Anisotropic Plastic and Damage Behavior of a High Strength Pipeline Steel

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ABSTRACT

High strength pipeline steels have different plastic properties in each direction. This anisotropy is developed by TMCP processes in a heavy plate mill. The process may also lead to anisotropic ductility and toughness of the plate.

The purpose of this study is to develop a constitutive model integrating anisotropic behavior and ductile damage for a high strength pipeline steel.

The model is based on a set of experiments on various smooth, notched and cracked specimens and on a careful fractographic examination of the damage mechanisms. The model is also based on an extension of GTN model which includes plastic anisotropy.

Provided brittle delamination is not triggered, the developed model can accurately describe the plastic and damage behavior of the steel. The developed model is then used as a numerical tool to investigate the effect of plastic anisotropy on ductile crack extension. It is shown in particular that it is not possible to obtain a unified description of rupture properties for notched and cracked specimens tested along different directions without accounting for plastic anisotropy.

INTRODUCTION

Economic studies have shown that development of oil and gas transportation over long distances requires the use of high grade steels whose mechanical properties allow to substantially increase the internal pressure for a given pipe thickness. Research projects have then been focused on the development of API grades X80 and X100 (Hillenbrand et al., 2004; Okatsu et al., 2002) and more recently to grades X120 (Hillenbrand et al., 2004). Their mechanical behaviour needs to be characterized both in terms of plastic behaviour and crack growth resistance. In particular resistance to ductile crack initiation and longitudinal propagation needs to be evaluated to assess the high-grade pipelines structural integrity.

In practice, standards recommend the use of Charpy-V or drop weight tear tests in relation with semi-empirical correlations to predict the outcome of full-scale burst tests of pipelines (Civalleri et al., 1981; Maxey, 1981; Wiedenhoff et al., 1984). These correlations have been established on lower grade steels. Results of recent full-scale testing campaigns (Vogt et al., 1993; Demofonti et al., 2003) have shown that these correlations no longer hold for the new grades. This requires further studies on ductile damage of these new high-grade steels. Compared to older steel, the X100 materials exhibit a larger plastic anisotropy. In particular Lankford coefficients measured during tensile tests strongly differ from unity (Treinen et al., 2008; Tanguy et al., 2008). In addition their hardening capability is reduced.

The aim of this paper is to characterize and model the plastic and damage behaviour of a X100 pipeline steel which was supplied as a plate from which tubes are produced. For this purpose, a micromechanical Gurson-type (Tvergaard, 1990) model is used as transferability between laboratory specimens and structures is of primary importance. The model is extended to take into account plastic anisotropy. Simulations are based on experimental results obtained on a large set of mechanical tests. The investigated material and the experimental techniques are first presented. The model used to describe the material includes two ingredients: a specific yield surface accounting for plastic anisotropy, a model coupling plasticity and ductile damage. The different tests are then simulated. Finally the model is used to discuss the effect of plastic anisotropy on rupture.

MATERIAL AND TESTING

Material

The material of this study is a high strength steel that is used to manufacture X100 pipelines. It was supplied as a 18.4 mm thick plate. The nominal chemical composition is given on Table 1. The plate was elaborated using thermo-mechanical controlled rolling and accelerated cooling (TMCP process). The resulting microstructure is mainly ferritic-bainitic with a clear band-like structure.

As second phase particles are well known to be at the origin of cavity nucleation, a particular attention was paid to their characterisation. X-ray analysis carried out on polished surfaces reveals that most observed inclusions are composed of calcium sulfide (CaS), titanium nitride (TiN), aluminum or magnesium oxides (Al₂O₃, MgO). An inclusion volume fraction equal to 1.35 × 10⁻⁴ was evaluated using quantitative image analysis. High magnification scanning electron microscope (SEM) observation of etched (Nital) surfaces reveals the presence of martensite-austenite (M-A) islands as shown on fig. 1. Despite processing, particle remains mainly isotropic: spherical CaS, cubic TiN, equiaxed M-A. In addition, the material also contains small carbides (Fe₃C cementite). Due to material processing, the plate has an anisotropic plastic behaviour so that it is important to keep track of the material principal axes. In the following the longitudinal direction corresponding to the rolling direction is referred to as L; the transverse direction is referred to as T and the short transverse (thickness) direction is referred to as S.

Testing procedures

A comprehensive characterisation of the mechanical properties of the material was carried out along the different material directions using...