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SIMPLE ANALYTICAL DEPENDENCE OF ELASTIC MODULUS ON HIGH TEMPERATURES FOR SOME STEELS AND ALLOYS

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ABSTRACT

Modules of elasticity are the most important physical quantities, included in the various engineering calculations at the determining of the strength and stability of machine parts and constructions and the natural frequencies of the moving parts of machines and mechanisms. The knowledge of them is necessary for the metallurgical technological calculations. The accuracy of the determining of the values of the elastic modules and their changes due to the influence of various factors is of great interest, since the requirements for the reliability of the metallurgical and engineering products, saving in materials and reducing the weight of constructions have increased. For the investigating of the stress state of the solidifying ingots (without which it is impossible to choose the optimal technological regimes of their production) and the designing of metal equipments, the information about the values of the elastic modules and the rheological behavior of metals and alloys at high temperatures is necessary. The investigations of the influence of various factors, including temperature, on the elastic modules of metals are extremely important. The mechanical properties of metals and alloys (for example, strength, plasticity, toughness, and others) depend on both microstructure (number of phases, their dispersion, distribution, mutual arrangement) and substructure (defects of crystal structure, their density, mobility, interaction with each other and with the atoms of impurities) and are in a certain way connected with the interatomic interactions in metals. Therefore, the correlations between the mechanical properties and the elastic modules of materials are not accidental. In this paper, based on the analysis of experimental data about the dependence of the elastic modulus of elasticity (young modulus) for various steels and alloys, the analytical dependence of the elastic modulus on temperature for the heat-resistant steels and alloys, used in the production of steel sheets and steel pipes of large diameter for main pipelines, is obtained. The results of investigation can be widely used in the metallurgical and machine-building plants.

1. Elastic properties of steels

To describe the elastic properties of the isotropic and polycrystalline (quasi-isotropic) bodies [1–37], we use the normal elastic modulus (young modulus) E, the shear modulus G, the all-round compression modulus (the volume compression modulus) K, the compressibility $æ = 1/K$ and the Poisson ratio μ, which are related to each other by known relations of the ideal elasticity theory:

$$E = \frac{18KG}{6K + 2G}, \quad \mu = \frac{3K - 2G}{6K + 2G}.$$

The reverse dependencies have the form

$$K = \frac{E}{3(1 - 2\mu)}, \quad G = \frac{E}{2(1 + \mu)}.$$

The force influence on the body causes a deformation in its material, the quantitative description of which is possible with the help of Hooke's law. For the isotropic material under the single-axis longitudinal stretching (compression), the Hooke's law has the form [1–3, 14–17]

$$\sigma = E\varepsilon,$$

where σ is a stress, ε is a relative deformation.

The study of the behavior of the elastic waves in bodies showed that the velocities of their spreading are functionally related to the above modules.

For the infinitely long beams, the propagation velocity of longitudinal wave v_{long} and shear wave v_{shear} are described by expressions [1–3, 32]:

$$v_{long} = \sqrt{\frac{E}{\rho}}, \quad v_{shear} = \sqrt{\frac{G}{\rho}},$$

where ρ is the density of the material.

The velocity of the propagation of longitudinal wave in an unbounded isotropic medium is expressed through the elastic constants in the form:

$$v_{long} = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}}.$$

The modern methods of determination of elastic modulus are mainly based on the direct measurement of the quantities associated with the elastic characteristics and their derivatives. Measuring the stresses and corresponding deformations in the body, we find the static (isothermal) values of elastic modules. Measuring the propagation velocity of the elastic waves in the body, we determine the dynamic (adiabatic) values of the elastic modules.

The elastic modules are included in all the equations of the mechanics of deformable rigid body and associated with other physical quantities. For example, for an ideal elastic medium, the physical relations of the generalized Hooke's law has the form [1–3, 26–30]

$$\sigma_{ij} = 2G\left(\varepsilon_{ij} + \left(\frac{3K}{2G} - 1\right)\varepsilon g_{ij}\right),$$

where σ_{ij} and ε_{ij} are the components of the stress tensor and deformation tensor, $\varepsilon = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$ is the average deformation.

For an ideal elastic medium, the Lame's equations of motion have the form [14–17, 26–30]

$$\rho\frac{dv_i}{dt} = F_i + G\nabla^2 u_i + \frac{3K+G}{3}\nabla_i(\nabla_k u^k),$$

where v_i are the components of the velocity vector, u_i and u^k are the components of the displacement vector, $\Delta = \nabla^2$ is the Laplace's operator (Laplacian), ∇_i is an absolute (covariant) derivative of the components of a tensor of the first rank.

2. Methods for determination of elastic properties of steels

Depending on the deformation velocity of the body, the methods for the determining of the elastic modules are conditionally divided into the static, dynamic and impulse methods [1–3, 31, 32, 35]. The specificity of the definition of elastic modules is that they are not directly measured. To do this, we use the phenomena in which the elastic modules are associated with various properties which can be directly measured.

The determination of the elastic modulus by the static method is associated with the measurement of the elastic component of deformation at low relative velocities of deformation (£1...10 s^{-1}) [31, 32]. Modules, measured by static methods, are isothermal. The values of the elastic modules, obtained by the static method, characterize not only the elastic characteristics of the material, but also the tendency to the stress relaxation. The degree of relaxation depends on the specific test conditions: the temperature, loading velocity and accuracy of load holding and so on. All this leads to the large statistical scattering of the measured values of the elastic modulus.

Besides, the static methods for determination of elasticity have the disadvantage — to obtain sufficiently accurate results, it is necessary to achieve the substantial deformation (the relative longitudinal deformation $\varepsilon \approx 10^{-3}$) in which there is a danger of going of material out the region of a linear-elastic behavior. This is particularly evident in the study of materials with low yield stress and also at high temperature measurements.

A diagram of the stretching of two steel specimens, made from the tube steels (the strength class K60), at a room temperature on the universal electromechanical testing machine Instron 5984 is shown in **fig. 1**. By means of the software Instron Bluehill 2, the yield stress σ_y and breaking point σ_b of the specimens' material can be obtained. For the first specimen σ_{y1} = 509 MPa and σ_{b1} = 609 MPa, for the second specimen σ_{y2} = 517 MPa and σ_{b2} = 615 MPa. Special software also allow us to determine the static modulus of elasticity of the specimens' material. In this case, $E \approx 2\times10^{11}$ MPa.

However, the accuracy of determination of elastic modulus (in contrast to the definition of the yield stress and breaking point) with the help of these software are far from ideal. This is due to the fact that at the initial stage of specimens' stretching, the dependence of the stress on the relative deformation is nonlinear (see fig. 1) and is not subject to the Hooke's law due to the presence of the residual stresses (that

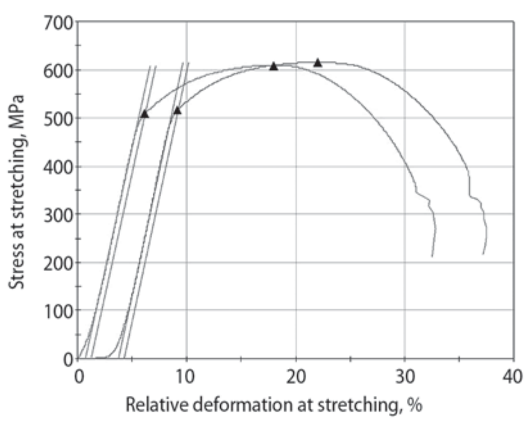

Fig. 1. Stretching diagram of two steel specimens from pipe steels at *T* = 20 °C

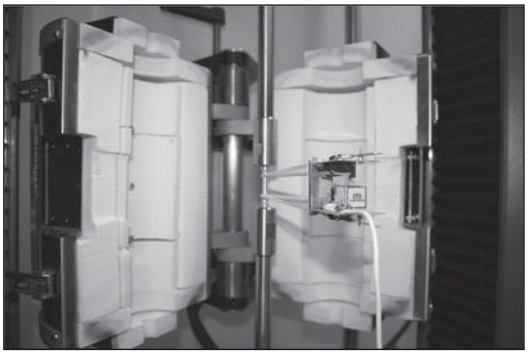

Fig. 2. The oven Instron W-8711-F for high-temperature testing of metals (from 300 °C up to 1200 °C) with extensometer port

have arisen during the specimens' manufacture) in the original specimens.

We note that the problem of a high accuracy of determination of the static elastic modulus exists in all first-rate producers of mechanical testing machines: MTS System Corporation (USA), Instron (UK), Zwick/Roell (Germany), Galdabini (Italy) [14–17, 26–30].

The special high-temperature furnaces are used to determine the static modulus of elasticity at high temperatures. The furnace Instron W8711-F for the high-temperature testing of metals (from 300 °C to 1200 °C) with a special high-temperature extensometer is shown in **fig. 2**.

One of the problems of the high-temperature mechanical testing to determine the static modulus of elasticity with high accuracy is the problem of achieving an isotropic (same) temperature on the entire surface of the tested metal specimens.

The dependence of the elastic modulus of metals and alloys on the high temperature must be taken into account in metallurgy in the hot rolling of steel sheet on sheet-rolling mills, hot flattening of steel sheet in the sheet straightening machines, press forming forgings from hot steel sheet, hot volume stamping of metal products and so on. For example, on the mill 5000 by SMS Siemag, the sheet-rolling of steel strips from the hot slabs at the stand Quarto (the maximum force of 120 MN) occurs at a temperature from 750 °C to 1050 °C, but the pre-flattening of hot steel strip on the five-roller sheet-straightening machine by SMS Siemag occurs usually in the temperature range from 600 °C to 760 °C [26–30].

The maximum relative velocity of deformation ($10^6...10^8$ s^{-1}) is achieved by means of the impulse method of measurement [31, 32]. Therefore, the obtained value of the elastic modulus is adiabatic (non-relaxed). The basis of the impulse method is the measurement of the passage velocity through the specimen the impact-elastic wave, the length of which is small compared to the size of the specimen. The spreading velocity of the longitudinal and transverse elastic waves is associated with the module of normal elasticity E. The shear modulus G is practically not measured due to the large methodological difficulties in the excitation and registration of the transverse elastic waves in the material.

The impulse method of the measuring of the elastic modulus has high accuracy. The accuracy of measurement results by this method is equal to 0.1 %. The method is widely used in the determining of the elastic characteristics of materials. However, there are a number of limitations to this method. A significant source of the systematic and random errors in the determining of the module of normal elasticity by the impulse method is the need for an intermediate measurement of the Poisson's ratio μ.

The dynamic methods of the determining of the elastic properties of materials allow to carry out measurements at a small relative deformation ($\leq 10^{-6}$) and have higher the sensitivity and accuracy compared to the static methods [31, 32]. When determining the elastic modulus of materials by the dynamic methods, the relative velocity of deformation is $10^3...10^4$ s^{-1}. The essential limitation of the use of the existing standard methods for the determining of the characteristics of the dynamic elastic modules of materials is an impossibility of their measurements at temperatures close to the melting point T_m of the material. This is due to the fact that at elevated temperatures in the material a creep appears. Herewith, the mechanical properties of the material change from elastic to viscoelastic properties.

The above-described methods allow to carry out the measurements on the homogeneous bar specimens at temperatures of 0.6 T_m. This is due to the fact that in the high-temperature region ($\theta = T/T_m > 0.6$) the deformation properties of the material are changed – the plastic deformation begins to manifest itself in the material. For example, the specimen, placed horizontally during the measurements, is bent by gravity (the neutral line of the specimen is curved). By virtue of this, the calculated dependencies cease to be fair. This is the main problem of the impossibility of using a standard specimen for measurements at temperatures above solidus (the temperature at which the low melting component of the alloy melts).

The scattering of experimental data, obtained by different authors with the help of the dynamic and static methods, increases dramatically, starting with the temperature of 800 °C ($\theta = 0.6$). At temperatures $T > 800$ °C ($\theta = 0.6$), there is a significant difference in the data obtained by different methods. At 1000°C ($\theta = 0.72$), the dynamic and static elastic modules are respectively equal to 115 GPa and 60 GPa. At the temperature of 1400 °C ($\theta = 0.96$), the decreasing of the elastic modulus in comparison with its value at a room temperature obtained by the static method is ~ 90%, but obtained by the dynamic method is ~ 50%. The lower value of the static modulus of elasticity in comparison with the dynamic one can be explained by the inelastic behavior of the alloy in the high-temperature region. The random error in the determining of the dynamic modulus of elasticity by the standard method in the high-temperature region is ~ 14%. The reliable measurements up to the temperature of alloy's solidus in this case is practically impossible.

3. Temperature dependence of elastic modulus of steels

The temperature is the most common factor influencing on the state of the system. The heating of metals can be intentional or associated with the technological operations in the manufacture of the machine details, inevitable in the operational conditions and, finally, accidental due to the temperature fluctuations of the external environment [1–37].

It is necessary to pay an attention to two features of behavior of the metal materials, caused by the temperature changes.

Firstly, one of the manifestations of heating (cooling) of solids is their thermal expansion (compression) due to the anharmonicity of the atomic oscillations. In turn, increasing the distance between atoms reduces their interaction, which must affect on the bond characteristics, including the elastic modules.

Table 1. **Dependence of elastic modulus *E* of steel grades on temperature, GPa**

Designation *E*	Grade of steel (alloy)	Temperature, °C									
		20	100	200	300	400	500	600	700	800	900
*E*1	36Х18Н25С2	200	197*	194*	191	186	178	171	162	154	147
*E*2	05ХН46МВБЧ	207	203	196	190	183	177	170	163	154	144
*E*3	ХН59ВГ-ИД	217	214	208	203	196	191	189	180	172	166
*E*4	ХН67ВМТЮ	212	208	203	197	192	185	178	170	161	151*
*E*5	ХН75ВМЮ	240	236	231	225	218	215	204	195	187	178
*E*6	ХН65КМВЮБ-ВД	230	227	222	217	211	204	200	188	181	171
*E*7	ХН64ВМКЮТ	225	222	219	214	209	201	193	186	177	168
*E*8	ХН65ВКМБЮТ	213	211	207	203	197	190	183	175	167	158

Secondly, the heating to a temperature close enough to the melting point leads the solid to an extreme (limiting) state, characterized by the instability of the crystal lattice and, therefore, by a special behavior of properties. The change in the state of a crystal lattice of metal under the influence of the thermal and power factors is determined by its deformation (changing in the interatomic distance) and is uniquely associated with the degree of changing in the elastic modules. Therefore, the quantitative regularities of the temperature dependence of the elastic modules in a wide temperature range (up to and including the melting point) are of a significant theoretical and applied interest.

The experimental data show that for different metals $E_m/E_0 = 0.35...0.55$, where E_0 is the elastic modulus at the zero temperature $T_0 = -273.15$ °C. In the polycrystalline metals into the temperature interval 0.5...0.6 T_m, the grain-boundary relaxation takes place. It is caused by an inelastic behavior of the grain boundaries. The relaxation process causes an additional deformation to the elastic deformation and therefore reduces the modulus. Therefore, the isothermal (relaxed) modulus of elasticity E_{is} differs significantly from the adiabatic (nonrelaxed) modulus of elasticity E_{ad} at the melting point. The value of the ratio E_{is}/E_{ad} at the melting point is ~ 0.85.

In the classical hand-book of steels and alloys [31], for 172 grades of steels and alloys obtained experimentally by different authors, the values of elastic modulus $E(T)$ from temperature T are given. The methods for determination of elastic modulus (the static, dynamic or impulse methods), which were used to obtain $E(T)$ at high temperatures T, unfortunately, are not specified in [31]. Only for 18 of the 172 alloys, the elastic modules are continuously given with the step $\Delta T = 100$ °C in the temperature range from 20 °C up to 900 °C. Of these 18 alloys, we excluded the alloys containing suspiciously abrupt changes (jumps and sharp bends of elastic modulus' curve) in the curvature of the elastic modulus, indicating low accuracy (or an error) of the experimental determination of $E(T)$.

Of the remaining alloys with a smooth change of the second derivative $d^2E(T)/dT^2$, we selected randomly 8 grades of steels and alloys and placed them in **tab. 1**. The values of the absent elastic modules are obtained by a linear interpolation from the given values of the elastic modules and are marked with a six-pointed asterisk * in tab. 1. The graphs of the temperature dependence of the elastic modules $E(T)$ for the steel grades from the table 1 shown in **fig. 3**.

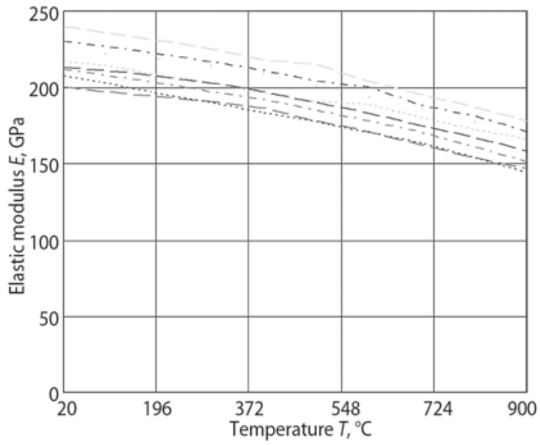

Fig. 3. Dependence of elastic modulus *E* on temperature *T* (tab. 1)

We denote by E_T the value of the elastic modulus $E(T)$ at the temperature T, °C. For example, $E2_{500} = E2(500) = 177$ GPa $= 177 \cdot 10^9$ Pa is the value of the elastic modulus E2 of the alloy 05ХН46МВБЧ at the temperature $T = 500$ °C.

The average value of the modulus of elasticity at the room temperature for the steels' grades from table 1 is equal to

$$Eav_{20} = \frac{E1_{20} + E2_{20} + E3_{20} + E4_{20} + E5_{20} + E6_{20} + E7_{20} + E8_{20}}{8}.$$

Let

$$E(T) = E_{20} + E\Delta(T), \quad E\Delta(T) = E(T) - E_{20}.$$

For example, $E2\Delta(T) = E2(T) - E2_{20}$, $E2\Delta(500) = E2\Delta_{500} = E2_{500} - E2_{20} = 177 - 207 = -30$ GPa.

The dependence of $E\Delta(T)$ on a temperature T for the grades of steels, given in tab. 1, shown in **fig. 4**. From fig. 4 we see that the curves $E1\Delta(T)$, $E2\Delta(T)$, ..., $E8\Delta(T)$ are quite tightly located to each other. The ratio of the maximum of the modulus of the difference between the values of $E1\Delta_{900}$, $E2\Delta_{900}$, ..., $E8\Delta_{900}$ to E_{20} is equal to 5 %. Therefore, they can be sufficiently accurately approximated by a single 'averaged' curve.

We calculate the average value of the functions $E\Delta(T)$ for given grades of steels at temperatures $T = 300, 500, 600, 900$ °C:

$$E\Delta av_{300} = \frac{E1\Delta_{300} + E2\Delta_{300} + E3\Delta_{300} + E4\Delta_{300} + E5\Delta_{300} + E6\Delta_{300} + E7\Delta_{300} + E8\Delta_{300}}{8},$$

$$E\Delta av_{500} = \frac{E1\Delta_{500} + E2\Delta_{500} + E3\Delta_{500} + E4\Delta_{500} + E5\Delta_{500} + E6\Delta_{500} + E7\Delta_{500} + E8\Delta_{500}}{8},$$

$$E\Delta av_{600} = \frac{E1\Delta_{600} + E2\Delta_{600} + E3\Delta_{600} + E4\Delta_{600} + E5\Delta_{600} + E6\Delta_{600} + E7\Delta_{600} + E8\Delta_{600}}{8},$$

$$E\Delta av_{900} = \frac{E1\Delta_{900} + E2\Delta_{900} + E3\Delta_{900} + E4\Delta_{900} + E5\Delta_{900} + E6\Delta_{900} + E7\Delta_{900} + E8\Delta_{900}}{8}.$$

From the experimental data [1–3, 32] follows that for steels near the melting point T_m the derivatives of the curves $E(T)$ and $E\Delta(T)$ on T are close to zero:

$$\frac{dE(T)}{dT}(T = T_m) \approx 0,$$

but the steels' elastic modules at the melting point T_m and zero temperature T_0 are connected between themselves by the ratio

$$E_m = E(T_m) \approx nE(T_0) = nE_0, \quad n = 0.5.$$

Therefore, the ratios are valid

$$\frac{dE\Delta(T)}{dT}(T = T_m) \approx 0,$$

$$E\Delta(T_m) \approx nE\Delta(T_0) - (1-n)E_{20}, \quad n = 0.5.$$

We approximate the dependence of $E\Delta(T)$ on T with the help of a polynomial of fifth order in T:

$$E\Delta_{sh}(T) = a_1(T-20) + a_2(T-20)^2 + a_3(T-20)^3 + a_4(T-20)^4 + a_5(T-20)^5,$$

$$\frac{dE\Delta_{sh}(T)}{dT} = a_1 + 2a_2(T-20) + 3a_3(T-20)^2 + 4a_4(T-20)^3 + 5a_5(T-20)^4.$$

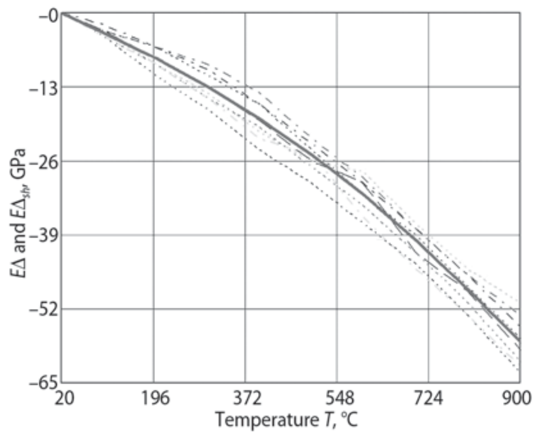

Fig. 4. Dependence of $E\Delta(T)$ (thin dotted lines, tab. 1) and $E\Delta_{sh}(T)$ (thick unbroken line) on temperature T

The boundary conditions for the determining of the unknown five coefficients a_i of the polynomial $E\Delta_{sh}(T)$ have the form

$$E\Delta_{sh}(300) = E\Delta av_{300},$$
$$E\Delta_{sh}(600) = E\Delta av_{600},$$
$$E\Delta_{sh}(900) = E\Delta av_{900},$$
$$\frac{dE\Delta_{sh}(T)}{dT}(T = T_m) = 0,$$
$$E\Delta_{sh}(T_m) = nE\Delta_{sh}(T_0) - (1-n)Eav_{20}, \quad n = 0.5.$$

Solving the obtained system of the inhomogeneous linear algebraic equations, we obtain the values of the coefficients a_i of the polynomial $E\Delta_{sh}(T)$:

$$a_1 = -0.043, \quad a_2 = -1.856\cdot10^{-7}, \quad a_3 = -4.513\cdot10^{-8},$$
$$a_4 = 1.305\cdot10^{-11}, \quad a_5 = 6.508\cdot10^{-15}.$$

The dependence of $E\Delta_{sh}(T)$ in the temperature range from 20 °C to 900 °C is shown in figure 4.

The approximation of the elastic modulus of steels has the form

$$E_{sh}(T) = E_{20} + a_1(T-20) + a_2(T-20)^2 + a_3(T-20)^3 + a_4(T-20)^4 + a_5(T-20)^5.$$

The obtained dependence of $E_{sh}(T)$ on T allows us to determine with high accuracy the elastic modulus of steels in the temperature range from 20 °C to 900 °C by the value of their elastic modulus at the room temperature ($T = 20$ °C). For example, for the steels in table 1, the relative errors in the determining of the elastic modulus with the help of the dependence $E_{sh}(T)$ at the temperature $T = 900$ °C are equal to

$$\frac{E1_{900} - E1_{sh900}}{E1_{20}} = 2.3\%, \quad \frac{E2_{900} - E2_{sh900}}{E2_{20}} = -2.6\%,$$

$$\frac{E3_{900} - E3_{sh900}}{E3_{20}} = 3.1\%, \quad \frac{E4_{900} - E4_{sh900}}{E4_{20}} = -1.6\%,$$

$$\frac{E5_{900} - E5_{sh900}}{E5_{20}} = -1.8\%, \quad \frac{E6_{900} - E6_{sh900}}{E6_{20}} = -0.6\%,$$

$$\frac{E7_{900} - E7_{sh900}}{E7_{20}} = 0.3\%, \quad \frac{E8_{900} - E8_{sh900}}{E8_{20}} = 1.2\%.$$

The dependences of $E(T)$ and $E_{sh}(T)$ on temperature T (from 20 °C to 900 °C) for the steel ХН67ВМТЮ are shown in **fig. 5**. From figure 5, we see that the curves $E(T)$ and $E_{sh}(T)$ are sufficiently closed to each other (a relative error equals 1.6 %). The dependence of $E_{sh}(T)$ on temperature T (from the zero temperature T_0 to the melting point T_m for steel ХН67ВМТЮ is shown in **fig. 6**.

In hand-book of steels and alloys [31], 29 alloys for which the experimentally found values of the elastic modules with increments $\Delta T = 100$ °C in the temperature range from 20 °C to 800 °C are given, however, the values of their elastic modules at a temperature of 900 °C are not known.

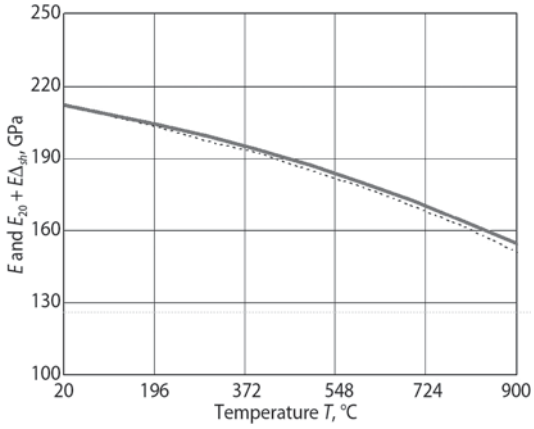

Fig. 5. Dependence of $E(T)$ (thin dotted line) and $E_{sh}(T)$ (thick unbroken line) on temperature T (from 20 °C up to 900 °C) for the alloy ХН67ВМТЮ

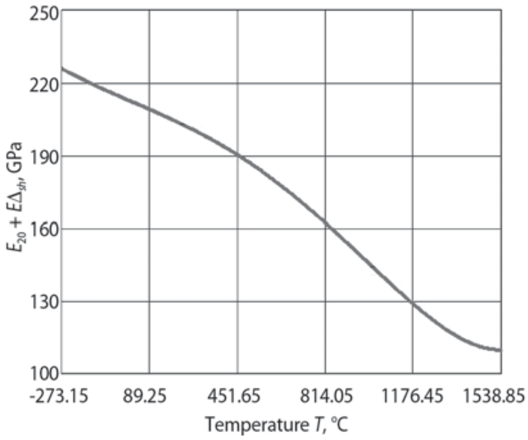

Fig. 6. Dependence of $E_{sh}(T)$ on temperature T (from the zero temperature T_0 to the melting point T_m) for the alloy ХН67ВМТЮ

Of these 29 alloys, we selected 10 alloys, having the most smooth changes of a curvature of the elastic modulus $E(T)$, and placed them in **tab. 2**. For the steels and alloys in tab. 2, the relative errors in the determining of the elastic modulus with the help of the dependence $E_{sh}(T)$ at the temperature $T = 800$ °C are equal to

$$\frac{E9_{800} - E9_{sh800}}{E9_{20}} = 3.0\%, \quad \frac{E10_{800} - E10_{sh800}}{E10_{20}} = 1.6\%,$$

$$\frac{E11_{800} - E11_{sh800}}{E11_{20}} = -3.8\%, \quad \frac{E12_{800} - E12_{sh800}}{E12_{20}} = -0.8\%,$$

$$\frac{E13_{800} - E13_{sh800}}{E13_{20}} = -0.2\%, \quad \frac{E14_{800} - E14_{sh800}}{E14_{20}} = -3.9\%,$$

$$\frac{E15_{800} - E15_{sh800}}{E15_{20}} = -2.8\%, \quad \frac{E16_{800} - E16_{sh800}}{E16_{20}} = -2.2\%,$$

$$\frac{E17_{800} - E17_{sh800}}{E17_{20}} = 1.2\%, \quad \frac{E18_{800} - E18_{sh800}}{E18_{20}} = 1.2\%.$$

Remark. It is also possible to approximate the dependence $E\Delta(T)$ using a polynomial of fourth order in T:

$$E\Delta_{sh}^{(4)}(T) = a_1^{(4)}(T-20) + a_2^{(4)}(T-20)^2 + \\ + a_3^{(4)}(T-20)^3 + a_4^{(4)}(T-20)^4,$$

$$\frac{dE\Delta_{sh}^{(4)}(T)}{dT} = a_1^{(4)} + 2a_2^{(4)}(T-20) + \\ + 3a_3^{(4)}(T-20)^2 + 4a_4^{(4)}(T-20)^3.$$

However, the accuracy of the determining of $E\Delta(T)$ falls in this case.

The boundary conditions for the determining of the unknown four coefficients a_i of the polynomial $E\Delta_{sh}^{(4)}(T)$ have the form

$$E\Delta_{sh}^{(4)}(500) = E\Delta av_{500}, \quad E\Delta_{sh}^{(4)}(900) = E\Delta av_{900},$$

$$\frac{dE\Delta_{sh}^{(4)}(T)}{dT}(T = T_m) = 0,$$

$$E\Delta_{sh}^{(4)}(T_m) = nE\Delta_{sh}^{(4)}(T_0) - (1-n)Eav_{20}, \quad n = 0.5.$$

Solving the obtained system of the inhomogeneous linear algebraic equations, we obtain the values of the coefficients a_i of the polynomial $E\Delta_{sh}^{(4)}(T)$:

$$a_1^{(4)} = -0.049, \quad a_2^{(4)} = 1.994 \cdot 10^{-5},$$
$$a_3^{(4)} = -7.675 \cdot 10^{-8}, \quad a_4^{(4)} = 3.706 \cdot 10^{-11}.$$

4. Conclusions

On the basis of the experimental data, the analytical dependence of the elastic modulus of steels, used in the produc-

Table 2. **Dependence of elastic modulus *E* of steel grades on temperature, GPa**

Designation E	Grade of steel (alloy)	Temperature, °C									
		20	100	200	300	400	500	600	700	800	900
*E*9	ХН60ВТ	218	–	–	–	204	198	192	184	176	160
*E*10	ХН55ВМТКЮ-ВД	218	–	–	–	–	–	–	181	173	163
*E*11	ХН65ВМТЮЛ	222	214	210	202	195	190	184	174	165	160
*E*12	06ХН28МДТ	195*	191	186	179	171	161	156	151	145	–
*E*13	ХН35ВТР	206	–	186	–	177	167	167	157	157	–
*E*14	ХН65ВМТЮ	219	–	206	201	196	193	183	176	162	–
*E*15	ХН70ВМТЮ	196	–	–	–	–	–	162	147	142	127
*E*16	ХН73МБТЮ	203	–	–	–	–	177	177	160	150	–
*E*17	ХН60КВМЮТ	210	207	203	198	192	185	178	171	164	–
*E*18	ХН65КМВЮТ	210	207	203	198	192	185	178	171	164	–

tion of steel sheets and steel pipes of large diameter, on the high temperatures is obtained. The results of the investigation can be used in the machine-building and metallurgical plants [1–37].

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