Original Russian Text: Zenkov E.V., Tsvik L.B. Formation of divergent testing efforts and experimental evaluation of material strength under biaxial stretching. *PNRPU Mechanics Bulletin*, 2015, no. 4, pp. 110-120. DOI: 10.15593/perm.mech/2015.4.07

PNRPU MECHANICS BULLETIN

№ 1-2, 2018

http://vestnik.pstu.ru/mechanics/about/inf/

DOI: 10.15593/perm.mech/eng.2018.1.09
UDC 629.4.015

THE FORMATION OF DIFFERENTLY DIRECTED TEST FORCES AND EXPERIMENTAL EVALUATION OF MATERIAL STRENGTH UNDER BIAXIAL STRETCHING

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ARTICLE INFO

Received: 16.07.2015
Accepted: 13.10.2015
Published: 30.06.2018

Keywords:

laboratory sample, differently directed forces, single-drive machine, contact reaction, finite element method, strength parameters, biaxial stretching, structural strength, modeling, strength criterion, stress-strain state

ABSTRACT

This article suggests a method intended to form differently directed test forces while conducting mechanical tests of laboratory material samples with the use of a standard single-drive testing machine. The method in question allows to generate a mentioned system of forces affecting a sample by using the sample's inclined edges and their contact reactions when it interacts with a prismatic support that has corresponding bevels. The article considers a diagram that is intended to support and load a prismatic sample and carries out the test force formation in question. It also gives reasons for choosing angles of the sample's inclined edges on the basis of design modeling of deformation of its model with the use of a numerical finite element method apparatus and resolution of a contact problem of a deformable solid body. The authors give recommendations on how to practically use optimal inclination angles of supporting surfaces in order to create a biaxial stretching diagram. The article provides the results of a design analysis of prismatic samples' strain-stress state depending on its main geometrical parameters. It also describes the approbation of the samples in question while determining strength parameters of tempered spring steel 50HFA being under biaxial stretching. The results obtained from destructing the samples are analyzed on the basis of the Pisarenko-Lebedev limit state equation. The parameters in question are determined on the basis of numerical analysis of the tested sample sets' strain-stress state at the time of their destruction. The conducted analysis considered a contact interaction of the sample with supporting elements and possible appearance of plastic deformations in the sample material. The authors give their experimental evaluation of a reduced limit value of the first main stress in the seat of destruction of the 50HFA steel samples under biaxial stretching as compared to the uniaxial one.

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Introduction

Structural strengths of machine parts should be occasionally evaluated in the context of their stress-strain state (SSS) [1-4]. It is important to consider SSS, for example, while evaluating statical strengths of choke units of pressure vessels, strengths of various parts (plates and shells) bended in two different directions under the effect of temperature drops and in other cases. A number of relevant strength calculation methods [5-10] rely on laboratory sample test results (samples having the same SSS in the seat of destruction as the part in question). For that purpose they usually use testing equipment with several power drives that generate differently directed effects on the sample under test. This paper describes methods intended to use standard single-drive machines and consider the part's SSS properties preliminarily determined [5] with the use of numerical modeling based on the finite element method (FEM).

Further, for definiteness, the Pisarenko-Lebedev equation is used as a limit material state (strength criterion) equation [2, 3]

$$\alpha\sigma_i^{prel} + (1-\alpha)\sigma_1^{prel} A^{1-\Pi} = \sigma_s, \qquad (1)$$

where α and A are empirical constants characterizing material strength and not depending on SSS types and levels in the seat of destruction (hereinafter referred to as “strength parameters”); σ_i is stress intensity

$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2}, \qquad (2)$$

σ_1, σ_2, σ_3 are main stresses, the SSS properties in the seat of possible destruction. Quantity Π [4, 5] in ratio (1) is included as a similarity criterion of the SSS of a part which strength is evaluated, and of the SSS of a working zone of a sample used for mechanical tests

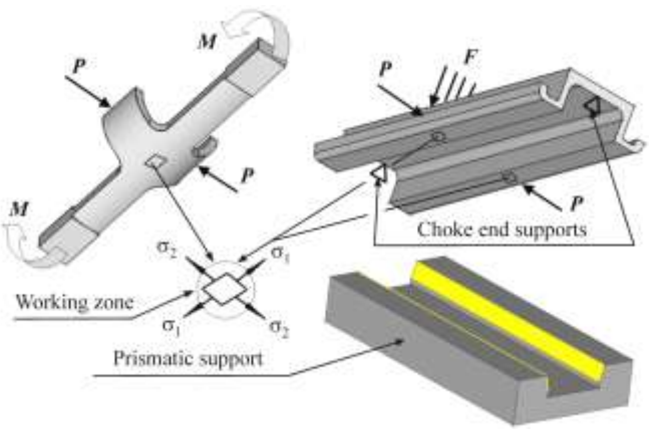
$$\Pi = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_i}. \qquad (3)$$

When criterion (1) is used to determine its strength parameters, they usually use testing machines of absolutely different types or machines with several power drives that can generate differently directed forces affecting the sample [6-9]. This circumstance complicates tests in a considerable way. The choice of quantity Π determined by equation (3) as a SSS property used in general strength criteria [2] is connected with the fact that its value considerably affects the location of the seat of destruction and a quantity of a corresponding limit value of SSS properties [11].

1. Setting a Problem and Methods of Forming Test Forces

The calculation and experimental evaluation of structural element strength [3, 5] that is based on ratio (1) includes destruction tests of chosen samples and the determination of strength parameters in ratio (1) according to the results of such tests.

The possibility of using single-drive testing machines is determined in the methods in question by the fact that necessary differently directed test forces affecting the sample are generated by contact forces [12]. A structural diagram of one of the known samples used for tests with machines of two power drives [6] is given in Fig. 1 *a*. In its working zone biaxial stretching is generated at the time of destruction.



a *b*

Fig. 1. Loading the samples with side ledges, (*a*) transverse forces **P** are generated by the testing machine's drive, (*b*) transverse forces **P** are contact reactions taking place on the sample's inclined supporting surfaces

This diagram shows that one of the test forces, i.e. force **P**, can be generated by a reaction that affects the sample under test, if its side ledges are placed on a corresponding prismatic support with bevels (Fig. 1, *b*).

The prismatic sample support and load diagram that implements this principle is presented in Fig. 1, *b*, its geometrical parameters are given in Fig. 2, *a*, the corresponding calculation model is given in Fig. 3.

The structural features of the prismatic sample in question are inclined supporting surfaces necessary for forming differently directed test forces. The sample’s serviceability requires some limitations of the angles of deviation of the mentioned surfaces from the vertical (angles γ in Fig. 2). In these circumstances angles γ are acceptable, if the contact interaction ensures a condition where in a contact zone the forces of this interaction are beyond the limits of a corresponding friction cone [13]. In case of small values of the coefficient of friction between the contacting surfaces the mentioned condition is executed with quite small values of γ.

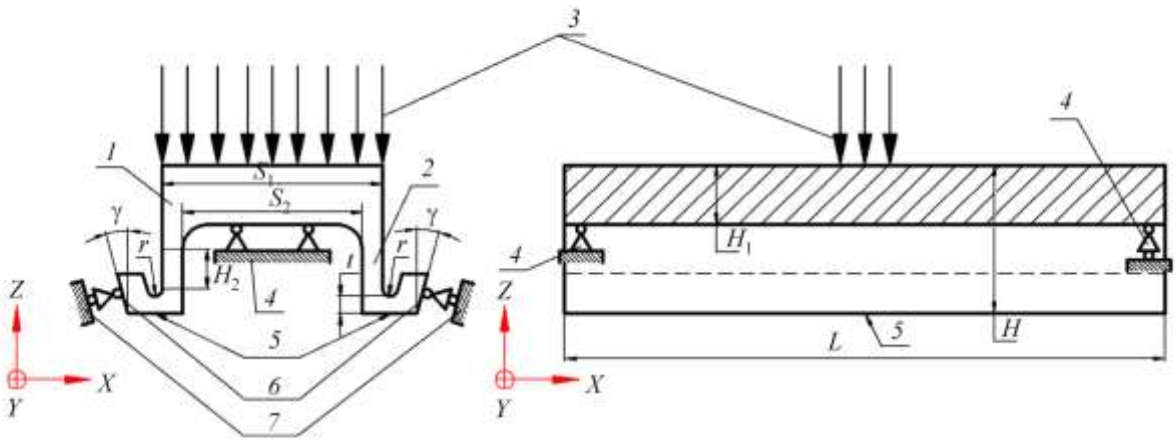


Fig. 2. Geometrical parameters and loading the sample with inclined supporting surfaces, *1* – sample, *2* – side ledges, *3* – force generated by the testing machine's pusher, *4* – end supports, *5* – working zone, *6* – sample's inclined surfaces, *7* – prismatic support's inclined surfaces

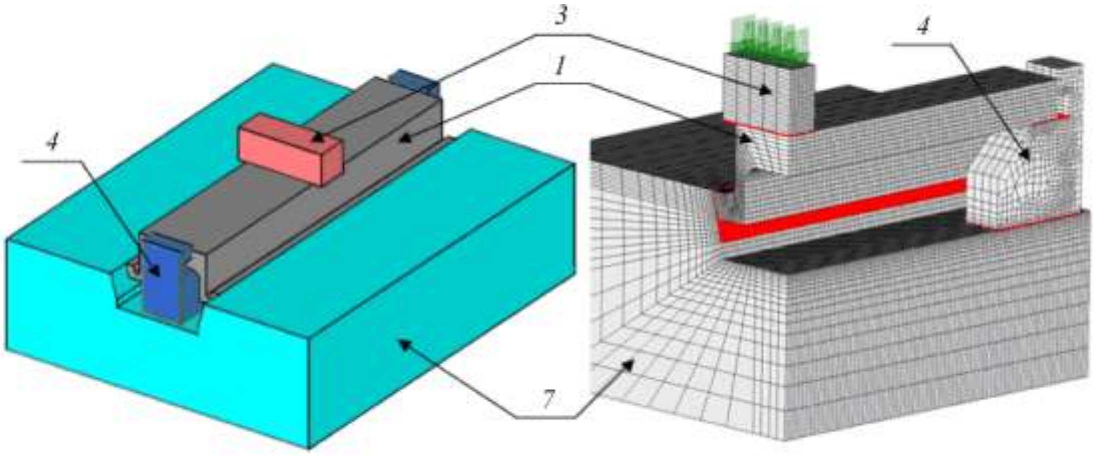


Fig. 3. Implementing the prismatic sample load diagram. (*a*) is the type of a full geometrical model, (*b*) is the design FE-model used for variational studies (part numbers correspond to Fig. 2)

2. Calculation Studies

In order to evaluate the effect of the size of angle γ and of the contact friction forces on the SSS in the sample's working zone, we conducted an evaluation of the mentioned SSS with the use of the FEM. The finite-element (FE) models of the contacting bodies were formed with the use of the MSC.PATRAN software system. While conducting the numerical analysis, we carried out FE discretization for both the sample and its supporting elements. Due to the sample's symmetry with regard to longitudinal and transverse planes, for the design modeling of the contact interaction with the supports, we considered its quarter with the establishment of the corresponding boundary conditions (Fig. 3, *b*). In the zones where the sample contacted the support, during the modeling we used the grid matching method and the necessary concentration of FE decomposition as a contact surface comes closer (Fig. 3, *b*). The similarity of the obtained FE solutions to those sought for was evaluated on the basis of the sequence of the concentrated decompositions with a subsequent halving of the maximum sizes of the used finite elements with regard to each of coordinate directions [5]. A contact interaction problem was solved with the use of the MSC.NASTRAN solver and the Coulomb bilinear friction model [14].

For the purpose of design evaluation of the effect of the size of angle γ, they chose a variant of structural design of the sample with the following geometrical properties: sample's length in longitudinal direction L = 220 mm (Fig. 2), its height H = 30 mm, thickness S_1 = 44 mm, S_2 = 36 mm, t = 4 mm. The prismatic support was then characterized by the following values: length in longitudinal direction L_{on} = 250 mm, height H_{on} = 70 mm, thickness S_{on} = 200 mm. The size of angle γ

$$0° \le \gamma \le 20° \quad (4)$$

changed while conducting the variational studies with the pace of 5°. While conducting the design modeling, it was assumed that the sample and the support are made of steel for which the Young modulus is E = 210.000 MPa and the Poisson ratio is ν = 0.3. The friction coefficient value was taken as equal to 0.2, which corresponds to [13] friction with regard to smooth steel surfaces (roughness parameter Ra = 1.25). Fig. 4 shows the cross (for the prismatic sample) section of the discrete model of the contact zone.

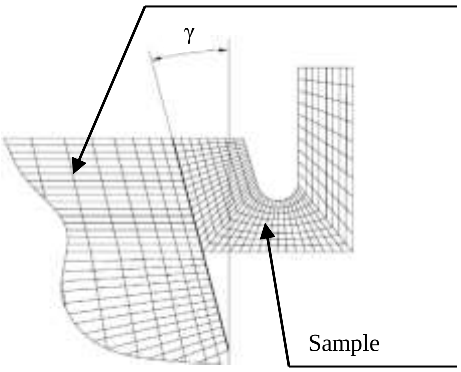


Fig. 4. Discrete model of the contact zone

The computational experiment results show that when angle γ has values not exceeding 20^0, the consideration of friction forces changes both values of the maximum contact pressures on the contact surfaces, and a maximum value of stress intensity in the working zone of the samples in question is by no more than 5 %.

In order to evaluate the applicability of prismatic samples when determining parameters α and A included in equation (1), we carried out a design analysis of their SSS depending upon main geometrical parameters [5]. Fig. 5 gives the results of calculation of quantity Π for values L = 220 mm, S_1 = 44 mm, S_2 = 36 mm, t = 4 mm, h_1 = 0.25, $h_2 \in [0; 0.28]$, $\rho \in [0.03; 0.06]$ and angle $\gamma = 15^0$, where

$$h_1 = \frac{H_1}{S_1} \in [0.25; 0.4];\; h_2 = \frac{H_2}{S_1} \in [0; 0.28]; \quad \rho = \frac{r}{S_1} \in [0.03; 0.06]. \tag{5}$$

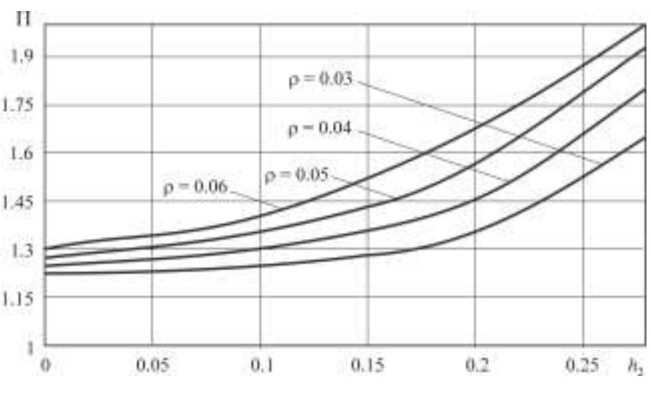
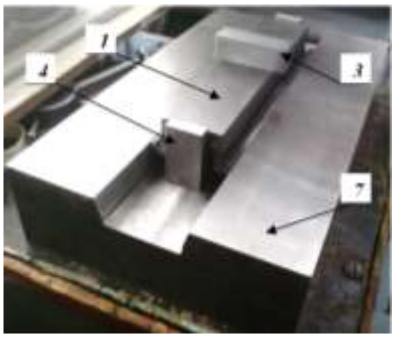


Fig. 5. Dependence of quantity Π on the value of the geometrical parameters of prismatic samples ρ and h_2

It follows that an increase in h_2 leads to an increase in value Π up to a maximum possible one under biaxial stretching of value Π = 2. The analysis of these and similar dependences shows that for any SSS of a structural element with the known value Π that works under biaxial stretching, it is always possible to choose one or several samples of types in question that model the type of this SSS with the same value Π.

3. Experimental Study Results

A special [1] machine allowed to experimentally study a decrease in value $\sigma_1^{пред}$ under biaxial stretching; the samples of relatively plastic steel 12X18H10T were destructed. So, it turned out that value $\sigma_1^{пред}$ in the seat of destruction decreased by more than 25 %, as compared to this material's traditional strength limit determined under uniaxial stretching. The sample presented in [12] can be used to study strength properties of various materials in similar situations. For example, it is interesting to study behaviors towards more brittle steels. For this purpose, this work allowed to carry out a destruction test (Fig. 6) of the samples made of tempered spring steel 50HFA and being



a

b

Fig. 6. Laboratory machine for testing prismatic samples: (*a*) positioning the sample in the prismatic support (part numbers correspond to Fig. 2), (*b*) positioning the prismatic support with the sample using the Instron 5989 single-drive testing machine's working table

under biaxial stretching dring the test. The standard round samples of this steel under uniaxial stretching were destructed. Their results show that steel is characterized by yield limit values $\sigma_y = 1{,}050$ MPa, strength limit $\sigma_s = 1{,}300$ MPa and relative elongation δ = 7.5 %. The diagram presented in Fig. 2 allowed to make two sets of samples (No. 1 and No. 2), three samples in each set. The sample sizes (see Table 1) were selected, so that in the working zone their SSS was characterized by value Π close to 1.9, which is typical, for example, of rectangular plates hingedly supported along four sides and loaded by uniform pressure.

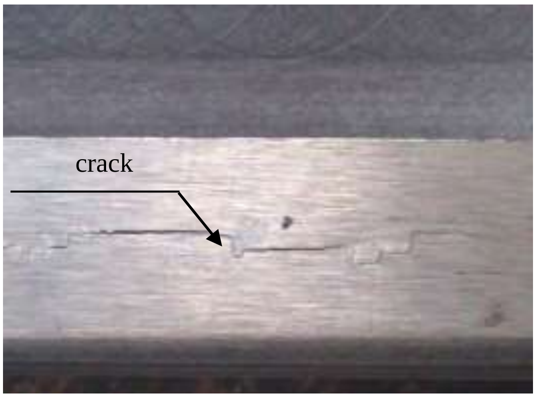
Table 1

Main sizes of experimental prismatic samples

H, mm	H_1, mm	H_2, mm	H_3, mm	S, mm	L, mm	t, mm No. 1/No. 2	r, mm	γ, deg
33	12	11	21	44	220	4/6	2	15

In order to evaluate the accuracy of the design diagram presented in Fig. 2, we compared the experimental deformation values for the first sample set and the corresponding design values in control points of the sample's side surface with the use of the digital image correlation method [15-17]. The comparison shows that their difference does not exceed 10 % [16].

Experimental destruction stages of one of the tested samples are given in Fig. 7.



a

b

Fig. 7. Initial crack and destructed prismatic sample, (*a*) crack appearing within the working zone, (*b*) destructed sample

The results obtained during the sample destruction were interpreted on the basis of the limit state equation (1) that was considered as an empirical formula, which coefficients α and A are determined according to the results of destruction of the laboratory samples, whose working zone is characterized by a certain value of quantity Π determined by the tested samples' structural features. In order to determine the values of the two mentioned coefficients, it is necessary to preliminarily destruct two structural variants of samples differing from each other by sizes and corresponding values of quantities $\sigma_i^{1\,prel}$, $\sigma_1^{1\,prel}$ and $\sigma_i^{2\,prel}$, $\sigma_1^{2\,prel}$, but identical (or close) by the value of coefficient Π in their working zones. In this case equations of type (1) corresponding to the two chosen structural variants form a system of algebraic equations that was solved in the case in question by the successive approximations method.

The prismatic samples whose sizes for sets No. 1 and No. 2 are given in Table 1 were destructed with the use of the Instron 5989 single-drive testing machine (Fig. 6, *b*). Forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ (in Fig. 1, $\boldsymbol{F}$ forces) applied from the testing machine's pusher to the tested samples of the first and second sets accordingly, at the time of destruction (according to the results of averaging of the experimental data for the three tested samples in each set), amounted to:

$$\boldsymbol{F}_1 = 205 \text{ kN}; \boldsymbol{F}_2 = 235 \text{ kN}. \quad (6)$$

A relative root-mean-square deviation of the mentioned values for both sets does not exceed 5 %. The obtained values of $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ forces were used as initial quantities for the numerical analysis of the samples' SSS at the time of their destruction. The mentioned analysis was carried out by the finite element method with the consideration of the fact that elastic-plastic deformations could take place in the sample material. And plastic flow equations with isotropic hardening (the Prandtl-Reuss equations [18]) are used as a mathematical model of the development of elastic-plastic deformations.

Table 2 provides the design data obtained on the basis of the experimentally established values of $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ forces and corresponding to the time immediately preceding the destruction. They allowed, by using the limit state equation (1), to determine the values of strength parameters α and A (the values included in these equations) for steel 50HFA. The corresponding calculation shows that they are determined by equations:

$$\alpha = 0.73; \; A = 0.40. \quad (7)$$

Table 2

Calculation SSS properties in the seat of destruction of the tested samples

Set No.	σ_1, MPa	σ_2, MPa	σ_i, MPa	Π
1	985	743	892	1.9
2	1,050	615	917	1.8

The obtained values fully determine strength parameters of the steel in question included in the equation (1) and allow to analyze and stress structural elements made of the same steel, which are characterized by equation $\Pi \approx 1.85$ in their critical sections.

Conclusions

Prismatic laboratory samples that are intended for destruction tests and have side inclined supporting surfaces resting on the corresponding prismatic supports and tested using a standard single-drive machine, during their loading, they are subject to the effect of differently directed forces causing biaxial stretching in these samples' working zone. This allows to simplify sample tests under such stretching, if not using the testing machines with several same-type or principally different power drives and considering the real SSS of a structural element whose strength is evaluated at the stage of laboratory studies.

The experimental approbation of the prismatic samples in question made of tempered spring steel 50HFA confirms their applicability for studying strength properties of materials under biaxial stretching. This allowed, for example, to establish that for the mentioned relatively brittle steel the limit value of the first main stress σ_1 under biaxial stretching with the coefficient of the type of stress state $\Pi = 1.85$ is considerably (almost by quarter) less than its strength limit $\sigma_в$ determined under uniaxial stretching.

References

1. Vilimok Ia.A., Nazarov K.A, Evdokimov A.K. Napriazhennoe sostoianie i prochnost' ploskikh obraztsov pri odnoosnom i dvukhosnom rastiazhenii [Intense condition and strength of flat specimens under uniaxial and biaxial tension] // Izvestiia TulGU. Tekhnicheskie nauki. 2013, No. 11, pp. 388-393.

2. Pisarenko G.S., Iakovlev A.P., Matveev V.V. Spravochnik po soprotivleniiu materialov – Kiev. [Handbook of resistance of materials]: Izd-vo Del'ta, 2008, 816 p.

3. Mekhanicheskie svoistva konstruktsionnykh materialov pri slozhnom napriazhennom sostoianii [The mechanical properties of structural materials under complex stress state] / A.A. Lebedev, B.I Koval'chuk [i dr.] // Pod red. A.A. Lebedeva. Kiev: Izd-vo Dom «In Iure»2003, 540 p.

4. Kogaev V.P., Makhutov N.A., Gusenkov A.P. Raschety detalei mashin i konstruktsii na prochnost' i dolgovechnost' [The calculations of machine parts and structures for strength and durability]. M.: Mashinostroenie, 1985, 224 p.

5. Tsvik L.B. Zen'kov E.V. Opredelenie prochnostnykh kharakteristik materialov eksperimental'nykh prizmaticheskikh obraztsov pri dvukhosnom rastiazhenii [Determining the strength characteristics of materials prismatic samples with experimental biaxial stretching] // Vestnik mashinostroeniia, 2015, No. 1, pp. 42-46.

6. Esiev T.S., Basiev K.D., Steklov O.I. Obrazets dlia ispytaniia metalla pri dvukhosnom napriazhennom sostoianii [The test piece of metal under biaxial stress state] // Patent RF № 2073842. – Opubl. 20.02.1997, Biulleten' izobretenii RF, 1997, No. 7.

7. Vansovich K.A., Iadrov V.I. Ustalostnye ispytaniia stal'nykh krestoobraznykh obraztsov s treshchinoi pri dvukhosnom nagruzhenii [Fatigue testing of steel cruciform specimens with a crack under biaxial loading] // Omskii nauchnyi vestnik 2012, No. 3, pp. 117-122.

8. Vansovich K.A., Iadrov V.I. Eksperimental'noe izuchenie skorosti rosta poverkhnostnykh treshchin v aliuminievom splave AK6 i v stali 20 pri dvukhosnom nagruzhenii [Experimental study of the rate of growth of surface cracks in the aluminum alloy and steel AK6 20 under biaxial loading] // Izvestiia Samarskogo nauchnogo tsentra Rossiiskoi akademii nauk, 2013, No. 4, pp. 436-438.

9. O vliianii kharaktera napriazhennogo sostoianiia na plastichnost' i razrushenie konstruktsionnykh stalei [On the influence of the nature of the stress state on the ductility and fracture of structural steel] / Iu.A Gagarin [i dr.] // Problemy prochnosti, 1978, No. 6, pp. 70-75.

10. Vazhentsev O.G. Prizmaticheskii obrazets dlia otsenki mekhanicheskikh svoistv materiala [Prismatic sample for evaluation of mechanical properties of materials] // Opisanie izobreteniia k avtorskomu svidetel'stvu SSSR № 1793320 A1, kl. G 01 N3/28. – Opubl. 07.02.93g. Biull. No. 5.

11. Ukreplenie otverstii i staticheskaia prochnost' osesimmetrichnykh shtutsernykh uzlov [Strengthening holes and static strength of axially symmetric choke assemblies] / L.B. Tsvik [i dr.] // Problemy mashinostroeniia i nadezhnosti mashin. 1993, No.1, pp. 58-65.

12. Zen'kov E.V., Tsvik L.B., Zapol'skii D.V. Prizmaticheskii obrazets dlia otsenki prochnosti materiala [Prismatic sample to estimate the strength of the material] // Patent RF № 2516599. – Opubl. 27.03.2014, Biulleten' izobretenii RF., 2014, No. 9.

13. Targ S.M. Kratkii kurs teoreticheskoi mekhaniki [A short course of theoretical mechanics.]. M.: Visshaya shkola, 1986, 416 p.

14. Galin L.A. Kontaktnye zadachi teorii uprugosti i viazkouprugosti. [Contact problems of the theory of elasticity and viscoelasticity] – M.: Nauka, 1980, 304 p.

15. Zenkov E.V., Andreev A.A. Metodika eksperimentalnogo issledovania polei deformaciy na osnove ispolzovania cifrovoi opticheskoi sistemi [Methods of experimental study of deformation fields through the use of digital optical system]. Problemi transporta Vostochnoi Sibiri: sbornik nauchnih trudov IV Vserossiskoi nauchno-prakticheskoi konferencii IrGUPS [Problems of transport of Eastern Siberia: Proceedings of the IV All-Russian scientific-practical conference IrGUPS]. Irkutsk, 2013, Ch. 1, pp. 95-99.

16. Zen'kov E.V., Tsvik L.B. Raschetno-eksperimental'naia otsenka napriazhenno-deformirovannogo sostoianiia laboratornogo obraztsa s galtel'nym [Calculation-experimental evaluation of the stress-strain state of the laboratory sample to fillet] // Vestnik IrGTU. Irkutsk, 2013, No. 9, pp. 70-78.

17. Sutton M.A., J.-J.Orteu, H.Schreier. Image Correlation for Shape, Motion and Deformation Measurements // University of South Carolina, Columbia, SC, USA, 2009. – 364 p.

18. Malinin N.N. Prikladnaia teoriia plastichnosti i polzuchesti [Applied theory of plasticity and creep.]. M.: Mashinostroenie, 1975, 398 p.