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MODELLING OF FIBERGLASS PIPE DESTRUCTION PROCESS

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The article deals with important current issue of oil and gas industry of using tubes made of high-strength composite corrosion resistant materials. In order to improve operational safety of industrial pipes it is feasible to use composite fiberglass tubes. More than half of the accidents at oil and gas sites happen at oil gathering systems due to high corrosiveness of pumped fluid. To reduce number of accidents and improve environmental protection we need to solve the issue of industrial pipes durability. This problem could be solved by using composite materials from fiberglass, which have required physical and mechanical properties for oil pipes. The durability and strength can be monitored by a fiberglass winding method, number of layers in composite material and high corrosion-resistance properties of fiberglass. Usage of high-strength composite materials in oil production is economically feasible; fiberglass pipes production is cheaper than steel pipes. Fiberglass has small volume weight, which simplifies pipe transportation and installation. In order to identify the efficiency of using high-strength composite materials at oil production sites we conducted a research of their physical-mechanical properties and modelled fiber pipe destruction process.

***Key words*:** oil pipes, composite materials, fiberglass, destruction process, equilibrium equations, tension, deformation, destruction criteria

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Introduction. Currently there are more than 350 thousand km of industrial pipe lines operating at the territory of Russia [1]. Annually up to 70 thousand accidents happen at industrial pipe lines. The major reason of these accidents is corrosive destructive processes; 55 % out of total number of accidents happen at oil gathering systems, and 30-35 % – at maintenance reservoir pressure systems; 42 % of pipes of lines operating life is about 5 years or even less, and 17 % of pipes – less than two years [4]. Annually oil production companies replace about 7-8 thousand km of pipes, i.e. 400-500 thousand tons of steel [3]. However, accidents often happen because of steel pipes wear due to corrosiveness of transported material. This leads to increase of breakdown maintenance costs of linear part of pipelines.

The average life span of industrial pipelines is from several months to 15 years. Accidents cause environmental pollution, production volume reduction, maintenance costs increase and expenditures on environment protection measures. Main reasons of these accidents are improper protection of pipes from corrosion, reduction of expenditures on corrosion protection renewal, deviations from construction norms during construction and installation stages [6]. In case of high corrosive materials, the steel pipes have thicker walls and the life span of the pipe is assumed to be longer.

Method of experimental research. The object of research is criteria of multi-layered composite pipes destruction.

The main aim of criteria analysis is to identify strength properties and a model of probable deterioration of a pipe under strain. The model of compositional pipes destruction includes loss pipe wall structural integrity with formation of matrix cracks and disturbance of adhesion in the area of matrix and fibers connection. There have been offered several criteria for creating a model of destruction. Hashin [10] introduced fatigue criteria to describe a model of fiber destruction and matrix damage. Jones and Hull [11] analyzed fiberglass pipes deterioration process using microscopic examinations and found out that integrity loss happened due to formation of lateral cracks, and in case of high load because of separation of layers. Frost and Cervenka [9] researched axial and ring tension of fiberglass pipes and discovered that matrix cracks were parallel to fibers and didn't damage a fiber itself. They empirically found the following destruction criterion when fiberglass pipe was wound at angles of ± 45, ± 55 and ± 75°:

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$$\left(\frac{\sigma_\tau}{\sigma_{\tau\text{ppa}}}\right)^2+\left(\frac{\tau}{\tau_{\text{раз}}}\right)^2+C\left(\frac{\sigma_\tau\tau}{\sigma_{\tau\text{раз}}\tau_{\text{раз}}}\right)=1,$$

where σ_τ, τ – tension and shift under a given load; $\sigma\tau_{\text{раз}}$, $\tau_{\text{раз}}$ and C – material properties.

The destruction of polymer fiber material happens in several stages. At the initial stage the first layer of composite material is damaged (First Ply Failure). After this the multi-layered material preserves its strength and can bear the load. On the second stage general deterioration of layers happens, which is accompanied by destruction of the last layer (Ultimate Laminate Failure). Some criteria enable modelling first layer damage but most of them describe only critical destruction of all material. The destruction of composite material is determined not only by physical-mechanical properties of its elements but its internal structure. The destruction of reinforcing fiber, split of binder matrix, damage of joint surface or interphase boundary are caused by different mechanisms and require different modelling tools. When complex structure material is reduced to homogeneous anisotropic material the internal boundaries of coupling are erased, which leads to experimental data variances.

To create mathematical model of fiber composite material destruction the following criteria are used: Tsai – Hill criterion of maximum stress; Tsai – Wu criterion; Hashin criterion; and Pak criterion.

The criterion of maximum stress in composite layer describes loads appearing during extension and compression of material. When stress (parallel or perpendicular to fiber axis) reaches the critical value, the following expression is correct [8]:

$$\sigma_1 \geq \sigma_1^*,\ \ \sigma_2 \geq \sigma_2^*,\ \ \tau_{12} \geq \tau_{12}^*.$$

The value of the variable σ_x, required for composite material destruction in case of applying single-axis extension, is expressed as a function of angle φ between stress and fiber axis for all three modes of destruction:

$$\sigma_x^* = \frac{\sigma_1^*}{\cos^2\varphi} = \frac{\sigma_2^*}{\sin^2\varphi} = \frac{\tau_{12}^*}{\cos\varphi\sin\varphi}.$$

Deformation in axial and ring direction is defined in the following way:

$$\varepsilon_x = \frac{\sigma_x}{E_x} - \upsilon_{yx}\frac{\sigma_y}{E_y},$$

$$\varepsilon_y = \frac{\sigma_y}{E_y} - \upsilon_{xy}\frac{\sigma_x}{E_x},$$

$$\gamma_{xy} = \tau_{xy} = 0.$$

Deformation in parallel and perpendicular direction of a fiber:

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} = [T']\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix},\quad [T'] = \begin{bmatrix}c^2 & s^2 & cs\\ s^2 & s^w & -cs\\ -2cs & 2cs & c^2-s^2\end{bmatrix},$$

where ε_1, ε_2 – deformation parallel and perpendicular to fibers; γ_{12} – shift deformation; c and s – abbreviations for $\cos\upsilon$, $\sin\upsilon$.

Mathematical expression of Tsai – Hill criterion:

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$$\left(\frac{\sigma_1}{\sigma_1^*}\right)^2+\left(\frac{\sigma_2}{\sigma_2^*}\right)^2-\left(\frac{\sigma_1\sigma_2}{\sigma_2^{*2}}\right)+\left(\frac{\tau_{12}}{\tau_{12}^*}\right)^2=1.$$

The Tsai – Wu criterion includes relation to shift deformation, which is not mentioned in Tsai – Hill criterion. It is one of the most widely used criteria for modelling composite materials failure process and helps to determine accurately the strength properties without experimental data:

$$F_i\sigma_i + F_j\sigma_i\sigma_j \le 1,$$

where σ – applied stress; F_i, F_j – strength parameters; $i, j = 1, 2, 3,\ldots6$.

It is assumed that composite fiber material with polymer binding and filling can be considered as a solid body with one singled out direction, along which the mechanical properties can vary. The singled-out direction matches the direction of reinforcing fiber. The destruction process is described if one of the five conditions defining destruction model is fulfilled: extension or compression of fibers, layers separation, etc.

When modelling destruction process for a composite pipe it is assumed that, fiber structure of a pipe wall corresponds the fiberglass layer winding angle, having a set of even layers of unidirectional reinforcing fiber [7].

General Hooke's law, describing stress-strain behavior, can be expressed in the following way:

$$\sigma = C_{ij}\varepsilon j,$$

where σ – stress components pictured at fig.1 in three coordinates axes x, y, z; $i, j = 1,\ldots6$; C_{ij}, ε_j – rigidity matrix and strain component.

Deformation is defined with following expressions:

$$\varepsilon_1=\frac{\partial u}{\partial x},\quad \varepsilon_2=\frac{\partial v}{\partial y},\quad \varepsilon 3=\frac{\partial w}{\partial z},$$

$$\gamma_{23}=\frac{\partial v}{\partial x}+\frac{\partial w}{\partial y},\quad \gamma_{31}=\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z},\quad \gamma_{12}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x},$$

where u, v, w – movements along coordinate axes x, y, z.

Elastic properties of unidirectional multi-layered fiberglass material are calculated using theory of micromechanics of composite structures (fig.2). The equation of limit stress [2] and Halpin – Tsai criterion [5] are used to determine elastic properties of composite layer in main axes form the following equations:

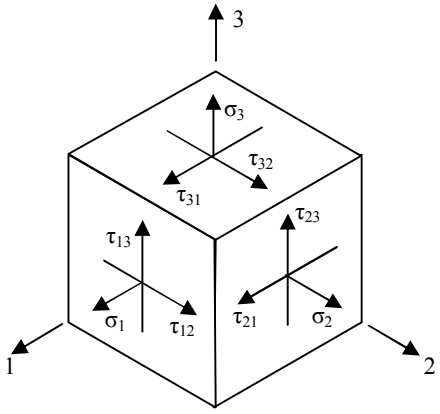


Fig.1. Element stress in three coordinate axes

composition equation

$$E_1 = E_fV_f + E_mV_m,$$

$$\upsilon_{12} = \upsilon_fV_f + \upsilon_mV_m;$$

equality of Halpin – Tsai

$$E_2=\frac{1+\xi\eta_в V_f}{1-\eta_в V_f},\quad G_2=\frac{1+\xi\eta_g V_f}{1-\eta_g V_f},$$

$$\eta_в=\frac{\frac{E_f}{E_m}-1}{\frac{E_f}{E_m}+\xi},\qquad \eta_g=\frac{\frac{G_f}{G_m}-1}{\frac{G_f}{G_m}+\xi},$$

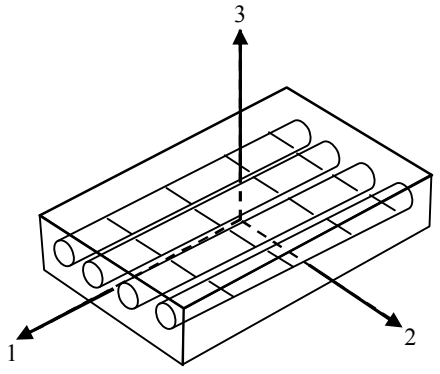


Fig.2. Unidirectional reinforced layer

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where E_1 and E_2 are longitudinal and transverse modules of elasticity of composite reinforcing layer; G_{12} – shift module; υ_{12} – Poisson ratio; V_f, E_f, E_m, G_f, G_m – module of elasticity and shift of reinforcing fiber (f) and matrix (m) in multi-layered material,

$$G_f = \frac{E_f}{2(1+V_f)}; \quad G_m = \frac{E_m}{2(1+V_m)}.$$

The fiberglass pipe wall is a part of multi-layered material and has orthotropic elastic properties, which depend significantly on winding angle θ. Thus, stress-strain state of multi-layered composite material could be described in the following way:

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = \begin{pmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{pmatrix} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ y_{12} \end{pmatrix},$$

$$Q_{11} = \frac{E_1}{1-\upsilon_{12}\upsilon_{21}}; \quad Q_{12} = \frac{\upsilon_{12}E_1}{1-\upsilon_{12}\upsilon_{21}} = \frac{\upsilon_{21}E_2}{1-\upsilon_{12}\upsilon_{21}}; \quad Q_{22} = \frac{E_2}{1-\upsilon_{12}\upsilon_{21}}; \quad Q_{66} = G_{12},$$

where Q_{11}, Q_{12}, Q_n – rigidity matrixes; E_1 and E_2 – module of elasticity of main axes on multi-layered material.

When reinforcing layers are deposed with arbitrary angle to main axes, the transformation matrix is used for stress and strain applied in axial and radial directions:

$$\begin{pmatrix} \sigma_{axial} \\ \sigma_{hoop} \\ \tau_{ax/hp} \end{pmatrix} = [T]^{-1} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [T]^{-1}[Q] \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \frac{1}{2}\gamma_{12} \end{pmatrix} = [T]^{-1}[Q][T] \begin{pmatrix} \varepsilon_{axial} \\ \varepsilon_{hoop} \\ \frac{1}{2}\gamma_{ax/hp} \end{pmatrix} = [\overline{Q}] \begin{pmatrix} \varepsilon_{axial} \\ \varepsilon_{hoop} \\ \gamma_{ax/hp} \end{pmatrix},$$

where $[\overline{Q}]$ – matrix rigidity parameter.

During algebraic transformations, the relationship between matrixes $[\overline{Q}]$ and $[Q]$ is expressed as:

$$\overline{Q}_{11} = Q_{11}\cos^4\theta + Q_{11}\sin^4 + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta,$$

$$\overline{Q}_{22} = Q_{11}\sin^4\theta + Q_{11}\cos^4 + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta,$$

$$\overline{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})\sin^2\theta + Q_{11}\cos^2\theta + Q_{12}(\sin^4\theta\cos^4\theta),$$

$$\overline{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta - ((Q_{22} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta),$$

$$\overline{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta - ((Q_{22} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta),$$

$$\overline{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + 2Q_{66}(\cos^4\theta + \sin^4\theta),$$

where θ – composite layer winding angle in ring and axial directions; it is assumed that layers are homogeneous and orthotropic.

Using the transformed matrix rigidity parameter, the elastic properties of pipe wall in xial and radial directions are described as:

$$E_{\text{ос}} = \overline{Q}_{11}(1 - \upsilon_{\text{ос}}\,\upsilon_{\text{кол}}),$$

$$E_{\text{кол}} = \overline{Q}_{22}(1 - \upsilon_{\text{ос}}\,\upsilon_{\text{кол}}),$$

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$$\upsilon_{\text{ос}} = \frac{\overline{Q}_{12}}{Q_{22}}, \quad \upsilon_{\text{кол}} = \frac{\overline{Q}_{12}}{Q_{11}}, \quad G_{\text{ос/кол}} = \overline{Q}_{66}.$$

Fig.3 shows a pattern of layering and deformation of reinforcing fibers of fiberglass pipe. Deformations caused by stress state are defined with the following equations:

$$\varepsilon_{\text{ос}} = \frac{\sigma_{\text{ос}}}{E_{\text{ос}}} - \upsilon_{\text{кол/ос}} \frac{\sigma_{\text{кол}}}{E_{\text{кол}}},$$

$$\varepsilon_{\text{кол}} = \frac{\sigma_{\text{кол}}}{E_{\text{кол}}} - \frac{\sigma_{\text{ос}}}{E_{\text{ос}}},$$

$$\gamma_{\text{ос/кол}} = \frac{\tau_{\text{ос/кол}}}{G_{\text{ос/кол}}},$$

where $E_{\text{кол}}$, $E_{\text{ос}}$ – modules of elasticity in longitudinal and traverse directions.

The theory of multi-layered materials provides quite accurate results in forecasting axial and ring deformations in fiberglass pipes under biaxial load. The table and fig.4 show comparison of theoretical calculations and results of experimental tests with fiberglass pipe.

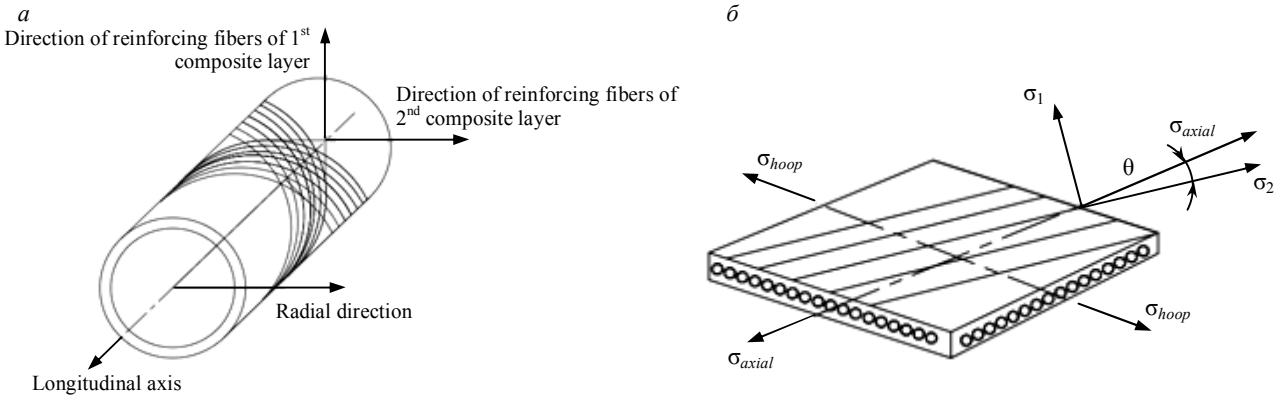


Fig.3. Pattern of layering (*а*) and deformation (*б*) of reinforcing fibers of fiberglass pipe

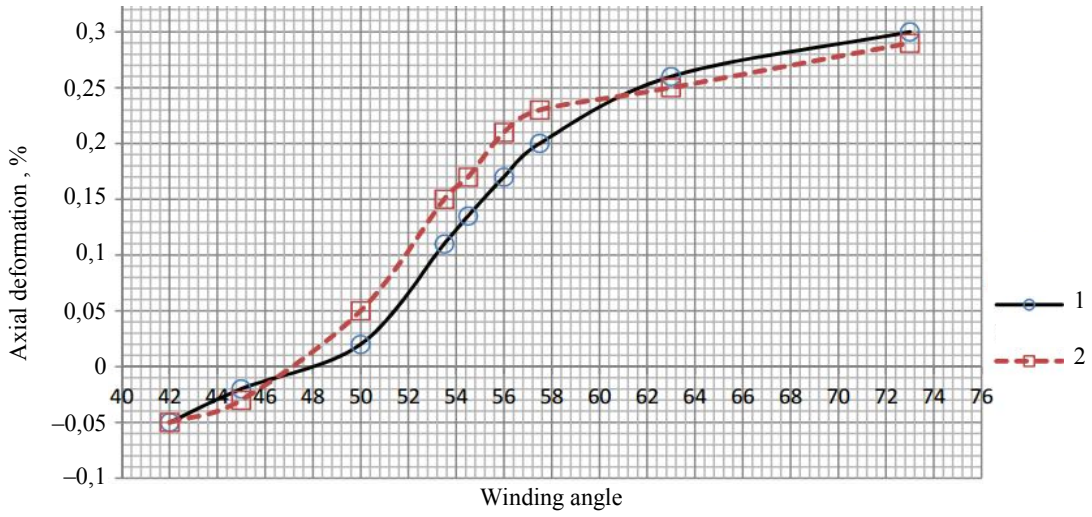


Fig.4. Comparison of experimental data (1) and Tsai – Wu criterion (2)

Comparison of theoretical calculations of axial deformation dependency on winding angle and results of experimental tests with fiberglass pipe

Winding angle	Experimental data			Theory of multi-layered materials		
	Pressure, MPa	$\varepsilon_{ос}$, %	$\varepsilon_{кол}$, %	$\varepsilon_{ос}$, %	$\varepsilon_{кол}$, %	Tsai-We criterion
42,00	95	–0,05	0,48	–0,05	0,51	0,9
45,00	120	–0,02	0,60	–0,03	0,58	1,1
50,00	130	0,02	0,50	0,05	0,51	0,9
53,50	170	0,11	–	0,15	0,57	1,2
54,50	166	0,13	–	0,17	0,54	1,1
57,50	160	0,20	–	0,24	0,46	1,0
63,00	110	0,26	–	0,25	0,27	1,0
73,00	92	0,29	–	0,31	0,19	1,0

Conclusions

We made a theoretical research of composite fiber materials destruction process and described criteria required for modelling of fiberglass pipe failure, which could be a possible solution of current issue of oil industry connected with high level of industrial pipeline corrosion. One of the possible directions of preventing corrosion is using pipes made of high-strength composite fiber materials having necessary strength properties and matching physical-mechanical requirements.

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