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A new experimental failure model based on triaxiality factor and Lode angle for X-100 pipeline steel

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ABSTRACT

API X-100 steel is one of the recently developed materials for production of gas transportation pipelines which has high strength and toughness. In order to study the failure of this material, experiments on smooth and notched round bars and flat notched specimens with different notch radius are done. Whereas this material is severely anisotropic in plastic region, Hill's 1948 anisotropic plasticity model is used to simulate this material. X-100 steel is highly ductile and necking occurs at early stages of plastic region.

Lode angle, which contains the effect of third invariant of deviatoric stress tensor, along with triaxiality factor are studied in the fracture of this material. Based on these experiments and analysis, a correlation is extracted for the failure strain of this material as a function of triaxiality and Lode angle which is very useful in pipeline failure analysis.

1. Introduction

Maximum stress, maximum strain and Tresca theories are known from failure criteria that use one parameter to predict failure of structures. The experiments by Bridgman [1] show that the strain at ductile fracture initiation is affected by hydrostatic stress which also is known as stress triaxiality effect and after that several researches have been done that prove the effect of hydrostatic stress on failure of ductile materials. Some of these researches are based on the micromechanical methods by Mc Clintock [2], Rice and Tracey [3], Gurson [4] and Tvergaard and Needleman [5]. Another group is thermodynamics based methods that works by Lemaitre [6] and Chow and Wang [7,8] are some samples. Purely experimental methods, for example works by Atkins [9], Johnson and Cook [10] and Bao [11], is the third group.

Recently, it is understood that besides the effect of stress triaxiality, another parameter which is related to third invariant of deviatoric stress tensor has an effect on the fracture of ductile materials. This parameter which usually is known as Lode angle was studied by Wilkins et al. [12] in the field of ductile fracture. Later Wierzbicki and his colleagues, for example Wierzbicki et al. [13], have started a series of researches on the effect of Lode angle on the fracture initiation.

Xue and Weirzbiki [14] have developed a fracture criterion with the effect of Lode angle and stress triaxiality. Their experiments show that in order to have more accurate results, it is necessary to combine the effects of Lode angle and triaxiality factor. In this work the failure strain is calculated by multiplying two functions. One of these functions shows the effect of Lode angle and the other shows the effect of triaxiality. Bai and Weirzbicki [15], according to experiments, suggested a fracture envelope in which fracture strain is an exponential function of triaxiality and a second order polynomial function of Lode angle. According to experiments and analysis done on aluminum 5083 alloy, by Gao et al. [16], failure strain is an exponential function of triaxiality while Lode angle does not have a considerable effect on the failure. Coppola et al. [17] suggested that based on different values of Lode angle, different branches of failure strain as a function of triaxiality can be considered. In the research done by Li et al. [18], a comprehensive review and comparison of the ductile failure models are done. In the latest study by Mirone and Corallo [19], it is found that, for the metals they tested, the hydrostatic stress has a significant role in failure, while the Lode angle does not affect the failure strains. Generally, this new group of fracture criteria is representable as a family of 3D surfaces correlating the failure strain, the Lode angle and the stress triaxiality.

Severe deformations caused by ground movement and seismic deformations have caused many problems during the operation of pipeline. Crossing harsh and very often "unknown or un-surveyed" areas involves complex ground hazards to be faced or anticipated,

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Fonzo et al. [20]. One of the main requirements of metals in gas pipeline is developing highly deformable pipe steel that is able to remain stable during intense seismic activity, Arabey [21]. The other main problem of pipelines is corrosion which causes different types of material loss in the body of pipe and in these cases the remaining load carrying capacity of the pipe is of crucial importance, this problem is mentioned in some studies by Hashemi [22,23], Ostby et al. [24,25] and Besel et al. [26].

API X-100 (also known as Grade 690) steel is one of the recently developed materials for production of gas transportation pipelines. This material is micro alloyed steel with high strength (yield stress in rolling direction: 690 MPa) and toughness (reduction of area at fracture: 80%). Moreover it shows a severe orthotropy in plasticity.

According to the above mentioned problems, it is really important to characterize the pipeline material thoroughly and to have a good estimation of the load carrying capacity and amount of deformation of the pipe material before failure in different loading condition. Different stress and strain based failure criteria are used for the failure of pipelines, for example, Lee et al. [27], but few studies are done on the material characterization and failure prediction of X100 grade in macro scale. Researches by Hashemi et al. [28,29], Tanguy et al. [30] and Liessem et al. [31] are from the main works done on the characterization and failure of this grade. Hashemi et al. [28,29] have used a modified Gurson failure model [4,32] and Von-Mises equivalent stress and Tanguy et al. [30] have utilized GTN model (Gurson, Tivergaard, Needleman) [33,34] associated with an anisotropic plasticity model, by Bron and Besson [35], to simulate failure in X100 pipeline steel. Liessem et al. [31] have announced required properties of X100 pipeline steel for strain based design. Gurson Model is a micromechanical model that need several constants; moreover, this model and the other models based on it, are not generally available in commercial finite element softwares and it is necessary to develop a subroutine to use these models in these softwares. Moreover, the effect of Lode angle is not covered in these models. The model used in the present research, is based on a simple elastoplastic finite element analysis and it does not need to develop a subroutine to use this model, further, it is possible to study the effect of both triaxiality and Lode angle. In other words, this model is more general, faster to apply, simpler and easier to use which is more useful in industrial application.

In this article, a more detailed study on the mechanical properties characterization and failure prediction of X100 steel is done. In order to take into account the orthotropy in material properties, Hill's 1948 plasticity model is used. Effect of necking on stress–strain curve is studied carefully and due to high ductility of the material large deformation finite element (FE) analyses are performed. In order to extract the failure properties of this material, a series of experiments and FE analysis on smooth and notched round bars and flat specimens are done. Triaxiality factor and Lode angle are the failure parameters that used in this study. Potential areas for X100 material are arctic or seismic regions with ground movements and the technology for such regions demands a strain based design, Besel et al. [26]. Therefore based on analysis and experiments a correlation is developed that gives failure strain as a function of Triaxiality factor and Lode angle.

In the next section, from a series of experiments, plasticity parameters and hardening curve are extracted. In Section 3, failure parameters are identified and explained. Section 4, devoted to experiments and FE analysis of notched specimens. Results and discussions are given in Section 5 and conclusion in Section 6.

2. Material properties

X-100 pipeline steel is high strength-micro alloyed steel obtained by means of a suitable combination of chemical composition and thermomechanical treatment parameters in order to have a correct balance between strength, toughness and weldability.

Due to production process of X-100 steel and different treatments, this material shows an anisotropic plastic behavior; therefore, Hill plasticity is selected to model the plastic behavior of this material. According to a number of researches, hydrostatic stress has an effect on yield surface and plastic flow of materials, Wierzbicki et al. [13] and Barsoum and Faleskog [35]. Hill's 1948 yield function, Hill [36], neglects this effect as shown in

$$\sigma_{eq}=\left\{\frac{3}{2}(h_{11}s_{11}^2+h_{22}s_{22}^2+h_{33}s_{33}^2+2h_{12}s_{12}^2+2h_{13}s_{13}^2+2h_{23}s_{23}^2)\right\}^{1/2} \quad (1)$$

which

$$s_{ij}=\sigma_{ij}-\sigma_h\delta_{ij} \quad (2)$$

$$\sigma_h=(\sigma_{11}+\sigma_{22}+\sigma_{33})/3 \quad (3)$$

In the above equations, σ_{ij}, σ_{eq}, h_{ij}, s_{ij}, σ_h and δ_{ij} are stress, equivalent stress, Hill parameter, deviatoric stress, hydrostatic stress and Kronecker Delta, respectively.

In order to extract the Hill parameters and isotropic hardening curve, simple tension smooth round bars in 0, 45 and 90 direction (with respect to rolling direction) and shear specimens are cut and tested. Round bar is shown in Fig. 1 and more details about these experiments are given in Ghajar et al. [37]. Hill parameters are calculated and reported in Table 1. These parameters and stress–strain curve, which is explained with more details in the following

Table 1
Hill parameters.

h11	h22	h33	h12	h13	h23
1.11	0.540	1.290	1.122	1.102	1

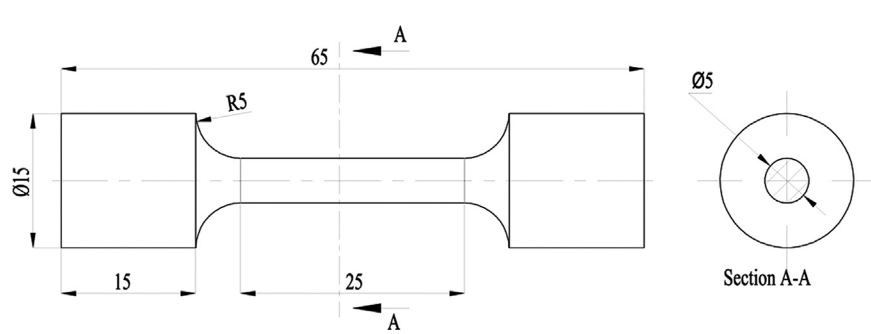

Fig. 1. Geometry of smooth round bar specimen, tested in 0, 45 and 90° directions with respect to rolling direction.