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Modelling of anisotropic hardening behavior for the fracture prediction in high strength steel line pipes

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A B S T R A C T

With the aim of improving prediction capabilities of FE simulation of anisotropic materials, a new plasticity model is proposed, based on Hill(48) criterion. The model provides a 3D description of the anisotropic behavior to represent the ductile hardening in all directions up to fracture; a Lode angle effect is also introduced, which allows a description of shear stress states. The model has been implemented into a commercial finite element code and calibrated with dedicated experimental laboratory methodology for high grade steel pipelines. A preliminary validation of the plasticity model, on a full scale a pipe burst test, is also provided.

1. Introduction

The plates manufacturing rolling process develops anisotropy in the final product, as it is particularly evident in cold rolling of steel sheets. Also thermo-mechanical controlled hot rolling and accelerated cooling of steel (TMCP process) on a plate thickness which may range, according to the product, from 15 to 30 mm, develops an amount of work hardening which is not fully recovered during cooling, with a retained anisotropic structure and elongated grains in the rolling direction. The plate final mechanical properties are so anisotropic as well.

Additionally, such thick plates are in some cases further cold worked as in the case of longitudinally welded large pipes for gas transportation. During the complex so called UOE shaping [1,2] the material undergoes to cold straining in specific directions, such as bending in the U and O shaping or circumferential expansion in the final calibration step.

The final mechanical properties of UOE pipes are known to be strongly different along the material principal axis, which in this case are also coincident with the pipe's ones [3]. Anisotropic or orthotropic material properties have an important influence on the pipeline performances. The yield limit is important in the circumferential direction in relation with the loads applied for the specific steel grade, represented basically by the service internal pressure. Furthermore, properties in the other directions also have an influence in the fracture behavior. For instance, the through thickness necking resistance is important in controlling the limit state represented by the material failure in burst and it is a key parameter in governing the ductile fracture initiation and the fracture propagation resistance in pipelines. The longitudinal fracture resistance is instead important in cases when the pipe is subject to extreme overloads in bending, with possible ductile tearing, such as in case of soil movement on buried pipelines during landslides. Additionally, wrinkle formation on local instabilities induced by severe bending are sites of strain concentration with risk of local fracture under triaxial stress states [4].

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Nomenclature

a_i	anisotropic coefficients
b, c	material parameters
g	deviatoric function
h	generalized Hill48 yield function
q	von Mises stress
r	Lankford coefficient
S	yield function
H_i	yield stress ratios
J_2	second invariant of deviatoric stress tensor
J_3	third invariant of deviatoric stress tensor
ε^p	equivalent plastic strain
ε_{ij}	strain tensor
σ_{ij}	stress tensor
θ	Lode angle
β	material parameter
γ	material parameter
$\varepsilon_{\mathrm{th}}$	material parameter
M_t	torque from torsion test
ω	rotation angle from torsion test

In all cases large straining beyond the plastic instability limit (necking) needs to be accurately described with a proper anisotropic plasticity constitutive law in order to capture the material ductile fracture behavior. In this sense, many efforts have been devoted to describe the plastic anisotropy in thin sheets obtained by cold rolling. A very comprehensive collection and description of specialized constitutive models is given in [5,6]. In spite of such amount of models proposed, few examples of application of anisotropic theories to thick section materials like UOE pipes may be found. We can cite the work of Besson and Shinoara [3,7], in which an API X100 steel grade for UOE pipelines has been studied.

All the previous approaches are developed under the hypothesis of uniform hardening behavior among the different directions. This means that the initial anisotropic deviatoric section is expanded uniformly with the increase of plastic deformation. The experimental evidences described in the present work obtained during tensile tests along the several material orientations have shown instead large directional differences in the hardening behavior. Furthermore, the stress–strain curve derived from tensile tests and from torsion tests shows a non-uniform hardening which cannot be captured by the standard Hill48 criterion. A modified criterion, taking into account for both directional hardening and Lode angle [8] sensitivity is so needed. Few examples can be found in literature about the modelling of non-uniform hardening. This has been treated for instance by Suh et al. [9] for sheets, by using the Hill48 criterion reduced to the plane stress state, but not taking into account for Lode angle sensitivity. A different approach was proposed by Stoughton et al. [10], which used a variable M exponent applied to the classical Hill's 79, Hosford's 79 and Barlat's 91 criteria, to calibrate the anisotropic hardening in Aluminium alloy sheets. Specifically for pipeline steels, Tsuru et al. [11] proposed a modified Hill48 criterion with four out of six variable coefficients (the three direct components and only one shear) dependent from the plastic strain to describe the non-uniform hardening. Also in this case the Lode angle sensitivity was not taken directly into account.

In this work, experiments are carried out on pipeline steels API X80 (48″ × 19 mm Pipe) and X70 (56″ × 22 mm Pipe) grade in the as received state. Tensile and torsion tests are carried out on round bars specimens extracted from the pipes along various directions (referred to the pipe axis) to study the anisotropy of the material. Starting from the Hill48 plastic anisotropic criterion, a new formulation is proposed to represent the behavior of the material. The new material constitutive equation, incorporating plastic anisotropy and Lode angle dependency, is calibrated by using the results from the experimental tensile tests and has been implemented into a commercial finite element code. Model validation has been proved by comparing the model results with those from experiments on small scale tensile tests. The model capability on fracture prediction has been further proved on the prediction of the burst pressure on a full scale internal pressure failure test performed on an API X70 pipeline steel.

2. Anisotropic stress–strain constitutive relations

Under the hypothesis that the material have an anisotropy with three orthogonal symmetry planes and three principal anisotropic axes x, y, z intersections of those planes, in the 1948 Hill [12] proposed a generalization of the von Mises yield criterion named Hill48 (Eq. (1))

$$F(\sigma_y - \sigma_z)^2 + G(\sigma_z - \sigma_x)^2 + H(\sigma_x - \sigma_y)^2 + 2L\tau_{yz}^2 + 2M\tau_{zx}^2 + 2N\tau_{xy}^2 = 1 \quad (1)$$