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Direct Observation of the Strain Aging Effects Using the in-situ Heating and Straining Stage for TEM

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One of the new concepts for American Petroleum Institute (API) X100 grade line pipe steels was the strain-based design (SBD) approach [1]. In order to fulfill the increasing demands for the harsh environmental applications, such as the artic and seismic area, the SBD was considered as a key solution for the X100 line pipe steels. Even though the strength could be diminished during the processing or designing, large uniform elongation is the key requirement for those applications. Many researchers have been focused on the alloy design to fabricate line pipe steels meeting both the transport efficiency and the performance by combining with microstructure and mechanical property analysis [2].

Full size X100 steel plate and pipe with 32mm thickness were selected and investigated in this study. The pipe shaping was achieved through UOE (U-ing, O-ing, and Expansion) piping process. The plastic deformation history of the surface was different from that of the center during the process. Tensile stress was applied to bottom of the plate along the transverse direction (TD) which corresponds to outer side of the pipe. On the contrary, compressive stress was applied to top of the plate along the TD. Due to this uneven deformation history, from the surface to the center, it was expected that the dislocation density and structure were different through the thickness. Furthermore, the tensile stress along the TD led to compressive stress along the longitudinal direction (LD), resulting in the Bauschinger effect [3]. The UOE process is typically followed by the anti-corrosion coating process, which requires heating the pipe up to 200-250°C. In that temperature range, solute atoms, such as carbon and nitrogen, can be diffused into the dislocation cores [4]. The yield point phenomena were revealed during the following tensile test on LD. Therefore, it is believed that the deformation behavior was determined by the result of the competition between the strain aging and the Bauschinger effect.

The average grain size was measured by using scanning electron microscope (SEM). The dislocation structures of the plate and pipe were observed and analyzed with selecting several layers through the thickness by using transmission electron microscope (TEM). To investigate both the strain and the thermal effect on the strain aging behavior of SBD X100 steels, in-situ heating and straining TEM stage was designed and applied to test the steels. Each step of process conditions, such as heating and applying stress, was simulated in the TEM while observing the microstructural change. The strain aging behavior and the Bauschinger effect were directly confirmed by observing dislocation motions.

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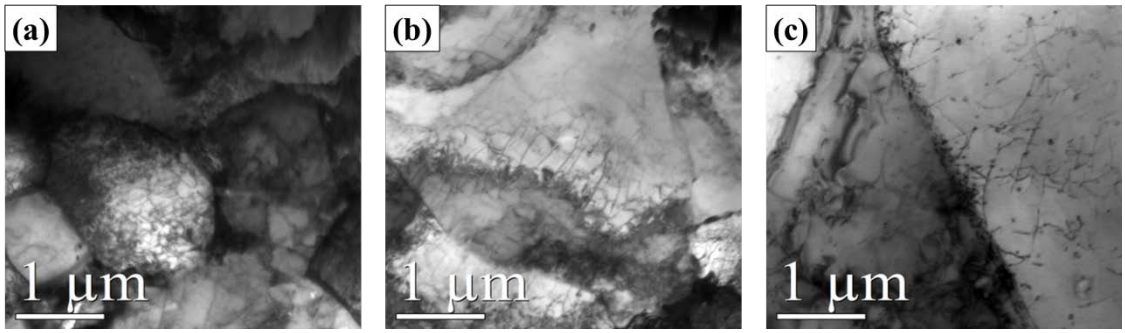

Figure 1. TEM images of dislocation structures of the steel after piping process: (a) near surface, (b) one quarter, and (c) center of the sample

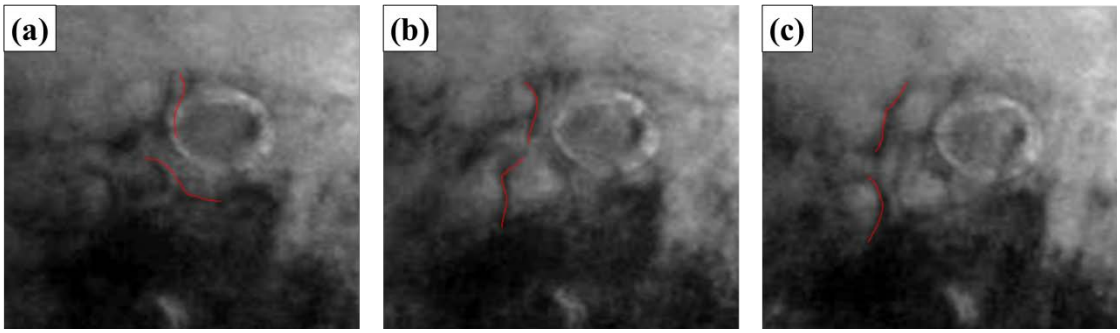

Figure 2. TEM images captured during the in-situ straining. Dislocations (marked as red lines) were gradually unpinned from the precipitate under continuous loading.

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