Strength and ductility of medium carbon steel after equal channel angular pressing

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Abstract. Upon the ECA pressing at 400°C of the AISI 1045 steel with 0.45% C, the processes of dynamic recovery are developed with the formation of subgrains of ~320 nm in size and isolated grains of submicron size with high-angle boundaries. The fragmentation and partial spheroidization of the cementite lamellae is observed within the pearlite colonies. Deformation in pearlite grains is not sufficient, either to break down the cementite lamellae structure or to produce the refinement of ferrite grains. Annealing of the deformed steel with 0.45%C after ECA pressing causes the perfection of the recovered structure in ferrite and further processes of fragmentation, spheroidization, and coagulation of carbide phase. Annealing at $T = 550\, ^\circ\mathrm{C}$ for 5 h leads to almost complete spheroidization of carbides with an average size of ~280 nm and increases to some extent the average ferrite grain (subgrain) size to ~410 nm. The submicron grain-subgrain structure of the steel with 0.45%C causes a significant strengthening ($\text{YS} = 960\, \text{MPa}$) at a retention of satisfactory elongation ($\text{EL} = 8\%$). Subsequent annealing at $T = 550\, ^\circ\mathrm{C}$ for 5 h increases ductility to $\text{EL} = 14\%$ and decreases the yield strength to $\text{YS} = 745\, \text{MPa}$.

1. Introduction

Equal-channel angular (ECA) pressing allows one to obtain submicro- and even nano-crystalline state in bulk billets of different metals and alloys including commercial ones. Now the application of this method for the achievement of ultrafine-grained structure in iron-based alloys, in particular, in steels attracts increasing interest. A series of articles on low-carbon steels are published up until now [1-6], but there is virtually no data on the ECA pressing of medium-carbon steels.

The aim of the present work was to study the structure formation in ferrite and carbide phases of the medium carbon steel (0.45% C) upon ECA pressing and subsequent annealing purposely for the improvement of mechanical properties.

2. Experimental Procedure

Commercial 0.45%C steel – AISI 1045 (0.45% C; 0.63% Mn; 0.23% Si; 0.18% Cr; 0.043% Al; 0.02% Cu) was taken for the study; in the initial state, the steel was air-quenched from 960°C after holding for 2 h. The ECA pressing of the steel samples of dia. 10 x 60 mm in size was performed at $T = 400\, ^\circ\mathrm{C}$ by $N = 4-6$ according to route Bc at an angle of 120° between the channels. The initial and deformed
structure was examined with an "Olympus PME 3" optical microscope, JEM 1000 transmission electron microscope, and an LEO 430i scanning electron microscope. The tensile properties were measured with an INSTRON 3382 testing machine using the specimens of 20 mm in length and 3 mm in diameter.

3. Results and Discussion
The size of the initial ferrite grains and pearlite colonies before deformation was about 15 µm. After ECA pressing by 4 and 6 passes, the examination by optical microscopy and scanning electron microscopy (SEM) revealed the fragmentation of the pearlite colonies. Their average size decreased to 8 µm. The SEM analysis showed that both discontinuous and wavy morphologies of cementite lamellae are presented in the deformed structure. The beginning of lamellae fragmentation is noticeable after ECA pressing for 4 passes, and the beginning of spheroidization is revealed after 6 passes. The transmission electron microscopy (TEM) examination of the thin foils after four passes (N = 4) showed the imperfect subgrained structure with rather thick subgrain boundaries, high density of lattice and grain-boundary dislocations, and an average subgrain size of about 0.4 µm. The beginning of the fragmentation processes is clearly seen inside the pearlite colonies. As the number of passes increases to 6, the average subgrain size decreases to ~0.3 µm, and the substructure becomes more perfect due to the dynamic recovery, which leads to subgrain-boundary thinning and to density decrease of free dislocations (Fig. 1a). A banded contrast at some boundaries indicates the local appearance of high-angle boundaries. This evidences the beginning of the transformation of the subgrained structure into submicrocrystalline one, i.e., the dynamic recrystallization proceeds. The beginning of the fragmentation and spheroidization processes is clearly observed in the pearlite colonies (Fig. 1b).

ECA pressing by N = 6 increased the yield strength and ultimate tensile strength by a factor of about 2.5 (up to 960 MPa), and 1.5 (up to >1 GPa), respectively (Table 1). The elongation in this case decreased more than by a factor of 2 (to ~8%), and the yield ratio became 0.95. For the improvement in ductility, an post-deformation heat treatment was performed. Annealing at 500°C for 3 h after ECA pressing did not virtually change the structure: the processes of the carbide spheroidization were expressed very weakly. Even after annealing for 50 h, the spheroidization was not completed, and the carbide distribution remained nonuniform.

The SEM analysis showed that, upon annealing at 500°C after the ECA pressing by N = 6 compared to that by N = 4, the cementite lamellae fragmentation was more pronounced, the
spheroidization both inside and outside the pearlite colonies occurred more rapidly; and the carbide size outside the pearlite colonies after annealing for 50 h was larger, 0.4 µm vs. 0.3 µm (the average carbide size inside the pearlite colonies after annealing for 50 h was 0.15 µm for both states) (Fig. 2).

| State                      | YS, MPa | UTS, MPa | EL, % | RA, % |
|----------------------------|---------|----------|-------|-------|
| Normalization              | 402     | 725      | 18.1  | 22    |
| ECAP, N=4                  | 892     | 981      | 6.3   | 43    |
| ECAP, N=6                  | 960     | 1013     | 7.7   | 31    |
| ECAP,N=6+heating at 500°C(10 h.) | 798     | 829      | 12.6  | 51    |
| ECAP, N=6+heating at 550°C(5 h.) | 746     | 830      | 13.8  | 45    |

At steel annealing at temperature of 550°C, the carbide spheroidization processes occurred more rapidly. After annealing for 3 h, the lamellar morphology of the pearlite colonies was still noticeable, but, already after annealing for 5 h, a virtually completely spheroidized structure was observed (Fig.3). In this case, the spheroidization inside the pearlite colonies was completed. As a whole, the distribution of spherical carbides with an average diameter of ~0.3 µm in the ferrite matrix was substantially more uniform than that was after annealing for 50 h at 500°C. The ferrite had predominantly grained structure with an average grain size of ~0.4 µm. Annealing at 550°C (5 h) decreased YS to ~750 MPa, but the elongation in this case increased to 14% and the yield ratio decreased from 0.95 to 0.90 (Table 1, Fig. 4).

### 4. Conclusions
1. Upon the ECA pressing at 400°C of the steel with 0.45% C, the processes of dynamic recovery at the unsteady stage are developed in ferrite with the formation of subgrains of ~320nm in size and isolated grains of submicron size with high-angle boundaries. The fragmentation and partial spheroidization of the cementite lamellae are observed in the pearlite colonies.
2. Annealing of the steel with 0.45%C after ECA pressing causes the perfection of the recovered structure in ferrite (decrease in the density of free dislocations, thinning of the subgrain boundaries, and insignificant subgrain growth) and further processes of fragmentation, spheroidization, and
coagulation of carbide phase. Annealing at $T = 550^\circ C$ for 5 h leads to almost complete spheroidization of carbides with an average size of ~280 nm and somewhat increases the average ferrite grain (subgrain) size to ~410 nm.

3. The submicron grain-subgrain structure of the steel with 0.45%C causes a significant strengthening (YS = 960 MPa) at a retention of satisfactory elongation (EL = 8%). Subsequent annealing at $T = 550^\circ C$ for 5 h increases ductility to EL = 14% and decreases the yield strength to YS = 745 MPa.

![Figure 3](image1.png)

**Figure 3.** Structure of 0.45%C steel after ECAP at 400$^\circ$C (N=6) and heating (550$^\circ$C, 5h.). TEM

![Figure 4](image2.png)

**Figure 4.** Mechanical properties of 0.45%C steel: 1-ECAP; 2-ECAP + heating 500$^\circ$C, 10 h.; 3-ECAP + heating 550$^\circ$C, 5 h.

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