Materials Science and Engineering A 528 (2011) 3829–3832

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Comparison between recrystallization mechanisms in copper and Ti-IF steel after a low amount of deformation

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ARTICLE INFO

Article history:
Received 17 November 2010
Received in revised form 18 January 2011
Accepted 19 January 2011
Available online 26 January 2011

Keywords:
Stored energy
Recrystallization mechanisms
Ti-IF steel
Copper

ABSTRACT

A comparison is proposed between results published recently on recrystallization of bcc (body-centered cubic) alloys such as Ti-IF steel and on face-centered cubic (fcc) material such as copper. The stored energy during the deformation by both crystallographic structures and the evolution of the microstructure during recrystallization (recovery, coalescence, subgrain growth and grain growth. . .) are detailed. The similarity of mechanisms involved during the recrystallization is discussed.

1. Introduction

When deformation amount is sufficient, the cold rolled copper develops preferentially the cubic component $\{1\,0\,0\}\langle 0\,0\,1\rangle$ during annealing [1] and the deformed Ti-IF steel develops the γ fiber $\{1\,1\,1\}\langle uvw\rangle$ after recrystallization annealing [2–5].

Several works have been devoted to study the texture development during recrystallization, using the stored energy according to crystallographic orientation. In fact, it is now well known that the stored energy is the main driving force for recrystallization [6,7].

Concerning the fcc materials, Etter et al. [8] have showed, using stored energy measurements by neutron diffraction, that the cubic component is characterized by a low stored energy comparatively to other components. These results concerning the Fe–50%Ni steel were confirmed by Jakani et al. [9] for the cold rolled copper. Thus, all fcc materials characterized by low or moderate stored energy develop preferentially component with weak stored energy during annealing.

On the contrary, Ti-IF steel develops the $\{1\,1\,1\}\langle uvw\rangle$ fiber (characterized by high stored energy) during primary recrystallization annealing. In fact, Lesnes [4], Oyarzábal et al. [10] and Borbely et al. [6,11], have shown that the γ fiber ($\{1\,1\,1\}\langle uvw\rangle$) stores more energy than the α fiber ($\{hkl\}\langle 1\,1\,0\rangle$) during deformation. However, in the cited works, the γ fiber is characterized by the $\{1\,1\,1\}\langle 1\,1\,2\rangle$ component only. But if components belonging to the γ fiber are considered separately, it appears that components of weak stored energy inside the fiber develop preferentially during recrystallization as for copper [12].

All these observations show that components with low stored energy are developed during recrystallization annealing at the expense of components with high stored energy. Then, it appears a clear similarity in the recrystallization behaviour for those materials pushing to continue the comparison between the deformed microstructures and their evolution during annealing.

With the intention of making comparison between bcc and fcc materials, results of two doctoral thesis at the University of Paris-Sud are compared. The first is devoted to the recrystallization mechanisms of the cold drawn copper (commercial electrolytic tough pitch, ETP) [13] and the second concerns the Ti-IF steel deformed by cold rolling (40%) or by tensile strain (35%) [14]. Several papers were published during and after both works [9,12,15,16] but new results are presented in the present discussion.

2. Deformed states

After cold drawing (40%), texture of copper is composed of two fibers $\langle 1\,0\,0\rangle$//ND (ND: normal direction parallel to the extrusion direction) and $\langle 1\,1\,1\rangle$/ND, the latter is dominating. On the contrary, the fiber $\langle 1\,0\,0\rangle$//ND is predominant after recrystallization. Benyoucef et al. [17] have shown that the $\langle 1\,0\,0\rangle$//ND fiber has a well formed cellular microstructure (Fig. 1a) (microstructures are

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doi:10.1016/j.msea.2011.01.075

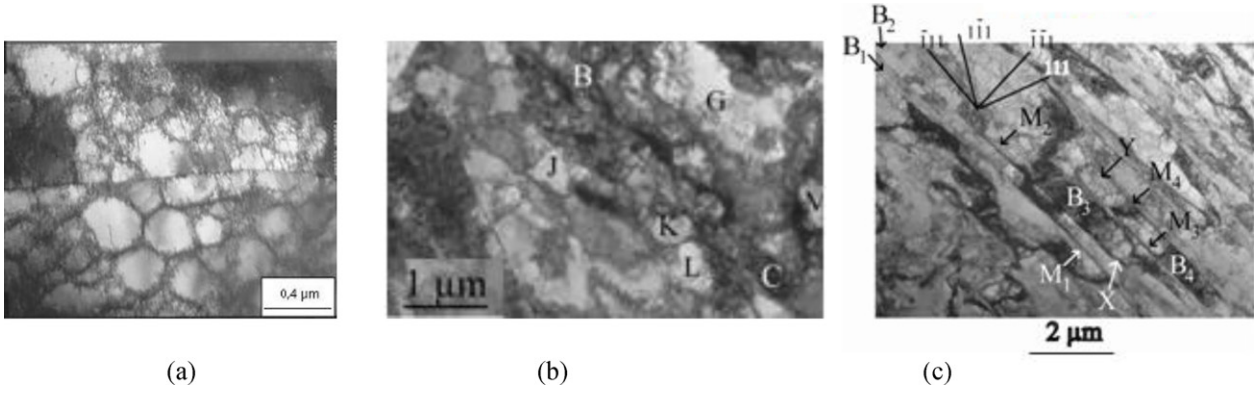

Fig. 1. Substructure of the cold drawing copper (40%): (a) ⟨0 0 1⟩//ND fiber, (b) ⟨1 1 1⟩//ND fiber, and (c) ⟨1 1 0⟩//DN.

Table 1
Stored energy values (J/mol) after cold drawing (40%) in copper.

Texture components	⟨0 0 1⟩//ND	⟨1 1 1⟩//ND
Stored energy (J/mol)	1.8	3.6

observed on transverse section of specimen). Cells structure has been related to a dynamic recovery mechanism during deformation by many authors [18,19]. The substructure of the ⟨1 1 1⟩//ND grains has a dense distribution of dislocations. Some cells are however observed in this orientation, but they remain poorly developed and are surrounded by diffuse walls Fig. 1b. The texture is also composed of ⟨1 1 0⟩//ND grains in low proportion. These grains are characterized by a lamellar band substructure (Fig. 1c). All these observations are in agreement with stored energy estimation. Indeed, the neutron diffraction measurement [13] has proved that the ⟨1 0 0⟩//ND is characterized by a low stored energy (Table 1). The ⟨1 1 0⟩//ND stored energy is not estimated because of their low proportion in the deformed state.

Samet-Meziou [14] shows similar results in the case of Ti-IF steel after 40% cold rolling (Fig. 2). In the deformed state, the texture is composed of the γ fiber with a strong {1 1 1}⟨1 1 2⟩ component but the {1 1 1}⟨1 1 0⟩ orientation develops during annealing. The component {1 0 0}⟨0 1 1⟩ of the α fiber is also present although with very low fraction. For the {1 1 1}⟨1 1 0⟩ orientation which belongs to both α and γ fibers, the substructure is characterized by cellular substructure (Fig. 2a). The {1 0 0}⟨0 1 1⟩ component belonging to the α fiber, is characterized by equiaxed dislocation cells of diffuse walls. On the contrary, the majority of the γ fiber components present a lamellar substructure. For example, the {1 1 1}⟨1 1 2⟩ component is characterized by lamellar bands separated by dense straight dislocations walls almost perpendicular to the rolling direction (RD) (Fig. 2b). These results are in agreement with the stored energy estimation using the neutron diffraction (global approach) or the EBSD/TEM coupled with Dillamore model (local approach) [16]. Table 2 shows that the stored energy increases from {0 0 1}⟨1 1 0⟩ to {1 1 1}⟨1 1 2⟩.

Then, according to the deformed substructure results, it is very important to distinguish between different components of the γ fiber, in terms of substructure morphology and stored energy, to study the recrystallization mechanisms.

Table 2
Stored energy values (J/mol) of a cold rolled (40%) Ti-IF steel.

Texture component	{0 0 1}⟨1 1 0⟩	{1 1 1}⟨1 1 0⟩	{1 1 1}⟨1 1 2⟩
Stored energy (J/mol)	3.0	6.0	8.0

3. Recovered states

Recovery stage is achieved at short annealing time. Thus, first nuclei are created and develop at the expense of matrix after attaining a critical size [20]. The nucleus formation is favored by cellular substructure. Indeed, adjacent cells coalesce into nucleus by dislocation annihilation or rearrangement. Fig. 3 displays that cell coalescence is developed in the cold drawn copper as well as in cold rolled Ti-IF steel. Cell growth can also occur but has been less observed than cell coalescence. When nucleus develops and achieves a critical size, it grows at the expense of its first neighbors whose sizes are smaller. Let us note that misorientation gradient between cells can favor the nucleus growth [21,22].

Obviously, when cell walls are diffuse it takes a longer time for the substructure to recover and form a real cellular structure able to evolve by coalescence and/or growth. This is verified in cold drawn copper, in which ⟨0 0 1⟩//ND nucleus (cellular structure) grow easily compared to ⟨1 1 1⟩//ND nucleus (diffuse dislocation walls) and this gives an advantage for the ⟨0 0 1⟩//ND orientation in the final texture of recrystallization.

4. Recrystallized states

Nuclei located in the grain boundaries or in the vicinity of the grain boundaries, having reached a critical size (depending on the crystallographic orientation [16]), can grow at the expense of neighboring grain considering two parameters: the strong misorientation and the strong difference of the stored energy between nuclei and the matrix. The observed mechanism is the "bulging" or the Strain Induced Grain Boundary Migration (SIBM) [20]. So, in the case of cold drawn copper (40%), Fig. 4a shows a ⟨1 0 0⟩//DN nucleus developing by bulging. This SIBM mechanism occurs mainly in cellular substructures and develops to the detriment of lamellar substructure (Fig. 4a). Similar examples are also observed in cold rolled Ti-IF steel (Fig. 4b). In these microstructure, the {1 1 1}⟨1 1 0⟩ nucleus at the grain boundary develops by bulging at the expense of the {1 0 0}⟨1 1 0⟩ characterized by diffuse cells.

During annealing, lamellar structures are also going to evolve. Indeed, generalized recovery has been widely observed in the lamellar structures. In a first step, a lamellar band begins to micro-bulge and invades the neighboring band, so enabling the development of a recrystallized zone inside a grain (Fig. 5).

Because of very low mobility of straight sub-boundaries (with infinite radius), the lamellar sub-structure must slightly modify its morphology to be able to consume the neighboring bands [23]. This is the reason why nucleus formation, with critical size required for recrystallization, is very slow in lamellar structures compared to cellular ones. This explains also why, in the