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MATRIX FOR THE IDENTIFICATION OF METALS

S. V. Serikov

In the twenty-first century, fundamental questions remain concerning the identification of metals and their alloys with respect to operational reliability. Before formulating a definition of "operational reliability" and giving that concept a physical meaning, let us briefly review the essence of the problem. At present we have the following.

1. Primary information about a material is obtained by uniaxial tension of flat or round specimens up to fracture, in accordance with GOST 1497-84 and GOST 10006-80, thereby determining the mechanical properties: the ultimate tensile strength σ_b, the yield strength σ_{02} and the elongation δ_5 at a fixed temperature T and strain rate $\dot{e} > 0$.

2. It is possible, with modern microscopes, to determine the macro- and microstructure of a material down to atomic resolution.

3. By the notched-specimen impact bending test (GOST 9454-78) the impact toughness A_K is determined. Impact toughness here is to be understood as the work of impact referred to the initial cross-sectional area of the specimen at the notch.

4. To determine the crack-resistance characteristics of a metal, specimens with a pre-grown fatigue crack are tested in accordance with GOST 25.506-85. Crack resistance is assessed by one or several force, deformation and energy quantities: K_{1c}, K_c, K_{QT}, Δ_5, I_c.

5. The method of assessing the endurance limit σ_{-1} is based on testing smooth and notched specimens under a symmetrical rotating-bending loading scheme, with a base of about 10^7 cycles [1].

6. Methods are known for assessing the fracture toughness and also the resistance to fatigue fracture of titanium alloys [2].

Corresponding international standards have been developed for items 1–6: ISO 12135, ASTM E1290, ASTM E1737.

It is precisely solid-state physics, in all its varieties and directions, that is able to provide world industry with structural materials. And yet, among the abundance of questions and problems of modern science, fracture mechanics occupies a special place.

Scientific articles and books are written about strength, residual life, the safety of machine components and so on, but the subject of the operational reliability of a particular material — the basis of every product — is absent. The research scientist or designer is at a loss when trying to make use of the methods named above, which contain many limitations and difficulties in practical application. For example, to narrow the search among the great variety of steels developed for the production of electric-welded tubes or of seamless oil-grade tubing, industry standards are introduced. In the first case tubes are divided into strength classes [3], in the second into strength groups [4], in accordance with the standard API 5CT / ISO 11960:2004 (USA).

In the light of modern achievements in fracture mechanics, and of metals in particular, high strength properties of a material do not always coincide with high operational reliability — especially when dynamic loads and the intensity of deformation are taken into account.

In the author's opinion, the calculation-experimental method developed for identifying metals and their alloys with respect to operational reliability, in the form of a genome-forming matrix [5, 6], deserves the attention of the scientific community:

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

where μ is the dynamic viscosity coefficient, with the dimension [Pa·s], and A_* is the specific energy of fracture [J/m^2]. The parameter A_* is an integral quantity of the specific work of formation and propagation of a crack in the volume of viscoplastic material under consideration [5]. The coefficient μ characterises the internal friction of the material when it is deformed at a non-zero strain rate ($\dot{e} > 0$). It depends substantially on the structure.

The determination of σ_b, σ_{02} and δ_5 in the matrix is carried out in accordance with GOST 1497-84 and GOST 10006-80 by tension of flat or round specimens up to fracture. The quantitative evaluation of μ and A_* is given by the formulas [6]:

for tension of a flat specimen

$$\mu = (\sigma_b - \sigma_{02}) / 2\dot{e}, \quad A_* = (c\delta_5\sigma_{02}^2) / (2E\dot{e}) \cdot (1 + 2\mu\dot{e}/\sigma_{02})^2 \quad (2)$$

for tension of a round specimen

$$\mu = (\sigma_b - \sigma_{02}) / 3\dot{e}, \quad A_* = (c\delta_5\sigma_{02}^2) / (2E\dot{e}) \cdot (1 + 3\mu\dot{e}/\sigma_{02})^2 \quad (3)$$

Here E is Young's modulus and c is the velocity of longitudinal sound waves, $c = (E/\rho)^{1/2}$, where ρ is the density.

By definition, the material under consideration possesses high operational reliability when the parameters μ and A_* have maximum values. They combine in themselves such characteristics as strength, crack resistance, endurance limit and fracture toughness at a fixed strain rate and temperature.

The physical essence of formulas (1)–(3) is based on the solution of the mathematical model of unsteady deformation of a strip and of a bar under axial tension up to fracture, in the scheme of an isotropic viscoplastic continuous medium, taking into account [5]:

— compliance with the laws of thermodynamics;

— an energy criterion of fracture;

— the hypothesis that unloading of the elastic wave in the vicinity of the crack formed in the material takes place at the velocity of longitudinal sound waves.

For all the fundamental nature of the formulation of the mathematical model with prescribed initial and boundary conditions, under certain physically justified assumptions a class of exact analytical solutions of the model has been determined for the simplest regions [5]: a rectilinear strip, a round bar, a ring, a cylinder and a sphere. In every case the experimental fact of the existence of a ductility peak in real metals and alloys as a function of the strain rate ($\dot{e} > 0$) has been confirmed theoretically, extending as far as superplasticity [7]. This makes it possible to reduce technological costs substantially in metal forming — for example in the production of seamless tubes from expensive metals [8]. The method of identifying metals (1)–(3) is valid over a wide range of strain rates, $\dot{e} = (10^{-5}–10^{5})$ 1/s, and of test temperatures [9].

In the case of large impulsive pressures and strain rates ($\dot{e} \geq 10^5$ 1/s), where the strength properties of the material may be neglected, considering the mathematical model of a metal disc loaded by a plane shock wave in the scheme of a viscous fluid, we obtain the equation [10]:

$$\mu = 3\rho_0 u_0(u_0 - u_1) / 2\dot{e} \quad (4)$$

where ρ_0 is the initial density; u_0 is the velocity of the shock-wave front; u_1 is the mass velocity of the material; $\dot{e} = u_1/h_0$ is the strain rate; and h_0 is the height of the disc specimen. In [10], on the basis of known investigations of commercially pure metals by the shock-wave method [11], values of μ were obtained from formula (4) for 55 different metals at $\dot{e} = 10^5$ 1/s (50–60 GPa) and $\dot{e} = 1.75 \cdot 10^5$ 1/s (100–110 GPa). For example, for aluminium μ = 4.83 kPa·s and for niobium μ = 20.33 kPa·s ($\dot{e} = 10^5$ 1/s). The highest value of the dynamic viscosity coefficient is that of iridium, μ = 106.12 kPa·s ($\dot{e} = 10^5$ 1/s) and μ = 57.16 kPa·s ($\dot{e} = 1.75 \cdot 10^5$ 1/s). It is precisely iridium compounds that are found in the ground after catastrophic impacts [12]. The values of the parameters μ and A_* for various materials over a wide range of loads are of separate scientific interest.

The performance of the calculation-experimental method (1)–(3) set out here, with respect to assessing the operational reliability of metals and their alloys, has been confirmed by many specific investigations (see, for example, [5, 13]). As an example, consider a comparison of (1)–(3) with experimental data on the endurance limit of the metals studied.

It is known [14] that an increase in the surface roughness of titanium products leads to a reduction in the endurance limit σ_{-1}. Table 1 summarises the experimental data σ_b, σ_{02}, δ_5 and σ_{-1} for flat specimens of titanium alloy VT20 with various surface treatments [14]. From formulas (2), at E = 103 GPa, ρ = 4.5 g/cm^3, $c = (E/\rho)^{1/2}$ = 4784 m/s and $\dot{e} = 0.25 \cdot 10^{-2}$ 1/s (+20 °C), in accordance with GOST 1497-84, we obtain the numerical values of μ and A_* (see Table 1). From Table 1 it follows that, on reducing the surface roughness from 60 µm to 0.05 µm — by more than 1000% — the increase in the endurance limit is observed to be within 10%. The parameter A_* is more sensitive. Titanium specimens after polishing have the maximum value of the specific energy of fracture (A_* = 1490 GJ/m^2), which cannot be said of the structural parameter μ = 12 GPa·s.

Consider another example of assessing the endurance limit for structural steels on a base of 10^7 cycles [1]. Table 2 presents the experimental data σ_b, σ_{02}, δ_5 and σ_{-1} and the calculated values of μ and A_* from formulas (2) at E = 200 GPa, ρ = 7.85 g/cm^3, c = 5050 m/s and $\dot{e} = 0.25 \cdot 10^{-2}$ 1/s (+20 °C). Here the maximum values A_* = 547 GJ/m^2 and μ = 34.4 GPa·s coincide with the highest endurance limit, that of steel 15G2AF (σ_{-1} = 250 MPa). Consequently, by definition, this steel possesses high operational reliability in comparison with steels 15KP and 08GSYuT.

The third example relates to aluminium alloys [1]. Table 3 summarises the experimental data for tension up to fracture of flat aluminium specimens in accordance with GOST 1497-84: $\dot{e} = 0.25 \cdot 10^{-2}$ 1/s (+20 °C), E = 71 GPa, ρ = 2.7 g/cm^3, c = 5128 m/s. The endurance limit σ_{-1} is determined on a base of 10^7 cycles. The parameters μ and A_* were determined from formulas (2). From Table 3 it follows that the maximum value of the endurance limit, σ_{-1} = 190 MPa for aluminium alloy AMg6, coincides with the maximum values of the parameters μ = 40.6 GPa·s and A_* = 355 GJ/m^2. Alloy AMg6 therefore has the higher operational reliability in comparison with the other alloys, AMg6N and D16AT.

The promise of applying matrix (1) in developing new normative and technical documentation (GOST, TU, OST) for the industrial production of rolled metal products with high service properties and economic efficiency is shown in the author's work [15].

In conclusion we note that, according to the data of Tables 1–3 and the results of the investigations [13], it follows that by no means in every case does high strength of a material correspond to high operational reliability.

Table 1. Endurance-limit data and mechanical properties of titanium alloy VT20 as a function of roughness [13].

No.	Type of surface treatment	Roughness (µm)	σb (MPa)	σ02 (MPa)	δ5 (%)	σ−1 (MPa)	µ (GPa·s)	A* (GJ/m²)
1	Sandblasting	50–60	970	875	13.8	520	19.0	1206
2	Matting	0.2–1.2	980	920	15.9	550	12.0	1419
3	Polishing	0.03–0.05	980	920	16.7	575	12.0	1490

Table 2. Experimental endurance-limit data and mechanical properties of steels [1], with calculated values of the dynamic viscosity coefficient and the specific energy of fracture.

No.	Steel	σb (MPa)	σ02 (MPa)	δ5 (%)	σ−1 (MPa)	μ (GPa·s)	A* (GJ/m²)
1	15KP	380	230	27	180	30.0	334
2	08GSYuT	540	403	30	250	27.4	442
3	15G2AF	532	410	32	250	34.4	547

Table 3. Experimental endurance-limit data and mechanical properties of aluminium alloys [1].

No.	Aluminium alloy	σb (MPa)	σ02 (MPa)	δ5 (%)	σ−1 (MPa)	μ (GPa·s)	A* (GJ/m²)
1	AMg6	360	157	19	190	40.6	355
2	AMg6N	430	343	7	—	17.4	187
3	D16AT	424	322	10	112	20.4	260

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