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EFFECT OF STRESS RATIO ON FATIGUE CRACK GROWTH RATE
UTICAJ ODNOSA NAPONA NA BRZINU RASTA ZAMORNE PRSLINE

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Keywords
- fatigue crack growth
- stress intensity factor range
- R-ratio
- correlation model
- lifetime predictions

Abstract

Despite all the efforts made trough the years, lifetime estimation of components subjected with variable amplitude loading is still a major problem for engineering calculation. Introduction of risk-based methods and damage tolerance imposed ample studies on material mechanical properties, especially on fatigue crack growth. Knowing that fatigue crack growth rate is strongly influenced by the R-ratio, a series of models, that explain the stress ratio effect on fatigue crack growth rate, are proposed. Consequently, the purpose of our paper is to present a calculation mode of fatigue crack growth rate, taking into consideration also the effect of the R-ratio.

Ključne reči
- rast zamorne prsline
- opseg faktora intenziteta napona
- R-odnos
- korelacijski model
- predviđanje veka

Izvod

I pored svih višegodišnjih napora, određivanje radnog veka komponenti izloženih opterećenju promenljive amplitude je još uvek veliki problem u inženjerskim proračunima. Uvođenje metoda zasnovanih na riziku i toleranciji oštećenja postavilo je obimne studije mehaničkih osobina materijala, posebno za rast zamorne prsline. Znajući da je brzina rasta zamorne prsline u velikoj meri zavisna od R-odnosa, predložen je niz modela koji objašnjavaju uticaj odnosa napona na brzinu rasta zamorne prsline. U skladu sa tim, namena ovog rada je da prikaže način proračuna brzine rasta zamorne prsline, uzimajući u obzir i uticaj R-odnosa.

INTRODUCTION

The influence of the stress ratio on fatigue crack growth rate was and still is an intensive studied subject, due to the complexity of the variable loads, that stress different components and structures.

Still from the 70's, together with the concept of crack closure proposed by Elber, Eq. (1) /1/, and the model developed by Walker, Eq. (3) /2/, has raised the idea of correlating the crack propagation data for different stress ratios into one curve corresponding to a specific *R*-ratio, for which one knows the material constants from the equation adopted for calculating the lifetime, based on fatigue crack growth rate. Recently, Kujawski /3-5/, proposed a calculus model by which he marks out the possibility of correlating crack propagation data for different stress ratios, without using the concept of crack closure.

$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^m \tag{1}$$

$$\Delta K_{eff} = K_{\max} - K_{op} \tag{2}$$

$$\frac{da}{dN} = C\left[\left(1-R\right)^p \Delta K\right]^m \tag{3}$$

Due to the difficulty encountered in expressing fatigue crack growth rate for different *R*-ratios, the proposed model is aimed to sustain the trend of correlating fatigue crack growth data for different stress ratio in one curve.

THE PROPOSED MODEL

Based on the Kujawski assumption that to each fatigue crack growth rate corresponds a value of stress intensity factor range, specific to each *R*-ratio, one can write:

$$\frac{da}{dN} = C(\Delta K_0)^{n_0} = C(\Delta K_{0.1})^{n_{0.1}} \tag{4}$$

in which ΔK_0 represents the stress intensity factor range for $R = 0$ and n_0 is the slope of $da/dN = f(\Delta K_0)$ curve; $\Delta K_{0.1}$ represents the stress intensity factor range for $R = 0.1$ and $n_{0.1}$ is the slope of $da/dN = f(\Delta K_{0.1})$ curve, /6/.

In the logarithm form, Eq. (4) reads:

$$n_0 \log \Delta K_0 = n_{0.1} \log \Delta K_{0.1} \tag{5}$$

$$\frac{\log \Delta K_0}{\log \Delta K_{0.1}} = \frac{n_{0.1}}{n_0}$$

By noting the ratio $\alpha^* = \frac{n_{0.1}}{n_0}$, it results:

$$\log \Delta K_0 - \alpha^* \log \Delta K_{0.1} = 0$$

$$\text{or} \quad \log \Delta K_0 - \log(\Delta K_{0.1})^{\alpha^*} = 0 \tag{6}$$

$$\log\frac{\Delta K}{(\Delta K_{0.1})^{\alpha^*}}=0 \quad \text{or} \quad \frac{\Delta K_0}{(\Delta K_{0.1})^{\alpha^*}}=1 \tag{7}$$

From relation (7) it results:

$$\Delta K_0=(\Delta K_{0.1})^{\alpha^*} \tag{8}$$

By introducing Eq. (8) in Paris equation and graphic presentation of $da/dN = f[(\Delta K_{0.1})^{\alpha^*}$, crack growth data corresponding to stress ratio $R = 0.1$ will condensate around the propagation curve, corresponding to stress ratio $R = 0$.

A problem which must be solved, is the determination of parameter α^*. From relation (6) it results that:

$$\log\Delta K_0=\alpha^*\log\Delta K_{0.1} \tag{9}$$

Equation (9) is a straight line in log-log plot, and α^* parameter represents the slope of $\Delta K_0 = f(\Delta K_{0.1})$ variation.

For numerical determination of α^*, fatigue crack growth data for six R-ratios for Al 2024-T3 alloy are used (Fig. 1).

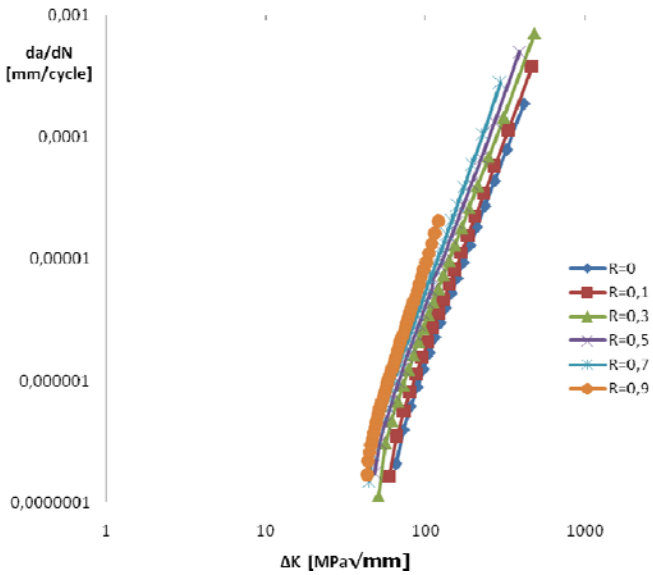

Figure 1. Fatigue crack growth rate vs. stress intensity factor range, Al–2024-T3 alloy.

Slika 1. Brzina rasta zamorne prsline u funkciji opsega faktora intenziteta napona, legura Al–2024-T3

VERIFICATION OF PROPOSED METHOD

For model testing, we used referred data of fatigue crack growth rates for different stress ratios in steel and Al alloys.

Figure 3 shows fatigue crack growth data based on variation of stress intensity factor range for three R-ratios in rolled carbon steel, 1005-1012, according to Refs. /7, 8/. After applying Eq. (10), data of crack propagation are plotted into one curve with stress ratio $R = 0$, Fig. 4. Figure 5 represents data of fatigue crack propagation for stress ratios between 0 and 1, of cast alloy steel (A536 Grd 80-55-06, /9, 10/) and in Fig. 6 the correlation curve resulted after applying the proposed model for crack propagation data for $R = 0$.

First of all, we determined the material constants for the considered material $C = 2.38e^{-12}$ and $n_0 = 3.421$, based on crack growth curve corresponding to $R = 0$.

Secondly, for each fatigue crack growth rate corresponding to $R = 0$, we identified ΔK values, for each stress ratio ($\Delta K_{0.1}$, $\Delta K_{0.3}$, $\Delta K_{0.5}$, $\Delta K_{0.7}$, $\Delta K_{0.9}$); after that we made a graphic representation of the variations $\Delta K_0 = f(\Delta K_{0.1}$, $\Delta K_{0.3}$, $\Delta K_{0.5}$, $\Delta K_{0.7}$, $\Delta K_{0.9})$.

Based on a slope statistical analysis, resulted for each straight line, we calculated the mean value of parameter α^*:

For		For	
$R = 0 \ldots 0.5$	$\alpha^* = 1.35953$	$R = 0.5 \ldots 1$	$\alpha^* = 1.842$
$R = -0.5 \ldots 0$		$R = -1 \ldots -0.5$	

By introducing relation (8) in Paris equation, we calculate the fatigue crack growth rate for each considered R-ratio:

$$\frac{da}{dN}=C\left[\left(\Delta K_{0.1}\right)^{\alpha^*}\right]^{n_0} \tag{10}$$

as presented in Fig. 2.

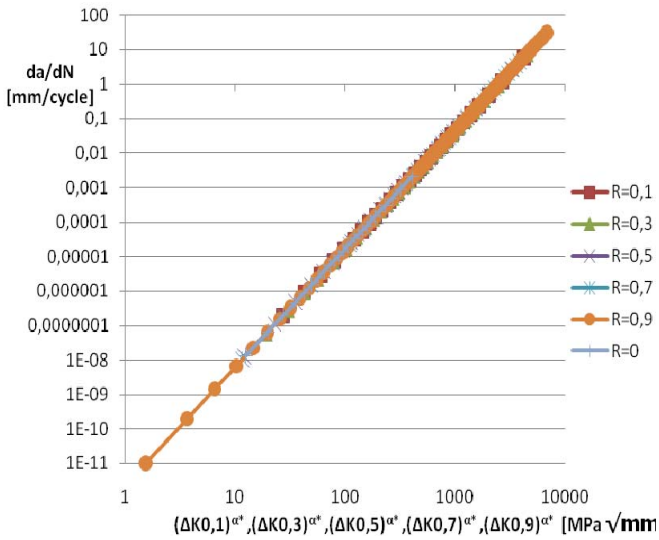

Figure 2. Variation curve for $R = 0$ resulted after correlating the data of crack growth rate in Al–2024-T3 alloy.

Slika 2. Krive promene $R = 0$ posle korelacije podataka za brzinu rasta prsline za leguru Al–2024-T3

Relation (10) is applied also on crack propagation data in Al–7475-T7351 alloy, for positive, in Fig. 7, and for negative stress ratios in Fig. 9, /11, 12/. Corresponding correlation curves for crack propagation data for $R = 0$, for Al–7475-T7351 alloy are given in Fig. 8 for data from Fig. 7, and in Fig. 10 for data in Fig. 9.

EXPERIMENTAL VERIFICATION OF THE MODEL

The model is verified by crack growth data for stress ratios $R = 0.1$ and 0.3 in S355J2H steel. Crack growth tests were made according to ASTM E647, under computer control on servo-hydraulic testing machine Walter-Bai, model LHV-100 using standard CT specimens (Fig. 11), and the elastic compliance technique for crack length determination.

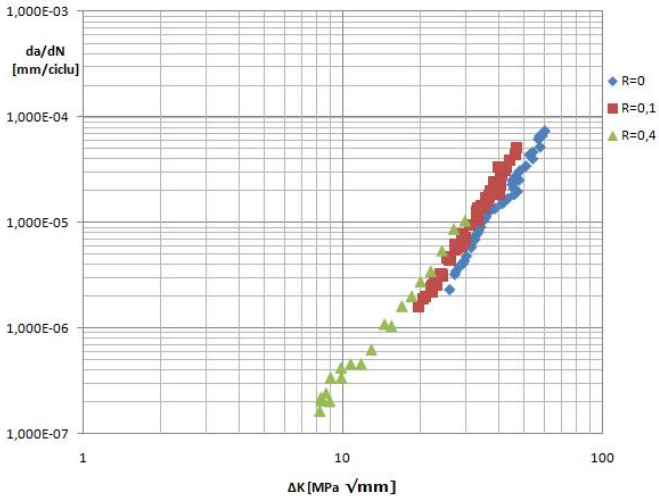

Figure 3. Variation curves *da/dN* = *f*(Δ*K*) for rolled carbon steel, 1005-1012 /7, 8/.
Slika 3. Krive promene *da/dN* = *f*(Δ*K*), valjani ugljenični čelik, 1005-1012 /7, 8/

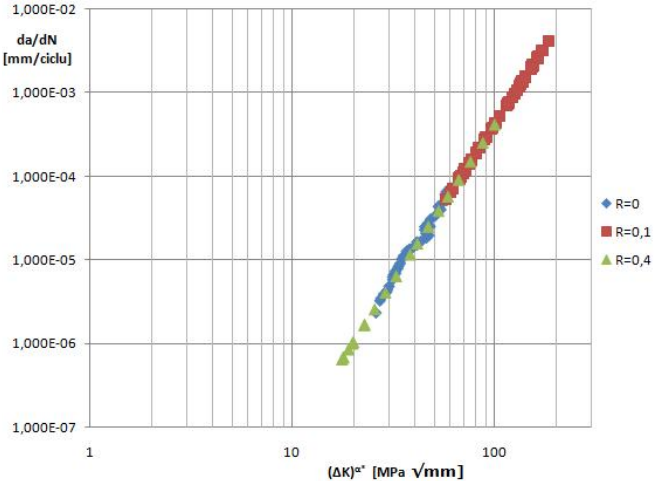

Figure 4. Correlation curve for crack propagation data for *R* = 0, rolled carbon steel, 1005-1012.
Slika 4. Korelacijske krive za podatke rasta prsline za *R* = 0, valjani ugljenični čelik, 1005-1012

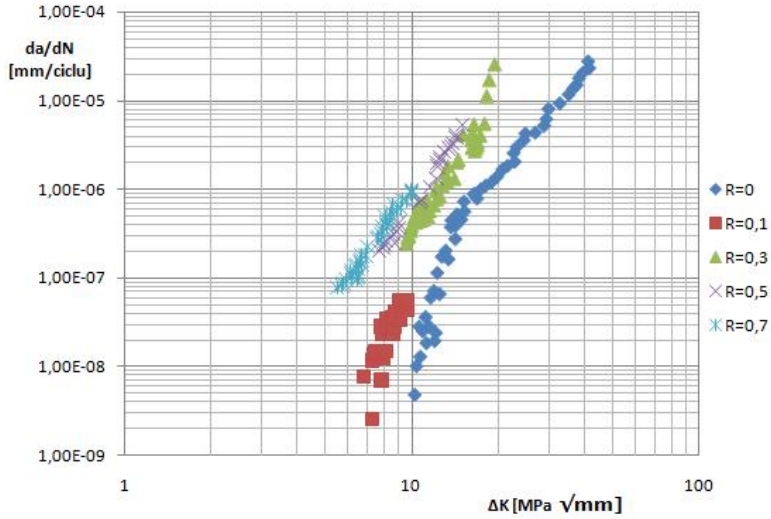

Figure 5. Variation curves *da/dN* = *f*(Δ*K*) for cast alloy steel, A536 Grd 80-55-06 /9, 10/.
Slika 5. Krive promene *da/dN* = *f*(Δ*K*) za liveni legirani čelik, A536 Grd 80-55-06 /9, 10/

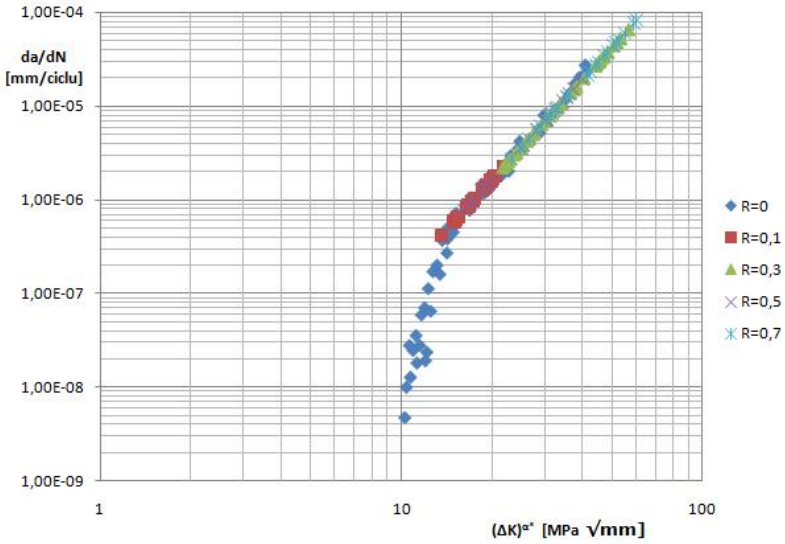

Figure 6. Correlation curve for crack propagation data for *R* = 0, for cast alloy steel, A536 Grd 80-55-06 /9, 10/.
Slika 6. Korelacijske krive za podatke rasta prsline za *R* = 0, za liveni legirani čelik, A536 Grd 80-55-06 /9, 10/

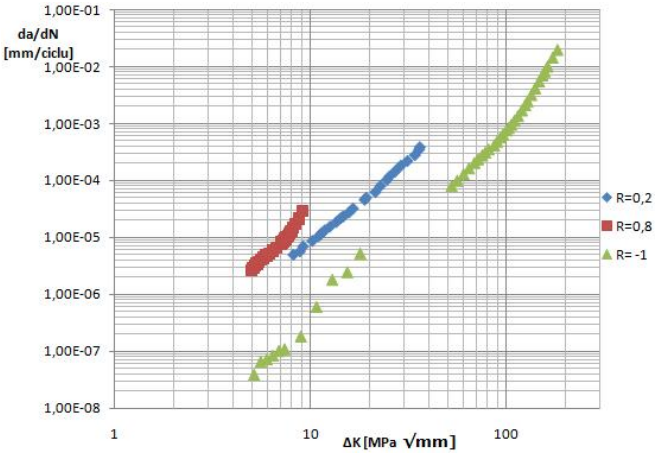

Figure 7. Variation curves *da/dN* = *f*(Δ*K*) for Al–7475-T7351 alloy, /11, 12/.
Slika 7. Krive promene *da/dN* = *f*(Δ*K*) za leguru Al–7475-T7351, /11, 12/

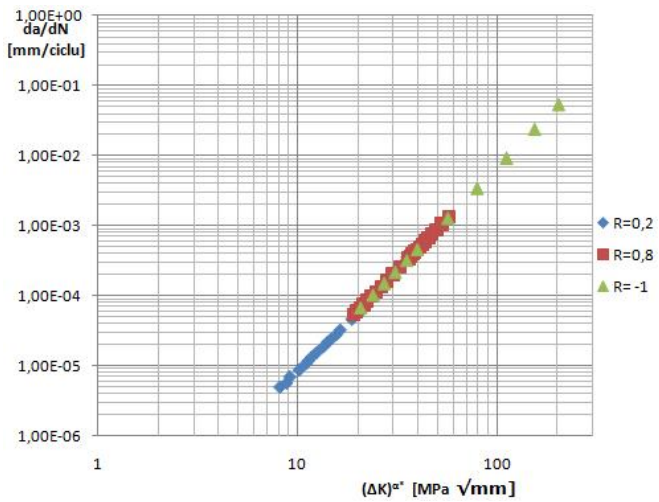

Figure 8. Correlation curve for crack propagation data for *R* = 0, for Al–7475-T7351 alloy, /11, 12/.
Slika 8. Korelacijske krive za podatke rasta prsline za *R* = 0, za leguru Al–7475-T7351, /11, 12/

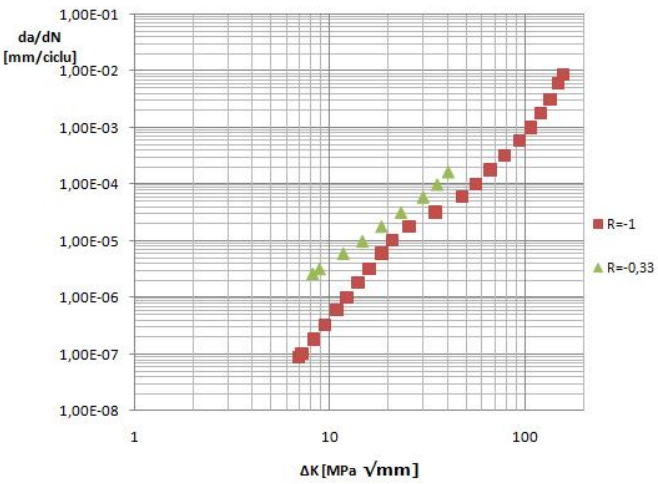

Figure 9. Variation curves *da/dN* = *f*(Δ*K*) for negative stress ratios, in Al–7475-T7351 alloy.
Slika 9. Krive promene *da/dN* = *f*(Δ*K*) za negativne odnose napona, za leguru Al–7475-T7351

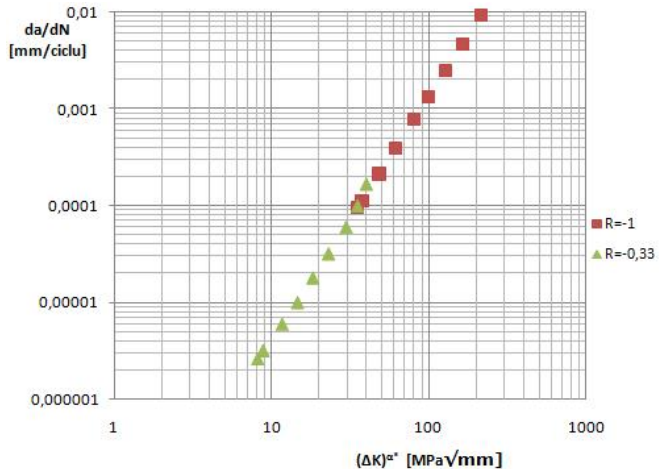

Figure 10. Correlation curve for crack propagation data for *R* = –0.33, for Al–7475-T7351 alloy.
Slika 10. Korelacijske krive za podatke rasta prsline za *R* = –0.33, za leguru Al–7475-T7351

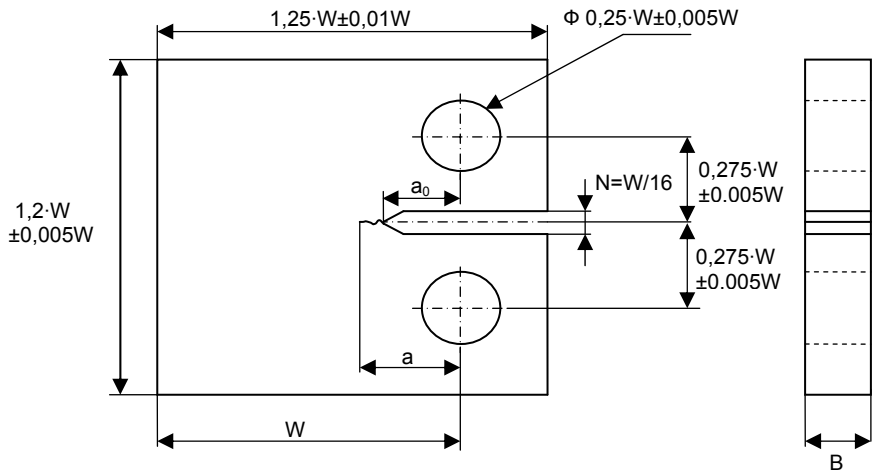

Figure 11. CT specimen for fatigue crack propagation tests (B = 10 mm, W = 46 mm).
Slika 11. CT epruveta za ispitivanje rasta zamorne prsline (B = 10 mm, W = 46 mm)

Based on the proposed model the resulted crack growth data, Fig. 12, is correlated around $da/dN = f(\Delta K)$ corresponding to $R = 0.1$. First, we calculate constants $C_{0.1}$ and $n_{0.1}$ for propagation curve with $R = 0.1$ and relation (10) is applied for crack propagation data corresponding to $R = 0.3$, producing the correlation:

$$\left(\frac{da}{dN}\right)_{0.3} = C_{0.1}\left[\left(\Delta K_{0.3}\right)^{\alpha^*}\right]^{n_{0.1}} \tag{11}$$

Derived correlation curves are presented in Fig. 13.

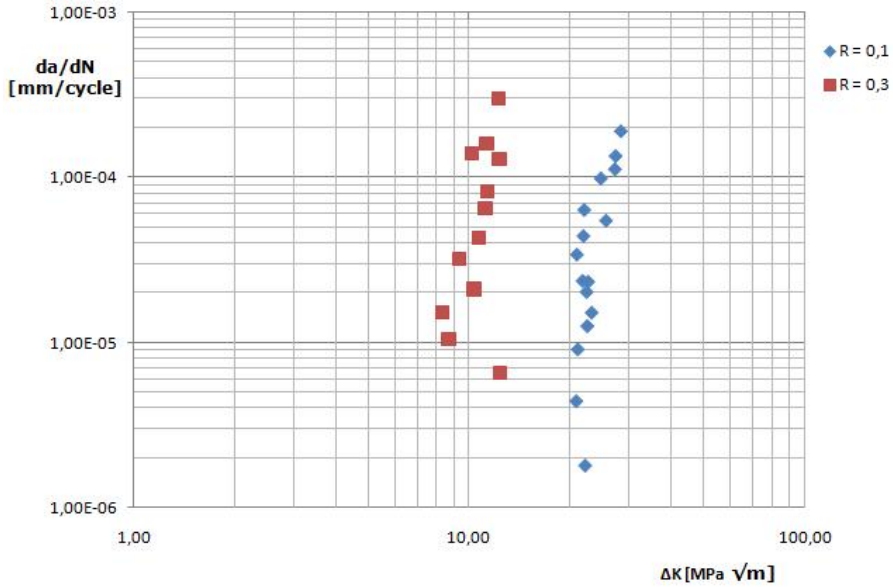

Figure 12. Crack propagation data in S355J2H steel.
Slika 12. Podaci o rastu prsline, čelik S355J2H

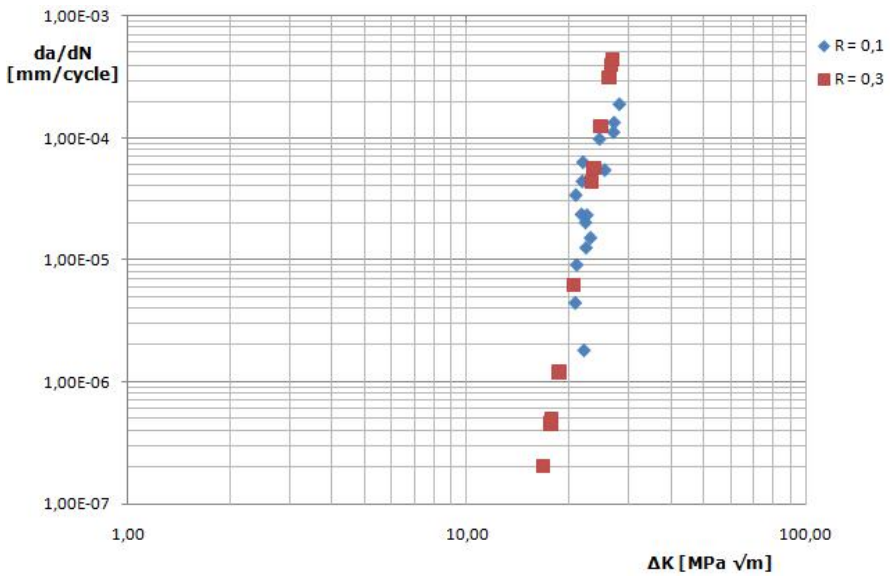

Figure 13. Correlation curve for $R = 0.1$, S355J2H steel.
Slika 13. Korelacijske krive za $R = 0.1$, čelik S355J2H

CONCLUSIONS

This paper describes a model for correlation crack propagation data for different stress ratios into one single crack propagation curve with specified R-ratio. The model can be applied in the stable crack growth region (Paris region) and has the advantage that knowing crack growth data for a specified R-ratio, one can predict lifetime for variable loads of different stress ratios. Results obtained from verification of model show a good capacity of crack growth data correlation both for positive and negative stress ratio and also give a guarantee about the determination of α^* parameter.

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