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Structure formation, phase transformations and properties in Cr–Ni austenitic steel after equal-channel angular pressing and heating

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Abstract

It is shown that cold equal-channel angular pressing (ECAP) of corrosion resistant austenitic 0.07%C–17.3%Cr–9.2%Ni–0.7%Ti steel leads to formation of submicrocrystalline structure: generally oriented subgrains and cells with separated grains (100–250 nm in size). The steel samples 20 mm in diameter and 80 mm in length were subjected to ECAP at room temperature for four passes. The angle between the channels was 120°. ECAP promotes the martensitic transformation which becomes more active only after four passes, leading to the formation of 45% martensite. During heating, the fraction of high-angle boundaries and the volume of austenite are increased, and the microstructure becomes more equiaxed. Submicrocrystalline structure with grain size 150–250 nm and 80% of austenite was obtained upon heating to 550 °C. Such structure exhibits a substantial strain hardening (yield strength 1090 MPa relative to the initial with 320 MPa) and an elongation of 12%.

Keywords: Austenitic steel; Equal-channel angular pressing; Nano- and submicrocrystalline structure; Martensitic transformation

1. Introduction

At present, great attention is paid to the processes of severe plastic deformation (SPD) due to the opportunity of the formation of ultrafine-grained structures upon deformation [1,2]. Equal-channel angular pressing (ECAP) as one of the most advantageous SPD method allows to prepare nano- and submicrocrystalline samples as large as 20–40 mm in diameter and 100–150 mm in length [2–4]. The pieces of such size can be widely used for medical tools and implants; in particular, they are already tested for titanium [2].

The purpose of the present work was to study the opportunity of the submicrocrystalline structure formation in Cr–Ni austenitic steels upon ECAP and to determine the mechanical characteristics of such materials. The Cr–Ni austenitic steels were chosen for the opportunity of their application in medicine.

2. Experimental procedure

The 0.07%C–17.3%Cr–9.2%Ni–0.7%Ti (wt.%) steel samples of 20 mm in diameter and 80 mm in length were subjected to ECAP at room temperature for four passes by the route B_c. The angle between the channels was 90° for first pass and 120° for another three passes. The total true deformation was about $e = 3.2$ [5].

The structure analysis has been carried out using a light microscope "Olympus PME 3"and transmission electron microscope JEM-100CX. We studied the longitudinal section. The samples were examined by X-ray diffraction using a DRON-1UM diffractometer. The phase composition was determined using a PHAN% program of the quantitative phase analysis taking into account the texture formation [6]. Microhardness was defined using the M-400-H "Leco" hardness testing machine with 50 g load. The mechanical properties were determined using an INSTRON 1196 testing machine at a strain rate of 1.5 mm/min.

3. Results and discussion

3.1. Severe plastic deformation by equal-channel angular pressing

3.1.1. Structure evolution

After ECAP, the initial grained structure elongated along the sample axis was observed for all passes upon metallographic

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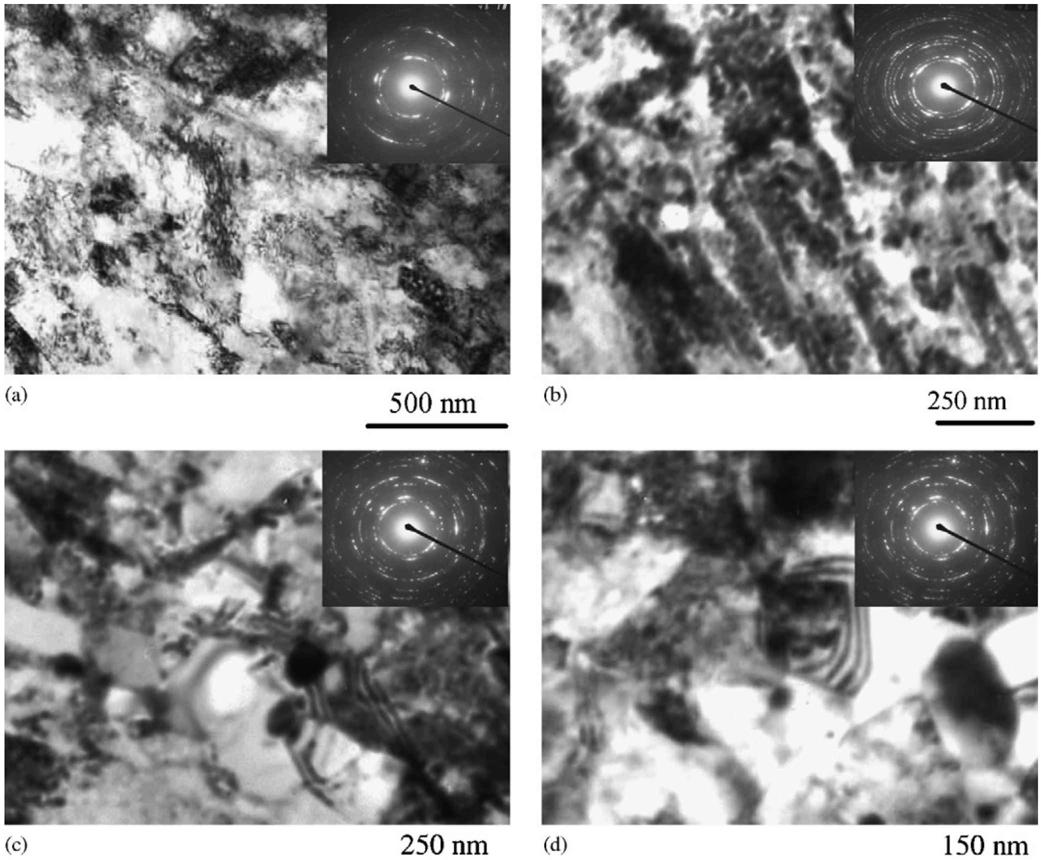

Fig. 1. TEM images after ECAP and subsequent heating. (a) ECAP, $N = 4$, (b) ECAP + $T = 550\,^{\circ}$C, 30 min, (c) ECAP + $T = 550\,^{\circ}$C, 30 h and (d) ECAP + $T = 600\,^{\circ}$C, 30 min.

examination. No structure inside the elongated grains was revealed by etching. The intragranular structure was observed only upon the electron-microscopic examination.

After ECAP, the structure inside the grains consists of oriented structure elements of 100–250 nm in size (the spacing between the boundaries of grains and/or subgrains) (Fig. 1a) and isolated equiaxed grains of the same size. Isolated small reflections in the electron-diffraction pattern also indicate the presence of high-angle boundaries.

The oriented structure elements are transformed into the equiaxed ones due to the formation of dislocation bridges. An increase in the degree of misorientation of subgrain boundaries leads to the formation of new grains. The nucleation of equiaxed grains was observed also upon the cellular structure development, which is accompanied by decreasing dislocation density, thinning cell boundaries and increasing degree of cell boundary misorientation. The formation of new grains, which are more perfect than the initial deformed grains, i.e., the process of dynamic recrystallization upon cold deformation by ECAP reminds the processes of the recrystallization “in situ” (according to Rossard) [7], continuous recrystallization (according to Doherty) [8] and dynamic continuous polygonization [9], which are generally known to occur upon hot deformation. The same mechanism was observed in ref. [10].

To obtain the perfect submicrocrystalline structure, it is necessary either to increase the degree of deformation or to subject the obtained structure to heating [11]. The reached high degree of deformation (four passes at a channel intersection angle of 90°) allowed the authors [12] to obtain a more perfect structure with a grain size of ∼100 nm. The used equipment did not allow us to increase the number of passes. Therefore, we studied the possibility to obtain the developed submicrocrystalline structure upon heating after ECAP.

3.1.2. Phase transformations

Cold SPD of the Cr–Ni austenitic steel leads to martensitic transformation [13,14]. It was found that, upon ECAP by the used schedule, the austenitic 0.07%C–17.3%Cr–9.2%Ni–0.7%Ti steel undergoes martensitic transformation (Fig. 2). In this case, the transformation does not occur up to completion and is intensified only after fourth pass, when the martensite content reaches 45%. Such “sluggish” behavior of martensite transformation can be explained by the lower applied pressure upon ECA pressing under the given conditions compared with torsion under a pressure of 6 GPa [13,15].

3.1.3. Mechanical properties

Severe plastic deformation by ECAP significantly increases the microhardness (Fig. 3). The microhardness of the austenitic steel in the as-quenched state is 2.3 GPa, while after ECAP it increases to 4 GPa already after two passes, and a further change in microhardness is insignificant. Even increase in the marten-