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Ultrafine Grained Austenite in a Low Carbon Vanadium Microalloyed Steel

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Abstract: Ultrafine austenite grains with average size of 2 μm were successfully obtained by combining thermo-mechanical control process followed by reheating in a vanadium microalloyed steel. The mixed microstructure transformed from pancaked austenite formed during controlled rolling has a higher density of high angle boundaries, compared to that transformed from equiaxial austenite. It contributes to increasing nucleation density of austenite grain during the reheating process. A certain volume fraction of undissolved nano-sized (Ti, V)C particles, which are formed during the controlled rolling process and/or the reheating process, effectively inhibit austenite grain growth and consequently refine austenite grain size significantly. The critical grain size of austenite calculated by Gladman model agrees well with the experimental result.

Key words: TMCP; grain refining; grain boundary; nucleation; carbide

Grain refinement is an effective way to improve both strength and toughness. Since the grain size of austenite decomposition products decreases with decreasing austenite grain size, many efforts have been made to refine austenite grains. In the Thermo Mechanical Controlled Processes (TMCP), recrystallization and non-recrystallization rolling are used to refine austenite grain, of which the minimum size or thickness is 10—20 μm in C-Mn steels and 5—10 μm in steels microalloyed with Ti and Nb[1-2]. Controlled austenitization is another effective way to obtain ultrafine grained austenite in heat treatment steels, such as rapid cyclic transformation, reversion from tempered and cold rolled martensite. The former, which includes 2 — 4 cycles of rapid austenite-martensite transformation, was employed to obtain austenite grain of 1—10 μm[3-5]. The latter including tempering and further heavily cold rolling was attempted to refine austenite grain size to 1—5 μm[6-7].

As mentioned above, however, the controlled austenitization method requires rigorous conditions while austenite grain refinement in TMCP is limited to above 5 μm for the limitation of strain during non-recrystallization rolling. In the present work, ultrafine equiaxial austenite grain smaller than 5 μm was successfully obtained by TMCP and conventionally simple austenitization in a vanadium microalloyed steel. The mechanism of ultra-grain refinement of austenite was clarified.

1 Material and Methods

A low carbon low alloyed steel containing C 0.26%, Mn 1.1%, Si 0.5%, V 0.28%, Ti 0.02%, and N 0.002% (mass percent) and other additions was investigated. A 25 kg ingot was prepared by vacuum melting and casting. After forging, the plate with thickness of 11 mm (hereinafter denoted as specimen A) was obtained by hot rolling after soaking at 1453 K for 3.6 ks as shown in Fig. 1. The rough rolling above 1223 K was carried out in austenite recrystallization region to refine the equiaxial austenite. The finishing rolling was applied in the non-recrystallized region below 1123 K to acquire pancaked austenite, followed by accelerated

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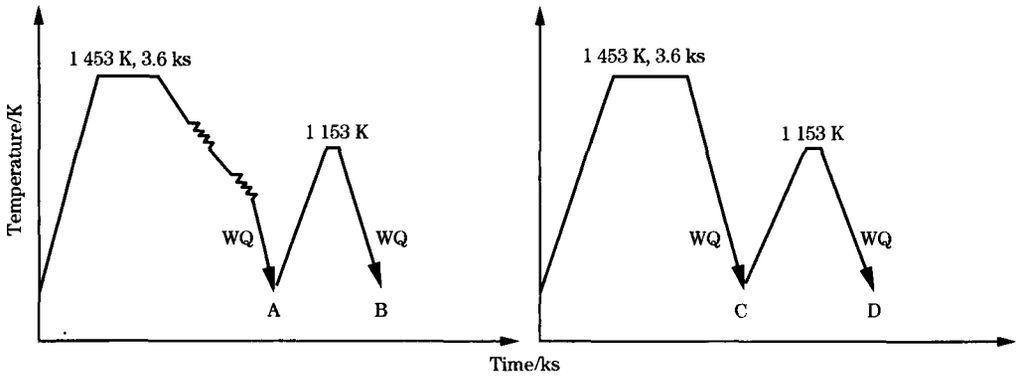

WQ—Water quenching.

Fig. 1 Schematic diagram of rolling process and thermal-simulation experiment

cooling to ambient temperature. The specimen of 20 mm×15 mm×11 mm cut from the rolled plate was continuously reheated to 1153 K at the heating rate of 5 K/s and further quenched by water. This specimen was denoted as specimen B hereinafter. Specimen C was obtained by direct quenching after soaking at 1453 K for 3.6 ks without hot rolling and specimen D was obtained by reheating specimen C to 1153 K with the same heating rate and further quenched by water. In order to clarify the effect of undissolved precipitation particles for austenite refinement, the specimens were reheated to 1153 K and 1223 K, and heated for 3.6 ks after rolling, respectively.

The microstructure was characterized by means of optical microscopy, electron backscattered diffraction and transmission electron microscopy with energy-dispersive spectroscopy. The specimens for microstructure observations were polished by conventional metallographic techniques. The prior austenite grain boundary was etched by a mixed solution of picric acid, hydrochloric acid and surface active agent. Grain size was determined by linear analysis using the following equation[7]:

$$d_\gamma = 1.128\bar{l} \quad (1)$$

where $\bar{l}$ is the average intercept length. For each specimen, more than 1000 grains were measured to ensure the accuracy. Electron backscattered diffraction measurement was operated on electropolished specimens with the step size of 0.1 μm and the accelerated voltage of 20 kV. Transmission electron microscopy observation was operated at 200 kV on carbon replicas, which was prepared through electrolytically extracting in the same etchant at the voltage of 2 V after etching in 4% nital and depositing a thin carbon film.

2 Results and Discussion

Fig. 2 shows the morphology and size of austenite grains in specimens A to D. As shown in Fig. 2 (a), the average thickness of pancaked austenite was (10.1±0.2) μm in specimen A. Ultrafine austenite grains were obtained in specimen B which was reheated to 1153 K after controlled rolling. As Fig. 2 (b) shows, the average size of austenite grain in specimen B was (2.0±0.2) μm. In contrast, the average grain size of austenite in specimen C without rolling was (102.3±3.0) μm [Fig. 2 (c)]. Compared with specimen B, austenite grain with the average size of (11.0±1.0) μm in specimen D was quite larger [Fig. 2 (d)].

According to the classical nucleation theory, nucleation rate increases with increasing the density of nucleation sites, which contains the face, edge and corner of grain boundary with large misorientation proposed by J W Cahn[8]. It is known that austenite could nucleate at prior austenite boundaries, ferrite grain boundaries, ferrite/martensite boundaries and various lath martensite boundaries, including lath, sub-block, block and packet boundaries. The reversed austenite nucleation sites depend on the reheating temperature and the heating rate[9-13]. The reversed austenite tends to nucleate at lath boundaries in martensitic and bainitic steels during heat treatment in two-phase region under a low heating rate[9-13]. On the contrary, the austenite tends to be formed at the high angle boundaries such as prior austenite grain boundaries when the heating rate was increased or the heat treatment was carried out at a high temperature[9-13]. N Nakada et al[14] studied the austenite nucleation behavior in 13% Cr-6% Ni martensitic stainless steel, and reported that acicular