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Methods of Increasing the Strength of Metals and Their Impact on Operational Reliability

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Abstract—Based on examples of experimental data on increasing the strength of metals through combined thermomechanical processing (MTP, TMP, NHTMP, HTMP, TMMP), an experimental computational method for identifying metals with respect to operational reliability is proposed. A material matrix of seven physically justified parameters, easy to determine, has been defined. Specific examples of the method's efficiency for structural alloy steels are provided.

Keywords: parameter matrix, metal identification, combined methods of thermomechanical processing
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Methods for increasing the strength [1] of structural low-alloy steels through combined thermomechanical processing (TMP) are known, as well as technological methods for increasing static and cyclic strength, heat resistance of metals and alloys based on these methods. In [2], it is stated that the optimum structural state leading to the greatest strengthening of the metal is the creation of a structure that ensures uniform energy absorption by the crystal lattice and maximum energy capacity of individual volumes of the metal during deformation.

In addition to traditional heat treatment methods (annealing, quenching), the following combined methods [2] are known today: TMP, mechanical-thermal processing (MTP), low-temperature thermomechanical processing (LTMP), high temperature thermomechanical processing (HTMP), thermomechanical magnetic processing (TMMP), thermal magnetic processing (TMP). The MTP used to improve properties, unlike TMP, is not associated with polymorphic transformation of the worked material.

Experience shows that for each metal, there is an optimal degree of deformation and annealing temperature that provide the highest heat resistance after MTP. This allows for establishing optimal MTP parameters for each considered material. However, the question of the influence of these processing methods on crack resistance and operational reliability as a whole remains open. It is not excluded that in some cases, while increasing the strength of the material through combined processing, the indicators of endurance limit and crack resistance may decrease.

To answer these questions, we will turn to the developed method of metal identification [3], where the material itself is considered as a matrix of seven physically justified and easy-to-determine parameters:

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

Here, σ_u is the ultimate tensile strength of a flat or round specimen at a given deformation 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 energy of fracture. The parameter A^* is an integral value of the specific work for crack formation and propagation, essentially determining the level of material crack resistance. The coefficient μ characterizes internal friction in the metal and significantly depends on the micro- and macrostructure. According to definition [3], the higher the values of μ and A^* at given loads and temperatures, the higher the operational reliability of the material under consideration when used in specific products. Accordingly, the indicators of metal endurance limit and crack resistance are higher.

The determination of σ_u, σ_{02}, δ_5 is carried out in accordance with State standards GOST 1497–84, GOST 10006–80 during tension of flat or round specimens until failure. The quantitative assessment of μ, A^* is determined as follows:

in the case of tension of a flat specimen

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

in the case of tension of a round specimen

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

Table 1. Influence of mechanical-thermal processing (MTP) of alloy steels on their operational reliability

No.	Material	Material state	σ_u, MPa	σ_{02}, MPa	δ_5, %	μ, GPa s	A^*, GJ/m^2
1	EI617	Initial	1156	724	24.6	86.4	651
		After tension by 1% at 600°C	1173	821	20.7	70.4	704
		After tension and annealing during 100 h at 600°C	1215	885	19.5	66.0	771
2	EI437	Initial	928	668	22.1	52.0	498
		After tension by 0.3% at 600°C	1079	719	17.1	72.0	446
		After tension and annealing during 100 h at 600°C	1126	752	21.5	74.8	614
3	10Kh18N9	Initial	715	228	57.5	97.4	151
		After tension by 10% at 600°C	721	289	58.6	86.4	247
		After tension and annealing during 100 h at 600°C	774	394	43.3	76.0	339

Here, E is the Young's modulus, c is the speed of sound of longitudinal waves.

In publication [2], fundamental research by domestic and foreign authors on increasing the strength of metals using combined modes, listed above, is summarized. Let us consider the known experimental data in light of Eqs. (1)–(3). For example, in [2], Table 4 presents studies on the influence of MTP on the mechanical properties of heat-resistant alloys EI617, EI437, and regular stainless steel 10Kh18N9. Plastic deformation during MTP was carried out by tension of flat specimens at 600°C with a deformation rate of $\dot{e} = 0.25 \times 10^{-2}$ L/s to final deformations of 0.3–10.0%. After active tension, the specimens were held in an unloaded state at 600°C for 100 hours.

Table 1 presents data on the mechanical properties of EP617, EP437, 10Kh18N9 in the initial state and after MTP. Knowing the values of σ_u, σ_{02}, δ_5 from Table 1, we calculate the parameters μ, A^* using Eq. (2) with fixed values of $\dot{e} = 0.25 \times 10^{-2}$ 1/s, $E =$ 200 GPa, $c = 5050$ m/s and record the numbers into Table 1. From the data of μ, A^* in Table 1 for EI617, 10Kh18N9 after MTP, a decrease in μ and an increase in A^* were obtained. The alloy EI437 behaves differently: an increase in μ and a "drop" to min $A^* =$ 446 GJ/m^2 during tension by 0.3% at 600°C. A clear decrease in crack resistance level. In all cases, an increase in the strength properties of the steels under consideration is observed.

It is known [2] that when thermomechanical action is applied to the metal, physicochemical processes are activated, leading to the formation of a certain structural state for each type of treatment. The main strengthening factors considered are: increasing the density of dislocations; creating dislocation barriers; reducing grain size; increasing the degree of dispersion of secondary phases; polymorphic transformations. Hence, it follows that the nature of the change in the viscosity coefficient μ after MTP for steels has many degrees of freedom. It can be assumed that with an increase in the specific fracture work A^* and a decrease in μ, the density of dislocations increases or the grain size decreases.

Let us consider to experiments on HTMP of structural steels. HTMP of quenchable steels is carried out according to the following scheme [4]: austenitization at 1050–1200°C; cooling to temperatures not lower than the A_3 point; plastic deformation by 25–30% at a temperature above the A_3 point; immediate quenching in water or oil; low-temperature tempering at 100–200°C. The main goal of plastic deformation during HTMP is to create a fine-grained structure in the initial austenitic structure.

The data on the mechanical properties of structural steels 03Kh8, 27Kh8, 47Kh8, 50KhN4M, and tool steel N11 in their initial state (numerator) and after HTMP (denominator) are summarized in Table 2 ([2], Table 7). As in the first case, the values of μ and A^* were calculated using Eq. (2). Analysis of Table 2 reveals an increase in the strength characteristics of σ_u, σ_{02}, and the specific fracture energy A^* after HTMP in all cases. However, the dynamic viscosity coefficient μ shows the opposite trend. Only steel 50KhN4M experienced an increase in μ from 117.6 to 141.2 GPa s. For the other steels, a decrease in μ was observed, especially for steel 47Kh8, which decreased by nearly 7 times. This fact still needs further investigation. In [2] it was mentioned that the most beneficial effect of HTMP is the significant increase in the strength properties of the steel while simultaneously improving the combination of strength and plasticity.

The LTMP of steels is carried out according to the following technological scheme [4]: austenitization at 1000–1100°C, cooling to the temperature range of metastable austenite existence below the recrystallization initiation temperature, plastic deformation at 75–95% strain at this temperature, water or oil quenching, and low-temperature tempering. The main difference

Table 2. Influence of high-temperature thermomechanical processing (HTMP) of structural steels on their operational reliability

No.	Material	σ_u, MPa	σ_{02}, MPa	δ_5, %	μ, GPa s	A^*, GJ/m^2
1	03Kh8	980/1323	921/1274	10/8.5	11.8/9.8	428/697
2	27Kh8	1421/1960	1313/1911	8.3/8.6	21.6/9.8	723/1586
3	47Kh8	1960/2303	1490/2234	6.0/8.3	94.0/13.8	673/2092
4	50KhN4M	2352/2646	1764/1940	5.0/9.0	117.6/141.2	786/1710
5	N11	2127/2254	1656/2078	7.0/8.0	94.2/35.2	969/1744

In the numerator are values at standard heat treatment, in the denominator—after HTMP.

Table 3. Influence of low-temperature thermomechanical processing (HTMP) of structural steels on their operational reliability

No.	Steel	σ_u, MPa	σ_{02}, MPa	δ_5, %	μ, GPa s	A^*, GJ/m^2
1	50KhN4M	1372/2548	980/1715	5/8	78.4/166.7	242/1188
2	40KhN5S	1891/2078	1205/1676	8/5	137.2/80.4	587/709
3	31KhN5S	1989/2254	1539/2009	3/1.5	90.0/49.0	359/306
4	40KhN7S	2332/2646	1509/1823	8/6.5	164.6/164.6	920/1091
5	42KhN5S	1813/2264	1411/2009	2/1.5	80.4/51.0	201/306

In the numerator are values at standard heat treatment, in the denominator—after LTMP.

between LTMP and HTMP is the cooling delay of the austenitized steel in the supra-martensitic temperature range and the deformation of the austenite in the metastable state.

Let us consider the experimental data (see [2], Table 10) on the influence of LTMP on the mechanical properties of structural steels. Table 3 presents σ_u, σ_{02}, and δ_5 values for five steels: 50KhN4M, 40KhN5C, 31KhN5C, 40KhN7S, 42KhN5S, as well as the calculated values of μ and A^*. From Table 3, it can be seen that LTMP significantly increases both the strength properties and the parameters μ and A^* for steel 50KhN4M. In other cases, this is not true regarding μ and A^*. For example, steel 31KhN5S experienced a decrease in plasticity and μ, A^*.

There are other types of strengthening treatments for steel, such as TMMP and TMP. They involve subjecting the steel to an electromagnetic field during quenching at the moment of austenite transformation into martensite. According to data from [2], Table 19, Table 4 presents the mechanical properties of alloyed steels after standard heat treatment (numerator) and after "thermomagnodynamics" (denominator), as well as the values of μ and A^* calculated using Eq. (2) for the given σ_u, σ_{02}, and δ_5. For four steels, there is an increase in strength properties while maintaining plasticity. Additionally, the specific fracture energy A^* and the dynamic viscosity coefficient μ also increased, except for steel 4340, where μ decreased by more than 3 times. The yield strength σ_u decreased by ~12% while maintaining σ_{02}. It is evident that the applied method is not optimum for steel 4340.

It should be noted that the development of the matrix identification concept (1) was based on the fundamental principles of fracture mechanics. The main hypotheses [5] were used: metal deformation is simulated in an isotropic viscoplastic medium with a nonzero strain rate, and the failure criterion is energy-based. The dimension of parameter A^* coincides with the dimension of impact viscosity A_k, but it

Table 4. Influence of thermomechanical processing (TMP) of alloyed martensitic steels on their operational reliability

No.	Steel	σ_u, MPa	σ_{02}, MPa	δ_5, %	μ, GPa s	A^*, GJ/m^2
1	4130 (chromium-molybdenum)	1617/1989	1509/1578	10/11	21.6/82.2	1150/1383
2	4340 (chromium-nickel-molybdenum)	2568/2293	1852/1852	11/11	143.2/44.1	1905/1905
3	6150 (chrome vanadium)	2048/2568	1813/2136	10/9	47.0/86.4	1660/2074
4	6152 (chrome vanadium)	1921/2470	1686/2029	9/9	47.0/88.2	1292/1871
5	431 (stainless)	1235/1852	857/1235	17/10	75.6/123.4	630/770

In the numerator are values at standard heat treatment, in the denominator—after TMP.

Table 5. Experimental data of endurance limit, mechanical properties of steels [1] and calculated values of dynamic toughness coefficient and specific energy of fracture

No.	Steel	σ_u, MPa	σ_{02}, MPa	δ_5, %	σ_{-1}, MPa	μ, GPa s	A^*, GJ/m^2
1	15kp	380	230	0.27	180	30.0	72.1
2	08GSYuT	540	403	0.30	250	27.4	246.0
3	15G2AF	532	410	0.32	250	34.4	271.6

has a fundamentally different physical meaning and is not related, for example, to the configuration of a "notch" on the sample. Essentially, matrix (1) defines the genome of the metal.

By comparing matrices, conclusions can be drawn about the operational reliability of the material. For example, Table 5 presents experimental data on the fatigue limit for steels 15kp, 08GSYuT, 15G2AF after 10^7 cycles, as well as their mechanical properties during tensile testing of flat specimens [1]. Parameters μ and A^* were calculated using Eq. (2) for the considered steels with $E = 200$ GPa, $c = 5050$ m/s, and $\dot{e} = 0.25 \times 10^{-2}$ L/s, according to State standard GOST 1497–84. Comparing the corresponding matrices for each steel in Table 5 leads to the unambiguous conclusion that steel 15G2AF has the highest operational reliability compared to other steels. For steel 15G3AF, the highest values of $\mu = 34.4$ GPa s and $A^* = 271.6$ GJ/m^2 were obtained. There is no clear answer regarding the fatigue limit σ_{-1} from Table 5.

Thus, matrix (1) provides the engineer–researcher with a sufficiently informative tool for evaluating the influence of technological routes and types of heat treatment on the operational properties of the obtained material. See, for example, [6] regarding titanium alloys. Also, note the work [7], which presents a thermodynamic theory of viscoplasticity valid for a wide range of deformation rates and temperatures. It is shown here that when explaining the sensitivity of viscoplastic materials to changes in strain rates, two mechanisms are most significant: thermal activation and dislocation damping caused by phonon viscosity.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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