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THE INFLUENCE OF STRAIN RATE ON THE STRENGTH THE CONSTRUCTIONAL LOW-ALLOY STEEL

The article presents the results of the influence strain rates on the increase in strength of tested constructional steel. Elastic deformation simply involves stretching of atoms away from their equilibrium separation. Plastic deformation occurs through collective movement of atom planes. Therefore, you should first estimate the stress required to move one plane across another. The dislocations are the basis for plastic deformation. The formation and interaction of dislocations require an analysis of the issues of plastic deformation, the effect of temperature, strain rate and the stress-strain. Johnson and Cook proposed the unified constitutive laws. The Equation Johnson and Cook includes a strain hardening term, a strain-rate term, and a temperature-dependence term. This equation describes well the results of research. Studies have shown that the growth strain rate very substantially affect the increase in strength properties of the constructional steel 15G2ANb.

Keywords: *steel, dynamic properties of steel, strain rate, dislocations*

Introduction. Experimental studies showed that the increase in the load rate, and hence in the strain rate, results in an increase in the yield point. Determining the dependence of the strength of the brittle material on the load rate causes the problem to become complex. Increase of the strength of material due to additional inertia resistance is to be estimated. Increasing the load rate will make the material more brittle.

The elastic deformation consists in stretching the crystal lattice without disturbing its equilibrium. This strain is due to the movement of atomic planes. Therefore, the values of the stresses causing the displacement of the planes relative to each other should be determined. Dislocations play a key role in plastic deformation. Studies have shown that the stresses needed to displacement dislocation are much less than the stresses needed to completely move the plane relative to its neighborhood.

Due to the fact that dislocations cause real deformation, the stress values are 10÷100 times smaller than theoretical shear stresses. The problem of dynamic loading of samples is still open, for varying load rates. In this work, a preliminary diagnosis of this problem was made on the example of steel intended for shipbuilding. The aim of the study was to perform dynamic stretching tests and assess dynamic characteristics of ship materials at different strain rates.

The paper presents the theoretical basis of the problem and the influence of the load rate on the physical characteristics of the material, so called material sensitivity effect on the strain rate.

The basis of the materials strain. The problem of plastic deformation, influence of temperature, strain rate, dependence of the stress from the strain requires analysis of the formation and interactions of dislocation.

Dislocation density ρ_D is the length of dislocation lines (m) per unit volume (m^3).

The estimation of strain associated with dislocation motion is consider on a sample subjected to a static tensile test with a rectangular cross-section of 2,0×10 mm and a length of 50 mm.

The volume of the sample is $V = 1000\ \text{mm}^3 = 10^{-6}\ \text{m}^3$.

Assume, for the specimen is copper, Burgers vector is $b = 0{,}256\cdot10^{-9}$ m, for ferrite $b = 0{,}248\cdot10^{-9}$ m, and for molybdenum $b = 0{,}2725\cdot10^{-9}$ m. The strain due to motion of dislocation is [1]:

$$\varepsilon = \rho_D b l, \tag{1}$$

where l — distance moved by the dislocations.

The form of the equation Orowan is obtained by the differentiate of the expression (1) relative to time [1–4, 8, 9]. $d\varepsilon/dt = \dot{\varepsilon} = \rho_D b v$, where v is the average dislocation velocity.

If the molybdenum specimen has a single dislocation of 2 mm length (thickness of the specimen), which moves 10 mm (entire width of the specimen), the strain value is:

$$\varepsilon = \rho_D b l = \frac{0{,}002\,\text{m}}{10^{-6}\,\text{m}^3}(0{,}2725\cdot10^{-9}\,\text{m})\times$$
$$\times(0{,}010\,\text{m}) = 5{,}45\cdot10^{-9},$$

from this it follows that a single dislocation causes very small amount of strain. The actual deformation occurring in the mechanical test will be obtained if the movements of millions and billions of dislocations are taken into account [1].

The simplest model expressing the dependence of stress-strain can be written in the form of energetic law [1]:

$$\sigma = K\varepsilon^n, \tag{2}$$

where ε — strain; *K*, *n* — constants, for example, $n \cong 0,5$ — for some coppers and $n \cong 0,15$ — for some steels [1].

Based on equation (2) the stress value is zero at zero strain. This indicates the disatvantage of this equation Ludwig's equation is a modification of dependency (2) [1]:

$$\sigma = \sigma_0 + K\varepsilon^n, \tag{3}$$

where σ_0 —yield point.

However, in the equation (2) and in equation (3) there isn't the dependence stress on strain rate. The simplest model the dependence stress on the strain rate can be written as [1]:

$$\sigma = C \cdot \dot{\varepsilon}^m, \tag{4}$$

where *C, m* — constants.

For austenitic stainless steels, *m* is on the order of 0,035.

Based on equations (2) and (3) and additional terms, Johnson–Cook's law was developed as the equation [1, 5]:

$$\sigma = (A + B\cdot\varepsilon^n)\left[1 - \left(\frac{T - T_r}{T_m - T}\right)^m\right](1 + C\ln\dot{\varepsilon}), \tag{5}$$

where T_r — reference temperature, (e.g., *RT*); T_m — melting temperature; *A*, *B*, *C*, *m*, *n* — constants.

In equation (5) the stress depends on the strain hardening term, a strain rate sensitivity term, and temperature term.

Constants in equation (5) can be selected from the literature for a given material type [1, 6, 7].

If the modulus of elasticity is independent of the strain rate, the elastic strain rate results from the Hooke's law:

$$\dot{\varepsilon}_{el} = \frac{1}{E}\frac{d\sigma}{dt}. \tag{6}$$

The increase in the strain rate results in a marked increase in the yield stress at dynamic tensile. The stretching rate is described in the form of the Arrhenius equation, which defines the dislocation movement through a crystalline network containing point defects:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left(-\frac{\Delta G(\sigma)}{kT}\right), \tag{7}$$

where $\dot{\varepsilon}_0$ — constant; *k* — Boltzmann's constant ($1{,}38\cdot10^{-23}$ *J/K*); *T* — temperature; Δ*G* —activation energy is a function of stress.

Based on dependencies (1) $\varepsilon = \rho_D bl$ and $\dot{\varepsilon} = \frac{d\varepsilon}{dt}$ than $\dot{\varepsilon} = \rho_D b\frac{dl}{dt}$.

In the dislocation obstacle, where *dl* is the distance between the obstacles, *dt* will be reffered to as Δ*t* for this discrete event to be a waiting time for the thermal energy. The following relationship is expressed by Boltzmann equation [1]:

$$\Delta t = \frac{1}{\nu_0 \exp\left(-\frac{\Delta G(\sigma)}{kT}\right)}, \tag{8}$$

where v_0 — the atom vibrational frequency, which is on the order of 10^{11} σ^{-1}. This gives

$$\dot{\varepsilon} = \rho_D \cdot b \cdot l \cdot \nu_0 \exp\left(-\frac{\Delta G}{kT}\right) = \dot{\varepsilon}_0 \exp\left(\frac{\Delta G(\sigma)}{kT}\right). \tag{9}$$

The approximate value is:

$$\dot{\varepsilon}_0 = \rho_D \cdot b \cdot l \cdot \nu_0 \approx (10^{14}\,\mathrm{m}^{-2})(2{,}5\cdot10^{-10}\,\mathrm{m})\times$$
$$\times(5\cdot10^{-8}\,\mathrm{m})(10^{11}\,\mathrm{s}^{-1}) = 1{,}2\cdot10^{8}\,\mathrm{s}^{-1}.$$

The size Δ*G*(σ) is determined by the dislocation displacement under the stress. The distance traveled by the obstacle may be taken as vector *b* Burgers, while the dislocation that has moved can be assumed to be the distance between obstacles and is *l*.

The force acting on dislocation is σ·*b*·*l*. Because the dislocation has moved to the distance b, the work done by it is $\sigma\cdot b^2\cdot l$. If the total activation energy characterizing the interaction of the obstacle — dislocation is *G*, then:

$$\Delta G = G - \sigma b^2 l \tag{10}$$

and

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left(-\frac{\Delta G(\sigma)}{kT}\right) = \dot{\varepsilon}_0 \exp\left(-\frac{G - \sigma b^2 l}{kT}\right) \tag{11}$$

work performed by stress has effectively reduced the required energy of thermal activation.

Hence, the stress relations [1]:

$$\sigma = \frac{G}{b^2 l} - \frac{kT}{b^2 l}\ln\left(\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}\right). \tag{12}$$

Stress can be determined starting from the Peierls mechanism.

The equation describes the resistance that the crystal lattice resists dislocation slip:

$$\sigma = \frac{2K}{1-\nu}\exp\left(-\frac{4\pi\xi}{b}\right); \quad \xi = \frac{h}{2(1-\nu)}, \tag{13}$$

where *K* — Kirchhoff module; *h* — distance between planes of slipping; *b* — Burgers vector; ν —Poisson's ratio.

Own research. Static and dynamic research were performed for 15G2ANb steels according to PN-H-84018, S355N to EN 10025-32004 [10]. This is a steel with increased strength and ferritic-pearlitic structure. This steel can be used, for example, for pressure vessels and other welded constructions used at low temperatures. Table 1 gives the chemical composition of the steel under test.

Table 1 — Chemical composition of 15G2ANb alloy steel [10]

C	Mn	Si	Cu	Al	other
0,15	1,45	0,35	0,2	0,02	Nb 0,04 V 0,1 Mo 0,1

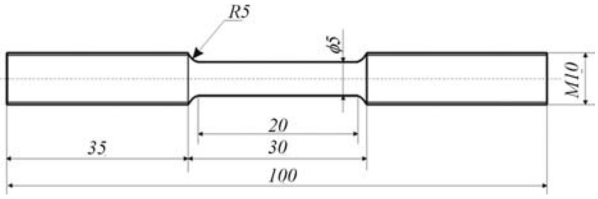

Figure 1 — The geometry of the sample for static and dynamic stretching tests

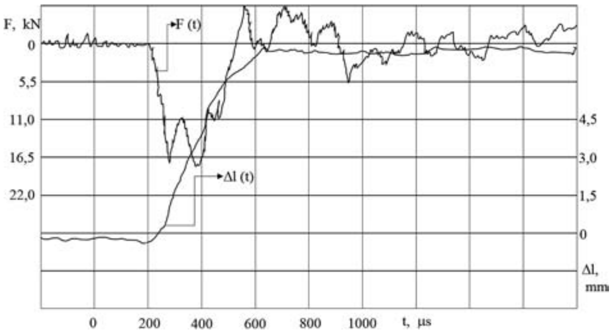

Figure 2 — The dependence force on the time $F(t)$ and displacement $\Delta l(t)$ for a dynamic steel tensile test 15G2ANb on a rotary hammer for the stretching speed V_n = 30 ms^{-1} [10]

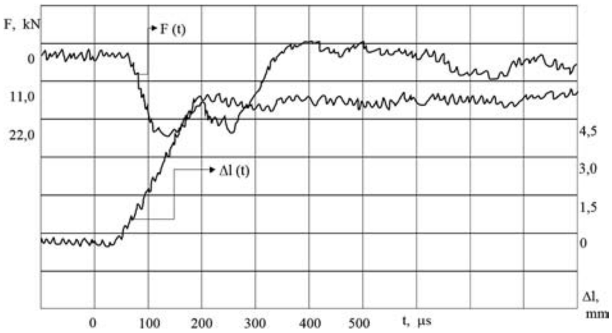

Figure 3 — The dependence force on the time $F(t)$ and displacement $\Delta l(t)$ for a dynamic steel tensile test 15G2ANb on a rotary hammer for the stretching speed V_n = 40 ms^{-1} [10]

Static and dynamic stretching tests were performed on samples whose geometry and dimensions are shown in figure 1. Static tensile testing was performed on a universal strength machine, while dynamic tensile test on a rotary hammer. The collective test results are reported in the report [10].

Dynamic stretching of samples was carried out on a rotary hammer. Tensile strength and strain rate was measured. The measuring position and method of recording results are described in detail in [10]. The dynamic tensile test was performed on samples at a speed of 10, 20, 30 and 40 m/s.

Elaboration and analysis of results of research. The strength R_m, R_{md} and yield strength R_e, R_{ed} of static and dynamic tensile of 15G2ANb steels were determined in a stretching test. For example the diagrams stretching samples for stretching speed V_n = 30 ms^{-1} and V_n = 40 ms^{-1} are shown in figures 2 and 3.

The measurement results of 15G2ANb steel in the stretching speed range v = 0÷40 ms^{-1} are shown in table 2 and figure 4.

Evaluation of results of research. Based on the results of the studies presented in the charts and tables it was found that the strain rate of the samples of the tested 15G2ANb steel increased the strength properties. The strength values of 15G2ANb steels for dynamic characteristics are higher than for static stretching tests. Figure 5 shows the stress-strain curves for several strain rate and constant temperature and one curve for temperature T = 500 K predicted using Johnson–Cook equation (5).

The strength steel 15G2ANb test at elevated temperature (T = 500 K) was not performed. The course of the curve and the strength properties of the steel to be tested can be determined from the equation (5). The results of the tests and the Johnson–Cook equation show an increase in the yield point and tensile strength of the material with increasing tensile speed. This has to do with the dislocation processes that were described earlier.

Figure 6 shows the stress-strain rate curves for constant temperature and different strain values.

Characteristics were derived on the basis Johnson–Cook model (5).

The ratio of the maximum values of the dynamic yield point Red and the tensile strength R_{md} (for v = = 40 ms^{-1}) to the corresponding static values R_e and R_m

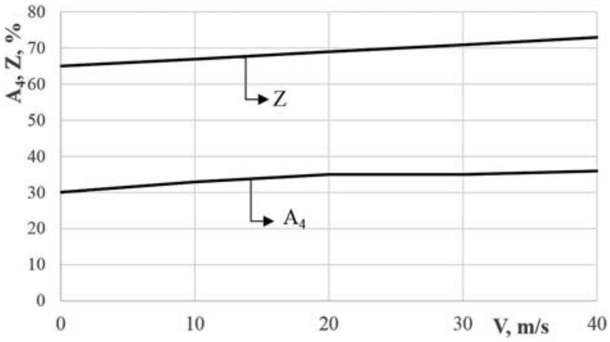

Figure 4 — Plasticity parameters of steel 15G2ANb: Z — reduction of area at fracture; A_4 — strain for various stretching speed

Table 2 — Static and dynamic properties of 15G2ANb steel

Sample diameter, mm	5,0$^{+0,1}$				
Stretching speed, m/s	≈0	10	20	30	40
R_m, R_{md}, MPa	520	580	810	880	990
R_e, R_{ed}, MPa	355	635	685	720	790
Reduction of area at fracture, Z, Z_d %	65	67	69	71	73
Strain, A_4, A_{4d} %	30	33	35	35	36

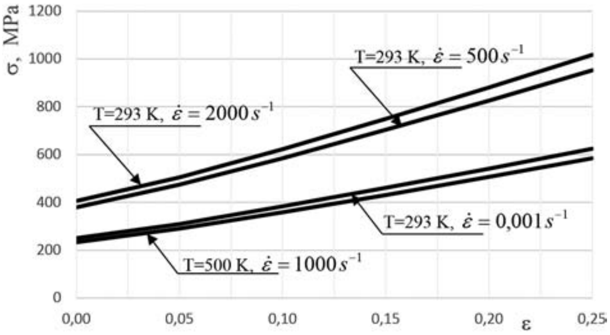

Figure 5 — Predicted stress-strain curves in 15G2ANb steel using the Johnson–Cook equation (5)

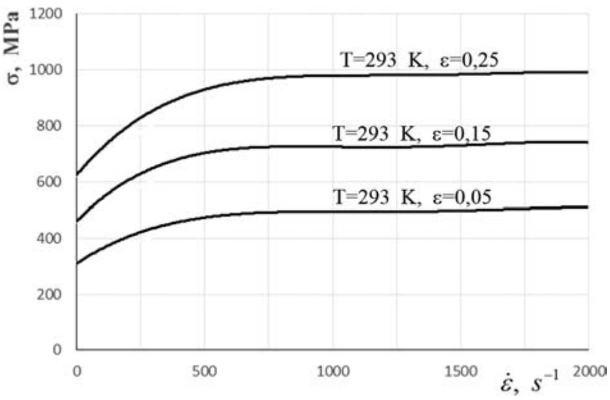

Figure 6 — Stress-strain rate curves in 15G2ANb steel for different strain values

for the tested 15G2ANb steel are respectively R_{md}/R_m = = 1,90; R_{ed}/R_e = 2,22. Plastic properties increased little Z_d/Z = 1,12; A_{4d}/A_4 = 1,20.

Conclusions. In the area of the fracture in the so-called neck area, the material breaks during the static or dynamic stretching of the sample. The research of the metallographic specimens has shown that voids have formed. The occurrence of voids is related to loss of material continuity [5]. Usually, plastic flow of material does not change its volume. The process of destroying or damaging the material is associated with the creation of voids. Damage can be defined by a function, depending on stresses, plastic strain, plasticity work, pressure, strain rate and temperature.

Proper processes of nucleation and void growth must be included in the dynamic crack model. The heterogeneity of the material is the second phase particles, the grain boundaries and the subgrain boundary, and earlier plastic flow of material. The results of the 15G2ANb steel studies have shown that the increase the strain rate causes strengthens the material (increase in yield point R_{ed}/R_e = 2,22 and strength R_{md}/R_m = 1,90) and plasticity behavior at the level of static properties.

The strain rate is often described by the Arrhenius equation if it is assumed that the basis for the flow of a metal is a thermally activated process that determines the dislocation movement through a crystalline network containing point defects.

Conclusions from static and dynamic studies are the basis for modeling the dynamic strain of steel as an elastic / visco-plasticity material.

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ВЛИЯНИЕ СКОРОСТИ ДЕФОРМАЦИИ НА ПРОЧНОСТЬ НИЗКОЛЕГИРОВАННОЙ КОНСТРУКЦИОННОЙ СТАЛИ

В статье представлены результаты исследования влияния скорости деформации на повышение прочностных свойств типичной низколегированной конструкционной стали. Упругая деформация обеспечивает смещение атомов из их равновесного положения. Пластическая деформация происходит за счет *коллективного движения атомных плоскостей и необходимо провести оценку напряжения, требуемого для перемещения одной плоскости скольжения относительно другой. При этом формирование и взаимодействие дислокаций требует учета особенностей пластической деформации, влияния температуры, скорости деформации и напряженно-деформированного состояния. Проведенный в работе анализ основан на использовании уравнения Джонсона и Кука, включающего параметры упрочнения, скорость деформации и температурную зависимость. Показано, что уравнение Джонсона и Кука хорошо описывает результаты исследования. Установлено, что рост скорости деформации существенно увеличивает прочностные свойства высокопрочной конструкционной стали 15G2ANb.*

Ключевые слова: *сталь, динамические свойства стали, деформированное состояние, дислокация*

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