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Memory effects of transformation textures in steel and its prediction by the double Kurdjumov–Sachs relation

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Abstract

The phenomenon that the transformation texture near the initial texture reproduces after the phase transformation cycle such as ferrite (α, body-centered cubic) → austenite (γ, face-centered cubic) → α is called a texture memory. In this study, the texture change in a 0.1% C–1% Mn hot-rolled steel sheet during the α → γ → α transformation cycle was studied via neutron diffraction and the transformation texture prediction based on a variant selection rule that we call the double Kurdjumov–Sachs (K–S) relation. The texture change observed by neutron diffraction, which clearly showed the texture memory, could be quantitatively reproduced by the proposed variant selection rule adopted into the calculation method based on the spherical harmonics expansion of orientation distribution functions. Therefore, it is most likely that the texture memory in steel is caused by the preferential selection of those K–S variants that reduce the interfacial energy between a precipitate and two adjoining parent phase grains at the same time, which we call the double K–S relation.

Keywords: Low carbon steel; Texture memory effect; Phase transformation; Orientation relationship; Neutron diffraction

1. Introduction

Crystallographic texture of materials often remains rather unchanged after the phase transformation cycle from one phase to another and back to the initial phase by temperature variation, a phenomenon that is referred to as texture memory [1,2]. Such a phenomenon has been reported for various materials such as iron and steel [2–10], titanium [11], zirconium [12,13] and even minerals like quartz [1,14], in which the crystallographic orientation relationship is held between parent and product phases. This implies that from several to dozens of crystallographically equivalent orientations, which are allowed under the orientation relationship, only specific ones occur after the phase transformation, a corresponding phenomenon called variant selection. Without such variant selection, one would expect the texture to blur during such phase transformation cycles. However, it has been confirmed microscopically that the martensite (α′) in steel can transform into γ, recovering the original orientation of the prior γ during the α′ → γ reverse transformation [3]. It is also known in diffusive transformation that the texture is often well maintained through phase transformation cycles, such as α → γ → α in steel [4–10] and hexagonal close-packed → body-centered cubic → hexagonal-close packed in Ti [11] and Zr [12,13], whereas grain structures greatly alter during those cycles. Nevertheless, the mechanism causing this memory effect is still unclear. Although the influence of the variant selection concerning the orientation relationship has been inferred as this mechanism, the selection rule has not been clarified enough. The purpose of this study is

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to clarify the mechanism of the texture memory during the $\alpha \rightarrow \gamma \rightarrow \alpha$ transformation cycle in steel by combining in situ high temperature bulk texture measurements by neutron diffraction and the texture prediction based on the proposed variant selection rule [15–18] and spherical harmonic expansion (SHE) of orientation distribution functions (ODF) [19].

The texture memory during the $\alpha \rightarrow \gamma \rightarrow \alpha$ transformation was first studied via ODF analysis in detail by Inagaki and Kodama [4,5] for hot-rolled 0.08% C–2.2% Mn–Ni–Mo–Nb steel. It was reported that the texture with strong $\{311\}\langle 011\rangle$ and $\{332\}\langle 113\rangle$ orientation components was retained after heating to 910 °C and cooling to the ambient temperature either by water quench or air cool with an unexpectedly small decrease in intensity. This phenomenon clearly indicated that the variants permitted by the orientation relationship between α and γ occurred unequally to stabilize the texture through the two phase transformations. Note that the orientation relation between α and γ is known to be close to the Kurdjumov–Sachs (K–S) relation [20], $\{111\}_\gamma//\{110\}_\alpha$ and $\langle 110\rangle_\gamma//\langle 111\rangle_\alpha$, or the Nishiyama–Wasserman (N–W) relation [21,22], $\{111\}_\gamma//\{110\}_\alpha$ and $\langle 110\rangle_\gamma//\langle 100\rangle_\alpha$, and the K–S and N–W relations have as many as 24 and 12 crystallographic variants, respectively. Yoshinaga and co-workers [6,7] later reported similar memory effects for cold-rolled steel as well, in which almost perfect memory effect was observed in Mn-added interstitial-free (IF) steel. The transformation texture and the texture memory in steel have been reviewed by Ray and Jonas [23] and Hutchinson et al. [2], respectively.

Several possible mechanisms have been proposed such as the ones related to the transformation strain [6], the precipitates to stabilize α at an elevated temperature [7] and the special boundaries formed upon heating [2,8]. They all involve some microstructural sites by which the variant that has acted on the first transformation is actually "memorized" and the same path becomes more available than the others for the backward transformation on cooling. Therefore, according to these mechanisms, the variant selection for the texture memory should occur only on cooling, although the variant selection that can act on both processes should not be excluded from the possible mechanisms, as has been inferred in the study of the texture memory in Ti [11] and Zr [13]. In fact, Brückner and Gottstein [10] and Wenk and co-workers [9] have recently conducted the high temperature diffraction measurements for textures in cold-rolled steel sheets via X-ray and pulsed neutrons respectively, and they have reported that variant selection has intensely acted not only on cooling but also on heating. This fact indicates that the texture memory might not be caused by the memory of the variant path during the first transformation but rather be caused by the two more-or-less "independent" variant selections in two successive phase transformations.

On the variant selection for the $\gamma \leftrightarrow \alpha$ transformation in steel, the present authors have proposed a selection rule in which the variants that hold the K–S relation or the near K–S relation with two adjoining parent phase grains preferentially nucleate (see Fig. 1) [15–18]; we call this selection rule the double K–S relation hereafter. For the double K–S relation to be able to be satisfied at the majority of ordinary boundaries, the relation on one side of the grain boundary is allowed to deviate up to ~10° from the exact K–S relation. By this selection rule, the texture of the hot-rolled sheet steel has been quantitatively reproduced by the calculation from the texture of retained γ in the same steel. Furthermore, quite recently, during the preparation of this paper, Lischewski and Gottstein [24] have reported by an in situ observation of orientation relation via electron back scattering diffraction (EBSD) that the double K–S relation is indeed held between α and γ in steel as hypothesized in the literature [15–18], and they could reproduce the texture memory by this relation. However, as the EBSD measurement always does, their texture measurement has suffered from insufficient statistics due to a small number of observed grains, and it might have been influenced by the presence of surfaces in whose vicinity the product phase nucleated and grew. Therefore, this study aimed to thoroughly investigate the phenomenon of texture memory in steel by neutron diffraction and the analysis based on the double K–S relation.

2. Experiment procedures

The hot-rolled steel sheet with the chemical composition listed in Table 1 was prepared using a hot-rolling simulator [16]. The hot-rolling was finished at about 820 °C, which was just above the calculated paraequilibrium Ae_3 for the steel (818 °C). Immediately after hot-rolling, the steel sheet

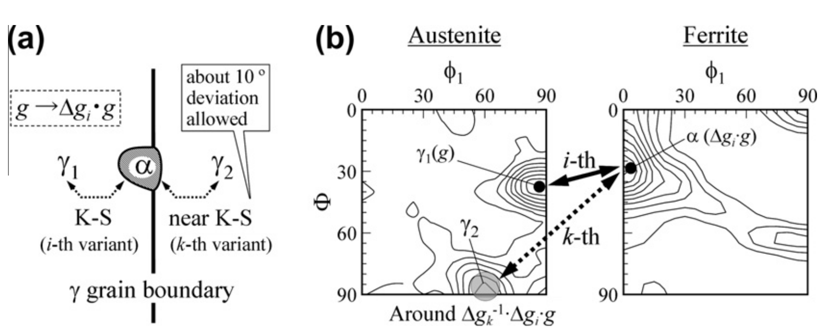

Fig. 1. Schematic representations of (a) the double K–S relation and (b) its influence on variant selection.