Anisotropic Damage Behavior in High Strength Line Pipe Steels

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ABSTRACT.

High strength steel line pipes have different mechanical properties (plasticity, ductility and toughness) in each direction. This anisotropy is developed by thermo mechanical control process (TMCP) in a heavy plate mill and 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 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. Furthermore, a new damage model based on the GTN model was proposed, in order to represent anisotropic damage behavior in high strength line pipe steels.

KEY WORDS: high strength steel; anisotropy; damage; ductile fracture

INTRODUCTION

As consumption of energy is increasing worldwide, the demand for 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 harsh environments. Environmental loads by offshore ice, discontinuous permafrost and seismic activity impose a strain demand on the pipeline structures transporting the oil and gas from these remote resources to the population centers.

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

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

For the accurate prediction of strain demand in the new design, we need to consider strain limits at both tensile and compressive side during pipe’s bending deformation (Tsuru, 2008; Igi, 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, what is called orthogonal anisotropy (Shinohara, 2006; Tsuru 2008).

The effects of the strength anisotropy in UOE pipes on the strain capacity under the bending moment have recently been studied (Tsuru, 2008). A constitutive model with anisotropic strain-hardening based on Hill’s quadratic yield function was developed. The numerical analysis indicated that the anisotropic hardening significantly affected the buckling resistance, especially under high internal pressure.

Moreover, some current reports have indicated that the pipe properties including the anisotropy between the hoop and longitudinal tensile properties of the pipe could have an influence on the tensile strain limit (Wang, 2007; Gordon, 2007). The literatures demonstrated that poor strain hardening in the hoop direction due to the pipe forming produced the elevated crack driving force. However, few studies have been performed to investigate effect of the anisotropy on crack growth resistance of the pipe. The orthogonal anisotropy is enhanced by pre-straining as well as development of crystallographic texture. An attempt has been made to clarify effect of the anisotropic strength on toughness and ductility in the plate state (Tanguy, 2008). The objective of this study is to reveal anisotropic damage behavior of high strength line pipe steels by conducting fracture toughness tests for as-received and pre-strained X100 plate steels.

MATERIAL AND EXPERIMENTAL PROCEDURE

The tested steel was a high strength steel plate with 16mm thickness. The plate was produced in a commercial heavy plate mill for experimental manufacture of X100 UOE line pipe. The chemical composition is shown in Table 1. The steel was made through thermo-mechanical controlled rolling and accelerated cooling process (TMCP). The microstructure was a dual phase structure consisting of fine polygonal ferrite and granular bainite, as shown in Fig. 1.

Table 1 Chemical compositions of the steel used in this study

<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>0.034</td>
<td>Ni, Cr, Cu, Nb</td>
</tr>
</tbody>
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