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THE STUDY OF THE EFFECT OF TEMPERATURE ON THE ABILITY OF METALS TO ACCUMULATE ENERGY DURING THEIR PLASTIC DEFORMATION

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The subject of research is the surface layer of highly loaded parts, friction units of mining machines and equipment. The article presents a theoretical analysis of the factors that determine the ability of the material of the surface layer of parts to accumulate energy in the process of plastic deformation. It is suggested that the activation character of the accumulation of energy by metals.

Based on the theory of diffusion, it was shown that the mobility of atoms, as well as the accumulated energy, are determined by the ratio of the test temperature to the melting temperature.

Key words**:** machine parts; surface layer; accumulated energy; temperature; degree of deformation; tensile strength

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Introduction. It is known that the surface layer of highly loaded parts, friction units of mining machines and equipment is a key element in ensuring the required operational properties. As a rule, it is the surface material volumes that perceive the greatest external influences during the machine operation and are the main object of technological operations of mechanical, electrophysical and a whole range of other processing methods that affect the structure, chemical composition, material properties [3, 5-8].

When solving problems of describing, evaluating and predicting the state of the surface layer after technological or operational impacts, many researchers determine a set of individual and complex indicators that directly or indirectly reflect the physical processes occurring in the material. These indicators include the microhardness, depth, degree and hardening gradient, the magnitude and sign of residual stresses of the first kind, the specific accumulated deformation energy. The specific accumulated deformation energy is of particular interest for studying in view of the close relationship of the accumulated deformation energy with the regime parameters of technological effects [9].

Formulation of the problem. The theory of dislocations allows us to determine the magnitude of the specific energy of defects (dislocations) formed during plastic deformation using the formula [4]

$$W = QGb^2\Lambda , \tag{1}$$

where W – specific energy stored, J/m^3; Q – proportionality coefficient depending on the ratio of dislocation types, Q = 0.5–1; G – shift modulus, Pa; b – Burgers vector, m; Λ – dislocation density, m^{-2}.

The change in the density of dislocations in metals during their strain hardening is due to the physical and mechanical property – the increment of the conditional yield strength by the quadratic dependence

$$\sigma = \sigma_{0.2} + \alpha Gb\sqrt{\Lambda} , \tag{2}$$

where σ – stress required to effect plastic deformation; $\sigma_{0.2}$ – stress meaningful material yield strength; α – coefficient (inter-dislocation interaction parameter).

Then, taking into account (1) and (2), we obtain the expression [4]

$$W = \frac{Q}{\alpha^2 G}(\sigma - \sigma_{0.2})^2 . \tag{3}$$

Formula (3) indicates the effect on the stored energy of the deformation mechanism of strain hardening. Taking into account the thermally activated nature of the processes in the zone of plastic deformation, other significant factors include the temperature of deformation, as well as the structural-sensitive properties of metals, including the physical and mechanical ones. Thus, first of all, a theoretical analysis of the influence of temperature conditions on the ability of metals and alloys to absorb energy during their plastic deformation is of interest.

Methodology. It is known that the temperature affects the mobility of the atoms of the crystal lattice, the closer the current temperature to the melting point, the greater the mobility of the atoms. The temperature dependence of the diffusion coefficient is described by the Arrhenius equation:

$$D = D_0 e^{-\frac{H}{RT}} , \tag{4}$$

where D_0 – preexponential factor; H – activation energy; R – absolute gas constant; T – absolute temperature.

Taking into account the known correlation between the activation energy of self-diffusion H and the melting point of metals T_{mel} [2], expression (4) can be represented as follows:

$$D = D_0 e^{-\frac{K_N T_{\text{mel}}}{RT}} , \tag{5}$$

where K_N – almost constant value.

Figure 1 shows the dependence of the accumulated strain energy (at $T = 293$ K and the degree of deformation $\varepsilon = 20$ %) on the homological temperature. With an increase in the homologous temperature, the accumulated strain energy during the transition from a more refractory metal to a less refractory metal decreases at the same accumulated strain and temperature (in Fig.1, they correspond to 20 % and 293 K) [4].

Discussion. As a result of statistical processing of the accumulated strain energy data for various degrees of plastic deformation, its dependence on the homological temperature and degree of plastic deformation was established:

$$W = 5.7 \varepsilon e^{\frac{2T_{\text{mel}}}{RT}} , \tag{6}$$

where W – accumulated deformation energy, MJ/m^3; ε – degree of deformation; T_{mel} – melting temperature, K; R – absolute gas constant, J/(K·mol); T – absolute temperature, K.

The obtained dependence, which is valid for the second stage of deformation hardening of materials, reveals a linear relationship between the accumulated energy, the degree of deformation, and the density of dislocations. Thus, in the first approximation for the studied metals it is possible to assume the linear nature of the change in the accumulated energy with increasing degree of deformation.

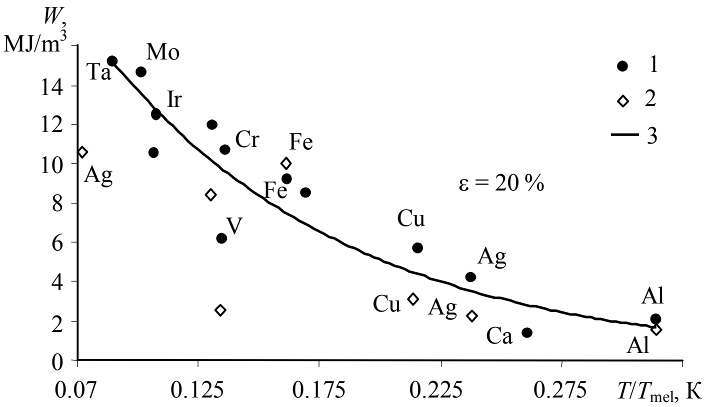

Fig.1. Change in stored deformation energy from homological temperature at $\varepsilon = 20$ %
1 – calculated values of W; 2 – experimental values of W; 3 – regression line, $R^2 = 0.84$

Of particular interest is the analysis of the effect of ultimate strength on the accumulated strain energy at the same homologous temperature. The correlation dependence shown in Fig.2 with the degree of deformation $\varepsilon = 10$ %, indicates that the stronger the material, the more it accumulates energy, all other things being equal.

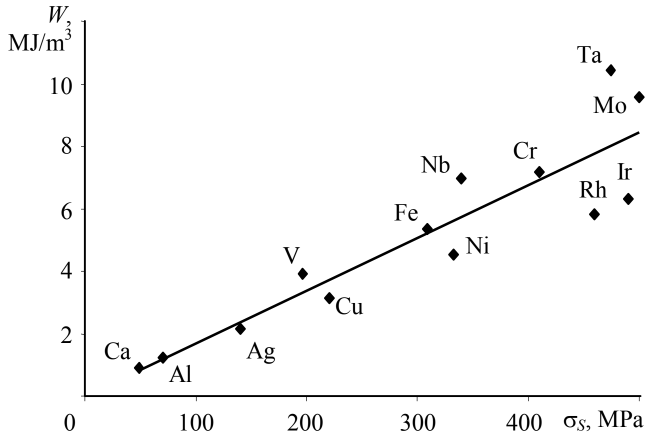

Fig.2. The amount of stored energy depending from the strength limit of the metals under study $\varepsilon = 10$ % (accuracy of approximation $R^2 = 0,75$)

Many researchers in the study of the accumulation of energy by metals during plastic deformation were limited to considering only pure metals, which are characterized by a uniform crystal structure. It should be noted that steel and iron-based alloys differ from pure iron by the structure characteristics (amount of carbon, alloying elements, impurities, etc.). Consequently, in the transition from pure iron to steel, we should expect changes in the structural-sensitive properties, the most important of which are mechanical properties. In this connection, it is important, in addition to considering the influence of homologous temperature, to study the influence of the structure of the material on the accumulated deformation energy.

Influence of material structure. Three groups of materials related to carbon, alloyed steels and nickel-based superalloys were selected as the object of research. Baseline data for the calculation are presented in the table. The value of the coefficient на was calculated on the basis of a hypothesis based on the regularities of the accumulated deformation energy revealed by V.M.Greshnov [1]

$$\alpha = 0{,}159 e^{\frac{100}{T}}, \tag{7}$$

where T – temperature, K.

Physical and mechanical properties of materials and coefficient calculated for them α

Material	Strength limit, σ_S, MPa	Yield limit, σ_Y, MPa	Shift modulus, G, GPa	Burgers vector, $b \cdot 10^{-10}$, m	Coefficient α
		Carbon steel			
08	330	200	80	2,87	0.20
10, 10кп	340	210			0.20
15	380	225			0.22
20, 20кп	410	250			0.22
25	530	275			0.26
30	540	320			0.26
35	520	310			0.26
40	570	320			0.26
45	600	340			0.28
50	630	350			0.28
55	640	360			0.28
		Alloy steels and alloys			
30Г	550	290	80	2,87	0.28
50Г	650	370			0.28
60Г	700	380			0.30
35Г2	630	370			0.28
30Х	900	700			0.21
50Х	1100	900			0.20
20ХГ	800	600			0.23
15Х	750	560			0.23

End of a table

Material	Strength limit, σ_S, MPa	Yield limit, σ_Y, MPa	Shift modulus, G, GPa	Burgers vector, $b \cdot 10^{-10}$, m	Coefficient α
40X	1000	800			0.22
50XФA	1250	1080			0.20
X18H9T	600	280			0.30
H23H18	920	630			0.28
12X18H9T	620	320			0.30
Heat resistant nickel base alloys					
XH77TЮP	1020	660	80	3,5	0.34
XH70BMTЮ	1140	750			0.34
XH73MБTЮ	1200	800			0.34
XH50BMKTЮP	1220	785			0.35
XH70MBФ	800	370			0.39
XH62BMKЮ	950	500			0.39

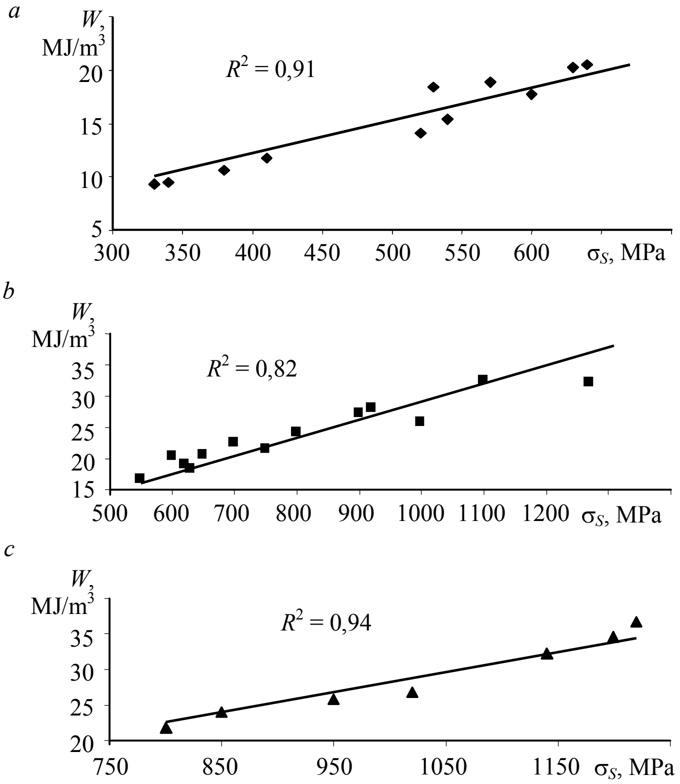

Fig.3. Dependence of the accumulated energy on the limit of strength of carbon steel (*a*) alloyed steels (*b*) and superalloys (*c*) at ε = 20 %

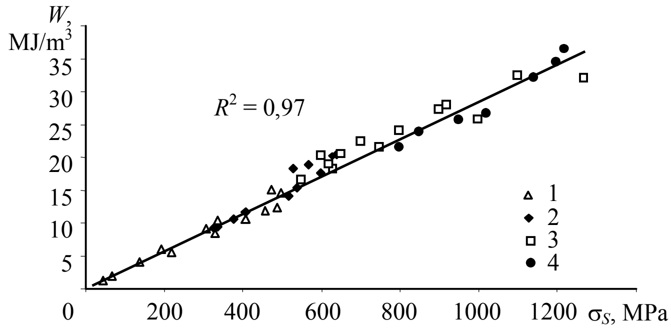

Fig.4. Dependence of the accumulated energy on the strength of pure metals, carbon, alloyed steels and high-temperature alloys at ε = 20 %

1 – pure metals; 2 – carbon steel; 3 – alloyed steels; 4 – heat resistant alloys

Let us consider the effect of strength limit on the ability of the studied steels and alloys to absorb deformation energy during plastic deformation. Fig.3 shows the dependence of the accumulated energy on the tensile strength at the degree of deformation ε = 20 % for carbon steels (Fig.3, *a*), alloyed steels (Fig.3, *b*), heat-resistant alloys (Fig.3, *c*).

A combination of the graphs under consideration (Fig.3), as well as dependencies for pure metals (see Fig.2), is presented in Fig.4 [4]. There is a close correlation between the values under consideration, which is valid for all groups of metals under consideration.

The authors obtained a linear regression equation of the following form

$$W = 0{,}12\varepsilon\sigma_S , \qquad (8)$$

где σ_S – material strength limit, MPa.

Equation (8) clearly demonstrates the linear dependence of the accumulated energy on the degree of plastic deformation of the material and its tensile strength.

Conclusion

1. The dependence of the accumulated energy on the degree of metal deformation and dislocation density is established. At the second stage of strain hardening, the dependence becomes linear.

2. The influence of the material structure as a factor determining the ability of materials to accumulate energy during plastic deformation is shown.

3. A linear relationship has been established between the accumulated energy of the deformation of metals and the ultimate strength of the material.

REFERENCES

1. Greshnov V.M., Lavrinenko Yu.A., Napalkov A.V. Prediction of the destruction of metals in the processes of cold plastic deformation. Message 1. Approximate model of plastic deformation and destruction of metals. *Problemy prochnosti*. 1999. N 1, p. 76-85 (in Russian).
2. Drapkin B.M. On some regularities of diffusion in metals. *Fizika metallov i metallovedenie*. 1992. N 7, p. 58-63 (in Russian).
3. Maksarov V.V., Kosheleva E.V. Improving the accuracy and quality of manufacturing parts from titanium and titanium alloys on the basis of preliminary local plastic deformation. *Kachestvo i zhizn'*. 2016. N 3, p. 61-65 (in Russian).
4. Prokof'ev M.A. Technological support of the parameters of work hardening of the surface layer during grinding based on the determination of the latent deformation energy: Ph.D. thesis in Engineering Science. Rybinskaya gosudarstvennaya aviatsionnaya tekhnologicheskaya akademiya. Rybinsk, 2006, p. 16 (in Russian).
5. Knudsen T.A. An experimental study of plastic deformation of materials: PhD thesis. Technical University of Denmark. 2008.
6. Maksarov V.V., Krasnyy V.A., Olt J.J. Increase of wear and fretting resistance of mining machinery parts with regular roughness patterns. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*. 2016. Vol. 27(1), p. 151-156.
7. Maksarov V.V., Krasnyy V.A.The formation of surface roughness of piston rings for the purpose of improving the adhesion of wear-resistant coatings. *Key Engineering Materials*. 2017. N 736, p. 73-78.
8. Mohammad S.M., Ramezan A.M. A study of stored energy in ultra-fined grained aluminum machined by electrical discharge machining. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2016. Vol. 231. Iss. 23, p. 4470-4478.
9. Taheri M., Weiland H., Rollett A. A method of measuring stored energy macroscopically using statistically stored dislocations in commercial purity aluminum. *Metallurgical and Materials Transactions*. 2006. Vol. 37, p. 19-25. DOI: 0.1007/s11661-006-0148-1.

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