Effect of aggressive media on working capacity of composite elements in mechanical engineering

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Abstract Composite elements can improve not only the strength but also the protective properties of engineering products, thus reducing corrosion losses. At present, there is no sufficient study of the environment influence on the working capacity of composite elements, in particular on the decrease of their crack resistance. The article discusses the calculation and experimental methodology, which allows increasing the accuracy and reliability of the assessment of crack resistance of composite elements under the influence of aggressive media. The presented methodology can be implemented without a test facility by testing directly experimental specimens. To determine the magnitude of the crack propagation energy, a mathematical model is proposed that includes only one independent parameter (radius of curvature). The authors investigated qualitative and quantitative characteristics of the effect on the fracture toughness of such aggressive media as machine oil and water. It is shown that the effect of air and machine oil on the crack resistance is approximately the same. A decrease in crack resistance by 1.56-11.1 times is observed under the influence of water. The composite elements based on the VAK-A adhesive composition have the highest crack resistance in aggressive media.

1. Introduction
The integrated effect of mechanical loads, temperature and aggressive media is a characteristic feature of the operation of various elements of metal engineering structures.

The elements of metal structures, used in various fields of mechanical engineering, undergo corrosion during operation. This results in a decrease in their bearing capacity and often premature decommissioning of facilities leading to significant losses of labor and material resources. For example, statistics from the American Petroleum Institute show annual corrosion costs of the oil and gas industry estimated at $ 2 billion. At the same time, the cost of corrosion control is about $ 500 million annually [1–4].

One of the promising solutions to this problem is the use of composite materials such as metal-reinforced polymer coating, in other words, the metal-polymer materials that combine the protective properties of coatings with the mechanical strength of the metal (substrate) [5–13].

However, the capabilities of such coatings have not yet been enough studied. In particular, there are no sufficiently proven recommendations on the use of polymer coatings under the influence of aggressive media (machine oil, water and etc.).

One of the main working capacities of the polymer coatings (bearing capacity, durability, etc.) is crack resistance, which depends on the amount of adhesion – the bonding force of the adhesive with the matrix.
Currently, a large number of theoretical and experimental methods is used to determine the crack resistance of polymer coatings and adhesive joints [14–24].

A major drawback of existing experimental techniques is the need for test facilities. Thus, they cannot be directly used to assess crack resistance under the influence of aggressive media on polymer coatings.

A modified calculation and experimental methodology has been developed for assessing the crack resistance of polymer coatings operating in aggressive media without the use of a testing facility.

2. Methodology for assessing crack resistance of composite elements

2.1. Methodology description

The essence of the proposed method lies in the fact that the experimental specimen consists of two beams made in the form of a circular arc. They are forcibly straightened and connected using an adhesive joint. Then the straightener is removed. The beams tend to take their original shape which results in a crack formation in the adhesive line (Figure 1).

![Figure 1. Crack formation pattern: 1 – beams (the shape of beams before connection is shown by dashed lines); 2 – adhesive composition; 3 – crack](image)

The implementation of the developed methodology is as follows. Beams are preliminarily bent so that the displacements are in the zone of elastic deformations. For example, a three-roll bending machine can be used.

After this, the beams acquire a curvilinear shape and their radius of curvature is described by an arc of a circle with a radius $R$.

To eliminate the residual stresses arising in the beams due to the bending of the specimen, the heat treatment is performed.

Then the beams are straightened using special brackets, and an adhesive composition is applied to their inner surface. Then the beams are joined together and held for a certain time until the composition is cured.

Upon that, the brackets are removed and the beams tend to acquire their original shape. Due to the action of the elastic moment $M$, the experimental specimen is wedged from two sides, as a result cracks are formed.

Thus, the pre-bent beams allow the loading of the polymer coating without the use of special devices.

It is recommended to pre-bend the beams in a way that the neutral axis of their individual sections had the shape of arcs of circles with different radii. In this case, the constant magnitude condition of the cracking force within the sample length section is achieved.
2.2. Mathematical models and calculation algorithm

To assess crack resistance, the crack propagation rate $\dot{a}$ is taken as a dependent parameter, and the crack propagation energy $G$ is taken as an independent parameter [19–22].

The initial data for determining the crack propagation energy is a system of expressions that includes the dependences for determining the potential energy, bending moment, and radius of curvature [25, 26]:

$$
U = \int_0^L \frac{1}{2EJ} M^2(x) dx;
$$

$$
M(x) = \frac{d^2 y}{dx^2} EJ;
$$

$$
R \approx \frac{1}{d^2 y / dx^2},
$$

where $E$ – module of elasticity of beams; $J$ – moment of inertia of the cross sections of cantilever beam.

The joint solution of the system of expressions (1) allows obtaining the dependence for determining the potential energy of the adhered specimen

$$
U = \int_0^L \left[ \frac{1}{2R^2(x)} \left( E_1 J_1 + k E_2 J_2 - \frac{(E_1 J_1 - k E_2 J_2)^2}{(EJ)_0} \right) \right] dx,
$$

where $R$ – the radius of curvature of the beams before adhering; $k$ – coefficient depending on the characteristics of the material and the size of beams; $(EJ)_0$ – bending stiffness of a unit length of the glued beams.

The expression for determining the energy of crack propagation can be written as

$$
G = -\frac{1}{b} \frac{dU}{da}.
$$

where $b$ – the width of the adhesive seam.

Taking into account the dependences (2) and (3) we obtain the expression for the crack propagation force. We assume that the experimental specimen consists of two cantilever beams made with the same moduli of elasticity $(E_1 = E_2 = E)$ and inertia $(J_1 = J_2 = J)$.

Then the expression for determining the crack propagation energy with the accepted assumptions and dependencies (7) and (8) can be written as follows

$$
G = \frac{1}{2bR^2} \left[ EI(1+k) \frac{[(1-k)EI]^2}{(EJ)_0} \right].
$$

The expression is convenient for use, since it contains only one independent parameter – the radius of curvature $R$, which can be determined through the deflection of the beam as

$$
R = \frac{l^2}{8f},
$$

where $f$ – the deflection of the beam; $l$ – the base length of the beam when measuring the magnitude of the deflection.

The measurement of crack opening $a$ can be done using a microscope.
3. Results of calculation and experimental studies

The studies used polymer coatings based on the following adhesive compositions: VAK-A, Sprout-9M, Sprout-Plus, the characteristics of which are given in the Table 1. In the experimental specimen, St 3 steel was a substrate and T-II-GVS-9 fiberglass was a reinforcing material.

| Physical and chemical properties | Adhesive composition | Sprout-9M | Sprout-Plus | VAK-A |
|----------------------------------|----------------------|-----------|-------------|-------|
| Strength in air at:              |                      |           |             |       |
| uniform separation, MPa         |                      | 7.5       | 8.4         | 10.8  |
| shear, MPa                      |                      | 7.0       | 7.0         | 10.1  |
| Strength in water at:            |                      |           |             |       |
| uniform separation, MPa         |                      | 4.6       | 5.7         | 7.7   |
| shear, MPa                      |                      | 4.1       | 5.2         | 7.3   |
| Strength in machine oil at:      |                      |           |             |       |
| uniform separation, MPa         |                      | 6.5       | 8.6         | 8.6   |
| shear, MPa                      |                      | 5.4       | 7.8         | 8.2   |

The polymer coatings were applied in air. Then the experimental specimens were kept for 90 hours in various media – in air, in machine oil and water. After that, the kinetics of crack growth was evaluated.

Figures 2–4 present diagrams showing the kinetics of subcritical crack growth in polymer coatings under the influence of various media, obtained on the basis of experimental data processing.

The figures show the upper limit of the rate of crack propagation according to the averaged values of the experimental points.

Figure 2. Pattern of the air effect on the destruction of various adhesive compositions: 1 – Sprout-9M; 2 – Sprout-Plus; 3 – VAK-A

Figure 3. Pattern of the machine oil effect on the destruction of various adhesive compositions: 1 – Sprout-9M; 2 – Sprout-Plus; 3 – VAK-A
Figure 4. Pattern of water effect on the destruction of various adhesive compositions: 1 – Sprout-9M; 2 – Sprout-Plus; 3 – VAK-A

Table 2 compares the crack resistance characteristics of polymer coatings made on the basis of various adhesive compositions.

| Energy of crack propagation, J/m² | Average speed of crack propagation, mm/c |
|----------------------------------|------------------------------------------|
|                                  | Sprout-9M | Sprout-Plus | VAK-A |
| Water                            |           |             |       |
| 100                              | 1.0·10⁻²  | –           | 1.1·10⁻⁵ |
| 200                              | 1.8·10⁻²  | 1.5·10⁻³   | 1.7·10⁻⁴ |
| 300                              | 1.5·10⁻¹  | 1.1·10⁻¹   | 1.2·10⁻² |
| 400                              | –         | 1.6·10⁻¹   | 1.2·10⁻¹ |
| Air                              |           |             |       |
| 100                              | 1.3·10⁻⁵  | –           | –     |
| 200                              | 1.2·10⁻²  | 1.9·10⁻⁴   | 1.0·10⁻⁴ |
| 300                              | 1.0·10⁻¹  | 1.2·10⁻²   | 1.2·10⁻³ |
| 400                              | –         | 1.1·10⁻¹   | 1.0·10⁻² |
| Machine oil                      |           |             |       |
| 100                              | 1.2·10⁻⁵  | –           | –     |
| 200                              | 1.1·10⁻²  | 1.0·10⁻³   | 1.8·10⁻⁵ |
| 300                              | 1.5·10⁻²  | 1.2·10⁻²   | 1.2·10⁻³ |
| 400                              | –         | 1.1·10⁻¹   | 1.1·10⁻¹ |

The statistical processing of the experimental results showed: the relative error of a series of measurements \( a \) varies in the range of 9.3..17.5%; the test variance can be considered homogeneous, since the maximum values of the Cochren criterion for all series of measurements do not exceed critical \( G_0 = 0.390 < G_{0.95} = 0.480 \) [27].

4. Conclusion
The test results showed that machine oil have a very small effect on the rate of crack propagation in comparison with the air.

This is explained by the fact that machine oil have a higher molecular weight, and this is an obstacle to their diffusion into the adhesive composition, as well as the lack of chemical interaction of the composition with machine oil.

Specimen tests in water showed that the effect of water on the adhesive joint leads to an increase in the rate of crack propagation by 1.56-11.1 times (in the range \( G = 200 \ldots 300 \) J/m²), depending on the size \( G \) and type of adhesive composition.
Obviously, water causes chemical changes in the adhesive composition. This is the main reason for the decrease in crack resistance of polymer coatings and adhesive compounds under the influence of water. The greatest crack resistance when exposed to aggressive media has a composite element based on the VAK-A adhesive composition. The crack resistance of the Sprout-9M and Sprout-Plus adhesive compositions is lower.

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