Influence Voltage Pulse Electrical Discharge In The Water at the Endurance Fatigue Of Carbon Steel

I.A. Vakulenko[1, a], A.G. Lisnyak[2, b]

1 – Department of Materials Technology, Dnepropetrovsk National University of Railway Transport named after Academician V. Lazarian. Street. Lazarian, 2, Dnepropetrovsk, Ukraine, 49010, Tel. 38 (056) 373 15 56, ORCID 0000-0002-7353-1916

2 – Department "The technology of mining machinery" Dnepropetrovsk National Mining University, pr. Karl Marx, 19, Dnepropetrovsk, Ukraine, 49027, Tel. 38 (0562) 46 99 81, ORCID 0000-0001-6701-5504

a – dnuzt_texmat@ukr.net

b – aleklisn@gmail.com

Keywords: hardness, distribution, impuls pressures, electric digit, limited endurance

ABSTRACT. Effect of pulses of electrical discharge in the water at the magnitude of the limited endurance under cyclic loading thermally hardened carbon steel was investigated. Observed increase stamina during cyclic loading a corresponding increase in the number of accumulated dislocations on the fracture surface. Using the equation of Cofino-Manson has revealed a decrease of strain loading cycle after treatment discharges. For field-cycle fatigue as a result of processing the voltage pulses carbon steel structure improvement, followed by growth of limited endurance decrease per cycle of deformation. With increasing amplitude of the voltage loop gain stamina effect on metal processing voltage pulses is reduced. The results can be used to extend the life of parts that are subject to cyclic loading.

Introduction. In the process of cyclic loading of carbon steel, the extent, to which the cycle amplitude exceeds fatigue limit, affects the character of structural change considerably [2]. For this reason, the rate of increase in the number of crystalline defects, and evenness of their distribution in the metallic matrix are the determinants of the conditions of the fatigue damage sites formation in metals and alloys [14]. Considering that, dislocations are basic carrier units of plastic deformation [3], the possibility of purposeful control over the process of their growth and redistribution under the fatigue loading can be considered a promising direction of development of the measures on improvement of the finite life. The information on the use of electric pulse effects [6, 10] in the carbon steel after a certain degree of plastic deformation can serve as example. As a result, there was such a change in the internal structure of a metallic material, which was required to achieve a desired set of properties.

Status of the problem. At the certain stage of the development of metal materials processing technology, in the production of complex shapes, especially of plate stock of considerable size, they detected certain difficulties in the implementation of the technical solutions. One of the ways to solve this problem was the proposal to use the shock wave resulted by an electric discharge in liquid [4].

Based on numerous studies [4–8], it was found that this technology allows not only the manufacturing of products by the formation of a complex deformed state but also managing a range of properties. Based on this, we can confidently assume that the value of the energy of pulse loading, its momentum distribution [7, 13] may significantly change the result to be achieved. Considering the existence of a certain threshold dependence of the impulse of voltage being formed, it is possible to obtain the result of different quality, ranging from the reinforcing effect to the metal weakening [4, 11, 12]. In most cases, the effect of hydraulic shock caused by the electric discharge in liquid for many metallic materials has reinforcing nature [4, 5], which is supposed to be followed by the change in the number of accumulated dislocations. Thus, if the effect has reinforcing nature, the increase in the dislocation density may be expected. Considering that the result depends on a large number of individual factors, the cumulative effect often leads to qualitatively opposite results. For example, the rise of the stress wave amplitude increases the number of dislocations [4]. On the other hand, the pulse length largely determines the conditions for the movement of the dislocation structures. Most of the known experimental data concerns the study of the influence of the electric discharge shock waves in liquid on the properties of metallic materials under static loading [5]. Based on this, we can confidently assume that the assessment of the impact of this effect on the behavior of the metal under the fatigue is quite an important issue.

Purpose. Assessment of the impact of voltage impulses of the electric discharge in liquid on the behavior pattern of carbon steel under fatigue loading.

Methodology. The carbon steel of the railway wheel pair axle with 0.45% carbon content was the material under research. The content of other chemical elements corresponded to the grade composition. The samples for alternating bending test under symmetric loading cycle were metal sheets of 1 mm thick, 15 mm wide and 180 mm length. The samples were subjected to martensite quenching and tempering at 300°C, for 1h. The analysis of the fracture surfaces was performed using a scanning electron microscope and fractography techniques; the dislocation density was evaluated by X-ray methods [1].

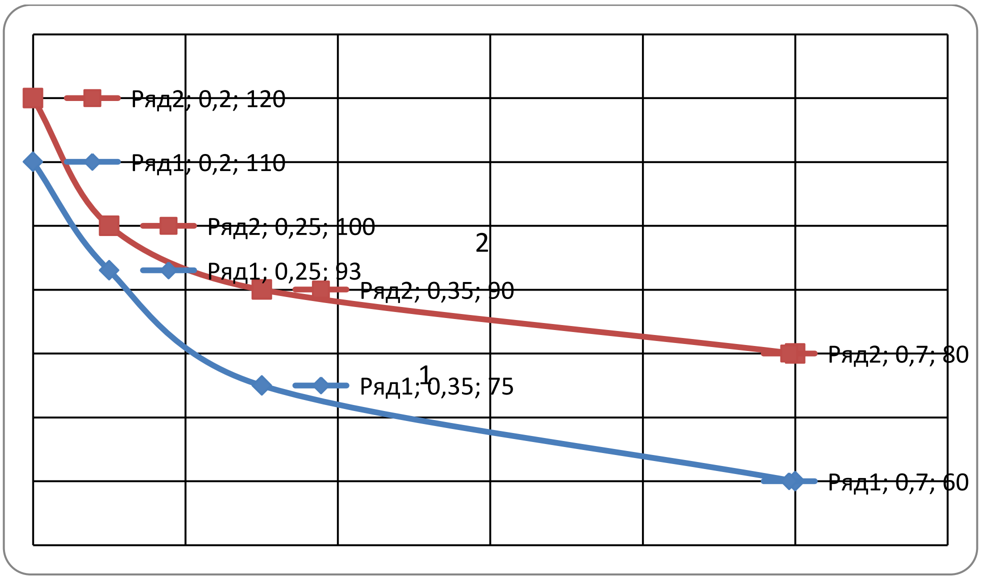
Metal fatigue testing was performed under alternating bending under symmetric loading cycle by means of the ten-station test machine “Saturn-10”. Electrical discharge impulse action on the samples of steel in water was performed by the “Iskra-23”, with the amplitude of the voltage to a maximum of 2 GPa. The total number of pulses was about 10^4, at the frequency of 2-3 Gts.

Results. Selection of the structural state of steel after martensite quenching and subsequent tempering at 300°C was driven by the possibility of achieving, under the high density of dislocations, enhanced values of fatigue resistance of a metal under cyclic loading. From the analysis of the internal structure of the metal, it follows that after quenching and tempering at 300°C, there the stages occur in the process of dispersed carbide particles liberation at the dislocations, both in the middle and at the boundaries of martensite laths. Besides, as follows from the results of studies [9], the development of dislocation recombination processes resulting in a decrease in their total amount should always result in the lowering of their mobility. Therefore, we can confidently assume that most of the dislocations that have appeared in the metal as a result of mentioned thermal treatment are immobile to different extents.

The analysis of the shock stress treatment effect on the fatigue behavior of a metal was carried out in a particular sequence. Fatigue curve was build first, for the samples that had undergone the thermal treatment (Fig. 1, curve 1), by which the finite life of the metal was determined. Further, the newly prepared samples were loaded, under the corresponding amplitudes of the cycle to the level of 0.6–0.7 of the value of the finite life. Then they were subjected to the shock stress. Further, the cyclic loading continued until the final destruction of the samples. Finite life value is the total number of cycles including the number of cycles before the shock stress treatment and after it, up to the final destruction of the sample (Fig. 1, curve 2).

The analysis of fatigue curves shows the expected difference in the evolution of the fine crystalline structure of the metal depending on the treatment applied. Indeed, for the similar amplitudes of loading there is a clear increase in the fatigue resistance of the metal that has been subjected to the shock wave impulse.

σ_a, $Mpa \times 10$



$N_i \times 10^6$ cycle.

Fig. 1. The diagrams of cyclic loading steel 45 after tempering and annealing at 300° C (♦) and after treatment of SS (■).(Stress straik).

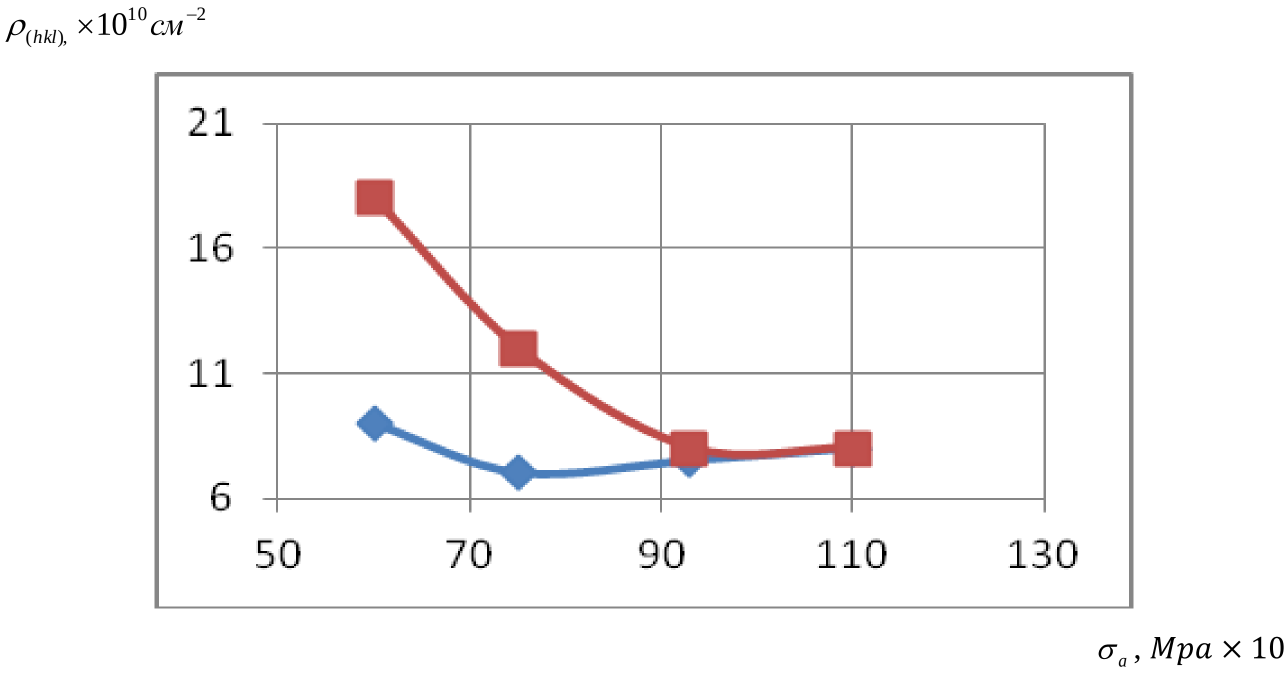
To explain the observed increase in the finite life of the metal, the dislocation density was estimated by the interference (110) and (211) on the fracture surfaces of the samples.

Regardless of the treatment (before and after the shock stress), the decrease in the amplitude of the cycle is followed by the accumulation of the amount of dislocations in the volume of metal under plane-strain loading. The absolute values of $\rho_{(hkl)}$ are of great interest. Thus, during cyclic loading at high amplitude the absolute values of the dislocation density at the fracture surface of the samples are almost the same. It can be explained by the fact that under high cyclic overstress the formation of elementary shifts within the structural element of steel causes significant plastic deformations localization, simultaneously with the rapid transition of the metal to the plane-strain condition. Further, during the subsequent decrease of σ_a the increase in the accumulated number of dislocations occurs, with the rate of increase ρ_{211} that is significantly higher than the corresponding value ρ_{110} (Fig. 2, *a*).

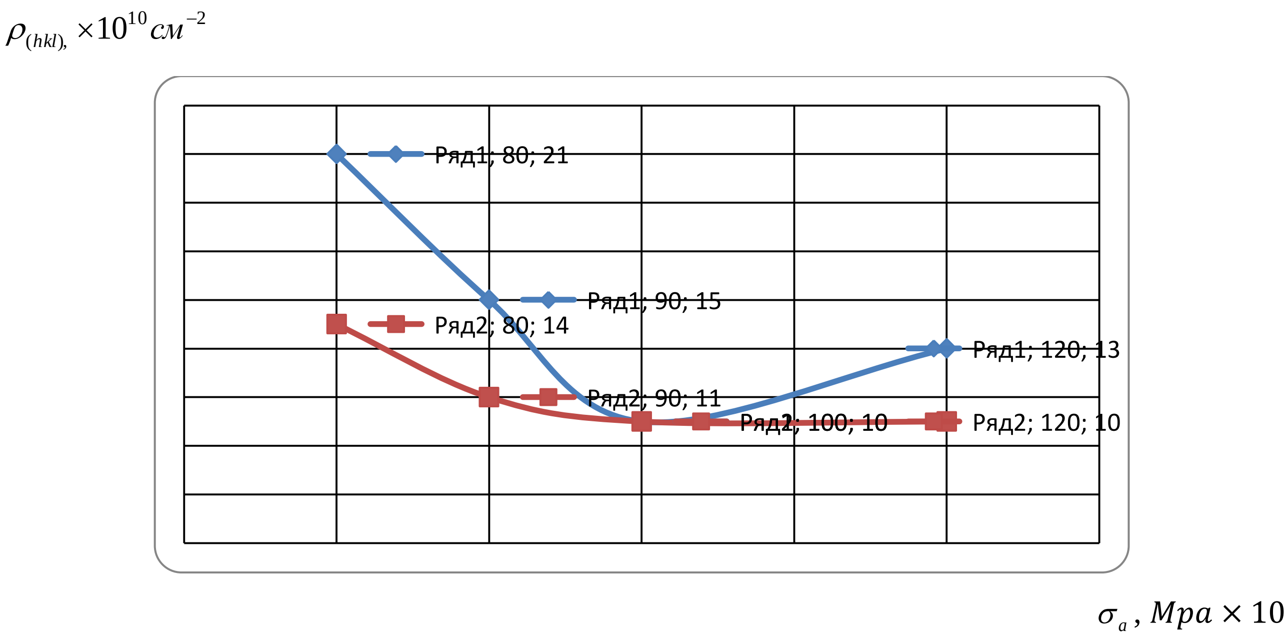
The nature of the changes of ρ_{211} and ρ_{110} (Fig. 2, *a*) corresponds to the known experimental data for metal loading under unidirectional static and cyclic loading [2].

By treatment of the metal that had been subjected to the preliminary cyclic loading (up to 0.6-0.7 of the value of the finite life with certain σ_a) by shock wave impulses, we have received the qualitative differences in the nature of the change of the dislocation density on the investigated interference (Fig. 2, *b*). The received level of absolute values: ρ_{211} is less than ρ_{110}, and their change rate with the decrease of σ_a appeared quite unexpected.

In order to explain the nature of the observed effect of the shock stress on the finite life under cyclic loading, we analyzed the fracture surface of the samples.



a)



b)

Fig.2. The change of dislocations density, estimated on interferences (110) - ♦ and (211) - ■ depending on amplitude of cyclic loading and preliminary treatment: without SS (a) and after SS (b).

The general analysis of fracture pattern in the samples after $256 \cdot 10^3$ cycles with the amplitude of 950 MPa (Fig. 3) shows that the surface of fracture was formed by a mixed mechanism. It is indicated by the presence of chips inside grains (Fig. 3, *A*) and formation of the faceted surfaces of intergranular fracture (Fig. 3, *B*) at the fracture surface.

The mechanism of formation of the chips inside grains is associated with the high overload along the cycle. The first phase of structural changes caused by the emergence of elementary shifts within the individual grains due to the movement of the unevenly distributed dislocations. Randomly oriented shifts lead to the rapid partition of the grain into pieces, the boundaries of which are the series of microcavities. The fatigue microcracks appear and extend along the specified boundaries due to the local low resistance of the metal [15]. In the case of discrepancy of surfaces of the simultaneously growing microcracks, in the places where they meet, a step or another boundary appears that separates the other fragments (light lines in Fig. 3).

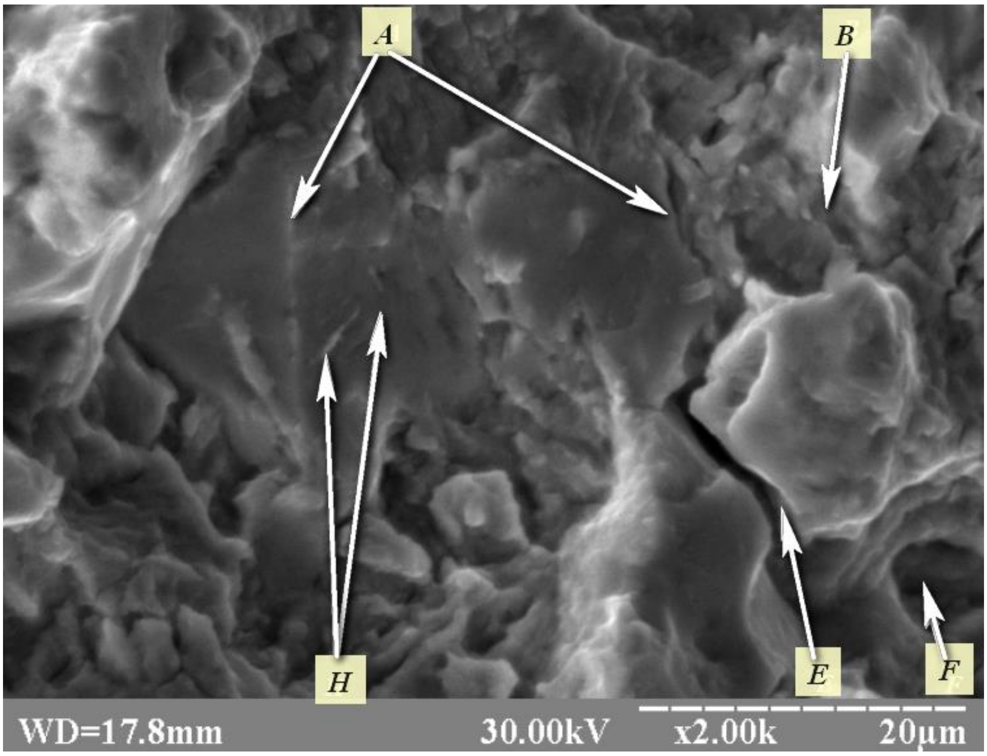


Fig.3. Fractographic investigation of the sample after the 260x. $\cdot 10^3$ *cycles at an amplitude of 950 MPa.*

Formation of the facets of intergranular fracture has a different mechanism. Instead of the chip within the grain, due to the reduction of the cyclic overload in individual grains, the microcavities appear near the angle boundaries, which reduces the bond between individual grains in the metal. Moreover, the movement of dislocations near the large angular boundaries for several crystallographic systems results in a series of vacancies. Under the influence of cyclically varying loads in the metal, the areas accumulating the vacancies near the grain boundaries turn into volumes with high concentrations of microcavities, along which the fatigue crack grows. The more detailed analysis shows additional features, which indicate the participation of other failure mechanisms in the formation of the fracture. In fact, there are dimples (F) on the fracture surface. These elements of the structure of the fracture surface explain the emergence of a significant number of microcracks (E), which grow mostly at the ferrite grain boundaries. Based on this, it can be assumed that the sample loading conditions with an amplitude of 950 MPa correspond to low-cycle fatigue, with the finite life of 256 thousand of cycles.

The reduction of the amplitude to 750 MPa is followed by the expected prolongation of finite life (up to 350 thousand of cycles). The analysis of the fracture surface (Fig. 4) testifies to the mixed mechanism of fracture just as under higher amplitude of loading. While under 950 MPa, the fracture surface is formed mainly due to the chips inside grains and formation of the faceted surfaces of intergranular fracture, under 750 MPa the chips inside grains do not appear (Fig. 4, B, *A* label).

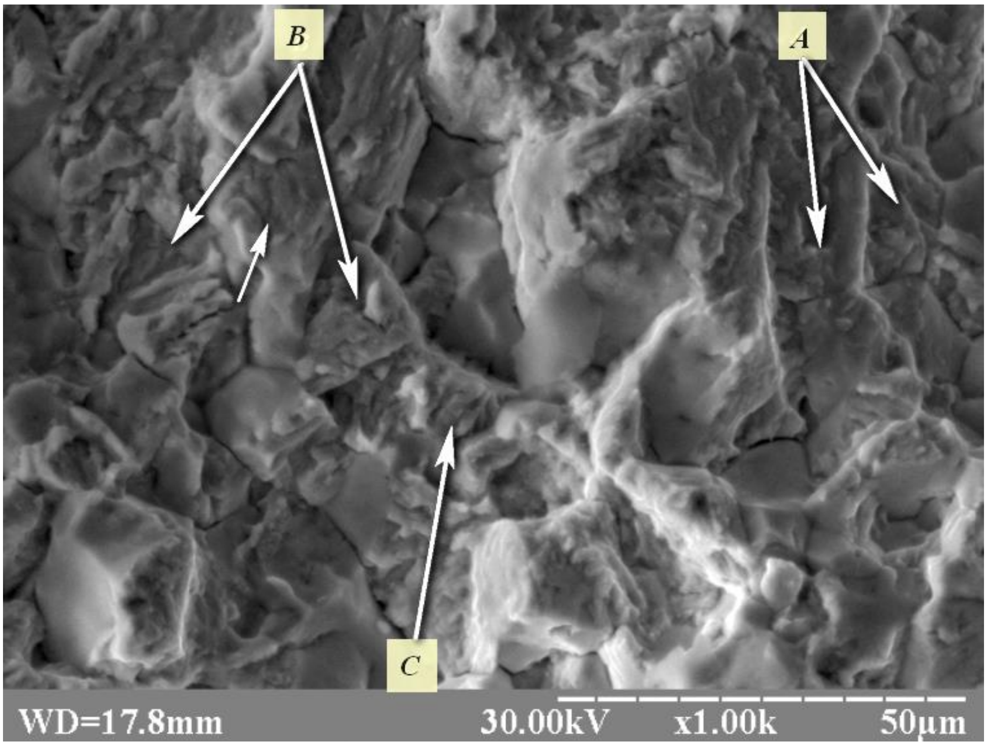


Fig.4. Fractographic investigation of the sample after 370 x10^3 cycle at an amplitude of 750 MPa.

The formation of the separation areas with the crests, which look like the light lines (Fig. 4, *A* label), and the intergranular fracture facets (*B* label) with a significant dispersion should be considered the dominating mechanism of the fracture surface formation. The sign that confirms the fatigue resistance improvement is the fewer number of decompositions and microcracks. At the same time, the number of pits of different sizes and shapes increased; this indicates an increase in the number of microcavities in the plane of the growing crack. Moreover, on the surface of the fracture, the occurrence of the sites with an equidistant arrangement of lines can be observed. The lines have external characteristics similar to fatigue striations (*C* label). Based on the analysis of the fracture it can be assumed that under the loading amplitude of 750 MPa the behavior of the sample corresponds to the conditions of low-cycle fatigue with the signs explaining the increase in the number of cycles to failure.

After the shock stress processing of the samples, the fracture surfaces have a slightly different structure (Fig. 5).

According to the external characteristics, the elements of the fracture surface (Fig. 5) has been formed by the mixed mechanism with almost the same range of particle dimensions as compared to the sample that has not undergone the shock stress (Fig. 3). The fracture pattern analysis (Fig. 5) shows the absence of the signs indicating the chip formation within the grains, which was observed in Fig. 3. At the same time, a considerable part of the fracture surface is occupied by the facets of intergranular fracture (Fig. 5, *A* label). There is approximately the same number of micro-cracks as in the sample that has not undergone the shock stress (Fig. 3), which are located along the grain boundaries (Fig. 5, *B* label), decompositions (*C*), separation areas with the crests (*D*) and dimples (*F*).

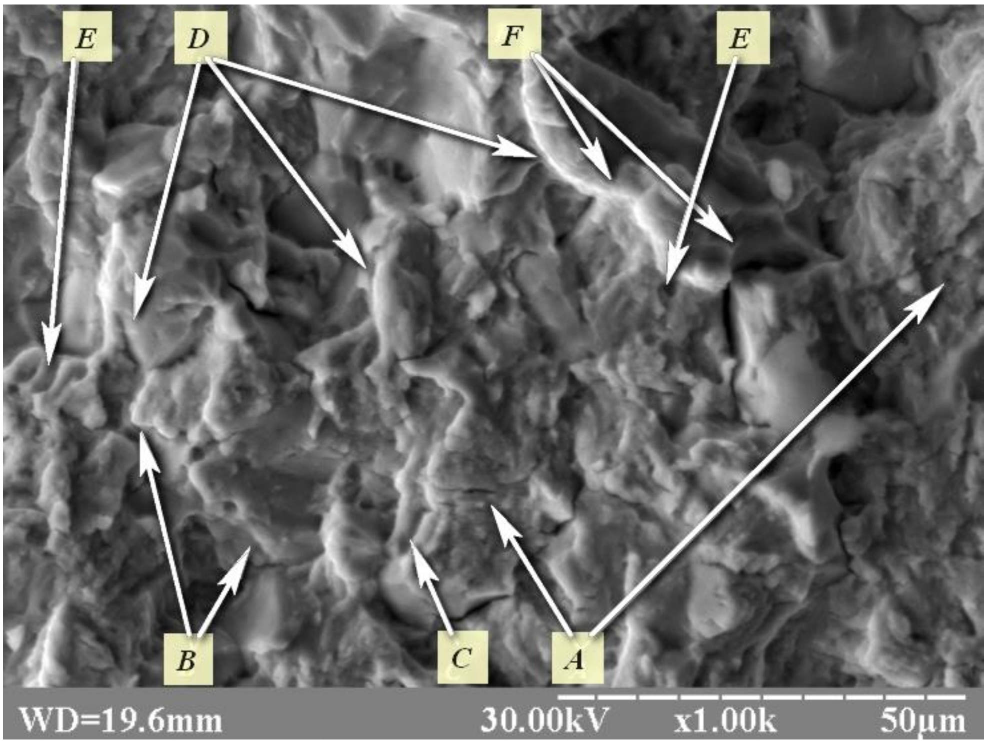
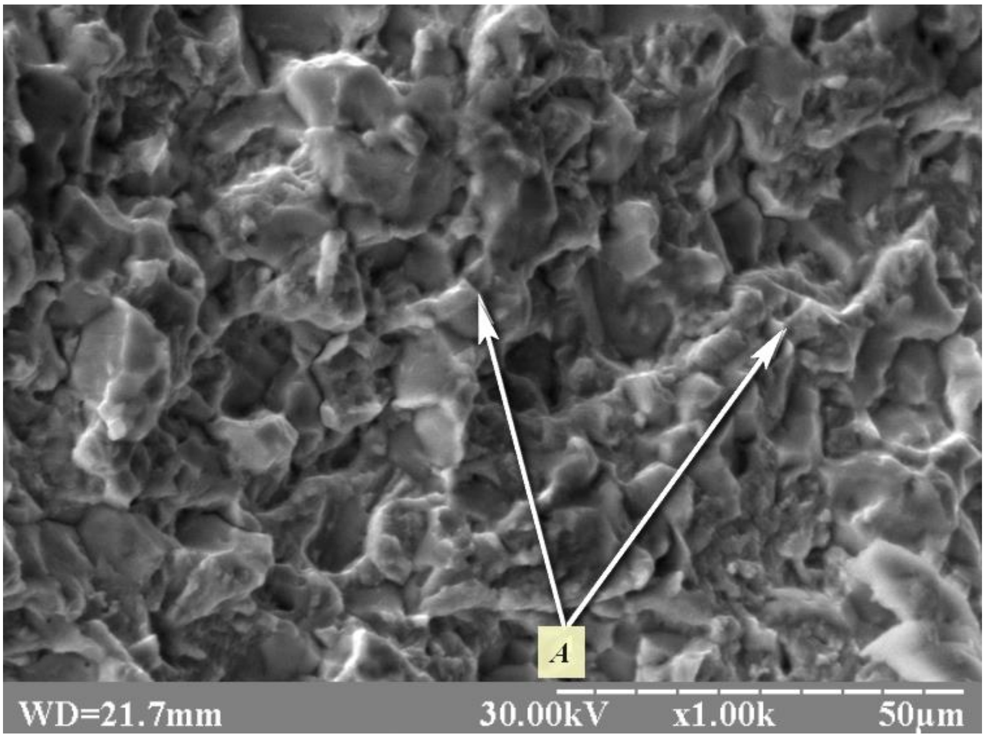


Fig. 5. The fracture surface of the sample with an amplitude 1000 MPa, after the total number of 260 x10 3 cycle with UN interim treatment.

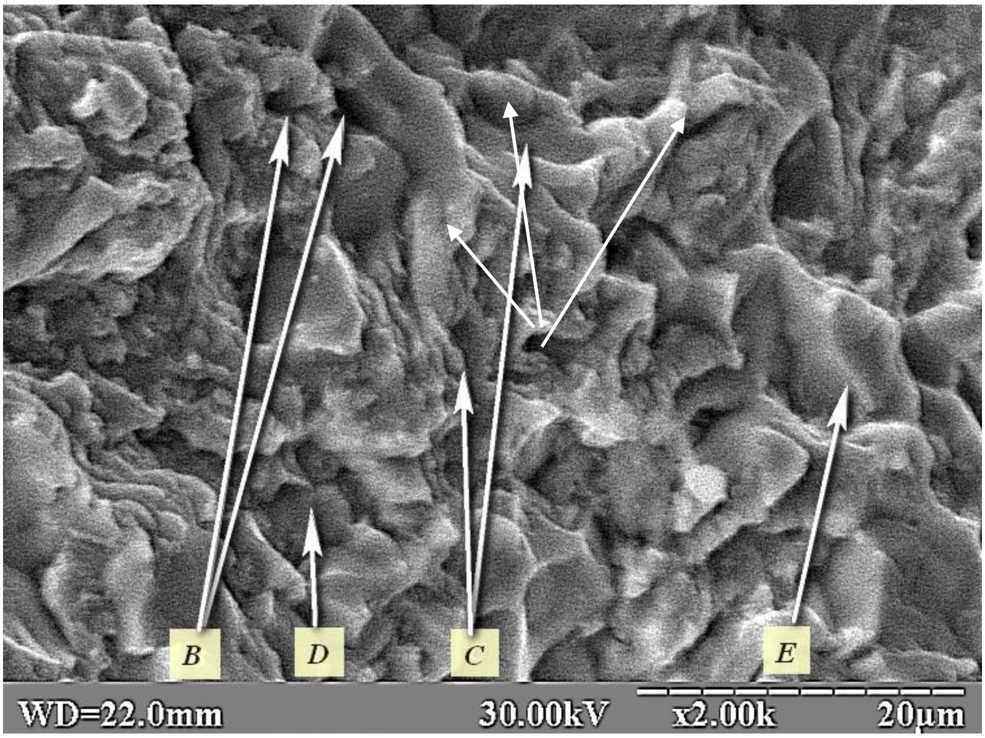
As for the presence of the fatigue striations as in the case of the sample shown in Fig. 3, it is quite difficult to determine uniquely, although there are similar sections (*E*). By means of the comparative analysis of the fracture surfaces and the obtained level of finite life, it is quite difficult to determine the influence of shock stress for the high-stress low-cycle region. On the other hand, it is known that in proportion to the degree of cyclical overload the influence of the static component on the development of fatigue phenomena increases. The static component that determines the effect of the deformation and precipitation hardening treatment on the structural changes, in fact, can mask the effect of the shock stress treatment. The confirmation of the above explanations may be received under the lower degree of the cyclic overload.

Fig. 6 presents the fracture pattern of the sample that survived 370 thousand cycles at an amplitude of 900 MPa, which has undergone the intermediate shock stress processing. In comparison to the sample with the same number of cycles to failure but without shock stress treatment (Fig. 4), the degree of dispersion of the fracture elements that has undergone the shock stress is higher. Firstly, the facets formed on the fracture surface have a more equiaxial shape (Fig. 6, *a*, *A* label). Compared to the fracture surface of the sample shown in Fig. 4, there are large areas with very small dimples (Fig. 6, *b*, *B* label); their formation mechanism is based on the coagulation of microcavities [2]. At the same time, there is a certain number of facets with crests of separation (*C*) and equidistant arrangement of the metal decomposition (*D*), with a low number of the facets of intergranular fracture (*E*). In the case of reduction of the test results to the equal cycle amplitude, the finite life of the metal after the shock stress treatment increases by about 30 %.

Summary. The voltage impulse treatment of metal produced by the electric discharge in water contributes to the increase of finite life of the carbon steel under cyclic loading. With the rise of the cycle amplitude, the gain in fatigue resistance resulted by the shock stress declines.



a)



b)

Fig. 6. The fracture surface of the sample with an amplitude of 900 MPa, after the total number of 370 x10^3 cycle with UN interim treatment.

References

[1] Gine A. Rentgenografiya kristallov [Roentgenography of crystals]. Moscow, Gosudarstvennoye izdatelstvo fiziko-matematicheskoy literatury Publ., 1961, 604 p.

[2] Nott Dzh.F. Osnovy mekhaniki razrusheniya [Fundamentals of fracture mechanics]. Moscow, MetallurgiyaPubl., 1978. 256 p.

[3] Yefremenko V.G., Murashkin A.V., Ivanchenko Ye.P. Sovershenstvovaniye sostava i termicheskoy obrabotki staley dlya nozhey kholodnoy rezki listovogo prokata [Improvement of composition and heat treatment of steels for knives for cold cutting of sheet metal]. Stal – Steel, 2007, no. 1, pp. 75-77.

[4] Meyers M.A., Murr L.B. Udarnyye volny i yavleniya vysokoskorostnoy deformatsii metallov [Shock waves and phenomena of high-rate deformation of metals]. Moscow, Metallurgiya Publ., 1984. 510 p.

[5] Chachin V.N. Elektrogidravlicheskaya obrabotka mashinostroitelnykh materialov [Electro-hydraulic processing of engineering materials]. Minsk, Nauka i tekhnika Publ., 1978. 184 p. [In Russian]

[6] Yao K-F., Wang J., Zheng M. A research on electroplastic effects in wire-drawing process of an austenitic stainless steel. Scripta Materialia, 2001, vol. 45, issue 15, pp. 533-539. doi: 10.1016/s1359-6462(01)01054-5.

[7] Ait Aissa K., Achour A., Camus J. Comparison of the structural properties and residual stress of AIN films deposited by dc magnetron sputtering and high power impulse magnetron sputtering at different working pressures. Thin Solid Films, 2014, vol. 550, pp. 264-267. doi: 10.1016/j.tsf.2013.11.073.

[8] Conrad H. Effects of electric current on solid state phase transformations in metals. Materials Science and Engineering : A, 2000, vol. 287, issue 2, pp. 227-237. doi: 10.1016/s0921-5093(00)00780-2.

[9] Dhadeshia H.K.D.H. Bainite in Steels. Cabridge, The University Press Publ., 2001. 454 p.

[10] Vakulenko I.A., Nadezdin Yu.L., Sokirko V.A. Electric pulse treatment of welded joint of aluminum alloy.Nauka ta prohres transportu. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu– Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport,2013, no. 4 (46), pp. 73-82. doi:10.15802/stp2013/16584.

[11] Tang G., Zhang J., Zheng M. Experimental study of electroplastic effect on stainless steel wire 304L.Materials Science and Engineering : A, 2000, vol. 281, issue 1-2, pp. 263-267. doi: 10.1016/s0921-5093(99)00708-x

[12] Morgan W.L., Rosocha L.A. Surface electrical discharges and plasma formation on electrolyte solutions. Physics of Low-Temperature Plasmas, 2012, vol. 398, pp. 255-261. doi: 10.1016/j.chemphys.2011.06.037.

[13] Razavian S.M., Rezai B., Irannajad M. Numerical simulation of high voltage electric pulse comminution of phosphate ore. Intern. Journal of Mining Sci. and Tech., 2015, vol. 25, issue 3, pp. 473-478. doi:10. 1016/j.ijmst.2015.03.023.

[14] Vakulenko I.A., Proydak S.V. The Influence Mechanism of Ferrite Graine Size on Strength Stress at the Fatigue of Low-Carbon Steel. Nauka ta prohres transportu. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu – Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport, 2014, no. 1 (49), pp. 97-104. doi: 10.15802/stp2014/22668 [In Russian].