International Journal of Solids and Structures 71 (2015) 79–90

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

On the path-dependence of the fracture locus in ductile materials: Experiments

Shamik Basu [a], A. Amine Benzerga [a,b,*]

[a] Department of Materials Science and Engineering, Texas A&M University, College Station, TX 77843, United States
[b] Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843, United States

ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form 31 May 2015
Available online 17 June 2015

Keywords:
Fracture locus
Ductile fracture
Stress triaxiality
Nonproportional loading

ABSTRACT

Guided by previous theoretical analyses, an experimental program was designed to probe the path-dependence of the fracture locus in ductile materials. The material and loading conditions were chosen so that cavitation-induced failure is the basic damage mechanism. In one set of experiments, round notched specimens of different notch acuities were deformed to complete rupture and a nominal strain to fracture initiation was recorded for each specimen. In another set of experiments, sufficiently large specimens were prestrained in simple tension up to incipient necking, then round notched bars were cut out, again varying the notch acuity, and subsequently deformed to rupture. The latter experiments thus produce a step-jump in stress triaxiality, as opposed to a weakly varying triaxiality in the former. The evolution of stress triaxiality at failure locations was determined by finite-element calculations using an associated flow model and a hardening curve identified experimentally up to a strain of 2.0. The designed program enabled a comparison between the fracture loci with and without load path change. It also allowed qualitative comparisons to be made with previously published theoretical results. A theory of ductile fracture that is posited as a stress-state dependent critical fracture strain model is generally inadequate. The findings here partially illustrate the extent to which this applies.

1. Introduction

This work is motivated by the recent theoretical analyses of Benzerga et al. (2012) who examined the effect of loading path on the fracture locus of ductile materials by means of micromechanical finite-element calculations of a periodic unit cell containing a central void. In the cell model, fracture is identified with an abrupt drop of stress carrying capacity of the cell due to plastic flow localization in the intervoid ligament and elastic unloading elsewhere. The unit cells were subjected to several proportional loading paths, characterized by constant values of stress triaxiality. The strain-to-failure was recorded for each path and the locus relating it to triaxiality was thus uniquely determined. The process was repeated for a set of nonproportional loading paths. For these cases, the strain-weighted average of stress triaxiality was used to plot the fracture locus. With these definitions, it was found that the failure locus for nonproportional loadings differs substantially from that for radial paths. Of particular importance are the cases where the strain to fracture decreased by a large amount as a result of nonproportional loading. One aim of this work is therefore to examine experimentally the validity of the findings of Benzerga et al. (2012). Structural materials usually do not contain initial voids, and if they do the voids are not distributed periodically. In addition, load/strain path changes may affect the hardening behavior of the material in ways that were not represented accurately in the cell model where a simple J_2 flow model was adopted with power law hardening.

More broadly, this study aims at understanding the effects of load path changes and pre-straining on the ductility of materials. Industrial metal forming processes involve complex deformation histories which consist of numerous strain path alterations. Pipe reeling processes as well as cold bending, ground movement or simply accidental loading result in pre-straining the constituent materials. The effect of prestrain on the fracture toughness of steels was investigated by Clayton and Knott (1976), Amouzouvi and Bassim (1983) and Sivaprasad et al. (2000) among others. A common trend is that prestrains in excess of some critical value are usually found to affect adversely the toughness. The critical prestrain is comparable with the uniform strain, and this establishes some connection between the decrease in toughness and the decrease in hardening capacity with prestraining. However, the

* Corresponding author at: Department of Materials Science and Engineering, Texas A&M University, College Station, TX 77843, United States. Tel.: +1 979 845 1602; fax: +1 979 845 6051.

E-mail address: benzerga@tamu.edu (A.A. Benzerga).

http://dx.doi.org/10.1016/j.ijsolstr.2015.06.003
0020-7683/

effect of prestrain on the intrinsic damage and fracture mechanisms is not well understood. In another set of studies, the effect of non proportional loading was investigated in initially crack-free specimens of various steels (Marini et al., 1985; Arndt et al., 1996; Chae et al., 2000). Various kinds of deviations from a characteristic fracture locus obtained with no path change were evidenced but incompletely rationalized.

In the present work, the material is chosen so that cavitation induced failure prevails under tensile loadings. Cavitation here refers to the usual processes of void nucleation, growth and coalescence (Garrison and Moody, 1987). In addition, the loading conditions are chosen so that shear failure is avoided. Axisymmetric stress states are known to be more stiff with respect to shear banding (Rice, 1976). Therefore, axisymmetric smooth and notched bars are exclusively used. Other types of specimens have gained interest in recent years in order to induce combined tensile and shear stress states (Dunand and Mohr, 2011; Faleskog and Barsoum, 2013; Haltom et al., 2013). The basic fact, however, that not all laboratory specimens can be mapped onto a characteristic fracture locus remains largely understated in the literature. Consider for instance some fracture strain nominally associated with a given specimen geometry. For this fracture strain to be characteristic of the material two conditions must be met. First, a stress state indicator such as the triaxiality should undergo minimal variations in time at the location of crack initiation. Incidentally, spatial variations of triaxiality should also be minimized. Second, specimen level plastic instabilities, such as necking or shear banding, must be avoided. These conditions are rarely met *stricto sensu* in any specimen of any material. Nevertheless, deviations from the ideal characteristic locus may vary significantly from one specimen geometry to another. While triaxiality evolution post-necking is most often accounted for in reporting fracture loci, the strong nonproportionality inherent to shear band formation is commonly disregarded. As a result, the nominal fracture strain obtained from, or mapped onto the load–deflection curve is often erroneously associated with the triaxiality (or the stress state indicator) that was prevalent for most of the deformation history. Such nominal fracture strain may be representative of the specimen as a structure, not of the constituent material at the stress state prevalent prior to the onset of the plastic instability. As it turns out, the above two conditions are most closely met in round notched bars. By way of consequence, these specimens are also ideal for imparting controlled step-variations in triaxiality.

Ludwik and Scheu (1923) tested specimens with circumferential notches of varying depth and sharpness. Mechanical analysis of these specimens naturally led to introducing the stress triaxiality parameter as the ratio of the mean normal stress to some deviatoric stress measure. Lode (1925) subjected tubes of iron, copper, and nickel, to combined tension and internal pressure and examined the effect of intermediate principal stresses on yielding. Orowan (1945) carried out some pioneering work to explain the physics of ductile fracture. He rationalized why the stress state arising from the geometry would concentrate plasticity-induced damage to the center of the specimen. Bridgman (1952) developed a correction method to obtain the uniaxial true stress–strain relations beyond necking. Mackenzie et al. (1977) and the Beremin group (1981) documented the strong dependence of the strain to failure upon stress triaxiality and rationalized it on the basis of void growth theory (Rice and Tracey, 1969); also see (Needleman and Tvergaard, 1984). In the past decade, several groups have revivified the interest in the Lode effect; see (Faleskog and Barsoum, 2013; Haltom et al., 2013) and references therein. One cannot emphasize enough that what is measured in these experiments is some apparent, not *intrinsic* fracture locus. The apparent locus may be affected by extrinsic factors such as the occurrence of plastic instabilities or emergence of strong gradients, as indicated above and discussed later.

The paper is organized as follows. The experimental procedure is presented in Section 2. This includes tests with and without path change, a nominal definition of strain to failure that solely relies on experimental measurements, post-necking measurements in simple tension, and fractography. Section 3 lays out the computational procedure used to infer the large-strain hardening behavior of the material as well as triaxiality variations in all specimens. All results are gathered in Section 4 and discussed in Section 5.

2. Experimental procedure

2.1. Material

The material used in this study is a medium-carbon A572 Grade-50 steel (0.23 C, 1.35 Mn, 0.05 S, 0.4 Si, all in %wt) supplied as a 2-inch thick cold-rolled plate. This steel is commonly used in applications that require high strength to weight ratio. The microstructure is ferrito-pearlitic with an average grain size of 25 μm, Fig. 1. This material is chosen because the microscopic damage mechanisms are well known. Under tensile loading, void nucleation occurs at rather small strains, either at sulfides or oxides. Significant progressive cavitation occurs until a macroscopic crack initiates, induced by the coalescence of the largest voids; see e.g. (Benzerga et al., 2004). Post-mortem fractography was used to ascertain the fracture mode in all tested specimens. The choice of a thick cold-rolled plate is also expected to minimize complications associated with plastic anisotropy. The latter is indeed typical when hot-rolled, much thinner plates of the same microstructure are considered (Benzerga et al., 2004).

2.2. Experiments without path change

Slender rectangular bars were cut from the plate in the rolling direction, machined into 16 mm diameter cylinders then lathe machined into round notched (RN) bars and fine-polished in the notched region, Fig. 2(b). The diameter at the notch root was $\phi_0 = 5.12$ mm. The notch acuity is described by the dimensionless parameter $\zeta = 10^* R/\phi_0$ with R being the notch radius, Fig. 2(c). The three specimen geometries depicted in Fig. 2(b) have ζ values of 9.3, 4.6 and 1.5. The lower the value of ζ, the sharper the notch and the higher the stress triaxiality. In addition, wider diameter ($\phi_0 = 9.2$ mm) smooth tensile bars were machined with a gage length of 66 mm, Fig. 2(a). The wider diameter was chosen in anticipation of the second set of experiments to be described next.

All specimens shown in Fig. 2 were deformed until rupture using a servo-hydraulic MTS machine with load cell capacity of 110 kN. Special threaded holders with 16 mm diameter were machined using the lathe to mount the samples on the machine. The cross-head speed was adjusted from one specimen to another so

Fig. 1. Microstructure of A572 steel with ferrite (bright phase) and pearlite (dark phase) revealed using a 5% nital solution. The rolling and through-thickness directions are horizontal and vertical, respectively.