The development of modern diagnostic methods and means of controlling the initiation of microcracks in metal structures that are in a stress-deformed state

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Abstract.
The possibility of detecting the depth of a micro defect in metals has been proved at the moment of its formation under the action of a load based on the results of simultaneous monitoring of temperature changes on the opposite surfaces of the object of control. Taking into account the fact that in the case of the formation of a defect at a depth other than \(\frac{1}{2}\) the sample thickness along its central axis, there will be a time delay in the observation of the maximum temperature on the opposite surfaces of the object of study. The research results are the basis for improving the existing method and system for controlling the moment of microcrack initiation.

Keywords:
- load
- micro defect
- thermal conductivity
- temperature distribution
- depth of micro defect
- control
Deterioration of a structure can be defined as any change in a structure's dimensions, shape and structural properties or its individual part. As a result, it loses its ability to satisfactorily perform predetermined functions. Different approaches and theories are used to describe the destruction process.

The destruction process is often associated with the formation of new surfaces. Therefore, in the calculations related to this, attention is paid to surface energy.

According to the kinetic concept of strength, the breaking of interatomic bonds is carried out due to actual thermal fluctuations, and not due to the action of voltage. However, the role of mechanical tension in the kinetic system is huge.

A large part of the destructive energy is obtained due to the accumulated thermal energy of the body, and not only due to the work of external forces. The external force plays the role of a valve that facilitates and directs thermal fluctuations.

Physical, mechanical and chemical changes occur in the metal structure under the action of any loads acting on the element of the metal structure. This restructuring of the metal structure is accompanied by energy changes which, as a result of energy dissipation, turn into thermal energy. Applying the thermodynamic theory of destruction, it is proved that the change in energy characteristics can be used as an informative parameter to determine the pre-defect state.

The analysis of the actual technical state of the metal structure during operation based on the calculated values of the energy characteristics depending on the applied load allows us to determine the change in the degree of efficiency and makes it possible to predict its working life.

**Research results.**

The main parameter that must be controlled with the help of existing methods is the moment of transition of the metal from the pre-defective to the defective state, that is, the formation of the micro defect and energy changes observed during structural transformations and the occurrence of discontinuities in the metal of the structure.

It is known that the destruction of metal and their alloys with a change in structural levels is accompanied by the transformation of internal energy, which ultimately turns
into thermal energy, and this is accompanied by a change in temperature in the zone of defect formation. The above makes it possible to determine the temperature distribution in the structure of the metal under the influence of loads at the more micro defect formation. The process of heat transfer from the micro defect nucleation zone, as a source of heat, occurs with the help of thermal conductivity.

At this stage of research, the task of registering the energy of the heat source and its position in a certain limited volume is solved. Such a problem is called the inverse problem of heat conduction. In the theory of differential equations, such an inverse problem is incorrect and its solution cannot be obtained analytically. For an approximate solution, it is necessary to determine the exact distribution of temperature on the surfaces of the sample and its change over time.

The release of heat at the moment of defect formation is an almost instantaneous phenomenon. In the following moments, it can be assumed that the redistribution of temperature in the volume and on the surface occurs uniformly. This leads to a somewhat simplified consideration of the physical picture of the temperature field.

If we assume that the sample under study has defects (cracks, cavities) that also affect the temperature distribution, then the solution to this problem will contain deviations from the real picture. This is due to the shielding effect on free surfaces. The calculated thermal effect of the formed defect as a heat source will contain inflated values. And this will lead to a false, overestimated idea of the size of the formed defect. Therefore, we will assume that the investigated object is defect-free.

Let us consider the thermodynamic model [4] based on the thermal conductivity equation in the following form:

\[ \text{div}(a \cdot \text{grad}(T)) + \frac{q}{c\rho} = \frac{\partial T}{\partial t}. \]

However, given that the state of the object under the influence of load is characterized by dynamic processes of formation and annihilation of various types of defects, it is
not possible to ignore the fact that defects constantly interact, and the amount of heat released during the reconstruction of the latter is significant.

Studies of the defective microstructure of metal [5] show that during plastic deformation, microcracks are formed, near which there is a maximum accumulation of point defects, the number of which decreases depending on the distance from the microcrack. Therefore, for mathematical calculations, it is reasonable to assume that the propagation of heat from the energy source can be described using a Gaussian distribution.

The equation for determining the amount of heat from the source will have the form [6]:

\[
Q(\vec{r}) = \left( \frac{2}{\pi\sigma} \right)^{\frac{3}{2}} \cdot P \cdot \exp \left( -2 \frac{||\vec{r} - \vec{r}_0||^2}{\sigma} \right),
\]

where \( P \) is the power of the heat source; \( \sigma \) – is the average square deviation; \( \vec{r}_0 \) – is the position of the thermal energy source.

The given thermodynamic model was the basis of the developed system for controlling the development of micro defects in metal structures under the influence of load. The conducted experimental studies confirmed that an informative parameter that characterizes the moment of crack initiation is a jump-like change in temperature [7].

The obtained results of experimental studies with the help of the created control system made it possible to get closer to the issue of predicting the depth of the micro defect, however, it was not possible to solve this task to the end, due to obtaining an incomplete picture of the temperature distribution on the surface of the control object in a predetermined zone of probable defect formation, due to the location of the thermal sensor on one of the surfaces of the control object [4].

At the next stage of research, the thermodynamic model was improved and temperature distributions from the heat source on two opposite surfaces of the simulated sample, with centres located on the same axis, were obtained. This made it
possible, taking into account the time distribution and time correlation of the temperature change, to approach the calculation of the size and location of the formed defect.

To determine temperature distributions, a sample was modelled in the form of a parallelepiped with dimensions of 0.5 x 0.15 x 0.08 m, with physical and mechanical properties of structural steel Ст20 (St20). To solve the heat conduction equation, appropriate initial and boundary conditions are determined [8].

We assume that before the load is applied, a uniform temperature distribution is observed in the sample and its two opposite ends are at a constant temperature of 150°C, so the boundary conditions are:

\[ T(x,5,z,t) = T(x,-5,z,t) = 15 \]

With a known large-scale level of a micro defect, which is 10-200 microns, the amount of heat released during its formation is 36-40 J [1]. The action of the source, which creates this thermal effect, is short-lived. This made it possible to obtain temperature distributions on the parallel surfaces of the sample depending on the depth of the source of the energy change (Fig. 1, 2). The calculation was carried out in the environment of the Flex PDE software package of PDE Solution Inc [9].

![Figure 1](image_url)

**Isolines of temperature distribution on the upper range of the modelled sample**
Modelling of the temperature distribution is carried out for the case when the microcrack, which is formed as a result of deformation, will appear along the axis of symmetry of the sample. To obtain the results of the temperature measurement, the thermal sensors should be placed on both sides of the tested sample. Such an arrangement will allow us to obtain information about the temperature of the surface of the sample at the central symmetrical points. In the simulated experiment, a defect (microcrack) will appear between the thermal sensors. Therefore, they will record the highest surface temperature.

By changing the coordinates of the source of energy changes along the central axis, different temperature distributions were obtained on the planes of the opposite faces of the simulated sample.

This difference shows that in the case of the formation of a defect at a depth other than \( \frac{1}{4} \) the thickness of the sample along its central axis, there will be a time delay in observing the maximum temperature on the opposite surfaces of the research object.

The speed of heat wave propagation as a result of heating by a point source in the metal is determined

\[
w = \sqrt{\frac{c}{\tau_p}},
\]
where \( \varepsilon = \frac{\lambda}{c\rho} = 3.7 \times 10^{-11} \) – coefficient of thermal conductivity (\( \lambda \) – coefficient of thermal conductivity).

The delay time between the values of the maximum temperatures on the upper and lower surfaces, depending on the coordinate \( z \) and the thickness of sample \( d \), will have the following form:

\[
\Delta t = \frac{d}{2w} + \frac{z}{w} - \frac{d}{2-w} = \frac{2z}{w},
\]

where \( w \) is the speed of heat wave propagation as a result of heating by a point source in the metal; \( d \) – the thickness of the modelled sample; \( z \) is the distance from the upper and lower surfaces to the origin of coordinates.

Table 1 shows the dependence of temperature \( T_{\text{max}} \), temperature difference \( \Delta T_{\text{max}} \) and delay time \( \Delta t \) on the micro defect position coordinate \( z \).

The maximum value of the temperature on the surface \( T_{\text{max}} \) and the temperature difference \( \Delta T_{\text{max}} \) on the upper and lower surfaces depending on the \( z \) coordinate is obtained (Fig 3).

**Figure 3**

Dependence of the maximum temperature value on the surface \( T_{\text{max}} \) and the temperature difference \( \Delta T_{\text{max}} \) on the upper and lower surfaces due to the \( z \) coordinate.
Table 1 Dependencies of temperature $T_{\text{max}}$, temperature difference $\Delta T_{\text{max}}$ and delay time $\Delta \tau$ on the micro defect position coordinate $z$.

<table>
<thead>
<tr>
<th>$z$, mm</th>
<th>$T_{\text{max}}$, $^\circ\text{C}$</th>
<th>$\Delta T_{\text{max}}$, $^\circ\text{C}$</th>
<th>$\Delta \tau$, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>23.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.5</td>
<td>23.6</td>
<td>0.6</td>
<td>0.007</td>
</tr>
<tr>
<td>1</td>
<td>23.8</td>
<td>1.0</td>
<td>0.021</td>
</tr>
<tr>
<td>1.5</td>
<td>24.1</td>
<td>1.6</td>
<td>0.031</td>
</tr>
<tr>
<td>2</td>
<td>24.25</td>
<td>1.95</td>
<td>0.065</td>
</tr>
<tr>
<td>2.5</td>
<td>24.4</td>
<td>2.3</td>
<td>0.092</td>
</tr>
<tr>
<td>3</td>
<td>24.45</td>
<td>2.5</td>
<td>0.150</td>
</tr>
<tr>
<td>3.5</td>
<td>24.5</td>
<td>2.8</td>
<td>0.206</td>
</tr>
</tbody>
</table>

The temperature-time dependences of the detected thermal distribution on the opposite surfaces of the object of research were established, depending on the depth of the source of energy changes. The possibility of determining the location of the defect is shown, provided that the thermal sensors are clearly located in the zone of probable formation of the micro defect (along the axis of the location of the thermal sensors).

The research results are the basis for improving the existing method and system of controlling the moment of microcrack initiation.

References:

GENERAL ENGINEERING AND MECHANICS

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