FEATURES OF PLASTIC FLOW AND FRACTURE OF SUBMICROCRYSTALLINE ARMCRO-IRON WITH BANDED FRAGMENTED SUBSTRUCTURE

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ABSTRACT

Structural state, character of plastic flow at various scale levels, fracture and mechanical properties of armco-iron subjected to equichannel angular pressing by different deformation routes with subsequent annealing were studied with transmission electron, optical and scanning tunnelling microscopes. It was determined that the banded fragmented structures or equiaxed structures are formed in the bulk of the submicrocrystalline armco-iron specimen depending on the mode of equichannel angular pressing.

The research of a strain-induced relief shown that plastic flow of submicrocrystalline armco-iron with banded fragmented structure is strongly localised near the ends of the specimen. At the same time the most of working part of the specimens remains almost undeformed. Plastic flow is realised by development of localised deformation meso- and macrobands. Fracture of the specimens occurs along the macrobands of localised plastic deformation. The stress-strain curves for the specimens are characterised by a stage of strong work hardening followed by a lengthy area of decrease in deforming stresses. The stage of work hardening on the stress-strain curve corresponds to the appearance of the set of localised plastic deformation mesobands. The reduction of deforming stresses is caused by macroband propagation.

It is found that strong localisation of plastic deformation and low plasticity take pace until banded fragmented structure is preserved. Fracture of banded fragmented structure under annealing causes the involving of the bulk of the material into plastic flow. As a result, stress-strain curves take a usual shape.

1. INTRODUCTION

Low plasticity of materials with nano- and submicrocrystalline structure is caused by strong localisation of plastic deformation. However, structural heterogeneity within the bulk of submicrocrystalline materials prohibits finding an exact classification of correlation between the degree of material submicrocrystallinity and the shape of its stress-strain curve.

Of great interest is the formation of various banded fragmented structures depending on the mode of equal channel angular pressing [1] in order to investigate the character of macrolocalisation and its effect on the subsequent fracture of loaded specimens.

Annealing of submicrocrystalline specimens at temperature gradually increasing up to primary recrystallisation reveals the correlation between the evolution of banded fragmented substructure and the development of plastic deformation at micro-, meso- and macroscale levels. The latter, in its turn, contributes to revealing importance of banded fragmented substructure in fracture of submicrocrystalline materials and the shape of their stress-strain curves.

This work is devoted to systematic investigation of the effect of banded fragmented structure on the character of deformation localisation and subsequent fracture of submicrocrystalline armco-iron as well as on its mechanical properties.

2. EXPERIMENTAL PROCEDURE

In this work armcro-iron preliminary annealed at 953 K for 2.5 hour was investigated. Equichannel angular pressing was realized at room temperature using special equipment. This equipment consists of two channels of the identical cross-section areas intersecting at an angle of 90°. Equichannel angular pressing was carried out by two various routes of deformation: the orientation of billet remains constant in the first mode (route A according to classification [2]), in the second mode (route B) the billet was rotated about its axis on 90° after each pass.

After equichannel angular pressing the sizes of ingots were 70×14×14 mm^3. The specimens for a mechanical test were obtained by a spark cutting in the form of a double-sided shovel with the sizes of a working part 2×1×15 mm^3. Then the submicrocrystalline armcro-iron specimens obtained by route B were subjected to annealing in vacuum at 523, 623 and 723 K for 1 hour.

The structural researches were performed by means of transmission electron microscope. The foils for the investigations were cut out in three perpendicular planes. The plastic deformation was studied in situ with optical and scanning tunnelling microscopes (STM). Static uniaxial tension tests with an automatic recording of the loading diagram were carried out with loading velocity 1.3×10^{-6} m/s at room temperature. The microhardness was measured by microhardness tester with the Vickers pyramid. The indenter load was equal to 100 g. ($H_{\mu} \sim 2300$ (route A, 4 passes), ~ 2900 (route A, 12 passes) and ~ 3000 MPa (route B, 4 passes)).

3. EXPERIMENTAL DATA

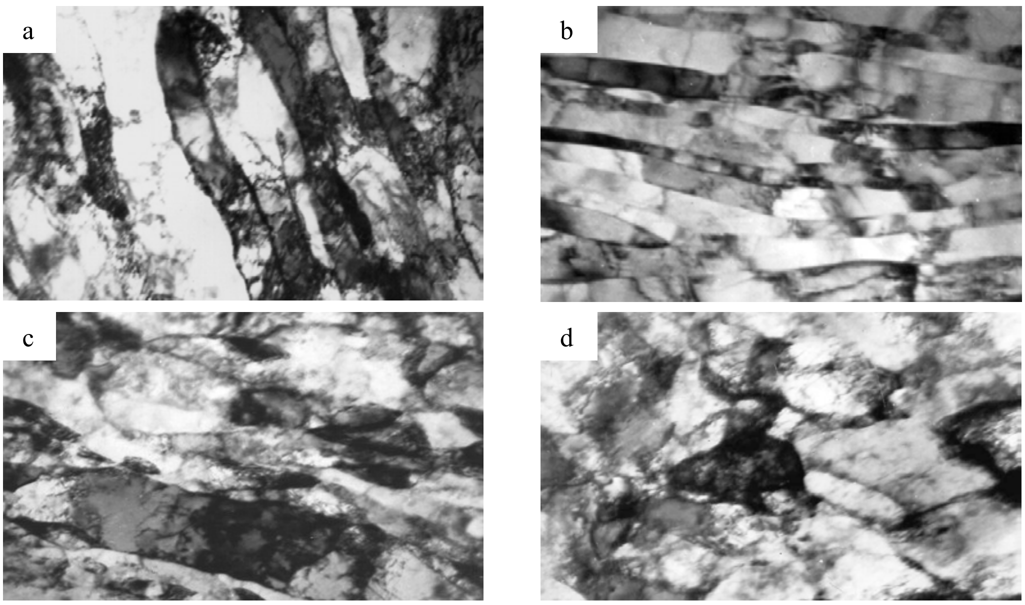

Fig. 1. TEM-images of substructures formed in α-Fe specimens under equichannel angular pressing by route A, 4 passes (a); route A, 12 passes (b), route B, 4 passes (c, d); ×35000

The investigations by transmission electron microscopy (TEM) confirm that armcro-iron specimens are characterized by submicrocrystalline state. After equichannel angular pressing the predominant type of substructures is deformation microbands divided by subboundaries into elements of anisotropic ellipsoidal shapes (Fig. 1). Under deformation by route *A* the increase of pass quantity from 4 to 12 results in reduction of their longitudinal (l) and transverse (d) sizes. After 4 passes $l = 800$ nm, $d = 130$ nm, and after 12 passes $l = 300$ nm и $d = 60$ nm. Under deformation by route B the anisotropy factor is decreased, the longitudinal and transverse sizes are 1050 and 350 nm, respectively. Moreover, under deformation by route B the areas with quasi-homogeneous subgrains are observed, which inclusion volume fraction is about 30 % (Fig. 1(d)).
The annealing of armcro-iron specimens, which were subjected to preliminary equichannel angular pressing by route B, at temperature 523 K does not change greatly the material substructure (Fig. 2(a)). The dislocation density within subgrains is about 3×10^{10} cm^{-2} as before. Increase of annealing temperature up to 623 K leads to general formation of equiaxial subgrains. Their mean sizes are 410 nm (Fig. 2(b)). At the same time the deformation microbands do not almost observed. Annealing at 723 K results in recrystallisation with formation of grained structure (Fig. 2(c)).

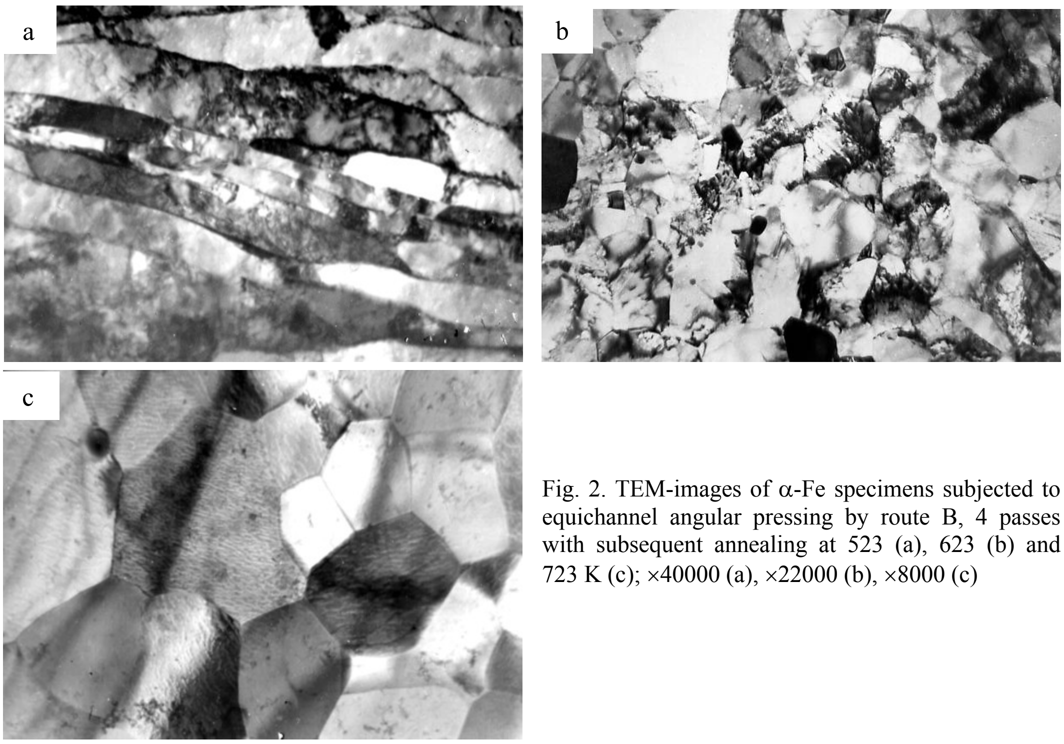

Fig. 2. TEM-images of α-Fe specimens subjected to equichannel angular pressing by route B, 4 passes with subsequent annealing at 523 (a), 623 (b) and 723 K (c); ×40000 (a), ×22000 (b), ×8000 (c)

The plastic deformation of untreated armcro-iron is developed by propagation of the Lüders band and then distributed homogeneously along the entire working part of loaded specimens. On the contrary, after preliminary equichannel angular pressing (independently of route and pass quantity) the plastic flow of submicrocrystalline armcro-iron specimens is strongly localized under loading. The meso- and macrobands of localized deformation are developed on the surface and lateral face of the specimens. Note that the plastic deformation is realized only at the specimen ends, whereas the most of specimen working part remains almost undeformed (Fig. 3).

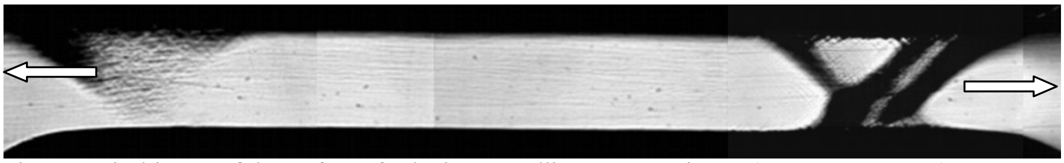

Fig. 3. Optical image of the surface of submicrocrystalline α-Fe specimens (route A, 12 passes); ε = 6%. The size of image 17.5×2.2 mm^2

The mesobands of localized plastic deformation appear on the working part of the specimen at $\varepsilon \sim 0.5\%$ (Fig. 4). They are generated at the ends of the specimen and propagate in the direction of maximum tangential stresses. The set of the mesobands is observed both on the surface and lateral face. The mesoband width is about 70 μm. At $\varepsilon > 2\%$ larger-scale macrobands are formed against the mesobands (Fig. 5). They propagate at an angle of 45° to the axis of tension. The velocity of the macroband propagation is ~ 3×10^{-5} m/c. The analysis of microhardness distribution shows the great reduce of microhardness within macroband. The latter evidences the material softening (Fig. 6). Since the elongation of the specimen under loading occurs, in general, owing to the deformation within macrobands, the macrobands are the bulged-in material. Their width and depth increase with the strain increasing. Deformation localization at the macroscale level is observed in two configurations. Deformation is developed by propagation of two parallel (Fig. 5(a)) or conjugate macrobands (Fig. 5(b)). The macroband propagation causes global loss of shear stability and development of localized neck in the specimen.

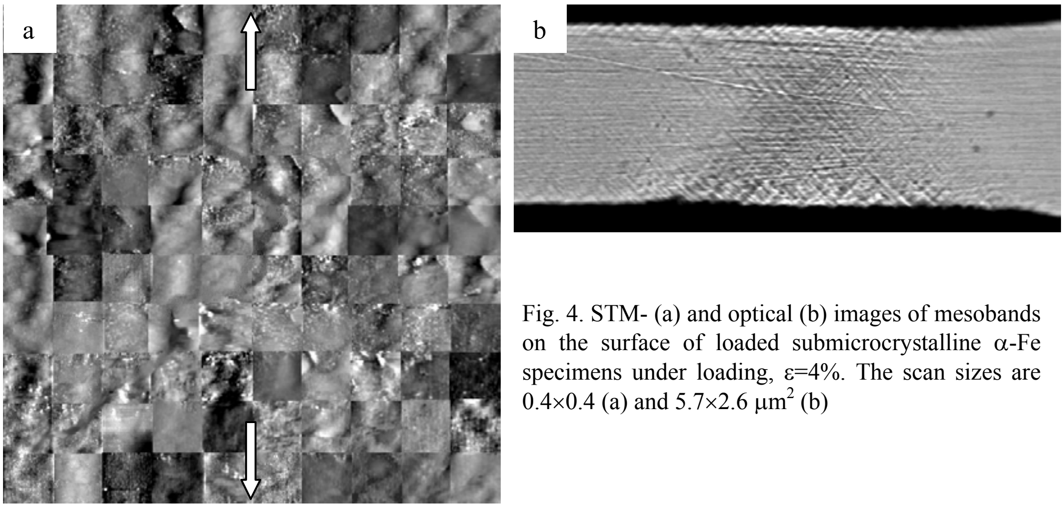

Fig. 4. STM- (a) and optical (b) images of mesobands on the surface of loaded submicrocrystalline α-Fe specimens under loading, ε=4%. The scan sizes are 0.4×0.4 (a) and 5.7×2.6 μm^2 (b)

The subsequent annealing greatly changes the character of plastic flow of submicrocrystalline armcro-iron specimens. The plastic deformation of the specimens subjected to thermal treatment at 523 and 623 K is distributed homogeneously along their working part (Fig. 7). However, macrobands of localized deformation appear at $\varepsilon \geq 4$ % at the ends of the specimens. When annealing temperature increases up to 723 K the deformation again propagates as the Lüders band.

At the same time the localization of plastic deformation does not occur right up to beginning of fracture.

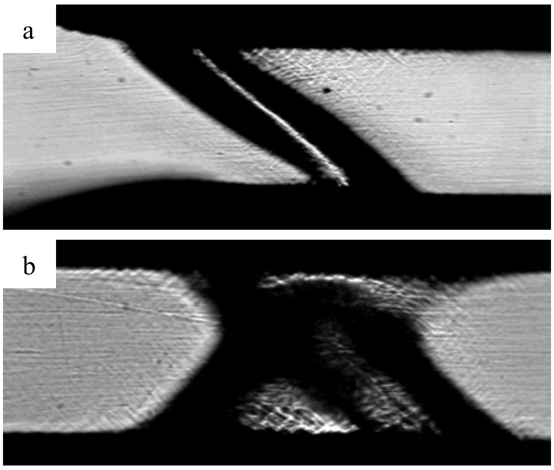

Fig. 5. Different types of the propagation of the localized deformation macrobands, ε = 5 %. The image sizes are 5.7×2.6 mm^2

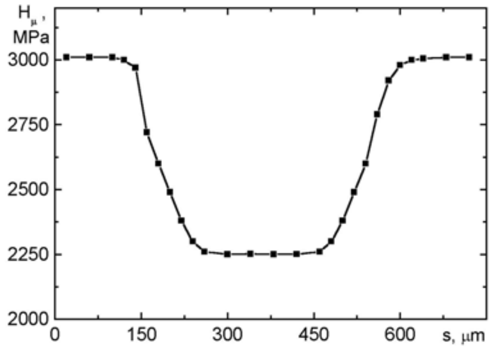

Fig. 6. The microhardness distribution along the width of the localized deformation macrobands

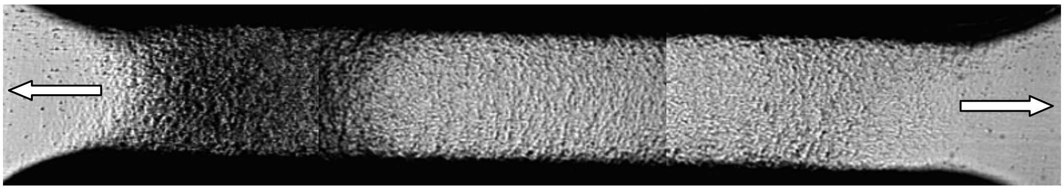

Fig. 7. Optical image of α-Fe specimens subjected to equichannel angular pressing by route A and 4 passes (a) with subsequent annealing at 523 K (b), ε = 6%. The size of image 17.5×2.5 mm^2

Uniaxial-tension tests revealed that both equichannel angular pressing and subsequent annealing greatly change the shape of stress-strain curves and mechanical properties of loaded armcro-iron specimens (Fig. 8 and 9). According to Fig. 8, after equichannel angular pressing the yield plateau disappears and the stress-strain curves are characterized by strong work hardening followed by a long section of strength decrease. The shape of stress-strain curves is governed by the character of meso- and macroband propagation. The stage of work hardening on the stress-strain curve corresponds to the appearance of the set of localized plastic deformation mesobands. The reduction of strength characteristics is caused by macroband propagation.

The mechanical properties of submicrocrystalline armcro-iron is governed by the mode of equichannel angular pressing. The more pass quantity the higher strength and the lower plasticity. The mechanical properties peak in the case of 4 passes by route B.

The subsequent annealing of submicrocrystalline armcro-iron specimens essentially changes their mechanical properties (Fig. 9). The level of internal stresses in armcro-iron specimens subjected to equichannel angular pressing by route B followed by annealing at 523 K is reduced and therefore their strength increase up to 520 MPa. Increase of annealing temperature results in the recrystallization and strength reduction. After annealing at 723 K the plasticity of armcro-iron specimens is greatly increased (Fig. 9(curve 4)).

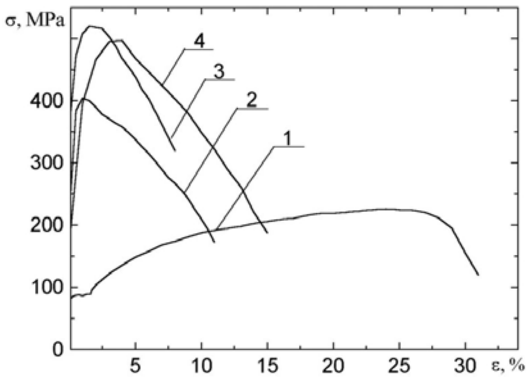

Fig. 8. The stress-strain curves for armco-iron specimens (1), subjected to equichannel angular pressing by route A, 4 passes (2); route A, 12 passes (3) and route B, 4 passes (4)

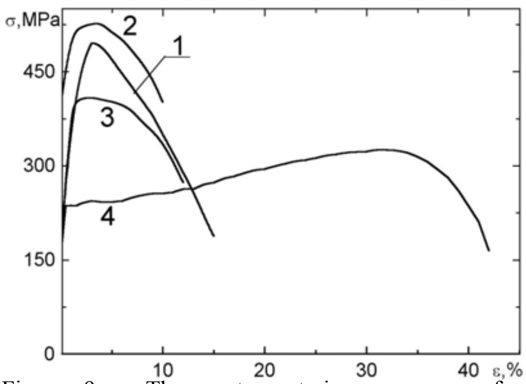

Fig. 9. The stress-strain curves for submicrocrystalline armco-iron specimens (1), subjected to subsequent annealing at 523 (2), 623 (3) and 723 K (4)

4. CONCLUSION

The structural state, character of plastic flow, fracture and mechanical properties of armcro-iron subjected to equichannel angular pressing by various deformation route with subsequent annealing were studied. It was found that submicrocrystalline armcro-iron has high tendency to localization of plastic deformation. Plastic flow is realized by the development of meso- and macrobands at specimen ends, whereas the most of specimen working part remains almost undeformed.

The shape of stress-strain curves is governed by the character of meso- and macroband propagation. The stage of work hardening on the stress-strain curve corresponds to the appearance of the set of localized plastic deformation mesobands. The reduction of strength characteristics is caused by macroband development.

Internal structure and mechanical properties of investigated specimens are governed by the route and pass quantity of equichannel angular pressing. Optimal mechanical properties are observed in the case when the billet was rotated about axis on 90° after each pass.

The subsequent annealing decreases in the level of internal stresses or result in recrystallization governing the delocalization of the plastic flow. Mechanical properties of submicrocrystalline armcro-iron specimens can be widely changed depending on annealing temperature.

References

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[2] Valiev, R.Z., Aleksandrov, I.V., Nanostructured Materials: Production, Structure and Properties, Nauka, Moscow, 1999, p. 244.