UDC 621.774.35

NEW KNOWLEDGE ON THE STRENGTH OF METAL

S. V. Sierikov
LLC "SURA LTD" (Dnipro, Ukraine)

At present, the strength of metals — in particular, of rolled metal products — is determined by tension to fracture of standard (flat or round) specimens at a fixed strain rate, in accordance with the normative documentation (GOST 1497-84, GOST 10006-80). From this experiment, the fundamental material parameters σ_b, σ_{02}, δ_5 are determined. These are, respectively, the ultimate tensile strength, the yield strength, and the relative elongation. Later, with the appearance of Mesnager and Charpy specimens, the impact-strength parameter A_k (GOST 9454-78) was "legislatively" introduced into the fracture mechanics of metals. Even so, research engineers and designers of real products today still have no calculation methods that would evaluate a finished product not only for strength but also for operational reliability. In response to this natural demand, scientists of the USSR Academy of Sciences developed a method for determining the crack-resistance characteristics of metals (GOST 25.506-85). Analogous standards, each with its own specifics, have been developed abroad: ASTM E1290, ASTM E1737, ISO 12135, BS 7448.

Numerous studies are carried out on the foundation of the methods listed. For example, an international classification of pipe steels for oil and gas pipelines into strength classes has been developed [1, 2]. Or, in the development of a manufacturing technology for seamless tubes from new grades of titanium alloys, the main criterion was precisely the principle of increasing the strength characteristics of the material [3]. And this is understandable, since the methods for crack resistance and impact strength have substantial limitations in practical implementation (see, for example, [4]). A simple question: why do hot-rolled tubes made of corrosion-resistant steels (GOST 9940-81) and titanium alloys (GOST 21945-76) have statutory limits on the value of impact strength A_k, whereas for cold-deformed tubes (GOST 9941-81, GOST 22897-86) there are no requirements for A_k? Moreover, all these tubes are widely used in nuclear and power engineering.

Consequently, on the basis of GOST 9454-78 and GOST 25.506-85, it is not possible to predict the operational reliability and the endurance limit of the material. Evidently, real metals are not an elastic material, and their fracture under deformation depends not only on the strength properties but also substantially on the ductility properties [5]. For example, a component of the tensioning-and-recoil mechanism of the idler wheel of the powerful T-800 tractor (ChTZ) is a steel spherical vessel filled with compressed air and operating under an internal pressure of up to 50 MPa [6]. By design, the sphere diameter was specified as 270 mm. The task was set: to choose the manufacturing technology for the sphere, its material, and its wall thickness — with the condition that this unit withstand three times the working pressure over the temperature range (+50 °C, −60 °C). In an emergency situation, loss of continuity of the shell must not be accompanied by fragment formation. That is, a criterion for the operational reliability of the pressure vessel has been formulated. Or, more simply: a tubular metal load-bearing bicycle frame possesses high endurance if, under dynamic loading, it does not lose local continuity but only changes shape — for example, the appearance of a dent on the surface of the frame without a through crack.

In the author's monograph [5], a new calculation–experimental method for the identification of metals is set out in detail, based on modern achievements in the fracture mechanics of a deformable solid. It genuinely makes it possible to predict the operational reliability and the endurance limit of a metal structure [7]. In the article [8], a calculation of the economic effectiveness of the developed method is presented.

The identification of metals is based on the determination of a matrix of seven fundamental parameters [4, 9]:

$$(\sigma_b, \sigma_{02}, \delta_5, \mu, A^*, \dot{e}, T) \quad (1)$$

Here μ is the coefficient of dynamic viscosity; A^* is the specific fracture energy; $\dot{e}$ is the strain rate; T is the temperature at which the specimens are tested. The parameter μ characterizes internal friction in the material and depends substantially on the structure. The parameter A^* is an integral value of the specific work required to initiate and propagate a crack in the volume under consideration [5]. By definition, the larger the value of A^* at given loads, the higher the operational reliability of the material under consideration; and, as shown in [7], the higher the endurance limit (σ_{-1}).

Quantitative determination of the matrix parameters σ_b, σ_{02}, δ_5 is carried out from tensile tests of flat or round specimens at a fixed strain rate $\dot{e}$ and temperature T, in accordance with GOST 1497-84 and GOST 10006-80.

Evaluation of the quantities μ and A^* is determined by the formulas [4]:

in the case of tension of a flat specimen:

(2)

in the case of tension of a round specimen:

(3)

Here c is the longitudinal-wave (sound) velocity in the material under consideration; E is Young's modulus. Approximately, below we take c = (E/ϱ)^(1/2), where ϱ is the density.

In the author's works (1981–1991; see the bibliography of article [4]), it was theoretically substantiated that real metals and their alloys have a ductility peak as a function of the strain rate. The conditions for superplasticity can be predicted [10]. In this case, the maximum value of the relative elongation $\delta_5$max of the deformed material is determined by the relations [4]:

in the case of tension of a flat specimen:

(4)

in the case of tension of a round specimen:

(5)

Here the parameters A* and μ are calculated by formulas (2)–(3) at a fixed strain rate ė and temperature, in accordance with GOST 1497-84 and GOST 10006-80. Formulas (4)–(5) are very useful in practice in metal forming (pressure working) under cold deformation (see, for example, [11]). They make it possible to optimize the technological process through the choice of the speed regime in the deformation zone.

Methodological approaches in the field of continuum mechanics, on the one hand, and solid-state physics, on the other, should be mutually complementary. Hence, remaining within the framework of the mathematical model of unsteady deformation of an isotropic viscoplastic medium, it is feasible to evaluate the parameter μ for metals under shock-wave loading of disk-shaped specimens. In this case, upon impact we have a pressure range of (100–1000) GPa at a strain rate of $(0.05–3.0)\cdot10^6$ 1/s. Here the strength characteristics of the material are practically zero. What remains is the coefficient of dynamic viscosity μ, which is determined by the formula [12]:

. (6)

where ϱ_0 is the density of the material studied; u_0 is the shock-wave propagation velocity; u_1 is the mass (particle) velocity of the material; $\dot{e} = u_1/h_0$ is the strain rate; h_0 is the height of the disk specimen.

In [12], values of μ are presented for 55 technically pure metals at $\dot{e} = 1\cdot10^5$ 1/s and $\dot{e} = 1.75\cdot10^5$ 1/s. Analysis of the data shows that the maximum value of the coefficient of dynamic viscosity belongs to the metal iridium (μ = 106.12 kPa·s at $\dot{e} = 1\cdot10^5$ 1/s and μ = 57.16 kPa·s at $\dot{e} = 1.75\cdot10^5$ 1/s). Correspondingly, at $\dot{e} = 1\cdot10^5$ 1/s: aluminum (μ = 4.85 kPa·s); titanium (μ = 8.36 kPa·s); iron (μ = 15.57 kPa·s); chromium (μ = 25.28 kPa·s); nickel (μ = 27.06 kPa·s); molybdenum (μ = 47.47 kPa·s). It now becomes clear why it is precisely traces of iridium (Ir) that are found in the earth at sites of catastrophic explosions. The remaining metals evaporate (see, for example, [13]).

The results of the development of the manufacture of tubes from new high-strength titanium alloys (5V, 37) have been published [3]. Together with the already traditional alloys, let us perform their identification according to matrix (1). Let us consider seamless cold-deformed tubes manufactured by SE "NTZ" (Nikopol): 16×1.5 mm (alloy PT7M), 20×2.5 mm (PT7M), 20×1 mm (PT1M); and tubes manufactured by OJSC "ChMZ" (Glazov): 18×2 mm (5V), 32×2 mm (5V); as well as hot-rolled tubes manufactured by JSC "ChTPZ" (Chelyabinsk): 260×45 mm (PT3V) and by OJSC "ChMZ" (Glazov): 213×16.5 mm (37). The data for tubes made of the alloys (PT7M), 5V, 37 presented below were obtained from [3] after averaging.

Table 1 summarizes data on the mechanical properties of tubes made of the alloys under consideration at a test temperature of +20 °C. The matrix parameters μ and A^* were determined by formulas (3) at the fixed values: E = 103 GPa, ϱ = 4.5 g/cm³, c = 4784 m/s, $\dot{e} = 0.25\cdot10^{-2}$ 1/s. The last value is in accordance with GOST 1497-84. Table 2 presents the mechanical properties at elevated test temperatures. In Table 3, for hot-deformed tubes, the parameters μ and A^* were determined by formulas (2). More detailed information on the operational reliability of 260×45 mm tubes (PT3V) is published in [14].

From the analysis of the data of Tables 1 and 3 with respect to the specific fracture energy A^*, the advantage clearly lies with alloys 5V, 37 [3]. The scope and level of the research work, carried through to implementation, is very impressive. However, there is a remark. For such a research team — representing the flagship of advanced Russian scientific and technical thought (NRC “Kurchatov Institute” – CRISM “Prometey”) — the normative and technical documentation on the mechanical properties of the developed alloys traditionally ends with the note “not less than.” Over a hundred years one can get used to this — but not the inquisitive scientist. For example, for tubes made of aluminum alloys (GOST 18475-82, OST 1.90038-88), there are restrictive notes on the strength properties — “not less than” and “not more than.” A logical question arises: and what if it is more, or less? The author understands that, according to the current GOST, the product is rejected and a quality certificate is not issued. And these limits were chosen and enshrined in law on the basis of statistical research data, in accordance with GOST 1497-84 and GOST 9454-78, taking into account the objective scatter in the chemical composition of rolled metal products and other objective and subjective considerations. In the author’s opinion, it is expedient to make use of matrix (1) for the identification of metals and to develop a kind of “scale” of operational reliability, or of the endurance limit. And rolled metal products with a low indicator should not be rejected; rather, a use should be found for them in that quality — but now with a certificate.

Let us turn to the data of Table 1. For the 20×2 mm tube (PT1M), with an aluminum content of 0.28 % in its chemical composition, the parameter A^* is higher compared with the 16×1.5 mm (PT7M) and 20×2.5 mm (PT7M) tubes, which have higher strength properties. This once again confirms the idea that the operational reliability of rolled metal products depends not only on the strength properties but also on the ductility properties.

The functionality of matrix (1) and formulas (2)–(6) has been confirmed across a wide range of materials at high and low temperatures, and under thermohydrogen treatment [5]. In particular, the influence of anisotropy and neutron-flux irradiation on the operational reliability of zirconium has been studied [15]. Note that Young’s modulus varies with the test temperature, as well as with the chemical composition of the material.

Naturally, everything new in science requires study of the subject in the full diversity of its questions. To dream a little: were the fundamental principle of metal identification based on matrix (1) to be introduced into the normative and technical documentation for rolled metal products, it would be necessary to carry out a complex of research work at the state level. Much still remains unclear in the content of the matrix itself. For example, how does the value of the coefficient of dynamic viscosity μ correlate with the parameter of specific fracture energy A^*? Or with the endurance limit? What strain rate should be enshrined in the standards for testing standard specimens to fracture, in order to obtain more objective information about the dynamic properties of the material? It would be expedient to test the developed calculation–experimental method (1)–(3) on materials obtained on the basis of nanotechnology. A topic suggests itself: the identification of the steels used to manufacture electric-welded tubes for trunk oil and gas pipelines, with the aim of eliminating avalanche-like (catastrophic) failures in service. The main ideas of the method are patented in the Russian Federation (No. 2543673, 2015, Bulletin No. 7; No. 2818505, 2024, Bulletin No. 5).

Matrix (1), as in medicine, is the genome of the material. Knowing the actual content of the matrix, one realizes the optimal possibility of applying the metal in a specific product. It is an indispensable working tool for the researcher–metallurgist. And here it would make sense for the Nobel Prize in Physics committee to assess the scientific significance of the fundamental formulas (1)–(6).

Table 1. Mechanical properties of tubes made of various titanium alloys at +20 °C.

No.	**Tube size**	**Alloy**	**σ_b, (MPa)**	**σ_{02}, (MPa)**	**δ_5, (%)**	**μ, (GPa·s)**	A^* (GJ/m^2)

	(mm)						
1	16×1.5	PT7M	598	490	21	14.4	693
2	20×2.5	PT7M	607	519	20	11.7	684
3	20×2.0	PT7M	500	412	33	11.8	765
4	18×2.0	5V	985	835	17	20	1512
5	32×2.0	5V	979	871	18	14.4	1590

Table 2. Mechanical properties of tubes made of various titanium alloys at +150 °C, +350 °C, +450 °C.

No.	**Tube size (mm)**	**Alloy**	**Test temp. (°C)**	**σ_b, (MPa)**	**σ_{02}, (MPa)**	**μ, (GPa·s)**
1	16×1.5	PT7M	350	329	235	12.5
2	20×2.5	PT7M	350	382	265	15.6
3	20×2.0	PT7M	150	373	294	10.5
4	18×2.0	5V	450	643	499	19.2
5	32×2.0	5V	450	633	488	19.3

Table 3. Results of mechanical tests of specimens of hot-deformed tubes: 213×16.5 mm made of alloy 37 and 260×45 mm made of alloy PT3V.

Spec. No.	**Alloy**	**Tube size (mm)**	**σ_b, (MPa)**	**σ_{02}, (MPa)**	**δ_5, (%)**	**A_k, KCU (kJ/m^2)**	A^* (GJ/m^2)	**μ, (GPa·s)**
1	37	213×16.5	913	881	14	82	1084	6.4
2	37	213×16.5	912	878	16	99	1236	6.8
3	37	213×16.5	911	877	15	78	1156	6.8
4	37	213×16.5	916	888	14.8	91	1154	5.6
5	PT3V	260×45	794	686	12	78	701	21.5
6	PT3V	260×45	755	695	12.5	81	660	12.0
7	PT3V	260×45	755	676	10	107	528	15.8
8	PT3V	260×45	735	676	10	98	500	11.8

References

1. Pyshmintsev I. Yu., Lozovoy V. N., Struin A. O. Problems and solutions in the application of high-strength tubes for trunk gas pipelines of a new generation. — In: Nauka i Tekhnika v Gazovoy Promyshlennosti (Science and Technology in the Gas Industry). Moscow, 2009, No. 1, pp. 22–30.

2. Pyshmintsev I. Yu., Maltsev A. N., et al. Structure and properties of low-carbon pipe steels subjected to pneumatic testing. Moscow: Stal', 2011, No. 2, pp. 75–81.

3. Martynova T. A., Rtishcheva L. P., et al. Development of a manufacturing technology for tubes made of high-strength titanium alloys. // Titan, 2023, No. 4, pp. 55–61.

4. Serikov S. V. A mathematical model of a viscoplastic medium as a method of metal identification. // Stal', 2024, No. 3, pp. 42–47.

5. Serikov S. V. A Blow to Impact Strength (Udar po udarnoy vyazkosti). Moscow: INFRA-M, 2024. — 160 p. DOI 10.12737/2161513 / ISBN 978-5-16-020157-3.

6. Makhutov N. A., Serikov S. V., et al. Quantitative comparison of the fracture character of spherical shells under pressure at reduced test temperature. Problemy Mashinostroeniya i Avtomatizatsii (Problems of Mechanical Engineering and Automation). Moscow, 1991, issue 1, pp. 64–73.

7. Serikov S. V. Evaluation of the endurance limit of metals. // Stal', 2023, No. 8, pp. 46–49.

8. Serikov S. V. Development of normative and technical documentation on the crack resistance of metals. / Stal', 2024, No. 5, pp. 32–35.

9. Serikov S. V. Identification of titanium alloys. // Titan, 2023, No. 4, pp. 49–53.

10. Serikov S. V. On the strain rate of metals. // Izvestiya AN SSSR. Metally (News of the USSR Academy of Sciences. Metals), 1989, No. 2, pp. 48–52.

11. Serikov S. V. Features of the production of seamless tubes from niobium, tantalum, and titanium alloys. // Titan, 2020, No. 3–4, pp. 82–85.

12. Serikov S. V. The coefficient of dynamic viscosity of metals and titanium alloys. // Titan, 2018, No. 3, pp. 16–20.

13. Mineraly. Sokrovishcha Zemli (Minerals. Treasures of the Earth). Moscow, 2012, issue 15, p. 72.

14. Safyanov A. V., Serikov S. V. Assessment of the operational reliability of hot-rolled tubes made of titanium alloy PT3V. // Titan, 2021, No. 3, pp. 43–46.

15. Serikov S. V. The influence of anisotropy and neutron-flux irradiation on the operational reliability of iodide zirconium. // Titan, 2024, No. 1, pp. 23–25.