Microstructure of Heat-Affected Zone in Steel 45 Irradiated by High Power Ion Beam

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Abstract – Methods of X-ray diffraction and metallography with use slanting type was applied for research of heat-affected zone in medium-carbon steel 45 at various regimes of high power ion beam irradiation. Essential influence of regimes high power ion beam irradiation on formation of grain structures in heat-affected zone was revealed. It is established, that high power ion beam irradiation lead to the redistribution of carbon between available phases. Observed change of microhardness of surface layer steel 45 after high power ion beam irradiation was connected with the formation of a microstructure in heat-affected zone. Here the formation of large ferrite grains has led to the reduction of microhardness, and the formation martensite phase has led to its increase.

1. Introduction

The zone with the changed physical-chemical and mechanical properties is formed at surface layers of metal materials at high power ion beam (HPIB) treatment. [1]. The structural-phase condition of this zone is determined by dynamics of thermal and stress fields which arise in surface layer because of absorption of energy beam and an initial condition of a material also. The heat-affected zone (HAZ) adjoins directly to a surface and it is formed generally under influence of high temperature [2–5]. The thermal mode of HAZ formation can be changed over a wide range by change of HPIB parameters. The aim of the present work is the research of a microstructure of HAZ which is formed in steel 45 at HPIB treatment with various modes.

In the present work, samples steel 45 have been investigated. Steel 45 concerns to medium-carbon qualitative steel which is used widely in the industry. By now, modification of steel 45 by laser radiation and low-energy high-current electron beams has been investigated well [2, 3, 5].

2. Technique of experiment

Samples were annealed in the vacuum furnace at temperature 500 °C within two hours for removal of hardening after grinding and polishing. Samples irradiation carried out a high power ion beam with the following parameters: beam composition H^+ (30%), C^{+n} (70%); particles energy ~ 0.3 MeV; average current density on a target – (40–150) A/cm^2; pulse duration – 60 ns.

The microhardness was measured on hardness PMT-3 by Vickers method. The phase structure and crystal parameters was determined from the analysis of X-Ray diffraction received on diffractometer "Dron-3M" on Cr-radiation ($\lambda = 2.289$ Å). That has allowed an analysis of the thin surface layers modified by HPIB treatment. Metallographic analysis was carried out on slanting type with a corner 1° on an optical microscope "Biolam". The microhardness was measured on hardness PMT-3 by Vickers method.

3. Results and their discussion

Absorbed energy of ions at HPIB treatment causes heating a target down to the melting and the evaporation of a surface layer [4]. The outflow velocity of evaporation products can be so great, that the target gets mechanical recoil momentum. Heating and the subsequent cooling lead to structural and phase transformations at material. The overheating at melting and fast cooling can result in formation of the metastable solid solution and the phases absent on the equilibrium state diagram of processed system. The heating of surface layers and the rise of temperature gradients in a material are lead to generation of thermal stress which can reach the significant size exceeding yield stress and short duration strength.

The analysis of X-Ray diffraction patterns has shown that at not irradiated annealed state of steel 45 the surface layer thickness ~7.7 microns contain α-phase (ferrite), a small amount cementite Fe_3C and oxide FeO. The phase structure has changed after HPIB treatment. For samples irradiated with current density 150 A/cm^2 the formation of austenite phases are not revealed by X-Ray diffraction. HPIB treatment with current density 50 and 100 A/cm^2 result in the occurrence of a small amount of γ-iron (austenite) and increase the content carbide phases. The crystal parameter of α-phase decreases with increase of the current density beam. This parameter is minimal for the samples irradiated by HPIB with current density 100 A/cm^2. It testifies to about redistribution of carbon at HPIB treatment. The greatest increase of the content of cementite phases observed at HPIB irradiation with current density 100 A/cm^2 and residual austenite observed at irradiation with current density 50 A/cm^2. The formation of a high-temperature δ-phase and martensite is not revealed also.

Calculations of dislocation density executed from the analysis of the physical broadening diffraction peaks have shown that its maximal value is fixed also at current density 100 A/cm^2. It speaks about significant plastic deformation at this an irradiation mode.

HAZ morphology investigated with the help of layer analysis on slanting type. Fig. 1 shows the microstructure of surface steel 45 till HPIB irradiation. The microstructure is submitted by grains of ferrite with the size ~ 15 microns, and pearlite.

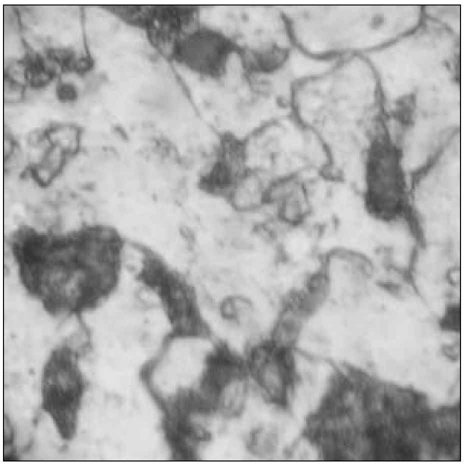

Fig. 1. Microstructure of surface St 45 till irradiation HPIB, ×500

The sizes of ferrite grains have decreased up to ~10 microns and the pearlite has the increased contents carbide phases (Fig. 2) after HPIB irradiation with current density 50 A/cm^2. Thus, pearlite exists in two forms – lamellar and granular.

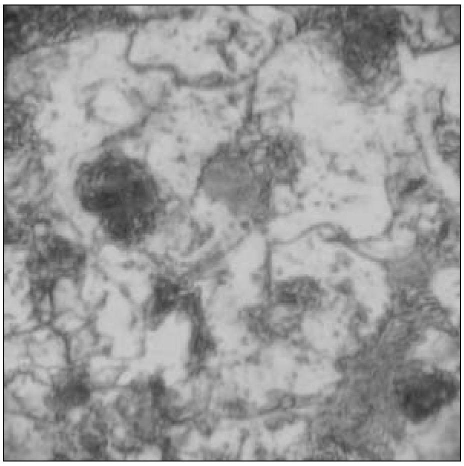

Fig. 2. Microstructure of surface St 45 after irradiation HPIB with j = 50 A/cm^2, n = 3 pulse, ×500

The optical microscopy of slanting type has not allowed to allocate a layer, directly adjoining to surface < (0.1–0.3) μm.

Figure 3 shows the microstructure of subsurface layer in the field of slanting type thickness ~ 0.5 μm after irradiation by HPIB with j = 50 A/cm^2.

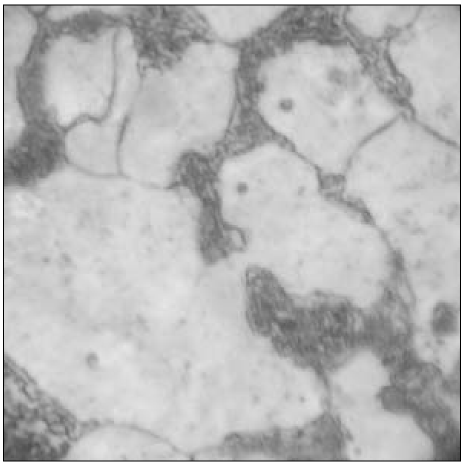

Fig. 3. Microstructure of surface layer St 45 thickness ~ 0.5 μm after irradiation HPIB with j = 50 A/cm^2, n = 3 pulse, ×500

The microstructure of this layer essentially differs from a microstructure of a surface has been established. Large ferrite grains with the sizes ~ 20–25 μm and fine-grained pearlite structure have been found out. The growth ferrite grains testify to about processes of collective recrystallization in this layer. The microstructure feature of this layer is presence inside crystals α-phase of cementite particles with rounded form.

On the depth ~1 μm the microstructure represents a mix of ferrite and pearlite. Feature of this layer is also large recrystallized ferrite grain and presence cementite grids on joints of ferrite and pearlite. The microstructure is similar initial on the big depths in limits HAZ.

Figure 4 shows the surface microstructure of samples St 45 after HPIB irradiation with current density 100 A/cm^2.

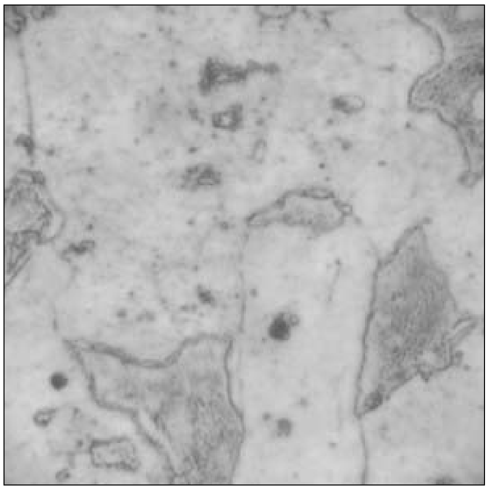

Fig. 4. Microstructure of surface layer St 45 after irradiation HPIB with j = 100 A/cm^2, n = 3 pulse, ×500

It is visible, that after HPIB irradiation the microstructure of a surface represents ferrite with inclusions cellular tertiary cementite and ledeburite. The ledeburite grains with size 15 μm are formed as a result of hardening from pearlite isolation. The sizes of ferrite grains have increased up to ~ 40 μm in comparison with not irradiated samples.

Figures 5 and 6 shows the microstructure in the slanting type field of thickness ~ 0.5 and 1 micron, respectively. Feature of the first layer is presence cementite grids and the formation of sorbite.

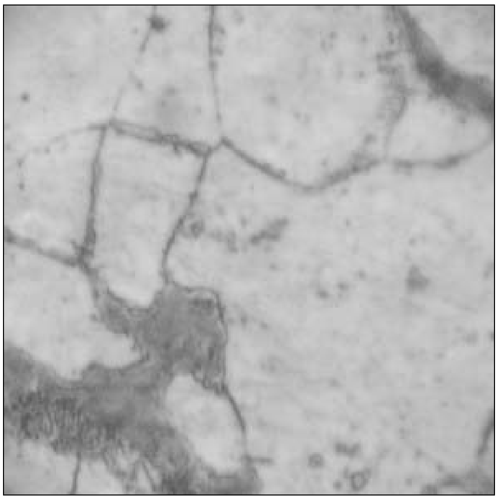

Fig. 5. Microstructure of subsurface layer St 45 thickness ~ 0.5 μm after irradiation HPIB with $j = 100$ A/cm^2, $n = 3$ pulse, ×500

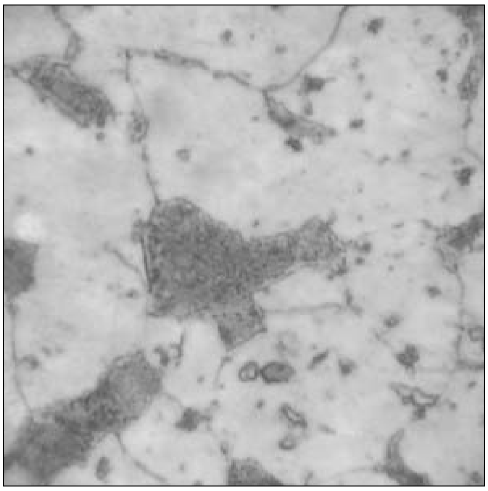

Fig. 6. Microstructure of subsurface layer St 45 thickness ~ 1 μm after irradiation HPIB with $j = 100$ A/cm^2, $n = 3$ pulse, ×500

The formation of gird, granular cementite and sorbite testify to a significant degree of heterogeneity of structure on depth of HPIB modified layer. It speaks that together with processes collective recrystallization at high-speed cooling there are processes of decomposition. In this case at decomposition occur basically pearlite transformations and are not fixed martensite transformations which are carried out at lower temperatures.

Figure 7 shows a microstructure of a surface sample St 45 after HPIB irradiation with current density 150 A/cm^2. The microstructure of a irradiation surface is submitted crushed ferrite grains (~7–10 μm), granular cementite and rather large martensite inclusions.

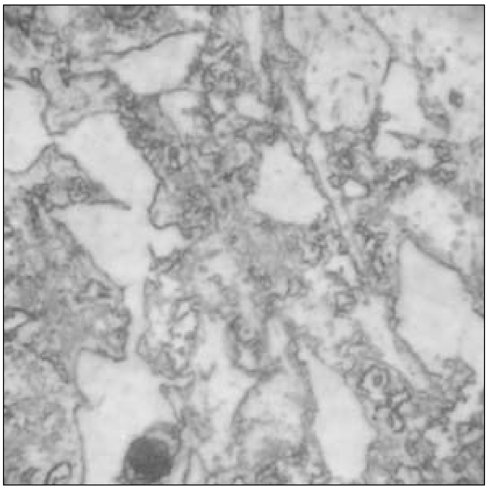

Fig. 7. Microstructure of surface layer St 45 after irradiation HPIB with $j = 150$ A/cm^2 , n=3 pulse, ×500

As martensite is not fixed by X-ray diffraction, it was most likely formed so-called martensite. It is a heterogeneous mix oversaturated α-solution (non-uniform concentration) and the particles which have not stood apart yet carbide. In underlaying layers, the microstructure is ferrite- fine pearlite with small inclusions granular cementite (Fig. 8).

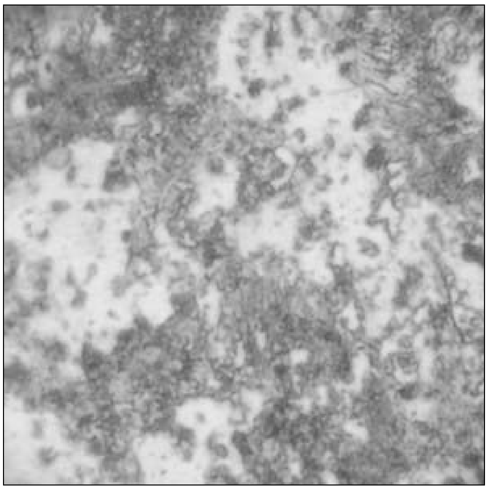

Fig. 8. Microstructure of subsurface layer St 45 thickness ~ 0.5 μm after irradiation HPIB with $j = 150$ A/cm^2, $n = 3$ pulse, ×500

Microstructure feature of these layers is the blur of ferrite borders and the formation of fine-pearlite hardening. Moreover the thickness of a layer with such microstructure makes ~ 2 μm in the field of slanting type. Further, the microstructure passes smoothly in initial.

Figure 9 shows dependence of the microhardness from penetration indenter for St 45 before and after HPIB irradiation.

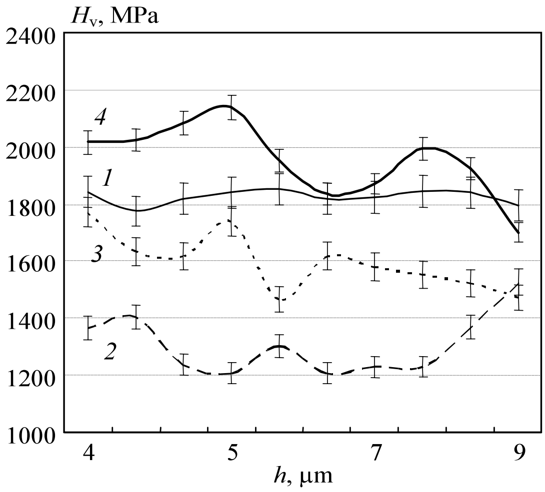

Fig. 9. Dependence of the microhardness from penetration indenter for St 45 before and after HPIB irradiation

The received dependences testify that significant growth ferrite grains in the samples HPIB irradiated with current density 50 and 100 A/cm^2 is accompanied by reduction of microhardness. The increasing of microhardness in the samples HPIB irradiated with j = 150 A/cm^2 is connected to formation of martencite crystals, increasing of dispersiveness ferrite-cementite particles and the formation of firmer fine pearlite hardening.

Thus received results allow to present HAZ as multilayered structure in which layers smoothly pass each other and their sizes, the microstructure depend from current density HPIB. The generated microstructures render essential influence on size of microhardness. The formation of large ferrite grains led to reduction of values of microhardness and formation martensite and fine-perlite phases led to increase microhardness.

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