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Effects of coiling temperature and pipe-forming strain on yield strength variation after ERW pipe forming of API X70 and X80 linepipe steels

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ABSTRACT

Since pipes are undergone repeated tension and compression strains during pipe-forming, and flattening, flattened sheets often show too higher or lower yield strength than hot-rolled coils, which poses to difficulties in satisfying yield strength standards. In this study, effects of microstructure and pipe-forming strain (thickness/diameter (t/D)) on yield strength variation were investigated in X70 (483 MPa) and X80 (552 MPa) linepipe steels fabricated by controlling Mo content and coiling temperature, and their yield strength, strain hardening exponent, and Bauschinger stress parameter were measured by tension-compression tests with varying tensile-pre-strain. In the X80 steels whose Mo content was higher than that of the X70 steels, the higher Mo content promoted the formation of low-temperature transformed microstructures such as acicular ferrite (AF), granular bainite (GB), bainitic ferrite (BF), and martensite-austenite (MA) constituent, which played a role in decreasing Bauschinger effect. The reduction in yield strength was smaller in the X80 steel than in the X70 steel. As the coiling temperature decreased, the volume fractions of AF, BF, and pearlite increased, while those of QPF, GB, and MA decreased, and led to the increase in yield strength by about 30 MPa. The yield strength slightly increased after the pipe forming at higher coiling temperature, while it was largely reduced at lower coiling temperature. When the steels having different t/D were compared, the yield strength after the pipe forming increased largely by 65 MPa under the higher t/D as the strain hardening effect overrode the Bauschinger effect. In order to prevent or minimize the large reduction in yield strength after the pipe forming, low-temperature transformation microstructures, coarse grain size, and high t/D were desirable.

1. Introduction

Linepipe steels used for the long-range transportation of crude oil or natural gas require high strengths to endure the high-pressure [1–4]. Widely used API X70 or X80 grade (483 MPa or 552 MPa) linepipe steel sheets are fabricated in a coil form, leveled, and then pipe-formed. Among various forming processes, electrical resistance welding (ERW) process is generally used because of its excellent productivity. After pipe forming, outer and inner sides of pipes are subjected to different strains, *i.e.*, tensile strains on the outer side and compressive strains on the inner side, which are also varied with pipe-forming strain expressed by thickness/diameter (t/D) ratio. Since mechanical properties of pipes are measured after flattening of pipes, pipes are undergone repeated tension and compression strains. According to this strain history, flattened sheets often show too higher or lower yield strength than hot-rolled coils, which poses to difficulties in satisfying the yield strength standards required by the American Petroleum Institute (API). Prolonged time of several months and expensive prices are usually consumed in pipe forming, flattening, property testing, and feedback, finding causes and solutions for preventing large variation in yield strength is essentially needed.

The decrease in yield strength under repeated tension and compression strains is generally explained by Bauschinger effect [5–8]. The Bauschinger effect increases as back stresses are raised by increasing mobile dislocations whose generation, migration, and pile-up are affected by microstructures existed in linepipe steels. Their microstructures are quite complicated because they consist of low-temperature transformation microstructures such as acicular ferrite, granular bainite, and bainitic ferrite, which individually influence both strain hardening and Bauschinger effect [9–12]. Deformation amount, *i.e.*, pipe-forming strain (t/D), also affects the strain hardening and Bauschinger effect [11,13]. The yield strength generally increases with

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increasing t/D and resultant strain hardening, whereas it decreases with increasing Bauschinger effect [5,14–17]. Therefore, effects of microstructure and t/D on yield strength should be systematically analyzed in order to identify the variation in yield strength and to investigate the competing mechanism between strain hardening effect and Bauschinger effect, but very few studies have been conducted.

The present study mainly investigated the competing mechanism in relation with microstructural factors and deformation strain. API X70 and X80 steel sheets were fabricated with different Mo content and coiling temperature to control their constituent phases. And then they were formed to pipes with different t/D ratios by the ERW process to analyze the effect of deformation strain. Their complicated microstructures are defined in detail, and their strain hardening and Bauschinger effects were quantified by tension-compression tests. Yield strengths of leveled sheets and flattened actual pipes were measured and compared with respect to the competing mechanism between strain hardening effect and Bauschinger effect. By investigating the correlation between these yield strength variations after the pipe forming and microstructural factors, methods for preventing or minimizing the unexpected large increase or decrease in yield strength after the pipe forming were suggested. This study is expected to contribute microstructural design and to hold down unnecessary time and spending in advance.

2. Experimental

2.1. API X70 and X80 linepipe steel sheets

Commercial API X70 and X80 grade linepipe steels were used in this study, and their chemical compositions are shown in Table 1. According to a minimum yield strength level of linepipe steels, the X70 (483 MPa) and X80 (552 MPa) steels are referred to as X70 and X80 steels, respectively, for convenience. The only Mo content is higher in the X80 steel than in the X70 steel. Ar_3 temperatures of the X70 and X80 steels are estimated to be 769 °C and 753 °C, respectively. Their rolling conditions are shown in Table 2. An overall grain refinement effect was expected by rolling with a high rolling reduction ratio (over 80%) in the non-recrystallized region of austenite after austenitization at 1215 °C~1235 °C. The finish delivery temperature (FDT) was 800–825 °C in the austenite region above Ar_3. After the finish rolling, the steels were cooled from FDT to 490 °C ~580 °C, and were coiled. The final sheet thickness was 12–19 mm.

2.2. Pipe forming processes

The hot-rolled coils were leveled with a leveler for the subsequent electrical resistance welding (ERW) pipe forming process. Pipes of 508 mm in outer diameter were fabricated by the ERW along the transverse direction under pipe-forming conditions, as shown in Table 2. The pipe-forming strain (t/D) indicates a maximum strain at outer and inner sides of pipe. According to coiling temperature and t/D, the X70 steel sheets coiled at high (550 °C~580 °C) and low (510 °C~540 °C) temperatures and pipe-formed with high and low t/D (0.0374 and 0.0250) are referred to as 'X7-HH' and 'X7-LL', respectively, for convenience. Also, the X80 steel sheets coiled at high (540 °C~570 °C) and low (490 °C~520 °C) temperatures and pipe-formed with low t/D (0.0236) are referred to as 'X8-HL' and 'X8-LL', respectively.

2.3. Microstructural analysis

The leveled steel sheets were polished and etched in a 2% nital solution, and microstructures of longitudinal-short transverse (L-S) planes were observed by and a scanning electron microscope (SEM, model; JSM-6330F, JEOL, Japan). Since the differentiation between martensite-austenite constituents (MA) and other microstructures was difficult in SEM micrographs, the specimens were etched in a LePera solution and observed by an optical microscope [18]. Electron back-scatter diffraction (EBSD) analysis (step size; 0.08 μm) was conducted by a field emission scanning electron microscope (FE-SEM, Quanta 3D FEG, FEI Company, USA). EBSD specimens were mechanically polished and electro-polished at room temperature in a solution of CH_3COOH (92%) and $HClO_4$ (8%) at an operating voltage of 32 V. The data were then interpreted by orientation imaging microscopy (OIM) analysis software provided by TexSEM Laboratories, Inc.

2.4. Tension test

Tension specimens were obtained from the 1/2 thickness location of the leveled sheet and flattened pipe. The direction of tensile specimen in the leveled sheet was prepared along the transverse direction, considering that the ERW pipe forming was deviated by 90° from the rolling direction. The direction of tensile specimen of the flattened pipe was circumferential direction, which was corresponded with the tensile direction of the sheet. Round specimens (gage diameter; 6 mm, gage length; 25 mm) were prepared, and were tested at room temperature at a strain rate of $5\times10^{-3}\ s^{-1}$ in accordance with the ASTM standard test method [19] by a universal testing machine (model; 8801, Instron, Canton, MA, USA) of 100 kN capacity. The 0.2% offset stress and lower yield point were determined to be yield strength in the steels showing continuous and discontinuous yielding behavior, respectively.

In order to analyze a strain hardening effect, stress-strain curves were formalized by constitutive equations [20,21]. Swift's equation, which is a major constitutive equation, was used because a material constant, *b*, was additionally included as a complementary term in Hollomon's equation [21,22]:

$$\sigma = a(\varepsilon_p + b)^N \tag{1}$$

where σ, ε_p, a, b, and N are the flow stress, plastic strain, strength index, material constant, and strain hardening exponent, respectively.

2.5. Tension-compression tests

In order to analyze the Bauschinger effect, the tension-compression tests were conducted on leveled sheets. Round specimens having a gage diameter of 6.35 mm and a gage length of 12.5 mm were prepared along the transverse direction at the 1/2 thickness location of the leveled sheet, and were tested at room temperature at a strain rate of $5\times10^{-3}\ s^{-1}$ in accordance with the ASTM E606-92 standard test method [23] by a universal testing machine (model; Instron 8801, Instron, Canton, MA, USA) of 100 kN capacity.

The t/D was changed in the range of 0.0236–0.0374 in the four steels (Table 2). Since the strain subjected to the pipe forming was varied with the sheet thickness as shown in Fig. 1, the strain gradient at the distance X from the center of the sheet thickness could be expressed by the following simple equation:

Table 1
Chemical compositions of the API X70 and X80 steels. (wt%).

Steel	C	Mn	Si	Ni+Cu	Cr	Mo	Al	Ti+Nb+V
X70 X80	& \$2lt;0.06	& \$2lt;1.5	0.3	& \$2lt;0.6	& \$2lt;0.4	0.1 0.3	0.03	& \$2lt;0.15