Anisotropic Damage Behavior in High-Strength Line Pipe Steels

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High-strength steel line pipes have different mechanical properties (plasticity, ductility and toughness) in each direction. This anisotropy is developed by a thermo-mechanical control process (TMCP) in a heavy plate mill and a cold forming process in a pipe mill. In this study, experimental work was carried out using both as received and pre-strained (up to 6% along the T direction) steel plates for X100-grade pipes, in order to analyze anisotropic toughness. Compact tests were conducted in the longitudinal (L) and transverse (T) directions. Further, a new damage model based on the GTN model was proposed, in order to represent anisotropic damage behavior in high-strength line pipe steels.

INTRODUCTION

As consumption of energy is increasing worldwide, demand for the development of oil and gas resources in remote locations becomes strong. These development areas are often far from major consumers because the potential locations are in harsh environments. Environmental loads by offshore ice, discontinuous permafrost and seismic activity impose a strain-caused burden on the pipeline structures transporting the oil and gas from these remote resources to the population centers.

While the stress-based design (SBD) of pipelines is normally preferred, the nature of these environmental loads makes (SBD) a necessity in these harsh environments. The accurate prediction of the environmentally imposed strain by pipeline designers, and the accommodation of this strain by installation of advanced steels for pipelines, are essential to the operation of a safe and reliable pipeline.

The basic materials requirements for the SBD line pipe steels are generally the control of longitudinal yield strength, low yield-to-tensile strength (Y/T) ratio, high strain-hardening exponent, high uniform elongation, and good toughness (Glover and Rothwell, 2004). Additionally, aging effects on tensile properties during the coating process must be minimized and fully characterized (Shinohara et al., 2005; Timms et al., 2005).

For the accurate prediction of strain demand in the new design, we need to consider strain limits at both tensile and compressive sides during the pipe’s bending deformation (Tsuru et al., 2008; Igi et al., 2008).

In order to determine these strain limits, the full-size pipe bending test and the curved wide-plate tests are performed. Finally, the numerical simulations using finite element analysis (FEA) are utilized for specifying the effective mechanical properties in the pipes, checking the predicted values against the experimental results. Recently, the detailed mechanical properties of UOE line pipes in practical use have been discussed for investigating the high reliability of SBD. The strengths in UOE pipes are distributed by the plastic strain developed in the pipe forming process, so the strain capacity under the bending moment is dependent on the loading orientation. The strength is also different between the longitudinal direction and the circumferential direction, the so-called orthogonal anisotropy (Shinohara et al., 2006; Tsuru et al., 2008).

The effects of strength anisotropy in UOE pipes on the strain capacity under the bending moment have recently been studied (Tsuru et al., 2008). A constitutive model with anisotropic strain-hardening based on Hill’s quadratic yield function was developed.

Orthogonal anisotropy is enhanced by pre-straining as well as development of crystallographic texture. This study’s objective is to reveal the anisotropic damage behavior of high-strength line pipe steels by conducting fracture toughness tests for as-received and pre-strained X100 steel plates.

MATERIAL AND EXPERIMENTAL PROCEDURE

The tested steel was a high-strength, 16-mm-thick steel plate. The plate was produced in a commercial heavy-plate mill for experimental manufacture of API X100-grade UOE line pipe. The chemical composition is shown in Table 1. The steel was made through thermo-mechanical controlled rolling and an accelerated cooling process. The microstructure was a dual-phase structure.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ti</th>
<th>N</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.051</td>
<td>0.2</td>
<td>1.95</td>
<td>0.007</td>
<td>0.0015</td>
<td>0.012</td>
<td>0.004</td>
<td>Ni, Cr, Cu, Nb</td>
</tr>
</tbody>
</table>

Table 1 Chemical compositions of steel used in this study.