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Mechanical properties and fracture characteristics of high carbon steel after equal channel angular pressing

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ABSTRACT

The ultra-microduplex structure was fabricated in a fully pearlitic Fe–0.8 wt% C steel after equal channel angular pressing (ECAP) at 923 K via the Bc route. The microstructures and mechanical properties, before and after deformation, were investigated using scanning electron microscopy and mini-tensile tests. The cementite lamellae are gradually spheroidized by increasing the number of ECAP passes. After four passes, the cementite lamellae are fully spheroidized. Microhardness and the ultimate tensile strength of pearlite increase with the strain, up to a peak value (after two passes) and then decrease significantly. The yield strength, elongation and percentage of reduction in area increase with the number of ECAP passes. The tensile fracture morphology changes gradually from brittle cleavage to typical ductile fracture after four passes.

1. Introduction

The ultrafine grained (UFG) steel is an advanced high performance structure material, since it has high strength, excellent plastic deformation performance, and can be processed superplastically at high strain rates and low temperatures. Grain refinement, which can synchronously enhance material's strength and toughness, is the main aim of research and development for the new generation steels. There are many techniques of grain refinement for carbon steels, associated with severe plastic deformation [1–4] and advanced thermo-mechanical processes [5–7]; however, most of the studies have focused on low or medium carbon steels. High carbon steels are widely used in industries. Therefore, from the application point of view, it is of great interest to synchronously obtain ultrafine microstructure and excellent mechanical properties for high carbon steels.

Furuhara and Maki, [8] reported that ultrafine $(\alpha+\theta)$ microduplex structures (average sizes of ferrite grains (α) and cementite particles (θ) were 0.4 and 0.3 μm, respectively) were achieved by severe warm rolling of $(\alpha+\theta)$ microstructure at 923 K for ultra-high-carbon steels (> 1.0 wt% C, such as SUJ2 Fe–1.4Cr–1.0C steel). Significant dynamic recovery of α grain had happened after warm rolling, and the uneven microduplex structures caused the difference in mechanical properties. Meanwhile, the strain of warm rolling was very large, so higher requirements were needed for the rolling equipment. Wang et al. [9] also obtained the $(\alpha+\theta)$ microduplex structures in a fully pearlitic 65Mn steel by ECAP via the C route at 923 K, and the effective strain was up to 5. The average sizes of the α grains were reaching the level of 0.3 μm, and the θ particle size distribution was bimodal. The grain size of the bulky θ particles was about 0.6 μm, and the average diameter of fully spheroidized θ particles was about 0.1 μm. However, the mechanical properties were not studied in detail in Ref. [9]. In the previous study [10], an ultrafine $(\alpha+\theta)$ microduplex structure was fabricated by warm cross-wedge rolling (WCWR) at the surface layer of high carbon steel rod, where equiaxed α grain size was about 0.4 μm and the fully spheroidized θ particles were 0.1–0.2 μm in size. However, the spheroidization of the θ particles was non-uniform from the surface to the center. In the central region of the rod, original θ lamellae was fragmented, but the spheroidization was not complete. In the present study, the Fe–0.8 wt% C steel with a fully pearlitic structure was processed by equal channel angular pressing (ECAP) via the Bc route at 923 K. The underlying microstructure evolution mechanism was revealed and the mechanical properties were also systematically studied. The results discussed in this paper could provide some useful experimental support for the development and applications of ultrafine-grained high carbon steel materials.

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2. Materials and experimental procedure

2.1. Materials

The material used in this study was commercial high carbon steel (Fe–0.8 wt% C). To ensure the full evolution of pearlite, all specimens were vacuum annealed at 1273 K for 30 min and then placed into a salt bath furnace at 873 K for 30 min. This was followed by water cooling outside the furnace.

2.2. Experimental procedure

The ECAP work was done in Central Iron and Steel Research Institute for Structural Materials. The samples used for ECAP were machined into cylindrical bars, 49 mm in length and 8.3 mm in diameter. Repetitive pressing was feasible, as the sample's cross-section remained unchanged. The ECAP experiments were conducted using a split die with two channels intersecting at inner angle of 120° and outer angle of 30°. Therefore, the strain per path was 0.62 [11]. Up to four passes of ECAP were conducted on the samples at 923 K using the Bc route method, in which the specimen was rotated 90° along the longitudinal axis between the passes. It is known that the Bc route method is effective in obtaining a homogeneous microstructure [12]. Before extrusion, the die was preheated to 573 K and the samples were heated up to the deformation temperature and held for 20 min. The samples were pressed at a pressing speed of $\sim$2 mm/s to prevent surface cracking. The time from taking out the samples from the furnace to finishing 1 per pass of ECAP was less than 30 s. The specimen and the die were both coated with graphite and MoS_2 for lubrication, before being placed in the entrance channel at the testing temperature.

The samples used for the metallographic investigation were cut from transverse cross-sections by wire-electrode cutting method, before and after ECAP, and were then subjected to several successive steps of grinding and polishing. After that, the samples were etched in a 4 vol% nitric acid solution, and scanning electron microscopy (SEM, Hitachi-S4300) was used for microstructure analysis. Mini-tensile test specimens with a gage length of 6 mm and cross-sections of 1×2 mm^2 were sectioned along the longitudinal axes. The mini-tensile test was conducted on Gleeble 3500 thermo-mechanical simulator, with a chuck moving velocity of 0.2 mm/min. The morphologies of the fracture surfaces were observed using JSM-5610LV SEM. Microhardness was measured using MH-3 Vickers microhardness tester with 200 g normal load and 10 s holding time on the as-polished regions. An average microhardness value was determined based on 5 indentation measurements.

3. Results and discussion

3.1. Microstructure before and after ECAP

Fig. 1 shows the SEM micrographs before and after different passes of ECAP. The initial microstructure of the as-received Fe–0.8 wt% C steel is shown in Fig. 1a. It can be seen that the initial microstructure was fully pearlite. After one pass, the cementite lamellae shears in a regular way, as seen in Fig. 1b, the cementite plates remain parallel to each other, but they are in a discrete form, indicating the occurrence of the cementite lamella breakage during ECAP. In addition, the discrete cementite lamella are severely bent and kinked, and the occurrence of spheroidization in a small portion of cementite can be also found. The spheroidized cementite particles remain at the initial cementite lamellar domain. The present observation reveals that cementite possesses a considerable capability for plastic deformation under the deformation mode induced by the present ECAP. Fig. 1c and d are the SEM micrographs of the sample after two and three ECAP passes, respectively. After two passes, the cementite lamellae are fully fractured and then spheroidized. The shape of the cementite is a short bar, or an ellipse, as seen in Fig. 1c. With further increase in strain, in Fig. 1d, spheroidization of the cementite lamellae is increased and most of the cementite lamellae are transformed to particles. After four passes, as seen in Fig. 1e, the microstructure of pearlite consists of nearly spheroidized cementite particles, with only a few lamellae still present. This indicates that the cementite lamellae are fully spheroidized. The driving force for spheroidization is the reduction of the interfacial surface area between ferrite and cementite that occurs when the structure transforms from lamellar to spheroidal [13]. Meanwhile, with further ECAP, the plastic deformation is accelerated [14,15] and the driving force for spheroidization increases. Therefore, the cementite lamellae are gradually spheroidized by increasing the number of ECAP passes. In addition, the effect of the deformation temperature is also significant. Wetscher et al. [16] deformed a fully pearlitic R260 steel rail by ECAP, at room temperature. After three passes, the lamellae spacing decreased significantly, but globular cementite was not found. This was most likely an effect of the elevated 923 K temperature, during which this ECAP experiment was conducted. The high deformation temperature increases iron and carbon atoms diffusion, and thus promotes cementite spheroidization. Consequently, the cementite lamellae are fully spheroidized. The microstructure of ECAP ultrafine-grained high carbon steel was investigated and the corresponding grain refinement mechanism initiated by ECAP was explored in the previous work [17].

3.2. Mechanical properties

The engineering stress–strain curves from the mini-tensile test of the high carbon steel samples before and after different ECAP passes at room temperature are shown in Fig. 2. After three and four ECAP passes, the stress–strain curves exhibit the obvious yielding point and the discontinuous yielding phenomena, to some extent compared with that of the original lamellar pearlite structure specimen. According to the polycrystalline yield theory, the obvious yield point attributes to the dislocation pile-up on the ferrite grain boundaries, and dislocations activation in ferrite grains. However, the original lamellar pearlite, ferrite, is divided into brittle and hard lamellar cementite. Without multi-directional free slip-deformation ferrite does not have the ability for cooperation–deformation. Obstacles effect of the cementite lamellae on deformation is beyond the grain boundaries. Thus, pearlite structures are unable to offer high plasticity. Correspondingly, there is no obvious yield point in the stress–strain curve. According to Lin et al. [18], as long as granular carbide occurs in the grain boundary region, avoiding closed pearlite lamellae, the obvious yield point occurs, which validates the results of this paper. As indicated by Hayashi et al. [19], the dispersed cementite particles can significantly affect the plasticity of refined-grain ferrite steels. The smaller the cementite particles, the more uniform the plasticity is. Song et al. [20,21] also showed that the dispersed fine cementite particles can effectively improve the ability of work hardening.

Fig. 3 shows the mechanical properties of pearlite before and after different ECAP passes. It can be seen that the microhardness and the ultimate tensile strength (UTS) of pearlite increase with strain, up to a peak value (two passes), and then decrease significantly, but after four passes, the values slightly increase. This is due to the joint action of work hardening, spheroidization of the cementite lamellae and grain refinement. The microhardness and