Mechanisms of Dynamic Rearrangement of the Defect Substructure of Industrial Steels

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Abstract – The initial stage of dynamic recrystallization initiated in steels by a high-current electron beam has been studied using the TEM method. It has been shown that the degree of dynamic recrystallization is dictated by the value of the stacking fault energy γ_{SF}. In steels with relatively low values of γ_{SF} (15–20 mJ/m^2) centers of dynamic recrystallization developed by the mechanism of pair coalescence of subgrains, no matter what the crystalline lattice type is. The increase in γ_{SF} to 35–40 mJ/m^2 causes a changeover to the mechanism of multiple subgrain coalescence. At much higher values of γ_{SF}, dynamic recrystallization evolves by migration of local regions of large-angle grain boundaries.

1. Introduction

The problem on the mechanism of the formation of recrystallization centers (nuclei) is a crucial point of the recrystallization theory [1]. This problem, as applied to static recrystallization, has been examined thoroughly in theoretical and experimental works [2]. The regularities by which nuclei of new grains are formed in the course of dynamic recrystallization are less well understood. This is due to the high rate of structural and substructural changes, to the dynamic conditions of rearrangement of the dislocation substructure (when continuously applying high stresses at high temperatures), and to structural changes on quenching immediately upon deformation [3]. One of the few methods used to assess the structural transformations associated with dynamic recrystallization as such is quenching of specimens immediately upon high-temperature deformation [4].

This paper analyzes the results of studies on the mechanisms of the formation of dynamic recrystallization centers and on the kinetics of recrystallization in steel specimens subjected to a low-energy high-current electron beam (LHEB).

2. Materials and Experimental Procedure

The material to be examined was b.c.c and f.c.c steels characterized by essentially different stacking fault energies (γ_{SF}). Table 1 presents the values of γ_{SF} for the materials in question and the modes of LHEB treatment [5]. It was assumed that high-rate quenching from the liquid state was accompanied by plastic deformation of near-surface layers of steel under the action of thermomechanical stresses. The attendant high temperatures initiated dynamic rearrangement of the defect substructure of steel. The extremely high rates of quenching made it possible to determine the initial stages of development of the given process. Studies were conducted by thin-foil transmission electron microscopy. The foils were obtained by electrolytic thinning of plates cut from surface layers of the irradiated materials.

3. Results and Discussion

It has been found that despite the unconventional methods of thermomechanical treatment (LHEB irradiation) the mechanism of dynamic rearrangement of the dislocation substructure is governed to a great extent by the value of γ_{SF}, adhering to the tendencies observed with traditional methods. Namely, in a material with a relatively high value of γ_{SF} (armco-iron, 140–240 mJ/m^2) the origination of dynamic recrystallization centers is not observed. With e-beam energy densities $E_S = 3.2$ and 30 J/cm^2, a globular-net (ball-net) dislocation substructure is found. In the Fe-0.02C-5Cr alloy ($\gamma_{SF} \sim 120$ mJ/m^2) the initial stages of dynamic recrystallization proceed though the formation of a subgrain structure along the grain boundaries.

In steels with a low value of γ_{SF} (15–50 mJ/m^2), the stage of the formation of dynamic recrystallization centers (DRC) is observed (Fig. 1). The extremely high quenching rates on exposure of the material to LHEB treatment allowed us to study the mechanism of their formation. It has been ascertained that in steels with comparatively low values of γ_{SF} (15–20 mJ/m^2) DRC's are formed by the mechanism of pair coalescence of subgrains, regardless of the crystalline lattice type (Fig. 2,a). The increase in γ_{SF} to 35–50 mJ/m^2 causes a changeover to the mechanism of multiple subgrain coalescence (Fig. 2,б).

The dynamic recrystallization centers originate in a cellular substructure. Some cells are grouped in regions (crystallization center). The average size of a center $D \sim 1$ μm and that of the cells in it $d \sim 0.2$ μm. The size of a critical nucleus (L_{cr}) is dictated by the ratio of the specific energy of a large-angel boundary (γ_{lb}) to the specific energy of a small-angle boundary (γ_{sb}) [1, 2]:

Table 1. Characteristics of the structure and modes of irradiation

Steel	Type of the crystalline lattice	Stacking fault energy, mJ/m^2	LHEB parameters*	
			E_S, J/cm^2	τ, µs
Fe-10^{-4}C	b.c.c.	140–473	2.0–2.5	0.8
Fe-10^{-2}C	b.c.c.	140–240	3.2 and 30	2.5
Fe-0.02C-5Cr	b.c.c.	~120	3.2–30	2.5
08Cr15Ni5Co4	b.c.c.	20–30	4.5 and 30	2.5
Cr18Ni9	f.c.c.	13–22	9	2.5
12Cr18Ni10Ti	f.c.c.	36–40	9	2.5
110Mg13	f.c.c.	25. 45–48	22	2.5
7Cr17	f.c.c.	~64	2.5 and 30	2.5

* E_S is the energy density, τ is the e-beam pulse duration

$$L_{cr} = \frac{\gamma_{lb}}{\gamma_{sb}} \cdot d = f \cdot d ,$$

where d is the average subgrain size. Following the data available in [2], let us assume that $f \cong 4$–5. Then, a subgrain resulted from coalescence can be a nucleus, providing its size is four-five times larger than the average size of adjacent subgrains.

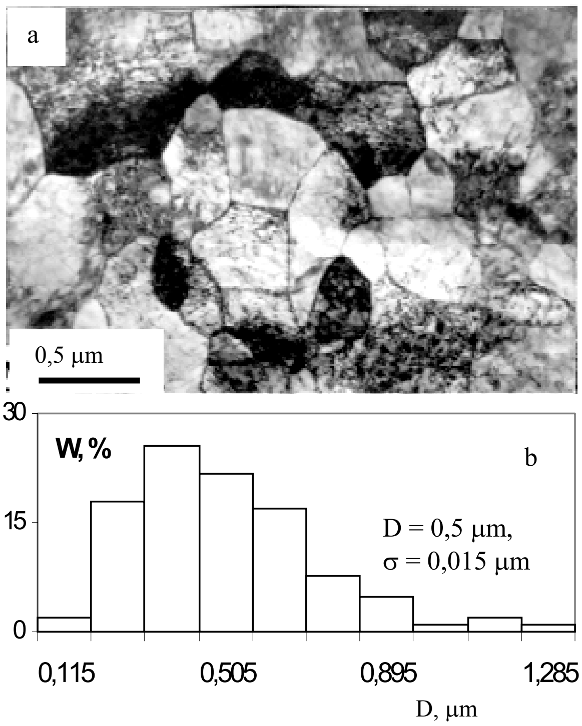

Fig. 1. TEM image (a) and bar chart (b) of subgrains formed in 08Cr15Hi5Co4 steel due to quenching from the liquid state upon LHEB exposure (4.5 J/cm^2, 2.5 µs)

The above estimates ($D = 5d$) show that the size of the regions formed in 110Mg13 steels (Fig. 2,б) correspond to that of critical dynamic recrystallization nuclei. The value of the misorientation of the "nucleus – matrix" interface, along with sizes, is no less important characteristic of a recrystallization center. Dark-field analysis has revealed that in the majority of cases

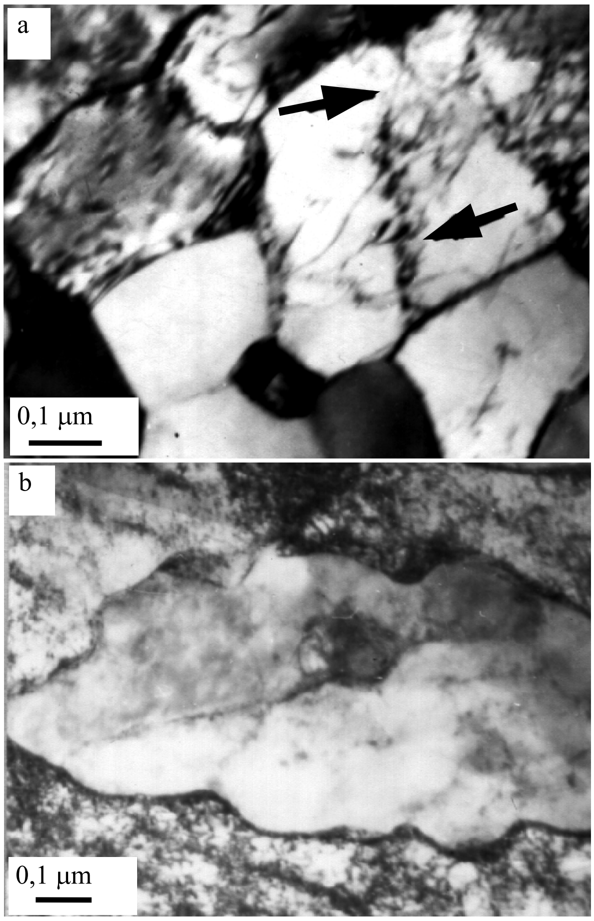

Fig. 2. TEM image of the substructure formed in Cr18Hi9 (a) and 110Mg13 (b) steel near-surface layers upon LHEB treatment. The scattered boundary of the interface of adjacent subgrains is indicted by arrows

the recrystallization nuclei observed in 110Mg13 steel are separated from the surrounding volume by large-angle boundaries. An example of selected area diffraction patterns of the 12Cr18Ni10Ti steel structure is given in Fig. 3. Indexing of the selected area diffraction pattern (Fig. 3,b,c) shows that the subgrains belong to three different planes of the γ-iron reciprocal lattice: (110), (114) and (116). The minimum misorientation angles between these planes: (110)/(114) θ = 33.56°; (110)/(116) θ = 37.26°; (114)/(116) θ = 13.75°.

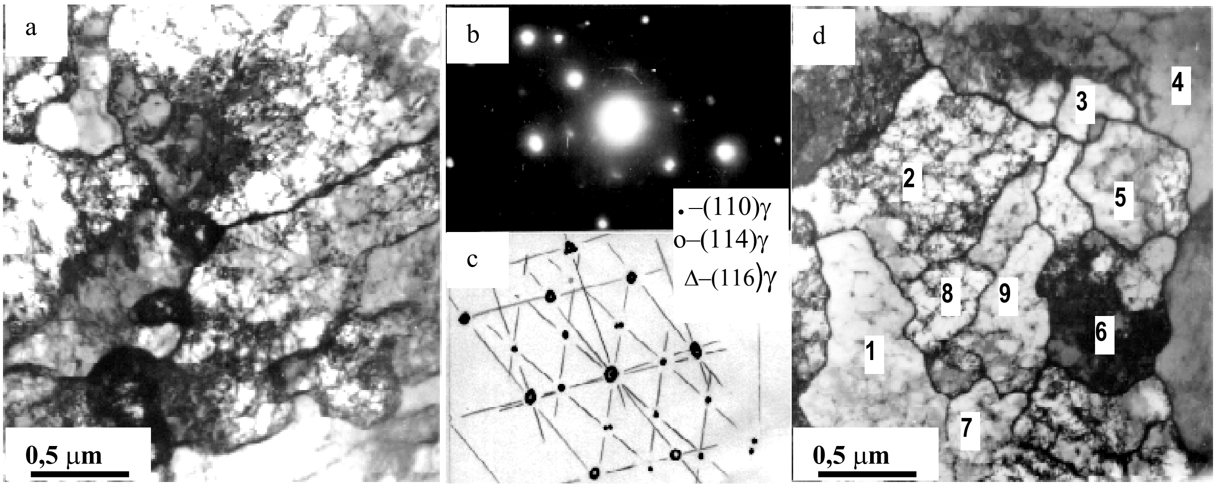

Fig. 3. TEM image of the 12Cr18Ni10Ti steel substructure formed upon LHEB treatment. a, d – light fields, b – selected area diffraction pattern for (a), c – schematic representation of indexing the selected area diffraction pattern. Dynamic recrystallization subgrains are numbered

Consequently, the misorientation between the dynamic recrystallization nuclei formed in 110Mg13 and 12Cr18Ni10Ti steels and the volume surrounding them is sufficient for intensive growth. With much higher values of γ_{SF} (~65 mJ/m^2), dynamic recrystallization of steel occurs by migration of local regions of large-angle grain boundaries.

Investigation into the evolution of the dislocation substructure with discretely increasing E_S has revealed "critical" substructures which give rise to DRC's. The following patterns of the evolution of the substructure have been determined, depending the value of γ_{SF}:

– steel with a low stacking fault energy (γ_{SF} ~ ~ 15–25 mJ/m^2):

chaos → nets → cells → subgrains → DRC;

– steel with an average stacking fault energy (γ_{SF} ~ 35–50 mJ/m^2):

chaos → nets → cells → DRC;

– steel with a high stacking fault energy (γ_{SF} ~ 120 mJ/m^2):

chaos → nets → DRC.

At γ_{SF} ~ 140–240 mJ/m^2, steel is softened mainly by the mechanism of dynamic recovery (polygonization).

The kinetics of dynamic recrystallization under the conditions of high-rate quenching has been studied on Cr18Ni9 steel (Table 1). The specimens were subjected to single LHEB treatment (10–25 keV; 2,6, 5, 6, 9, 16, and 37 J/cm^2; 2.5–3 μs). It has been found that the LHEB-initiated dynamic recrystallization of Cr18Hi9 steel is threshold in character. At $E_S \le 5$ J/cm^2, no progress in dynamic recrystallization is revealed despite the high dislocation density (~$6\cdot10^{10}$ cm^{-2}, Fig. 4,a) that is associated with a short-run thermomechanical action. The further increase in LHEB energy density (i.e., an increase in the time of thermomechanical exposure) results in a subgrain structure and in an increase in average subgrain size

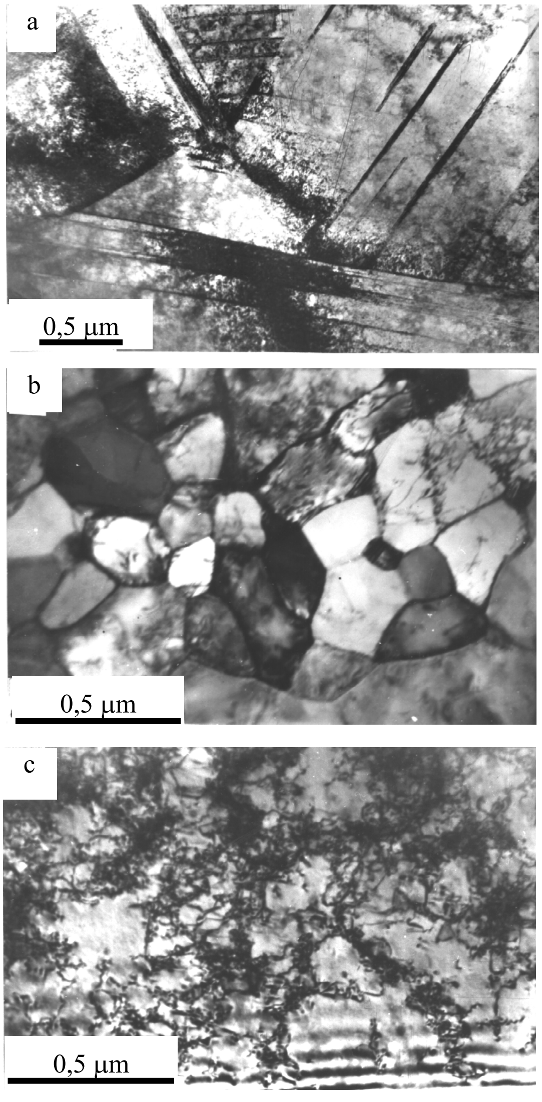

Fig. 4. TEM image of the Cr18Ni9 steel structure formed in a near-surface layer upon LHEB treatment, E_S (J/cm^2): a – 5, b – 9, c – 37.

and material volume where this process has made progress (Fig. 4,b). At $E_S \sim 37$ J/cm^2, the process of primary recrystallization is brought to completion. The formed structure (subgrains and recrystallized grains) contains a dislocation substructure with a high dislocation density that is indicative of the dynamic character of the process (Fig. 4,c).

4. Conclusion

It has been shown that high-rate quenching of steel surface layers from the liquid state leads to dynamic rearrangement of the defect substructure of the material The degree to which this process develops is governed by the value of the stacking fault energy γ_{SF}. In a material with a relatively high value of γ_{SF} (armco-iron, 140–473 mJ/m^2) a net-ball dislocation substructure is observed and in doped steel (γ_{SF} = 15–40 mJ/m^2) a dynamic recrystallization substructure is found.

The mechanism of the formation of dynamic recrystallization centers in b.c.c. and f.c.c. steels has been investigated. It has been ascertained that in steels at a relatively low value of γ_{SF} (15–20 mJ/m^2) dynamic recrystallization centers are formed by the mechanism of pair coalescence of subgrains, no matter what the crystalline lattice type is. The increase in γ_{SF} to 35–40 mJ/m^2 causes a changeover to the mechanism of multiple subgrain coalescence. At much higher values of γ_{SF}, dynamic recrystallization evolves by migration of local regions of large-angle grain boundaries.

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