Microstructural Interpretation of Effective Fatigue Threshold of Structural Steel

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Key words: Effective fatigue threshold, austenitic steel, extrinsic toughening, closure model

Abstract. In the case of plain strain conditions, the shear misfit of crack flanks causing the roughness-induced crack closure is determined by the asymmetry of configurations of crack-wake dislocations and by a low value of the size ratio S_R (the plastic zone size/the characteristic microstructural distance). The crack wake dislocations produce also the plasticity induced crack closure as a result of a near-tip mismatch perpendicular to crack flanks. These extrinsic shielding effects can be quantitatively estimated according to recently published theoretical concepts [1−3] that were applied to the austenitic steel of Japan provenience in the threshold region of fatigue crack propagation. Related fatigue experiments were based on a standard load shedding technique associated with monitoring of the crack closure level. The surface roughness was analysed by means of the optical chromatography that enables a 3D reconstruction of fracture morphology. Calculated and measured effective threshold values of about 2.2 MPa.m$^{1/2}$ are practically identical. Total levels of the extrinsic toughening induced by the austenitic microstructure are rather low when compared to those identified in ferritic- and ferritic-austenitic steels.

Theoretical considerations

The plasticity induced crack closure (PICC) and the roughness induced crack closure (RICC) are known as two important mechanisms for fatigue crack tip shielding and lead to an apparent increase in the resistance to fatigue crack propagation [1]. Although a plenty of studies on these mechanisms have been done hitherto [2, 3], our understanding and a prediction capability remain still rather insufficient. Recently, some new concepts concerning the closure effects were proposed [4, 5]. Asymmetric arrangements of stored crack-wake dislocations and low values of the size ratio S_R (the characteristic microstructural distance divided by the plastic zone size) were found to be of basic importance for the shear misfit of crack flanks causing RICC under plain strain conditions. The crack wake dislocations cause also PICC as a result of a near-tip mismatch perpendicular to crack flanks. According to newly derived formulae including these effects, an estimation of maximum levels of both RICC and PICC can be made for metallic materials in the whole fatigue crack propagation regime.

The crack-wake dislocations on both sides of crack flanks independently contribute to PICC [4]. As a simple model, only two narrow bands of dislocations can be considered here to tilt the volume elements in the crack wake. This transfers the material to the crack tip and results in PICC under plain strain conditions. When the arrangement of crack-wake dislocations is asymmetric, the shear misfit of crack flanks causes a long-range RICC on rough fracture surfaces. An additional short-range contribution to RICC comes from the shear irreversibility ahead the crack tip [5]. The necessary conditions for RICC (the asymmetry and the roughness) are well fulfilled when $S_R \geq 1$, i.e. when the characteristic microstructure distance (the mean grain size or the interparticle spacing) is comparable or higher than the plastic zone size [5, 6]. On the other hand, when the plastic zone embraces, at least, several grains or particles, i.e. $S_R << 1$, the RICC can be neglected. However, the size ratio does not have any significant considerable effect on the PICC ratio.

The aim of this paper is to apply the unified model [7] to investigation of the extrinsic fracture toughness component and the effective fatigue-threshold value of the austenitic steel made in Japan.

Considering the local stress intensity factors (SIFs) K_I and K_II and associated displacements produced by the totally asymmetric dislocation band near the crack tip, one can derive the following expression for the maximum long-range (LR) closure ratio:

$$\left(\frac{\delta_{cl}}{\delta_{\max}}\right)_{LR} = C\sqrt{S_R\left(R_S^2-1\right)}, \tag{1}$$

where C is a dimensionless constant ($C = 0.125$ is usually employed), nearly independent on the material and R_S is the surface (area) roughness of the fracture surface [8]. The maximal short-range (SR) component (a totally irreversible slip) can be written as

$$\left(\frac{\delta_{cl}}{\delta_{\max}}\right)_{SR} = \frac{3\left(R_S-1\right)}{\sqrt{6}+3\left(R_S-1\right)}. \tag{2}$$

Due to an enormous variability in the characteristic microstructure distance in engineering materials and for the sake of simplicity, one can divide the grains (or interparticle spacings) into two categories; to those of $S_R \geq S_{Rc}$ (maximal level of RICC, $S_R \geq 1$) and those of $S_R < S_{Rc}$ (no RICC, $S_R \to 0$), where $S_{Rc} = d_c/r_p$ is a critical boundary value of about 0.5 ($S_{Rc} \in \langle 0.2, 1\rangle$ [8]). Then, the parameter

$$\eta = \int_{S_{Rc}}^{\infty} p\left(S_R\right)\mathrm{d}S_R \approx \exp\left[-\left(\frac{0.886\, S_{Rc}}{S_{Rm}}\right)^{2.2}\right], \tag{3}$$

where $p(S_R)$ is the Weibull probability density and S_{Rm} is the mean value of the size ratio, expresses a statistically averaged weight of S_R in the phenomenon of RICC.

On the contrary to RICC, dislocation arrays on both sides of crack flanks contribute to PICC. This effect remains practically unaffected by the size ratio and can be simply assessed [7] as

$$\left(\frac{\delta_{cl}}{\delta_{\max}}\right)_{PICC} = 2C. \tag{4}$$

Assuming Eqs. (1) and (2) multiplied by the probability parameter (3), and Eq. (4), the total level of the closure ratio reads

$$\left(\frac{\delta_{cl}}{\delta_{\max}}\right)_{tot} = \frac{K_{cl}}{K_{\max}} = C\eta\sqrt{R_S^2-1} + \frac{3\eta\left(R_S-1\right)}{\sqrt{6}+3\left(R_S-1\right)} + 2C. \tag{5}$$

Because $\Delta K_{eff} = K_{\max} - K_{cl}$, and according to Eq. (5), the effective value of the SIF range can be expressed as

$$\Delta K_{eff} = \left(1 - C\eta\sqrt{R_S^2 - 1} - \frac{3\eta\left(R_S - 1\right)}{\sqrt{6} + 3\left(R_S - 1\right)} - 2C\right)\frac{\Delta K}{1 - R}, \tag{6}$$

where ΔK is the applied SIF range and R is the cyclic ratio. Values of ΔK_{eff} can be identified experimentally by measuring the crack closure. The effective threshold value ΔK_{eff} represents a pure material resistance against the crack propagation and should be nearly independent on the cyclic ratio and microstructure parameters of a particular material.

Experimental

Fatigue crack growth (FCG) rate tests were carried out using 18 mm thick compact C(T) specimens made of austenitic steel SUS316L (the chemical composition in Table 1) in a MTS servo-hydraulic machine. The first two tests were performed at room temperature using the cyclic ratios $R = 0.1$ and $R = 0.3$ for steadily decreasing ΔK. In the third test the value $K_{\max} = 15.5$ MPa.m$^{1/2}$ was kept constant. The threshold values ΔK_{th} and $\Delta K_{eff,th}^{\exp}$ in all tests correspond to the crack growth rate $\mathrm{d}a/\mathrm{d}N = 10^{-11}$ m/cycle. Crack closure was evaluated by analyzing the load versus crack opening displacement (COD) curves.

Table 1 Chemical composition

Material	C	Ni	Cr	Mo	Si	Mn	P	S
SUS316L	0.019	12.30	17.32	2.87	0.49	0.83	0.028	0.001

The mean grain size of the steel was of 28 μm. Values of the area roughness R_S were measured by means of the profilometer MicroProf FRT (based on the chromatic aberration method) for z-axis measurement, equipped by the FRT Mark III software for 3D surface reconstructions. All the experimental data are summarised in Table 2.

Table 2 Experimental data

Test No	$R_p0.2$ [MPa]	R_S	R	ΔK_{th} [MPa.m$^{1/2}$]	$\Delta K_{eff,th}^{\exp}$ [MPa.m$^{1/2}$]
1	217	1.37	0.1	3.54	2.19
2	217	1.40	0.3	2.93	2.20
3	217	1.42	0.8	2.65	2.65

Theoretical results and discussion

The computed values of the statistical factor η and the effective SIF range $\Delta K_{eff,th}^{cal}$ are displayed in Table 3. The values $C = 0.125$ and $S_{Rc} = 0.5$ were used in agreement with above mentioned presumptions. The calculated and the measured effective threshold values are practically identical (about 2.2 MPa.m$^{1/2}$) – compare Tables 2 and 3. Note that, in ferritic steels, this value is of 2.75 MPa.m$^{1/2}$ [6, 9]. As expected, no closure was identified in the threshold region of the test No. 3 because of very high value $R = 0.8$ reached at $\mathrm{d}a/\mathrm{d}N = 10^{-11}$ m/cycle. In this case, obviously, the identity $\Delta K_{eff,th}^{\mathrm{cal}} = \Delta K_{th}$ can be applied.

Table 3 Computed values

Test No	η	$\Delta K_{eff,th}^{\mathrm{cal}}$ [MPa.m$^{1/2}$]	Extrinsic component [%]
1	0.76	2.13	39
2	0.70	2.30	22
3	–	(2.65)	0

The last column in Table 3 shows a percentage contribution of the total extrinsic component $\Delta K_{eff,th}^{\mathrm{cal}}$ (corresponding to the crack closure) to the measured values ΔK_{th} that can be expressed as $\left(\Delta K_{th} - \Delta K_{eff,th}^{\mathrm{cal}}\right).100/\Delta K_{th}\,[\%]$. The values reveal a rather low participation of the extrinsic toughening induced by the austenitic microstructure when compared to 53% in the ferritic steel [5] and 75% in the ferritic-austenitic duplex steel [10].

Conclusions

The fatigue threshold behaviour of the austenitic steel at room temperature has been investigated by means of experimental and theoretical approaches. The main results can be summarised as follows:

(i) The calculated values of effective fatigue thresholds (closure corrected) are in very good agreement with experimental data.

(ii) Total levels of the extrinsic toughening induced by the austenitic microstructure are rather low when compared to those identified in ferritic- and ferritic-austenitic steels.

Acknowledgment

This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic in the frame of the project MSM 0021630518 and by the Czech Science Foundation in the frame of the project 101/05/0493.

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