EFFECT OF TEMPERATURE ON FATIGUE THRESHOLD ($\Delta K_{th,t}$): 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 $\Delta K_{th,t}$ in a wide temperature range has been offered. Numerical estimation of predicted $\Delta K_{th,t}$ values for aluminium, $\alpha$-titanium and $\alpha$-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 $\Delta K_{th,t}$ values with calculated ones has been carried out according to the technique being suggested.

INTRODUCTION

Effective threshold stress intensity factor range, $\Delta K_{th,t}$, 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 $\Delta K_{th,t}$ 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 $\Delta K_{th,t}$ 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, $\alpha$-titanium and $\alpha$-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 $I$-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 $W_i = \hbar \nu$ ($\nu$ - vibration frequency of $I$-mode, $\hbar$ - 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 $W_i$ values which is affected by alloying and thermal treatment only to insignificant extent. However the latter affect the position of principal threshold energy level $W_i$ in discrete spectrum corresponding to the principal threshold $I_p$ - mode of vibrations. According to the author the fracture of interatomic bonds in lattice takes place during superposition of $I_p$ - mode quantum vibrations (phonons). So, the discrete threshold energy levels $W_i$ 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 \(dK_{\text{act, min}}\) in a wide temperature range. In addition to 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 exists a definite microcrack length \(a_u\) that does not affect fatigue limit. It is assumed [4,5] that the value of \(a_u\) 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 \(a_u\) not affecting the fatigue limit has been introduced. Spectra of possible values \(a_i (a_i = \lambda_i / 2, \lambda_i = c / v_i)\), where \(c\) - the velocity of light - have been defined for many metals (Table 1).

**TABLE 1. Calculated levels \(a_i\) for several metals at room temperature.**

<table>
<thead>
<tr>
<th>Metal</th>
<th>(a_i) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mg</td>
<td>0.232</td>
</tr>
<tr>
<td>Al</td>
<td>0.412</td>
</tr>
<tr>
<td>Ti</td>
<td>0.203</td>
</tr>
<tr>
<td>Fe</td>
<td>0.177</td>
</tr>
<tr>
<td>Ni</td>
<td>0.350</td>
</tr>
<tr>
<td>Cu</td>
<td>0.517</td>
</tr>
</tbody>
</table>

with package defects

Apparently, similar spectra of \(a_i\) 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 \(a_i\) in spectrum, will determine the level of \(a\) (from spectrum) peculiar to \(a_u\) given specific alloy.

The hypothesis [7] that for metal materials the value of fatigue striation spacing is multiple of wave half-length 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 \(s_r = \lambda_p / 2\), where \(\lambda_p = 2\pi c / \omega_p\) - wave length of plasmon; \(\omega_p\) - plasma frequency) for the metals with known values \(\omega_p\) [8] has been calculated (Table 2). Comparison with experimental data available showed that minimum striation spacing \(s_r\) for alloys comes to be close to the value \(a_u\) for the alloy base.

**TABLE 2. Several constant values of metals.**

<table>
<thead>
<tr>
<th>Constants</th>
<th>Li</th>
<th>Mg</th>
<th>Al</th>
<th>Ti</th>
<th>Fe</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\omega_p) (10^6) rad/sec</td>
<td>1.24</td>
<td>1.61</td>
<td>2.32</td>
<td>2.67</td>
<td>2.40</td>
<td>2.96</td>
<td>2.90</td>
</tr>
<tr>
<td>(\lambda_p) (10^9) m</td>
<td>15.14</td>
<td>11.70</td>
<td>8.10</td>
<td>7.05</td>
<td>7.85</td>
<td>6.36</td>
<td>6.49</td>
</tr>
</tbody>
</table>

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According to break mechanism, by fracture under plain strain being independent of loading conditions, the relation between the stresses $\sigma$, 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:

$$\sigma = \frac{K}{\sqrt{2\pi r}}$$  \hspace{1cm} (1)

It was accepted that the crack starts its propagation close to the effective threshold stress intensity factor range, $K_{eff}$ (with $K_{eff}$), at the moment when in the zone of plastic strain of $r_p$ size, at the crack tip, the energy equal to one of the threshold energy levels $W_t$ calculated on the basis of phonon theory of fracture is absorbed. Earlier [7] local fracture stress $\sigma_p$ was approximately estimated in accordance with recommendation [8] to be

$$\sigma_p = \sqrt{2W_t}.$$  \hspace{1cm} (2)

New data, mentioned above, enables one to define $\sigma_p$ more precisely. Considering [10] for the specimens of final dimensions one has:

$$K_p = Y\sigma_p\sqrt{a_0} = \frac{0.85WL_E}{1 - \mu^2}$$  \hspace{1cm} (3)

where $a_0$ - critical stress with which the crack of $a_0$ length starts its propagation; $L$ - having a length dimension and equal to $10^{-3}$ m; $Y$ - calibration coefficient. Assuming that the equation (2) is valid in the scope of micropores [11] and accepting $Y\sigma_p = \sigma_p$ and $a_0 = a_p$, one obtains:

$$\sigma_p = \frac{0.85WL_E}{(1 - \mu^2)a_p}$$  \hspace{1cm} (4)

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

$$\Delta K_{eff} = \frac{0.894WL_Es_a}{(1 - \mu^2)a_p}$$  \hspace{1cm} (5)

or in the following form:

$$\Delta K_{eff} = K_p \frac{s_a}{a_p}$$

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

Expressions (4) and (5) can be used for estimation of $\Delta K_{eff}$ at various temperatures as well. In this paper effective threshold $\Delta K_{eff}$ is defined for alloys on the base of aluminium, $\alpha$ - titanium, $\alpha$ - iron in a wide temperature range: from 4K to 800K for titanium and iron alloys. Data required for calculation of $W_t$ (according to procedures stated in [2,3]), $s_a$ value, $E$ and $\mu$ 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 AKsat,t, 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 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 frequencies in spectrum. It can be assumed that beginning with the definite temperature mentioned above, the energy of the so-called zero vibrations \( W_0 = h_\nu / 2 \) 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 \( AK_{sat,t} \) 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 \( AK_{sat,t} \).

REFERENCES

Figure 1: Calculated spectrum \( dK_{ef,th} \) value for steels and experimental data of different authors. Dark symbols - \( dK_{ef,th} \); light symbols - \( dK_{th} \) (when \( R > 0.7 \)).
Figure 2: Threshold $\Delta K_{\text{eff,th}}$ values as a function of temperature: a - aluminium alloys (*$\Delta K_{\text{eff,th}}$ is defined by expression (5)); b - titanium alloys; c - steels.