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ASSESSMENT OF IN-SERVICE RELIABILITY OF CAPILLARY TUBES IN THE COLD-WORKED[1] CONDITION

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Normative and technical requirements for steel capillary tubes are set out in GOST 14162-79: Steel tubes of small sizes. Tube manufacture and supply are carried out both in the soft, heat-treated condition and without heat treatment, in the cold-worked[1] condition. In the latter case, mechanical properties are not specified. In this situation, variations are possible over a wide range of changes in the strength and ductility properties of the tube material. Given the widespread use of capillary tubes in critical pipelines and structures, the issue of their in-service reliability is currently relevant. Moreover, due to the small geometric dimensions, traditional approaches for testing impact strength (GOST 9454-78), crack resistance (GOST 25.506-85), and fracture toughness K_{1c} (ASTM E23, ASTM E1737), in our case do not work. As an example, two of the most frequently ordered capillary tubes were selected: 2,5x0,3 mm and 3,0x0,5 mm made of steel 12X18H10T (GOST 14162-79, group A). Tube blanks were prepared with sizes (diameter × wall thickness): 3,0x0,3 mm; 3,2x0,3 mm; 4,8x0,28 mm; 5,0x0,28 mm; 5x0,5 mm. All tubes were preliminarily heat-treated on an electrical-contact unit (ECU). Regime: heating to 10500C, air cooling.

The first four sizes were drawn on the drawing mill to the finished size 2,5x0,3 mm without intermediate heat treatments. The fifth was drawn to the size 3,0x0,5 mm. In all cases, the tolerances for diameter ±0,05 mm and wall thickness ±0,03 mm were maintained. The chemical composition of the tube blanks was similar: carbon (0,09÷0,10), nickel (9,55÷9,70), chromium (17.8÷18,0).

Table 1 presents data on the mechanical properties of the material of a 2,5x0,3 mm tube after heat treatment and drawing with different degrees of deformation. Table 2 presents analogous data for a 3,0x0,5 mm tube. As follows from Table 1, increasing the degree of cold-work of the tube up to 100% increases the tensile strength of steel 12X18H10T by almost a factor of two and reduces ductility by a factor of ten. The question is: is this good or bad for the in-service reliability of the tubes themselves?

To answer this question, we will use an experimental–calculation method for identifying metals with respect to in-service reliability in the form of a genome-forming matrix of seven parameters [1,2]:

1. *In this document, the term "cold-worked" refers to the "nagartovannoe" condition, i.e., a material state obtained by* ***cold plastic deformation*** *that produces* ***strain hardening (work hardening)****, without heating to recrystallization temperatures.*

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

Here σ_b is the ultimate tensile strength of a flat or round specimen at the specified strain rate and test temperature **T**; σ_{02} is the yield strength[2] ; δ_5 is the 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 [3]. 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. Hence, the larger the value of A_* at given loads, the higher the in-service reliability of the material under consideration.

Determination of σ_b, σ_{02} and 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 formulas [1]:

in the case of tension of a flat specimen

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

in the case of tension of a round specimen

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

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

Taking into account $\dot{e}$=0,25·10^{-2} 1/s, according to GOST 1497-84 and GOST 10006-80, Tables 1 and 2 provide values of μ and A* obtained using formulas (3), where for steel 12X18H10T the following values were adopted [4]: E=210 GPa, ρ=7,9 g/cm3, c=5156 m/s. Analyzing the data of Tables 1 and 2 with respect to the specific fracture energy A*, we conclude that the level of in-service reliability and crack resistance of capillary tubes decreases with the degree of cold-work. It is reasonable that, under intensive deformation of steel 12X18H10T without intermediate heat treatments, the formation of local crack-initiation zones increases significantly. Note that in GOST 14162-79 for capillary tubes supplied in the cold-worked condition, mechanical properties are not specified. From the data of Tables 1 and 2, it follows that it is necessary to limit the degree of cold-work of tubes in order to maintain a high level of in-service reliability. At the same time, as the degree of cold-work of tubes made of steel 12X18H10T increases, the level of magnetization of the material increases. In the initial, heat-treated condition, 2,5x0,3 mm tubes are non-magnetic. The grain size of the microstructure of specimen No. 3 (Table 1) is larger (7 points) compared to specimen No. 4 (Table 1), where it is 9 points. In this case, the grains of the austenitic steel in specimen No. 4 are elongated in the drawing direction.

2. *In this document, the term "yield strength" refers to the "predel tekuchesti" and is used in the standard engineering sense as the* ***stress at which plastic deformation begins****; where applicable, it is understood as the 0.2% proof stress (Rp0.2) if the yield point is not distinctly defined.*

Let us consider the product range of tubes whose production is governed by the specifications: TU14-3-837-79, TUU 14-8-37-2001, TU1740-577-568978-35-2013: Seamless cold-deformed capillary tubes made of alloy EP648(KhN50VMTIuB). These normative documents apply to the supply of extra-thin-walled tubes made of the precipitation-hardened alloy EP648, intended for the manufacture of high-temperature heat exchangers and aerospace products. The question of their crack resistance is relevant.

Table 3 presents the mechanical properties of 5x0,3 mm and 2,5x0,3 mm tubes made of alloy EP648, obtained in tension tests of tubular specimens 200 mm long, in accordance with GOST 1497-84 at $+20^0$C and =0,25·10-2 1/s. Using formulas (3), the parameters μ and $\mathbf{A}_*$ were determined at E=230 GPa, ρ=8,5 g/cm3, c=5202 m/s. From Table 3 it follows that heat treatment of tubes made of alloy EP648is important for increasing in-service reliability. At the same time, cold-worked 2,5x0,3 mm tubes are non-magnetic, in contrast to 2,5x0,3 mm tubes made of corrosion-resistant steel 12X18H10T.

It is known that seamless cold-deformed aluminum tubes and tubes made of aluminum alloys are widely used in the aerospace industry. The chemical composition and mechanical properties of the applied materials are regulated by standards (GOST, OST, ASTM, DIN). For example, GOST 18475-82: Cold-deformed tubes made of aluminum and aluminum alloys; OST 1.90038-88 and OST 1.92096-83: Aviation tubes made of aluminum alloys. Obviously, the issue of in-service reliability of the tubes under consideration is currently highly relevant.

Let us consider a practical example of the supply of 6x1 mm and 16x1 mm tubes made of alloy 5052 (analog of AMg2) and 22x1 mm tubes made of alloy 6A02 (analog of AV) manufactured in the PRC. Table 4 provides the mechanical properties of these tubes at $+20^0$C at the time of delivery. From the data of Table 4 it follows that, in terms of mechanical properties, the tube material does not meet the requirements of GOST 18475-82 and OST 1.90038-88. Conclusion: the tubes were delivered in the cold-worked condition, without the appropriate heat treatment.

In order to launch them into main production, it is necessary to perform heat treatment so that the mechanical properties comply with GOST and OST. Table 5 presents heat treatment regimes for 6x1mm tubes (AMg2) and data from tensile tests of tubular specimens 200 mm long up to fracture at $+20^0$C, according to GOST 1497-84. From Table 5 it follows that all variants of the heat treatment regimes for 6x1 mm tubes satisfy the requirements of GOST 18475-82. And here the main question in the physics of metals is: by what criterion should “correct” heat treatment be determined so that the tubes have the highest in-service reliability?

Let us again refer to matrix (1). Using formulas (3) at $\dot{e}$=0,25·10^{-2} 1/, E=70 GPa, ρ=2,7 g/cm3, c=5092 m/s, we obtain numerical values for the specific fracture energy $\mathbf{A}_*$ and the coefficient of dynamic viscosity μ. The mechanical properties of 6x1 mm tubes made of alloy AMg2 under various heat treatment regimes and the values of μ and $\mathbf{A}_*$ are presented in Table 5. From this table it unambiguously follows that the optimal heat treatment option is item 3: heating to 370^0C, holding for 10 min., air cooling. In this case, we have the maximum value of the parameter $\mathbf{A}_*$=274 GJ/m2, compared to the initial condition $\mathbf{A}_*$=98 GJ/m2. Similarly, using matrix (1), it is feasible to determine energy-efficient heat treatment regimes for 16x1 mm tubes (alloy AMg2) and 22x1 mm tubes (alloy AV) with a high level of crack resistance.

Analyzing normative and technical documents of domestic and foreign publications (GOST, OST, ASTM, DIN) for all rolled metal products (bar, sheet, tubes, rails…), a natural question arises: from which physical postulates were the specific numerical values determined that impose certain limits on the ultimate tensile strength $\boldsymbol{\sigma}_\mathbf{b}$, yield strength $\boldsymbol{\sigma}_{\mathbf{02}}$, elongation $\boldsymbol{\delta}_\mathbf{5}$, impact strength $\mathbf{A}_*$, fracture toughness $\mathbf{K}_{\mathbf{1c}}$, and endurance limit $\boldsymbol{\sigma}_{\mathbf{-1}}$?

At the same time, the basic provisions in the listed documentation, at least for GOST and OST, were developed during the period (1960–1970) and were subsequently only extended, without changing the essence. It should be noted that the calculation–experimental method for identifying metals (1)–(3) is based on modern achievements in fracture mechanics [5] and, in the author's opinion, makes a fundamental contribution to metallurgy. The economic effectiveness of the method is illustrated in [1]. Obviously, the existing GOST, OST, TU, ASTM, and DIN in the field of certification of rolled metal products with respect to in-service reliability require refinement or replacement.

Moreover, based on the data of Table 5, the recommended heat treatment regimes for rolled metal products should be reconsidered considering matrix (1). At present, the criterion of optimal heat treatment is considered to be compliance with the requirements for mechanical properties, including impact strength. In this case, we have several degrees of freedom in technological chains that are not always optimal in terms of energy consumption and, again, in-service reliability. The parameters μ and $\mathbf{A}_*$ indicate the correct choice.

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Table 1. Mechanical properties of the 2,5x0,3 mm capillary tube made of steel 12X18H10T at various degrees of cold work.

No.	Drawing route	σb, (MPa)	σ02, (MPa)	δ5, (%)	μ, (GPa·s)	A* (GJ/m^2)
1.	2,5x0,3 мм (initial, after heat treatment)	720	368	40	46,9	1021
2.	3,0x0,3 мм →2,5x0,3 мм (20% deformation)	1022	852	10	22,7	515
3.	3,2x0,3 мм→2,5x0,3 мм (28% deformation)	1136	975	6,0	21,5	382
4.	4,8x0,3 →2,5x0,3мм (92% deformation)	1250	1022	5,0	30,4	385
5.	5,0x0,3 мм→2,5x0,3 мм (100% deformation)	1335	1174	4,0	21,5	352

Table 2. Mechanical properties of the 3,0x0,5 mm capillary tube made of steel 12X18H10T.

No.	Drawing route	σb, (MPa)	σ02, (MPa	δ5, (%)	μ, (GPa·s)	A* (GJ/m2)
1.	3,0x0,5 мм (initial, after heat treatment)	760	410	49	46,7	1396
2.	5,0x0,5 мм →3,0x0,5 мм (67% deformation)	1168	1062	9	14,1	605

Table 3. Mechanical properties of tubes made of alloy EP648 (KhN50VMTIuB). at $+20^0C$.

No.	Tube size	σb, (MPa)	σ02, (MPa)	δ5, (%)	μ, (GPa·s)	A* (GJ/m2)
1.	5x0,3 мм	880	522	41	47,7	143
2.	2,5x0,3 мм	1013	596	37	55,6	172
3.	2,5x0,3 мм (without heat treatment)	1506	1278	5	30,4	51

Table 4. Mechanical properties of tubes made of aluminum alloys (AMg2, AV) manufactured in the PRC at the time of delivery (07.07.2025г., Dnipro).

No.	Alloy	Tube size	σb, (MPa)	σ02, (MPa)	δ5, (%)	Requirements for annealed tubes					
						GOST 18475-82			OST 1.90038-88		
						σb, (MPa)	σ02, (MPa)	δ5, (%)	σb, (MPa)	σ02, (MPa)	δ5, (%)
1.	AMg2	6x1	310	290	7	155	60	10	155-215	---	15
2.	AMg3	16x1	312	293	7	155	60	10	155-215	---	15
3.	AV	22x1	242	205	19	not more than 145	---	17	---	---	---

Table 5. Mechanical properties of 6x1 mm tubes made of alloy AMг2 (5052) under various heat treatment regimes.

No.	Heating (0C)	Holding time (min)	σb, (MPa)	σ02, (MPa)	δ5, (%)	A* (GJ/m2)	μ, (GPa·s)
1.	300	20	225	105	31	228	16,0
2.	300	40	222	90	31	222	17,6
3.	370	10	232	116	35	274	15,5
4.	370	20	227	118	34	253	14,5
5.	370	40	227	118	33	246	14,5
6.	370	60	225	116	30	220	14,5
7.	370	90	237	116	30	244	16,1
8.	370	120	231	116	30	232	15,3
9.	Initial condition		310	290	7	98	2,7