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Definition of yield limit of machines details by a contact method

M. Matlin*, S. Lebskiy, E. Kazankina**, V. Kazankin****, D. Manukyan*******
**Volgograd State Technical University, Lenin Ave 28, 400131 Volgograd, Russia, E-mail: matlin@vstu.ru*
***Volgograd State Technical University, Lenin Ave 28, 400131 Volgograd, Russia, E-mail: detmash@vstu.ru*
****Volgograd State Technical University, Lenin Ave 28, 400131 Volgograd, Russia, E-mail: detmash@vstu.ru*
*****Volgograd State Technical University, Lenin Ave 28, 400131 Volgograd, Russia, E-mail: detmash@vstu.ru*
******Volgograd State Technical University, Lenin Ave 28, 400131 Volgograd, Russia, E-mail: detmash@vstu.ru*

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1. Introduction

Nowadays design calculations of the majority of machines details are carried out on a condition of durability which consists that working in dangerous section of stresses σ should be less than allowable σ_{adm}. Thus the working stress σ depends on the sizes of dangerous section and working loadings, and allowable stress σ_{adm} determined as σ_{pl}/n, where σ_{pl} - limiting (or dangerous) stress, and n - safety factor. In this case, even with static loading of threaded connections, calculated factor of safety prescribed is quite large in size, typically in the range 2.5 - 6.7 (depending on steel grade and diameter of the bolt) [1], because they believe that the carving on the surface of the workpiece creates considerable stress concentration. At durability calculation of the details made of plastic materials in conditions of the influence of static loadings, a limiting stress is yield limit $\sigma_{0.2}$ of materials. Standard methods of the definition of yield limit provide test for stretching of the samples made from material of the detail. Such approach causes significant difficulties, as for the control it is necessary to destroy a ready detail for making a sample; if the detail is too small to make a sample from the stretching test is impossible.

For example, in work [2] yield limit of the material of hot water pipelines is shown (experimentally, by stretching of sample, cutting from pipes) to increase after long exploitation. Obviously, water had to be drained, then sample was cut and then pipe was repaired.

In recent years the problem of exploitation of technical objects became increasingly important. Gas pipelines with a lifetime of more than 20 years constitute 43.8% of their total length, 20.2% had exhausted standard lifetime. Oil pipelines have larger lifetime: 73% of the length - more than 20 years and 40.6% employ more than the normative period of 33 years. Therefore there is a necessity to assess the residual life of pipelines to motivate the safety of their exploitation. There is a reduction of plastic and viscous properties of the metal in the long exploitation of trunk pipelines. Reduction of the plastic properties of metal pipes is due to strain aging and may cause a discrepancy of mechanical properties regulatory performance, and in some cases, the cause of brittle fracture of pipelines.

In the exploitation of pipelines plastic and viscous properties of the metal are changed due to strain aging. Plastic and viscous properties of the metal are determined by the ratio of yield limit to tensile strength ($\sigma_{0.2}/\sigma_t$).

One way to assess the residual lifetime of pipeline metal by the ratio ($\sigma_{0.2}/\sigma_t$) is the method proposed in [3]. However, a disadvantage of this method is that the samples for research are made of plates of pipe metal from emergency stock or of the metal subjected to a preliminary heat treatment, which is then subjected to artificial strain aging at different of plastic deformation. A lot of sample's processing slows down the process of assessing the residual life of the pipeline, as well as used for sample preparation pipe is not suitable for further exploitation.

Thus, the problem of nondestructive control of hardware's yield limit is actually. We think that it is advisable to use laws of elastoplastic contact of solid bodies [4, 5] (indenter and testing material of detail). This approach is used, for example, in work [6] for operational definition of steel's impact elasticity and in [7] for research of distribution of stresses and strains in the thick-walled spheres under external pressure.

2. Description of method

In the given work the method of [8] the definition of yield limit by results of elastoplastic introductions of spherical indenter, basing on the laws [4] relating intensity of pressure and deformations in the center of contact platform (spherical indenter and the surface of detail) to the pressure and deformations at monoaxial stretching of the sample, made from the detail's material, is applied. The choice of the indenter sphere due to the fact that ball indentation provides a continuous increase in the degree of strain as it is deepening, it is very important for obtaining of the relationship of hardness with other mechanical properties. It is known, charting the hardness with a conical or pyramidal indenter requires the use of indenters with different angles and at the same time, a spherical indenter can be regarded as an indenter with a variable angle of taper, increasing with increasing depth.

According to this method spherical indenter (a ball with diameter D) is introduced under loading F into the tested surface of a detail. Measuring after unloading diameter d_0 of residual print and a conditional yield limit of the material is calculated by the equation

$$\sigma_Y = \frac{0.955(1-2\nu_2)F}{d_0^2\left[78\left(\frac{d_0}{D}-9.43K_1\frac{F}{d_0^2}\right)(1-2\nu_2)\right]^{245/HD}} \qquad (1)$$

where $K_1 = \left(1-\nu_1^2\right)/\pi E_1$; ν_1 and E_1 are Poisson's ratio and the modulus of elasticity of the indenter material, *HD* is plastic hardness of the material of the detail, determined in accordance with GOST 18835-73; ν_2 is Poisson's ratio of material of a detail.

Eq. (1) is based on the laws of the deformation theory of plasticity, which assumes that under constant external conditions (constant strain rate at atmospheric pressure and room temperature), regardless of the stress-strain state for the material we have a unified deformation curve describing the relationship of the intensity σ_i stress state of the material with the intensity of ε_i its deformed state. At the same time, we specifically performed an experimental study that compared the values of stress intensity $\sigma_{i,0}$ at the center of contact with the values of true stress $S = \sigma_i$, determined by results of tests on samples in tension showed that for identical values of ε_i, values $\sigma_{i,0}$ is somewhat lower than the values *S*; this difference decreases with increasing strength and hardness of the material. Such a situation arises, apparently due to the lack of consideration of the forces of friction in the contact. Meanwhile, it is known that friction in the contact leads to increased pressure in the contact. To match the diagrams of deformation introduced a special correction factor e^{ε_p}, where ε_p is limiting uniform deformation of the test material.

Let's note, that at the control of details which hardness do not exceed 450 MB, spherical indenter of thermally processed steel with hardness not less HV 8500 MPa (for example, the balls usually used in roll bearings) can be used. At test of details of greater hardness it is necessary to use balls or tips from an alloy (for example, from an alloy tungsten carbide such as VK-3) with hardness not less HV 12000 MPa or diamond.

3. Experimental investigations

Experimental check of the Eq. (1) has been executed on the samples from carbon and alloyed steels and also titanic alloys.

Preliminary by stretching test of samples in accordance with GOST 1497-84 a yield limit $\sigma_{0.2,t}$ is determined. Then in flat platform made on the head of a sample tested for fracture, steel spherical indenter with the diameter D = 5 mm was introduced with the help Brinelle's press. Diameter d_0 of residual print was measured on a tool microscope the MIM - 2 and $\sigma_{0.2}$ calculated by Eq. (1). For finding-out of the influence of a degree of loading F/D^2 and sizes of relative diameter d_0/D of residual print on results of calculations under the Eq. (1) special research on steels of various hardness has been made: *HD* from 1236 to 5433 MPa (Table 1). It has shown, that at the change of F/D^2 in a wide range from 74 to 11777 MPa values of $\sigma_{0.2}$ determined with use of Eq. (1), differed no more than on 4% from results of tension test. It allows to realize the described method at the modes of loading, typical for the measurement of hardness on Brinelle *HB* or plastic hardness *HD* when relative diameter of residual print can be in the range $0.2 \le d_0/D \le 0.6$.

In Table 2 the values of $\sigma_{0.2,t}$, obtained by the authors by tension of samples and by introduction spherical indenter ($\sigma_{0.2}$) are compared. Statistical processing of experimental results has shown, that for the investigated materials the average of error distribution of $\sigma_{0.2}$ definition by the described method makes 2.8%, thus with the probability of 90% the greatest error does not exceed 7%.

In Table 3 the results of definition of $\sigma_{0.2}$ are compared with the data of strength experiment, which presented in the work [9] for various steels. Values of plastic hardness *HD*, which are needed for using of Eq. (1), are determined by known analytic relations that determine relationship between *HD* and *HB*. In the table is shown that accuracy of described method does not exceed (4.6)% in most cases.

In this case the scatter of data for various grades of materials received by strength test, fit into the border due to possible fluctuations of Poisson's ratio (0.28-0.32). It should also be born in mind that at strength test averages values of mechanical properties are determined and yield limit, as determined by results of indentation, characterizes the properties of material in the contact zone, i.e. in small scale. The latter allows to control durability of material in a local surface areas that are points or lines of dangerous section, where there are the greatest stress.

It is obvious, that the size $\sigma_{0.2}$ determined under the Eq. (1) does not depend on the scale effect influence, resulting in decrease of characteristics of durability at increase of the area of cross-section of a sample (detail). Updating of values $\sigma_{0.2}$ with the purpose of the scale effect the influence can be executed under the formulas resulted in [10].

The described method also has been tested at the definition of yield limit of real details. Bolts M20 (thread pitch 2.5 mm) and M24 (thread pitch 3 mm) class of the durability 8.8 made of steel 40Ch have been chosen as details. We shall note, that carving connections are widely used in constructions of various machines: it is known, that on average up to 60% of details in machines have a groove. So, for example, according to [11] in of a glider of the plane of heavy class such as "Boeing" is used about 200 to 400 thousand bolts, and in a glider of the plane for single up to 25 thousand ones. Obviously, one hundred percent control of such compounds can not be realized because of their small size.

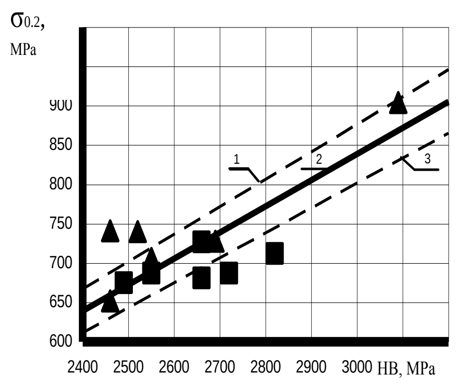

Fig. 1 Dependence of a yield limit $\sigma_{0.2}$ on hardness of steel bolts. Lines are constructed on the described method with the use of Eq. (1): *1* - for $\nu_2 = 0.28$, *2* - for $\nu_2 = 0.29$, *3* - for $\nu_2 = 0.30$; badges - the experimental data received at test for a stretching; ▲ - bolt M24, ■ - bolt M20

Table 1

Investigation of influence of the loading degree F/D^2 and the relative diameter d_0/D on the value of yield limit steel samples calculated by the formula 1 ($\nu_2 = 0.28$; D = 5 mm)

F/D^2, MPa	Sample 1 HD 1236 MPa, $\sigma_{0.2,t}$ = 235 MPa			Sample 2 HD 2402 MPa, $\sigma_{0.2,t}$ = 490 MPa		
	d_0/D	$\sigma_{0.2}$	$\sigma_{0.2}/\sigma_{0.2,t}$	d_0/D	$\sigma_{0.2}$	$\sigma_{0.2}/\sigma_{0.2,t}$
	-	MPa	-	-	MPa	-
73.6	0.295	226	0.962	0.232	470	0.959
196.2	0.461	225	0.957	0.361	489	0.998
294.3	0.553	227	0.966	0.434	502	1.024
392.4	0.629	227	0.966	0.493	510	1.041
588.6	0.754	229	0.974	0.596	514	1.049
784.8	0.860	228	0.970	0.680	519	1.059
981.0	0.944	233	0.991	0.756	520	1.061
1177.2	1.000	246	1.047	0.822	523	1.067

Table 2

Comparison of the values of yield limit, obtained by introduction of spherical indenter ($\sigma_{0.2}$) and by stretching test ($\sigma_{0.2,t}$)

Material of sample	HD, MPa	$\sigma_{0.2,t}$, MPa	d_0, mm	$\sigma_{0.2}$, MPa, under Eq. (1)	$\frac{\sigma_{0.2}}{\sigma_{0.2,t}}$
Steel 10	1487	275	2.628	279	1.015
Steel 20	1570	320	2.521	313	0.978
Steel 12Ch2BN4	4493	1010	1.625	1034	1.024
Steel 15ChGNT	4527	1050	1.620	1041	0.991
Steel 20Ch	5297	1150	1.528	1197	1.041
Steel 20ChN3	3841	917	1.735	883	0.963
Steel 38ChC	3532	804	1.791	815	1.014
Steel 40Ch	4208	981	1.665	974	0.993
Steel 40ChG	4591	1099	1.582	1089	0.991
Steel 40ChN	4532	1030	1.620	1041	1.011
Steel 40ChC	4385	1055	1.640	1011	0.958
Steel 40ChNMo	3394	834	1.819	784	0.94
Steel 45Ch	4591	1001	1.612	1054	1.053
Steel 25ChGT	5433	1216	2.519	1214	0.998
Titanium WT6	3473	654	2.138	622	0.95

Notice. For steel: F = 7.36 kN, D = 5 mm, $\nu_2 = 0.28$; for sample from the titanium: F = 9.81 kN, D = 5 mm, $\nu_2 = 0.31$.

Table 3

Comparison of the values of yield limit, determined with the use of the Eq. (2) (at $\nu_2 = 0.3$) by introduction of spherical indenter ($\sigma_{0.2}$) and by stretching test ($\sigma_{0.2,t}$) [9]

Grade of steel	Thermal treatment	HB, MPa	$\sigma_{0.2,t}$, MPa	$\sigma_{0.2}$, MPa, under Eq. (2)	$\frac{\sigma_{0.2}}{\sigma_{0,2,t}}$
12Ch2N4	Hardening in oil with 790°, letting down 170°°	3434	952	940	0.987
18ChNW	Normalization with 950°, hardening in oil with 860°, letting down 170°, 2,5 hour	3728	1030	1033	1.003
37ChN3*	Hardening in oil with 860°, letting down 550° -1 hour, cooling in oil	3306	1020	975	0.956
U4*	Hardening in water with 840°, letting down 550°	2639	834	754	0.904
30ChGC	Hardening in oil with 890°, letting down 600°	2992	853	800	0.937
30ChGC	Hardening in oil with 890°, letting down 400°	4346	1246	1235	0.991
30ChGC	Hardening in oil with 890°, letting down 200°	4885	1383	1405	1.016
U2	Normalization with 900°	1923	432	460	1.065
40Ch10C2Mo	Hardening in oil with 860°, letting down 550°	2904	736	767	1.042

Notice. * - calculation under the Eq. (1) at $\nu_2 = 0.28$.

Table 4

Dependence of yield limit for steels on hardness of Rokvell (scale B)

Hardness on Rokvell *HRB*	Yield limit $\sigma_{0.2}$, MPa	
	Carbonaceous steels	Alloyed steels
60	208	225
64	226	247
68	246	268
72	268	296
76	300	330
80	335	367
84	376	410

According to GOST 1759.4-87 [12] yield limit definition of stretching test of the whole bolts or the samples turned from them. It is obvious, that thus a bolt completely destroy. At the same time, this rapid nondestructive control could significantly improve the reliability of bolted connections, and thus increase the reliability and safe operation of vehicles in general**.** For an estimation of the described nondestructive method of control $\sigma_{0.2}$ preliminary stretching test of the specified bolts (it agrees GOST 1759.4-87) has been carried out with the help of a program-technical complex for the test of metals IR 5143-200 equipped with a personal computer.

We shall note, that for the tested bolts the minimal value of yield limit (in accordance with GOST 1759.4-87) makes 660 MPa. It has been tested on 6 bolts of each diameter. Apparently from Fig. 1, concurrence of results of definition of a yield limit at stretching test of bolts and at use of the described method (Eq. (1)) is satisfactory: the greatest difference does not exceed 8% (at $\nu_2 = 0.29$ in the Eq. (2), and the disorder of experimental values $\sigma_{0.2}$ has bilateral character. These results show that in the cases studied, the presence of a stress concentrator (thread) on the surface of the part has practically no effect on the value of $\sigma_{0.2}$, corresponding to a smooth test sample in tension. This allows the design of threaded connections, working in such conditions, set much lower value of the design safety factor *n*, that is, to identify and use the reserves of strength bolting, and, consequently, reduce its size and weight.

4. Conclusion

The described method can be realized in several variants distinguished by the order of definition of a conditional yield limit.

By the first variant the value of $\sigma_{0.2}$ is defined by direct introduction of spherical indenter into a tested surface of a detail. At the choice of working loading, the diameter of spherical indenter, requirements to the preparation of tested surface it is necessary to follow the instructions of GOST 18835-73 or GOST 9012-59. As the loading device it is possible to use Brinelle's press, stretching-compression machines, manual screw press, etc. Then under the Eq. (1) a yield limit is calculated.

By the second variant the value of $\sigma_{0.2}$ is defined by carrying out of the test of a detail on Rokvell's device (scale B). This variant is based on the fact that at constant values of elastic constants (ν and E) the value of $\sigma_{0.2}$ depends only on plastic hardness *HD*. At the same time it is known, that between the values *HD* and hardness *HRB* there is an analytical interrelation.

$$HD = 88300 / (130 - HRB) \tag{2}$$

Using Eq. (1) and Eq. (2), the table (which fragment is shown in Table 4) for the definition of $\sigma_{0.2}$ on the measured values of hardness *HRB* is constructed. It is obvious, that at test of details with identical elastic properties of a material (for example, at test only of steel details) it is possible directly to calibrate a scale of Rokvell device in the values of $\sigma_{0.2}$. Similar way it is possible to construct tables for the definition of hardness properties on the measured values of numbers of a hardness of Rokvell (scale C) HRC_e or Brinelle.

Fig. 2 Special ruler for the express train – control of the durability of steel hardware

For an operational definition of hardness directly on the surface of finished products (in this case, bolts) can, for example, be used the methods proposed in [13, 14].

Thus, the method described in [14] lies at the basis of GOST 18661-73 [15], who with the help of portable hardness testers hammering [16] allows us to control the hardness of the surface of finished products, including low stringency.

For practical realization of the described method in conditions of manufacture, operation and repair the experimental batch of a special ruler (Fig. 2) for the express train-control of the durability of steel hardware is developed and let out (developed and released).

References

1. **Birger, I.A.; Shorr, B.F.; Iosilevich, G.B.** 1993. Strength Analysis of Machine Parts: the Directory, Moscow: Mechanical Engineering 640 p. (in Russian).
2. **Janutėnienė, J.; Didžiokas, R.; Gintalas, M.** 2009. Analysis of the variation of metals mechanical properties depending on operation time, Mechanika 1(75): 26-30.
3. Patent 2221231 RF, МКИ G01N3/00. The method for determining the residual life of the metal pipeline /B.V. Budzulyak, V.V. Kudryavtsev, № 2002105603/28 Publish 10.01.04.
4. **Matlin, M.M.; Kazankina, E.N.; Kazankin, V.A.** 2009. Mechanics of initial dot contact, Mechanika 2(76): 12-15.
5. **Matlin, M.; Lebsky, S.; Mozgunova, A.; Frolova, A.** 2007. Features of the case parts made of aluminium alloys, Mechanika 6(68): 19-25.
6. **Baron, A.; Bakhracheva, J. A.** 2007. Method for impact strength estimation, Mechanika 4(66): 31-35.
7. **Borisov, A.V.** 2010. Elastic analysis of multilayered thick-walled spheres under external load, Mechanika 4(84): 28-32.
8. Patent 2086947 RF, МКИ^{4}G01N3/00. Way of definition of a liquid limit of materials /Y.I. Slavskiy, M.M. Matlin.- Publish 10.08.97. Bul. №22.
9. **Davydenkov, N.N.; Belyaev, S.E.; Markovec, M.P.** 1945. Origination of the basic mechanical characteristics of steel with help of measurements of hardness, Factory Laboratory 11(10): 964-973 (in Russian).
10. **Kogaev, V.P.; Makhutov, N.A.; Gusenkov, A.P.** 1985. Calculations of Details of Machines and Constructions on Durability and Working Life: the Directory, Moscow: Mechanical Engineering 224 p. (in Russian).
11. **Wafin, R.K.; Dunaev, V.V.; Shirshov, A.A.** 2007. Bolt's connections with a radial tightness, the Bulletin of Mechanical Engineering 5: 3-9 (in Russian).
12. GOST 1759.4-87 (ISO 898/1-78) Bolts, screws and studs. Mechanical properties and test methods. Preface 01.01.89 (in Russian).
13. A.c. 1401345 (USSR) Method of determine the maximum hardness of the materials / Bansyavichus R. I., Vasauskas V. S. Etc. published в Б. И. 1988, No. 21 (in Russian).
14. A.c. 280022 (USSR) The method for determining the hardness of materials. Drozd M.S., Slavskiy Yu.I., published в Б.И. 1970, № 27 (in Russian).
15. GOST 18661-73 Steel. Hardness measurement by method of impact indentation.-Ent.01.01.74 (in Russian).
16. **Gudkov, A.A.; Slavskiy, Yu.I.** 1982. Methods for Measuring the Hardness of Materials and Alloys, Moscow: Metallurgy 168 p. (in Russian).

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MAŠINŲ DETALIŲ TAKUMO RIBOS NUSTATYMAS KONTAKTINIU METODU

R e z i u m ė

Aptarta, kaip neardomuoju metodu pagal sferinio indentoriaus įspaudos į bandomos medžiagos paviršių parametrus nustatoma metalo gaminių sąlyginė takumo riba.

M. Matlin, S. Lebsky, E. Kazankina, V. Kazankin, D. Manukyan

DEFINITION OF YIELD LIMIT OF MACHINES DETAILS BY A CONTACT METHOD

S u m m a r y

The technique of nondestructive definition of yield limit of hardware by the parameters of introduction of spherical indenter in a tested surface of the material is described.

Keywords: yield limit, machines details contact method.

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