Regularities of bainitic steel deformation transition

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Abstract. Quantitative analysis of defect and carbide subsystems evolution in medium-carbon bainitic steel subjected to compressive strain up to 36% was performed by means of transmission electron diffraction microscopy. Dislocation substructure and carbide phase parameters dependence on degree of deformation are identified, possible reasons of staging in their changes are discussed. It is suggested that the reason for bainitic steel softening at high (over 15%) degrees of deformation is activation of deformation microtwinning process.

1. Introduction

Attention of physical material science researchers is recently drawn to study of bainitic transformation in steels [1-3]. Steels with bainitic structure, due to the set of their characteristics (good welding properties, high creep-resistance and relatively high strength), are widely used in automobile production, energy production, production of rails, high-strength pipes for oil and gas industry, etc. [4, 5].

Products use often leads to deformation effects, resulting in plastic deformation. In turn, understanding of structure formation regularities and steel properties under plastic deformation is essential for mechanical hardening process control. To identify promising areas for application of technologies, based on plastic deformation after heat treatment, it is necessary to investigate hardening effect dependence on structural state of material and parameters of deformation processing mode, to establish cause-and-effect relationships between phenomena that determine comprehensive improvement of properties.

The aim of present work is to study formation and evolution of phase composition and defect substructure of bainitic steel under active compressive plastic strain.

2. Materials and methods

30Cr2Ni2MoV structural steel [6] was used as a research material. Austenitization of steel was carried out at temperature of 960 °C, during 1.5 hours, with subsequent air cooling. Deformation of steel was carried out by axial compression at rate of ~7·10⁻³ c⁻¹ in 4x4x6 mm³ columns in “Instron-1185” type test machine. Compression is more convenient to use as a mean of deformation, since it enables to
achieve more severe deformation than under tension. Study of structure and phase composition of steel was carried out by means of electron diffraction microscopy of thin foils.

3. Results and discussion

Typical profile of steel strain hardening curves is shown on Figure 1a. Mathematic processing of strain hardening curves shows that $\sigma$-$\varepsilon$ dependence is parabolic and is described by polynomial of the fourth degree. Differentiation of $\sigma$-$\varepsilon$ dependence curve allows to determine the coefficient of steel strain hardening

$$\theta = \frac{\partial \sigma}{\partial \varepsilon}$$

![Figure 1](image.png)

**Figure 1.** Curve of strain hardening (a) and strain hardening coefficient dependence from degree on deformation (b) for bainitic steel.

Analyzing results shown on Fig. 1b, two stages of strain hardening can be distinguished: the stage with parabolic $\sigma$-$\varepsilon$ dependence or decreasing hardening coefficient $\Theta$, and a stage and with slightly varying negative value of hardening coefficient. Transition from the first stage to the second one occurs in 19 ... 25% interval of strain degree. Destruction of test samples of steel occurred at $\varepsilon \approx 0.4$ through cleavage generating several large fragments. It is obvious that samples deformation behavior is determined by change in material phase composition and defect substructure. Consider this question in more detail.

Bainite transformation of steel leads to formation of multiphase structure [7, 8]. The main is $\alpha$-phase (solid solution based on body-centered cubic lattice), additional phases are $\gamma$-phase (solid solution based on face-centered cubic lattice) and iron carbide (cementite).

Martensite (shear) mechanism of ferrite formation results in generation of dislocation substructure of reticulate type with relatively high scalar density of dislocations in bainite plates, that comprises $\approx 7*10^{10}$ cm$^{-2}$ in investigated steel, indicating shear mechanism of $\gamma \rightarrow \alpha$ transformation. Plastic deformation of steel increases scalar density of dislocations (Fig. 2a). Dislocation substructure does not change - reticulate substructure remains unchanged. Scalar density of dislocations depends on degree of deformation. Namely, at $0 \% < \varepsilon < 18 \%$ scalar density of dislocations increases monotonically. With increase in degree of deformation ($18 \% < \varepsilon < 36 \%$) scalar density of dislocations remains practically unchanged.
One possible reason for a significant reduction in rate of dislocations concentration at the late stressing stages is switching in additional mechanism of material deformation. Twinning may be one of such mechanisms, performed under deformation. Objectively, study performed within this research revealed substantial increase in volume of material containing deformation microtwins, at deformation degree exceeding ≈18 % (Figure 2b). Typical image of steel volume containing micro-twins of deformation origin is shown in Figure 3.

Elastic stress occurring due to shear mechanism of $\gamma \rightarrow \alpha$ transformation not only leads to formation of substructure with high dislocation scalar density, but also to fragmentation of bainite plates, i.e. to segmentation of plates into areas with small-angle disorientation.

Increase in deformation degree leads to decrease in average longitudinal dimensions of the fragments. Whereas transverse fragments dimensions are limited by bainite plates boundaries and during deformation stay almost unchanged. Decrease in average size of the fragments occurs against the backdrop of increase in degree of disorientation. Similar to dislocation scalar density behavior, change in size of the fragments shows up certain staging: at deformation degree of $\varepsilon > 26$ % change in average size of fragments practically stops. We can assume that fragments size reaches certain critical value (≈200 nm). It is shown [9] that such structure is not capable of further evolution during deformation process (so-called critical structure), it is preferential place for micro-cracking.

Figure 2. Dependence of dislocations scalar density (a) and volume of material containing microtwins, (b) on degree of deformation.

Figure 3. Electron microscope image of steel structure after $\varepsilon = 36$ % deformation; a – light field; b – micro diffraction pattern; c – dark field obtained in reflection [101] $\alpha$-Fe; arrows indicate: on (a) and (c) – microtwins of deformation origin; on (b) – a reflection, in which dark field is obtained.
Electron-microscopic micro-diffraction analysis of steel by means of thin foils method has identified bend contours of extinction (Figure 4). Presence of these contours indicates bend and twist of the material crystal lattice [10-12]. It is found that in steel before deformation (initial state) and in steel after deformation of small extent (≈5%) contours are mostly arranged crosswise bainite plates, crossing the plate from one edge to the other (Fig. 4b). After large deformation (ε≈18% or more) ring contours are formed in material embracing certain areas of the plates (Figure 4c).

**Figure 4.** Electron microscopic image of bend contours of extinction; a, d – micro diffraction patterns; b, c - light field; extinction contours are indicated by arrows; b – ε = 5%; c - ε = 30%.

Quantitative analysis of steel structure demonstrated that with increase in extent of deformation, number of contours per a unit of image area (contours surface density) increases (Figure 5, curve 2). At the same time average crosswise dimensions of contours (Figure 5, curve 1) reduce. The first fact indicates increase in amount of stress raisers in material with the rise in extent of deformation, the second one points on increase of material crystal lattice bend and twist amplitude [10-12].

**Figure 5.** Dependence of average transverse dimensions of contours h (a, curve 1), and their surface density ρ (a, curve 2) on extent of deformation.
Deformation of steel is accompanied by significant transformation in material carbide subsystem. Initially, lamellar particles (ratio of longitudinal size (L) to transverse size (d) L/d ≈ 8) are transformed into ellipsoidal at the last stage of deformation (L/d ≈ 5). At the same time inside bainite crystals (on dislocations and boundaries fragments) particles of round shape are found, their number is increasing with increase in extent of deformation.

Location of cementite particles is changing: with increase in deformation extent volume fraction of particles located on boundaries of bainite plates is increasing, and by the time of sample fracture almost all cementite is located on intraphase boundaries (boundaries of grains and plates of ferrite) (Figure 6a, curve 1). Increase in volume fraction of cementite particles located on intraphase boundaries proceeds non-monotonically: it is very rapid in deformation extent range of 5 % < ε < 10 % and is significantly slower at deformation of higher extent. The reason for an abrupt increase in fraction volume of cementite particles located on intraphase boundaries can lay in transformation of residual austenite and origination of α-phase and cementite, initiated due to steel deformation. Genuinely, micro diffraction electron microscopic studies revealed the fact of rapid decrease in volume fraction of retained austenite at steel deformation of low extent (ε≈10 %) (Figure 6b).

Initial stage of deformation (ε≈10 %) is accompanied by an increase in total proportion of cementite particles in steel (Figure 6a, curve 3); at deformation of high extent volume fraction of cementite in steel is reduced. This means that atomic carbon transfers to defects of steel crystal lattice (dislocations, sub-boundaries and boundaries) and to solid solution based on α-phase.

Stated facts in total allows for assumption that there are two concurrent processes taking place in steel during deformation: (1) dissolution of cementite particles formed during bainitic transformation in ferrite plates and (2) emission of cementite particles on dislocation substructure elements ("strain age") and on intraphase boundaries (subsidiary transformation of residual austenite).

Comparison of the results shown on Figure 1, Figure 2, Figure 5 and Figure 6, brings us to the statement that transition from the first stage of steel deformation to the second one is conditioned by the following change in material structure-phase state: first, by completion of intensive accumulation of dislocations, secondly, by initiation of deformation microtwinning, thirdly, by completion of bainite plates fragmentation, fourthly, by reaching maximum density of bend extinction contours, fifthly, by significant increase in steel solid-solution strengthening. Considering together, those processes result in propagation of areas with critical substructure in material having a potential of micro-cracking with subsequent destruction of sample.

4. Conclusions
It is shown that 30Cr₂Ni₃MoV bainitic steel plastic deformation by means of uniaxial compression is followed by, first, increase in dislocations scalar density and volume of material with deformation microtwins, secondly, decrease in average longitudinal size of fragments and increase in degree of their disorientation, thirdly, increase in number of stress raisers and material crystal lattice bend and twist amplitude. Revealed are stages of changes in steel structure parameters. Change of deformation mechanism is suggested as follows: on the first stage of stressing (0 % < ε < 18 %) deformation is mostly conditioned by dislocations move; on the second stage (18 % < ε < 36 %) by of dislocations move and twinning.

Quantitative electron microscopic micro diffraction analysis of steel phase composition evolution under plastic deformation by means of uniaxial compression is performed. It is shown that carbide transformations in bainitic structures occur within two concurrent processes – dissolution of cementite particles formed during bainitic transformation in ferrite plates, and emission of cementite particles on dislocation substructure elements as part of “strain aging”. Concurrently subsidiary transformation of residual austenite initiated by steel deformation is observed.

5. References
[1] Quidort D and Bréchet Y 2002 Scripta Materialia 47 151–156
[2] Clarke A J et al 2008 Acta Materialia 56 16–22
[3] Borgenstam A et al 2009 Acta Materialia 57 3242–52
[4] Matrosov Y I et al 1989 Steel for Main Gas Pipelines (M.: Metallurgy) p 288
[5] Pavlov V V et al 2007 Metallurgist 4 51–53
[6] Pridantsev M V et al 1980 Structural Steel: Reference Book (M.: Metallurgy) p 288
[7] Kurdyumov V G et al 1977 Transformations in Iron and Steel (M.: Science) p 236
[8] Bhadeshia H K D H 2001 Bainite in Steels (London: Institute of Materials) p 460
[9] Rybin V V 1986 Large Plastic Deformations and Fracture of Metals (M.: Metallurgy) p 224
[10] Hirsch P et al 1977 Electron Microscopy of Thin Crystals (Huntington, NY: Krieger) p 574
[11] Konyeva N A and Kozlov E V 1982 Soviet Physics Journal 8 3–14
[12] Ivanov Y F et al 2010 Hard Construction Steel: The Structure and Hardening Mechanisms (Novokuznetsk: Siberian State Industrial University) p 174