The New Nondestructive Method of the Material Fatigue Process Zone Size Determination using the Thermoelectric Power Measurements

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Abstract. The fatigue process zone (FPZ) size was introduced as one of the fundamental parameter of fatigue fracture mechanic. There are known some destructive experimental and calculation methods of FPZ size determination. New non-destructive method based on measurement of the local thermoelectric power (TEP) spatial distribution in the stress concentrator (notch) vicinity and estimation of particular point coordinate for determination FPZ size is proposed.

Introduction

Most known nondestructive methods used for material fatigue evaluation are not able to receive information about the kinetic of fatigue processes on earlier stages. At the same time the non-destructive evaluation of fatigue processes on initial stages is very interesting for fatigue phenomena interpretation and crack initiation mechanism understanding. The contemporary knowledge about fatigue processed led to the formation to the fatigue process zone (FPZ) concept. The FPZ size $d*$ is introduced as fundamental linear material parameter needed for the construction lifetime estimation. All earlier known methods of FPZ size estimation are destructive. In this paper new nondestructive method for FPZ size $d*$ estimation based on local thermoelectric power measurements is proposed and presented.

Fatigue process zone size concept

According with developed phenomenological model the FPZ size $d*$ as material linear structural parameter was proposed [1]. It was assumed, that due to decreased (in compare with material volume) surface yield stress and particular free surface (the possibility of dislocation output and points defect formation), the plastic deformation is localized and structural defects are accumulated in this zone. These processes predetermine the formation of specific surface zone - FPZ, size (depth) of which is determined as characteristic parameter d^* (see Fig. 1). The material FPZ is specific below-surface zone, where next crack initiation is occurred [2]. The FPZ size is characteristic material constant in given conditions, such as loading amplitude, temperature and environment, and are defines the maximum local stress range $\Delta\sigma_y^*$ located at the characteristic distance d^* from notch tip (Fig. 1).

The FPZ boundary is main physical barrier for micro structurally short (with length a_n) and physically small (with length a_{tr}) macro cracks development (figure 1), because with deeper cracks propagation from the surface a magnitude of the local stress and prior material strain is more intensive. In other words, the FPZ size is characteristic distance d^* that defines the initial length of a macro crack for a given material. By FPZ concept the criterion of micro crack to macro crack transition was obtained as: $a_i = d^*$, that occurs after N_i loading cycles (Fig.1).

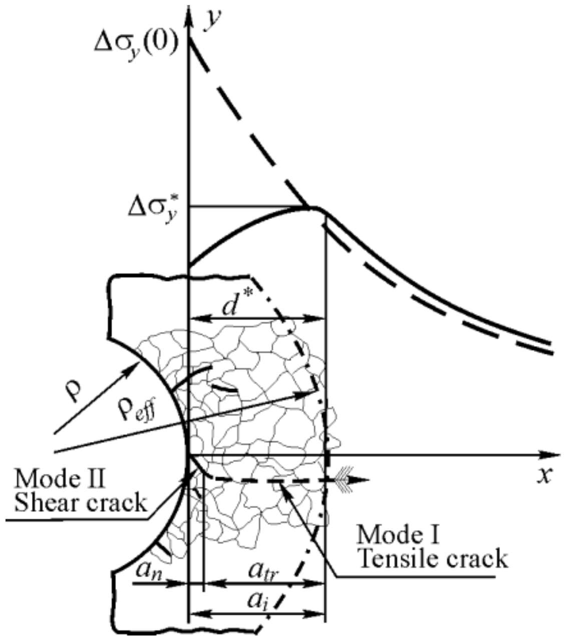


Figure 1. Schemes of FPZ formation and stress distribution at the tip notch (*a*) and growth of small fatigue cracks in this zone (b).

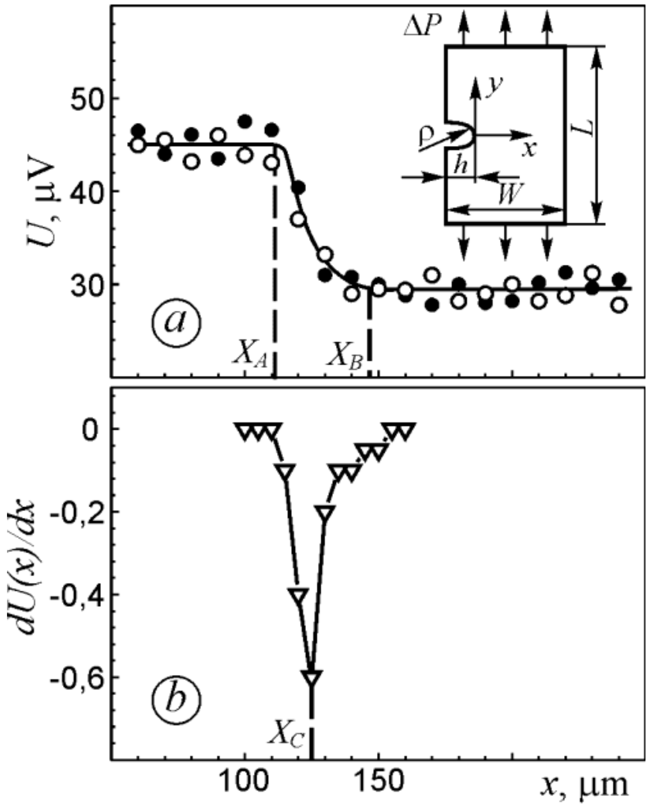
So, the FPZ size d^* is proposed as new structural parameter of materials needed to define the material fatigue durability. The changes in material structure during long time exploitation must be reflected in FPZ size.

There are different methods of FPZ size estimation based on fatigue testing of specimens with different notch radius or based on X-ray analyzing of below-surface layers on different depths [1, 2]. All these methods are destructive because the specimens destroy is needed.

The FPZ size estimation by local thermoelectric power measurement

The thermoelectric power (TEP) method based on Seebeck-effect application is widely used for non-destructive material structure evaluation. The method is based on the measurement of TEP, which occurs between measuring thermo-electrode and tested material. The TEP method is widely used for some applications, such as, the steel sorting, the alloys chemical composition evaluation, the decarburized and carburized layers depth estimation, the measurement of residual austenite content, the estimation of metal deformation level, the investigation of structural changes after annealing, etc [3].

As was mentioned above all known method for FPZ size measurements are destructive and very difficult in realization. Therefore new non-destructive method of parameter d^* determination is proposed and investigated [4-5]. The proposed method is based on the evaluation of local TEP distribution in the vicinity of notch tip. From obtained distribution analyzing the coordinates of characteristic points are determined. The distance between characteristic points and notch tip is considered to be FPZ size.



○ − Measurement along OX axis; ● − In reverse direction.

Figure 2. The estimation of parameter d^* in D16T aluminum allow with local TEP (U) distribution application at the notch tip after 0,2 N_i cycles of loading.

On Fig. 2 the scheme of specimen loading with stress concentrator (notch) is presented. The TEP distribution U (x) obtained by measurements along OX axis (white symbols) and in reverse direction (black symbols) is presented (Fig. 2a). The characteristic point for FPZ size estimation can be defined as point between X_A and X_B using the TEP distribution derivative dU (x)/dx (Fig.2b). The better precision can be achieved when the characteristic point is defined as minimum point X_C on correspondent derivative distribution.

For more precise FPZ size estimation the TEP distribution must be obtained by truncated cone form of thermo-electrode tip. The thermo-electrode tip diameter **d** must be choose in accordance with medium size **D** of structural elements and FPZ size d^* from conditions $\boldsymbol{D > d_к < 0{,}1d^*}$. We can estimate D = 0,005 − 0,05 mm, d^* = 0,2 − 0,3 for plastic ($\delta \geq 10\%$) constructive materials and D = 0,005 − 0,05 mm, d^* = 0,05 − 0,1 materials with small plasticity ($\delta < 10\%$). From these conditions the thermo-electrode tip diameter must be $d_к$ = 0,02 − 0,03 mm for plastic and $d_к$ = 0,005 − 0,01mm for a low-plastic materials.

So, proposed method permits the non-destructive and quick evaluation of FPZ size both on experimental specimens and on real constructions.

For FPZ size investigation special experimental device "Contact-1" (Fig. 3) was designed [5]. The experimental device for local TEP measurements "Contact-1" was built on the base of the standard device for hardness measurements. The thermo-electrode was installed in the place of hardness pyramid and specimen was mounted on the moving platform.

Figure 3. The experimental device for local TEP measurement - «Contact-1».

The aluminum alloy degradation investigations by FPZ size measurements

The aluminum D16T1 alloy in delivery condition and after simulated and exploitative degradation was investigated.

The heating conditions at cycling were selected in temperature range 20-190 ^{0}C, which is in compliance with aluminum D16T alloy aging temperature. The joint influence of loading and heating was realized with special equipment for fatigue evaluations with high temperature camera. The temperature fatigue evaluations were carried out by 80 MPa cyclic tension loading with frequency 10-15 Hz, stress ratio R = 0,1 during 100000 cycles.

For in-service degradation investigations the real aircraft skins after 30 year of exploitation were applied (45870 hours, 31950 flights).

The local TEP was measured with brass thermo-electrode with tip diameter dк = 25 microns, which was loaded to tested surface with force 0,2 N. The temperature difference between the thermo-electrode and tested surface was 50º C.

The FPZ sizes *d** of D16T aluminum alloy in delivery condition and after real and simulated degradation measured by TEP method are presented in Table 1.

Table 1. The comparison of FPZ sizes *d** for D16T aluminum alloy in delivery condition and after degradation.

<table>
<tr><th colspan="2" rowspan="2">Material</th><th colspan="2">FPZ sizes d^*, microns</th></tr>
<tr><th>Specimens with fatigue cracks</th><th>Specimens with notch radius 1,9 mm</th></tr>
<tr><td colspan="2">Delivery condition</td><td>205</td><td>215</td></tr>
<tr><td rowspan="3">After cycling</td><td>20 C</td><td>195</td><td>195</td></tr>
<tr><td>100 C</td><td>180</td><td>190</td></tr>
<tr><td>190 C</td><td>145</td><td>140</td></tr>
<tr><td colspan="2">25 years exploitation</td><td>150</td><td>155</td></tr>
</table>

The simulated and exploitation degradation led to appreciable FPZ size d^* reduction in comparison with value of FPZ size in delivery condition. By parameter d^* analyzing we can see that the simulated degradation at 190 º C heating practically correlate with real exploitation degradation. The degradation causes the parameter d^* reduction near 30%.

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Conclusions

- The fatigue process zone size d^* was introduced as one of the fundamental parameter of the material fatigue fracture mechanic.
- New non-destructive method of the fatigue process zone size determination by the local thermoelectric power spatial distribution near the notch tip vicinity is proposed.

References

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