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ON THE ISSUE OF STRENGTH GROUPS OF ELECTRIC-WELDED AND SEAMLESS STEEL PIPES

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Abstract. Using the example of electric-welded steel pipes for main gas pipelines, seamless oil-grade pipes, and boiler pipes made from various steel grades, testing by the calculation–experimental method of the operational reliability of the studied pipes is presented. The promise of classifying pipes not by strength groups, as indicated in standard API 5CT/ISO 11960:2004, but by reliability categories is shown.

Keywords: genome-forming matrix, specific fracture energy, dynamic viscosity coefficient, strain rate, temperature.

Fundamental practical questions regarding the identification of rolled metal products with respect to operational reliability remain open to this day. Let us consider this topic using the examples of electric-welded steel pipes intended for high-pressure main gas pipelines and seamless casing and tubing of the oil grades.

Standards have been developed here in which, in the first case, pipes are divided into strength classes [1], and in the second — into strength groups [2], according to API 5CT/ISO 11960:2004. In light of modern achievements in fracture mechanics — in particular, of metals — high strength properties of a material by no means always coincide with high operational reliability [3], especially when dynamic loads and deformation intensity are taken into account.

In what follows, we make use of the calculation–experimental method of metal identification in the form of the genome-forming matrix [4, 5]:

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

Here σ_b is the ultimate tensile strength of a flat or round specimen at the specified strain rate $\dot{e}$ and test temperature T; σ_{02} is the yield strength; δ_5 is the relative elongation; μ is the coefficient of dynamic viscosity; A^* is the specific fracture energy. The parameter A^* is an integral value of the specific work required to initiate and propagate a crack. In essence, it determines the level of crack resistance of the material. The coefficient μ characterizes internal friction in the metal and depends substantially on the micro- and macrostructure. By definition [3], the larger the value of A^* at given loads and temperature, the higher the operational reliability of the material under consideration when used in specific products. Correspondingly, the indicators of the endurance limit and crack resistance of the metal are higher [3].

Determination of σ_b, σ_{02}, δ_5 is carried out in accordance with GOST 1497-84 and GOST 10006-80 in tension of flat or round specimens up to fracture. Quantitative evaluation of μ and A^* is determined by the formulas:

in the case of tension of a flat specimen

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

in the case of tension of a round specimen

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

Here E is Young's modulus; c is the longitudinal wave velocity, $c = (E/\rho)^{1/2}$; ρ is the density.

In what follows, on the basis of matrix (1) and formulas (2)–(3), we show the possibility of creating a new, physically substantiated standard for the gradation of steel pipes by categories of operational reliability.

As an example, let us use the data of [1], where pneumatic tests were carried out on electric-welded pipes 1420 mm in diameter made of steels having a ferrite–bainite structure. All the steels under consideration belong to the same strength class K65 (X80). Table 1 presents the results of the studies [1]: mechanical properties and impact strength values A_k (KCV) at +20 °C and −40 °C. The crack resistance of the steels was also evaluated according to standard BS 7448: the parameter CTOD — the crack-tip opening displacement corresponding to the onset of crack motion — was determined. Note that the parameters A^* and A_k have the same dimension but, by definition, a different physical meaning.

Taking into account that the mechanical characteristics of the steels were determined in tension to fracture of cylindrical specimens Ø6 mm at $\dot{e} = 0.25 \cdot 10^{-2}$ 1/s (+20 °C), according to GOST 1497-84, the data of Table 1 make it possible to determine the numerical values of the remaining parameters μ, A^* of matrix (1) by formulas (3). Table 2 presents these numbers; for the steels under consideration, the calculations assumed: $E = 200$ GPa, $\rho = 7.85$ g/cm³, c = 5050 m/s.

From the data of Table 2 with respect to the parameter A^*, it follows that steels of the same strength class have different categories of operational reliability. The highest level belongs to steel 06G2MB ($A^* = 503$ GJ/m²). A quite low one — to steel 05G2NDB ($A^* = 370$ GJ/m²). Conventionally, the steels under consideration can be divided into two categories: high (06G2MB, 07G2MB(1), 08G2MB) and low (07G2MB(2), 05G2MFB, 05G2NDB).

The character of the influence of the structural parameter μ on the operational reliability of the material requires additional investigation. The maximum value of the dynamic viscosity $\mu = 7.9$ GPa·s corresponds to steel 05G2MFB at $A^* = 397$ GJ/m². Note here that the minimum value $\mu = 3.7$ GPa·s corresponds to the minimum value $A^* = 370$ GJ/m² and to the CTOD value of 0.76 mm for steel 05G2NDB. Comparing the values of A^* and A_k (KCV), one can hypothetically note, for steel 06G2MB, the correspondence of the maximum value $A^* = 503$ GJ/m² to the minimum A_k (KCV) = 1.54 MJ/m² (−40 °C).

Let us consider a second example. At present, the oil and gas industry is in need of pipes made of steels of type 20Kh13, resistant to carbon-dioxide corrosion, in cold-resistant design. The technical requirements for casing and tubing made of corrosion-resistant martensitic-class steel containing 13% Cr and (0.16–0.22)% C are given in standard API 5CT/ISO 11960:2004 (strength group L80, type 13Cr). The requirements for the mechanical properties of the pipe material according to this standard are: $\sigma_b \geq 655$ MPa, σ_{02} = (552–655) MPa, $\delta_5 \geq 15\%$.

The data of studies of flat specimens of steel pipes of strength group L80 made of steel 20Kh13 under various heat-treatment regimes [2] are presented in Table 3. Correspondingly, Table 4 summarizes the calculated data of μ and *A** by formulas (2) at E = 200 GPa, c = 5050 m/s, ρ = 7.85 g/cm³, $\dot{e} = 0.25 \cdot 10^{-2}$ 1/s. From Table 4 it follows that the heat-treatment regime substantially affects the operational reliability of the pipe material, while remaining within strength group L80 according to standard API 5CT/ISO 11960:2004. If items 1–3 of Table 4 are evaluated with respect to the parameter *A**, the maximum level of operational reliability of steel 20Kh13 is obtained when the heat-treatment regime corresponds to item 3 of Table 3. Methods of increasing the strength of metals and their influence on operational reliability are set out in more detail in article [6]. Note here that Young's modulus *E* depends on the chemical composition of the steel and the test temperature.

As a third example, let us consider the domestic assortment of steel boiler pipes [7]. Table 5 presents the normative requirements for mechanical properties and the calculated data of the parameters μ and *A** by formulas (2), with the same data for *E*, ρ, c, $\dot{e}$ as in the previous examples. Averaged values of the parameters σ_b, σ_{02} were assumed in the calculations. Note that the normative-technical document [7] presents the mechanical properties of boiler pipes for eleven different steel grades when testing specimens cut in the longitudinal and transverse directions of rolling. For brevity, Table 5 presents five positions characteristic in their properties. Analyzing them with respect to the parameter *A**, we arrive at the conclusion of the high operational reliability of boiler pipes made of steel 12Kh18N12T (*A**max = 663 GJ/m²) compared with steel 15GS (*A**min = 218 GJ/m²) — even though the latter steel has higher strength properties compared with steel 20 (*A** = 280 GJ/m²).

Again, a natural question arises to the developers of technical specifications for boiler pipes of quite critical application. From what physical considerations were the lower — and in several cases upper — limits on the strength parameters σ_b, σ_{02} adopted for the steels under consideration? And what if they are higher, or lower? In practice, understandably, this is a reject. But in essence? A more proprietary approach suggests itself here. It is expedient to grade boiler pipes not by strength characteristics but by the parameter *A** — operational reliability. Correspondingly, electric-welded pipes for main pipelines and seamless oil-grade pipes should be divided not into strength groups [1, 2] but into reliability categories, according to formulas (1)–(3).

CONCLUSION

A worldview question: when boarding an aircraft with the aim of arriving safely at our destination, do we settle comfortably into a strong seat and fly in a strong aircraft powered by a strong engine on strong wings? No! There is only one thought — we fly in a reliable aircraft with a reliable crew. The strength of metal is but one component of operational reliability. For example, in the course of a bicycle race, riders not infrequently collide in the heat of competition. If, in such a case, the tubular frame of one bicycle breaks or bends, while that of another receives only a deep dent and the athlete continues the race — that is precisely the operational reliability of the bicycle as a whole.

The method of identifying metals by means of the genome-forming matrix (1) includes not only the strength characteristics σ_b, σ_{02} and the ductility characteristic δ_5 of the real material, which possesses viscoplastic properties, but also the structural component μ, together with the crack-resistance and endurance parameter *A** at a given deformation per unit time $\dot{e} > 0$ and a fixed temperature *T*. The dynamics in time of the material deformation process is thereby taken into account. Formulas (1)–(3) reflect new knowledge in the physics of metals and in materials science. They make it possible to identify viscoplastic materials — including media with nano-properties — with respect to operational reliability, and thereby to grade rolled metal products not into strength groups but into physically better-substantiated reliability categories.

Table 1. Mechanical properties of the investigated steels [1].

No.	Steel grade	σ_{02}, (MPa)	σ_b, (MPa)	δ_5, (%)	KCV_{+20}, (J/cm^2)	KCV_{-40}, (J/cm^2)	CTOD (mm)
1	07G2MB(1)	613	664	19.8	258	250	0.33
2	07G2MB(2)	684	714	15.6	365	328	0.30
3	08G2MB	687	717	17.0	360	167	0.13
4	06G2MB	662	713	19.6	347	154	0.17
5	05G2MFB	581	640	19.2	360	350	0.61
6	05G2NDB	602	630	18.5	367	363	0.76

Table 2. Calculated values of the coefficient of dynamic viscosity μ and the specific fracture energy A*.

No.	Steel grade	μ, (GPa·s)	*A**, (GJ/m^2)
1	07G2MB(1)	6.8	441
2	07G2MB(2)	4.0	402
3	08G2MB	4.0	441
4	06G2MB	6.8	503
5	05G2MFB	7.9	397
6	05G2NDB	3.7	370

Note: the chemical compositions of steels 07G2MB(1) and 07G2MB(2) differ within tolerance in Cu, Mo, Al, S.

Table 3. Mechanical properties of steel 20Kh13 under various heat-treatment regimes [2].

No.	Quenching (°C)	Tempering (°C)	σ_b, (MPa)	σ_{02}, (MPa)	δ_5, (%)	A_k (KCV) −30 °C, (J/cm^2)	A_k (KCV) −65 °C, (J/cm^2)
1	1000	710	770	600	25	34	27
2	960	670	810	660	24	41	33
3	930	670	820	650	25	45	44

Table 4. Calculated values of the coefficient of dynamic viscosity μ and the specific fracture energy A* for steel 20Kh13 depending on the heat-treatment regime.

No.	μ, (GPa·s)	A^*, (GJ/m^2)
1	34	748
2	30	795
3	34	849

Table 5. Mechanical properties of steel boiler pipes at +20 °C (TU14-3R-55-2001, longitudinal specimens).

No.	Steel grade	σ_b, (MPa)	σ_{02}, (MPa)	δ_5, (%)	A_k (KCV), (J/cm^2)	μ, (GPa·s)	A^* (GJ/m^2)
1	20	412–549	216	24	49	52.9	280
2	15GS	not less than 490	294	18	59	39.2	218
3	12Kh1MF	441–637	274	21	59	53.0	308
4	10Kh9FB-Sh	not less than 600	400	19	78	40.0	345
5	12Kh18N12T	539–686	216–392	35	—	61.7	663

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