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Computation of Effective Fatigue Thresholds Based on a New Concept of Crack Closure

Jana Horníková[a], Pavel Šandera[b] and Jaroslav Pokluda[c]
Brno University of Technology
Technická 2, CZ-61669 Brno
Czech Republic
[a]hornikova@fme.vutbr.cz, [b]sandera@fme.vutbr.cz, [c]pokluda@fme.vutbr.cz

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Abstract. A new theoretical concept of crack closure under plain strain was applied to assess the effective fatigue threshold under various loading condition for selected aluminium and titanium alloys of different microstructures. The concept is based on the long-range effect of geometrically necessary dislocations remaining in the wake of propagating fatigue cracks. Calculated threshold values $\Delta K_{\mathrm{eff,th}}$ for 7475 aluminium alloy are about 1.9 MPa.m$^{1/2}$ (in vacuum) and 1 MPa.m$^{1/2}$ (in air), and about 2.5 MPa.m$^{1/2}$ and 3.3 MPa.m$^{1/2}$ for α-titanium and Ti-2.5%Cu, respectively. All calculated values are nearly independent on both the microstructure and the applied stress ratio and they are in a good agreement with experimental data.

Theoretical Concept

Asymmetric arrangements of stored crack-wake dislocations and low values of the size ratio $S_{\mathrm{R}} = d/r_{\mathrm{p}}$, d is the characteristic microstructural distance (e.g. the grain size) and r_{p} is the plastic zone size, were found to be of basic importance for both the roughness-induced crack closure (RICC) and the plasticity induced crack closure (PICC) in case of plain strain conditions [1, 2]. According to newly derived formulae including these effects [3, 4], an estimation of RICC and PICC can be made for metallic materials in the whole fatigue crack propagation regime. Consequently, effective range of the stress intensity factor (SIF) can be calculated particularly near the threshold. This theoretical method was already applied in order to explain the extreme fatigue threshold values measured in case of duplex steel [5]. The aim of this paper is to extend the application to titanium and aluminium alloys.

When a long fatigue crack grows under constant remote ΔK and R (the stress ratio), and under conditions of small scale yielding and plane strain, a plastically deformed strip (a static plastic zone) of a constant height is always formed by stored crack-wake dislocations. However, only a narrow band of geometrically necessary dislocations, and a related local crack-tip SIFs k_{I} and k_{II}, can be considered to model RICC and PICC [3]. As a result, the effective value of the SIF range can be expressed as

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

where $C \approx 10^{-1}$ is a dimensionless constant (nearly independent on the material) and R_{S} is the roughness of the fracture surface. The statistical parameter $\eta \in \langle 0,1 \rangle$ is defined as

$$\eta = \int_{S_{\mathrm{Rc}}}^{\infty} p\left(S_{\mathrm{R}}\right)\mathrm{d}S_{\mathrm{R}} \approx \exp\left[-\left(\frac{0.886\,S_{\mathrm{Rc}}}{S_{\mathrm{Rm}}}\right)^{2.2}\right], \tag{2}$$

where $p(S_{\mathrm{R}})$ is the Weibull probability density, $S_{\mathrm{Rm}} = d_{\mathrm{m}}/r_{\mathrm{p}}$ is the mean value of the size ratio and $S_{\mathrm{Rc}} = d_{\mathrm{c}}/r_{\mathrm{p}}$ is its critical boundary value of about 0.5 ($S_{\mathrm{Rc}} \in \langle 0.1, 1.0\rangle$). One can expect $\eta \to 0$ when $S_{\mathrm{Rm}} \ll 1$ and $\eta \to 1$ when $S_{\mathrm{Rm}} \geq 1$. Values of ΔK_{eff} can also be identified by measuring the crack closure effect. In case of crack branching, however, these values can be much higher than those of the intrinsic threshold ΔK_{int}, since

$$\frac{\Delta K_{\mathrm{int}}}{\Delta K_{\mathrm{eff}}} = 1 - \eta + \eta\sqrt{\frac{g}{R_{\mathrm{S}}}} \leq 1, \tag{3}$$

where $g < 1$ is the normalized local crack driving force corresponding to the branched front [2].

Estimation of Effective Fatigue Thresholds of Aluminium and Titanium Alloys

The assessment of $\Delta K_{\mathrm{eff,th}}$ values can be made using Eq. 1 together with relevant values of measured ΔK_{th}, the yield stress $R_{\mathrm{p}}0.2$ (to check the plastic zone size) and the roughness R_{S}. The values of C and S_{Rc} are chosen (within the above mentioned permissible ranges) to obtain the best fit, i.e. the smallest scatter of theoretical data.

Table 1: Experimental data and calculated effective fatigue thresholds ($C = 0.125, S_{\mathrm{Rc}} = 1.0$) in air and vacuum for 7475 aluminium alloy.

	Measurement					Calculation	
	R_{S}	d_{m} [μm]	σ_{y} [MPa]	R	ΔK_{th} [MPa.m$^{1/2}$]	η	$\Delta K_{\mathrm{eff,\ th}}$ [MPa.m$^{1/2}$]
vacuum	1.30	18	505	0.1	4.0	0.87	1.89
	1.21	18	455	0.1	2.9	0.95	1.53
	1.90	80	451	0.1	8.8	0.76	1.92
	1.25	80	445	0.1	4.1	0.99	1.94
air	1.30	18	505	0.1	2.6	0.98	1.11
	1.21	18	455	0.1	1.7	1.00	0.87
	1.36	80	451	0.1	2.7	1.00	0.99
	1.25	80	445	0.1	2.2	1.00	1.03

All the calculated $\Delta K_{\mathrm{eff,th}}$ values for tests in air lie close to 1, which is perfectly within the experimental range reported by Pippan for aluminium alloys [6]. Values for the vacuum tests are distinctly higher as also shown by the experiment [7].

Table 2: Experimental data and calculated effective fatigue thresholds ($C = 0.15, S_{\mathrm{Rc}} = 0.3$) in air for α-titanium.

	Measurement					Calculation	
	R_{S}	d_{m} [μm]	σ_{y} [MPa]	R	ΔK_{th} [MPa.m$^{1/2}$]	η	$\Delta K_{\mathrm{eff,\ th}}$ [MPa.m$^{1/2}$]
α-titanium	1.30	40	430	0.07	6.0	0.98	2.02
	1.30	40	430	0.35	5.0	0.96	2.47
	1.30	35	260	0.07	5.3	0.88	2.01
	1.30	35	260	0.35	4.3	0.79	2.58
	1.30	230	220	0.07	7.0	0.99	2.35
	1.30	230	220	0.35	5.8	0.97	2.84
	1.30	20	630	0.07	6.0	0.99	2.02
	1.30	20	630	0.35	4.3	0.98	2.07
	1.30	210	580	0.07	10.0	1.00	3.30
	1.30	210	580	0.35	8.0	1.00	3.78

Threshold experimental data and calculated values for various α-titanium grades of different mean grain sizes [8] are collected in Table 2. Calculated values lie in a sufficiently close range of $(2.0, 3.8)$ MPa.m$^{1/2}$ contrary to the large scatter of experimental ΔK_{th} data. The computed range is in a satisfactory agreement with the averaged measured value of 2.1 MPa.m$^{1/2}$ [9]. The somewhat higher values of the great of $d_{\mathrm{m}} = 210\,\mu\mathrm{m}$ might be a consequence of more pronounced crack branching or tilting (see Eq. 3).

Table 3: Experimental data and calculated effective fatigue thresholds ($C = 0.2, S_{\mathrm{Rc}} = 0.3$) in air for titanium alloy Ti-2.5%Cu.

	Measurement					Calculation	
	R_{S}	d_{m} [μm]	σ_{y} [MPa]	R	ΔK_{th} [MPa.m$^{1/2}$]	η	$\Delta K_{\mathrm{eff,\ th}}$ [MPa.m$^{1/2}$]
alloy	1.15	580	420	0.07	9.0	1.00	3.31
	1.15	10	499	0.35	7.0	0.65	3.31

Experimental and theoretical threshold data for two grades of Ti-2.5%Cu are displayed in Table 3 [10]. The microstructures consisted of coarse lamellar colonies of $d_{\mathrm{m}} = 580\,\mu\mathrm{m}$ and a fine basket weave Widmanstätten microstructure of $d_{\mathrm{m}} = 10\,\mu\mathrm{m}$, respectively. The calculated effective threshold values of 3.3 MPa.m$^{1/2}$ are very close to the averaged measured value $\Delta K_{\mathrm{eff,th}} = 3.2\,\mathrm{MPa.m}^{1/2}$ for Ti-6Al-4V alloys [11].

Conclusion

The new theoretical concept of crack closure, based on the effect of crack wake dislocations, was applied to selected aluminium and titanium alloys. Computed values of the effective fatigue threshold reveal a very small scatter and lie close to those obtained in experiments.

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References

[1] R. Pippan, G. Strobl, H. Kreuzer and C. Motz: Acta Mater. Vol. 52 (2004), p. 4493.

[2] J. Pokluda, P. Šandera and J. Horníková: Fat. Fract. Engng. Mater. Struct. Vol. 27 (2004), p. 141.

[3] J. Pokluda and R. Pippan: Mater. Sci. Eng. A (2006), in press.

[4] J. Pokluda, P. Šandera and J. Pippan, in: *9th International Fatigue Congress*, Atlanta (2006), in press.

[5] G. Chai and J. Pokluda, in: *9th International Fatigue Congress*, Atlanta (2006), in press.

[6] R. Pippan, M. Berger and H. P. Stüwe: Metallurgical Transactions Vol. 18A (1987), pp. 429-435.

[7] R. D. Carter, E. W. Lee, E. A. Starke, Jr. and C. J. Beevers: Metallurgical Transactions Vol. 15A (1984), pp. 555–563.

[8] J. L. Robinson and C. J. Beevers: Metal Science Journal Vol. 7 (1973), pp. 153–159.

[9] J. K. Gregory, in: *ASM Handbook, Fatigue and Fracture* Vol. 19, edited by S. R. Lampman et al., ASM Int. (1996), pp. 845–853.

[10] S. H. Wang and C. Müller: Materials Science and Engineering Vol. A255 (1998), pp. 7–15.

[11] B. L. Boyce and R. O. Ritchie: Engineering Fracture Mechanics Vol. 68 (2001), pp. 129–147.