If it is taken into account that the equivalent stresses from internal pressure, self-compensation, and weight loads in steam lines permitted by OST 108.031.02–75 may reach the long-term strength limit, and the stress concentration in the areas of transitions, holes, tee joints and other elements is equal to approximately three, then the data in Tables 1 and 2 and Fig. 3 actually reflect the probability parameters of the rate of defect propagation and endurance of the components of the steam lines made of 12Kh1MF steel in areas of their geometrical heterogeneity. In straight sections of the steam lines, the parameters of endurance and crack propagation rate are an order of magnitude higher. For example, as a result of calculation processing of the previously examined experimental data it was established that the rate of propagation of crack-like defects with a depth of up to 2 mm, which can be passed in inspection of straight sections of steam lines of various standard dimensions in 12Kh1MF steel, is equal to $(0.6\text{-}1.0)\cdot 10^{-4}$ mm/cycle and in the areas with stress concentration it is equal to $(1.0\text{-}2.0)\cdot 10^{-3}$ mm/cycle.

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EXAMINATION OF THE CRACKING RESISTANCE OF CORROSION-RESISTING GLASS-REINFORCED PLASTICS BY ACOUSTIC EMISSION METHODS

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It was shown in [1, 2] that cracking resistance is one of the main characteristics of the efficiency of corrosion-resisting glass-reinforced plastics (CRGP), and comparable values of stress intensity factors K_Q were determined for discretely reinforced structures of the CRGPs (K_Q is the cracking resistance of thin and flat specimens with respect to the start of crack propagation which is not always equal to K_{Ic}).

It was assumed that the fracture toughness of the composites which reflects the resistance of the material to crack propagation does not characterize unambiguously its cracking resistance because it does not determine the resistance of the material to crack formation (K_0).

The concept of macrostresses developed by M. Ya. Leonov and K. P. Rusinko [3, 4] was used as a basis for deriving a number of variants of the relationship between the values of K_0 and K_{Ic} [5-8].

For a material with randomly distributed microcracks, the resistance to macrocrack initiation is

$$K_0 \approx 0.66K_{Ic}. \qquad (1)$$

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TABLE 1. Physicomechanical Characteristics of CRGPs (Random Reinforcement)

Composite	Content of reinforcing material, %	Tensile strength, MPa	Young's modulus, MPa	Poisson's ratio	Calculated value of K_0, N/mm$^{3/2}$	K_Q, N/mm$^{3/2}$	Variance factor, %	Experimental value of K_0 N/mm$^{3/2}$	Variance factor, %
PN-15	—	50	3000	0,36	13,6	19,1	9,0	19,1	9,0
PN-15+ LVV-SP	10	70	4000	0,33	17,7	32,2	13,6	13,3	12,1
PN-15+MB	30	100	9000	0,31	20,4	67,5	14,3	9,4	13,7

In the case of a composite with hard linear inclusions [7, 8] we have

$$\frac{K_0}{K_{Ic}} = \frac{\pi(x-1)}{2\sqrt{2x}\ln x}, \tag{2}$$

where $x = \frac{3-\nu}{\nu+1}$; ν is Poisson's ratio.

In a more general case of initiation of brittle fracture at inclusions, fibers, and voids, the relationship between K_0 and K_{Ic} has the form [6]:

$$\frac{K_0}{K_{Ic}} = \frac{x+3}{2\sqrt{2}(x+2\sqrt{2}\nu)} B(\nu); \tag{3}$$

$$B(\gamma) = \frac{4\nu\sqrt{1+\sqrt{2}} + (3-\nu)\sqrt{2} - (1+\nu)}{2\sqrt{2(1+\sqrt{2})}\,(1+\nu)}. \tag{4}$$

In the above relationships (1)-(3), the value of K_0 depends either directly on K_{Ic} or on K_{Ic} and a complicated function of ν. However, this relationship does not always reflect accurately the capacity of a number of composite materials to resist initiation of cracks in them. As indicated by data in Table 1, an increase of the degree of filling of the matrix (polyester resin PN-15) with the reinforcing material is accompanied by an increase of the strength and fracture toughness of the composites with a slight reduction of Poisson's ratio. The theoretically calculated, from Eq. (3), values of K_0 (experimental methods of evaluating K_0 are not available at the present time) show that K_0 increases with increasing degree of filling.

At the same time, an increase of the degree of filling of the matrix of the composite is accompanied by an increase of the total microheterogeneity of CRGP which increases the probability of formation of cracks in the composite; this predetermines a reduction, not an increase, of K_0, as indicated by the presented calculated data.

It is probable that the above result is associated with the fact that the model of theoretical calculations of K_0 (an elastic matrix with an absolutely rigid stringer in the longitudinal and transverse directions with the ideal interface) differs from the real CRGP. The adhesion strength of the matrix with the glass fiber may be higher or lower than the cohesion strength of the matrix. The stringers are flexible in the transverse direction and have a specific strain capacity in the longitudinal direction, and the modulus of elasticity of the fibers is not a constant value because it depends on the nature of the material, the diameter and number of single fibers, their defectiveness, and other factors [9].

In the present work, it is proposed to determine the cracking resistance of CRGP (resistance of the material to crack initiation K_0 and resistance to crack propagation K_Q) using the acoustic emission (AE) method. The investigations were conducted on flat wedge-shape specimens of the double cantilever beam type. The stress intensity factor was determined using the method proposed in [10]. In contrast to [2], the form and dimensions of the specimens (Fig. 1) were accepted on the basis of the fact that it was subsequently necessary to expose these specimens in solutions of corrosive media in the stress state. Examination of the effect of the corrosive medium on the variation of the parameters K_Q and K_0 of the composites in the stress state is the subject of a separate report.

In the present work, the specimens of the composites in the nonstressed state were exposed to an aqueous solution of an alkali and hydrochloric acid by immersing them in the corrosive medium in glass exiccators which were placed in thermal cabinets of SNOL-3-5 type. The specimens were exposed for 24 h with automatic maintenance of the required temperature. After completion of exposure, the specimens of the CRGPs were rinsed in distilled water, dried using filter paper, and within 2 h after removal from the solution subjected to mechanical testing.

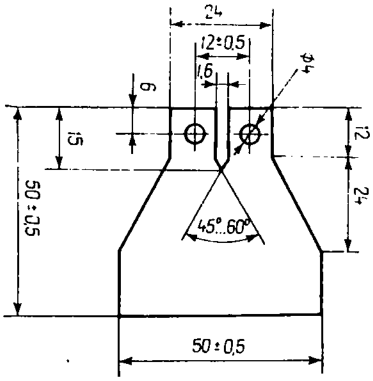

Fig. 1. Form and dimensions of specimens for examining cracking resistance of CRGP.

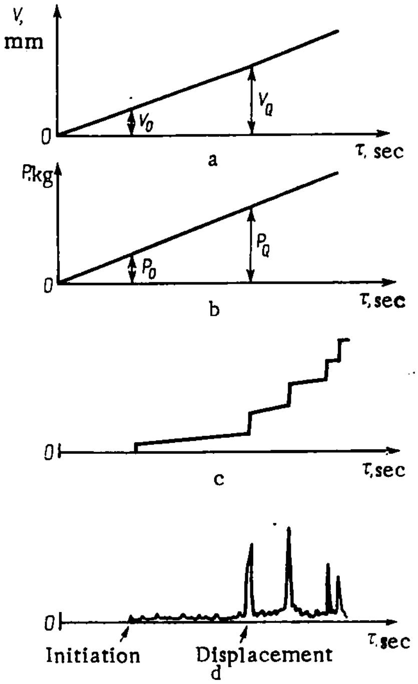

Fig. 2. Typical curves of CRGP: a) opening of the crack edges; b) force; c, d) respectively, the integral and differential parameters of AE.

The tensile test of the specimens prior to and after exposure in the corrosive media was carried out by loading using a special device in a R-5 tensile machine at a speed of 1 mm/min. In loading, synchronous recording on the real-time scale was carried out for force P, opening of the crack edges V, and differential and integral parameters of AE with time markings, corresponding to the appearance of AE signals and displacement of the notch-crack (Fig. 2).

A specially developed system was used which made it possible to record the AE signals in analog form. The main parameters of the system are given below:

Working frequency band, kHz	100-2000
Sensitivity, μV	No less than 3
Dynamic range, dB	60
Time constant of the detector of the level of AE signal, sec	0.1
Cut-off frequency of high-pass filter, kHz	100, 300, 700, 1200
Cut-off frequency of low-pass filter, kHz	300, 700, 1200, 2000

The acoustic emission system contains a number of nonstandard electronic units and also an N-327-3/5 automatic recording device, a pulse counter, a Ch-3-34 frequency meter, and an

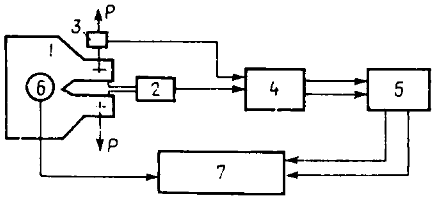

Fig. 3. Functional diagram of the method of evaluating cracking resistance of CRGP: 1) CRGP specimens; 2) displacement (crack edge opening); 3) force transducer R-01; 4) 8-ANCh-7M amplifier; 5) PDS-021M x–y automatic recorder; 6) piezotransducer; 7) electronic system for registrations of AE signals and recording of the forces and crack edge opening.

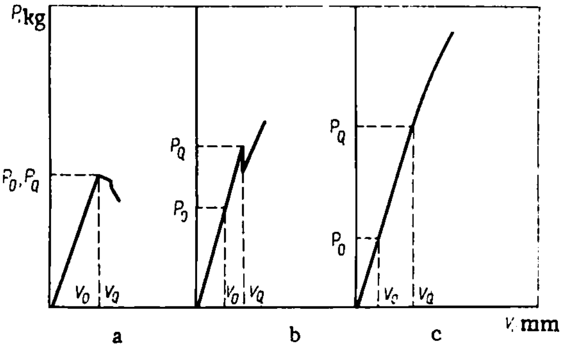

Fig. 4. Load-crack edge opening displacement curves for various CRGPs: a) PN-15; b) PN-15 + LVV-SP; c) PN-15 + MB (V_0, V_Q are the crack edge opening displacement at the instant of appearance of the first AE signal and crack displacement, respectively).

S8-11 oscilloscope. The AE signals are received by a measuring transducer and amplified in a wide-band low-noise preamplifier (K = 60 dB) in the frequency band corresponding to the main resonance frequency of the measuring transducer. After transferring to the processing unit, the signal is fed, through the amplifier of video pulses, to the unit for measuring the level of AE signals and to three identical activity measuring channels. The unit for measuring the signal level consists of a detector whose output voltage is proportional to the rms value of the incoming signals within a period of 0.1 sec. The activity measurement unit consists of a series-connected comparator with a controllable triggering threshold, a shaper of nonpulses, an averaging amplifier, and a limiting device. The unit converts the input sequence of the signal to a varying (τ = 0.1 sec) voltage whose level is proportional to the activity of the AE signals.

The activity measurement range is switched using a coil with decimal divisions which reduce the frequency of signals supplied to the averaging amplifier. The normalized pulses are fed to an external counter. The oscillator generates a pulsed sequence for setting and calibrating the system.

The signals were recorded in the frequency range 200-400 kHz. To confirm that auxiliary mechanical noise is not recorded, reference loading trials were conducted on identical specimens without a notch with the force twice as high as the force required for crack displacement. The correspondence of the AE signal with the start of crack displacement was confirmed on the reference specimens by simultaneous recording of the instant of crack displacement by three methods: optical, recording of the force–crack edge opening displacement diagrams, and recording of the differential and integral diagrams of the AE signals.

TABLE 2. Experimental Data on the Resistance of CRGPs to Initiation K_0 and Propagation K_Q of Cracks in Them

Composite	Medium	Medium temperature, °C	K_0, N/mm$^{3/2}$	Retention factor of K_0	K_Q, N/mm$^{3/2}$	Retention factor of K_Q	Initial state of composite	
							K_0, N/mm$^{3/2}$	K_Q, N/mm$^{3/2}$
PN-15 + polyethylene terephthalate	5 % HCl	+23	15,0	0,536	15,0	0,536	28,0	28,0
	5 % HCl	+80	13,6	0,486	13,6	0,486	28,0	28,0
	10 % NaOH	+23	11,3	0,403	11,3	0,403	28,0	28,0
	10 % NaOH	+80	10,5	0,375	10,5	0,375	28,0	28,0
PN-15 + LVV-SP	5 % HCl	+23	13,0	0,977	27,6	0,857	13,3	32,2
	5 % HCl	+80	9,0	0,677	22,0	0,683	13,3	32,2
	10 % NaOH	+23	10,9	0,819	21,7	0,674	13,3	32,2
	10 % NaOH	+80	6,8	0,511	12,0	0,373	13,3	32,2
PN-15 + MB	5 % HCl	+23	7,5	0,798	41,4	0,613	9,4	67,5
	5 % HCl	+80	7,0	0,745	32,4	0,480	9,4	67,5
	10 % NaOH	+23	7,2	0,766	26,3	0,370	9,4	67,5
	10 % NaOH	+80	6,0	0,638	18,3	0,270	9,4	67,5

The functional diagram used in the experimental procedure is shown in Fig. 3. The investigations were conducted on cured polyester resin PN-15 and randomly reinforced composites PN-15 + LVV-SP; PN-15 + MB; PN-15 + polyethylene-terephthalate cloth, developed on the basis of PN-15 resin. The characteristics of the examined materials are published in [1].

In determining, on the load—crack edge opening displacement diagram, the instants of generation of the first signals of AE and displacement of the notch-crack, the compliance of the specimens C and the rate of its variation were determined in relation to the notch-crack length dC/dl. The experimentally determined value of dC/dl was used to calculate the calibrating constant of the examined wedge-shaped specimen

$$m = \frac{E \cdot b}{8} \cdot \frac{dC}{dl}, \tag{5}$$

where E is Young's modulus; b is the thickness of the specimen.

The values of K_0 and K_Q were determined from the equations

$$K_0 = \frac{P_0}{b} \sqrt{4m}; \tag{6}$$

$$K_Q = \frac{P_Q}{b} \sqrt{4m}, \tag{7}$$

where P_0, P_Q are the loads, respectively, at the instant of appearance of the first AE signal and crack displacement.

The resultant diagrams made it possible not only to calculate the K_0 value of CRGP but also determine more accurately the instant of displacement of the notch-crack for the composites whose load—crack edge opening displacement diagram does not contain the typical jump indicating the instant of crack displacement, e.g., in the case of the material reinforced with glass mat MB (Fig. 4).

The results of determination of the K_0 and K_Q values of the matrix (PN-15 polyester resin) and of the composites based on this matrix are presented in Table 1.

The resultant data are in complete agreement with the previously published data and also with the considerations regarding the increase of the resistance of the randomly reinforced CRGPs to propagation of cracks in them with the simultaneous reduction of the resistance to crack formation associated with the increase of their structural heterogeneity [1, 4]. The absolute value and ratio of K_0 and K_Q are regarded as sufficiently informative parameters of the efficiency of CRGPs.

The above-described method was used to examine the strength of the effect of the corrosive media on the parameters of cracking resistance after exposing the CRGPs for 3 months in aqueous solutions of 5% HCl and 10% NaOH (Table 2). The above-mentioned corrosive media were selected as most representative and active in respect of the standard service conditions of the CRGPs.

The data presented in Table 2 indicate that for the first material based on PN-15 resin reinforced with 10% polyethylene terephthalate cloth, the values of K_Q and K_0 coincide.

This is determined by the most brittle nature of failure of this composite. The identical nature of failure (Table 1) was recorded for the pure matrix (PN-15), whereas the remaining composites which showed more ductile fractures gave different values of K_Q and K_0 for the same material.

Analysis of the results presented in Table 2 shows that the resistance to crack initiation K_0 and the resistance to crack propagation K_Q during the action of the corrosive media decrease in all the structures of CRGPs. The kinetics of variation of the values of K_0 and K_Q of the CRGPs in various service conditions must be determined by long-term tests (or by accelerated tests by, for example, fatigue loading in the medium) with the determination of the critical values of K_0 and K_Q corresponding to the start of seal failure, i.e., the start of phase penetration of the medium through the composite.

CONCLUSIONS

1. A method was proposed of evaluating the crack formation resistance of CRGPs based on the determination of the value of stress intensity factor K_0 corresponding to the first AE signal.

2. The detection of the stages of initiation and propagation of the cracks on the basis of the AE signals made it possible to determine accurately the start of crack displacement in all the types of the CRGPs and increase the accuracy of determination of the values of stress intensity factor K_Q.

3. The experiments have shown that the theoretically derived relationship between the factors characterizing the resistance of the material to crack propagation K_Q and initiation K_0 for the type CRGP composites must be determined more accurately.

4. For the examined CRGP structures, we determine the values of the stress intensity factors K_Q and K_0 in the initial condition and after 3 months exposure of the specimens in alkali and hydrochloric acid at temperatures of 23 and 80°C. This made it possible to evaluate and compare the cracking resistance of the materials and their efficiency in the corresponding service conditions.

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