МАТЕРІАЛОЗНАВСТВО

UDC 669.14.018.8:[620.178:539.4]

I. O. VAKULENKO[1], S. O. PLITCHENKO[2*], K. Yu. SHEVELIEVA[3]

[1]Dep. «Condensed Matter Physics», Dniprovsky State Technical University, Dniprobudivs'ka St., 2, Kamianske, Ukraine, 51900, tel. +38 (097) 437 72 21, e-mail vakulenko_ihor@ukr.net, ORCID 0000-0002-7353-1916
[2*]Dep. «Applied Mechanics and Materials Science», Ukrainian State University Science and Technologies, SEI DIIT, Lazaryan St., 2, Dnipro, Ukraine, 49010, tel. +38 (056) 373 15 18, e-mail plit4enko@ukr.net, ORCID 0000-0002-0613-2544
[3]Dep. «Condensed Matter Physics», Dniprovsky State Technical University, Dniprobudivs'ka St., 2, Kamianske, Ukraine, 51900, tel. +38 (067) 147 27 29, e-mail katerin.120201@gmail.com, ORCID 0009-0000-7201-4426

The Effect of Stress Pulses on the Limited Endurance Under Cyclic Loading of Thermal-Hardened Carbon Steel

Purpose. The assess effect of stress pulses on the cyclic endurance of thermal-hardened carbon steel. **Methodology**. A sheet with a thickness of 1 mm was selected for the study, made of steel with 0.42% *C* after thermal hardening. The treatment consisted of quenching and tempering at 300 °C. The samples were subjected to cyclic loading on the Saturn-10 machine, under a symmetrical cycle of alternating bending, with a frequency of 100 min^{-1}. Treatment with pulses of stress was carried out under conditions of «Iskra–23». To determine the effect pulses of stress on the cyclic endurance, samples after 50–60% by limit of endurance were subjected to doing pulses of stress. After completion treatment pulse of stress, the samples continued to be cyclically loaded until the moment of failure. The density of dislocations was measured by method of X-ray structural analysis on a DRON-3 diffractometer, by interferences (110), (211), (321). The complex of properties after thermal strengthening was determined under static tension, at a strain rate of 10^{-3} s^{-1}. **Findings**. After processing with pulses of stress studied, thermally hardened steel with a hardness of 46–47 HRC, an increase in hardness by 11 % was obtained. According to the analysis of the cyclic loading curves of thermally hardened carbon steel, it was determined that due to the action pulses of stress, an increase in limit of endurance occurs in a wide range of cyclic overload. Structural studies have determined that, in proportion to decrease at magnitude of cyclic overload, an increase limit of endurance corresponds to higher number accumulated dislocations by different slip systems. **Originality**. The increase at density of dislocations from the action pulses of stress is due to the development processes of partial unlocking of dislocations after thermal strengthening and activation systems of sliding, which are not characteristic of these loading conditions of the steels. As a result of the action pulses of stress, the propagation deformation per cycle occurs at lower amplitudes of load, due to formation of an additional number of dislocations. According to analysis lines of French, it was determined that participation of an increased number of dislocations at propagation of deformation per cycle shifts a moment transformation of reversible damages into irreversible ones, towards an increase at number of cycles. **Practical value**. The obtained research results can be useful for assessing by influence of an external source of stress on the behavior of a carbon steel product under cyclic loading.

Keywords: carbon steel; dislocation; cycle amplitude; stress pulse; cyclic endurance

Introduction

Under cyclic loading, the proportion of mobile dislocations at structure and their redistribution are among the many factors that determine limited endurance of a metallic material [25]. The application of influences such as the introduction of additional harmonics into the load cycle formation scheme, the action of electric current pulses [12], or surface stresses of various origins [15, 23, 26] are capable varying degrees influence on structural transformations under cyclic loading. Compared with simple static loading schemes, the nature of plastic deformation metals and alloys under the action of a high-power stress pulse has significant differences [5, 19, 21]. Against the background various changes in the internal structure [26], the features

doi: https://doi.org/10.15802/stp2025/337870

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)
Наука та прогрес транспорту, 2025, № 3 (111)

of origin and propagation plastic deformation [25] deserve attention. In proportion to increase at power acting mechanical pulse, the stresses are able to reach the levels of theoretical strength of the metal material, by absence signs of plastic deformation. This is due to the short duration of pulse, on the order of 10^{-6} to 10^{-9} seconds [17], the duration of which is not enough to begin of development relaxation processes of the arising stresses.

At same time, under action of the stress pulse, one should expect qualitative differences at nature of the nucleation and movement of dislocations, which will contribute to the emergence of high localization of plastic deformation and anomalous nature of changes at complex properties of the metallic material [2, 4, 11]. Moreover, depending at power a pulse of the applied stress, one can observe a qualitatively different nature impact on the complex of properties [3, 7, 14]. Indeed, experimental studies [25] have determined that in proportion to the increase at power of the pulse, the strengthening effect of the metallic material will increase. However, in appearance, the nature of the change at strengthening effect most likely resembles an extreme dependence [6, 13].

Based on this, the value of pulse power, when the hardening effect changes to softening, is a completely expected phenomenon and is called the critical value [25]. Thus, in accordance with a nature of the metal material, the hardening technology and the structural state [6, 10, 13, 18], depending on the power of stress pulse, it is quite reasonable to obtain a qualitatively different effect of the impact: from hardening to softening [27–29].

Purpose

The assess effect of stress pulses on the cyclic endurance of thermal-hardened carbon steel.

Methodology

To study influence of the surface stress pulse on the behavior under cyclic loading, a sheet 1 mm thick, made of ordinary quality steel with a carbon concentration of 0.42%, was selected. Considering the fairly wide application technology thermal hardening of products at machine-building industry, the structural state of the steel after thermal hardening was selected for the research. The treatment consisted of heating to temperatures higher than Ac_3, quenching in oil and tempering at 300 °C for 1 hour.

Flat-shaped samples, with a special fillet, with a structure after thermal hardening were subjected to cyclic loading under conditions at Saturn-10 testing machine. The choice of the machine is due to the possibility of simultaneous loading of up to 10 samples, with different cycle amplitudes, which significantly reduces the time for obtaining test results for the construction of the cyclic loading curve. The loading scheme of the sample corresponded to a symmetrical cycle of alternating bending, at a loading frequency of 100 min^{-1}, at room temperature of the tests.

The construction and analysis of the cyclic loading curve were carried out for sections of limited endurance [8, 16, 17]. The boundary between at formation of reversed and non-reversed damages was determined by the methods [8]. The surface stress pulse treatment of the samples was carried out on the «Iskra–23» bath-type equipment. The stress pulses order of 1–2 GPa arose from an electric discharge in water, at voltage of 15–18 kV. The pulse energy was 10–12 kJ.

The treatment was completed after reaching approximately 15 thousand pulses, at a frequency of 2–3 Hz [24]. To determine effect stress pulses on cyclic endurance, the samples were subjected to stress pulses after 50–60% of the limited endurance. After the pulse treatment, the samples continued to be cyclically loaded until the moment of failure.

The effect assessment consisted of a comparative analysis limited endurance of the steel after thermal hardening and after treatment with stress pulses, until the moment of final failure.

To identify microstructure, the metal was etched in a standard etchant (4% HNO_3 solution in ethanol). The elements of the microstructure were studied using light and electron microscopy [1].

The dislocation density was measured by the method of X-ray structural analysis [9], on a DRON–3 diffractometer, by interferences (110), (211), (321).

The complex of properties after thermal hardening was determined under static tension, at a strain rate of 10^{-3} s^{-1}. As a characteristic at strength of the steel, after the action of stress pulses, the Rockwell hardness was chosen [20].

doi: https://doi.org/10.15802/stp2025/337870

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)
Наука та прогрес транспорту, 2025, № 3 (111)

Findings

According structural analysis of the studied steel, after quenching was formed a structure of lath martensite with a lath width of the order of 1 μ, with a certain density of dislocations (Fig. 1, *a*).

a

b

Fig. 1. Structure of steel after quenching (*a*) and tempering at a temperature of 300 °C (*b*). Magnification is 18000

In the martensite crystals, appearance of thin layers at form of twins is observed. When larger face of the martensite lath coincides with the foil plane, presence of randomly oriented, dispersed particles of cementite with shape of intermittent lines is determined. Heating the steel to 300 °C after quenching, contributes to the additional release of carbide particles on groups of dislocation in the volume of the martensite laths (Fig. 1, *b*).

The existence a section of the structure with partial loss of contrast is evidence of the development dislocation recombination processes. As a result, against the background of a decrease at number of dislocations, there is an increase at heterogeneity of their location in martensite crystals (Fig. 1, *b*).

The appearance of carbide phase particles in wide walls of dislocations indicates the almost complete absence of mobile dislocations in the steel after tempering. This is confirmed by the hardness (46–47 HRC) and the qualitative coincidence complex of the properties with known results [22, 25]. After treatment pulses of the stress thermal hardened steel with a hardness of 46–47 HRC, an increase at hardness by 11% was obtained. Based on this, according to obtained effect influence on hardness, the used stress pulse power is less than the critical value.

The influence of treatment pulses of the stress on the cyclic loading curves is shown in Fig. 2, *a*.

First, regardless of the structural state at steel (thermal hardened or treatment of stress pulse), the shape of curves remained practically unchanged. In general, for the studied range σ_a, pulse treatment leads to a shift of the curve to region of higher cycle amplitudes. At same time, the difference at values of limited endurance (for convenience, will to denote N_i – limited endurance after thermal strengthening and after action of stress pulses – N_i') indicates by existence of a qualitative dependence on the degree of cyclic overload (*K*), which is equal to the ratio σ_a/σ_{-1}, where σ_{-1} is the maximum amplitude of the cycle under conditions of unlimited endurance.

Thus, for small *K* (regions *B′C′* and *BC*, Fig. 2, *a*) for the same σ_a, treatment with stress pulses leads to a significant increase in limited endurance: $N_i' > N_i$.

For example, for $\sigma_a \sim 550$ MPa ($\lg\sigma_a = 2{,}74$), $N_i \sim 3.6\cdot10^5$ c, while $N_i' \sim 1.3\cdot10^6$ c (Fig. 2, *a*). As degree of cyclic overload increases, difference between N_i' and N_i (ΔN) gradually decreases. This is due to an acceleration of the transition from one section to another (i.e. *B′* and *B*), and the difference at angular coefficients for sections *A′B′* and *AB*.

doi: https://doi.org/10.15802/stp2025/337870

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)
Наука та прогрес транспорту, 2025, № 3 (111)

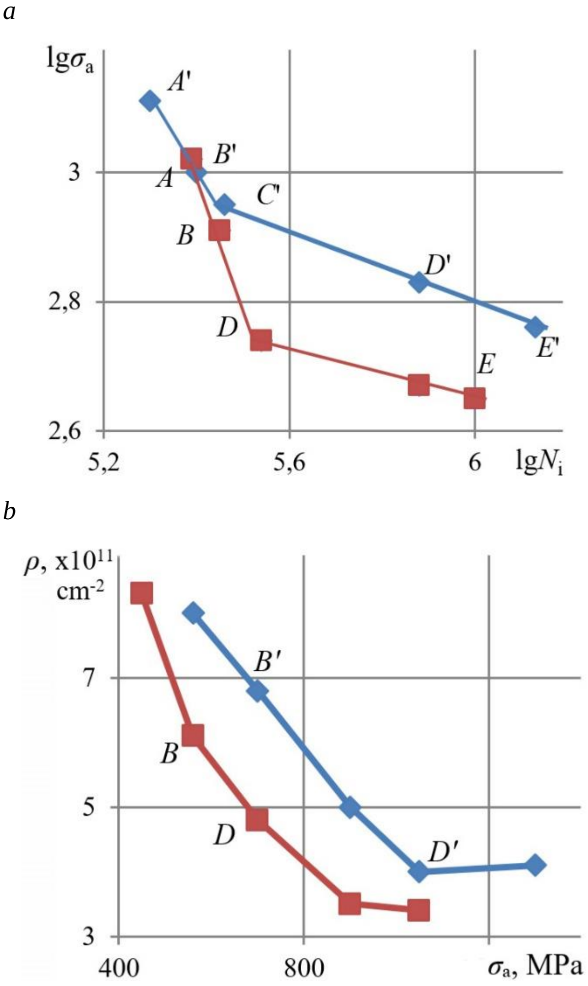


Fig. 2. Logarithmic curves cyclic loading of the carbon steel (*a*) and change in total dislocation density by three interferences (*b*) after thermal hardening (■) and stress pulse treatment (♦)

As a result, with the same cycle amplitude (i.e. *A*), the condition will be achieved when $N_i' \approx N_i \approx 2.5 \cdot 10^5$ c. At same time, extrapolation of the section *AB* of curve into the region of increasing σ_a indicates achievement of conditions when $N_i' < N_i$ will be. Thus, the treatment of thermally hardened steel with pulses of stress has a qualitatively different nature impact on the cyclic endurance depending degree of cyclic overload.

Starting from the region of large amplitudes, where effect pulses of the stress is minimal or absent altogether (i.e. *A*), moving along the dependence $\sigma_a \sim f(N_i)$ towards increasing N_i is accompanied by a corresponding increase at cyclic endurance of the metal.

To determine the nature influence pulses of the stress on the cyclic endurance, change of concentration defects in the crystalline structure of steel was assessed. Considering that dislocation represents an elementary carrier of plastic deformation, the measurement of their number (ρ_{hkl}) was carried out for three crystallographic slip systems. This is due to the fact that action of the emerging stress pulse of different power is capable of local temperature increase [17], then the activation of different dislocation slip systems should be a completely expected phenomenon. Thus, for steels with a bcc crystal lattice, for the temperature range from low temperatures to +180 °C, the movement of dislocations occurs predominantly by the crystallographic planes {211}.

For temperatures of 200–630 ºC, the {110} systems are activated to a greater extent, and above 1170 ºC – {321} [25].

According to a formal assessment, in the form of a scalar sum over three dislocation slip systems, it was determined that action of stress pulses contributes to an increase at concentration of dislocations to ensure an increase at limited endurance of cyclic loading (Fig. 2, *b*).

The given dependence of the limited endurance on σ_a should actually be determined by the ratio between volumes of metal in the plane deformed and volumetric stressed state. The given ratio, in turn, determines the magnitude of the deformation per cycle and the number of dislocations that provide it. To estimate the deformation per cycle, the Coffin-Manson equation was used [8, 16]:

$$\varepsilon_i \cdot \left(N_i\right)^a = b , \qquad (1)$$

where ε_i is the deformation per load of the cycle, N_i is the limited endurance, *a* and *b* are constants, for carbon steels they are 0.5 and 1, respectively [25].

After substituting the values of *a* and *b* into (1) and performing transformations, ε_i is determined by:

$$\varepsilon_i = \frac{1}{\left(N_i\right)^{0,5}}. \qquad (2)$$

After substituting in (2) for the same σ_a corresponding values of N_i, it was found that the deformation per cycle decreased by approximately 20% after the action of stress pulses.

doi: https://doi.org/10.15802/stp2025/337870

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

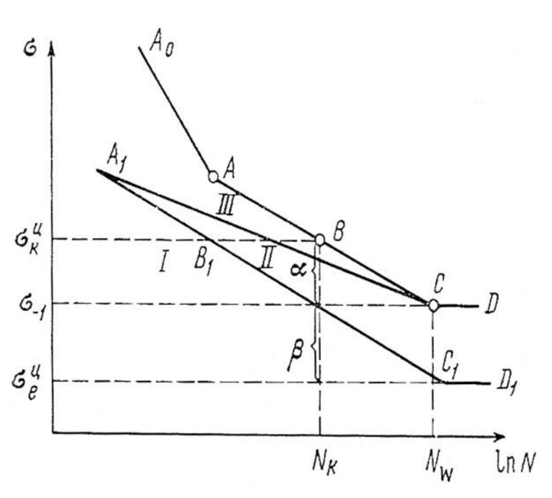
Наука та прогрес транспорту, 2025, № 3 (111)

To determine the increase in cyclic endurance, the slope a line of the French (k) was estimated. According to the scheme shown in Fig. 3, *a*, for the region limited endurance of steel, k is determined by the ratio:

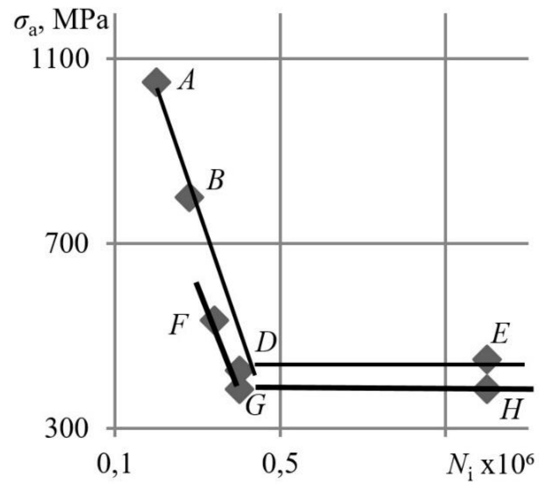
$$k = -tg\gamma = -\left[\frac{\alpha}{\left(N_i^D - N_i^F\right)}\right]. \qquad (3)$$

where γ is a slope a line of the French, α is a constant characteristic, N_i^D and N_i^F are the number of cycles to failure of the samples for the corresponding load amplitudes (points D, F respectively).

a



b



c

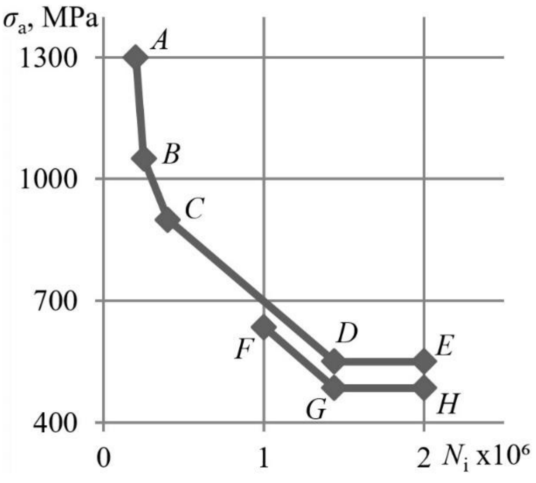


Fig. 3. Methodology for determining the angle of inclination line of the French (lines: the fracture A_0, A, B, C, D; formation of the sub microcracks A_1, B_1, C_1, D_1 and microcracks A_1, C, D) (*a*) and corresponding application of the method for analyzing cyclic loading curves after thermal strengthening (*b*) and the action of stress pulses (*c*)

After substituting in (3) $\alpha = 85$ MPa for both thermally hardened steel (Fig. 3, *b*) and after treatment with stress pulses (Fig. 3, *c*), the corresponding values of k were determined.

It was determined that after action of the stress pulses $k = 1.24 \cdot 10^{-4}$ MPa/c, and after thermal hardening $2.8 \cdot 10^{-3}$ MPa/c.

The formally, according to (3), k is a measure decrease at cycle amplitude to ensure an increase at

doi: https://doi.org/10.15802/stp2025/337870

limited endurance by one cycle. On other hand, a line of the French (A_1C, Fig. 3, *a*) is the boundary separating areas formation are reversible damages (submicrocracks) from non-reversible (microcracks).

Indeed, according to the given scheme (Fig. 3, *a*), for a certain cycle amplitude ($\sigma_к^п$), in the region (*I*) up to a number cycles of loading a point of B_1, there are no metal damages. If the number of cycles exceeds the value B_1, conditions for the formation of submicrocracks are created (area *II* of the diagram).

Given the very small size of submicrocracks and the insufficient intensity of stresses in it a mouth, their growth is significantly inhibited. The specified conditions for the existence of sub microcracks are called often the incubation period of growth. With further accumulation of loading cycles (more than point B_1), a gradual increase in their length occurs in accordance with the increase at intensity of stresses at its mouth.

Further, at the moment of crossing a line of the French, the size of damage and the corresponding intensity of stresses will contribute to an increase at rate of growth of the metal damage. There is a transition from the incubation period to growth at a constant growth rate (region *III*).

Crossing the *ABC* line is accompanied by further changes in the kinetics of damage growth: from growth at a constant rate to accelerated. Depending on the accumulated number of cycles, the accelerated growth of the microcracks very quickly passes into an uncontrolled stage, with subsequent final destruction. Under such circumstances, a smaller *k* the higher limit endurance of the metallic material should be expected. In order to confirm influence action pulses of the stress on the endurance under cyclic loading, let us estimate change at dislocation density (Λ), which a necessary to maintain conditions of the continuous deformation propagation during the loading cycle:

$$\Lambda = \frac{\Delta\rho}{\Delta N_i}, \quad (4)$$

where $\Delta\rho$ is the change at number of dislocations according to the change at number of cycles N_i.

For points *B* and *D* of cyclic loading curve, for steel after thermal hardening (Fig. 2, *b*) $\Delta\rho = \rho_B - \rho_D$, Λ_1 by (4) will be equal to $4.8 \cdot 10^4$ cm^{-2}/c.

Similarly, Λ_2 was determined (after stress pulse treatment), which was $2.7 \cdot 10^5$ cm^{-2}/c. The excess of Λ_2 over Λ_1 is approximately an order of magnitude. Thus, formation of an additional density of the mobile dislocations should be considered as promoting propagation of deformation at a reduced amplitude of the loading cycle.

Thus, for carbon steel with a structure after thermal hardening, the formation of an additional number of mobile dislocations due to pulses of the stress may be based on the unlocking of dislocations formed at thermal hardening, or due to the activation of other slip systems not characteristic of these cyclic loading conditions.

Originality and practical value

Experimental studies have determined that the action of stress pulses from an external source contributes to an increase at limited endurance of carbon steel under cyclic loading. The used analysis crystallographic systems of dislocation slip showed that simultaneously with the increase in limited endurance, there is an increase at accumulated density of dislocations in different crystallographic systems of the slip.

The kinetics of the change at density of dislocations depending on the degree of cyclic overload indicates the existence of different mechanisms of dislocation growth under the action of stress pulses. In general, the obtained effect can be associated with the development of two qualitatively different mechanisms. The first is the partial unlocking of dislocations formed due to the formation of tempering martensite crystals. According to this mechanism, the detachment of dislocations from the attachment sites changes number of mobile dislocations in the {110} and {211} slip systems. The second mechanism is the activation of the {321} slip systems, which is not characteristic of these loading conditions.

A combined analysis nature of change at dislocation density by different slip systems from the magnitude of limited endurance found of existence influence degree of cyclic overload of the metal. Indeed, for same stresses of the cycle amplitude, effectiveness of the stress pulse action shifts towards decrease cyclic overload degree. This is due to fact that action of stress pulses, due to the formation of an additional number of dislocations,

doi: https://doi.org/10.15802/stp2025/337870

contributes to the propagation of deformation per cycle at lower load amplitudes.

An additional confirmation of the above position is the analysis curves of French. According results obtained, it was determined that participation of an increased number of dislocations at propagation of deformation per cycle shifts the moment transformation of reversible damage into irreversible damage towards an increase in the accumulated number of cycles.

Effect of changing number accumulated of dislocations from the action of an external source of stress pulses has practical significance for assessing the service life of products made of heat-hardened steels under cyclic loading. With an increase at degree of cyclic overload, the effect of pulse from an external stress source decreases. The result presented has practical significance, especially under conditions appearance of the unpredictable additional, cyclically varying stresses during operation of the products.

Conclusions

1. Analysis of the cyclic loading curves of thermal hardened carbon steel has determined that due to the action pulses of stress, the value of limited endurance increases in a wide range of cyclic overload.

2. Structural studies have determined that, in proportion to the decrease at magnitude of cyclic overload, increase in limited endurance corresponds to a higher number of accumulated dislocations by to different sliding systems.

3. The increase at density of dislocations from the action pulses of stress is due to development processes of unlocking of dislocations formed after thermal strengthening and activation of slip systems not characteristic of steels at that conditions.

4. As a result, action pulses of stress, the propagation of deformation per cycle occurs at lower load amplitudes, due to the formation of an additional number of dislocations.

5. Analysis by lines of the French, it was determined that participation of an addition number of dislocations at propagation of deformation per cycle shifts a moment of transformation of submicrocracks (the damage is reversible) into microcracks (the damage is irreversible) ones, towards an increase at number of cycles.

LIST OF REFERENCE LINKS

1. Вакуленко І. О. *Структурний аналіз в матеріалознавстві* : навч. посіб. Дніпропетровськ : Вид-во Маковецький, 2010. 124 с. ISBN 978-966-1507-52-3.
2. Askerov Kh. A., Vakulenko I. O. Evaluation of the influence of dispersion of pearlite on the fatigue of carbon steel. *Materials Science*. 2020. Vol. 56. P. 214–217. DOI: https://doi.org/10.1007/s11003-020-00418-w
3. Bhamu R. K., Shukla A., Sharma S. C., Harsha S. P. Vibration response of steam turbine healthy and cracked blade under the stress stiffening and spin softening effects. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*. 2022. Vol. 236, No. 2. P. 224–243. DOI: https://doi.org/10.1177/14644193221078656
4. Braut S., Tevčić M., Butković M., Božić Ž., Žigulić R. Application of modified Locati method in fatigue strength testing of a turbo compressor blade. *Procedia Structural Integrity*. 2021. Vol. 31. P. 33–37. DOI: https://doi.org/10.1016/j.prostr.2021.03.007
5. Casalino G., Moradi M., Karami Moghadam M., Khorram A., Perulli P. Experimental and numerical study of AISI 4130 steel surface hardening by pulsed Nd:YAG laser. *Materials*. 2019. Vol. 12, No. 19. Art. 3136. DOI: https://doi.org/10.3390/ma12193136
6. Cheng Y., Wang Y., Lin J., Xu S., Zhang P. Research status of the influence of machining processes and surface modification technology on the surface integrity of bearing steel materials. *The International Journal of Advanced Manufacturing Technology*. 2023. Vol. 125. P. 2897–2923. DOI: https://doi.org/10.1007/s00170-023-10960-x
7. Cheng Z., Wang S., Wu G., Gao J., Yang X., Wu H. Tribological properties of high-entropy alloys: A review. *International Journal of Minerals, Metallurgy and Materials.* 2022. Vol. 29. P. 389–403. DOI: https://doi.org/10.1007/s12613-021-2373-4

doi: https://doi.org/10.15802/stp2025/337870

8. D'Antuono P. An analytical relation between the Weibull and Basquin laws for smooth and notched specimens and application to constant amplitude fatigue. *Fatigue & Fracture of Engineering Materials & Structures*. 2020. Vol. 43, No. 5. P. 991–1004. DOI: https://doi.org/10.1111/ffe.13175
9. Jain A., Dhapekar N. K. Methods of sample preparation in X-ray diffractometer (XRD). *International Journal of Advance Research and Innovative Ideas in Education (IJARIIE)*. 2022. Vol. 8, No. 3. P. 190–192. URL: http://ijariie.com/AdminUploadPdf/METHODS_OF_SAMPLE_PREPARATION_IN_X_RAY__DIFFRACTOMETER__XRD__ijariie16518.pdf?srsltid=AfmBOorNi8z3PCrKxW2PHBQl2l5lOsGgtlp-UqaAWOoTO9nmgEK0tCZH
10. John M., Ralls A. M., Dooley S. C., Vellooridathil Thazhathidathil A. K., Perka A. K., Kuruveri U. B., Menezes P. L. Ultrasonic surface rolling process: Properties, characterization, and applications. *Applied Sciences*. 2021. Vol. 11, No. 22. Art. 10986. DOI: https://doi.org/10.3390/app112210986
11. Kafaei A., Salmani F., Lakzian E., Wróblewski W., Vlaskin M. S., Deng Q. The best angle of hot steam injection holes in the 3D steam turbine blade cascade. *International Journal of Thermal Sciences*. 2022. Vol. 173. Art. 107387. DOI: https://doi.org/10.1016/j.ijthermalsci.2021.107387
12. Kim M.-J., Bui-Thi T.-A., Kang S.-G., Hong S.-T., Nam Han H. Electric current-induced phenomena in metallic materials. *Current Opinion in Solid State and Materials Science*. 2024. Vol. 32. Art. 101190. DOI: https://doi.org/10.1016/j.cossms.2024.101190
13. Klumpp A., Ruf M., Dietrich S., Schulze V. Long crack propagation and closure in DC(T) specimens of Ni-based superalloy Inconel 718 and stainless steel AISI 301 after shot peening. *Engineering Fracture Mechanics*. 2022. Vol. 269. Art. 108551. DOI: https://doi.org/10.1016/j.engfracmech.2022.108551
14. Krechkovska H., Hredil M., Student O., Svirska L., Krechkovska S., Tsybailo I., Solovei P. Peculiarities of fatigue fracture of high-alloyed heat-resistant steel after its operation in steam turbine rotor blades. *International Journal of Fatigue*. 2023. Vol. 167, Part B. Art. 107341. DOI: https://doi.org/10.1016/j.ijfatigue.2022.107341
15. Lesyk D. A., Martinez S., Mordyuk B. N., Dzhemelinskyi V. V., Lamikiz A., Prokopenko G. I., Iefimov M. O., Grinkevych K. E. Combining laser transformation hardening and ultrasonic impact strain hardening for enhanced wear resistance of AISI 1045 steel. *Wear*. 2020. Vol. 462–463. Article 203494. DOI: https://doi.org/10.1016/j.wear.2020.203494
16. Maierhofer J., Kolitsch S., Pippan R., Gänser H.-P., Madia M., Zerbst U. The cyclic R-curve – Determination, problems, limitations and application. *Engineering Fracture Mechanics*. 2018. Vol. 198. P. 45–64. DOI: https://doi.org/10.1016/j.engfracmech.2017.09.032
17. Murakami Y., Takagi T., Wada K., Matsunaga H. Essential structure of S-N curve: Prediction of fatigue life and fatigue limit of defective materials and nature of scatter. *International Journal of Fatigue*. 2021. Vol. 146. Article 106138. DOI: https://doi.org/10.1016/j.ijfatigue.2020.106138
18. Peng Y., Liu Z., Chen C., Gong J., Somers M. A. J. Effect of low-temperature surface hardening by carburization on the fatigue behavior of AISI 316L austenitic stainless steel. *Materials Science and Engineering: A*. 2020. Vol. 769. Article 138524. DOI: https://doi.org/10.1016/j.msea.2019.138524
19. Rivaz A., Mousavi Anijdan S. H., Moazami-Goudarzi M., Nazari Ghohroudi A., Jafarian H. R. Damage causes and failure analysis of a steam turbine blade made of martensitic stainless steel after 72,000h of working. *Engineering Failure Analysis*. 2021. Vol. 131. Article 105801. DOI: https://doi.org/10.1016/j.engfailanal.2021.105801
20. *Rockwell hardness testing: ISO 6508, ASTM E18*. URL: https://www.zwickroell.com
21. Salleh M. N. M., Ishak M., Aiman M. H., Zaifuddin Q., Quazi M. M. The effect of laser surface hardening on the surface hardness of mild steel. *IOP Conference Series: Materials Science and Engineering, 5th International Conference on Mechanical Engineering Research 2019 (ICMER 2019)* (Kuantan, Malaysia, 30-31 July 2019). 2020. Vol. 788. Art. 012014. DOI: https://doi.org/10.1088/1757-899X/788/1/012014
22. Schönbauer B. M., Mayer H. Effect of small defects on the fatigue strength of martensitic stainless steels. *International Journal of Fatigue*. 2019. Vol. 127. P. 362–375. DOI: https://doi.org/10.1016/j.ijfatigue.2019.06.021
23. Švábenská E., Pizurová N., Roupcová P., Chlupová A., Brajer J., Foldyna J., Schneeweiss O. Effect of shock wave on microstructure of silicon steel. *Surfaces and Interfaces*. 2020. Vol. 20. Art. 100415. DOI: https://doi.org/10.1016/j.surfin.2019.100415

doi: https://doi.org/10.15802/stp2025/337870

24. Vakulenko I. A., Kurt B., Raksha S. V., Askerov H., Hryshchenko M. A. The effect of stress pulses on the cyclic endurance of steel axle wheel-set. *Materials of the International Conference on Materials Science, Mechanical and Automotive Engineerings and Technology in Cappadocia/Turkey (IMSMATEC'19)* (Nevsehir, Turkey, 21-23 June, 2019). Nevsehir Haci Bektas Veli University. Nevsehir, 2019. P. 355–359. URL: https://crust.ust.edu.ua/handle/123456789/11676
25. Vakulenko I. A., Vakulenko L., Dal S., Asgarov Kh., Bolotova D., Kurt B. *Structure evolution in steels of railway wheels at manufacture and operations* / ed. S. Dal. Ankara : Nobel Bilimsel Eserler, 2023. 270 p.
26. Wu J., Zhao J., Qiao H., Hu X., Yang Y. The new technologies developed from laser shock processing. *Materials*. 2020. Vol. 13, No. 6. Art. 1453. DOI: https://doi.org/10.3390/ma13061453
27. Yang F., Liu P., Zhou L., He W., Pan X., An Z. Review on anti-fatigue performance of gradient microstructures in metallic components by laser shock peening. *Metals*. 2023. Vol. 13, No. 5. Art. 979. DOI: https://doi.org/10.3390/met13050979
28. Yoshinaka F., Nakamura T., Takeuchi A., Uesugi M., Uesugi K. Initiation and growth behaviour of small internal fatigue cracks in Ti-6Al-4V via synchrotron radiation microcomputed tomography. *Fatigue & Fracture of Engineering Materials & Structures.* 2019. Vol. 42, No. 9. P. 2093–2105. DOI: https://doi.org/10.1111/ffe.13085
29. Zhou L., Zhao T., Yu Y., Liu P., Pan X. Effect of laser shock peening on high-cycle fatigue performance of 1Cr18Ni9Ti/GH1140 weld. *Metals*. 2022. Vol. 12, No. 9. Art. 1495. DOI: https://doi.org/10.3390/met12091495

І. О. ВАКУЛЕНКО[1], С. О. ПЛІТЧЕНКО[2*], К. Ю. ШЕВЕЛЄВА[3]

[1]Каф. «Фізика конденсованого стану», Дніпровський державний технічний університет, вул. Дніпробудівська, 2, Кам'янське, Україна, 51900, тел. +38(097) 437 72 21, ел. пошта vakulenko_ihor@ukr.net, ORCID 0000-0002-7353-1916
[2*]Каф. «Прикладна механіка та матеріалознавство», Український державний університет науки і технологій, ННІ ДІІТ, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38(056) 373 15 18, ел. пошта plit4enko@ukr.net, ORCID 0000-0002-0613-2544
[3]Каф. «Фізика конденсованого стану», Дніпровський державний технічний університет, вул. Дніпробудівська, 2, Кам'янське, Україна, 51900, тел. +38(067) 147 27 29, ел. пошта katerin.120201@gmail.com, ORCID 0009-0000-7201-4426

Вплив імпульсів напруження на обмежену витривалість при циклічному навантаженні термічно зміцненої вуглецевої сталі

Мета. Оцінити вплив імпульсів напруження на циклічну витривалість термічно зміцненої вуглецевої сталі. **Методика.** Для дослідження обраний лист товщиною 1 мм зі сталі з 0,42 % *С* після покращення. Обробка складалася з гартування та відпуску при 300 °С. Зразки піддавалися циклічному навантаженню на машині Сатурн-10 за симетричного циклу знакозмінного згину, з частотою 100 хв$^{-1}$. Обробку імпульсами напружень проводили за умов «Іскра–23». Для визначення дії імпульсів поверхневих напружень на циклічну витривалість зразки, після 50–60 % обмеженої витривалості, піддавалися дії імпульсів напруження. Після завершення імпульсної обробки, зразки продовжували циклічно навантажувати до моменту руйнування. Густину дислокацій вимірювали за методикою рентгенівського структурного аналізу на дифрактометрі ДРОН-3, за інтерференціями (110), (211), (321). Комплекс властивостей після термічного зміцнення визначали за статичного розтягу, при швидкості деформації 10^{-3} с$^{-1}$. **Результати**. Після обробки імпульсами напружень досліджуваної, термічно зміцненої сталі з твердістю 46–47 HRC, отримали підвищення твердості на 11 %. За аналізом кривих циклічного навантаження термічно зміцненої вуглецевої сталі визначено, що завдяки дії імпульсів напружень відбувається збільшення обмеженої витривалості в широкому діапазоні циклічного перевантаження. Структурними дослідженнями визначено, що пропорційно зниженню величини циклічного перевантаження, підвищенню обмеженої витривалості відповідає більш висока кількість накопичених дислокацій за різних систем ковзання. **Наукова новизна.** Збільшення густини дислокацій від дії імпульсів напружень обумовлено розвитком процесів часткового розблокування дислокацій після термічного зміцнення та активації, не характерних для сталей систем ковзання. В результаті дії імпульсу напружень, розповсюдження деформації за цикл відбувається при більш низьких амплітудах навантаження, завдяки утворенню додаткової кількості дислокацій. За аналізом ліній Френча визначено, що участь підвищеної кількості дислокацій в розповсюдженні деформації за цикл, зсуває момент перетворення обернених ушко-

doi: https://doi.org/10.15802/stp2025/337870

джень в не обернені, в бік збільшення кількості циклів. **Практична значимість**. Отримані результати досліджень можуть бути корисними для оцінки впливу зовнішнього джерела напруження на поведінку виробу з вуглецевої сталі за циклічного навантаження.

Ключові слова: вуглецева сталь; дислокація; амплітуда циклу; імпульс напруження; циклічна витривалість

REFERENCES

1. Vakulenko, I. O. (2010). *Strukturnyi analiz v materialoznavstvi: Navchalnyi posibnyk*. Dnipropetrovsk: Makovetskyi Publishing. (in Ukrainian)
2. Askerov, Kh. A., & Vakulenko, I. O. (2020). Evaluation of the influence of dispersion of pearlite on the fatigue of carbon steel. *Materials Science, 56*, 214-217. DOI: https://doi.org/10.1007/s11003-020-00418-w (in English)
3. Bhamu, R. K., Shukla, A., Sharma, S. C., & Harsha, S. P. (2022). Vibration response of steam turbine healthy and cracked blade under the stress stiffening and spin softening effects. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 236*(2), 224-243. DOI: https://doi.org/10.1177/14644193221078656 (in English)
4. Braut, S., Tevčić, M., Butković, M., Božić, Ž., & Žigulić, R. (2021). Application of modified Locati method in fatigue strength testing of a turbo compressor blade. *Procedia Structural Integrity, 31*, 33-37. DOI: https://doi.org/10.1016/j.prostr.2021.03.007 (in English)
5. Casalino, G., Moradi, M., Karami Moghadam, M., Khorram, A., & Perulli, P. (2019). Experimental and numerical study of AISI 4130 steel surface hardening by pulsed Nd:YAG laser. *Materials, 12*(19), 3136. DOI: https://doi.org/10.3390/ma12193136 (in English)
6. Cheng, Y., Wang, Y., Lin, J., Xu, S., & Zhang, P. (2023). Research status of the influence of machining processes and surface modification technology on the surface integrity of bearing steel materials. *The International Journal of Advanced Manufacturing Technology, 125*, 2897-2923. DOI: https://doi.org/10.1007/s00170-023-10960-x (in English)
7. Cheng, Z., Wang, S., Wu, G., Gao, J., Yang, X., & Wu, H. (2022). Tribological properties of high-entropy alloys: A review. *International Journal of Minerals, Metallurgy and Materials, 29*, 389-403. DOI: https://doi.org/10.1007/s12613-021-2373-4 (in English)
8. D'Antuono, P. (2020). An analytical relation between the Weibull and Basquin laws for smooth and notched specimens and application to constant amplitude fatigue. *Fatigue & Fracture of Engineering Materials & Structures*, *43*(5), 991-1004. DOI: https://doi.org/10.1111/ffe.13175 (in English)
9. Jain, A., & Dhapekar, N. K. (2022). Methods of sample preparation in X-ray diffractometer (XRD). *International Journal of Advance Research and Innovative Ideas in Education (IJARIIE), 8*(3), 190-192. Retrieved from http://ijariie.com/AdminUploadPdf/METHODS_OF_SAMPLE_PREPARATION_IN_X_RAY__DIFFRACTOMETER__XRD__ijariie16518.pdf?srsltid=AfmBOorNi8z3PCrKxW2PHBQl2l5lOsGgtlp-UqaAWOoTO9nmgEK0tCZH (in English)
10. John, M., Ralls, A. M., Dooley, S. C., Vellooridathil Thazhathidathil, A. K., Perka, A. K., Kuruveri, U. B., & Menezes, P. L. (2021). Ultrasonic surface rolling process: Properties, characterization, and applications. *Applied Sciences, 11*(22), 10986. DOI: https://doi.org/10.3390/app112210986 (in English)
11. Kafaei, A., Salmani, F., Lakzian, E., Wróblewski, W., Vlaskin, M. S., & Deng, Q. (2022). The best angle of hot steam injection holes in the 3D steam turbine blade cascade. *International Journal of Thermal Sciences, 173*, 107387. DOI: https://doi.org/10.1016/j.ijthermalsci.2021.107387 (in English)
12. Kim, M.-J., Bui-Thi, T.-A., Kang, S.-G., Hong, S.-T., & Nam Han, H. (2024). Electric current-induced phenomena in metallic materials. *Current Opinion in Solid State and Materials Science, 32*, 101190. DOI: https://doi.org/10.1016/j.cossms.2024.101190 (in English)
13. Klumpp, A., Ruf, M., Dietrich, S., & Schulze, V. (2022). Long crack propagation and closure in DC(T) specimens of Ni-based superalloy Inconel 718 and stainless steel AISI 301 after shot peening. *Engineering Fracture Mechanics, 269*, 108551. DOI: https://doi.org/10.1016/j.engfracmech.2022.108551 (in English)
14. Krechkovska, H., Hredil, M., Student, O., Svirska, L., Krechkovska, S., Tsybailo, I., & Solovei, P. (2023). Peculiarities of fatigue fracture of high-alloyed heat-resistant steel after its operation in steam turbine rotor blades. *International Journal of Fatigue, 167*(Part B), 107341. DOI: https://doi.org/10.1016/j.ijfatigue.2022.107341 (in English)

doi: https://doi.org/10.15802/stp2025/337870

15. Lesyk, D. A., Martinez, S., Mordyuk, B. N., Dzhemelinskyi, V. V., Lamikiz, A., Prokopenko, G. I., Iefimov, M. O., & Grinkevych, K. E. (2020). Combining laser transformation hardening and ultrasonic impact strain hardening for enhanced wear resistance of AISI 1045 steel. *Wear, 462-463*, 203494. DOI: https://doi.org/10.1016/j.wear.2020.203494 (in English)
16. Maierhofer, J., Kolitsch, S., Pippan, R., Gänser, H.-P., Madia, M., & Zerbst, U. (2018). The cyclic R-curve – Determination, problems, limitations and application. *Engineering Fracture Mechanics, 198*, 45-64. DOI: https://doi.org/10.1016/j.engfracmech.2017.09.032 (in English)
17. Murakami, Y., Takagi, T., Wada, K., & Matsunaga, H. (2021). Essential structure of S-N curve: Prediction of fatigue life and fatigue limit of defective materials and nature of scatter. *International Journal of Fatigue, 146*, 106138. DOI: https://doi.org/10.1016/j.ijfatigue.2020.106138 (in English)
18. Peng, Y., Liu, Z., Chen, C., Gong, J., & Somers, M. A. J. (2020). Effect of low-temperature surface hardening by carburization on the fatigue behavior of AISI 316L austenitic stainless steel. *Materials Science and Engineering: A, 769*, 138524. DOI: https://doi.org/10.1016/j.msea.2019.138524 (in English)
19. Rivaz, A., Mousavi Anijdan, S. H., Moazami-Goudarzi, M., Nazari Ghohroudi, A., & Jafarian, H. R. (2021). Damage causes and failure analysis of a steam turbine blade made of martensitic stainless steel after 72 000 h of working. *Engineering Failure Analysis, 131*, 105801. DOI: https://doi.org/10.1016/j.engfailanal.2021.105801 (in English)
20. ZwickRoell. (n.d.). *Rockwell hardness testing: ISO 6508, ASTM E18*. Retrieved July 5, 2025, from https://www.zwickroell.com
21. Salleh, M. N. M., Ishak, M., Aiman, M. H., Zaifuddin, Q., & Quazi, M. M. (2020). The effect of laser surface hardening on the surface hardness of mild steel. In *IOP Conference Series: Materials Science and Engineering, 788*, 012014. DOI: https://doi.org/10.1088/1757-899X/788/1/012014 (in English)
22. Schönbauer, B. M., & Mayer, H. (2019). Effect of small defects on the fatigue strength of martensitic stainless steels. *International Journal of Fatigue, 127*, 362-375. DOI: https://doi.org/10.1016/j.ijfatigue.2019.06.021
23. Švábenská, E., Pizúrová, N., Roupcová, P., Chlupová, A., Brajer, J., Foldyna, J., & Schneeweiss, O. (2020). Effect of shock wave on microstructure of silicon steel. *Surfaces and Interfaces, 20*, 100415. DOI: https://doi.org/10.1016/j.surfin.2019.100415 (in English)
24. Vakulenko, I. A., Kurt, B., Raksha, S. V., Askerov, H., & Hryshchenko, M. A. (2019, June 21-23). *The effect of stress pulses on the cyclic endurance of steel axle wheel-set*. In *Papers presented at the International Conference on Materials Science, Mechanical and Automotive Engineerings and Technology in Cappadocia/Turkey (IMSMATEC'19) (pp*. 355-359), Nevsehir Haci Bektas Veli University. Nevsehir, Turkey. Retrieved from https://crust.ust.edu.ua/handle/123456789/11676 (in English)
25. Vakulenko, I. A., Vakulenko, L., Dal, S., Asgarov, Kh., Bolotova, D., & Kurt, B. (2023). *Structure evolution in steels of railway wheels at manufacture and operations* (S. Dal, Ed.). Nobel Bilimsel Eserler. (in English)
26. Wu, J., Zhao, J., Qiao, H., Hu, X., & Yang, Y. (2020). The new technologies developed from laser shock processing. *Materials, 13*(6), 1453. DOI: https://doi.org/10.3390/ma13061453 (in English)
27. Yang, F., Liu, P., Zhou, L., He, W., Pan, X., & An, Z. (2023). Review on anti-fatigue performance of gradient microstructures in metallic components by laser shock peening. *Metals, 13*(5), 979. DOI: https://doi.org/10.3390/met13050979 (in English)
28. Yoshinaka, F., Nakamura, T., Takeuchi, A., Uesugi, M., & Uesugi, K. (2019). Initiation and growth behaviour of small internal fatigue cracks in Ti-6Al-4V via synchrotron radiation microcomputed tomography. *Fatigue & Fracture of Engineering Materials & Structures, 42*(9), 2093-2105. DOI: https://doi.org/10.1111/ffe.13085 (in English)
29. Zhou, L., Zhao, T., Yu, Y., Liu, P., & Pan, X. (2022). Effect of laser shock peening on high-cycle fatigue performance of 1Cr18Ni9Ti/GH1140 weld. *Metals, 12*(9), 1495. DOI: https://doi.org/10.3390/met12091495 (in English)

Надійшла до редколегії: 19.05.2025
Прийнята до друку: 19.09.2025

doi: https://doi.org/10.15802/stp2025/337870