THE EFFECT OF STRESS PULSES ON THE CYCLIC ENDURANCE OF STEEL AXLE WHEEL-SET

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Abstract

For different temperature and speed deformation conditions, the nature of the increase in the number of defects in the crystal structure and the achieved complex of properties are due to the peculiarities of the internal structure of the metallic material. Compared with unidirectional static loading, the violation of the monotonous nature of the effective stress is accompanied by qualitative changes in the internal structure of metals and alloys. Thus, the pulsating nature of the acting stresses in case of fatigue, depending on the degree of cyclic overload per cycle, can lead to significant changes in the development of the processes accumulation and redistribution of defects in the crystal structure and, above all, dislocations. Based on this, the rate of accumulation of dislocations per loading cycle can be considered as one factor that will allow the development of measures to increase the cyclic endurance of metallic materials during fatigue. Compared to thermal technologies, treatments that are based on the use of short stresses pulses for moving defects in a crystal structure have gained some fame. In addition to sufficiently strong magnetic fields or high-power pulses of electric current, treatments based on mechanical effects on the metal can be used.

Keywords: fatigue, endurance, dislocation, stress, steel

1. Introduction

Over a rather long period of development of the machine-building industry, the technology of processing metallic materials using a shock wave of various origin was widely used [1]. This technology provides for the formation of a mechanical stress pulse sufficient to form a metal in the manufacture of large-sized products of complex shapes. Moreover, the use of stresses pulses allows not only to deform the metal, but also to weld individual elements. Regulation of power and pulse frequency allows you to solve complex technological problems. Thus, depending on the level of the generated stress, frequency, and the profile of the pulse itself, it is possible to achieve qualitatively different effects on the metal. An analysis of the known results of using this technology [2, 3] indicates the existence of certain conditions when the effect of a transmitted stress wave can lead to both hardening and softening of the metal. If the purpose of such a pulse treatment is still hardening, then the result can significantly exceed the effect of equivalent plastic deformation. Analysis of the known experimental studies [1, 4] shows that formation of a hydraulic shock from an electric discharge in water leads to a strengthening effect. In this case, an increase in the strength characteristics of the metallic material should be accompanied, at a minimum, by an increase in the density of defects in the crystal structure. On the other hand, there are results that indicate a quality different influence parameters of the pulse effect. Indeed, as indicated by the results of [1], an increase in the amplitude of the stress pulse contributes to an increase in the density of dislocations. A qualitatively different influence on the process of structural changes is observed from the side of the pulse duration. Thus, an increase in its duration leads in most cases to an influence on the process of moving dislocations. Thus, the ambiguity of the impact of pulsed loading on the nature of displacement and accumulation of dislocations indicates the need to continue research, including the development of fatigue processes. Based on this, the purpose of the work is to clarify the mechanism of the effect of stress pulses from an electric discharge in water on the fatigue endurance of carbon steel.

2. Material and research methods

The material for the study was steel 45 of the railway axle of the wheel-set (0.45% carbon) with the concentration of chemical elements within the brand composition. Samples for testing were made in the form of plates with a thickness of 1, a width of 15 and a length of 120-180 mm. The structural state of the steel corresponded to hardening for martensite from normal temperatures of heating and tempering at 300° C, for 1 hour. The microstructure was investigated using electron microscopy, the dislocation density was estimated by X-ray structural analysis.

Hardness was measured by the Rockwell method (HRC scale). Cyclic loading was carried out under conditions of symmetrical bending on the Saturn-10 testing machine at a temperature of +20° C. Processing stresses pulses (SP) from the electrical discharge in water was carried out using a Iskra-23 bath type used for cleaning casting products. Electric impulses were formed at a voltage of 15-18 kV with an energy of 10–12 kJ and an amplitude of 1-2 GPa. Metal processing was to set the number of pulses up to 15 thousand, at a frequency of 2-3 Hz.

3. Results

The modern level of industrial development is accompanied by an inevitable increase in the intensity operation of railway transport. Considering that the axis of the wheel-set is one of the most loaded elements, increasing the service life of its trouble-free operation is a pressing issue. The widespread use of hardening heat treatments suggests that simultaneously with an increase in the strength characteristics of carbon steels, the crack resistance of the metal decreases. Given that the axis of the wheel-set during operation is subjected to numerous cyclic loads, the study of the mechanism for the development of fatigue phenomena will make it possible to develop recommendations for improving its limited endurance.
Analysis of the microstructure indicates the formation of martensitic crystals with practically no signs of decay. Subsequent heating and aging at temperatures of 200° C and 300° C are accompanied by the onset of the precipitation of high dispersion carbide particles at the boundaries and inside martensitic crystals (Fig. 1a, b). When choosing the structural state of carbon steel, we were guided by the need to achieve high strength properties with a minimum level of the brittle component during the destruction of the metal. The loss of contrast in the walls of dislocations observed in some places and their simultaneous decoration by carbon atoms indicate effective blocking of dislocations in the case of loading.
After quenching and tempering, a hardness of about 47 HRC was achieved, which indicates that a high-strength state in steel has reached the same chemical composition. Processing steel SP led to an increase in hardness by an average of 10-12%. Based on this, it should be assumed

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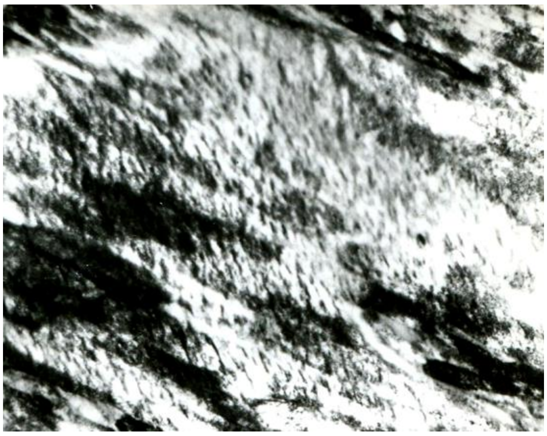

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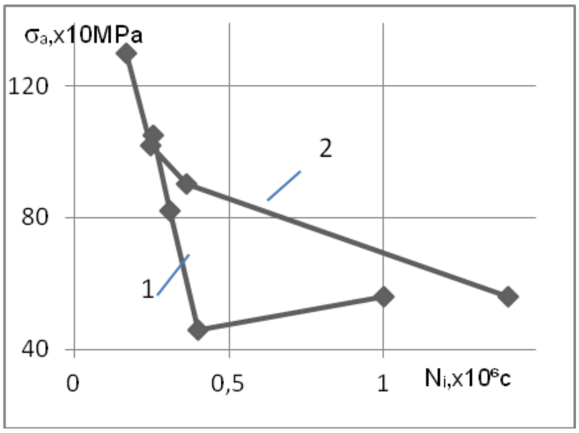
Fig.1.Structura steel 45 after tempering and annealing at 200° C (a) and 300° C (b). Magnification is 14000x1,3.

that the treatment by SP of thermally hardened carbon steel, according to the mode used, leads to additional hardening.
From a joint analysis of fatigue curves (Fig. 2a) [5], it was found that the treatment of SP, regardless of the degree of cyclic overload, is accompanied by an increase in limited endurance (ΔN_i) (Fig. 2b). Depending on the degree of cyclic overload, the magnitude of the increase in limited endurance varies. Thus, for the region of high-cycle fatigue, a decrease in the amplitude of the cycle is accompanied by a progressive increase in ΔN_i (Fig. 2b). For low-cycle fatigue, the picture is qualitatively different. In proportion to growth of σ_a a gradual decrease in the effect influence of SP is observed. At amplitudes of the order of 1 GPA, the increase in metal endurance practically stops. Thus, in general, it can be assumed that the treatment with SP of thermally hardened carbon steel can increase the limited fatigue endurance. On the other hand, there is a clear dependence of the effect on the degree of cyclic metal overload.
The assessment of the change density of dislocations (ρ)



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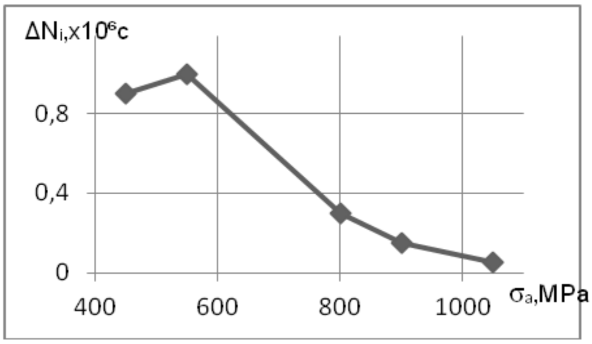

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Fig.2. Curves of fatigue: 1 - before SP, 2 - after (a) and the effect of σ_a on the growth of limited endurance after SP (b.

as a function magnitude of the cyclic overload was used to explain the mechanism influence of SP on the increase in endurance with fatigue thermally hardened steel. Figure 3 shows the nature of the change in the density of dislocations in the main crystallographic slip systems. Considering that ρ was estimated from the surface of the destroyed specimen, the nature of the accumulation dislocations corresponded to crack growth during fatigue under conditions of a plane-deformed state [6].

On the other hand, for low-cycle fatigue, proportional to the degree of cyclic overload increases the role static component of the cycle and, accordingly, the proportion of the metal in a volume-stressed state. In accordance with the data of [8], in this case, the number of dislocations on the surface of fatigue fracture should decrease. This is due to the fact that at high values of σ_a, dislocations accumulate to a greater extent in metal volumes near the crack growth surface. While on the surface itself, the dislocation density will decrease.

Additional evaluation of experimental results using the Kofin-Manson equation showed that for identical cyclic loading amplitudes, SP treatment reduces the metal deformation per cycle by about 20% [7]. Consequently, the process of introducing an additional number of dislocations into thermally hardened steel from the action of SP does not lead to the annihilation of dislocations. The

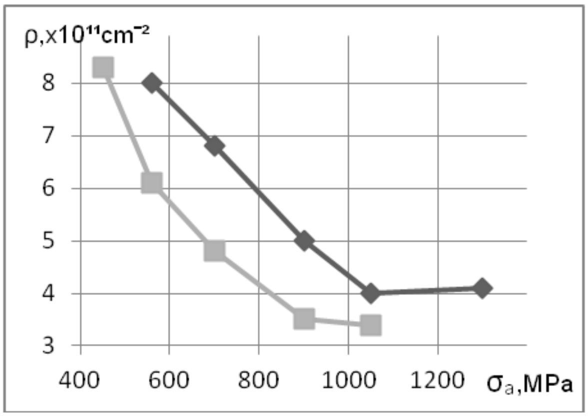
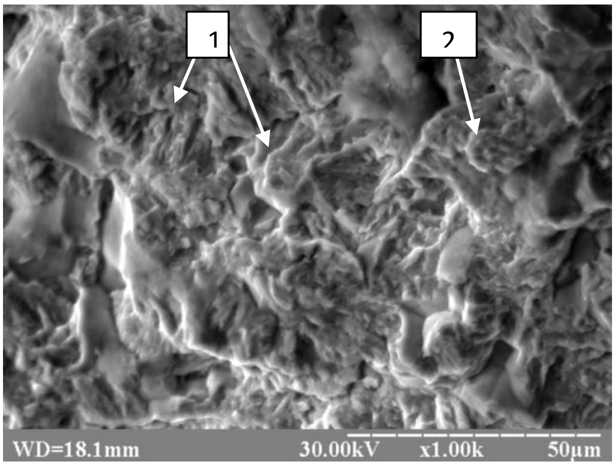


Fig.3. The cumulative effect of a change in the density of dislocations in three interferences (110), (211), (321) [7] depending on the amplitude of the cycle: before SP processing (■) and after (♦).

reduction in metal deformation per cycle indicates that fewer dislocations are required to maintain the continuity conditions for the propagation of deformation. As a result, for the same amplitude of cyclic loading, the SP treatment helps to reduce the rate of accumulation of dislocations and shifts the moment formation of the fatigue crack towards the increase in the number of cycles.

Additional confirmation of these provisions obtained in the analysis of the surfaces destruction. The comparison was carried out for approximately the same amplitudes of the fatigue loading cycle. The processes of nucleation and propagation of fatigue cracks largely depend on the degree of cyclic overload. The formed pattern on the surface allows to determine the type of the dominant mechanism of destruction metallic material. According to the accepted classification [8], the formation of relief elements on the surface of destruction is due to the development of qualitatively different mechanisms.

Figure 4 shows images of the sample surface (without SP treatment) after 1 million cycles with an amplitude of 560 MPa. For the degree of cyclic overload 1,2 the development of destruction occurs by a mixed mechanism. On surface of the fracture, there are no signs of cleavage inside the grains and the spread of micro cracks along their borders. There are significant planes with a relief in the form of pits (Fig. 4a, notation 1). These fracture elements are formed by the mechanism of combining micro pores and separation areas with formed crests (notation 2, 3). At higher magnification, features of the structure the emerging ridges are found. For the sample under study, the crests have a wavy shape (Fig. 4b, notation 3). A sufficiently large part of the fracture plane corresponds to areas with signs of fatigue grooves. A detailed analysis shows that within one facet can observe the spread of fatigue grooves with both constant direction and equidistant location of their fronts (Fig. 4b, designation 4) and disoriented (Fig.4b, designation 5).



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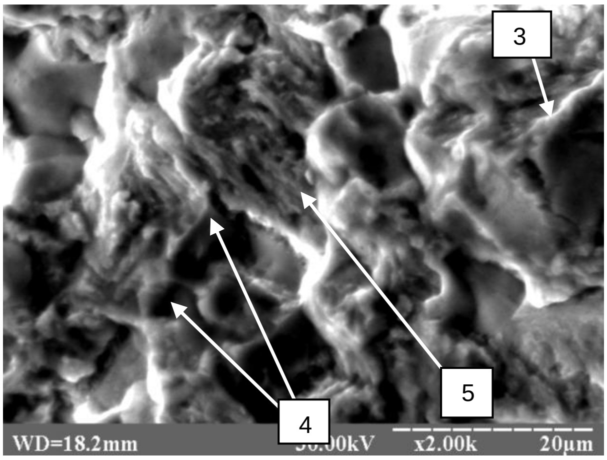

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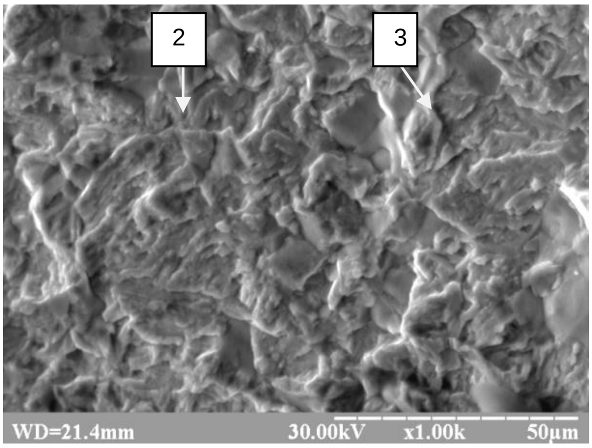
Fig.4. The surface of the destruction of the sample after 1 million cycles with an amplitude of 560 MPa.

Based on this, the wavy shape of the crests can be considered as the result of successive passing through several stages of fracture formation by various mechanisms, under conditions of a small degree of cyclic overload. A distinctive sign of the behavior of a metal with a low degree of overload is the increasing role of the processes of redistribution of defects in the crystal structure during a change in the sign of stress. As a result, the accumulation of defects in the crystal structure and their localization in individual micro volumes will slow down (Fig. 3), which will lead to a shift in the moment formation of the center destruction in the direction of increasing limited endurance [8].

Treatment of metal with SP led to an increase in cyclic endurance by about 1.5 times (Fig. 2b). A joint analysis of the fracture surfaces of Fig.4 and Fig.5 indicates the existence of quantitative and qualitative differences in the elements of the fracture structure. As a result, the SP treatment, in addition to a few smaller facets in size, is observed a change in the shape and size of the ridges. Combs formed after SP in most cases are thinner (Fig. 5a, notation 2 and 3), compared with similar elements (Fig. 4) and have a more wavy shape.

A similar result was obtained when comparing metal bundles. On the surface of the sample after the IN, thinner and significantly more distorted delaminations form (Fig.5b, symbols), with the simultaneous occurrence of a specific relief on their surfaces (Fig.5b, symbols 5). According to external signs, the lines have a similar appearance under conditions of multiple slip dislocations, during the deformation of ferrite low carbon steel. Thus, with a low level of cyclic overload, the formation of distorted lines on the delaminating surfaces can be considered as evidence of a possible change in the dislocation slip system after a certain number of fatigue cycles. An additional confirmation of this is a change in the



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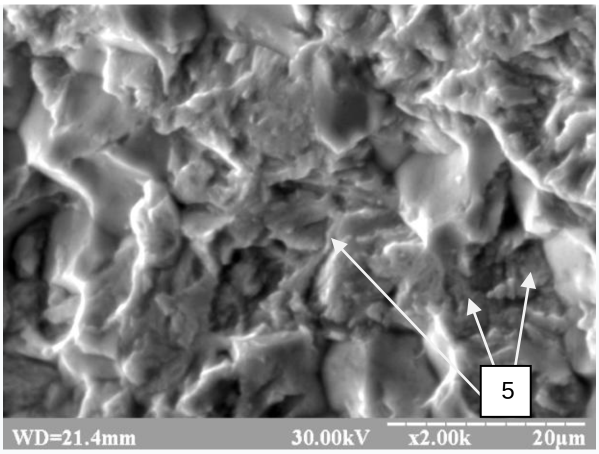

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Fig.5. The surface of the destruction of the sample after 1,44 million cycles with an amplitude of 560 MPa (after SP treatment).

ratio in the number of dislocations located in different slip systems. Indeed, with the exhaustion of the resource of accumulation of dislocations or the possibility of their movement along one slip system, another one apparently begins to work. A consequence of movement dislocations along the secondary crystallographic systems are the distortions of dispersed ridges on the surfaces of metal separation. A necessary condition of the above scheme is to maintain a high concentration of mobile dislocations in the process of cyclic loading. Thus, when the static component of the cycle is small, the introduction of an additional number of mobile dislocations and their recombination during SP treatment is one of the reasons increase of limited fatigue endurance.

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