ORAL/POSTER REFERENCE: ICF100424OR

FATIGUE CRACK PROPAGATION LIMIT CURVES FOR METALLIC AND NON-METALLIC MATERIALS

J. Lukács

Department of Mechanical Engineering, University of Miskolc
H-3515 Miskolc-Egyetemváros, Hungary

ABSTRACT

There are different documents containing fatigue crack propagation curves and rules for the prediction of crack growth. The research work aimed to develop a new method for determination of fatigue crack propagation limit curves and determination of limit curves for different metallic materials (steels, austempered ductile iron, aluminium alloys) and their welded joints and non-metallic materials (ceramic, polymer, composite), under different loading conditions, based on statistical analysis of test results and the Paris-Erdogan law. With the help of the characteristic values of threshold stress intensity factor range (ΔK_{th}), two constants of Paris-Erdogan law (C and n), fracture and fatigue fracture toughness (K_{Ic} and ΔK_{fc}) a new method can be proposed. The limit curves represent a compromise of rational risk and striving for safety.

INTRODUCTION

Reliability of a structural element having crack or crack-like defect is determined by the geometrical features of the structural element and the flaws, the loading conditions as well as the material resistance to crack propagation. There are different documents and standards containing fatigue crack propagation limit or design curves and rules for the prediction of crack growth [1, 2, 3, 4, 5]. The background of the limit curves and the calculations consists of two parts: statistical analysis of numerous experiments and fatigue crack propagation law, frequently the Paris-Erdogan law [6].

The research work aimed (i) to develop a new method for determination of fatigue crack propagation limit curves; (ii) determination of limit curves for different metallic materials and their welded joints, under mode I and mixed mode I+II loading conditions and for non-metallic materials under mode I loading condition.

EXPERIMENTS

Specimens made of micro-alloyed steel grades 37C, E420C and HSLA steel grade X80TM and their welded joints by gas metal arc (GMA) welding were tested. Specimens made of 10 Cr Mo 9 10 hot resistant steel and its welded joints by submerged metal arc (SMA) welding, specimens made of KL7D pressure vessel steel and its welded joints by manual metal arc (MMA) welding and specimens made of railway rail steel grade DO76 and HSLA steel grade QStE690TM were investigated, too. Welding of 37C steel was carried out with CO_2 gas, E420C steel with 80% Ar + 20% CO_2 gas mixture and X80TM steel with 82% Ar + 18% CO_2 gas mixture. Specimens made of austempered ductile iron (ADI) and specimens made of aluminium alloy types AlMg3, AlMg5, AlMg4.5Mn and their welded joints by GMA and pulsed GMA welding were tested, too [7]. Mechanical properties of base materials (bm) and weld metals (wm) are shown in Table 1.

TABLE 1

MECHANICAL PROPERTIES OF THE TESTED METALLIC MATERIALS AND WELD METALS

Material	R_y N/mm^2	R_m N/mm^2	A_5 %	Z %	KV(20^0C) J	KV(0^0C) J	KV(-20^0C) J
37C bm	270	405	33.5	63.5	–	>27	–
10 Cr Mo 9 10 bm	374	510	≥20	–	≥34	–	–
KL7D bm	390	535	≥19.0	–	–	–	≥40
E420C bm	450	595	30.7	–	–	>40	-
X80TM bm(1)	540	625	25.1	73.1	–	–	≥243
DO 76 bm	582	954	7.6	–	≥7	–	–
QStE690TM bm(2)	780	850	18.3	–	130	90	95
VIH-2 wm	410-485	535-585	22.0-24.8	40.9-63.9		46-80	29-61
ESAB OK Flux 10.62/ OK Autrod 13.20 wm	450	590	–	–	≥100	–	–
EB 12 wm	420-510	510-630	≥22.0	–	–	–	–
Union K56 wm	≥500	560-720	≥22.0	–	–	–	≥47
Böhler X90-IG wm(3)	≥890	≥940	≥16.0	–	–	≥100	≥90
AlMg3 bm	112	224	21.4	–	–	–	–
AlMg5 bm	185	288	14.5	–	–	–	–
AlMg4.5Mn bm	230	296	18.0	–	–	–	–

(1) KV (-60°C) = 128-208 J.

(2) KV (-40°C) = 35 J, KV (-60°C) = 20 J.

(3) KV (-40°C) = 80 J, KV (-60°C) = 60 J.

The investigated non-metallic materials were as follows: silicon nitride ceramics (Si_3N_4, Re_2O_3, SiO_2 and additive component Y_2O_3 or Yb_2O_3 or Dy_2O_3)[8, 9]; polymethyl methacrylate (PMMA) [10]; unidirectional carbon fiber reinforced plastic (CFRP), carbon fiber/epoxy, T300/914 [11, 12]; injection-molded composite, glass fiber/nylon 6, 6 [10, 13].

Compact tension (CT) and three point bending (TPB) specimens were tested for base materials and welded joints, while for testing of weld metal TPB type specimens were used. CT type specimens were cut from the sheets parallel and perpendicular to the rolling direction, so the directions of fatigue crack propagation were the same. For testing of weld metals cracks which propagate parallel or perpendicular to the axis of the joint were also distinguished. Compact tension shear (CTS) specimens were used for tests under mixed mode I+II loading condition. The specimens were cut parallel to the rolling direction, so the cracks were propagated perpendicular to the rolling direction. Tests were carried out according to the ASTM prescription by an universal electrohidraulic MTS testing machine. Experiments were performed by ΔK-decreasing and constant load amplitude methods, at room temperature, in air, following sinus-type loading wave form. Stress ratio was constant (R=0.1), crack propagation was registered by compliance and/or optical method.

DETERMINATION OF FATIGUE DESIGN LIMIT CURVES

Values of threshold stress intensity factor range (ΔK_{th}) and two parameters of Paris-Erdogan law (C and n) were measured according to prescriptions [14], values of fatigue fracture toughness (ΔK_{fc}) were calculated from crack length measured on the fracture surface of the specimens by the means of stereo-microscope. Fatigue crack growth was determined by secant or seven point incremental polynomial method.

On the basis of these results, mathematical-statistical samples were examined for each testing groups. As its method, Wilcoxon-probe was applied [15], furthermore statistical parameters of the samples were calculated. The mathematical-statistical samples of tested metallic materials and their welded joints can be found in earlier works [16, 17] and the samples of non-metallic materials are summarised in Table 2.

TABLE 2

MATHEMATICAL-STATISTICAL SAMPLES OF NON-METALLIC MATERIALS AND THEIR PARAMETERS

Material	Parameter	Element number of sample	Average	Standard deviation	Standard deviation coefficient
Silicon nitride ceramics (Si_3N_4)	n	11	23.54	4.447	0.1889
	K_{Ic}	9	5.24	0.400	0.0763
Polymethyl methacrylate (PMMA)	n	4	6.38	1.299	0.2035
Carbon fiber/epoxy (T300/914)	n	4	14.70	0.979	0.0666
Glass fiber/nylon 6,6	n	13	6.20	1.650	0.2659

Afterwards it was examined, what kind of distribution functions can be used for describing the samples. For this aim, Shapiro-Wilk, Kolmogorov, Kolmogorov-Smirnov and χ^2- probe were used at a level of significance ε=0.05. It was concluded, that Weibull-distribution is the only function suitable for describing all the samples. Taking this into account parameters of three parameter Weibull-distribution function were calculated for all the samples.

Based on the calculated distribution functions, considering their influencing effect on life-time, characteristic values of ΔK_{th}, n and ΔK_{fc}, were selected. With the help of these values a new method can be proposed for determination of fatigue crack propagation limit curves:

- the threshold stress intensity factor range, ΔK_{th}, is that value which belongs to the 95% probability of the Weibull-distribution function,
- the exponent of the Paris-Erdogan law, n, is that value belonging the 5% probability of Weibull-distribution function,
- the constant of the Paris-Erdogan law, C, is calculated on the basis of the correlation between C and n (Figure 1),

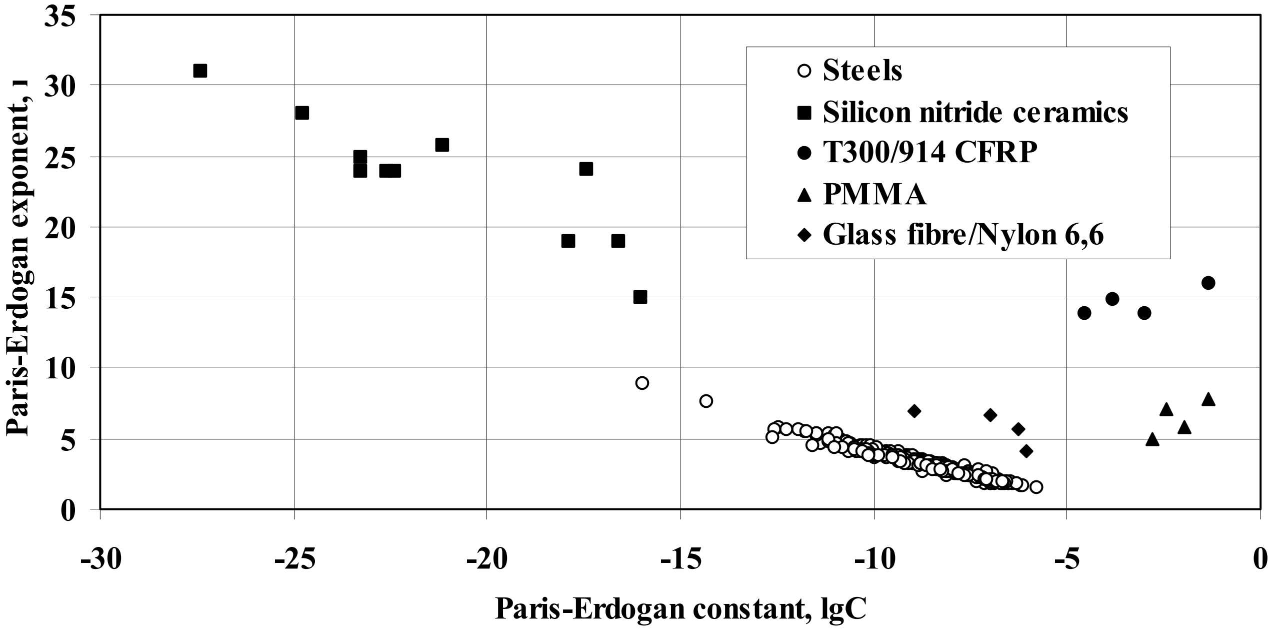

Figure 1: Connection between the exponent and the constant of Paris-Erdogan law

- the critical value of the stress intensity factor range or fatigue fracture toughness, ΔK_{fc}, is that value which belongs to the 5% probability of the Weibull-distribution function.

Figure 2 shows the proposed method shematically.

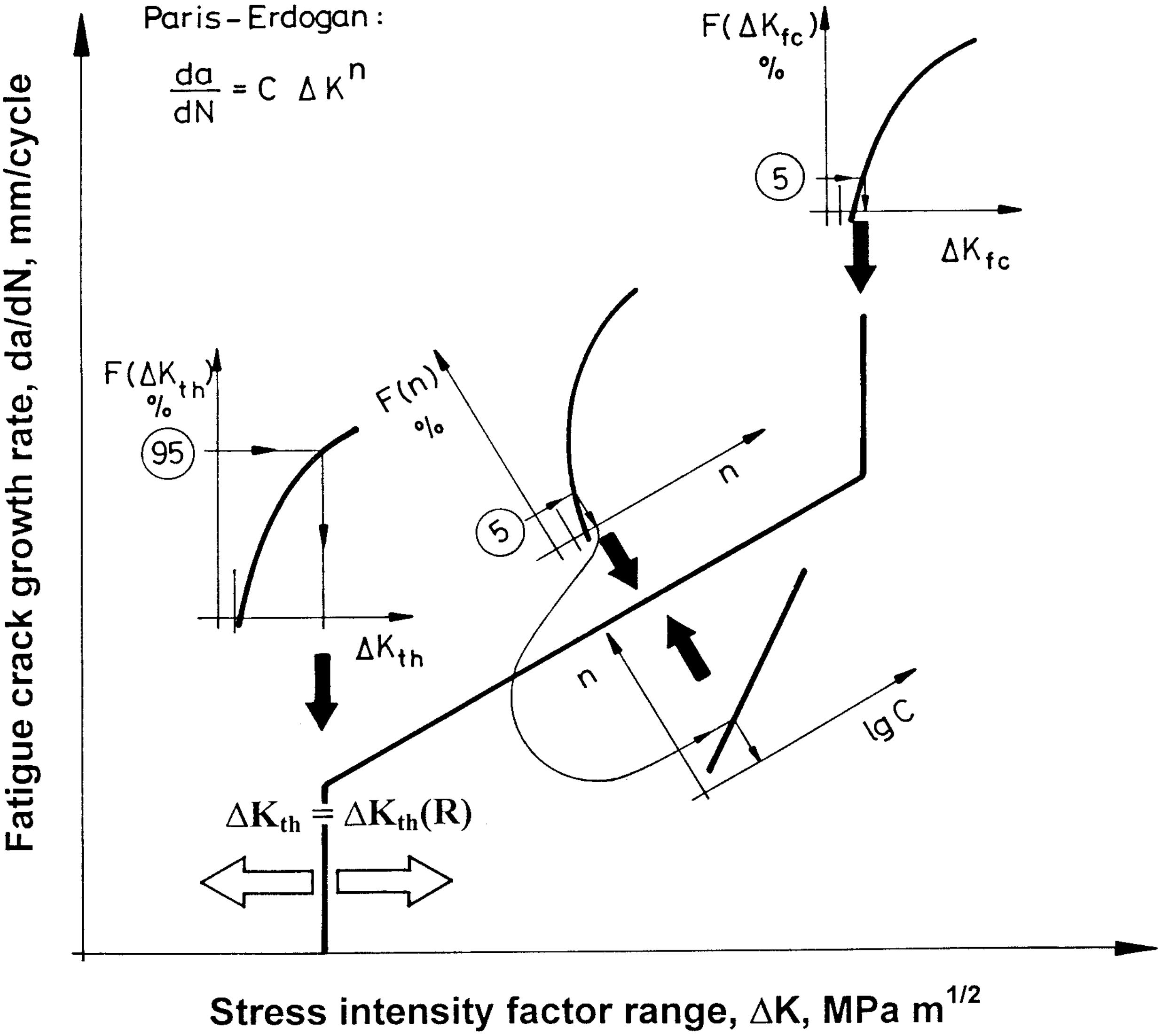

Figure 2: Schematic presentation of the proposed new method for determination of fatigue crack propagation limit curves

The details of fatigue crack propagation limit curves determined for non-metallic materials can be found in the Table 3 and for metallic materials and their welded joints are summarised in the Table 4.

TABLE 3
DETAILS OF FATIGUE CRACK PROPAGATION LIMIT CURVES FOR NON-METALLIC MATERIALS

Material	ΔK_{th}	C	n	ΔK_{fc}
	$MPam^{1/2}$	mm/cycle and $MPam^{1/2}$		$MPam^{1/2}$
Silicon nitride ceramics	–	5.80E-17	16.21	4.9(3)
PMMA	–	2.89E-04	4.24	–
T300/914	–(1)	5.92E-06	13.54	–
Glass fiber/nylon 6,6	–(2)	2.11E-05	4.03	–

(1) $\Delta K_{th}(R = 0.1) = 0.73$ $MPam^{1/2}$.

(2) $\Delta K_{th}(R = 0\text{-}0.2) = 1.12\text{-}2.4$ $MPam^{1/2}$.

(3) Based on K_{Ic} distribution function.

TABLE 4

DETAILS OF DETERMINED FATIGUE CRACK PROPAGATION LIMIT CURVES FOR METALLIC MATERIALS

Material	ΔK_{th}	n	C	ΔK_{fc}
	$MPam^{1/2}$	$MPam^{1/2}$ and mm/cycle		$MPam^{1/2}$
37C base material	10.4	2.98	8.22E-09	53
10 Cr Mo 9 10 base material	–(5)	1.40	1.33E-06	77
KL7D base material	–	2.65	2.04E-08	66
E420C base material	8.0	2.26	9.78E-08	92
X80TM base material	–	1.78	3.74E-07	129
DO76 base material	–	2.94	7.74E-09	76
DO76 base material(2), (3)	–	4.01	2.16E-10	–
QStE690TM base material	–	1.82	3.27e-07	–
QStE690TM base material(2), (3)	–	2.15	1.09E-07	–
37C welded joint	–(1), (6)	3.16	2.42E-09	70
10 Cr Mo 9 10 welded joint	–(1), (7)	1.76	4.54E-07	85
KL7D welded joint	–(1)	3.72	2.98e-10	–
E420C welded joint	–(1), (8)	2.74	1.16E-08	101
X80TM welded joint	–(1)	1.86	3.13E-07	–
ADI base material	–	2.80	6.05E-07	–
AlMg3 base material and welded joint	4.5(4)	2.75	3.94E-09	17
AlMg5 base material and welded joint	4.5(4)	3.02	2.06E-09	19
AlMg4.5Mn base material and welded joint	4.5(4)	3.06	1.87E-08	21

(1) It can be derived from data concerning to the base metal after the evaluation of characteristic and assessment of magnitude of residual stresses.

(2) Under mixed mode I+II loading condition.

(3) ΔK should be replaced by ΔK_{eff}.

(4) One distribution function was calculated from the test results of the three aluminium alloys.

(5) Average value of 2 tests: $\Delta K_{th} = 12.7\ MPam^{1/2}$.

(6) Average value of 16 tests under compressive residual stress: $\Delta K_{th} = 16.9\ MPam^{1/2}$.

(7) Average value of 3 tests: $\Delta K_{th} = 9.0\ MPam^{1/2}$.

(8) Average value of 4 tests under compressive residual stress: $\Delta K_{th} = 16.3\ MPam^{1/2}$.

DISCUSSION

For micro-alloyed steels and their welded joints both the threshold stress intensity factor range (ΔK_{th}) and the exponent of the Paris-Erdogan law (n) decrease with the increase of the strength of steel, while the fatigue fracture toughness (ΔK_{fc}) increases.

For metallic materials both the exponent of the Paris-Erdogan law (n) and the fatigue fracture toughness (ΔK_{fc}) for welded joints are higher than those of base materials.

The proposed method is suitable for determination of fatigue crack propagation design curves under mixed mode I+II loading condition. For this case stress intensity factor range (ΔK) should be replaced by effective stress intensity factor range (ΔK_{eff}).

The design curves of welded joints in the near threshold region are open. The threshold stress intensity factor range, ΔK_{th}, must be reduce by tensile residual stress field and may be increase by compressive residual stress field (e.g. welding residual stresses).

The limit curves of metallic materials locate among the design curves determined by various procedures.

CONCLUSIONS

Based on the results of our experimental tests, evaluated samples and data can be found in the literature the following conclusions can be drawn.

(i) The proposed method can be generally applied for determination of fatigue crack propagation limit curves for metallic materials and their welded joints under mode I and mixed mode I+II loading conditions and for non-metallic materials under mode I loading condition.

(ii) The limit curves represent a compromise of rational risk (not the most disadvantageous case is considered) and striving for safety (uncertainty is known).

(iii) Based on the determined fatigue design limit curves integrity assessment calculations can be done for operating structural elements and structures having cracks or crack-like defects.

(iv) Determination of fatigue crack propagation limit curves of non-metallic materials based on other fracture mechanical parameters (e.g. G, ΔG, ΔJ) requires further investigations

ACKNOWLEDGEMENTS

Author wish to acknowledge the assistance given by the National Scientific Research Foundation and the Hungarian Ministry of Education for supporting the research (OTKA F 4418, OTKA T022020 and MKM FKFP-0633/2000).

REFERENCES

1. Allen, R. J., Booth, G. S. and Jutla, T. (1988). *Fat. Fract. Eng. Mater. Struct.* 11, 45.
2. Allen, R. J., Booth, G. S. and Jutla, T. (1988). *Fat. Fract. Eng. Mater. Struct.* 11, 71.
3. Ohta, A. et al. (1989). *Trans. Jap. Weld. Soc.* 20, 17.
4. Merkblatt DVS 2401 Teil 1 (Oktober 1982). *Bruchmechanische Bewertung von Fehlern in Schweissverbindungen. Grundlagen und Vorgehensweise.*
5. Det norske Veritas, Classification Notes, Note No. 30.2 (August 1984). *Fatigue strength analysis for mobile offshore units.*
6. Paris, P. and Erdogan, F. (1963). *Journ. Bas. Eng., Trans. ASME.* 528.
7. Török, I. (1996). *Publ. Univ. Miskolc, Series C. Mech. Engng.* 46, 33.
8. Cornelissen, B. E. et al. (1994). *Acta Metall. Mater.* 42, 3055.
9. Sugeta, A., Jono, M. and Koyoma, A. (1966). In: *Proceedings of The Sixth International Fatigue Congress.* 3, pp. 1663-1668, Lütjering, G. and Nowack, H. (Eds.) Pergamon.
10. Hertzberg, R. W., Manson, J. A. and Wu, W. C. (1973). In: *Progress in Flaw Growth and Fracture Toughness Testing.* ASTM STP 536, 391.
11. Hojo, M. et al. (1986). In: *Proceedings of a Japan-US Joint Seminar on Advanced Materials for Severe Service Applications.* pp. 353-372. Elsevier.
12. Hojo, M. et al. (1994). *Eng. Fract. Mech.* 49, 35.
13. Mandell, J. F. (1990). In: *Fatigue of Composite Materials: Fatigue Behaviour of Short Fiber Composite Materials.* pp. 231-337. Elsevier.
14. ASTM E 647 (1988). *Standard test method for measurement of fatigue crack growth rates.*
15. Owen, D. B. (1973). *Handbook of statistical tables.* Vychislitel'nyjj Centr AN SSSR, Moskva. (In Russian).
16. Lukács, J. (1996). *Publ. Univ. Miskolc, Series C. Mech. Engng.* 46, 77.
17. Lukács, J.(2000). In: *Third International Pipeline Technology Conference.* 2, pp. 127-140, Denys, R. (Ed.) Elsevier Science B. V.