1. Introduction

Nondestructive testing system establishment, danger of defects evaluation depends on the notions about the fracture of loaded solid materials. Traditionally the mechanical approach is applied, which considers fracture as force act.

Another approach will be introduced in the lecture which considers meta-stable state of the solid body, caused by the loading. Fracture is the kinetic process of the meta-stable state disintegration activated by the thermal energy. In this aspect the prediction of the fracture is in the determination of the object life time $\tau$ under loading as the function of temperature-force influence and defects.

Life time, which is analogous to the remaining life of the object in engineering, depends on the choice of the limit state. In this lecture the growing macro-crack after accumulation of stable damages is taken as limit state. This choice of the limit state provides the most industrial safety.

For registration of damages in industrial conditions the acoustic emission method is applied. The notions of fracture activated by the thermal energy allow acoustic emission testing during exploitation without rise of working pressure, which is necessary in mechanical approach.

General model of the object remaining life prediction as the moment of macro-crack formation, which is determined during acoustic emission testing, will be represented in the lecture. Example of the model application for prolongation of the service life of the dangerous industrial object: underground LPG (liquefied petroleum gas) storage tank will be given.

2. Two approaches to the fracture

Two notions about the fracture exist nowadays.

A. Mechanical approach is used dating back to Galileo (1680). The rupture of atomic bonds is considered as force act which comes after the critical value of stress $\sigma^*$ is exceeded, which is called tensile strength. The measure of the object safety at stress $\sigma$ is the safety margin:
Prediction of the fracture in this case is in establishment of the dependence of value \( n \) from time and comparison of the current value \( n \) with allowable value \( n^* > 1 \).

The value of the tensile strength \( \sigma^* \) is measured during the rupture of the material specimen. It is impossible to predict or interpreter the measured value of \( \sigma^* \).

In 1920s the tensile strength of atomic bond \( \sigma_{\text{a}}^* \) have been calculated and the estimation \( \sigma_{\text{a}}^* = 0.1E \) have been obtained, where \( E \) – Young’s modulus. But the calculated value turned out to be for all materials bigger on 1-2 orders than measured value of the tensile strength, that is:

\[
\frac{0.1E}{\sigma^*} \approx 10^{-1} \times 10^2
\]  

Table 1. Ratio of the calculated to the measured value of the tensile strength of inter-atomic bond.

<table>
<thead>
<tr>
<th>Element, material</th>
<th>( \frac{0.1E}{\sigma^*} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>140</td>
</tr>
<tr>
<td>Fe</td>
<td>70</td>
</tr>
<tr>
<td>Cu</td>
<td>60</td>
</tr>
<tr>
<td>Ni</td>
<td>50</td>
</tr>
<tr>
<td>Pt</td>
<td>100</td>
</tr>
<tr>
<td>Pb</td>
<td>100</td>
</tr>
<tr>
<td>Ag</td>
<td>50</td>
</tr>
<tr>
<td>Zn</td>
<td>100</td>
</tr>
<tr>
<td>Carbon steels</td>
<td>70+20</td>
</tr>
<tr>
<td>Heat-resistant steel</td>
<td>30+15</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>40+10</td>
</tr>
<tr>
<td>Amorphous metals and alloys</td>
<td>3+6</td>
</tr>
</tbody>
</table>

Griffith (1920, England) tried to explain this difference (2) by the existence of cracks in the specimen before testing. It turned out to be later, that Griffith cracks and defects lower strength. It gave rise to nondestructive testing focused on defects detection. The principal goal of the mechanical approach to the fracture is to find defects and cracks.

Bekker (1925, Germany) tried to explain the difference between calculated and measured strength at the same time with Griffith by the influence of heat energy. For the time before fracture Bekker involved Gibbs-Arrenius equation:

\[
\tau = \tau_0 \exp \left( \frac{U(\sigma)}{kT} \right)
\]

But Bekker gave wrong equation for activation energy:
Equation (4) assumes thermal activation only for small volumes of atomic order that contradicts with Griffith calculation of crack size. Nondestructive testing and fracture mechanics, which investigates force instability of body with crack, have arisen. Bekker ideas have been rejected and forgotten for long time.

However, accumulation of the experimental data forced to return to the notions of the fracture activated by the thermal energy.

Two basic papers should be mentioned. Larson and Miller (1952, USA) obtained the following equation for steels at low stresses and high temperatures:

\[
\tau = \tau_0 \left( \frac{\sigma_0}{\sigma} \right)^n \exp \left( \frac{U}{kT} \right) \quad (5)
\]

Zhurkov (1953, USSR) obtained the empirical equation for higher stresses and any temperatures:

\[
\tau = \tau_0 \exp \left( \frac{U_0 - \gamma \sigma}{kT} \right) \quad (6)
\]

Zhurkov formula is true for all materials: polymers, metals, steels, composites, etc. Fracture occurs at stresses lower than the tensile strength. The notion about tensile strength is wrong.

New approach to fracture arises, which considers it not as mechanical, but as thermo-physical phenomenon. Fracture is the disintegration of the meta-stable state activated by the thermal energy, caused by the loading, after waiting of thermal activation during time \( \tau \). The barrier in (3) is given by the mechanism of crack formation.

It is considered that the formation of cracks is related to the carriers of plastic deformation. In crystals the carriers are dislocations and vacancies.

However, the universality of Zhurkov formula, which is true for crystals and amorphous bodies, forces to look for intrinsic mechanism of cracks formation not reducible to the plastic deformation.

We believe that the intrinsic mechanism of cracks formation is developing of thermal instability in phonon gas with the work by developing of free surfaces.

For the energy of activation the equation obtained:

\[
U = u \ln \left( \frac{\sigma}{\sigma_0} \right) + U_0 - \gamma \sigma \quad (7)
\]

parameters \( u, \sigma_0, U_0, \gamma \) are represented as characteristics of inter-atomic potential, inter-atomic distance \( a \) and the phonons mean free path \( \Lambda \).
The estimation (8) corresponds with data in Table 1 by the order of values, that allows to predict strength on the basis of the nondestructive measurements.

3. Prediction of the fracture as the activated by the thermal energy process.

The basic characteristic of the fracture is the object life time $\tau$, which depends on the temperature and stresses, showing the defects in the material caused by the welding joints, corrosion, etc. The basic are equations (3) and (7), but for practical purposes it is not convenient. We succeeded to obtain the upper estimation by expressing $\tau$ as the function safety margin $n$. The results are given on the picture.

$$
\sigma^* = \frac{0.1Ea}{\Lambda} = \left(10^{-1} + 10^{-2}\right)\sigma^* \quad (8)
$$

The estimation (8) corresponds with data in Table 1 by the order of values, that allows to predict strength on the basis of the nondestructive measurements.
In traditional mechanical approach the measure of the object reliability is the safety margin $n$, but no one can say what the life time is at given $n$. From the positions of the activated by the thermal energy fracture theory we succeeded to find the relation between $\tau$ and $n - \tau (n)$. For exploitation of the steel at room temperature during 100 years the safety margin $1.25$ is enough, as for $400^\circ C$ the necessary value is $3$.

Establishment of this relation allows reducing of the given value $n$ at the design mode of the object which will cause to the material and energy economy. When defects appear and material properties change after long exploitation, it is possible to estimate time before the fracture by measuring $n$ on the object. It is possible to carry out such measurement by traditional methods of nondestructive testing. We have developed two new methods for estimating of the safety margin on the basis of acoustic emission measurements. These methods are carried out during diagnostics of industrial objects in Russia.

4. Two stage model of the fracture.

Fracture mechanics investigates growth of macro-cracks in the object, but doesn’t consider its formation. We have developed new method for prediction of the moment of macro-crack formation and determination of this event.

It is well known, that the behavior of loaded material always contains two stages. On the first stage accumulation of stable damages (micro-cracks) takes place which causes formation of growing macro-cracks (second stage).

Owing to the thermo-activated nature of damages its generation has chaotic behaviour, that’s why statical integration of damages occurs with increasing of concentration. We have established theoretically in 1979 the concentration criterion for stages change: $K = L / r = e \approx 3$, where $L$ – average distance between damages, $r = e \approx 3$ – average size of damage.
This result is confirmed by enormous number of experiments. Damages were registered by different methods, including AE method. It is seen, that criterion doesn’t depend from material (polymers, metals, rocks), size of damages (from nanometer up to kilometer), forms of loading (strain, bend, static, cyclic).

5. Acoustic emission

Registration of micro-damages with acoustic emission is used for prediction of the object remaining life.

At mechanical approach it is assumed that AE appears only at stress growth (effect of Kaiser) or crack growth. That’s why AE tests are carried out during rise of pressure at pneumatic tests. But it is not so. This opinion is mistakenly.
At activated by the thermal energy approach AE exist at constant stress also. At this kinetics of AE reproduces creep curve. There are very few examples of such experimental data, but here is our result for steel at room temperature.

\[ \sigma = \text{const} \]

It gives the opportunity to use AE method during quasy-stationary exploitation without changing of operation parameters. It becomes possible to refuse from hydraulic and pneumatic test. We carry out such works during inspection of industrial objects in Russia.

6. Practical application

We are using acoustic emission testing method for remaining life estimation of industrial objects in Russia more than 15 years. For these purposes was founded service organization OOO
“ORK”, which has the license of Russian Federal Inspection of Industry.

Let us consider one example of remaining life estimation using registration of acoustic emission data. It is necessary to prove the prolongation of exploitation and estimate the term of further safe service for underground storage tank with liquefied petroleum gas after 40 years of exploitation with allowable pressure 1MPa. The usual service pressure is 0.5 MPa. During usual inspection, which is based on mechanical approach, the tank is emptied and washed out with water. Than through the tank throat the investigator in the gas mask gets into the tank, carries out visual inspection of the inner tank surface and measures the thickness of the tank wall. This method is dangerous, laborious and expensive.

In our method the ground is taken out from the upper part of the tank, where hydraulic isolation is partially removed and acoustic emission transducers are put on the tank surface. The configuration of acoustic emission transducers allows to carry out testing of 100% tank surface and location possible acoustic emission sources. The pressure is raised up to 0.85 MPa and hold out during 20 minutes. It is seen, that all registered acoustic emission signals are delocalized and there no growing macro-cracks.

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