INFLUENSE OF THE SHOCK WAVE TREATMENT ON FATIGUE CARBON STEEL

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Abstract. The process of introducing additional number of dislocations in the heat-hardened steel after shock wave pulse treatment apparently is not accompanied by the development of dislocation annihilation. Furthermore, implementation of the deformation per cycle for the area of high-cycle fatigue is ensured by the participation of more dislocations. Thus, in the process of shock wave pulse treatment, the vast number of introduced dislocations is mobile and able to interact with further cyclic loading or it takes place additional unlock of previously fixed dislocations after hardening and tempering. Overall, on the destruction surface after treatment with shock wave pulses it is found increased number of dislocations that are located in different crystallographic slip systems. They can be seen as evidence of the development of quite complex dislocation reactions that increases the metal limited endurance during cyclic loading.

Keywords: Shock Wave Pulses, Dislocation Density, French Line, Low-Cycle Fatigue, Limited Endurance.

1.Introduction.

According to the conditions of cyclic loading, increase in dislocations density and their redistribution being in a moving state are among the main factors that determine the fatigue limited endurance [1]. As compared to the thermal technologies the use of impacts from the introduction of additional harmonics in the load cycle or the use of effects of electric current pulses [2-4], stress pulse of shock waves of different nature is able to influence structural changes metallic materials.

In comparison with static conditions [5], the nature of plastic deformation of metals and alloys from the effect of shock wave pulse that is formed using explosives has significant differences [6]. First of all it is significant changes in the process of structural transformations due to the peculiarities of formation and propagation of dislocations and dislocation groups. Very high power of pulse and deformation rate during shock wave propagation, time during the pulse 10^{-6}-10^{-9} s lead to the stresses increase to the level of theoretical strength of metallic materials [7]. Under these conditions, qualitative changes in the nature of plastic flow leads to high localization of deformation and abnormal changes in the properties of most metal materials.

2. State-of-the-art

Significant difficulties in the implementation of technology of the pulse use of high power shock wave can be compensated using the stress pulse from the forming electrical discharge in the liquid. This approach can replace the effect of one powerful pulse for an unlimited number of controlled pulses of low-power from the discharge in liquid [8]. Based on the analysis of experimental studies it was determined that change in power, number of pulses from electrical discharge in the water [9] can significantly affect the complex of properties of metals and alloys. At the same time, according to different sources there is no clear nature of the impact of such pulse treatment on certain properties [10]. During pulse treatment of the shock wave in the liquid such effects as strengthening and softening of the metal are achieved. Such mixed results are caused by the total influence from the effect of specified number of different factors. According to information in the work [7] increasing the stress amplitude increases dislocation density and pulse duration to a greater extent influences the conditions of dislocations movement. Taking into account the fact that most studies are dedicated to analysis of the influence of shock wave treatment from electrical discharge in a fluid on the properties of metallic materials under static loading conditions [8,10], assessment of the influence on the behavior of metal fatigue is sufficiently pressing issue.

3. Material and Treatment

The carbon steel axle of a pair railway wheel containing chemical elements: C 0.40; Mn 0.85; Si 0.50; S 0.022 and P 0.017% was used as a material for research. The samples for fatigue tests were manufactured from the blank, form and dimensions are shown in the Figure 1. After production, the samples were subjected to thermal hardening using the following scheme: heating to the temperatures above Ac_3, holding to equalize the temperature and austenite homogenization followed by martensite hardening.

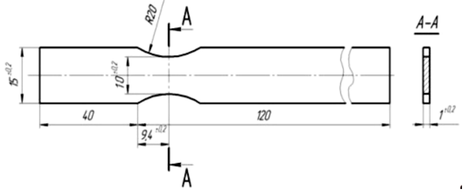


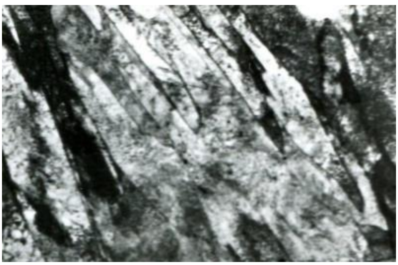
Fig.1. *The form and dimensions of samples for cyclic loading.*

After evaluation of hardening quality, the samples were subjected to tempering at 300 °C, duration 1 h. As the static strength characteristics the Rockwell hardness test was used. Metal pulse treatment was conducted using industrial equipment. Shock wave (SW) pulses were formed using electrical discharge in the water at the bathing installation "Iskra-23." At the electric voltage 15-18kV at the electrodes, the pulse with energy 10-12kJ and stress amplitude 1-2GPa arises. During treatment the samples were exposed to 15000 of pulses with frequency 2-3Hz. Cyclic loading of samples (Fig. 1) was conducted under conditions of symmetrical bending at the test machine "Saturn-10." Metal structure was studied using Electronic microscope. The dislocation density assessment was carried out using X-ray structural analysis [11] at the equipment of DRON-3 type.

4. Results

4.1. The structure.

After hardening the lath martensite structure with a high dislocation density is being formed (Fig. 2a). The lath width varies in the range to 1 micron. In some martensitic crystals the thin twin layers are determined. Given the coincidence of the bigger edge of the lath with the foil surface the dashed randomly oriented disengagements of cementite particles with high dispersion are observed. Heating of steel with martensitic structure to 300 °C leads to disengagement of dispersed carbide particles on dislocations, which are located in the middle of martensitic laths and their edges (Fig.2b). In some places of the structure research the signs of image contrast loss were identified. This shows the development of dislocations recombination, reducing their density. At the same time the emergence of areas with heterogeneous arrangement of dislocations was observed. Thus, decorating the broad walls of dislocations with carbon atoms can be seen as evidence of the almost complete absence of



a

b

Fig.2. *The structure of carbon steel after quenching (a) and tempering at 300 °C (b). Magnification 18,000.*

moving dislocations in the steel after hardening and tempering.

After quenching and tempering the hardness was 46-47 HRC and after SW treatment the hardness increased on average by 11% [9].

4.2. Cyclic loading.

Cyclic loading diagrams in terms of symmetrical bend cycle are presented in the Figure 3. Using the analysis of steel diagram (Fig. 3, curve (1) for the selected load amplitudes the values of limited endurance (N_i) were determined.

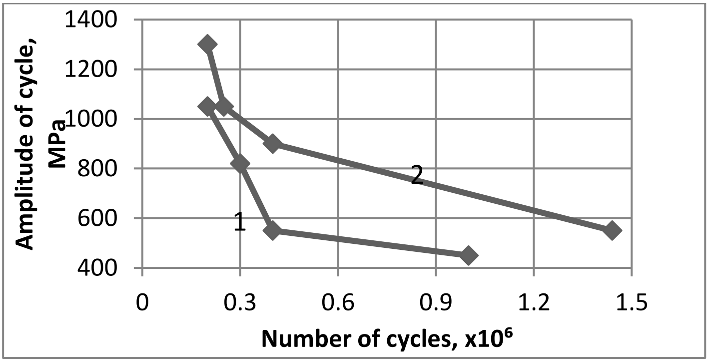


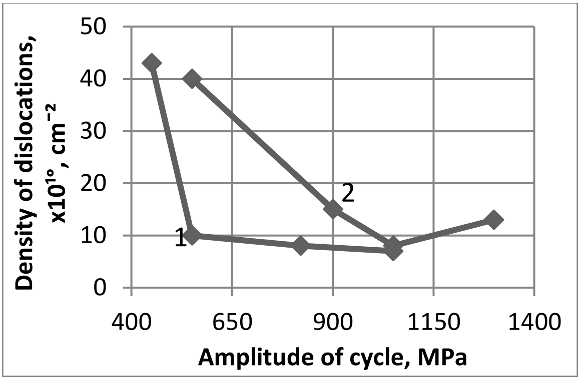
Fig.3. *Diagrams cyclic loading of carbon steel after quenching with tempering martensite at 300 $^{\circ}$C (1) and after action shock pulses (2).*

The samples to assess the impact of SW pulses for cyclic endurance were prepared as follows. Knowing the number of cycles that can endure the metal until destruction at a certain amplitude value (σ_a) it was carried out the load of samples to about 0.6-0.65 N_i .

Then they were exposed to SW pulses and were carried to failure. The value of limited endurance was estimated as the sum of the number of cycles until SW treatment and after the final destruction at the particular amplitude (Fig. 3, curve 2). Comparative analysis of the curves indicates the possibility of qualitative differences in the internal structure of the metal before and after exposure to SW pulses. Thus, for the area of low-cycle fatigue increase in the load amplitude is accompanied by lowering the differences in the values of limited endurance (before and after exposure to SW), which at σ_a = 1050MPa is almost absent. Further extrapolation of cyclic loading curves in the areas of high amplitude (greater than 1050MPa) shows no practical impact of SW treatment on limited endurance. Presented nature of limited endurance, the cumulative effect from the SW pulses can be seen as dependent on the degree of cyclic overload of metal. For low amplitude areas, location of the cyclic loading curve (2) above the curve (1) shows the development of strengthening processes. Taking into account existence of inversely proportional relationship between strength stress and plastic properties margin for the most of metal materials [12], to the strengthening level increase should correspond the lower resource of defects accumulation in the crystal structure until destruction. On this basis, the expected effect from the shock wave pulses should be directed towards reducing fatigue endurance. However, a comparative analysis of the curves (Fig.3) shows violation of these provisions. For the same amplitudes of cyclic loading (lower than 1050MPa) the effect of shock wave pulses is accompanied by unambiguous increase of fatigue endurance. Furthermore, the effectiveness of the SW pulses impact increases as the cyclic overload is being reduced. It is evidenced by a flatter course of the fatigue curve (2) as compared to the curve (1), Fig. 3. These results show the fact that the development of structural transformations in carbon steel during the shock wave pulses should occur at a different scheme in comparison with the effect from the strengthening during cold plastic deformation or thermal hardening [13]. In order to determine the nature of influence of the shock wave pulse on fatigue endurance the degree of dislocations accumulation in the metal volumes near the damage surface was evaluated.

Analysis of the fine crystal structure parameters demonstrates rather complicated impact of shock wave pulses on the dislocations redistribution in accordance with the conditions of cyclic loading (Fig. 4). Dislocation density measurements according to three slip systems demonstrate about the same impact of the value σ_a on the accumulated dislocation density by various interferences ($\rho_{(hkl)}$). However, a more detailed study can determine that corresponding break points on the curves for metal after exposure to SW pulses are shifted toward higher load amplitudes (Fig. 4), although the absolute values $\rho_{(hkl)}$ are largely the same. The constructed dependencies $\rho_{(hkl)} = f(\sigma_a)$ make it possible to consider the nature of change in dislocation density according to certain crystallographic slip systems. The need for such analysis is caused by activation of certain slip systems depending on temperature of deformation. For metal crystals with bcc lattice at the deformation temperatures up to 180 $^\circ$C the dislocation slip to a greater extent occurs on the planes {211}. Further temperature increase to 200-630 $^\circ$C corresponds to the consistent increase in the share of mobile dislocations in the planes {110}, and at the temperatures higher than 1170 $^\circ$C – in the planes {321} [14]. The fact is that the shock wave propagation is accompanied by thermal effect.

According to [7,15], when the stress behind the shock wave front achieves



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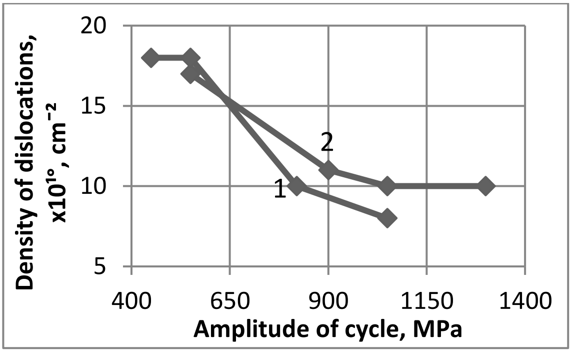

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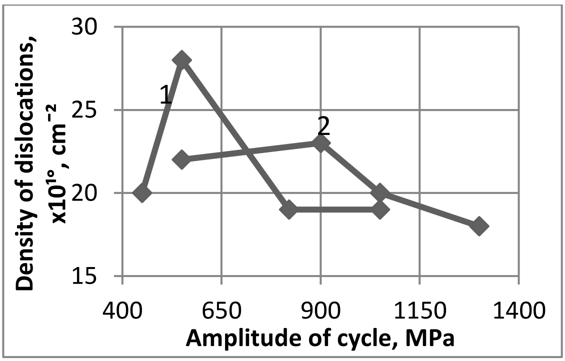


c

Fig.4. *Changing the density of dislocation by interference (110) - (a) (211) - (b) and (321) - (c) depending on the amplitude of cyclic loading. steel after improvement (1) and action pulses shock wave (2).*

the level of 35GPa the metal temperature may increase to 350°C. At sufficiently high power of pulse loading the temperature increase may go beyond a limit of beginning the phase of transformation processes. However, the structural changes in the metal take place during very short period of the pulse stress duration (10^{-7}-10^{-9} s). It is very difficult to explain only by the thermal nature of impact. Most likely the simultaneous occurrence of pulse stress with the local temperature increase behind the shock wave front lead to qualitative structural changes in the metal, which is very difficult to achieve under conditions of static load.

Given that the dislocation density was determined on the destruction surfaces of samples, the change nature and absolute values should correspond to the plane-strain condition of the metal, which is formed under conditions of accelerated growth of fatigue crack [12]. For small levels of cyclic overload origin and propagation of cracks occurs in the plane-strain condition. With the increase in the cyclic loading amplitude the role of the static part of the cycle begins to increase [2]. Consequently, the number of dislocations in metal volumes near destruction surface will drop. This is caused by increase of the metal share that is in the conditions of three-dimensional stress state with σ_a increase. On this basis, there will be a redistribution of dislocations between the metal volumes that are in plane-strain and three-dimensional stress states. The use of the main provisions of the dislocation mechanism of deformation propagation, evaluation of its value for the loading cycle will determine the nature of structural changes from the effect of the shock wave pulses.

In general terms, the ratio of the value of plastic deformation per loading cycle (ε_i) and the number of cycles that the metal can endure until destruction (N_i) obeys to the equation [12]:

$$\varepsilon_i \cdot (N_i)^a = b\,, \tag{1}$$

where a and b - are the constant values, for carbon steels they equal to 0.5 and 1, correspondingly [12]. After transformation the ratio (1), dependence for the assessment ε_i takes the following form:

$$\varepsilon_i = \frac{1}{\sqrt{N_i}} \tag{2}$$

After substituting in (2) of the corresponding values of cycles number until destruction (N_i) for the same amplitudes of cyclic loading it was identified approximately 20% reduction of deformation per cycle, as a result of metal pulses treatment. At the same time, the formal counting of the number of dislocations that are present in the metal under cyclic loading indicates their significant increase after shock wave treatment (Fig. 5). On this basis, we can assume that the process of introducing additional quantity of crystalline structure defects in the thermally hardened steel from the shock pulse effects is not accompanied by the development of process of dislocations annihilation. Combined analysis of the obtained results makes it possible to determine the impact of SW treatment on the increase of limited endurance of the carbon steel.

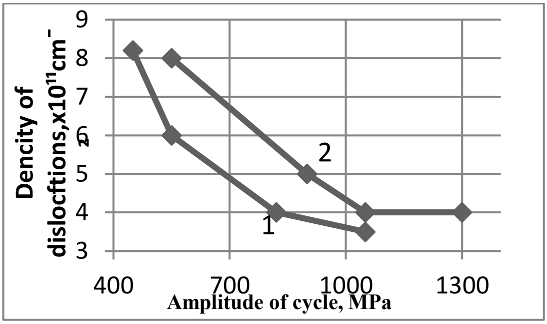


Fig.5. *The dependence of the total number of dislocations with the amplitude of cyclic loading (1 -steel after improvement, 2 action pulses shock wave).*

As a result of the shock wave pulse effect it is increased the number of dislocations in the metal that provide conditions for continuous distribution of deformation during the loading cycle. Reducing the value ε_i increases the evenness of dislocations in the metal, which increases cyclic endurance according to the ratio (2). Thus, structural changes in the metal per one loading cycle are provided by involving different numbers of dislocations in achieving the value ε_i. The simultaneous reduction of deformation per cycle and increase in the number of dislocations that are involved in maintaining the distribution of deformation conditions, lead to a shift in the emergence of the first areas with uneven distribution of dislocations toward higher cyclic endurance. Overall, the found increased number of dislocations can be considered as evidence of quite complex dislocation reactions that provide increase of the metal endurance during cyclic loading of thermally hardened carbon steel. At the same time it is known [12,15] that in proportion to the accumulation of defects crystal structure of the metal under cyclic loading, the degree of its damage increases and fatigue endurance is decreased. However, according to the Fig. 5 the metal treatment by the shock wave pulses has led to an increase in the accumulated number of dislocations and growth of the fatigue limited endurance (Figure 3). Under conditions of cyclic loading the change in sign of existing stresses significantly distinguishes the nature of dislocation movement, as compared to the unidirectional static deformation. Taking into account this fact, the balance between development of strengthening and softening process of the metal will determine the fatigue endurance increase. As a result, at the stage of forming micro cracks, the ability of mobile dislocations to redistribution between crystallographic slip systems will determine their accumulation resource and achieving the irreversible structural transformation. In the work [12] it was presented the need to construct the French line together with the cyclic loading curve. This line separates the moment of origin of such degree of metal damage, which leads to a decrease in fatigue endurance. According to the methodology [16] to construct the above mentioned line one should determine two stresses σ_γ and σ_β that are evaluated using three values α, β and σ_{-1}:

$$\sigma_\gamma = \alpha + \sigma_{-1} \quad (3)$$

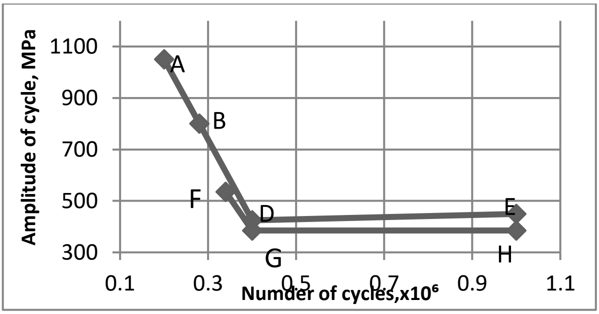
$$\sigma_\beta = \sigma_{-1} - \beta \quad (4)$$

Characteristics α and β are the permanent ones and for carbon steels they are equal to 85 and 65 MPa respectively [16]. The value σ_{-1} is the stress limit of steel (under conditions of unlimited endurance). It is determined by experiment. Using the experimental values σ_{-1} for investigated steel after hardening and tempering and after treatment by shock wave pulses together with the calculated values σ_γ and σ_β made it possible to construct the French line (connection of the points F and D) (Fig. 6). The presented line separates the are as with qualitatively different nature of metal damage occurrence under conditions of cyclic loading. For the loading amplitudes on the left from the line FG the conditions correspond to the incubation period of damage formation. The plane, which is limited by the lines FG and FD is an array of amplitude values, at which the metal gradually becomes softer. The area between the lines FD and $ABCD$ is an area of micro cracks growing to a critical size [12,16].

Substituting the corresponding values N_i into (2) for the same amplitudes it was found the deformation decrease by approximately 20% per loading cycle as a result of metal treatment by shock waves. To determine the nature of the phenomenon of increasing fatigue endurance let us use the assessment of angular slope coefficient of the French line (k) for the area of steel limited endurance before and after shock waves treatment. The value k is determined by analyzing the curves of cyclic loading (Fig.6) using the ratio:

$$k = -tg\gamma = -\frac{\alpha}{N_i^D - N_i^F},\qquad (5)$$

where γ - is the slope angle of the French line, α - is a constant characteristics [16], N_i^D, N_i^F - is the number of cycles until destruction of samples for the corresponding loading amplitudes (points D, F respectively). After substituting α =85MPa i N_i^D, N_i^F in (5) for steel in the state of hardening and tempering (Fig. 6a) and after shock waves treatment (Fig.6b) the appropriate values of the slope coefficient were determined. Comparative analysis determined that after SW treatment the value k (let us mark it k_1) is $1.24 \cdot 10^{-4}\ MPa/c$, and for steel in the state hardening and tempering (let us mark it k_2) is the value 2,8 $\cdot 10^{-3}\ MPa/c$.



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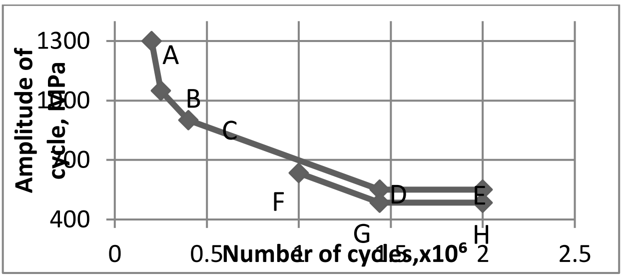

b

Fig.6. *The location line of French for the original condition (a) and actiopulses shock wave (b).*

Taking into account the fact that the assessment of the metal endurance under prescribed conditions of cyclic overload can be done using the endurance ratio (R) for k one can write:

$$k \approx \frac{1}{R} \quad (6)$$

After substituting k_1=1,24 $\cdot 10^{-4}\ MPa/c$ and k_2 =2,8 $\cdot 10^{-3}\ MPa/c$ into (6) we find that $R_1 > R_2$ approximately by an order of magnitude is ($8{,}3 \cdot 10^3$ and $3{,}6 \cdot 10^2\ c/MPa$, respectively). Using the analysis of these values it can be determined that increase in the steel endurance after SW treatment is caused by increase in the number of cycles with the increase of certain level of loading amplitude for 1MPa. The obtained result is confirmed by assessing of the number of dislocations that increase the fatigue endurance. Using experimental data on the dependence of dislocations number on the number of loading cycles (Fig.5) makes it possible to evaluate the dislocation density increase per one loading cycle (η):

$$\eta = \frac{\Delta\rho}{\Delta N_i}, \quad (7)$$

where $\Delta\rho$ - is changing the number of dislocations at the area of corresponding change in the number of cycles ΔN_i . For the points B and D of the cyclic loading curve of steel in the state after hardening and tempering (Fig.6) it is determined that $\Delta\rho = \rho_B - \rho_D$ (Fig.5), η_1 is $4{,}8 \cdot 10^4\, cm^{-2} / c$. The value η_2 is estimated similarly, it is equal to 2.7 $\cdot 10^5\ cm^{-2}/c$.

5. Conclusions.

The process of introducing additional number of dislocations in the heat-hardened steel after shock wave pulse treatment apparently is not accompanied by the development of dislocation annihilation. Furthermore, implementation of the deformation per cycle for the area of high-cycle fatigue is ensured by the participation of more dislocations.

Thus, in the process of SW treatment, the vast number of introduced dislocations is mobile and able to interact with further cyclic loading or it takes place additional unlock of previously fixed dislocations after hardening and tempering. Overall, on the destruction surface after treatment with shock wave pulses it is found increased number of dislocations that are located in different crystallographic slip systems. They can be seen as evidence of the development of quite complex dislocation reactions that increases the metal limited endurance during cyclic loading.

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