Structural Transformations of High-Carbon Austenite

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Abstract

In the present work structural transformations of high-carbon austenite is investigated. The effects of thermal conditions on the ductile iron structure transformation are evaluated by metallographic analyses, TEM, X-ray and mechanical testing. It has been shown that austenite transformation by quenching and isothermal annealing at the intermediate temperatures is similar for the examined cast irons and high-carbon steels.

Keywords: Bainite, Cast Iron, Hardening, Martensite, Plastic Deformation

Introduction

Recently a considerable attention has been paid to the bainitic nodular cast irons as a new type of constructional material. Total output of the bainitic nodular cast iron is continuously increasing. However, utilization of the latter is essentially limited. This is caused by the strict conditions that the cast irons should satisfy and by the lack of technology of producing the austempered ductile iron (ADI) (Voigt, R.C.1990).

High carbon austenite is the basic component for a wide range of steels and cast irons because structural and phase transformations develop main operating parameters of the above mentioned materials. Consequently, investigation of structural transformation regularities in austenite is of theoretical and practical importance. It is necessary to elaborate the scientific background of technologies in order to improve the properties of high carbon cast irons and carbon steels. (G.V. Kurdjumov, L.M. Utevsky, R.N. Entin, 1977).

Working Methodology

Low-silicon (2% Al) cast iron was produced for the experiments. The modification of the melt was conducted by mag-nesium vapors. The initial specimens for further quenching and austempering regimes were cast iron in the form of Y-blocks. The initial specimens, prepared using the mentioned method, have passed the multistep isothermal hardening after the austenitization at 900 °C for 60 min. for developing required ratio and sequence of the phase transformation products (lower bainite, tempered martensite and retained austenite). The structure of transformation products was investigated by SEM and metallographic microscopy. Quantity of the retained austenite was determined using standard X-ray method. The basic composition of the investigated alloy was determined using emission spectroscopy.

Results

Plastic deformation of martensite is the main conventional technological process of steel hardening in modern technologies based on the effect of twinning (TWIP) as well as transformation induced plasticity (TRIP). Consequently, for better development of the potential possibilities of Fe-C alloys it seems very likely to investigate structural characteristics of energy reduction possible mechanisms during mar-

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tensitic transformation.

Important information about the fine structure and the sequence of transformations in the austenite have been established using TEM, including micro diffraction, crystallographic analysis of the orientation relationship between phases, and of habit planes.

Orientation relationship, habit plane, orientation of tetragonal axes of martensite, bainite crystals, twins and carbide precipitation have been determined by micro diffraction and the track analysis on the surface and computer simulation of stereographic projections and electron diffraction patterns for two- phase and twinned crystals (Kuletia I.R., Dzigrashvili T.A., 1984).

Study of transformations in the retained austenite, formed after martensitic and partial bainitic transformations, has been carried out via in-situ heating the samples by the intensive electron beam in the column of microscope (Kutelia E.R., Utevsky L.M., 1969).

Alloys of Fe -1.63%C; Fe -3%Cr -1.5%C, closest by carbon concentration to the high-strength cast iron alloys, were chosen for investigation . Fe -3%Cr -1.5%C has been chosen to compare and model the austenite transformation in the cast iron.

Micro-structural aspects of ADI metallic matrix are also complex. After quenching the samples from austenitization temperature (850-950°C) to the room temperature the structure typical to high-carbon steels was fixed in the metallic matrix with 40% of the self-accommodating martensitic crystallites and 60% of the retained austenite (Fig.1a). Relatively small martensitic crystallites are observed close to the graphite inclusions while at a distance the crystallites are 5...10 times larger. In the samples quenched from 350...450°C, the structure typical to medium and high carbon steels is observed (Kuletia I.R., Dzigrashvili T.A., 1984). The crystallites of upper bainite, observed in the optical microscope on the preliminarily prepared surface, have a feather like shape (Fig.1b). The crystallites of lower bainite, formed in the same sample after the isothermal quenching from 250...300°C, have a needle like shape just as the martensitic crystallites (Fig.1c). The mixture of upper and lower bainite crystallites is observed at isothermal quenching from 300...350°C (Fig.1d).
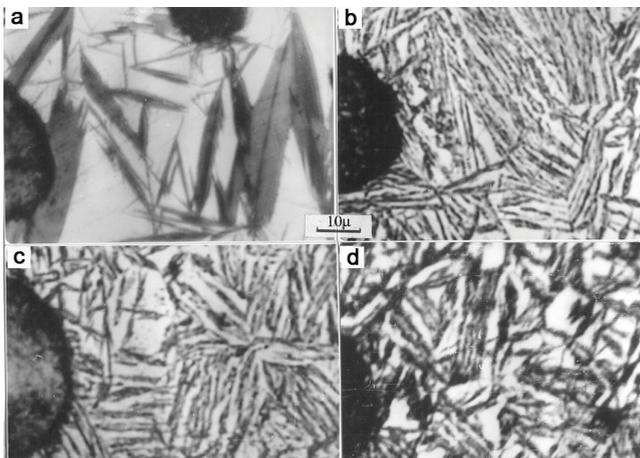
Figure 1. *Structure of the cast iron after different thermal treatments: a) Quenching from 900°C in water; b) Isothermal quenching from 400°C-1h; c) Isothermal quenching from 350°C-1h; d) Isothermal quenching from 270°C-1h*

Electron microscope images of the lower bainite crystallites, formed at the first stages of the transformation at 250°C, are of a thin lens-like ferrite crystallite shape with the cementite inclusions. Moreover, the cementite inclusions are oriented at 60° with regard to the long axis of the ferrite crystallites. In all crystallites of the lower bainite the cementite inclusions are of the same orientation (Fig.2a), and the Bagarjatski orientation relationship between the cementite and martensite lattices is held (BagarjtskyJu.L., 1950). This relationship is characteristic for the tempered martensite and shows that the cementite is precipitated directly from the α-phase (ferrite). The Bagarjatsky orientation relationship, given below in the form of the matrix equality (1) suites all the electron diffraction patterns obtained from the typical crystallites of lower bainite (Fig.2b).
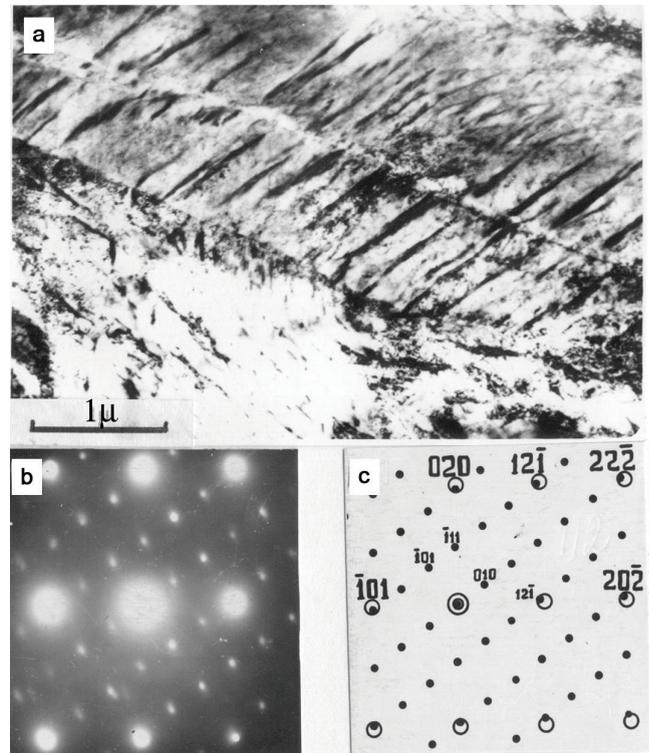
Figure 2. *Fine structure of the lower bainite: a) TEM image of the bainite crystallites formed at 250°C-1h;*
b) Corresponding electron diffraction pattern; zone axis $[101]^o \| [101]$ c.

$$
\begin{vmatrix} H \\ K \\ L \end{vmatrix}_{\alpha} = \begin{vmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 1 & 2 \end{vmatrix} \times \begin{vmatrix} H \\ K \\ L \end{vmatrix}_{c} \quad (1)
$$

Equality 1

Most of the upper bainite crystals, revealed in optical microscope on the preliminarily prepared surface, are long and quite wide. These crystals observed in electron microscope consist of almost the same orientated crystallites of α-phase with the long cementite inclusions between them (Fig. 3 - a).

In such crystals orientation relationship between cementite and ferrite is described by the matrix equality (2) first found in the crystals of upper bainite in carbon steels (Kutelia E.R., Utevsky L.M., 1969).

Equality (2) suites the typical crystals of upper bainite in the cast iron examined in this work (Fig.3b). Quenched samples, in which almost the half of the austenite was trans-

formed to the martensite, were isothermally heated at 200, 250, 300,350 400°C and kept during the time period just enough to transform the part of the retained austenite.
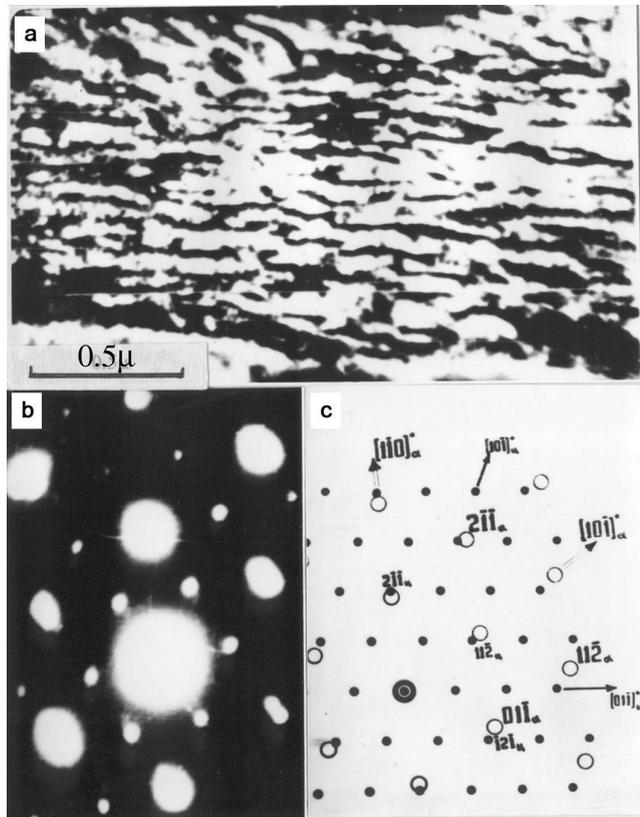
Figure 3. *Fine structure of the upper bainite: a) TEM image of the upper bainite formed after isothermal annealing at 400°C-0,5h; b) Electron diffraction pattern taken from the area shown on a); c) Scheme of the pattern: zone axis [111]°∥ [111]c*

$$\begin{vmatrix} H \\ K \\ L \end{vmatrix}_\alpha = \begin{vmatrix} 3 & 1 & 0 \\ 1 & 3 & 2 \\ 1 & 1 & 4 \end{vmatrix} \times \begin{vmatrix} H \\ K \\ L \end{vmatrix}_c \quad (2)$$

Equality 2

TEM studies showed that basic "frontal" growth of the bainite crystallites from all interfaces is observed at 200...350°C. The In-situ TEM examinations have also been carried out to observe the growth of the bainitic structures on the initial martensite and lower bainite crystallites (Fig.4).

Short term (1sec) heating of thin sample films, carried out in the column of microscope, showed that even in such short period of time the identically oriented cementite crystallites are growing from martensite/austenite interface; in the direction of the austenite (Fig.5 - a, b).

This process is followed by the "frontal" growth of the ferrite, so that in the beginning the cementite grows faster than α -phase. Additionally, it has been revealed that in the intermediate temperature range the rate of transformation of the retained austenite is much higher than in case of the original austenite. Moreover, after the partial bainitic trans-

formation at 200-350°C retained-austenite becomes more flexible with regard to austenite-martensite transformation (Fig.6). Consequently, this transformation can be completed by a series of heating and quenching from the intermediate temperatures. In the final product orientation relationship between the lattices of cementite and ferrite are described by the equalities (1) and (2) (Kutelia E.R., Utevsky L.M., 1969).
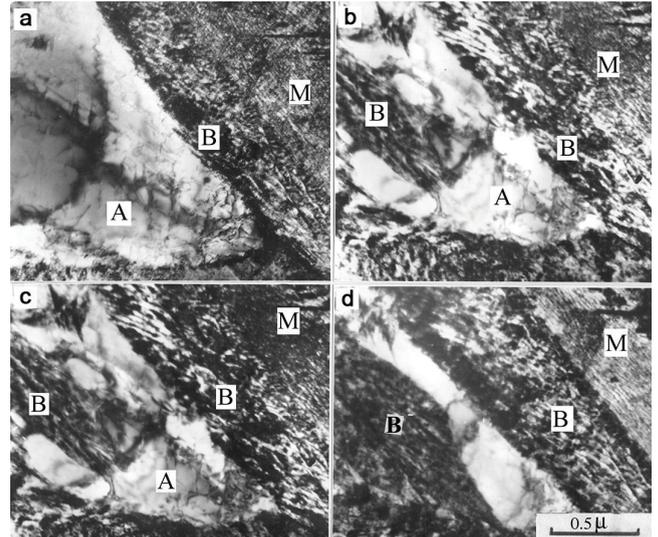
Figure 4. *Transformation of the retained austenite after partial martensitic transformation; TEM images: a) Austenite quenched after partial bainitic transformation at 300°C-1h; b) The same area after heating by the intensive electron beam during 10sec; c) Heating during 5sec; d) Third heating during 5sec, (10+5+5)sec*
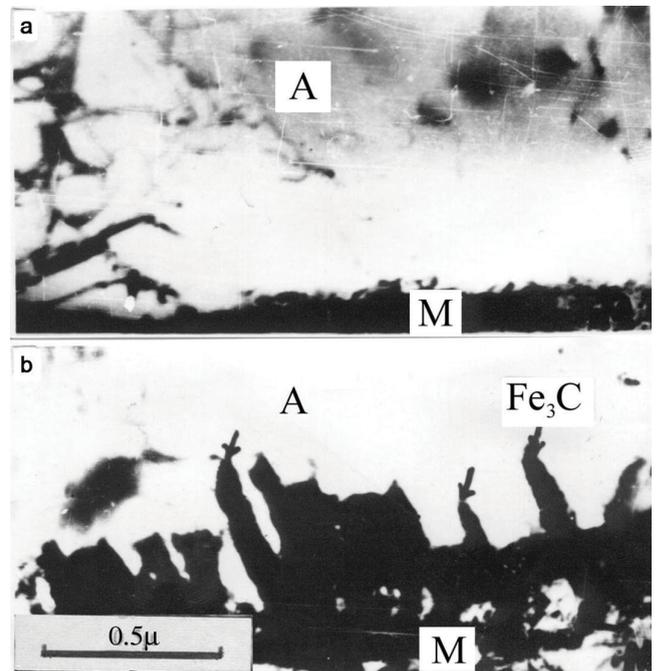
Figure 5. *TEM observation of the first stage of "frontal" growth of bainite crystallites from the martensite/retained austenite interface: a) Quenched sample; A-retained austenite; M-martensite; b) The same area after short term (1sec) heating by the electron beam in the column of microscope (~300°C).*
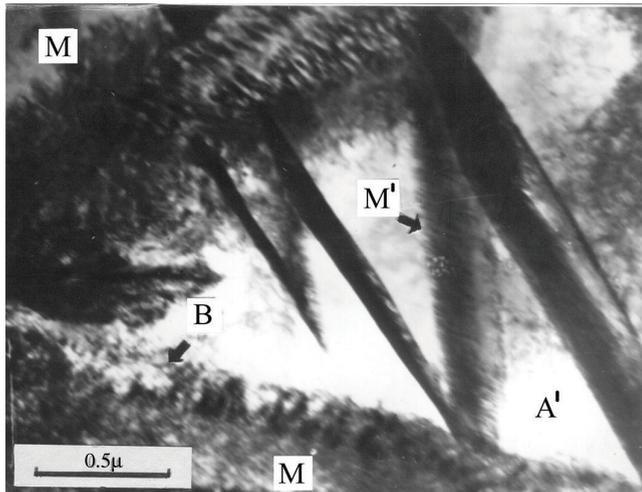
Figure 6. *Transformation of the retained austenite after the partial bainitic transformation and quenching in water, TEM image; M-initial martensite, B-bainite grown on the martensite crystal, M1- secondary martensite, A-austenite.*

Transformation of austenite at the intermediate temperatures and further cooling to the room temperature provides development of a complex crystalline aggregation, just like as in medium and high-carbon steels. In general, the aggregation is composed of: α-phase, formed via $\gamma \to \alpha$ transformation; carbides, precipitated from the α-phase as well as from austenite; retained austenite, with the different composition of carbon. In the latter the secondary martensite can also be formed after cooling.

The microstructure and the crystallography of transformation of the retained austenite, formed after martensitic as well as partial bainitic transformations, show that there are some different mechanisms of formation and growth of the bainite crystallites. In any case, the kind of the mechanism depends on the transformation temperature. At the higher temperatures of the intermediate range (>350°C) so called "longitudinal" growth is preferable, that creates a typical microstructure of the upper bainite. At the medium and lower temperatures so called "frontal" growth of the ferrite/cementite mixture dominates. These crystallites grow on the martensite/austenite and ferrite/cementite interfaces. In both cases the growth is initiated by the cementite. At the bottom of the intermediate temperature range, in final stages of decomposition of the retained austenite, direct precipitation of cementite from austenite takes place. Easy transformation of the retained austenite into martensite, after the partial bainitic decomposition via the "frontal" growth, is initiated by the cementite. The cementite in its turn reduces the carbon concentration ahead of the growing bainite crystallite. Consequently, number of austenite/martensite interfaces is increasing and the austenite decomposition provides the full vanishing of the latter.

In the steels investigated by the authors, most frequently, a perpendicular (deviation <10o) disposition of the tetragonal axes of the neighboring martensite crystals has been observed. It is important that the axis of Bain deformation in the areas of austenite that are being transformed into two twinned orientation of martensite form rectangle (90˚) to each other. For the areas that form the matrix orientation the axes are $[001]_\gamma$ and the areas forming twin orientation of martensite $[010]_\gamma$. However after transformation the angle between the twin c axes of the martensite is reduced up to

about 71°. That is why domination of a midrib of a big martensite crystal may not be sufficient for full relaxation of elastic tension. So far, further reduction of elastic energy needs additional twinning with other than midrib's twinning system. The latter process is taking place mainly in peripheral parts of the wide martensite crystals. In these parts of the crystals process of relaxation goes via movement and multiplication of dislocation with Burger vector other than Burger vector of the midrib twin dislocation. Experimental evidence of the latter is shown in Figure 7 a, b.
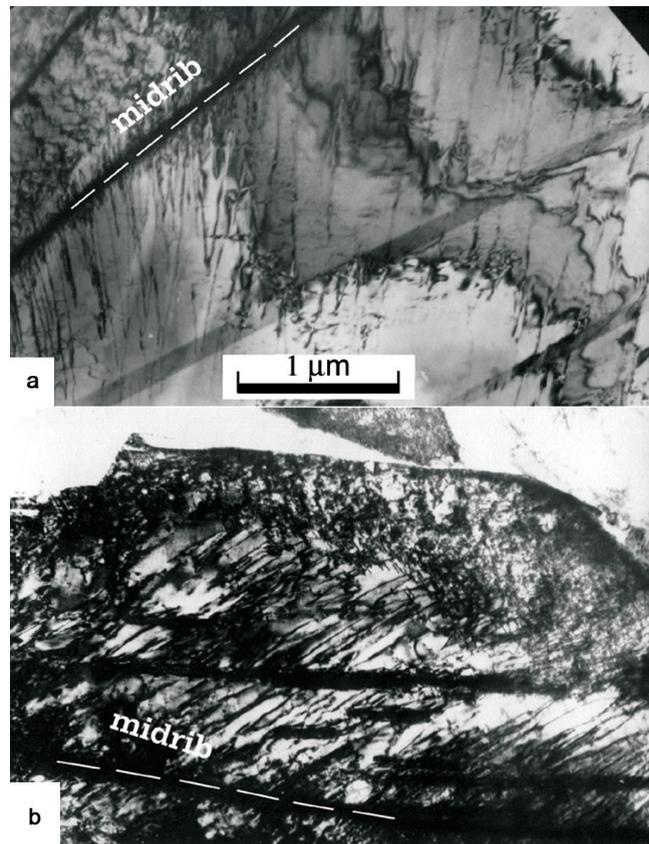
Figure 7. *Steel Fe-1, 7%C; a) TEM image of a large crystal of martensite grown in the bulk specimen; b) TEM image of the large surface crystal grown in the thin film.*

The sequence of $\gamma \to \alpha$ shear-like transformation of austenite inevitably leads to creation of elastic strains in initial phase as well as in martensite. Tendency of the heterophase system to the minimal free energy is supported by domination of martensite crystals formed by different orientation of the twins with different ellipses of deformation and by formation of a particular orientation between neighboring martensite crystals. Consequently, in the high carbon austenite (at the high rate of c/a) the groups of two crystals can be formed. These groups are self-accommodating and provide additional compensation of micro deformations. Most interesting from this point of view is "diamond-like" disposition of four martensite crystals. Disposition of reciprocal deformation ellipsoids for this case shows the nature of strains created during formation of such group of martensite crystals. This kind of compensation takes place for martensite crystals with habit plane $\{15.3.10\}_\gamma$ as well as $\{9.2.5\}_\gamma$. Characteristic angels between these four crystals, for each system of habit plane, allows us to carry out statistical evaluation of the distribution of different (by habit plane) type of

martensite crystals in the transformed volume of austenite of high carbon cast iron too. The austenite in the high strength cast iron is not homogeneous by carbon concentration (because of graphite inclusions). So during γ→α martensitic transformation in the different parts of austenite in cast iron formation of martensite crystals with different orientations of habit planes ({15.3.10}$_\gamma$, {9.2.5}$_\gamma$, {111}$_\gamma$) and also formation of self-accommodating system can be expected.

After enrichment of the retained austenite with carbon, precipitation of carbide (Fe3C) begins In the retained austenite (retained after martensitic and partial bainitic transformation) at the definite stage of isothermal transformation. It changes the mechanism of transformation from lower bainitic to upper bainitic.

In the upper region of intermediate temperatures the cementite crystals are originated and grow directly in austenite. The crystals are grouped in batches of plates with the habit plane (113)$_\gamma$ || (001)c and have a possibility to slip with regard to each other in the direction of growth.

Conclusion

Experimentally revealed regularities of the possible mechanisms of reducing the free energy and relaxation of tension during martensitic transformation of the high carbon austenite enabled us to establish background of a new technology based on combination of different sequence of treatments. These treatments are quenching, plastic deformation for complete use of twinning and/or transformation induced plasticity in order to form better combination of strenght and, plasticityof the high carbon steels and high streength cast irons (ADI), potential possibilities of which are not yet expired.

It has been shown that in the examined cast irons transformation of the austenite, by quenching as well as by isothermal annealing at the intermediate temperatures, is similar to the transformation of austenite in high-carbon steels. The regularities of micro-structural changes, revealed in this work, make the authors able to establish the scientific background for regulation of character and rate of transformations in the austenite.

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