Scripta Materialia xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Scripta Materialia

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

Analysis of recrystallization behavior of hot-deformed austenite reconstructed from electron backscattering diffraction orientation maps of lath martensite

Manabu Kubota [a,*], Kohsaku Ushioda [b], Goro Miyamoto [c], Tadashi Furuhara [c]

[a] Muroran R&D Lab., Technical Research & Development Bureau, Nippon Steel & Sumitomo Metal Corp., 12 Nakamachi Muroran, Hokkaido 050-8550, Japan
[b] Technical Research & Development Bureau, Nippon Steel & Sumitomo Corp., 20-1 Shintomi, Futtsu, Chiba 293-8511, Japan
[c] Institute for Materials Research, Tohoku University, 2-1-1 Katahira Aoba-ku, Sendai 980-8577, Japan

ARTICLE INFO

Article history:
Received 28 June 2015
Received in revised form 4 September 2015
Accepted 4 September 2015
Available online xxxx

Keywords:
Steels
Recrystallization
Austenite
Martensite
Electron backscattering diffraction

ABSTRACT

The recrystallization behavior of hot-deformed austenite of a 0.55% C steel at 800 °C was investigated by a method of reconstructing the parent austenite orientation map from an electron backscattering diffraction orientation map of lath martensite. Recrystallized austenite grains were clearly distinguished from un-recrystallized austenite grains. Very good correlation was confirmed between the static recrystallization behavior investigated mechanically by double-hit compression tests and the change in austenite microstructure evaluated by the reconstruction method. The recrystallization behavior of hot-deformed 0.55% C steel at 800 °C is directly revealed and it was observed that by addition of 0.1% V the recrystallization was significantly retarded.

Thermo-mechanical processing is a metallurgical process that integrates plastic deformation and heat treatment. TMCP (thermo-mechanical control process) and ausforming are major examples of thermo-mechanical processes. Ausforming generally utilizes work-hardened austenite prior to the martensitic or bainitic transformation. Therefore, it is important to control the state of work-hardened austenite to obtain the intended microstructures and properties when the ausforming process is applied. The microstructure of work-hardened austenite evolves through recovery and recrystallization in austenite as well as phase transformation from austenite to ferrite depending on the deformation-temperature and strain, and cooling process after deformation. However, it is difficult to directly reveal how the recrystallization process of austenite progresses, because it is difficult to observe the high temperature austenite phase at room temperature. Consequently, how the recrystallization of austenite progresses is investigated indirectly by using austenite-stabilized model alloys [1–3], or by double hit test [4–7], or by observing the microstructure of martensite, which is obtained by quenching steels from the austenite state to conserve the state of the austenite [8,9]. Since direct information on the actual state of work-hardened austenite is lacking, it is extremely difficult to investigate the changes in microstructure and crystal orientation through recrystallization in detail.

On the other hand, since there is a particular orientation relationship (OR) between martensite and the parent austenite, it is possible to reconstruct the parent austenite structure based on OR variant analysis. Some methods of reconstructing the austenite structure based on orientation maps of martensite or bainite measured by EBSD (electron backscattering diffraction) analysis have been proposed [10–12]. Recently, Miyamoto et al. [13] have developed a new program to reconstruct austenite orientation maps utilizing martensite orientation maps. In this new program, the local austenite orientation is determined based on numerical fitting for all measured points in a small region to determine the average austenite orientation of the region. The deformed austenite structure can thereby be reconstructed from ausformed martensite. The new program was applied to ausformed martensite, and the deformed austenite structure was successfully reconstructed and visualized [14,15]. However, the application has been limited to a specific case, and the state of austenite has not been discussed in detail in terms of the nucleation and growth of recrystallization, and texture development with recrystallization.

In the present study, the recrystallization behavior and texture development of work-hardened austenite of 0.55% C (mass%) steels with and without 0.1% V addition is investigated by double-hit compression tests verified by the method proposed by Miyamoto et al. [13].

There are few systematic studies that have investigated the recrystallization behavior of work-hardened austenite of high carbon steels. Therefore, SAE9254 containing 0.55% C, which is widely used for automotive springs, and a steel in which 0.1% V (mass%) was

* Corresponding author at: Railway Automotive & Machinery Parts Research Lab., Steel Research Laboratories, Technical Research & Development Bureau, Nippon Steel & Sumitomo Metal Corp., 1-8 Fuso-cho, Amagasaki, Hyogo 660-0891, Japan.
E-mail address: kubota.7ts.manabu@jp.nssmc.com (M. Kubota).

http://dx.doi.org/10.1016/j.scriptamat.2015.09.020
1359-6462/

added to SAE9254 were investigated as test steels. The chemical compositions are listed in Table 1. The 16 kg ingots were prepared by vacuum induction melting. They were hot-forged to round bars of 30 mm in diameter. The round bars were then homogenized at 1300 °C for 2 h and normalized at 925 °C for 0.5 h. Subsequently, they were austenitized at 1250 °C for 0.5 h, and then cooled to 1050 °C followed by compressing the material from 30 mm to 13 mm in height and cooling to room temperature. Consequently, fine ferrite/pearlite microstructures were obtained. Cylindrical specimens for a hot-deformation simulator (THERMECMATER-Z, Fuji Electronic Industrial Co., Ltd.), 8 mm in diameter and 12 mm in height, were cut from the hot-forged round bars.

Double-hit compression tests by one-dimensional compression were performed to quantify the static recrystallization behavior of the work-hardened austenite. Static recrystallization progress can be evaluated indirectly by analyzing the change in true stress–true strain curve of the first- and the second-hit deformation. The softening ratio (X) in the double-hit compression test as an index of static recrystallization progression during the period between the first and the second hit can be described as [6,7]:

$$X = \frac{\sigma_\varepsilon - \sigma_{y2}}{\sigma_\varepsilon - \sigma_{y1}} \quad (1)$$

where σ_{y1}, σ_{y2}, and σ_ε are the yield stress of the first hit, the yield stress of the second hit, and the maximum flow stress of the first hit, respectively. Both softening due to static recovery and softening due to static recrystallization are included in X. Fig. 1 shows a schematic illustration of the condition of the double-hit compression test. Specimens were heated at 1200 °C for 10 s. The applied strain at the first and the second hit was 0.3 and the strain rate was 2.5 s^{-1}. The yield stress was determined by the 2% offset method. The deformation temperature and holding temperature between the first hit and the second hit were kept at 800 °C.

Specimens for EBSD analysis were prepared by the following processes. Specimens are quenched by helium gas (cooling rate: 60 °C/s) just before the first hit, just after the first hit, or after holding for various periods of time at 800 °C. Information on the parent austenite structures before hot-deformation as well as after hot-deformation with various holding times were preserved as daughter lath martensite structures. Then, the specimens were cut along the direction which is parallel to the compression axis. The microstructures at the center of the specimens were observed. It is estimated by FEM (finite element method) analysis that the center of the section is a region that is subjected to true strain of 0.5 by the first hit. The orientation maps of lath martensite were measured by EBSD with a step size of 0.5 μm. The reconstruction program developed by Miyamoto et al. [13] was applied to reconstruct the parent austenite. In order to analyze the local austenite orientation and create an austenite orientation map, the area for analysis was automatically cropped by the program, and the local orientation of the parent austenite was calculated repeatedly. The mesh size for the reconstruction calculation was 5 × 5 μm^2 and the step size was 2.5 μm. The OR between martensite and austenite in reconstruction calculation was assumed to be the same as that in low carbon martensite [13]. Some orientation analysis such as the inverse pole figure and the grain orientation spread (GOS) map were applied to the reconstructed orientation map using TSL OIM-Analysis 7.

Fig. 2 shows the effect of 0.1% V addition on the static recrystallization behavior, which was investigated by double-hit compression tests. Softening of work-hardened austenite during holding at 800 °C

Table 1
Chemical conditions of the steels used (mass%).

	C	Si	Mn	P	S	Cr	Al	V	N
SAE9254	0.55	1.49	0.68	0.015	0.010	0.72	0.002	–	0.0050
0.1% V	0.56	1.50	0.68	0.016	0.010	0.68	0.003	0.10	0.0048

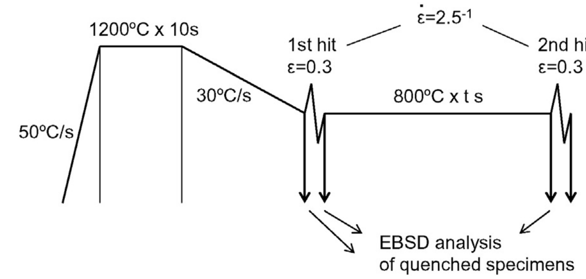

Fig. 1. Conditions of heating, deformation, and holding of specimens for the double-hit compression test and EBSD analysis.

subsequent to deformation at 800 °C is remarkably retarded by the addition of 0.1% V. Since the softening ratio is less than 20% even after holding for 10^4 s, it is considered that recovery and recrystallization are strongly retarded by the addition of 0.1% V.

The upper figures in Fig. 3 show the orientation maps of the lath martensite structure measured in the plane containing the compression direction (C.D.) measured by EBSD. Despite the fact that the accuracy in orientation maps is not sufficiently good, the area fraction of small equiaxed grains seems to increase with holding time in steel without V addition (Fig. 3(a)); however, it is likely to take a longer time until small equiaxed grains appear by the addition of 0.1% V (Fig. 3(b)). It was separately confirmed that these small equiaxed grains have a lath martensite structure by optical microscopy and orientation mapping by EBSD. These small equiaxed grains are assumed to be martensite, the parents of which are recrystallized austenite. Since lath martensite is generally composed of hierarchical complicated structures such as laths, blocks, packets, and prior-austenite, it is indeed difficult to clearly distinguish recrystallized austenite grains from un-recrystallized austenite grains.

The middle figures in Fig. 3 show the orientation maps for the C.D. in reconstructed austenite. It is very clear that the microstructure before deformation consists of equiaxed austenite grains having annealing twins here and there with a grain diameter of about 150 μm. Austenite grains are revealed to be elongated just after deformation, resulting in a very heterogeneous deformation structure. After holding the specimen at 800 °C, small equiaxed austenite grains, presumably recrystallized grains, commence to nucleate along the elongated prior-austenite grain boundaries as well as inside the elongated austenite grains, such as on annealing twins and deformation bands. It should be noted that orientations of small recrystallized austenite grains are reconstructed based on a number of martensite variants although fine variant structure in martensite is not clearly seen due to poor resolution of the ferrite orientation maps at this magnification. The elongated deformed austenite grains have significant misorientation within the grains. On the other hand, the small equiaxed austenite grains scarcely have misorientation. Furthermore, it is highly evident that

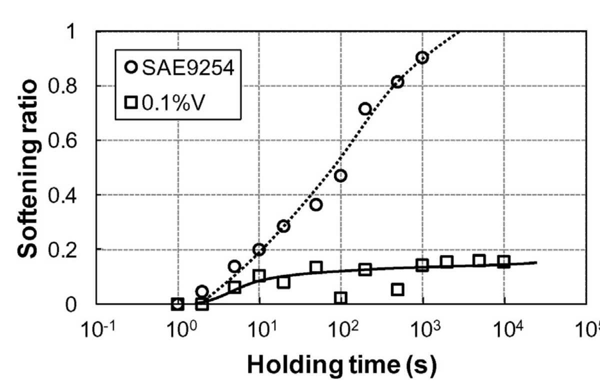

Fig. 2. Comparison of static softening behavior between SAE9254 and 0.1% V.

Please cite this article as: M. Kubota, et al., Analysis of recrystallization behavior of hot-deformed austenite reconstructed from electron backscattering diffraction orientatio..., Scripta Materialia (2015), http://dx.doi.org/10.1016/j.scriptamat.2015.09.020