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DETERMINATION OF FATIGUE CRACK GROWTH PARAMETERS IN WELDED JOINT OF HSLA STEEL

ODREĐIVANJE PARAMETARA ZAMORNOG RASTA PRSLINE KOD ZAVARENIH SPOJEVA OD HSLA ČELIKA

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Keywords
- HSLA steel
- crack growth rate
- fatigue threshold
- Paris' law

Abstract

The structural integrity and operational safety of welded pressure vessels primarily depends on the behaviour of weldments. In spite of all efforts in material production and improvements in welding techniques, including strict codes, requirements and directives, the crack occurrence in welded structures cannot be completely excluded. This is why fracture mechanics analysis is inevitable in the structural integrity assessment of all welded structures. Examples of practical application of fracture mechanics parameters in cracked pressure vessel structural integrity are considered. This paper shows the determination of parameters of the fatigue crack for constituents of welded joints produced of high strength low alloyed steel Nionikral-70 (yield strength 700 MPa). Results have shown that the position of notch and crack initiation affect the values of the stress intensity range of fatigue threshold ΔK_{th} *and parameters in the Paris' equation.*

Ključne reči
- HSLA čelik
- brzina rasta prsline
- granica zamaranja
- Parisov zakon

Izvod

Integritet konstrukcije i sigurnost u radu zavarenih posuda pod pritiskom uglavnom zavisi od ponašanja zavarenih spojeva. Pored svih uloženih napora u proizvodnji i poboljšanja postupaka zavarivanja, uključujući i stroge standarde, zahteve i smernice, pojava prslina u zavarenim konstrukcijama se ne može u potpunosti izbeći. Zato je analiza mehanike loma neophodna u proceni integriteta svih zavarenih konstrukcija. Razmotreni su primeri praktične primene parametara mehanike loma u integritetu posuda pod pritiskom sa prslinom. Rad prikazuje određivanje parametara zamorne prsline za konstituente zavarenih spojeva izrađenih od niskolegiranog čelika povišene čvrstoće Nionikral-70 (napona tečenja 700 MPa). Rezultati pokazuju da položaj zareza i inicijacija prsline utiču na vrednosti raspona napona za granicu zamora ΔK_{th} *i na parametre Parisove relacije.*

INTRODUCTION

The operation of a welded structure depends on its safety under the applied load. Requirements regarding the security of the structure posed to the manufacturer are very strict when failure might endanger human lives. Nevertheless, catastrophic failures still occur in exploitation of welded structures. In most cases failure is caused by the existence of cracks of critical size. Structural safety and integrity analysis have to consider the influence of the fatigue crack and its threshold value, eventually followed by in-service propagation through parent metal (PM), weld metal (WM) and heat-affected-zone (HAZ) of the welded joint. The corresponding data have to be defined in the material specification, since a detected crack can initiate after a certain time. For safe operation, possible mechanisms of crack growth to critical size should be analysed and the condition of a fracture occurrence must be considered, /1-7/.

Most frequent defects in welded structures are surface cracks, caused by imperfections in the welded joint, as are inclusions, overheating, corrosion damages, cracks in the fusion region, welder's markings. Surface crack propagation presents a significant problem, asking to consider also the events immediately after its initiation /8/. Owing to this, the relationship between crack growth rate per load cycle, *da/dN* (where a is the crack length, and N represents the number of load cycles) and fracture mechanics parameter, the stress intensity factor range, ΔK, has to be known.

The paper is aimed at determining the complete relationship *da/dN* vs. ΔK for welded joint constituents (PM, WM and HAZ) produced of high strength low-alloyed steel (HSLA) of nominal yield strength 700 MPa, for characterising the properties, since they are not required in the basic steel specification.

DETERMINATION OF CRACK GROWTH RATE

Paris, Gomey and Anderson have first proposed in 1961 that the crack growth rate, *da/dN*, might be correlated with the stress intensity factor range, ΔK, when the material is exposed to variable loading of constant amplitude, /9/. However, the leading journals in this area did not accept to publish the offered paper. This approach has been adopted for the characterisation of fatigue crack growth in the condition of small scale plastic deformation at the crack tip. Linear elastic fracture mechanics (LEFM) has postulated that the stress intensity factor range, determined according to remote stress and the cracked component geometry unambiguously characterize fatigue crack growth, even when the fatigue fracture mechanism is not known.

Under variable loads, the crack can initiate from an existing defect or damage at maximum values of stress, well below quasi-static fracture toughness. In the small-scale yielding condition, when the non-linear zone in fact represents a disturbance in the otherwise elastic material, Paris, Gomez and Anderson (1961), and later Paris and Erdogan (1963) had supposed that the crack growth under variable loads would follow the law, usually known as the Paris' law,

$$\frac{da}{dN} = C \cdot \Delta K^m \tag{1}$$

Here the stress intensity factor range, ΔK, is defined as

$$\Delta K = K_{\max} - K_{\min} \tag{2}$$

$K_{\max}$ and $K_{\min}$ are maximum and minimum stress intensity factors corresponding to the maximal load, $P_{\max}$ (or maximal nominal stress, $\sigma_{\max}$) and minimal load, $P_{\min}$ (or minimal nominal stress, $\sigma_{\min}$) in a cycle. Values C and m in Eq.(1) are constants obtained empirically, and depend on the properties and material microstructure, fatigue frequency, mean stress, the environment, loading mode, stress state and the applied temperature. The empirical law of crack growth, expressed by Eq.(1) and presented in Fig. 1 as a sigmoidal curve, is a most frequently used form for the characterisation of crack growth rate for a broad spectrum of engineering materials and testing conditions.

Three different regimes of crack growth can be recognised from the diagram in Fig. 1.

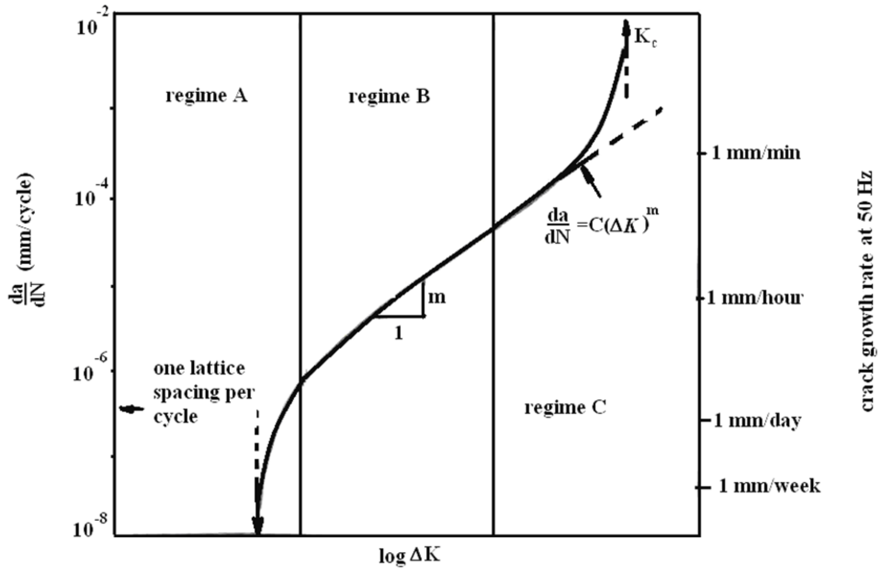

Figure 1. Different regimes of stable fatigue crack propagation, /9/.
Slika 1. Različiti režimi stabilnog rasta zamorne prsline, /9/

In the regime A, the average increment of crack growth is smaller than one lattice spacing per cycle, connected to a threshold stress intensity factor range, ΔK_{th}. Below this threshold, the crack either does not grow, or grows very slowly, followed by a very steep increase of *da/dN* with ΔK.

The law of Paris, Eq.(1), indicating the linear relationship in regime B between log(*da/dN*) and log(ΔK), is applied only on the segment of the growth curve related to stable fatigue growth.

Regime C corresponds to high ΔK values, when the crack propagates fast to final fracture, after reaching the critical stress intensity factor value K_c.

MATERIAL

The material used in the investigation is NIONIKRAL-70 (NN-70), a high strength low-alloyed steel (HSLA), of nominal yield strength 700 MPa and tensile strength 800 MPa, applied in the manufacture of welded pressure vessels for storing liquefied gas and also used in submarines. The chemical composition of NN-70 steel is presented in Table 1, and its mechanical properties are given in Table 2. Tensile properties of the NN-70 steel are presented in Fig. 2.

Table 1. Chemical composition of NIONIKRAL-70 (weight %).
Tabela 1. Hemijski sastav NIONIKRAL-70 (tež. %)

C	Si	Mn	P	S	Cr	Ni	Mo	V	Al
0.10	0.2	0.23	0.009	0.018	1.24	3.1	0.29	0.05	0.08

Table 2. Mechanical properties of NIONIKRAL-70.
Tabela 2. Mehaničke osobine NIONIKRAL-70

Specimen	Yield stress, $R_{p0.2}$ (MPa)	Tensile strength, R_m (MPa)
PM, parallel to rolling direction	780	820
WM	718	791
HAZ	750	800

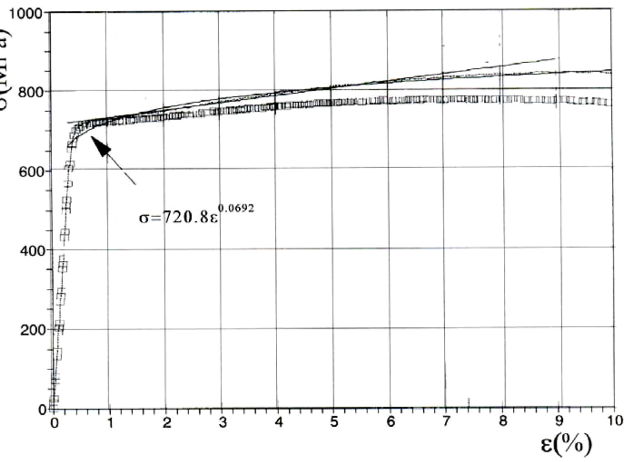

Figure 2. Stress vs. strain for steel NIONIKRAL-70.
Slika 2. Napon i deformacija za čelik NIONIKRAL-70

NIONIKRAL-70 steel is produced in the electric furnace, cast into ingots, rolled into slabs, and finally rolled into 18 mm thick plates. High strength is achieved by combining classical quenching and tempering, and additional grain refining by an optimal combination of chemistry, micro-alloying and corresponding precipitation. Care is devoted to obtain the best combination of strength, ductility, toughness, crack resistance to initiation and growth, and the stability of these properties at low temperatures, high resistance to fatigue and stress corrosion, and in any case – good workability and weldability, /10/.

SPECIMEN GEOMETRY

The manufacture of welded structures using HSLA steels is recommended because the structural mass is reduced due to the high strength, saving both material and energy. However, by increasing the strength, in general, the sensibility to cracking increases, what is of special importance for welded joints. Thus pre-cracked specimens are used for the determination of crack resistance and structural integrity assessment.

The specimen applied in this analysis is shown in Fig. 3. Standard single-edge notch bend specimens SEN(B) are used, of rectangular cross section, with grinded and polished faces, taken from shielded manual arc butt welded 18 mm thick plates. Specimen dimensions are: length L = 100 mm, width W = 16 mm and thickness B = 12 mm, with 2 mm deep notch.

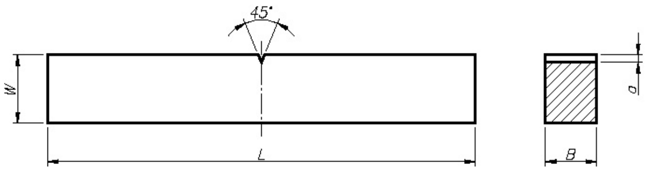

Figure 3. Standard single-edge notch bend specimen SEN(B) used in the experiments.
Slika 3. Standardna epruveta sa ivičnim zarezom za savijanje SEN(B) koja je upotrebljena u eksperimentima

EXPERIMENTS

The crack growing rate da/dN and fatigue threshold ΔK_{th} are determined by moment controlled bending test on the device RUMUL CRACTRONIC 160 Nm at the Welding Laboratory of the Faculty of Mechanical Engineering, University of Maribor, Slovenia. Tests are performed with specimens from parent metal (PM), weld metal (WM) and heat-affected-zone (HAZ). Crack growth is monitored by measuring potential drop by strain gauge RUMUL RMF A-5, measuring 5 mm length, located on the specimen face surface.

The data about the tested steel and applied electrodes are considered in Refs. /11-13/. Fatigue pre-cracks of 1.029 mm length are produced with frequency of 90 Hz in all specimens, applying the stress range in which the stress intensity factor $K_{\max}$ was lower than 15 MPa·m$^{1/2}$ for the PM, and 12 MPa·m$^{1/2}$ for WM, and 10 MPa·m$^{1/2}$ for HAZ.

For further crack propagation of 0.9 mm the load ratio of variable loading in tension is

$$R=\frac{\sigma_d}{\sigma_g}=0$$

with frequency of 63 to 97 Hz, depending on the maximal load. The strain gauge foil has fractured with fatigue crack growth, causing linear response of electrical resistance in the foil with the change in crack length, /14/.

ANALYSIS OF EXPERIMENTAL RESULTS

Experimental results are presented in diagrams log(da/dN) vs. logΔK, in Fig. 4 for PM, in Fig. 5 for WM, and in Fig. 6 for HAZ. The results for the three welded joint constituents are summarised in Fig. 7.

From Figs. 4 to 6 it is possible to determine coefficients C and m introduced in the Paris' law, Eq.(1), for welded joint constituents, and also the threshold values for the stress intensity factor range, ΔK_{th}. Results are listed in Table 3. Table 3 also contains experimentally determined values of plane strain fracture toughness, K_{Ic}, /12/. It is clear from the presented diagrams that the location of notch and fatigue pre-crack both affect the behaviour of the welded joint under variable loading.

Table 3. C and m in Paris' law and fracture mechanics parameters related to fatigue of welded joint constituents of NIONIKRAL 70.
Tabela 3. C i m u Parisovom zakonu i parametri mehanike loma sa zamorom konstituenata zavarenog spoja NIONIKRAL-70

Crack location	Coeff. C	Coeff. m	ΔK_{th} (MPa·m$^{1/2}$)	K_{Ic} (MPa·m$^{1/2}$)
PM	9.05×10^{-14}	4.76	5.85	158
WM	6.07×10^{-12}	2.393	5.82	120
HAZ	8.06×10^{-12}	3.054	4.3	147

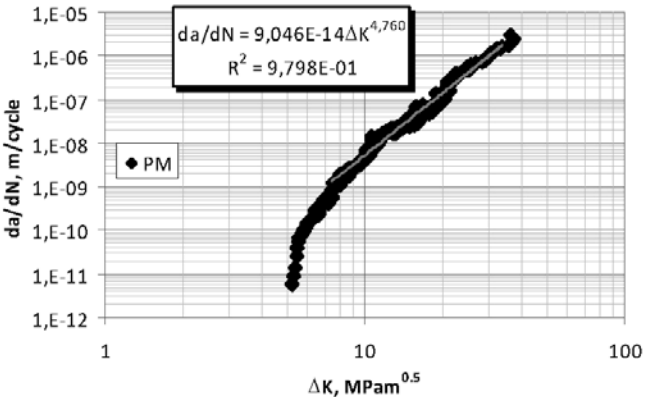

Figure 4. Plot of crack growth rate *da/dN* vs. stress intensity factor range Δ*K* for PM.
Slika 4. Promena brzine rasta prsline *da/dN* sa rasponom faktora intenziteta napona Δ*K* za PM

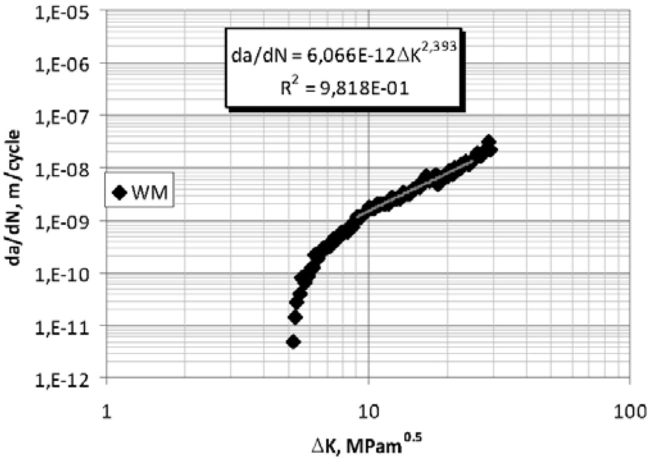

Figure 5. Plot of crack growth rate *da/dN* vs. stress intensity factor range Δ*K* for WM.
Slika 5. Promena brzine rasta prsline *da/dN* sa rasponom faktora intenziteta napona Δ*K* za WM

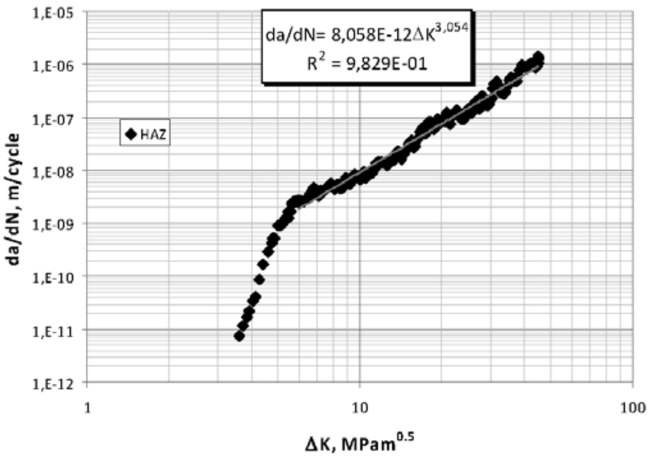

Figure 6. Plot of crack growth rate *da/dN* vs. stress intensity factor range Δ*K* for HAZ.
Slika 6. Promena brzine rasta prsline *da/dN* sa rasponom faktora intenziteta napona Δ*K* za HAZ

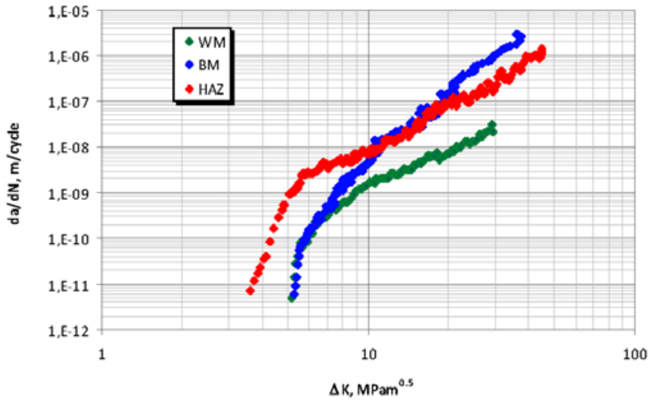

Figure 7. Comparison of crack growth rate *da/dN* vs. stress intensity factor range Δ*K* for welded joint constituents.
Slika 7. Poređenje brzine rasta prsline *da/dN* sa rasponom faktora intenziteta napona Δ*K* za konstituente zavarenog spoja

CONCLUSION

In order to extend the characterisation of crack behaviour for HSLA steel NN-70, the two fatigue parameters, fatigue threshold, ΔK_{th}, and coefficients C and m in the region of validity of Paris' law (so-called regime B, see Fig. 1) have been experimentally determined for the SMAW welded joint constituents (PM, WM and HAZ).

Fatigue threshold coincided well for PM and WM, Fig. 7, Table 3. Its value for HAZ has been found to be lower, ΔK_{th}, indicating that in these constituents the fatigue crack will initiate first. The slope of the crack growth rate is approximately parallel for PM and WM, but indicates a slower rate for WM. The crack growth rate line of HAZ intersects that of PM, indicating faster rate for PM in the first segment, the rate is the same for both PM and HAZ in the intersection region and the two lines are almost parallel in the final segment. For a crack growth rate in the HAZ the change of slope can be revealed in Fig. 6, what is attributed to different microstructures through which cracking has developed.

The data for plane strain fracture toughness K_{Ic}, from previous tests (Table 3), correspond to previously described behaviour.

The behaviour of the welded joint has shown that fatigue properties are not significantly reduced by welding, but for a better understanding of the fatigue crack behaviour in individual constituents of welded joints, a further investigation is necessary. It is also to remark that the tested specimens had grinded and polished faces, so that no effects of stress concentration from the weld overfill may contribute. Overfill grinding is prescribed only for extremely loaded pressure equipment, as are submarines and some reactors in the chemical processing industry.

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