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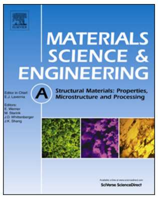

Quantitative study on yield point phenomenon of low carbon steels processed by compact endless casting and rolling

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ABSTRACT

Compact endless cast and rolling mill (CEM) is an innovative process to manufacture a hot-rolled steel strip by combining casting and hot-rolling processes. However, the yield point phenomenon (YPP) of low carbon steel strip-processed by CEM induces a negative effect in the steel product and an additional post-process is required to remove the YPP. In this study, the influence of the dislocation density and the grain interior solute atoms on the yield point elongation (YPE) of low carbon steels were quantitatively investigated using 3-dimensional atom probe tomography analysis and X-ray convolutional multiple whole profile fitting. The YPE of low carbon steel is suppressed as the dislocation density increases and carbon atom content decreases. Because the dislocation density of low carbon steel by the CEM process is increased by lowering the processing temperature, the yielding behavior of the CEM products can be eliminated without any additional post-processing. The quantitative study on the carbon/dislocation density and YPP of low carbon steel not only represents the theoretical basis of the role of carbon-dislocation interaction on YPP but also provides an effective solution to optimize the CEM process for superior products.

1. Introduction

Compact endless cast and rolling mill (CEM) is an advanced process technology that allows the mass production of highly valuable hot-rolled products through a directly connected configuration between casting and hot-rolling [1]. The CEM operates in both batch and continuous modes, i.e., endless and rolling modes, which are mutually convertible at any time. The endless rolling mode is selected for thin-gauge products (thickness: 0.8–3 mm) and converted into the batch rolling mode for thick-gauge products (thickness: 1.4–5 mm) or certain special steel grade products. This convertibility greatly expands the product range of the CEM process. Compared with conventional hot rolling processes, CEM can save not only time but also resources while producing an identical amount of hot-rolled coil as the conventional hot-rolling method; further, it is an eco-friendly process because of its competitive cost-saving measures during the processing, area, energy, CO_2, and capital expenditures. However, the yield point phenomenon (YPP) of the low carbon steel strip processed by CEM leads to stretcher-strain marks, or Lüders bands, and the localized bands of plastic deformation on the surfaces [2]. Therefore, it is necessary for steel producing companies to conduct additional skin pass milling to prevent these [3]. In light of this, the presence of YPP in low carbon steel is unfavorable for the quality of products as well as the practicality of the manufacturing process.

The YPP of steels has been widely investigated by many material scientists, especially researchers who have been involved in steel community. Based on multiple experimental results reported until now and the corresponding theoretical explanations, it is clear that YPP originates from dislocation locking by interstitial elements (e.g., carbon and nitrogen) which tend to diffuse into a dislocation core because a dislocation core is energetically higher than the other regions [4]. To prohibit YPP, several methods have been suggested in the previous studies. These include, (i) decarburizing and denitriding which can purify the steel products [5–9]; (ii) alloying with strong carbide or

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nitride forming elements [10], such as Al [11,12], Si [13–17], B [18–20] (nitride formers), Mo (carbide formers), Cr, V [21], Nb [22,23], Ti [24] (carbide and nitride formers); (iii) quenching from a high temperature which leaves the dislocations free of their Cottrell atmosphere [25–27]. However, these methods are difficult to apply to the CEM process due to an increased production cost in the additional purifying process, alloying elements, operation speed, and optimization problems.

Although the previous methods are mainly focused on removing solute-dislocation interaction by reducing solute atoms, increasing dislocation density can also be another efficient solution. For example, Keh et al. [28] reported that the quenched low carbon steel contains high dislocation density, which reduces the probability of interaction between the solute atoms and dislocations. Also, in the present authors' recent report [29], the yield point elongation (YPE) of twinning-induced plasticity steel decreases as the amount of dislocation density increases. These two reports represent that high dislocation density suppresses deformation instability by reducing solute concentration per dislocation. Therefore, controlling the dislocation density of products for inducing continuous yielding behavior by changing process conditions can be a good method of reducing YPP in CEM low carbon steels.

However, the exact quantitative investigation of the relationship among dislocation density, the number of interstitial elements, and YPE has not been reported. Since the quantitative relationship between dislocation density/amount of interstitial elements and YPP can provide optimized processing conditions for the CEM-processed low carbon steel without Lüders bands, the quantifications of dislocation density and interstitial elements become important work. Therefore, this study primarily concentrates on the establishment of methods for the precise quantitative analysis on the YPE with dislocation density and interstitial atoms. The material selected for this study is a typical low carbon steel with minimum alloying elements to exclude any additional effects. The accurate YPE value was obtained from the strain calculation of the digital image correlation method (DIC) during tensile tests while the dislocation density and concentration of inner solute atoms were measured by X-ray diffraction (XRD) and 3-dimensional atom probe tomography (3D-APT), respectively. Another goal of the study is to plot quantifiable graphs to describe the YPE in terms of dislocation density and interstitial atoms of low carbon steel and suggest solutions for the removal of YPP from low carbon steel products.

2. Experimental procedure

Table 1 shows the chemical composition of the low carbon steel product which was used to analyze the relationship between yield point elongation (YPE) and material parameters (i.e., dislocation density and amount of carbon) in the matrix. Fig. 1 represents the optical microscope (BX51M, OLYMPUS) microstructure of the initial sample. For the evaluation of mechanical properties, sheet type dog-bone tensile specimens with an ASTM standard (E 8M-04) and geometry modified tensile specimens (gauge length 6.4 mm) were machined along the rolling direction (RD) of the initial sample. All tensile tests were performed at room temperature with an initial strain rate of $1 \times 10^{-3}\ \mathrm{s}^{-1}$ in a universal testing machine (Instron 1361, Instron Corp., Canton, USA) in the RD of the plate. In particular, the strain distribution through the specimens during the tensile test was calculated by a digital image correlation (DIC: ARAMIS v6.1, GOM Optical Measuring Techniques) method for a quantitative measurement of YPE [30].

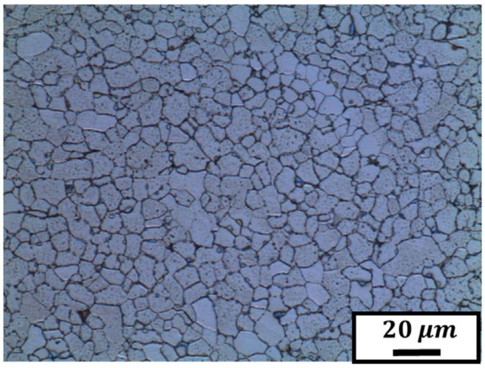

Fig. 1. Microstructure of CEM low carbon steel by optical microscope.

Fig. 2 illustrates the two-stage tensile test to prepare tensile specimens, which have various values of dislocation density in the specimen, by inducing pre-strain, similar to the skin-pass process. First, we used an ASTM sheet type tensile test specimen to perform the first tensile test to induce pre-strain for generating dislocations [Fig. 2(a)]. After the first tensile test, specimens for the second tensile tests (smaller specimen) were obtained from the gauge part of the first tensile tested specimen [see Fig. 2(b)] to evaluate the relationship between YPE and dislocation density. Dislocation density was estimated on the basis of the X-ray diffraction (XRD) patterns measured using the synchrotron at Pohang Light Source (PLS) in Pohang, South Korea. XRD analysis was performed using the 9B beam-line, high-resolution powder diffraction (HRPD), with a resolution of $\Delta E/E = 2 \times 10^{-4}$ and a beam size of 1 mm × 20 mm. Convolutional multiple whole profile (CMWP) fitting was performed for line profile analyses of the XRD data [31–36].

Table 1
Chemical composition of low carbon steel (wt%).

Fe	C	N	Al	Nb	Cr	Si
Bal.	0.0445	0.00065	0.0191	0.0001	0.033	0.028

Three-dimensional-atom probe tomography (3D-APT) (CAMECA, LaWaTAP) was used as a means of quantifying interstitial atoms inside the grains [37–39]. Rod-shaped specimens with pointed ends for 3D-APT measurements were machined using a dual-beam focused ion beam (FIB; FEI, Helios Nanolab 650) with typical lengths ranging from 200 to 300 nm. The wavelength of 3D-APT was 343 nm with its duration time achieving 500 femtoseconds.

3. Results

According to Table 1, the nitrogen content is negligible. Moreover, according to Fig. 1, the microstructure of the low carbon steel consists almost entirely of ferrite, which indicates that the effect of the secondary phase is negligible in evaluating the relationship between YPE and material parameters. As a result, only the dislocation density and carbon atom density will be used to compare the YPE of the CEM-processed low carbon steel. Before further evaluation, the sample size effect of two different specimens (i.e., ASTM sheet-type specimens and geometry modified specimens) should be confirmed to measure YPE precisely. Fig. 3 shows typical engineering stress–strain curves of the CEM low carbon steel with two different shaped specimens. Although different post-uniform elongation stages (grey region in Fig. 3) occur due to the geometrical effect, the YPE values of the two specimens are almost identical. This indicates that evaluating YPE could be performed using geometry modified specimens instead of the ASTM sheet-type specimens.

Fig. 4 represents each pre-straining stage during the first tensile test. Based on the YPE of low carbon steel (about 5%, in average), pre-straining stages were set up from 0 (elastic region) to 100% (end of the YPE). After each pre-straining stage, the second tensile test specimens were obtained from the gauge portion of the first tensile specimens. Differed by the obtained location of the specimen, the specimens were named as edge and center specimens and the second tensile test was performed to evaluate the YPE of each pre-strained specimen.

Fig. 5(a) shows the early stage ($\varepsilon < 0.05$) stress–strain curves of the pre-strained center specimens. The stress–strain curves indicate that the