EFFECT OF TEMPERATURE ON FATIGUE THRESHOLD ($\Delta K_{eff,th}$): PREDICTION

Yu. I. Ragozin and I. A. Oborina *

On the basis of fracture phonon conception being developed by the author the value prediction method of effective threshold stress intensity factor $\Delta K_{eff,th}$ in a wide temperature range has been offered. Numerical estimation of predicted $\Delta K_{eff,th}$ values for aluminium, α - titanium and α - iron based alloys has been carried out. It has been demonstrated that with temperature decreasing the fatigue threshold value increases up to definite limit and then decreases. Comparison of available experimental $\Delta K_{eff,th}$ values with calculated ones has been carried out according to the technique being suggested.

INTRODUCTION

Effective threshold stress intensity factor range, $\Delta K_{eff,th}$, is known to be one of the most important criteria of cyclic crack resistance. Its experimental determination in a fatigue test process is extremely labour - consuming. The difficulties are still growing if it is necessary to determine $\Delta K_{eff,th}$ at temperatures different from the room one. Therefore data concerning the value of that threshold under these temperatures are very limited [1]. Considering the importance of criterion $\Delta K_{eff,th}$ from the viewpoint of engineering design an attempt was made (probably for the first time) to predict the values of this characteristic in a wide range of temperatures for aluminium, α - titanium and α - iron based alloys on the basis of the phonon fracture model [2, 3].

While developing a new concept of solids fracture the author came [2, 3] to understanding of the decisive role of the phonon crystal subsystem in this process. The presence of dislocations in crystals causes the emergence of specific l- mode vibrations in phonon spectrum, the wavelength of which is specified by the effective width of characteristic dislocation cores in corresponding directions of lattice elastic waves propagation. A conception of threshold energy levels $W_l = h\nu_l$ (ν_l - vibration frequency of l - mode, h- Plank's constant) which the lattice can absorb by loading before fracture has been introduced. It has been proved that every metal (and alloy on its base) has its own discrete spectrum of W_l - values which is affected by alloying and thermal treatment only to insignificant extent. However the latter affect the position of principal threshold energy level W_l^k in discrete spectrum corresponding to the principal threshold l_k - mode of vibrations. According to the author the fracture of interatomic bonds in lattice takes place during superposition of l_k- mode quantum vibrations (phonons). So, the discrete threshold energy levels W_l specify the limiting local energy consumption and they represent new

* Technical University, Perm, Russia

constant values of materials. They have been calculated by molecular dynamics method for a number of commercially important metals with different types of crystal lattice. Knowing new energy criteria one can solve a number of applied problems. In particular by means of these material constants one can calculate the possible values of $\Delta K_{eff,th}$ in a wide temperature range. In addition to value W_l the calculating formula includes two new material constants: minimum fatigue striation spacing and minimum microcrack length which does not affect the fatigue limit.

THEORETICAL BASIS AND RESULTS

It is known that there exisis a definite microcrack length a_0 that does not affect fatigue limit. It is assumed [4,5] that the value of a_0 is independent of the solid form and the mode of its loading, and is determined only by the material nature. Proceeding from the assumption [6] concerning the origin of electromagnetic radiation in a certain discrete frequency band during the fracture process and interaction of the above radiation with the growing crack a concept of discrete spectrum existence of minimum microcrack length a_l not affecting the fatgue limit has been introduced. Spectra of possible values a_l ($a_l = \lambda_l / 2$, $\lambda_l = c / \nu_l$, where c - the velocity of light) have been defined for many metals (Table 1).

TABLE 1- Calculated levels a_l for several metals at from temperature air.

| Metal | a_l, mm | | | | | | | | | | |
	1	2	3	4	5	6	7	8	9	10	11
Mg	0.232	0.188	0.161	0.157	0.122	0.116	0.086	0.061			
Al	0.412	0.206	0.191	0.139	0.095						
Ti	0.203	0.165	0.159	0.109	0.101	0.077	0.055				
Fe	0.177	0.118	0.107	0.081	0.076	0.047	0.037				
Ni	0.350	0.175	0.169	0.113	0.084	0.063*	0.056*	0.051*	0.04*	0.025*	
Cu	0.517	0.258	0.223	0.174	0.110	0.096*	0.073*	0.072*	0.052*	0.051*	0.031*

* with package defects

Apparently, similar spectra of a_l values will be characteristic of the alloys based on these metals as well, and alloying and thermal treatment, practically not influencing the numerical values of a_l in spectrum, will determine the level of a (from spectrum) perculiar to a_0 given specific alloy.

The hypothesis [7] that for metal materials the value of fatigue striation spacing is multiple of wave halflength of plasma vibrations occurring with the main crack propagation has been put forward in this paper. On the basis of the model assumed minimum striation spacing s_e ($s_e = \lambda_p / 2$, where $\lambda_p = 2\pi c / \omega_p$ - wave length of plasmon; ω_p - plasma frequency) for the metals with known values ω_p [8] has been calculated (Table 2). Comparison with experimental data available showed that minimum stration spacing s_e for alloys comes to be close to the value s_e for the alloy base.

TABLE 2 - Several constant values of metals.

| Constants | Metals | | | | | | |
	Li	Mg	Al	Ti	Fe	Ni	Cu
ω_p, 10^{16} rad/sec	1.24	1.61	2.32	2.67	2.40	2.96	2.90
λ_p, 10^{-8} m	15.14	11.70	8.10	7.05	7.85	6.36	6.49

According to break mechanism, by fracture under plain strain being independent of loading conditons, the relation between the stresses σ_y perpendicular to crack propagation and the distance r from the crack edge is expressed by the following equation in agreement with the theory of linear elastic fracture mechanics:

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} \qquad (1)$$

It was accepted that the crack starts its propogation close to the effective threshold stress intensity factor range, $K_{eff,th}$ ($\Delta K_{eff,th}$), at the moment when in the zone of plastic strain of r_e size, at the crack tip, the energy equal to one of the threshold energy levels W_l calculated on the basis of phonon theory of fracture is absorbed. Earlier [7] local fracture stress σ_D was approximately estimated in accordance with recommendation [9] to be $\sigma_D(\Delta\sigma_D) = \sqrt{2W_i E}$. New data, mentioned above, enables one to define σ_D more precisely. Consdering [10] for the specimens of final dimensions one has:

$$K_{lc} = Y\sigma_p\sqrt{\pi a_p} = \sqrt{\frac{0{,}8 L W_i E}{1-\mu^2}} \qquad (2)$$

where σ_D - critical stress with which the crack of a_p length starts its propagation; L - having a length demension and equal to 10^{-3} m; Y - calibration coefficient. Assuming that the equation (2) is valid in the scope of microvolumes [11] and accepting $Y\sigma_p = \sigma_D$ and $a_p = a_l$, one obtains:

$$\sigma_D(\Delta\sigma_D) = \sqrt{\frac{0{,}8 L W_i E}{(1-\mu^2)\pi a_i}} \qquad (3)$$

Identifying the value r_e with the minimum spacing of fatigue striations s_e and assuming that $s_e = \lambda_p / 2$, in accordance with the hypothesis accepted above, we obtain the equation for calculating the criterion $\Delta K_{eff,th}$:

$$\Delta K_{eff,th} = 0{,}894\sqrt{\frac{L W_i E \lambda_p}{(1-\mu^2)a_i}} \qquad (4)$$

or in the following form:

$$\Delta K_{eff,th} = K_{lc}\sqrt{\frac{\lambda_p}{a_i}} \qquad (5)$$

Since alloying and thermal treament change the constants W_l, E and, apparently, λ_p only to a small extent, the relations (4) and (5) derived for pure metals are also valid for alloys based on them. Their own descrete spectrum of threshold energy levels W_l is characteristic for each metal and alloys based on them [2,3]. Hence, in accordance with equation (4) the descrete spectrum of values $\Delta K_{eff,th}$ is typical for them as well. As an example, Fig. 1 illustrates the levels $\Delta K_{eff,th}$ (horizontal lines) for room temperatures calculated by expression (4) and experimental values $\Delta K_{eff,th}$ for steels according to literature data. It can be seen that experimental values are grouped near calkulated threshold levels of $\Delta K_{eff,th}$ verifying the conclusion made above.

Expressions (4) and (5) can be used for estimation of $\Delta K_{eff,th}$ at various temperatures as well. In this paper effective threshold $\Delta K_{eff,th}$ is defined for alloys on the base of aluminium, α - titanium, α - iron in a wide temperature range: from 4K to 500K for aluminium alloys, from 4K to 800K for titanium and iron alloys. Data required for calculation of W_l (according to procedures stated in [2,3]), a_l value, E and μ as well, as a function of

temperature, have been taken from the manual [12]. Computation results have been graphically represented in Fig. 2. It can be seen that with temperature decreasing fatigue threshold increases up to definite value and then decreases. From the viewpoint of developed phonon fracture model this peculiarity of $\Delta K_{eff,th}$ criterion temperature dependence can be explained in the following way. With temperature decreasing beginning with a definite value for alloys on a given base, freeze - out of atomic vibration at ν_l frequency of discrete spectrum occurs. At first the vibrations at the highest frequency are not excited. With further temperature decreasing the process spreads to lower frequences in spectrum. It can be assumed that beginning with the definite temperature mentioned above, the energy of the so - called zero vibrations W_l^0 ($W_l^0 = h\nu_l / 2$) starts playing the decisive role in fracture process. The value of W was used for K threshold calculation in this case.

The experimental values of $\Delta K_{eff,th}$ obtained by different authors have been represented in Fig. 2. And although experimental data available are not sufficient for making final conclusion about the efficiency of the technique being suggested one can state an agreement between predicted and experimental values of $\Delta K_{eff,th}$.

REFERENCES

(1)   Liaw, P. K. and Logsdon, W. A., Eng. Fract. Mech., Vol. 22, No. 4, 1985, pp. 585 - 594.

(2)   Ragozin, Yu. I., Proc. 7th Int. Conf. Fract. (ICF 7), Houston, Vol. 6, 1989, pp. 3731 - 3738.

(3)   Ragozin, Yu. I., Proc. 8th Eur. Conf. Fract. (ECF 8), Turin, Vol. 2, 1990, pp. 1150 -1156.

(4)   El Haddad, M. H., Topper, T. H. and Smith K. N., Eng. Fract. Mech., Vol. 11, No. 2, 1979, pp. 573 - 584.

(5)   Lukas, P., Kunz, L., Weiss, B. and Stickler R., Fatigue Engng. Mater. Struct., Vol. 9, No. 3, 1986, pp. 195 - 204.

(6)   Ragozin, Yu. I., Proc. To be published in ECF 11, 1996.

(7)   Ragozin, Yu. I., Proc. 9th Eur. Conf. Fract. (ECF 9), Varna, Vol. 1, 1992, pp. 427 - 432.

(8)   Ashok, K. V., Surface Technol., No. 10, 1980, pp. 277 - 282.

(9)   Kator, A., Problems of Strength, No. 4, 1972, pp. 49 - 53.

(10)   Ragozin, Yu. I. and Antonov Yu. Ya., Mechanical Properties / Materials Desing: Proc. C-MRS Intern. '90, (B. Wu. Ed.), Beijing, Vol. 5, pp. 141 - 144, Elsevier, Amsterdam, Netherlands, 1991.

(11)   Esterling, D. M., Int. J. Fract., Vol. 17, No. 3, 1981, pp. 321 - 325.

(12)   Frantseva, I. N., Voronov, F. F. and Bakuta, S. A., Elastic Constants and Moduluses of Elasticity of Metals and Nonmetals, Naukova Dumka, Kiev, 1982.

(13) McHenry, H. I., Naranjo, S. E., Read, D. T. and Reed, R. P., Advances in Cryogenic Engineering, Plenum Press, Yew York, Vol. 24, 1978, pp. 519 - 526.

(14) Stasuk, S. Z., Crack Resistance of materials and Structure Elements, Naukova Dumka, Kiev, 1980, pp. 208 - 211.

(15) Fine, M. E., Horng, J. L. and Park, D. H., Proc. 2nd Int. Conf. Fatigue and Fatigue Thresholds, Birmingham, Vol. 2, 1984, pp. 739 - 748.

(16) Strizhalo, V. A. et al, Materials and Structures Strength at Cryogenic Temperatures, Naukova Dnmka, Kiev, 1988.

(17) Ravichandran, K. S., Scr. Met. et Mater., Vol. 24, No. 7, 1990, pp. 1275 - 1280.

(18) Troshchenko, V. T., Prokopenko, A. V. and Ezhov, V. N., Problems of Strength, No. 10, 1987, pp. 45 - 52.

(19) Paris, P. C. et al, ASTM STP 513, Part 1, 1972, pp. 141 - 176.

(20) Esaklul, K. A., Yu, W. and Gerberich, W. W., ASTM STP 857, 1985, pp. 63 - 83.

(21) Ostash, O. P., Kostyk, E. M. and Levina, I. N., Phys. - Chem. Mech. Mater., No. 4, 1988, pp. 63 - 71.

(22) Reinhard, P., Mater. Sci. and Eng. A, Vol. 138, No. 1, 1991, pp. 1 - 13.
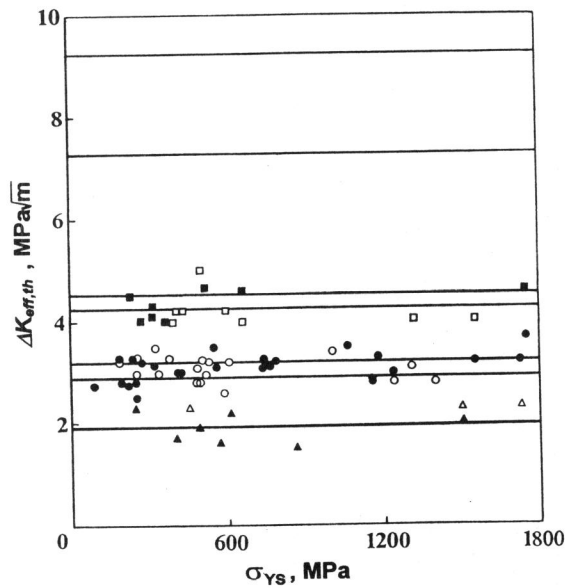
Figure 1 Calculated spectrum $\Delta K_{eff,th}$ value for steels and experimental data of different authors. Dark symbols - $\Delta K_{eff,th}$; ligth symbols - ΔK_{th} (when R > 0.7).
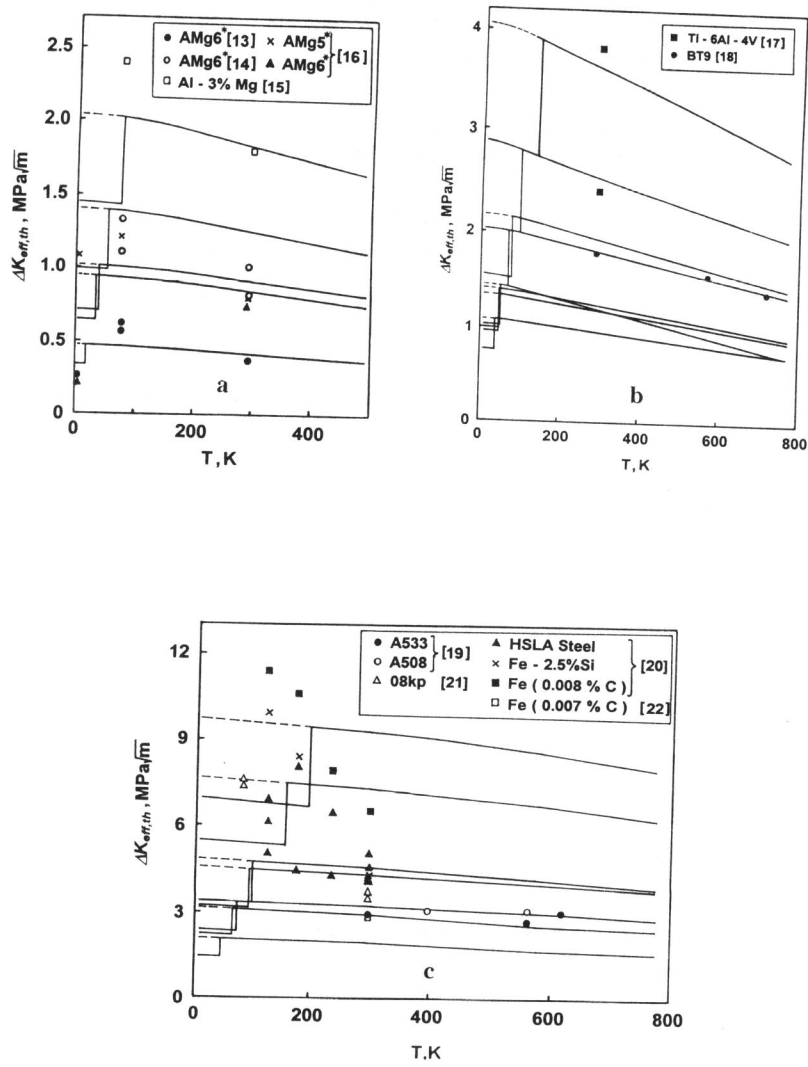
Figure 2 Threshold $\Delta K_{eff,th}$ values as a function of temperature: a - aluminium alloys (* $\Delta K_{eff,th}$ is defined by exression (5)); b - titanium alloys; c - steels.