International Journal of Mechanical Sciences 65 (2012) 203–212

Contents lists available at SciVerse ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

The effect of stress state on ductility in the moderate stress triaxiality regime of medium and high strength steels

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A R T I C L E I N F O

Article history:
Received 13 June 2011
Received in revised form
11 October 2012
Accepted 15 October 2012
Available online 26 October 2012

Keywords:
Ductile failure
Lode parameter
Triaxiality
Experiments
Micromechanics
Void coalescence

A B S T R A C T

Experiments on double notched tube specimens subjected to tension and torsion were conducted by Barsoum and Faleskog (2007) [8,9]. In this study a complementary experimental investigation was conducted on tensile round circumferentially notched bar specimens. The results from the current study were compared with the results from the double circumferentially notched tube specimens with stress triaxiality larger than 0.7 in order to asses the influence of the Lode parameter on ductility in the moderate stress triaxiality regime. The effective plastic strain, the stress triaxiality T and the Lode parameter L were determined at the center of the notch up to the point of onset of failure by means of finite element. The influence of the Lode parameter on the failure strain was significant for the high strength and low hardening material, whereas for the medium strength and high hardening material the influence of the Lode parameter was less distinguished. The experimental results were then analyzed with the micromechanical model proposed by Barsoum and Faleskog (2011) [15], which is based on the assumption that ductile failure is a consequence of that plastic deformation localizes into a band. The band consists of a square array of equally sized cells, with a spherical void located in the center of each cell, which allows for studying a single 3D unit cell with fully periodic boundary conditions. The unit cell is subjected to a proportional loading such that it resembles the stress state, in terms of T and L, from the experiments. The micromechanical model captures the experimental trend and the influence of L on ductility very well. It is found that the Lode parameter sensitivity increases by the combination of increase in the yield strength and decrease in strain hardening. The fractographical analysis reveals that this Lode parameter sensitivity is associated with the failure characteristics of the material.

1. Introduction

Ductile failure, commonly associated with the process of nucleation, growth and coalescence of microscopic voids, has been studied extensively in the past. Early studies by McClintock [1] and Rice and Tracey [2] of void growth in ductile materials focus on the behavior of a single void in an infinite block of plastic material and found that the rate of void growth and hence fracture by void coalescence is promoted by a high level of stress triaxiality. To quantify the influence of stress triaxiality on ductility [3] perform tests on smooth and round notched bar specimens and found that the ductility decreases with increase in stress triaxiality as would be expected from void growth models. Tvergaard and Needleman [4] analyze the necking and failure in a smooth round bar specimen subjected to tensile loading numerically by accounting for nucleation and growth of voids. Clausing [5] carries out experiments on notched plane strain specimens and notched axisymmetric specimens. He finds that the plane strain ductility is less than the ductility in axisymmetric specimens and that this difference increases for increasing material yield strength. Similar experiments are performed by Hancock and Brown [6] and are later analyzed numerically in [7]. However, all these studies have in common that the stress state governing failure is characterized only by the stress triaxiality. Recent experimental and numerical studies by Barsoum and Faleskog [8,9] show that it is insufficient to characterize the stress state only by the stress triaxiality in ductile failure. They perform tests on circumferentially double notched tube specimens loaded in combined tension and torsion at a fixed ratio. By characterizing the stress state with the stress triaxiality and the Lode parameter, which discriminates between axisymmetric and shear-dominated stress states, they successfully capture the transition between the

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http://dx.doi.org/10.1016/j.ijmecsci.2012.10.003

governing rupture mechanisms leading to ductile failure. They find that the transition is characterized by a drastic shift in the deviatoric stress state. In [9] a micromechanical model to study the experiments in [8] is developed and they find that the model, extended with a simple shear criterion, captures the experimental trends well. Bao and Wierzbicki [10] and Wierzbicki et al. [11] also observe that the stress triaxiality is insufficient to fully describe ductility and propose ductile failure criterion based on stress triaxiality and a parameter related to the Lode parameter.

The influence of the Lode parameter on void growth and coalescence is also studied numerically in the past. Zhang et al. [12], Kim et al. [13] and Gao and Kim [14] perform a systematic numerical analyses of a voided cell subjected to a macroscopic stress state characterized by stress triaxiality and the Lode parameter and find that the Lode parameter has a strong influence on void coalescence. In a most recent study, Barsoum and Faleskog [15] performs systematic numerical analyses of void-containing band and study the influence of the band orientation and the Lode parameter on void growth. Moreover, Nahshon and Hutchinson [16] proposes an extension of the Gurson continuum model that incorporates damage growth under low stress triaxiality and shear-dominated stress state. By characterizing the stress state by the use of the Lode parameter they capture the experimental trends observed in [10,8].

The main objective of the current work is to study the difference in ductility associated with the Lode parameter in the moderate stress triaxiality regime, which is here defined as triaxiality larger than 0.7. Hence, the stress state is characterized by the stress triaxiality T and the Lode parameter L defined as

$$T=\frac{\sigma_h}{\sigma_e},\quad L=\frac{2\sigma_{\mathrm{II}}-\sigma_{\mathrm{I}}-\sigma_{\mathrm{III}}}{\sigma_{\mathrm{I}}-\sigma_{\mathrm{III}}},\tag{1}$$

where σ_{I}, σ_{II} and σ_{III} are the principal stresses with $\sigma_{\mathrm{I}}\geq\sigma_{\mathrm{II}}\geq\sigma_{\mathrm{III}}$, and

$$\sigma_h=\tfrac{1}{3}(\sigma_{\mathrm{I}}+\sigma_{\mathrm{II}}+\sigma_{\mathrm{III}}),\quad \sigma_e=\tfrac{1}{\sqrt{2}}\sqrt{(\sigma_{\mathrm{I}}-\sigma_{\mathrm{II}})^2+(\sigma_{\mathrm{II}}-\sigma_{\mathrm{III}})^2+(\sigma_{\mathrm{I}}-\sigma_{\mathrm{III}})^2}.\tag{2}$$

The experimental results from [8] on the double notched tube specimen with $T>0.7$ were used here, which show variations in the Lode parameter between -1 and 0, corresponding to a uniaxial stress state and a pure shear stress state, respectively. In order to test the materials in consideration for a fixed L, a different specimen configuration than the double notched tube specimen needs to be used. For this purpose additional tests were performed on tensile round notched bar specimens, for which $L=-1$, and different T levels are obtained by varying the notch configuration. The experimental program is presented in Section 2. The experimental results then presented in Section 4 and analyzed in Section 3 with the micromechanical model proposed in [15]. To determine failure characteristics of the round notched bar specimen, a fractographical examination of the fractured specimens was undertaken, which is presented in Section 4.3. The work is concluded in Section 5.

2. Experiments

2.1. Material

Two materials were investigated, Weldox 420 and Weldox 960. The former material is a hot rolled medium strength steel and the latter material is a quenched and annealed high strength steel. Uniaxial tests on smooth round bar specimens, with the tensile axis oriented in the rolling direction of the plate, were performed for both the materials and the test data were fitted to the model in Eq. (3). For both materials Young's modulus E and Poisson's ratio ν were about 208 GPa and 0.3, respectively. Mechanical material properties and model parameters are listed in Table 1, where $R_{\mathrm{p0.2}}$ is the 0.2% offset yield strength, R_{m} is the ultimate tensile strength and $\bar{\varepsilon}_f^p$ is the effective plastic strain at failure averaged over the cross section of the neck. In Eq. (3), σ_0 represents the initial yield stress, ε_s an offset strain, ε_N a normalizing strain and $\varepsilon_0=\sigma_0/E$. The strain range $\varepsilon_0\leq\varepsilon\leq\varepsilon_s+\varepsilon_N$ defines the so-called Lueders plateau commonly observed for steels. Further details regarding the materials such as microstructural properties and chemical composition are provided in [8].

Table 1
Material parameters for the mechanical properties of Weldox 420 and Weldox 960.

Material	$R_{\mathrm{p0.2}}$ (MPa)	R_{m} (MPa)	$\bar{\varepsilon}_f^p$	σ_0 (MPa)	N	ε_0	ε_s	ε_N
Weldox 420	415	525	1.42	418	0.18	0.0020	0.0084	0.0162
Weldox 960	996	1051	1.27	956	0.059	0.0046	0	0.0046

$$\bar{\sigma}=\begin{cases}E\varepsilon, & \varepsilon\leq\varepsilon_0,\\ \sigma_0, & \varepsilon_0\leq\varepsilon\leq\varepsilon_s+\varepsilon_N,\\ \sigma_0\left(\dfrac{\varepsilon-\varepsilon_s}{\varepsilon_N}\right)^N, & \varepsilon>\varepsilon_s+\varepsilon_N.\end{cases}\tag{3}$$

2.2. Experimental program

Two different specimen configurations were considered in the experimental program. New tests were performed on round notched bar (RNB) specimens subjected to tensile loading, with the tensile axis oriented in the rolling direction of the plate. In addition, tests on double notched tube (DNT) specimens subjected to tensile and torsional loading performed in [8] were reconsidered. The experimental procedure of the RNB specimen is detailed below whereas the experimental procedure on the DNT specimen is briefly outlined. For a detailed outline on the specimen configuration and the experimental procedure for the DNT tests the reader is referred to [8]. Recently, the DNT specimen has been used in [17] to calibrate ductile fracture models.

A schematic representation of the RNB specimen is shown in Fig. 1(a), where $R=6$ mm is the radius of the specimen in the unnotched region, $a=3$ mm the depth of the notch and r the notch radius. Variations in the notch radius will give rise to different stress triaxiality levels in the center of the notch and five different values of the ratio a/r were considered for each material. The specific ratios a/r were established by means of finite element analysis, with the purpose to obtain a wide and evenly spaced range in stress triaxiality. The specific ratio $a/R=0.5$ was chosen on the premises that this gave a rather smooth stress distribution in the notch region. Note that for $a/r>1$, the shape of the notch is a semicircle. The notch dimensions are listed in Table 2 together with the number of specimens tested. The d_0/d_f ratio is also reported, which is the ratio of the initial cross sectional diameter $d_0=2(R-a)$ at the notched region over the final diameter d_f at failure of the RNB tests. In Fig. 1(c) a photograph of the complete set of specimens with different notch radius is shown for Weldox 420. The smooth notch at the very right in the photo corresponds to $a/r=0.2$, whereas the sharp notch at the very left in the photo corresponds to $a/r=4.0$. The tests were carried out with an Instron testing machine such that quasi-static loading conditions prevailed with a nominal displacement rate over the measuring distance $l_0=12.5$ mm of the order of 10^{-3} mm/s, which was later reduced at the onset of localized deformation. The axial displacement δ near the notch region was