Combining methods of severe plastic deformation as an effective way to increase the strength of metallic materials

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Abstract. The article reviews the combined methods of severe plastic deformation (SPD) for hardening metallic materials. The combined deformation processing, extrusion with the equal-channel angular pressing (ECAP) is presented. The comparison is made of the mechanical characteristics and the fracture mode of the Fe360 low carbon steel strengthened by the combined methods of extrusion with ECAP and ECAP with extrusion.

1. Introduction

The application of combined methods in the deformation processing of metallic materials, compared to single methods, provides greater opportunities in solving the problems of hardening, the selection of processing modes and, ultimately, achieving the desired physical and mechanical properties.

At the present stage of the development of deformation processing, SPD methods provide unique properties of metallic materials [1–12, etc.]. The SPD can result in changes in structure, phase state, strength, plasticity, microhardness, and other stress-related properties.

By the combined methods of processing materials, we understand the application of procedures of either one physical nature (e.g. mechanical) implemented in one technological process (even, possibly, in a single device), or of a different nature, or in a certain sequence at different time intervals [13]. Since each of the separately applied processing methods has certain limitations in achieving cumulative deformation and changing the structural-phase state in the material, the combination of methods has certain opportunities in solving the problem of optimal combination of high strength and ductility values of metallic materials [14, 15, etc.].

The processing methods can be combined in various sequences. The question is, if the sequence of stages in the execution of certain processing types can affect the physical and mechanical properties of materials.

A significant increase in strength and a decrease in ductility during ECAP with the subsequent extrusion of the Fe360 low carbon steel was shown in [13]. An increase in the ductility of the material was also noted in tensile tests at 213 K compared with tests at 293 K. The fracture behavior of the Fe360 steel specimens in the initial state and the ECAP and extrusion-hardened state is qualitatively identical, viscous with the formation of dimples by merging micropores [13].

The purpose of the research is to study and compare the mechanical properties and the fracture behavior of the low carbon Fe360 steel subjected to extrusion and ECAP with those after ECAP and extrusion.
2. Material and methods
The material under study is the Fe360 low carbon structural steel (0.18% C, 0.23% Si, 0.60% Mn, 0.01% Cr, 0.003% Ni, 0.01% P, 0.01% S, 0.05% Cu, 0.05% Al, remaining Fe). Chemical analysis was performed on a Foundry-Master atomic emission spectrometer (Worldwide Analytical Systems AG, Germany).

The combined processing was carried out as follows. First, a Fe360 steel bulk billet with a diameter of 11.8 mm and a length of 40 mm was extruded in a single pass at 673 K. During extrusion, the bulk billet was inserted into the input channel with a diameter of 12 mm, then it passed through a narrowing segment with a cone angle of 34°, and it was subsequently pressed into the output channel with a square cross section of 8×8 mm. Another billet with a diameter of 6 mm and a length of 50 mm was made from an extruded billet, which was pressed into a 6/19.8×50 mm bushing made from the same material. Then, ECAP of a composite billet having a diameter of 19.8 mm and a length of 50 mm was performed in a single pass at the same temperature as extrusion. The angle of the channels intersection during ECAP was 120°. Extrusion and ECAP were made on a PSU 125 3IM hydraulic press at 1250 kN with special equipment. After extrusion, the equipment was changed for ECAP. Prior to the deformation processing, the billet was preheated and kept in a muffle furnace to 673 K, then placed in processing equipment heated to 673 K with a rotary furnace. To reduce the friction of the surface of the billet against the walls of the die mouth, a ROSOIL-ANGELINA lubricant with flake graphite additives was applied. The equipment provided a deformation degree of 0.4 during extrusion and 0.64 during ECAP.

Samples for mechanical uniaxial tensile testing were made from the strengthened billets. Cylindrical specimens with a working area of 2 mm in diameter and 10 mm in length were tested for uniaxial tension using a UTS-20K machine (UTS TestSysteme GmbH, Lammerweg 29.D-89079 Ulm, Germany) at a constant loading rate of ≈3.33×10^{-5} m·s^{-1} at room temperature.

Fractures of the sample were studied by scanning electron microscopy (SEM) using a HITACHI TM3030 (Japan) scanning electron microscope at the SE mode.

3. Results and discussion
The strength characteristics of Fe360 steel are given in table 1. As can be seen, the yield stress and ultimate tensile strength for the steel hardened by extrusion and ECAP are ~15% lower than those for the material after ECAP and extrusion. This is probably due to the fact that the deformation processing method used at the initial stage of the combined treatment, which provides greater grain refinement with a higher deformation degree (0.64 during ECAP vs. 0.4 during extrusion), eventually leads to greater strength values.

| Steel state | Yield stress (MPa) | Ultimate tensile strength (MPa) | Relative narrowing ψ_{um} (%) |
|-------------|-------------------|-------------------------------|-----------------------------|
| As delivered | 324               | 484                           | 44.9                        |
| Extrusion, 673 K, n=1 + ECAP, 673 K, n=1 | 686               | 730                           | 31.8                        |
| [14]: ECAP, 673 K, n=1 + extrusion, 673 K, n=1 | 818               | 865                           | 25.1                        |

The macrorelief of the fracture surface of the Fe360 steel samples at 293 K is featured by the plastic fracture with a cup fracture formed on the neck of the stretched specimen with tightening in the deformation localization zone and the formation of shear lips. The fracture macro-surface is heterogeneous, matte. In all cases, the fracture surface includes two main zones: the central zone where the fracture originated and the fracture growth occurred, and the cut zone.

For the initial state, the fractures of the fibrous and peripheral parts of the fracture surface of the samples at 293 K, as in [16], are formed by the ductile fracture pattern (figure 1a). The fracture mode is determined by the formation of dimples by merging micropores.
Figure 1. Fracture microreliefs (central fibrous zone) of the Fe360 steel samples fractured at room: a – initial state; b – after extrusion and ECAP.

The fracture microrelief of the Fe360 steel specimens hardened by extrusion and ECAP, is qualitatively similar to that of the material in the initial state, as well as of the material hardened by ECAP and extrusion. The sizes of microdimples and dimples cover a wide range, which is caused by significant fluctuations in the grain and dispersed inclusions size in the examined steel. In the case of extrusion and ECAP, the micro dimples are of 0.25 μm, and the maximum size of the dimples in the fracture reaches ~20 μm, which is somewhat larger than in the case of ECAP and extrusion. The relative narrowing $\psi_{\text{um}}$ at the specimen rupture extrusion and ECAP is 31.8 %, which is 1.4 times less than that for steel in the initial state ($\psi_{\text{um}} = 44.9$ % at 293 K) and ~1.25 times higher than that for ECAP and extruded steel ($\psi_{\text{um}} = 25.1$ % at 293 K). The lined up micro dimples are seen on the fins of a normal fracture.

4. Conclusion
1. ECAP and extrusion of bulk billets of low carbon Fe360 steel increased the yield stress by 2.1 times, the ultimate tensile strength by 1.5 times and reduced ductility by 1.4 times. At this, the values of yield stress and ultimate tensile strengths during extrusion and ECAP were ~20% lower than those during ECAP and extrusion.
2. There were no qualitative differences in the fracture mode of steel before and after the combined processing by extrusion and ECAP. The fracture of the Fe360 steel specimens in its initial state and the extrusion and ECAP hardened state, as well as in the case of ECAP and extrusion, was viscous with the formation of dimples by merging micropores. The specimen fractures had a characteristic appearance with a central fibrous initiation fracture zone and slow fracture growth, as well as a peripheral cut zone. Some differences in the size and concentration of the dimples for the states after “extrusion + ECAP” and “ECAP + extrusion”, are apparently explained by the different ability to resist plastic deformation, nucleation and growth of microfracture due to differences in the size and density of inclusions in grain sizes, caused by the deformation processing methods in different sequences.

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