Method for accelerating diffusion processes when borating structural steels

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Abstract Strengthening structural steel using the chemical heat treatment (CHT) methods is widespread and well known. However, these methods have a series of drawbacks, which limit their scope. Deformation processes under shock-wave stress and their role in the diffusion development are of scientific and practical interest since the range of deformable alloys is not limited to the residual deformations within 2%. In this regard, the problem of using the effect of explosive deformation and evaluating its impact on the intensification of diffusion processes is important and relevant. The application of preliminary shock-wave stress as a stimulating factor for the intensification of subsequent diffusion processes during thermochemical treatment is demonstrated. It is proven that the use of this method made it possible to increase the diffusion layer depth by approximately two times along with a significant reduction of the operating cycle time. It is the first time when high-energy processing was used to increase the productivity of structural steel chemical heat treatment. It was established that preliminary shock-wave treatment leads to the intensification of diffusion processes, an increase in the saturation thickness of structural steel with boron. It was proven that the thickness of the diffusion layer varies based on the value of the true deformation. The efficiency of preliminary shock-wave treatment is demonstrated, which made it possible to increase the thickness of the borated layer by two times.

Keywords Mathematical model, Shock-wave stress, Chemical heat treatment (CHT), Borating, Microstructure, Diffusion layer, Rust resistance.

1. Introduction

The widespread application of chemical heat treatment (CHT) methods for strengthening structural steel is well known. Considering specific operating conditions, various methods of chemical heat treatment are applied to improve performance characteristics (wear resistance, rust resistance, heat resistance, etc.) [1-5].

1.1. Analysis of publications

The insufficient base components saturation thickness and the extremely low productivity of the alloying process at a relative inhomogeneity of the mechanical properties through the thickness of the saturation zone is the key disadvantage of the existing CHT methods [6-8]. The analysis of the available works on the increase of the CHT processes productivity indicates that along with traditional research in this area, a search is underway towards the diffusion processes intensification using preliminary treatment methods (ultrasound, chemical heat treatment, volumetric plastic deformation, etc.) [9-13]. The shortage of high-alloyed materials, heat-resistant and stainless steels and alloys is growing; therefore, the role of CHT is increasing every year. A significant contribution to the development and improvement of the theory and practice of CHT was made by O.M. Minkevich, M.S. Gorbunov, I.M. Spyrydonova, B.M. Arzapasov, V.L. Voroshnin and others. However, these methods have a series of drawbacks, which limit their scope. For example, the existing method of intensifying the nitriding process using preliminary surface plastic deformation makes it possible to increase the depth of the alloyed layer on one hand, but at the same time has quite a few significant challenges, where among the top ones is a significant permanent deformation of up to 20 - 50%, which is a problem for difficult-to-machine metals and alloys [14-17]. At the same time, deformation processes under shock-wave stress and their role in the diffusion development are of scientific and practical interest, since the range of deformable alloys is not limited at the level of residual deformations within 2%. In this regard, the problem of making use of the explosive deformation effect and assessing its impact on the intensification of diffusion processes is important and relevant [18-21].

1.2. Purpose of the paper

The application of preliminary shock-wave stress as a stimulating factor for the intensification of subsequent diffusion processes during thermochemical treatment is demonstrated.

2. Presentation of the basic material

Normalized low-alloyed 40X steel was chosen as a model material for the research, the plates made of which were subjected to explosion contact processing at a fixed angle ($\beta=90^0$) of the detonation front collision with a metal barrier and pressure of ≈35 kbar [22-25].

The selection of the shock-wave treatment parameters relied on the studies of the structure load characteristics and structure steel properties studies. The studies have shown, that the main feature of the metal shock-wave treatment impact is the short-term wave nature of the load propagation, which leads to isotropic strengthening due to phase transformations, dislocation density increase, significant distortion and refinement of grains, redistribution of residual stresses, which then subsequently leads to the increase of mechanical properties. Such metal alloys transformations occur under the application of "strong" shock waves with a front pressure of 130 kbar and above.

The parameters of the shock-wave load respective to the implementation conditions are as follows: pressure - 35 ... 40 kbar when using an explosive from a fine powder of ammonium nitrate composition at a detonation speed of 2500 ... 3000 m / s. Studies have shown 40X structural steel mechanical characteristics increase by 25 ... 30%.

Metallographic studies of metal samples illustrate that the selected shock-wave loading scheme demonstrates a significant slip bands increase within the structure and twins appearing at the same time, as a result of severe plastic deformation under shock wave treatment.

Borating was executed in boron powders (B_4C + 2–4 % NH_4Cl) at the temperature of $t=1050^0C$ throughout $\tau=5$ hours.

The surface layers of the metal were investigated using metallographic, X-ray spectral, and microdurometric analysis methods [26-28]. Microdurometric analysis through the depth of the diffusion layers was carried out according to the standard technique using a PMT-3 device with a stress of 50 g. Metallographic studies were carried out using a "Neophot-22" optical microscope.

The intensity of the shock stress was determined by the value of the explosive pulse, which during the experiments equaled to 200 H·c, 330 H·c, 400 H·c. The true deformation of the samples, which corresponded to these values, resulted in $\varepsilon_l=1,2\%$; $\varepsilon_l=1,8\%$; $\varepsilon_l=2,2\%$.

Microstructural studies have shown that as a result of the preliminary shock-wave stress during subsequent borating, the changes in the thickness of the borated layers occur. An increase in the thickness of the diffusion layer is observed in comparison with untreated samples, while the increase in the layer thickness depends on the intensity of the preliminary deformation.

Figure 1 shows the microstructures of 40X steel post borating. The steel surface layer boron saturation zone is represented by a white layer. The surface layer represents two phases, which are typical for borating, FeB and Fe_2B in particular. The FeB phase is located on the surface part of the continuous borides zone, and the Fe_2B phase is formed at its base. Both borides have a typical acicular structure.

Microstructural studies of borated samples showed that individual needle-shaped crystals of FeB and Fe_2B borides grow from the top of the surface into the metal. These crystals then gradually merge into a continuous layer. The samples', which were not previously treated with shock-wave stress, diffusion thickness layer equals 0,4 mm. At increasing the deformation intensity, the layer depth also increases. The maximum value of 0.86 mm the saturation area reaches at the deformation of ~2,2%, which corresponds to the impulse value of ~ 400 H·c. It should be mentioned that in comparison to the initial value (ε=0%), the thickness of the layer at residual deformation of ε=2,2%, doubled.

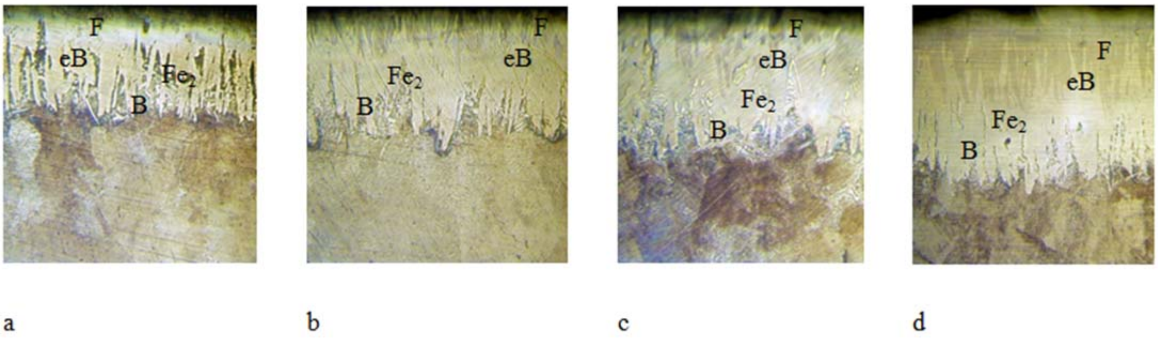

Fig. 1. Microstructure of the 40X steel post borating x400:
a – initial state; b – impulse I=200, H·c; c - impulse I=330, H·c; d - impulse I=400, H·c

The change in the thickness of the 40X steel saturated with boron layer for different values of the true deformation according to the experimental values is shown in Fig. 2.

The dependency $h = f\left(\frac{\Delta a}{a_0}\right)$ is approximated by a straight line and is presented by the equation:

$$h = h_0 + \alpha \cdot \ln\frac{\Delta a}{a_0} \quad (1)$$

where Δa - absolute deformation; a_0 - plate thickness; h_0 - initial thickness value of the diffusion layer without shock-wave treatment; α - the slope tangent of the diffusion layer thickness intensity growth to the axis of true deformation, depends on the borating material.

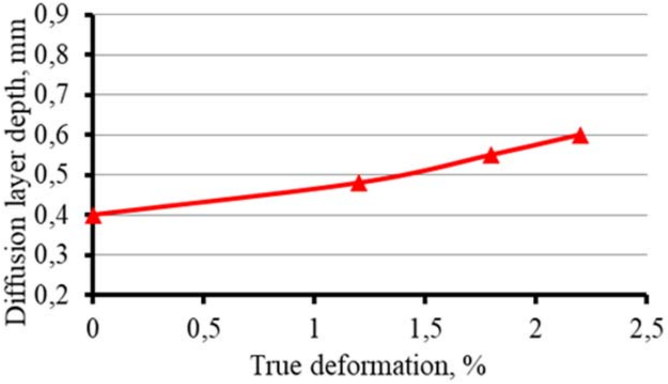

Fig. 2. Dependence of the microhardness of borated layers on the pulse value

The presented results prove that preliminary shock-wave stress significantly affects the intensification of the diffusion processes development during subsequent chemical heat treatment and at the first stage of the research can be explained as follows. The mechanism of this effect depends on the intensity of the shock-wave stress and the temperature of the CHT. When borating (t=1050^{0}C) after shock-wave stress, the dislocations are ordered with the formation of a cellular structure according to the following mechanism: residual compressive stresses formed after shock-wave stress relax during heating due to microplastic deformation [29-30].

Microdurometric analysis of the diffusion layers' depth was carried out according to the standard technique. Using the obtained measurement results, the curves of the distribution of microhardness H_V over the depth of the diffusion layer in borated samples after different intensities of preliminary deformation were plotted (Fig. 3).

The maximum microhardness of the borated layer obtained in undeformed samples is observed at a depth of 20 μm and is 2500 N/mm2 (Fig. 4). Preliminary shock-wave treatment at a pulse value of I=200 H·c leads to the increase of the microhardness at a depth of 20 μm, which is 1.5 times higher than the initial hardness value. In case of further increase of the pulse to 400 H·c, the microhardness in the surface layer with a depth of 20 μm increases insignificantly. As we move into the depth of the sample, the microhardness gradually decreases. The samples pretreated with shock waves exhibit the same trend, but their value is higher than that of undeformed samples.

The nature of the distribution of microhardness over the depth of the diffusion layer is more uniform for all samples at different impulse values: the maximum value of H_V is reached on the surface, after which the microhardness gradually decreases with distance from the surface into the depth of the sample and reaches the microhardness of the core. The transition of the microhardness to the core is smooth.

The X-ray structural analysis made it possible to establish the phase composition of diffusion layers after preliminary shock-wave stress and borating. The diffraction patterns obtained from the surface of the samples in the radiation of the Co anode are shown in Fig. 4.

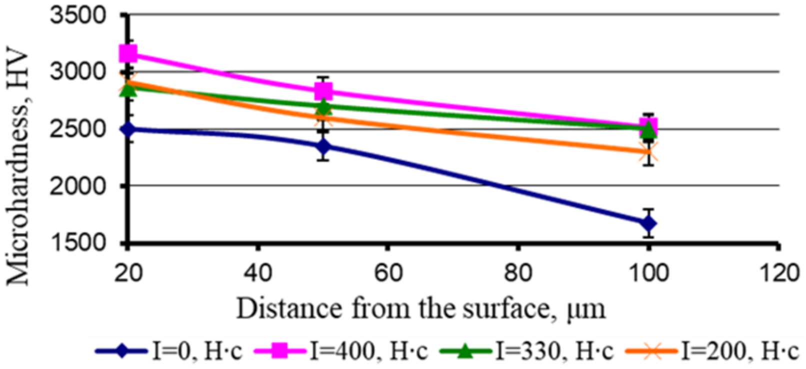

Fig. 3. Dependence of the microhardness of borated layers on the pulse value

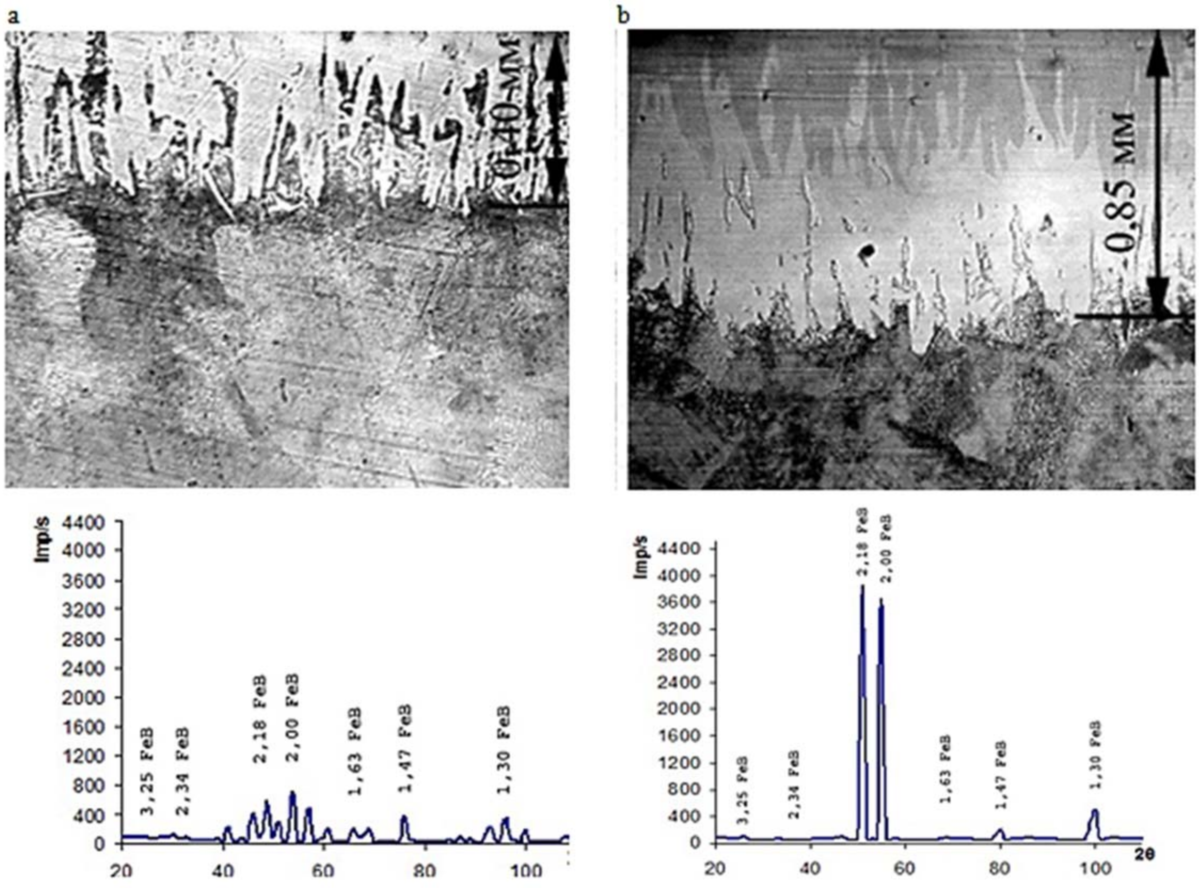

Fig. 4. X-ray spectral analysis of borated 40X steel samples:
a – without preliminary shock-wave stress; b – without preliminary shock-wave stress

According to the phase analysis data, the surface of the diffusion layer consists of the FeB phase.

The diffraction pattern of an undeformed sample (Fig. 4, a) shows that the diffraction lines have a low intensity, which indicates that the sample contains a very less amount of the FeB phase. A sharp increase in the line intensity is observed for the pretreated sample (Fig. 4, b) at diffraction angles in the range of 40 - 60 degrees, which may indicate a sharp increase in the solid phase amount.

3. Conclusions

It is the first time when high-energy processing was used to increase the productivity of structural steel chemical heat treatment.

It was established that preliminary shock-wave treatment leads to the intensification of diffusion processes, an increase in the saturation thickness of structural steel with boron.

It was proven that the thickness of the diffusion layer changes depending on the value of the true deformation.

The efficiency of preliminary shock-wave treatment is shown, which made it possible to increase the thickness of the borated layer by 2 times. This data is patented in Ukraine, patent numbers are № 7803, 27961, 83769.

Preliminary shock-wave loading is an effective stimulating factor for the intensification of the chemical-thermal treatment diffusion processes and significantly improves the performance characteristics of metal products at practically no permanent deformation.

It should be noted that stimulation of CHT processes by shock waves can find application in cases when the shape and material of the parts exclude the use of cold deformation at the required thickness of the diffusion layers of the working surface.

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