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The investigation of metals' damage through thermal field kinetics

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Abstract

The possibilities of modern equipment for measuring the temperature without a contact allowed us to calculate the characteristics of damage through the kinetics of thermal field formed on top of the developing crack, and thus to prognose crack resistance of the investigated object. The proposed method has some advantages with comparison to traditional methods.

1. Introduction

The proposed method allows to prognose both *static and cyclic crack resistance.* The tests were carried out on flat standard samples made of steel 20 and 45 with through central and lateral incisions, under the conditions corresponding to international standards. In addition to it, with the help of thermovisor Rubin MT, an average temperature of a spot 2 mm in diameter at the top of the incision was continuously fixed during the process of testing on the surface of the sample. It will be shown further that the material received as the result of the experiment allowed to calculate more precisely the characteristics of crack resistance.

2. Testing static crack resistance

Samples 10 mm thick with initial central incisions were tested. At such thickness, plastic damage occurs practically for all metals when a crack is developing. The aim of standard tests is to make a diagram $P—\mathcal{V}$ (P is the effort stretching the sample and $\mathcal{V}$ characterizes the widening of the crack), on which a characteristic point Q is fixed, defining the beginning of crack growth. By this point, the characteristics of static crack resistance are calculated (under some certain conditions).

At brittle (elastic) and elastic-plastic destruction we get so-called diagrams of I and II types, having the maximum or the local loading maximum around the characteristic point Q. In such cases the characteristic point is fixed precisely enough, and the characteristics of crack resistance, according to standard methods, are defined with a great degree of reliability.

At plastic destruction the diagrams of III type are obtained, where the characteristic point Q is defined through building a 5% secant *(figure 1).* This secant is supposed to separate on the diagram $P—\mathcal{V}$ the domain of geometric non-linearity, connected with the initial deformation of the incision (crack), from the domain where physical non-linearity is prevailable, which is connected with the formation of plastic zone on the top of the crack and the beginning of its movement. As many investigators point out [1], such methods may cause considerable errors when calculating the characteristics of crack resistance, as the peculiarities of the tested metals are not taken into account.

Parallel to the traditional diagram $P—\mathcal{V}$, another diagram was built: $P—\Delta T$, where ΔT is the

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increase of temperature at the end of the crack during a certain short period of time [2] . This diagram has three distinctly defined zones: in the first zone, a little fall of temperature takes place as the result of Thomson effect *(figure 1)* . It happens at purely elastic deformation. In the second zone, the temperature is stabilized due to the beginning of the process of plastic deforming and the movement of the crack. Then a sharp increase of temperature occurs. On the border between the first and the second zones the temperature curves have a characteristic form, and, what is important, the ordinate of the bending correlates with the ordinate of the point Q on the diagram $P—\mathcal{V}$. This bending has a distinct physical interpretation, is reliably fixed by standard equipment used for measuring the temperature without a contact.

The diagram $P—\Delta S$ was based on the diagram $P—\Delta T$, where ΔS is the change of specific entropy at the end of the crack, connected with the dispersion of energy in the form of heat, and calculated by the formula:

$$\Delta S = 2Cv\frac{T_2 - T_1}{T_2 + T_1} \tag{1}$$

Here Cv is the specific heat capacity of the material, $T2$ and $T1$ are the temperatures of the spot at the end and at the beginning of a given period of time. This entropy diagram by its characteristic form at the level of the point Q underlines even *more distinctly the beginning of the crack growth.*

The statistics analysis of the crack resistance characteristics, obtained by a traditional method and by the proposed thermodynamic method demonstrated that in the latter case these characteristics are defined more precisely.

3. Testing cyclic crack resistance

The increase of entropy at the end of the crack during the oscillation cycle ΔS appeared to be a very convenient diagnostic parameter for prognosing cyclic crack resistance of materials. Traditionally this question is solved in the fracture mechanics on the basis of Paris formula which connects the speed of the crack growth with the coefficient of stress intensity (CSI) [1,3] at one cycle of loading:

$$\frac{dl}{dn} = A \cdot \Delta K^m \tag{2}$$

where A and m are empirically defined parameters of the material, and dl/dn the speed of crack growth.

The formula (2) describes the middle part of the kinetics diagram defining, practically, the cyclic resistance of the sample.

In practical work more convenient variants of the Paris formula are used [3]. To calculate the cyclic resourse these formulas are necessary to be integrated. To do it, it is necessary to have an analytical dependence of maximal CSI on the length of the crack. Getting this dependence is a serious limitation to the usage of such an approach, as it may be calculated only for a very limited range of details with standard cracks, whereas the experimental method leads to difficulties with measuring the length of crack. Besides, the measurements are not always possible, especially if the crack goes deep into the detail.

The investigations, carried by us, showed that the speed of crack growth dl/dn correlates with the parameter ΔS^{1c} and also with $\Delta\phi^{1c}$ (the change of heat resourse intensity on top of the crack): on top of the crack, while the crack is developing and moving, the process of plastic

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deformation of the material takes place, which is connected with intense heat emission. We can say that a heat source with the intensity ϕ virtually propagates on top of the crack. The method proposed by us [4] allows to obtain the function $\Delta\phi^{1c}(n)$ through the temperature kinetics at the end of the crack.

To prognose the cyclic resourse of details with initial macrocracks, the following empiric dependencies were used [5]:

$$\frac{dl}{dn} = \vartheta^* \left(\frac{\Delta S^{1C}(n)}{\Delta S_*^{1C}} \right)^{m1} \tag{3}$$

or

$$\frac{dl}{dn} = \vartheta^* \left(\frac{\Delta \varphi^{1C}(n)}{\Delta \varphi_*^{1C}} \right)^{m2} \tag{4}$$

which can be regarded as peculiar kinetic fatigue diagrams, based on the results of testing several samples up to their destruction *(figure 2)*. In these formulas, l is the length of the crack, n is the number of loading cycles, ΔS_*^{1c} and $\Delta\phi_*^{1c}$ are the corresponding parameters at a given speed of crack growt $\mathcal{V}^*$, $m1$ and $m2$ are empirical coefficients. As we see from formula (2), the obtained curves are qualitatively identical to traditional diagrams $dl/dn = f(\Delta K)$; that is why in formulas (3) and (4) the structure of Paris formula is preserved.

To calculate the details working in a stationary regime of cyclic loading, the formulas (3) and (4) should be integrated:

$$\Delta l_{Cr} = \vartheta^* \int_0^{n_{Cr}} \left[\frac{\Delta S^{1C}(n)}{\Delta S_*^{1C}} \right]^{m1} dn \tag{5}$$

From this formula the lifetime of the detail n_{Cr} is defined, which corresponds to the crack growth to a critical length l_{Cr}. Practically there are no difficulties or limitations for obtaining any analytical dependence $\Delta S^{1c}(n)$. This dependence was calculated through the approximation of a corresponding experimental curve, obtained with the help of the thermovisor *(figure 3)*.

It should be noted that the dependence $\Delta S^{1c}(n)$ can be obtained both at stand testing and at industrial exploitation of the detail. If this is difficult, then the dependence $\Delta S^{1c}(n)$ can be obtained while testing the samples with the simultaneous building of a diagram $dl/dn = f[\Delta S^{1c}(n)]$, and in this case it can be regarded as the characteristics of the material.

The comparison of calculated and actual lifetimes of tested samples showed that the *precision of prognosing the resource is much higher* than with the help of traditional approach, both at one-step and multi-step loading. In our opinion the higher precision is accounted for by a better consideration of individual peculiarities of tested samples.

4. Limitations of the method

The samples which serve as the basis for receiving the corresponding parameters of the material and the details for which the resourse is prognosed must be similar as far as the heat is concerned. Practically it means that the samples and details must have the criterion Biot $Bi < 0.1$. In this case the temperature behaviour during the crack development on the surface of samples and details will be identical. But this limitation is not very rigid, and the majority of construction elements are not concerned by it.

The use of the proposed method is also difficult at non-stationary cyclic loading.

http://dx.doi.org/10.21611/qirt.1992.022

5. Conclusion

Thus, the proposed thermodynamic method of prognosing crack resistance of metals has *some advantages* in comparison with traditional approaches. These advantages consist in a *higher precision, universality and effectiveness.*

Beside the described usage of the method it is also used for determining individual endurance limit of details [6], for prognosing fatigue resistance of details without initial cracks [7], etc.

The development of thermal methods became possible only due to *possibilities of modern infrared thermography.* This method is successfully used for non-destructive control of durability of details at a number of plants in Russia.

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148

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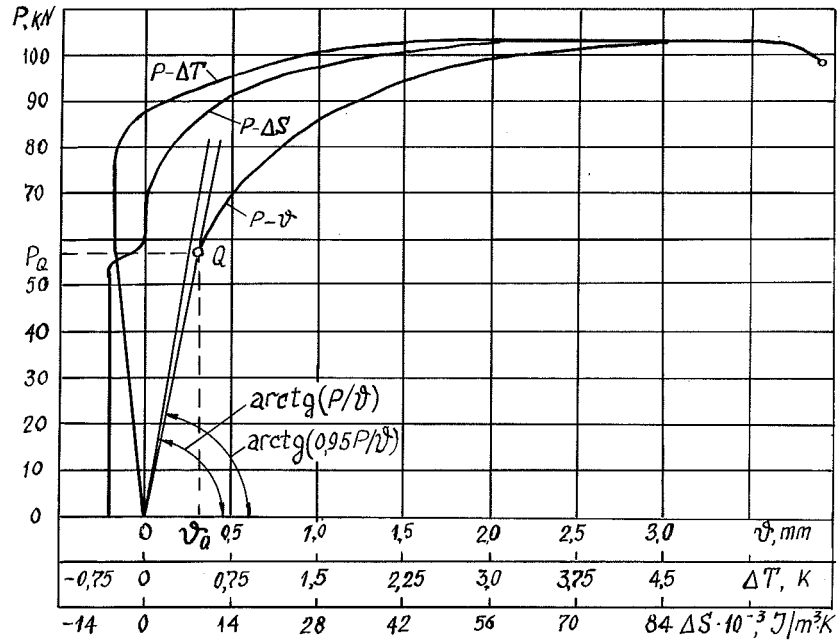

Fig.1. – The dependence of P on ϑ, ΔT and ΔS for one of the samples made of steel 20

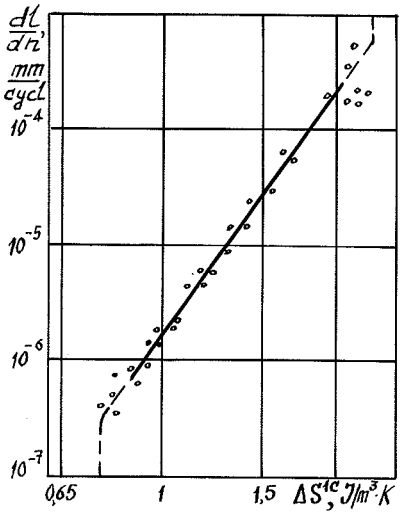

Fig.2. – The dependence $\frac{dl}{dn}$ on ΔS^{1C} (steel 20)

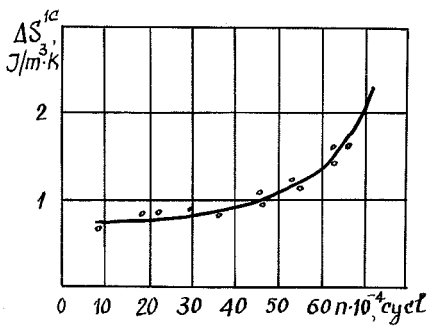

Fig.3. – The dependence of ΔS^{1C} on n, corresponding to the level of nominal tension $\sigma_n = 154\ MPa$ (obtained for steel 20)