

# Triaxiality Factor and Lode Angle Effects on Failure of X-100 Steel Considering Plastic Anisotropy

**G. Mirone**

Department of Mechanical and Industrial Engineering,  
University of Catania, Italy  
E-mail: gmirone@diim.unict.it

**A. Keshavarz**\*

Mechanical Properties Research Lab; Faculty of Mechanical Engineering,  
K.N.T. University of Technology, Tehran, Iran  
E-mail: a\_keshavarz@dena.kntu.ac.ir

\*Corresponding author

**R. Ghajar**

Faculty of Mechanical Engineering,  
K. N. T. University of Technology, Tehran, Iran  
E-mail: ghajar@kntu.ac.ir

**Received: 24 June 2012, Revised: 18 July 2012, Accepted: 5 August 2012**

**Abstract:** X-100 steel is one of the most recently developed materials for production of gas transportation pipelines. This material is severely anisotropic. Smooth and notched round bars with different notch radius and flat notched specimens with different notch radius and notch depth in tension are tested to characterize the failure of this material under quasi-static loading condition. Triaxiality factor that embodies the effect of mean stress and Lode angle are the parameters that affect failure. Lode angle is a recently introduced parameter in the fracture of ductile materials and contains the effect of third invariant of deviatoric stress tensor. The load-displacement curves and pictures taken by 2 photo cameras are used to study the effects of anisotropy, triaxiality factor and Lode angle on the failure of this material. Finally an experimental failure criterion is developed to model the failure of this material. In this failure criterion, strain at fracture initiation is a function of X and TF. Models that take into account the effect of Lode angle, Triaxiality factor and anisotropy in plasticity and damage are the current state of the art in the research of ductile materials.

**Keywords:** Failure Strain, Lode Angle, Necking, Plastic Anisotropy, Triaxiality Factor

**Reference:** Minore, G., Keshavarz, A. and Ghajar, R., "Triaxiality Factor and Lode Angle Effects on Failure of X-100Steel Considering Plastic Anisotropy", Int J of Advanced Design and Manufacturing Technology, Vol. 5/No. 4, 2012, pp. 27–31.

**Biographical notes:** **G. Mirone** is a professor of mechanical engineering in University of Catania and his research interests are static and dynamic fracture and smart materials. **A. Keshavarz** has received his PhD in mechanical engineering from K.N Toosi University of Technology and his research interests are damage and fracture mechanics and nonlinear analysis. **R. Ghajar** is a professor of mechanical engineering in K.N Toosi University of Technology. His field of study includes fracture mechanics and fatigue.

## 1 INTRODUCTION

Maximum stress theory, maximum strain theory and Tresca are from known failure criteria that use one parameter to predict failure. 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 and several researches have been performed that prove the effect of hydrostatic stress on failure of ductile materials [2-4].

Recently, it is understood that besides the effect of stress triaxiality, another parameter which is related to third invariant of deviatoric stress tensor has some effect on fracture of ductile materials. Wierzbicki et al., have started a series of researches on the effect of Lode angle on the fracture initiation [5].

Xue and Weirzbiki [6] have developed a fracture criterion with the effect of Lode angle and stress triaxiality. According to the experiments and analysis done by Gao et al., [7] on aluminum 5083 alloy, failure strain is an exponential function of triaxiality while Lode angle does not have a considerable effect on the failure. Coppola et al., [8] suggested that based on different values of Lode angle, different branches of failure strain as a function of triaxiality can be considered. In the experiments by Bai [9] on DH63, fracture strain indicated very weak dependency on Lode parameter on high stress triaxialities. In the latest study by Mirone and Corallo [10], it is found that for the metals they were tested, the hydrostatic stress has a significant role in failure, while the Lode angle does not significantly affect the failure strains.

According to the review provided in the above paragraphs, Lode angle and triaxiality factor have some effects on both flow behavior and fracture of ductile metals. In order to have a reliable view of the failure behavior of this material, a series of tests on smooth round bars in different directions are done to give a complete understanding of orthotropic behavior of this material. Then some other tests are done on notched round bars and notched flat bars to study the effects of triaxiality and Lode angle. At the end a failure criterion is developed to predict the strain at failure in different range of the experiments. In the next section, according to the tests of smooth round bars, material properties are extracted. Then, an introduction to failure parameters is given. The fourth section is devoted to experiments on notched specimens and failure criterion, and followed by conclusion in section five.

## 2 MATERIAL PROPERTIES

As mentioned in the introduction, X100 steel has an orthotropic plastic behavior. In order to extract the mechanical properties of this material two points should be considered. First, this material is highly ductile and most of its plastic history belongs to the post necking area in which the deformation of the material is no longer uniform. Because of this non-uniformity, it is not possible to use engineering elastoplastic curve for describing the behavior of this material. The second point is that after yielding, it shows orthotropic behavior.

In order to extract the true stress-strain curve of this material, a series of round bars have been machined in different directions of rolling plane. A Zwick Z-100 machine is used for tensile tests with crosshead speed of 1 mm/min. Due to anisotropy in plasticity, the round cross section of the specimen changes to ellipse with two larger and smaller diameters. During the test, two cameras are used to take pictures from the specimen, as shown in Fig. 1.



**Fig. 1** Two cameras and specimen

According to the method explained in [11], having obtained the pictures from these two cameras and having measured the angle of direction of larger diameter with the cameras, it is possible to extract larger and smaller diameters of the ellipse during loading. With these set of information it is possible to extract the true stress-strain curve of the specimen; but this curve is not the real material curve because of the effects of necking. There are several researches and methods for extracting the real material curve from experimental stress-strain curve. In this research MLR [12] polynomial is used to remove the effects of necking. Finite element simulation shows that this

polynomial is able to predict the real material curve accurately. As can be seen in Fig. 2, the modified material curve is able to predict the specimen's true stress-strain curve.

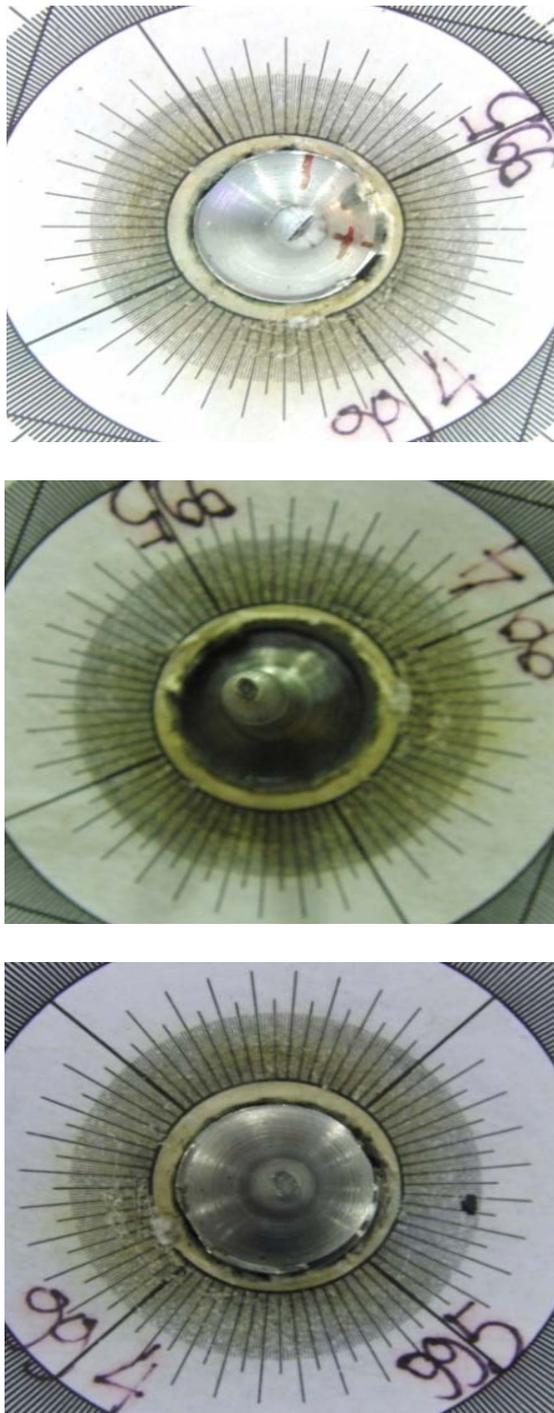


Fig. 2 Fracture surface of 0, 45 and 90 degree specimens

In order to model the orthotropic plasticity, Hill model is used which is quadratic. The yield criterion is shown in equation (1) and isotropic hardening is added to this formulation according to the curve of Fig. 2. The fracture surface of 0, 45 and 90 degree specimens are shown in Fig. 3.

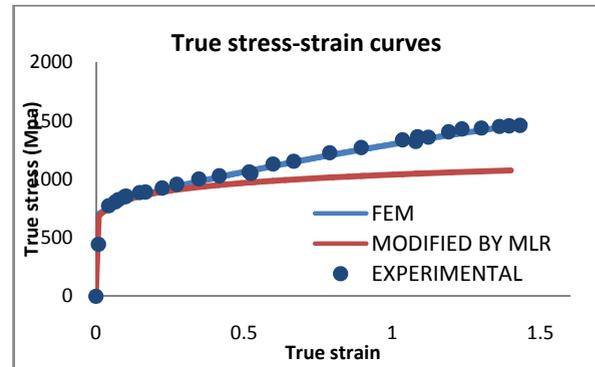


Fig. 3 True stress-strain curves depicting the FEM, experimental results and experimental results modified by the MLR

$$f(\sigma) = F(\sigma_z - \sigma_y)^2 + G(\sigma_z - \sigma_x)^2 + H(\sigma_x - \sigma_y)^2 + 3K\tau_{yz}^2 + 3L\tau_{xz}^2 + 3M\tau_{xy}^2 \quad (1)$$

### 3 FAILURE PARAMETERS

It is possible to convert each stress state to its principal values and in this way a 3\*3 matrix is replaced by a vector of 3 variables. If  $\sigma_{ij}$  is the stress tensor, then principal stress values are shown by  $\sigma_1, \sigma_2, \sigma_3$  such that  $\sigma_1 \geq \sigma_2 \geq \sigma_3$ . According to the models developed for plasticity and failure, it is preferred to use some other factors that have common usage in this field of study such as; triaxiality factor and Lode angle instead of working directly with principal stresses. The hydrostatic stress or mean stress and the deviatoric stress can be expressed respectively as;

$$\sigma_h = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{I_1}{3} \quad (2)$$

$$\sigma'_{ij} = \sigma_{ij} - \sigma_h \delta_{ij} \quad (3)$$

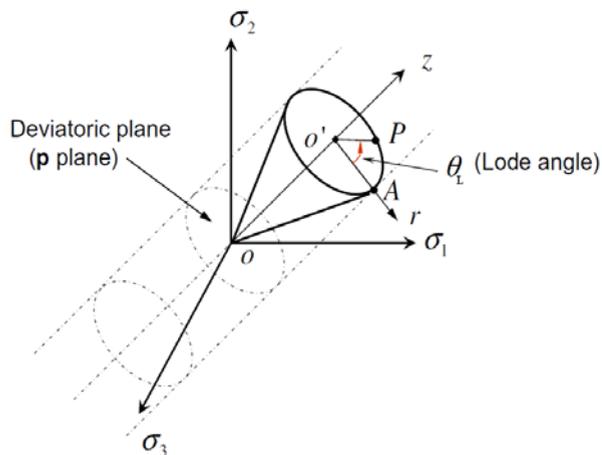
In the above equation,  $\delta_{ij}$  is the Kronecker Delta and  $I_1$  is the first invariant of stress tensor. Third invariant of deviatoric stress tensor is defined as;

$$J_3 = \sigma'_1 \sigma'_2 \sigma'_3 \quad (4)$$

Accordingly, triaxiality factor which is an indicator of the hydrostatic stress is as follows

$$TF = \frac{\sigma_h}{\sigma_{eq}} \quad (5)$$

In equation (5),  $\sigma_{eq}$  is the equivalent stress according to equation (1). Compared to other factors which are usually used in failure analysis of ductile metals, Lode angle, which is sometimes called Lode parameter, is a newer factor and less known. The Lode angle  $\theta_L$  is related to the normalized third deviatoric stress invariant. Defined through equation (6), the geometrical representation of Lode angle is shown in Fig. 4.



**Fig. 4** Lode angel ( $\theta_L$ ) in principal stress space [9], P: stress state, Oz: hydrostatic axis, O'r: line of  $\sigma_1 = -\sigma_3$

$$\theta_L = \tan^{-1} \left\{ \frac{1}{\sqrt{3}} \left[ 2 \left( \frac{\sigma'_2 - \sigma'_3}{\sigma'_1 - \sigma'_3} \right) - 1 \right] \right\} \quad (6)$$

It is possible to find the relation between Lode angle and third invariant of deviatoric stress tensor. This relation is shown in the following equation.

$$X = \cos \left( 3 \left( \theta_L - \frac{\pi}{6} \right) \right) = \frac{27J_3}{2\sigma_{eq}^3} \quad [13] \quad (7)$$

In literature, parameter 'X' is sometimes used as the Lode angle parameter; this has also taken place in this article.

## 4 EXPERIMENTS AND FAILURE CRITERION

### 4.1. Experiments

In order to study the effect of TF and X on the failure, a series of notched round bars (RB) and notched flat (FN) specimens are machined in zero degree direction and simple tension test have been performed on these specimens up to final failure. During the test the above mentioned cameras are used and deformations in three dimensions for marked points are measured. Broken specimens are shown in Fig. 5.



**Fig. 5** Fractured specimens

Finite element analysis of all specimens are performed using material data extracted in section (2) and X, TF and plastic strain are calculated for each integration point, then average values of X and TF are calculated. By comparing the curves from experiments and the same curves obtained from FE analysis, it is possible to detect the failure time in FE simulation. Averaged values of X and TF ( $X_{Avg}$  and  $TF_{Avg}$ ) measured during failure time at failure points, are introduced as failure values of the specimen.

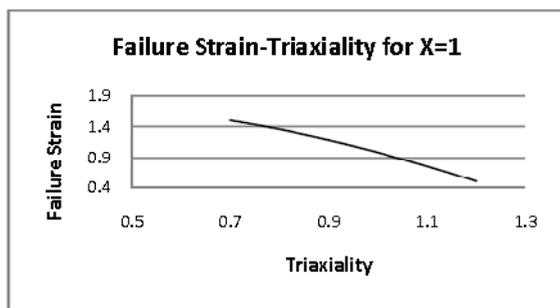
### 4.2. Failure Criterion

As the first step, a curve is fitted to the plastic strain- $TF_{Avg}$  values of round bars to give the failure strain as a function of  $TF_{Avg}$ . In round bars  $TF_{Avg}$  starts from 0.7 and goes up to 1.2 and  $X_{Avg}$  is always taken to be 1. This curve is shown in Fig. 6. As explained in the literature review, the effect of Lode angle on failure of ductile materials changes with material and triaxiality. In the next step, the effect of  $X_{Avg}$  should be entered into the above curve. In order to see the effect of  $X_{Avg}$  on the failure strain, the values of failure strain for FN specimens are calculated from the above curve and obtained results are compared with experimental results. According to the values of errors in Table 1, it

can be seen that failure strain is not affected considerably by  $X_{Avg}$ . However, it is possible to estimate failure strain in moderate and high  $TF_{Avg}$  and positive values of  $X_{Avg}$  with good accuracy from the curve in Fig. 6.

**Table 1** Error percentage of predicted values for failure strains in FN specimen

Specimen	% Error in failure strain	Average X ( $X_{Avg}$ )
FN-1	4.371	0.433
FN-2	1.819	0.251



**Fig. 6** Failure strain versus triaxiality curve for X=1

## 5 CONCLUSION

According to the application of X-100 pipeline steel, loading condition causes a positive X and TF values at failure. Therefore a series of tests are done to cover this range of X and TF at failure. Moreover, the elastoplastic behavior of this material is characterized as a prerequisite to failure analysis studies and the following results have been extracted. X-100 pipeline steel is highly orthotropic and an orthotropic plasticity model is needed to explain the behavior of this material.

X-100 pipeline steel is highly ductile and most of the plastic region in stress-strain curve is in post necking area. Therefore it is necessary to modify the curves from simple tension of smooth round bars to remove the effect of necking. MLR formulation that is used in this article can remove the effects of necking with good accuracy. Failure strain at X-100 pipeline steel decreases with increasing TF. Failure strain at X-100 pipeline steel is not sensitive to Lode angle in the range

of triaxialities higher than that of smooth specimen at failure.

## REFERENCES

- [1] Bridgman, P. W., "Studies in Large Plastic Flow and Fracture with Special Emphasis on the Effects of Hydrostatic Pressure", First ed. McGraw-Hill, New York, USA, 1952.
- [2] Rice, J. R. and Tracey, D. M., "On the ductile enlargement of voids in triaxial stress fields", Journal of Mechanics and Physics of Solids, Vol. 17, 1969, pp. 201- 217.
- [3] Gurson, A. L., "Continuum theory of ductile rupture by void nucleation and growth: Part I- Yield criteria and flow rules for porous ductile media", Journal of Engineering Materials Technology, Vol. 99, 1977, pp. 2-15.
- [4] Bao, Y., "Prediction of ductile crack formation in uncracked bodies", PhD Thesis, Dept. of Mech. Eng., MIT, U.S.A., 2003.
- [5] Wierzbicki, T., Bao, Y., Lee, Y. W. and Bai, Y., "Calibration and evaluation of seven fracture models", International Journal of Mechanical Sciences, Vol. 47, 2005, pp. 719-743.
- [6] Xue, L. and Wierzbicki, T., "Ductile fracture initiation and propagation modeling using damage plasticity theory", Engineering Fracture Mechanics, Vol. 75, 2008, pp. 3276-3293.
- [7] Gao, X., Zhang, T., Hayden, M. and Roe, C., "Effects of the stress state on plasticity and ductile failure of an aluminum 5083 alloy", International Journal of Plasticity, Vol. 25, 2009, pp. 2366-2382.
- [8] Coppola, T., Cortese, L. and Folgarati, P., "The effect of stress invariants on ductile fracture limit in steels", Engineering Fracture Mechanics, Vol. 76, 2009, pp. 1288-1302.
- [9] Bai, Y., "Effect of loading history on necking and fracture", PhD Thesis, Dept. of Mech. Eng., MIT, U.S.A., 2008.
- [10] Mirone, G. and Corallo, D., "A local viewpoint for evaluating the influence of stress triaxiality and Lode angle on ductile failure and hardening", International Journal of Plasticity, Vol. 26, 2010, pp. 348- 371.
- [11] Mirone, G. and Corallo, D., "A new method for the experimental determination of the post-necking true curve of anisotropic steels: application to damage and failure prediction", Engineering Fracture Mechanics, Under Review, 2011.
- [12] Mirone, G., "A new model for the elastoplastic characterization and the stress-strain determination on the necking section of a tensile specimen", International Journal of Solids and Structures, Vol. 41, 2004, pp. 3545-3564.
- [13] Xue, L., Ductile Fracture Modeling - Theory, Experimental Investigation and Numerical Verification, MIT PhD Thesis, U.S.A., 2007.