INTRODUCTION

Low-carbon steels are an important class of structural materials and find application in different branches of industry and building [1, 2]. Obtaining low-carbon steels with submicrocrystalline (SMC) and nanocrystalline (NC) structures offers the possibility of improving the initial parameters of strength. At present, there are exist numerous experimental works on severe plastic deformation (SPD), and the number of studies on the SMC and NC steels grows progressively with each year [3–24]. They demonstrate a good prospect for creating new high-strength materials with unique combinations of physical and mechanical properties. Obtaining SMC and NC steels is a nontrivial task, in particular, because of the complexity of the designing and production of special equipment for their deformation. At present, there are exist numerous experimental works on severe plastic deformation (SPD), and the number of studies on the SMC and NC steels grows progressively with each year [3–24]. They demonstrate a good prospect for creating new high-strength materials with unique combinations of physical and mechanical properties. Obtaining SMC and NC steels is a nontrivial task, in particular, because of the complexity of the designing and production of special equipment for their deformation. At present, the majority of works on SMC steels is carried out with the use of the method of equal-channel angular pressing (ECAP). The ECAP method does not make it possible to reach extreme degrees of deformation as, for example, upon torsion under a high quasi-hydrostatic pressure, but its obvious advantage is the possibility of obtaining bulky SMC workpieces. This advantage makes it possible to study not only the structure formed upon SPD, but also the mechanical properties of SMC steels during tension and compression.

The level of the strength properties and the strain hardening of steels essentially exceed the appropriate characteristics of pure metals. For this reason, the SPD of steels is frequently conducted at elevated temperatures, which do not exclude the occurrence of phase transformations. The latter not only play an important role in the process of the formation of the microstructure during deformation, but also determine the mechanical and functional characteristics of the workpieces obtained upon SPD. Depending on the heat treatment preceding SPD, ferritic–pearlitic or martensitic structures can be obtained in the low-carbon 10G2FT steel. Moreover, the microalloyed steel 10G2FT contains additions of vanadium and titanium, which are strong carbide-formers. Consequently, it is expedient to study the influence of the initial state of the steel (martensitic or ferritic–pearlitic) on the evolution of the structure upon ECAP and the transformations in the carbide subsystem, as well as to establish correlations between the microstructure and the mechanical properties of steels under consideration. In connection with the above-said, the purpose of this work is a study of the microstructure and mechanical properties upon tension of the low-carbon 10G2FT steel before and after ECAP in two initial states, namely, ferritic–pearlitic and martensitic.
EXPERIMENTAL

The 10G2FT steel (Fe–1.12Mn–0.08V–0.07Ti–0.1C) in the initial state after hot forging (the temperature of the end of forging ~1000°C, cooling in air) and normalization for 30 min at 950°C had a ferritic–pearlitic structure. The second party of samples, which was quenched from 1180°C (with holding for 30 min) into water, had a structure of packet martensite. The ECAP of cylindrical pieces with a diameter of 10 mm was conducted through route B$_c$ (4 passes) at $T = 200^\circ$C in the case of the ferritic–pearlitic state and at $T = 400^\circ$C in the case of the martensitic state (the angle of joining between the channels was $\Phi = 120^\circ$). After ECAP, the samples had a size of 60 mm in length and 10 mm in diameter. The equivalent deformation realized as a result of ECAP was calculated via the relation $\varepsilon_N = N^2/\sqrt{3}$ cot($\Phi/2$) [4] and was equal to 2.7.

The metallographic observations were carried out using an Olympus GX-71 optical microscope. The microstructure of the steel was studied with the aid of a Philips CM30 transmission electron microscope. The samples for the microscopic examination were obtained by the standard methods described in [25, 26]. The average size of structural elements was determined by the intercept method using optical and electron-microscopic photographs [27].

The dumbbell samples for the mechanical tensile tests with the size of the gage part of $2.6 \times 0.5 \times 10$ mm were spark-cut in the longitudinal section of the pieces. After mechanical grinding, the samples were electropolitically polished at a voltage $U = 20–30$ V in a solution of 25 ml of CrO$_3$ and 210 ml of H$_3$PO$_4$ at room temperature. The etching of metallographic polished sections was carried out in a solution of 25 g of CrO$_3$ and 250 ml of H$_2$O. The tension of the samples was performed at a rate of $3.5 \times 10^{-3}$ mm$^{-1}$ at room temperature. The microhardness was measured at a load of 200 g using a PMT-3M microhardness meter. The X-ray diffraction studies were performed on Shimadzu XRD-6000 diffractometer (with a monochromator) using Cu $K\alpha$ radiation. The parameters of the fine crystalline structure, i.e., microdeformation of a crystal lattice and size of coherent domains, were calculated by the approximation method [28].

The dislocation density was estimated based on an analysis of the profiles of Bragg maxima through the formula [29]

$$\rho_{hk\ell} = 2/\sqrt{3}(\varepsilon_{hk\ell}^2)^{1/2}/(D_{hk\ell}b),$$

where $D_{hk\ell}$ and $(\varepsilon_{hk\ell}^2)^{1/2}$ are the volume-averaged values of the sizes of coherent domains and microstresses in the direction perpendicular to the $(hk\ell)$ plane, and $b$ is the Burgers vector of dislocations (for $\alpha$ iron, $b \sim 0.248$ nm).

RESULTS AND DISCUSSION

Structure of Steels before and after ECAP

Figure 1 presents optical micrographs of etched polished sections of steel 10G2FT before and after ECAP in both initial states. The initial structure of the normalized steel 10G2FT before ECAP consists of a mixture of ferrite and pearlite. Pearlite has a lamellar structure; its fraction is no more than 20% in the volume of the material; the arrangement of pearlite grains in the structure has a stitched character (Fig. 1a). The ferrite and pearlite grains in the initial state have a quasi-equiaxed shape (Fig. 1a) with an average size of ferrite grains of 4.2 $\mu$m. Figures 2a and 2b display electron micrographs of the steel structure in the ferritic–pearlitic state before ECAP. The dislocation substructure of ferrite in the initial state has a network character; at grain boundaries, a fringe contrast is frequently observed (Fig. 2a), which indicates an equilibrium character of the boundaries in the initial state. The pearlite has a lamellar structure (Fig. 2b) with an average spacing between the Fe$_3$C plates $l \sim 45$ nm. Electron microscopy reveals particles of VC and TiC carbides 15–20 nm in size in the bulk of grains and at grain boundaries.

The quenching of the steel is accompanied by the formation of the structure of packet martensite (Figs. 1c, 1d). The average size of the former austenitic grains is 20 $\mu$m (Fig. 1c), the average width of martensite plates, 0.15 $\mu$m (Fig. 3a). The quenching does not lead to a complete $\gamma \rightarrow \alpha$ martensitic transformation; along the boundaries of the former austenitic grains and martensite crystals, interlayers of retained austenite ($\gamma$ phase) are revealed (Fig. 1c, 3b), whose volume fraction is a few percent. Together with retained austenite, particles of cementite Fe$_3$C were revealed in the structure, which, similar to the interlayers of retained austenite, are arranged along the boundaries of martensite crystals in the form of thin interlayers. In the bulk of grains, spherical particles of Fe$_3$C with an average size of 60 nm and finely dispersed VC and TiC carbides with a size of 5–10 nm were revealed. The defect substructure of martensite crystals consists of dense dislocation networks. After quenching, the X-ray diffraction patterns of steel 10G2FT contain, together with the reflections of $\alpha$ iron, lines of $\gamma$ iron (volume fraction no more than 5%) and VC and TiC carbides (Fig. 4b). The reflections from the VC and TiC carbides are weak, the volume fraction of these carbides does not exceed 2%.

The ECAP led to the formation of a submicrocrystalline grain/subgranular structure in the 10G2FT steel in both states (Figs. 2c, 2d, 3c, 3d). The average size of fragments after ECAP as determined from dark-field electron micrographs is 0.3 $\mu$m for both the ferritic–pearlitic and martensitic steels. The boundaries of the structural elements are smeared; numerous extinction contours are observed; a significant azimuthal smearing of reflections in the electron diffraction patterns is