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Effect of post-rolling cooling on the hot-rolled microstructure and texture of a new medium-carbon steel

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Abstract. Thermomechanical processing consisted of hot-rolling in the austenitic region with deformation both above and below the non-recrystallization temperature. Immediately after rolling, specimens were directly quenched in water to three different temperatures of 560 °C, 420 °C and room temperature. The first two samples, which were quenched to 560 °C and 420 °C, immediately cooled slowly in the furnace. The microstructure of samples quenched to 560 °C mostly comprised of upper bainite whereas the samples quenched to 420 °C mainly consisted of lath-type bainite. The microstructure of sample direct-quenched to room temperature was mainly martensite. The transformation texture of all samples at the mid-thickness position showed the same general texture, consisted of mainly α and γ fibers components with high intensities close to the transformed copper {112}<110>α, transformed brass {111}<112>α and rotated cube {001}<110>α components. However, the direct-quenched sample produced slightly more intense texture compared to the bainitic samples. The local texture of samples near the rolled surface owing to sever deformation showed the shear features consisting of major components of {112}<111>α, {110}<112>α and {110}<111>α.

1. Introduction

Thermomechanical controlled processing (TMCP) is a technological way to enhance the strength and toughness of steel plates at the same time by i) controlling the prior austenite structure through the rolling parameters and ii) controlling the subsequent phase transformation via control of the cooling path. Typically, TMCP of bcc steels is performed by applying a multi-stage hot deformation process, i.e. rough rolling and finish rolling stage, both above and below the non-recrystallization temperature (Tnr) [1,2]. Throughout the rough rolling stage, at above Tnr, deformation and repeated recrystallization is taken place simultaneously resulting in very fine austenite grain structure which will be elongated into narrow stretched grain structure (known as the pancake shape) after further deformation below Tnr. This unrecrystallized and elongated austenite grains are subsequently transformed to a desired fine microstructure which its characteristic depends on the applied cooling path. Crystallographic texture of the parent austenite develops as a result of both recrystallization and deformation without recrystallization. Moreover, owing to orientation relationships between the parent austenite and the daughter ferritic products such as bainite and martensite, the final ferritic microstructure also shows crystallographic texture [3]. Therefore, the cooling path may affect the microstructure and texture.
evolution during final stages of TMCP. Though that extensive research activities have so far been conducted to investigate the hot rolling process and physical metallurgy involved, especially texture development during deformation [4–6], the effect of post-rolling cooling condition is not yet fully studied and understood. Hence, the present work is intended to study the microstructural and textural changes during hot rolling and subsequent cooling of three different post-rolling cooling patterns. The cooling paths have been designed based on the studied material’s time-temperature-transformation (TTT) diagram to have upper bainite, lower bainite and martensite as the final microstructures.

2. Material and experimental procedures

The material used in this work (designed by the authors) was a new medium-carbon, low alloy steel microalloyed with Nb with the following composition: 0.4 C, 0.2 Si, 0.25 Mn, 0.90 Cr, 0.50 Mo and 0.013 Nb (wt. %). Initially, the studied material was cast using vacuum-induction melting (VIM) furnace and then cut to the slab-shape block (51x200x75 mm). Afterward, the blocks were reheated at 1200 °C for 3 hours and then were rolled on a pilot rolling mill to a final thickness of 10 mm. As illustrated in figure 1, rolling was performed in two stages, a 4-pass rough rolling above the Tnr in the temperature range 1200-1100 °C with a total reduction of 48 % followed by also a 4-pass finish rolling stage below Tnr such that the finish rolling temperature was 800 °C, slightly above the austenite finish temperature (A3). Immediately, the rolled strips were directly quenched in three different ways; for first two cooling cycles as highlighted in figure 1, the rolled strips were directly quenched in water to two quench-stop temperatures of 560 °C and 420 °C and then transferred to a furnace at the same temperature with related quench-stop temperature and allowed to furnace cool (approx. 0.01 °C/s) to ensure achieving upper bainite and lower bainite microstructure, respectively. For the third cycle, the rolled strip was directly water quenched to the room temperature to producing as-quenched martensite microstructure. The temperature of the material during the whole process was monitored via a thermocouple inserted in the middle of the blocks before rolling. The samples were labeled according to their expected final microstructure as Upper Bainite, Lower Bainite, and Martensite.

Regarding the microstructure and microtexture characterization, a Sigma Zeiss field emission scanning electron microscope (FESEM) equipped with electron backscatter diffraction (EBSD) was employed to examine the sub-surface and mid-thickness regions of all samples. EBSD mappings were recorded using an accelerating voltage of 15 kV, a working distance of 15 mm, a tilt angle of 70° and a step size of 0.3 μm. A detailed microstructural analysis was also performed on the EBSD image quality (IQ) data using a deconvolutional technique based on the method developed by DeArdo et al. [7].

Figure 1. The schematic infographic of hot-rolling schedule along with the post-rolling cooling paths including Cycle #1, #2, and #3 intended to produce final as-rolled microstructure of upper bainite, lower bainite and martensite, respectively.
3. Results and discussion

The micrographs of the final structures in the form of EBSD image quality along with the phase fraction calculation on the basis of normalized image quality numerical analysis are presented in figure 2. In general, all three samples showed deformation of the prior austenite grains along the rolling direction resulted a very fine as-rolled microstructure. It has been earlier reported that different morphologies varying in intrinsic dislocation density and consequently give the different IQ values [8]; accordingly, different microstructural constituents were detected in each sample based on their IQ value and marked on the microstructure images given in figures 2a-c.

The normalized IQ graphs (solid black lines in figures 2d-f) exhibited three different general outlines indicating three different microstructures, upper bainite with an augmented peak around ~50-60 (figure 2d), lower bainite with an augmented peak around ~30-40 (figure 2e), and martensite with a maximum peak around ~20-25 (figure 2e). To determine the fraction of each microstructural components, the normalized IQ curve was deconvoluted into multiple normally distributed peaks. Then, each peak was attributed to a specific morphology based on the location of peak (IQ value) and the ratio of area under each peak to the area of normalized IQ was considered as fraction associated to each component. The calculated values are given in the legend boxes.

The local crystallographic characteristics of the specimen were examined using EBSD measurement. The inverse pole figure (IPF) maps of sub-surface and mid-thickness of all samples from a randomly selected rolling – normal direction (RD-ND) section are presented in figure 3. The IPF images acquired from the sub-surface exhibited a very fine final microstructure which is originated from the extremely fine prior austenite grain structure due to the heavy deformation on the surface. Although the mid-thickness samples showed a bit coarser structure compared to the surface, the microstructural components were still very fine.

Figure 2. The EBSD-IQ maps of a) upper bainite, b) lower bainite and c) martensite along with the associated normalized IQ value curves (d, e, and f) and microstructural components fraction based on the IQ deconvolutional analysis. (UPB: (upper) plate-like bainite, ULB: (upper) lath-like bainite, GB: granular bainite, LPB: (lower) plate-like bainite, LLB: (lower) lath-like bainite, M: martensite, (P)F: (polygonal) ferrite, ATM: auto-tempered martensite, PATM: partially auto-tempered martensite, BB: block boundaries.)
Figure 3. Invers pole figure (IPF) maps obtained from RD-ND section of both sub-surface and centreline of upper bainite (a and d), lower bainite (b and e), and martensite (c and f).

The EBSD data obtained from an area of 250×250 µm similar to figure 3 were used to construct the orientation distribution functions (ODF) in three-dimensional Euler space using OIM TSL software. ODF is a common mathematical way to describe the occurrence frequency of popular/particular crystal orientations such that, on the orientation space of the polycrystalline specimen, a volume percentage of crystals with a specific orientation is calculated for each orientation. In BCC rolled materials (like the studied steel) the major texture components and fibers can be found in the φ2 = 45° section of Euler space [9]. Figure 4 presents a schematic illustration of the ideal position for these fibers and components in the φ2 = 45° section under both shear and planar deformation. Figures 5 (a, c, and e) shows the ODF φ2 = 45° section for the sub-surface EBSD data. Comparing figures 4 and 5, the sharp BCC shear texture components of {112}<111>α, {110}<112>α and {110}<111>α were observed almost in all cooling conditions. It has been reported [10,11] that since austenite is severely deformed by rolling below Tnr the intense shear texture components of {112}<110>γ, and {111}<211>γ form in the austenite close to the rolled surfaces that later, during cooling, they transform to the above-mentioned BCC shear components. However, the intensity of ferritic shear components close to the rolling surface can be also because of formation of ferrite (phase) on the surface that subsequently deformed in shearing form during the rolling process.

ODF maps at φ2 = 45° of the centerlines are demonstrated in figures 5 (b, d, and f). As expected, the ODF sections show that the texture of the samples was the typical texture of rolled carbon steel under planar strain condition when the pancaked austenite rolling texture produces transformation BCC texture components. In the other words, the centerline texture scheme of the alloys was essentially the same for all samples comprising mainly <111>/ND (γ) and <110>/RD (α) fibers, i.e. the main components of {113}<110>α, {111}<121>α and {323}<131>α. However, the intensity of the martensite sample was slightly higher compared to the both bainitic conditions. The texture intensity depends on several parameters including mainly steel chemistry, amount of deformation, initial austenite structure and grain size, and cooling rate during transformation [3]. As all of the above parameters were retained the same for all the specimen except post-rolling cooling condition, it could be assumed that the slight increase in texture intensity by increasing the cooling rate, especially in the martensite sample could be owing to higher rate of cooling.
Figure 4. The schematic infograph of the position of most common bcc rolled texture components and fibers in the ODF $\varphi_2 = 45^\circ$ section under both shear and planar strain along with the orientation of unit cell for each component.

Figure 5. ODF maps at $\varphi_2 = 45^\circ$ calculated from the EBSD data from both sub-surface and centreline of upper bainite (a and d), lower bainite (b and e), and martensite (c and f).

4. Conclusion

A novel medium-carbon low-alloy steel was subjected to a controlled rolling process in order to reduction of thickness from 50 mm to 10 mm. Directly after hot rolling, samples were quenched through three different cooling conditions. The microstructure and microtexture analysis revealed the main following results:

- According to the image quality analysis, quenching to the different quench-stop temperatures of 560 °C, 420 °C (following with subsequent furnace cooling) and room temperature resulted in different microstructure of upper bainite (50 % plate-like and 50 % lath-like), lower bainite (8 % granular, 20 % plate-like, 70 % lath-like, and 8 % martensite) and martensite (~50 % fresh martensite and (~50 % partially/fully auto-tempered martensite), respectively.
Samples showed almost the same general crystallographic characteristics consisted the typical BCC shear features near to the rolled surface and transformation texture components (under plane strain) at the mid-thickness. However, the texture was a bit more intense in martensite sample compared to the upper and lower bainite.

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