behaviour of welded joint as whole, as well as of their individual constituents, can be connected with the variation of the slope of valid portion of Paris curve. Lower crack propagation is confirmed on specimens from BM and from HAZ, requiring higher stress-intensity factor range for the same crack growth rate. Maximum fatigue-crack growth rate can be expected at the level of stress-intensity factor approaching to plane-strain fracture toughness - the condition for brittle fracture.

4. Conclusions

Following conclusions can be derived:

Structural and mechanical heterogeneities of a welded joint significantly affect the resistance to crack propagation, both in elastic and in plastic region. The heterogeneity of the mechanical properties of the welded joints, i.e. welded-joint components, is obvious from the values obtained for plane-strain fracture toughness, K_{Ic}, determined indirectly through the critical J_{Ic} integral.

Decisive effect on stress-intensity factor range ΔK and fatigue-crack growth parameters can be attributed to the location of machined notch and following initial crack, as well as to testing temperature.

The highest resistance to crack propagation, expressed by minimum fatigue-crack growth rate, exhibited the specimens pre-cracked in BM, and maximum fatigue crack-growth rate was found in the specimens pre-cracked in WM. This is directly connected with the effect of microstructural heterogeneity of welded-joint constituents on fatigue-crack growth rate da/dN.

The behaviour of pre-cracked specimens taken from different welded joint constituents (basic metal, weld metal, heat-affected-zone), tested at operating temperature (325°C) and under variable loading, regarding fatigue threshold and fatigue crack growth parameters, exhibited higher crack-growth rate when compared to room temperature, which can be explained by reduced properties at elevated temperature.

Acknowledgment

Authors of this paper would like to express their gratitude to the Ministry of Education, Science and Technological Development of Republic of Serbia, for their support through Project 451-03-9/2021-14/200325. Also, the authors would like to express their gratitude to the Military Technical Institute, where experimental tests of fracture mechanics parameters of welded steel joints for work at elevated temperatures were performed.

4. Zaključak

Na osnovu izvršenih ispitivanja mogu se izvesti sledeći zaključci:

Strukturne i mehaničke heterogenosti zavarenog spoja značajno utiču na otpornost širenja prsline, kako u elastičnoj tako i u plastičnoj oblasti. Heterogenost mehaničkih svojstava zavarenih spojeva, odnosno komponenti zavarenog spoja, očigledna je iz vrednosti dobijenih za žilavost loma, K_{Ic}, koja je određena indirektno preko kritičnog J_{Ic} integrala.

Odlučujući uticaj na opseg faktora intenziteta napona ΔK i parametre zamor - rast prsline, može se pripisati lokaciji mašinski obrađenog zareza i početne prsline, kao i temperaturi ispitivanja

Najveću otpornost na širenje prsline, izraženu minimalnom brzinom rasta zamorne prsline, posedovali su uzorci sa prethodno nanešenom prslinom u OM, a maksimalna brzina rasta zamorne prsline utvrđena je kod uzoraka sa prethodno nanešenom prslinom u MV. Ovo je direktno povezano sa uticajem mikrostrukturne heterogenosti komponenti zavarenog spoja na brzinu rasta zamornih prslina od da/dN.

Ponašanje uzoraka prethodno sa prethodno nanešenom prslinom uzorkovanih iz različitih delova zavarenog spoja (osnovni metal, metal šava, zona uticaja toplote), ispitanih na radnoj temperaturi (325°C) i pod promenljivim opterećenjem, u pogledu praga zamora i parametara rasta prsline od zamora, pokazuju veću brzinu rasta prslina u poređenju sa sobnom temperaturom, što se može objasniti smanjenim osobinama na povišenoj temperaturi.

Zahvalnica

Autori ovog rada žele da se zahvale Ministarstvu prosvete, nauke i tehnološkog razvoja Republike Srbije na podršci kroz Projekat 451-03-9/2021-14/200325. Takođe, autori se zahvaljuju i Vojnotehničkom institutu - Beograd, gde su izvršena eksperimentalna ispitivanja parametara mehanike loma zavarenih čeličnih spojeva za rad na povišenim temperaturama.

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