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Studies on the evolution of annealing twins during recrystallization and grain growth in highly rolled pure nickel

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ABSTRACT

An investigation on the evolution of annealing twins in a cold rolled (95% thickness reduction) high-purity nickel was reported as a function of annealing temperature. Electron backscattered diffraction (EBSD) analysis revealed that both the grain boundaries migration and the formation of cube texture promoted the proportion of Σ3 boundaries during recrystallization. Moreover, further increasing annealing temperatures showed that the frequency of annealing twins markedly decreases due to encountering of the growing cube-oriented grains one another during grain growth to form new LAGBs.

1. Introduction

Annealing twins were first observed by Carpenter and Tamura [1], in a variety of deformed and annealed face centered cubic (f.c.c.) metals and alloys. Subsequently, Gertsman et al. [2] revealed that annealing twins can strongly influence the microstructure and texture of deformed and annealed alloys. Then, studies on the evolution of annealing twins have become essential for improving materials performance.

Several models have been proposed to explain the mechanism of the formation of annealing twin. Gleiter [3] suggested that the transfer of atoms from one grain to another during grain boundary movement occurs in a faulty manner in terms of atomic packing. This model is plausible but some morphologies of twins are difficult to be rationalized by using this model. According to Meyers and Murr [4], twins "pop out" from grain boundary ledges, but the characteristics of the grain boundary area from which pop-outs occur were not explained. Combining the above suggestions, Mahajan et al. [5] argued that Shockley partial loops nucleate on consecutive {111} planes by growth accidents occurring on migrating {111} steps associated with a moving grain boundary. If the velocity of the boundary is high, the twin density will be higher. This model is an effective mechanism for rationalize the formation of annealing twins, namely so-called 'growth accident' mechanism. However, the presence of strong texture is not mentioned in these models.

Researches on grain boundary engineering [6] have shown that a high fraction of annealing twins boundaries (Σ3) contribute to an improved material property [7–11]. But in the study of superconducting substrates, the annealing twins in the substrates have shown their adverse effects [12]. Cube-textured nickel, because of its comparatively high melting point and resistance to oxidation, is widely used as substrates for coated conductors, i.e. the second generation of high-temperature superconducting tapes. The rolling assisted biaxially textured substrates (RABiTS™) method demonstrated the tremendous possibility of strongly cube textured nickel as substrates for coated high temperature superconductor (HTS) applications [13–15]. Since grain boundaries with misorientations greater than 10° dramatically decrease the critical current density of the epitaxially grown YBCO layer [16] and the large frequency of twin boundaries improve the high angle grain boundaries (HAGBs) fractions, the fraction of such boundaries in the substrate must be as low as possible. Therefore, a sharp cube texture ({001} ⟨100⟩) has to be generated in the Ni-based substrate, and subsequently be transferred via a certain ceramic buffer layer to the superconducting layer. However, annealing twins will form during the recrystallization of the substrates, which is unfavorable for the superconducting properties. The twins presented in the substrates will be reproduced in the LZO buffer layer ($La_2Zr_2O_7$ oxide), and amorphous crystallites in high concentration on twin zone can also be transferred to the buffer from the substrate [7,17], i.e., the LZO buffer layer reproduces exactly the grain morphology of the substrate obtained in the RABiTS process. Hence the annealing twins are considered as defects expected to inhibit epitaxial growth, reducing the number of twins is an obvious conclusion by the substrates manufacturers who have attempted to optimize composition and annealing procedure of their rolled substrate in order to maximize the

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cube texture content. However, very few publications have verified this fact [12], which is one of the reasons for the interest that it has generated.

Previous studies on Ni-based alloys by RABiTS [18–20] mainly concentrated on microstructures and textures produced by a variety of thermo-mechanical treatments. Little efforts were taken to research the relationship between the formation as well as evolution process of annealing twins and strong texture and the changes occurring during recrystallization. The availability of recent techniques such as Electron Back-Scattered Diffraction (EBSD) makes it possible to investigate and understand the potential sources for the behaviors found in earlier works [21]. It has been proclaimed that the recrystallization cube texture is strongly related to the rolling texture [22]. Texture transition in the rolling texture has been confirmed with increasing alloying content in many Ni alloys [23,24], which is usually attributed to the lowering of the stacking fault energy (SFE), which in turn affects the formation of twinning and cube texture [25]. In order to remove the influences of alloying and pay more attention on the annealing twins, pure nickel is chosen as the research object in this article. Since annealing twin is significant for texture control of nickel-based superconducting substrates during recrystallization, studies on its evolution and the dynamics is of great importance. Not only does it play an important role in intensifying the theory of metal-based substrates but also it acts as guidance to the industrial production.

2. Materials and methods

2.1. Specimen preparation and testing

An ingot of high purity (99.999%) nickel was cold-rolled to 50% to form a plate of 10 mm in thickness, then annealing at 1000 °C for 30 min in tube furnace was applied to randomize texture in the initial condition. Unidirectional cold rolling using 5% reduction per pass was applied to the homogenized annealing material, resulting in a total thickness reduction of 95%. Several samples were then annealed for 1 h at different temperatures in a tube furnace with protective atmosphere of argon and 4% hydrogen. For these isochronally annealed samples, hardness was measured using a load of 200 g with a dwell time of 15 s. In order to ensure the statistical significance, 15 indentations for each sample in this series were assessed to obtain an average value of hardness.

2.2. EBSD analysis

Some regions of the specimen after annealing were investigated using EBSD technique. The microstructures and textures of the annealing samples were characterized by a Channel 5 EBSD detector attached to a FEI Nova 400 Nano scanning electron microscope (SEM). To investigate the orientations, a step size of approximately one-tenth of the grain size in the rolling plane containing the rolling direction and transverse direction (RD-TD) was used. An area of $400 \times 400\ \mu m^2$ was characterized on each sample. At least three maps were taken for each condition and the horizontal direction is RD in all EBSD orientations maps. Because of the limited angular resolution of the EBSD technique [26], a critical misorientation angle of 2° was applied to observe boundaries in the orientation maps, where low angle grain boundaries (LAGBs) and high angle grain boundaries (HAGBs) were defined as boundaries between grains with misorientations 2–15° and > 15°, respectively. The average grain size was obtained with twins not included as separate grains. In the present experiment, the annealing twins in the FCC alloys included coherence and incoherence twin. The red lines marking the annealing twin boundaries were defined by applying a maximum deviation allowable by the Brandom criterion $\Delta\theta_{max} = 15°\Sigma^{-1/2}$, namely 8.66° [27]. The volume fractions of different texture components were determined within a spread of 15° around their respective ideal locations in Euler space.

3. Results and analysis

3.1. Microstructure evolution

Fig. 1a reveals the microstructure of the heavily rolled sample characterized by slightly discontinuous distribution. Fig. 1b shows typical rolling texture in the as-deformed condition, where the

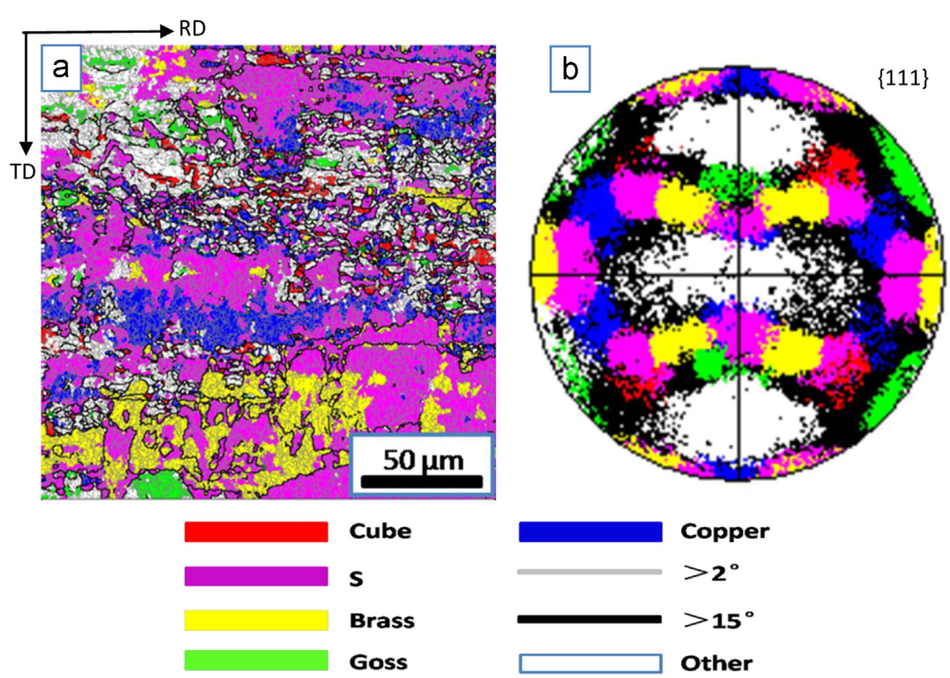

Fig. 1. (a) EBSD orientation maps of cold-rolled specimens (with a 95% reduction in thickness) and (b) {111} pole figure showing the crystallographic texture in the as-rolled condition. In this EBSD map, grains in red have the orientation of cube texture ({001}⟨100⟩), grains in purple are S orientation ({123}⟨634⟩), grains in green are goss texture ({011}⟨100⟩), grains in yellow are brass texture ({011}⟨211⟩), grains in blue are copper texture ({112}⟨111⟩), grains in white have random orientation, thin black lines refer to low angle grain boundaries, and thick black lines refer to high angle grain boundaries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)