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NUMERICAL INVESTIGATIONS OF THE CRACK RESISTANCE OF ION-EXCHANGE STRENGTHENED SHEET GLASS UNDER BENDING STRAINS

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The safety of reliable operation of aircraft and their durability essentially depend on the strength of the glazing, which is a critical structural element. There are a number of different requirements for glazing. To provide the necessary parameters, high-strength silicate glass is widely used, and special technologies for its strengthening are used. The analysis of the problem showed that the insufficient strength of aircraft glazing elements and the complexity of methods for monitoring the state of glass during production and operation due to the presence of microscopic surface defects, as well as the need for a reliable assessment of residual stresses, require that there be used new approaches and technical solutions for the development of modern technologies for creating structures. Ion exchange is one of the glass strengthening mechanisms, which makes it possible to reduce the negative effect of surface defects by artificially creating residual compressive stresses and reducing the thickness of the damaged layer. Computational studies, under bending strains, of the crack resistance of ion-exchange strengthened sheet glass were carried out using an in-house FEM-based software package developed to study the thermally stressed states of structures. The results obtained showed that the strength of real sheet glass fracture due to tensile stresses in bending is determined by crack-like surface defects. The creation of residual compressive stresses on the glass surface by ion exchange strengthening provides an increase in bending strength. With an increase in residual stresses and the depth of their distribution, the effect of ion-exchange treatment increases. If the depth of the zone of compressive stresses due to ion-exchange strengthening is much less than the depth of the surface crack, then the strength of the glass depends little on the maximum compressive stresses on the surface. The effect of ion-exchange strengthening increases significantly in the case of a decrease in the depth of the surface crack. The expediency of further research and comparison of calculation results with experimental data are shown. The developed technique will make it possible to solve important practical problems in studying the strength of the aircraft multilayer glazing and determining the optimal methods for eliminating defects.

Keywords*: aircraft, silicate glass, stress state, strength, residual stress, ion exchange, surface layer defects.*

Introduction

The development of domestic aviation equipment requires that there be improved the materials and glass structures used for cabins and cockpits in order to ensure their safe and long-term operation [1, 2]. The current problems of increasing the competitiveness of aircraft are insufficient glazing resource and the need to reduce the weight of their structures, and for military aircraft, also an increase in the bullet resistance of the glazing. The glazing of aircraft cabins and cockpits must withstand intense operational static and dynamic loads [3, 4].

Insufficient strength of aircraft glass elements is largely due to surface defects, as well as the complexity of methods for monitoring their condition during production and operation. Therefore, there is an increasing need to introduce new refined approaches to analyze the effect of surface defects and glass strengthening mechanisms on the stress-strain state, develop strengthening technologies and control the strength characteristics of structural elements and multilayer products in general, as well as create new technical solutions based on the use of modern technologies for strengthening sheet glass, methods of monitoring shock resistance and damage.

Silicate glass, strengthened by special technologies, allows providing the necessary strength parameters of glazing, which is why it is often used in aircraft construction. At the same time, the strength of silicate glass significantly depends on the presence of surface defects, which are determined by the production method, the technologies used in this case, and the conditions of transportation and storage. The presence in glass of microscopic surface defects, the complexity of methods for their control leads to an uncertainty in the state of the surface layer, which results in a significant scatter in the values of glass strength. A decrease in the negative effect of surface defects is possible due to various mechanisms of strengthening glass by artificially creating residual compressive stresses therein and reducing the thickness of the damaged layer.

Insufficient strength of aircraft glazing elements, the complexity of methods for controlling microscopic surface defects in glass during production and operation, as well as the need for a reliable assessment of the effect of artificially created residual stresses on increasing the strength of glass require that there be developed new calculation methods and technical solutions for the development of modern technologies for creating structures.

It is known that the strength of glass under tensile strains is much lower than under compressive ones, which is caused by the presence of small surface cracks. Glass is a very fragile material that breaks down due to cracking without noticeable plastic deformations. A measure of the crack resistance of a material is the value of the stress intensity factor K_{IC}. For ordinary glass, it is in the range of 0.4–0.7 MPa $\sqrt{\text{m}}$, which is a hundred times smaller than for steel. This allows us to conclude that cracks, even of very small sizes, significantly reduce the strength of glass.

Microscopic defects on the glass surface (microcracks) are present even in its original state. The surface layer with microcracks is most often due to the manufacturing process. It is formed by cooling float glass, pressing parts, or pulling rods and fibers. Under operating loads, the surface layer changes due to the modification of existing defects and formation of new microcracks [5, 6]. Fig. 1 shows a typical form of microcracks in real glass [6]. The action of various technological and operational factors leads to an uneven pattern of the location of defects, as a result of which, for technical glass, the strength limit under the action of tensile stresses can fluctuate from 10 to 3000 MPa.

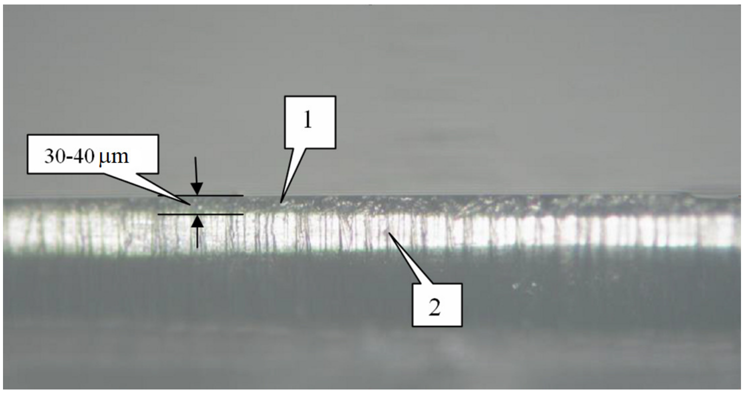


Fig. 1. The surface layer of sheet glass with cracks:
1 – surface layer microcracks; 2 – traces of macrocrack stoppage on the fracture surface of a glass sample during bend testing [6]

Reducing surface layer defects by mechanical treatment [7] and etching [8], as well as creating residual compressive stresses, which block the development of defects in the surface layer due to heat treatment and ion exchange (IE), are effective methods for increasing the strength of glass [9–12].

At present, in practice, the method of chemical strengthening based on IE as an alternative to thermal strengthening is being used increasingly. The method consists in displacing sodium ions by potassium or lithium ions in a thin surface layer of glass and creating compressive stresses in this zone. On the surface, they reach their maximum values and quickly decrease in thickness. These compressive residual stresses close surface cracks by contacting their faces [13, 14]. The patterns of the distribution of residual stresses for ionic and thermal strengthening processes are significantly different, which leads to a different level of increase in the strength of the samples, changing the fracture pattern. The magnitude of the residual compressive stresses in applying IE is significantly higher than the analogous values for thermal strengthening, and the depth of the layer with residual compressive stresses is much smaller. Fig. 2 shows a schematic representation of the indepth distribution of compressive stresses for strengthened float glass through the use of thermal and chemical strengthening [6]. The depth of the layer with residual compressive stresses in strengthened glass (solid parabolic curve) is about 21% of the glass thickness. The depth of this layer for ion exchanged glass (dashed line) is much smaller, and, depending on the strengthening mode, is 20–100 μm. The maximum residual tensile stresses in the inner layers of thermally strengthened glass are about 50% of the maximum level of compressive stresses on the surface. In strengthened glass, they reach 50–70 MPa, which, when structural elements collapse, lead to the formation of small fragments and a significant loss of the bearing capacity of structures. Residual tensile stresses in the inner layers of glass, which correspond to residual compressive stresses in the surface layers for ion exchanged glass, are much smaller, about 20 MPa. As a result, at the level of ultimate tensile and bending stresses characteristic of thermally strengthened glass, the fragmentation of the elements made of chemically strengthened glass during their brittle fracture is characterized by a significantly larger size of fragments, commensurate with those for elements made of unstrengthened float glass. Under local static and shock loading by solids, the fracture pattern of the surface of ion exchanged glass is also close to unstrengthened glass, which makes it possible to perform the cutting and mechanical processing of structural elements.

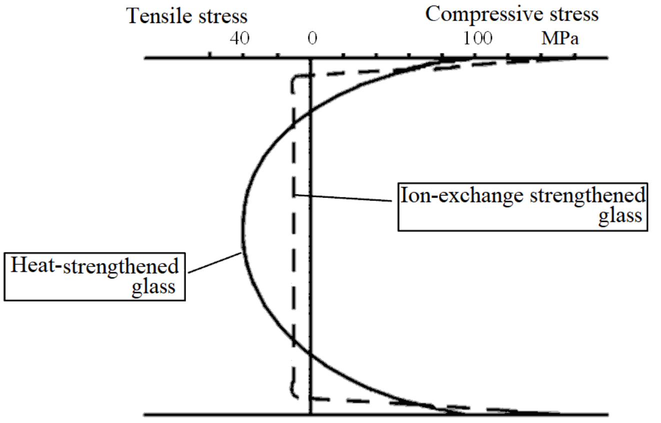


Fig. 2. Schematic representation of the in-depth distribution of compressive stresses for thermally and chemically strengthened float glass [6]

In the ASTM C 1422–99 standard [15], ion exchanged glass is classified according to two independent characteristics: residual compressive stresses and the depth of the strengthened layer. The document distinguishes five classes of glass by the stress level (with residual compressive stresses σ_{res} in the range from 7 to 172 MPa for class 1, and σ_{res}>690 MPa for class 5) and six classes depending on the depth of the strengthened layer (on the value less than 50 μm for class A and more than 500 μm for class F).

To determine the ultimate strength of strengthened glass σ_s, two averaged parameters are most often used: the ultimate strength of glass in the initial state σ_0 and the level of residual compressive stresses σ_{res} [16]

$$\sigma_s = \sigma_0 + k\sigma_{res} ,$$

where k is an empirical coefficient, which in most cases is determined experimentally.

The influence of ion exchange on the strength of glass, depending on the depth and intensity of the creation of residual stresses, has not been sufficiently studied, which is why the issues of the IE strengthening of glass are important and urgent.

Formulation of the Problem

As an example, consider a 5 mm thick sheet silicate glass sample with a surface defect and study the effect of IE strengthening on the overall increase in glass strength.

For a small surface crack of depth a, the stress intensity factor at the crack tip can be calculated from the relation [17]

$$K_I = 1{,}99\sigma\sqrt{a} , \qquad (1)$$

where σ is tensile stresses.

Let us assume that unstrengthened silicate glass is destroyed at a stress of 35.5 MPa, which practically coincides with the average strength of the silicate glass of such a thickness. For glass with K_{IC}=0.5 MPa$\sqrt{\text{m}}$, the critical depth of a surface crack, which leads to catastrophic fracture, is, according to (1), 50 μm.

The stress-strain state of glass during bending is determined using the results of solving the problem of the theory of elasticity for the case of plane deformation [18]. To simulate the fracture toughness of IE strengthened glass by the finite element method, we select, in the Cartesian coordinate system $r0z$, a rectangular region $0<r<0.35$ mm, -0.001 mm$<z<0.25$ mm . A surface crack with a tip at point B with a depth of 50 μm is located along the r axis (Fig. 3).

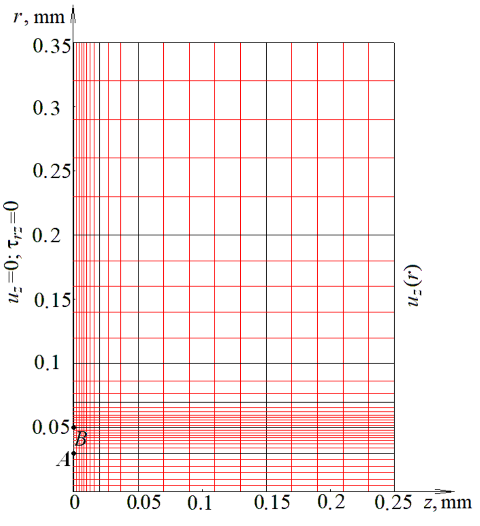


Fig. 3. Design scheme

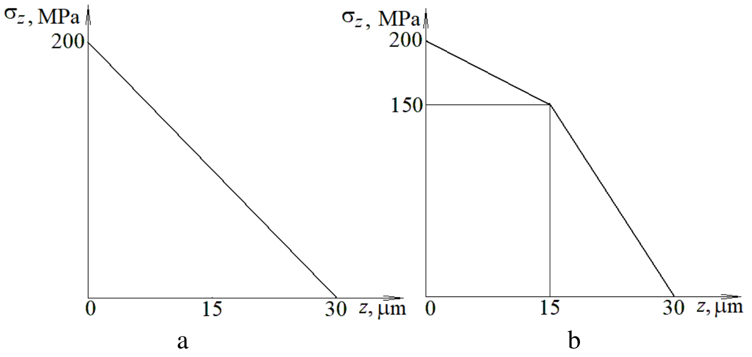
The neutral plane during the bending of a sheet is described by the equation r=0.25 mm. The side of the region z=0.25 mm moves in the direction of the z axis along the normal line to the neutral plane: $u_z(0.25)=0$; $u_z(0)=0.0013\times P$ (mm), where the loading parameter P takes the values 1, 2, 3. Characteristics of the glass material are the following: specific weight $\rho=2.52$ g/cm^3, elastic modulus E=68 GPa, Poisson's ratio $\nu=0.22$, coefficient of linear thermal expansion $\alpha=1.14\cdot10^{-5}$, used to simulate residual stresses through the use of thermal deformations $\varepsilon_T(r)=\alpha\cdot T(r)$.

On the side $z=-0.001$ mm, the boundary conditions of symmetry are set as $u_z=0$; $\tau_{rz}=0$. The compressive stresses of $\sigma_z=\dfrac{\alpha ET}{1-\nu}=200$ MPa, which are the result of the IE strengthening of the surface layer, at a depth of 30 µm at point A (Fig. 3) fall to zero, providing contact of surface crack faces. The OB segment in the figure corresponds to the depth of the initial crack, and OA corresponds to the compressive-stress action region, where a partial contact of the crack faces is possible. To simulate this phenomenon, 6 contact elements are introduced in the OA region.

Key Research Findings

A simplified description of the regularity of the in-depth variation of compressive stresses is used in this work (Fig. 4), since in IE strengthened glass the thickness of the layer to which these stresses are propagated is very small (30 µm). Both linear (Fig. 4, a) and bilinear (Fig. 4, b) (approximately describing the parabolic law of distribution in the compression region) approximations are used.

With the loading parameter P=1, the bending stresses σ_{bend} on the surface of unstrengthened glass are approximately 35.5 MPa, with P=2 – σ_{bend}=71 MPa.



a b

Fig. 4. Regularity of distribution of residual stresses:
a – linear approximation; b – bilinear approximation

Discretization of the sample under consideration into finite elements is shown in figure 3, and in the crack region, in figure 5. The size of the finite elements in the crack tip region is 2 µm. The stress intensity factor can be estimated by the relation [17]

$$K_{\mathrm{I}i}=\sigma_z\sqrt{2\pi r_i}\,, \tag{2}$$

where r_i is the distance from the crack tip to the centers of the finite elements that are on the crack extension. With the discretization under consideration, r_i = 1, 3, 5, 7, 9 µm.

A sharp decrease in stresses is observed on the first few finite elements from the crack tip. That is why, in practice, to calculate the stress intensity factor, the calculations use the results obtained for the third and fourth finite elements from the crack tip, while the stress intensity factors are averaged [19].

Table 1 shows the results of calculations of the stresses σ_{zi}, the stress intensity factor K_{I} obtained from relation (2), as well as the value of the crack half-opening on the surface in unstrengthened glass (without the IE strengthening of the glass). Here, σ_{z1}, σ_{z2}, σ_{z3}, σ_{z4} are the stresses σ_z in the first – fourth finite elements from the crack tip (point B). The results show that for unstrengthened glass, the stress intensity factor K_{I} at P=1 slightly exceeds the value of 0.5 MPa $\sqrt{\text{m}}$ taken as the critical limiting value, which is explained by the error in the calculations of the finite element method. Analyzing the results obtained, we can conclude that loading with the parameter P=1 is practically the highest loading that unstrengthened glass can withstand.

For IE strengthened glass, the calculation results are given in table 2. The numerator contains the values obtained for the linear law of distribution of compressive stresses during the IE strengthening of glass, and the denominator, for the bilinear one. The sixth column of the table shows the stress intensity factor at the crack tip; the seventh one, the value of the contact compressive stresses of the crack faces on the surface r=0; and the last one, the size of the contact zone of the crack faces.

The results obtained show that with an increase in the loading parameter the stress intensity factor at the crack tip increases, and the length of the contact zone of the crack faces decreases. In the case of a linear law of distribution of compressive stresses at P=3, there is no contact of the crack faces. With a bilinear law of distribution of compressive stresses, the contacting zone of the crack faces is somewhat larger, and the stress intensity factor at the crack tip is smaller. The loading parameter at which the stress intensity factor reaches the critical value K_I=K_{IC}=0.5 MPa $\sqrt{\text{m}}$ in the case of a linear distribution of compressive stresses, P=1.65, and of a bilinear one, P=1.7.

With the value of the loading parameter P=3 and the linear law of distribution of compressive residual stresses, there is no contact of the crack faces, and the half-opening of the faces on the surface $u_z(0)$=0.0684 μm. Thus, during IE strengthening, the crack faces are partially in contact, and in the absence of contact, the opening of the crack faces is significantly reduced. However, in IE strengthened glass with a crack depth of 50 μm, its fracture occurs earlier than the opening of the crack faces on the glass surface is achieved.

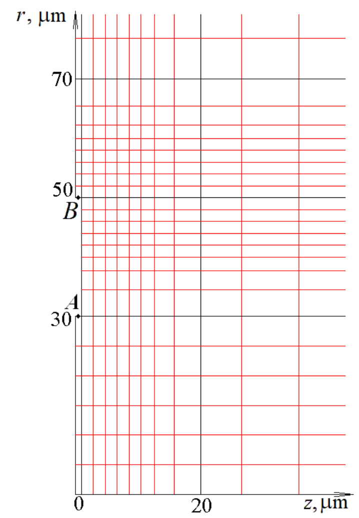


Fig. 5. Discretization of the domain into finite elements in the crack region

Table 1. Calculation results for unstrengthened glass

Type of loading	σ_{z1}, MPa	σ_{z2}, MPa	σ_{z3}, MPa	σ_{z4}, MPa	K_I, MPa $\sqrt{\text{m}}$	Half-opening of the crack faces on the surface (r=0) u_z, μm
P=1	258.4	115.8	91.5	77.8	0.514	0.0695
P=2	510.9	231.6	183.0	155.6	1.029	0.1391
P=3	775.3	347.4	274.5	233.4	1.543	0.2087

Table 2. Calculation results for IE strengthened glass

Loading parameter	σ_{z1}, MPa	σ_{z2}, MPa	σ_{z3}, MPa	σ_{z4}, MPa	K_I, MPa $\sqrt{\text{m}}$	σ_z (r=0), MPa	Contact of the crack faces
P=1	118.8	56.5	49.1	44.8	0.271	-27.1	z<24 μm
	110.6	53.1	46.6	42.9	0.244	-30.2	z<27 μm
P=2	282.8	132.4	111.9	100.2	0.612	-17.3	z<15 μm
	262.6	124.1	105.9	95.6	0.614	-21.3	z<20 μm
P=3	497.1	229.4	189.9	167.5	1.087	0	–
	439.4	205.2	172.5	154.0	0.994	-10.1	z<11 μm

Conclusions

The computational studies of the crack resistance of sheet glass, which is strengthened by ion exchange under bending strains, have been carried out using a software package developed in the Department of Vibration and Thermal Strength Research of A. M. Pidhornyi Institute of Mechanical Engineering Problems (National Academy of Sciences of Ukraine), using the finite element method, to study the thermally stressed state of structures. The results obtained showed that the fracture of real sheet glass due to tensile stresses during bending is determined by surface defects. With an increase in residual stresses and the depth of their distribution, the effect of IE treatment increases. The depth of surface cracks, based on the real strength of sheet glass, 35.7 MPa, reaches approximately 50 μm, which exceeds the thickness of the layer of compressive stresses that ensure contact of the crack faces. If the depth of the zone of compressive stresses from IE strengthening is much smaller than the depth of the surface crack, the strength of glass depends little on the maximum compressive stresses on the surface. The effect of IE strengthening increases significantly in the case of a decrease in the depth of the surface crack.

Since the residual stresses during IE strengthening are significantly inhomogeneous, the real values of the intensity factors K_{IC} for glass have a significant scatter. The results obtained require further research and refinement by comparison with experimental data.

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Чисельні дослідження тріщиностійкості іонозміцненного листового скла, при згинних деформаціях

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Безпека надійної експлуатації літальних апаратів і їх довговічність істотно залежать від міцності скління, яке є відповідальним конструкційним елементом. До скління висувається цілий ряд різних вимог. Для забезпечення необхідних параметрів широко використовується високоміцне силікатне скло та застосовуються спеціальні технології його зміцнення. Аналіз проблеми показав, що недостатня міцність елементів авіаційного скління й складність методів контролю стану скла при виробництві й експлуатації внаслідок наявності поверхневих дефектів мікроскопічних розмірів, а також необхідність достовірної оцінки залишкових напружень потребують застосування нових підходів і технічних рішень для розвитку сучасних технологій створення конструкцій. Іонний обмін є одним з механізмів зміцнення скла, який дозволяє зменшити негативний вплив поверхневих дефектів за рахунок штучного створення залишкових стискаючих напружень і зменшення товщини ушкодженого шару. Проведено розрахункові дослідження тріщиностійкості іонозміцненого листового скла при згинних деформаціях із застосуванням власного пакета програм, розробленого на основі методу скінченних елементів та призначеного для дослідження термонапруженого стану конструкцій. Отримані результати показали, що міцність руйнування реального листового скла від розтягуючих напружень при згині визначається тріщиноподібними поверхневими дефектами. Створення залишкових стискаючих напружень на поверхні скла шляхом іонообмінного зміцнення забезпечує збільшення міцності при згинанні. При зростанні залишкових напружень та глибини їх розподілу ефект від іонообмінної обробки збільшується. Якщо глибина зони стискаючих напружень від іонного зміцнення значно менше глибини поверхневої тріщини, міцність скла мало залежить від максимальних стискаючих напружень на поверхні. Ефект від іонного зміцнення суттєво зростає у випадку зменшення глибини поверхневої тріщини. Показана доцільність проведення подальших досліджень і порівняння результатів розрахунків з експериментальними даними. Розроблена методика дозволить розв'язувати важливі практичні задачі дослідження міцності багатошарового скління літальних апаратів і визначення оптимальних методів усунення їх дефектів.

***Ключові слова**: літальні апарати, силікатне скло, напружений стан, міцність, залишкові напруження, іонний обмін, дефекти поверхневого шару.*

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CONTACT INTERACTION OF STEAM TURBINE INNER CASING ELEMENTS DURING PLASTIC DEFORMATION

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A structure's material plasticity influence on the pattern of contact interaction of its elements during operation is studied. The stress-strain state problem for the inner casing of a steam turbine high-pressure cylinder operating at supercritical steam parameters (over 240 atm and 565 °C) is solved. The problem is solved by using a finite-element software package. A model of thermoplasticity with kinematic and isotropic hardening is considered. In carrying out the study, experimental strain curves were used for the materials of the connection. The main dependencies used in solving the problem are given. The method of solving the thermal contact problem of interaction of flange connector elements in the conditions of plasticity is based on the application of a contact layer model. To be able to take into account changes in the load from the fastening in the process of combined strain of both the fastening and the casing, first proposed is a method of the three-dimensional modeling of the thermal tightening of the fastening of the horizontal casing connector by applying the linear coefficient of linear expansion of the material. The proposed approach allows modeling the stress of the initial tightening of studs by specifying a fictitious change (decrease) of the coefficient of linear expansion of a stud given as a separate body in the calculation scheme. The magnitude of the specified change in the coefficient of linear expansion is determined from the relationship between the stress of the initial tightening in the stud and the required, for its creation, elongation, which is implemented in the calculation scheme in the presence of different values of linear expansion of both the stud and the casing. To conduct the numerical experiment, an ordered finite-element grid of the casing design was constructed. A 20-node finite element was used in the construction of the casing grid and the fastening. The effect of force loads and the temperature field, in which the structural element under consideration is operated, is taken into account. An analysis of the results of distribution of equivalent stresses and contact pressure during operation is carried out. The difference between the obtained results and the results of solving the problem in the elastic formulation is noted.

Keywords: *turbine, flange connector, casing, stress state, contact interaction, plasticity.*
