International Journal of Mechanical Sciences 83 (2014) 112–123

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Characterization of fracture loci in metal forming

P.A.F. Martins [a,*], N. Bay [b], A.E. Tekkaya [c], A.G. Atkins [d]

[a] Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] Department of Mechanical Engineering, Technical University of Denmark, DTU – Building 425, DK-2800 Kgs. Lyngby, Denmark
[c] Institute of Forming Technology and Lightweight Construction, Technical University of Dortmund, Baroper Str. 301, D-44227 Dortmund, Germany
[d] Department of Engineering, University of Reading, Box 225, Reading RG6 6AY, UK

ARTICLE INFO

Article history:
Received 25 January 2014
Received in revised form
25 March 2014
Accepted 1 April 2014
Available online 5 April 2014

Keywords:
Fracture forming limit diagram
Fracture loci
Crack separation modes
Sheet metal forming
Bulk metal forming

ABSTRACT

Fracture in metal forming can occur in three different modes: (i) tensile; (ii) in-plane shear; and (iii) out-of-plane shear (respectively the same as modes I, II and III of fracture mechanics). The circumstances under which each mode will occur are identified in terms of plastic flow and microstructural ductile damage by means of an analytical framework to characterize fracture loci under plane stress conditions that also takes anisotropy into consideration.

Experimental results retrieved from the literature give support to the presentation and show that plastic flow and failure in sheet forming results from competition between modes I and II whereas in bulk forming fracture results from competition between modes I and III.

1. Introduction

Workability in metal forming sets limits on the deformation that can be imparted to workpieces without failure. Knowledge of when failure occurs permits working schedules to be planned so that manufactured parts, which may have great added value at that point in the production sequence, will not end up being sold as scrap.

Necking is an undesirable surface blemish in components made from sheet metals, so limits in sheet metal forming are most often controlled by localized necking rather than by fracture. When the evolution of experimental in-plane strains under different loading paths is plotted in the in-plane principal strain space, the locus of strain pairs at which localized necking occurs is called the forming limit diagram (FLD) which was originally proposed by Keeler [1] for the tension–tension domain and extended by Goodwin [2] for the tension–compression domain. The overall locus for necking in the FLD is commonly designated as the forming limit curve (FLC) and may be regarded as the locus of all the in-plane strains where sharp changes in loading path occur since all prior loading paths become plane strain ($d\varepsilon_2 = 0$) after necking [3].

The FLD is used by tool and die designers to provide loading paths at all locations in components manufactured from sheet metal forming to ensure that localized necking does not occur (Fig. 1). In the tension–compression (left-hand) quadrant, there is plane stress plasticity theory to predict the in-plane strain pairs at which diffuse [4] and localized necks [5] occur and the angles with respect to the major loading axis at which localized necks form. In the tension–tension quadrant, theory predicts that diffuse necks will occur, but there is no continuum theory to explain the occurrence of localized necks that experiments show usually form perpendicular to the greatest tensile strain. This led Marciniak and Kuckzynski [6] to postulate the existence of locally-thinned regions in the sheet workpiece at which necks initiate and their theory provides loci for localized necking in both strain quadrants.

Strain combinations that lead to wrinkling (buckling) that are commonly associated with unsupported regions of sheets or sheets in only partial contact with tooling, may also be marked on the FLD where they occur in the tension–compression strain quadrant (Fig. 1).

If the fracture strains subsequent to necking are superimposed on the FLD axes of strain, a fracture forming limit diagram (FFLD) is obtained. The strain loading paths are characterized by a sharp change towards plane strain deformation after crossing the FLC (refer to the loading paths OABC and ODE in Fig. 1a) [7].

Under certain conditions tensile fracture can precede necking in traditional sheet metal forming processes, particularly when loading under biaxial tension [8], in which case the FFLD rather than the FLD determines the deformation achievable. This is schematically shown in Fig. 1b where the loading path OF leads to failure by fracture without previous necking and, therefore, without experiencing change in direction towards plane strain deformation.

The interaction between fracture and necking in traditional sheet metal forming requires use of both the FLD and the FFLD to

* Corresponding author.
E-mail address: pmartins@ist.utl.pt (P.A.F. Martins).

http://dx.doi.org/10.1016/j.ijmecsci.2014.04.003
0020-7403/

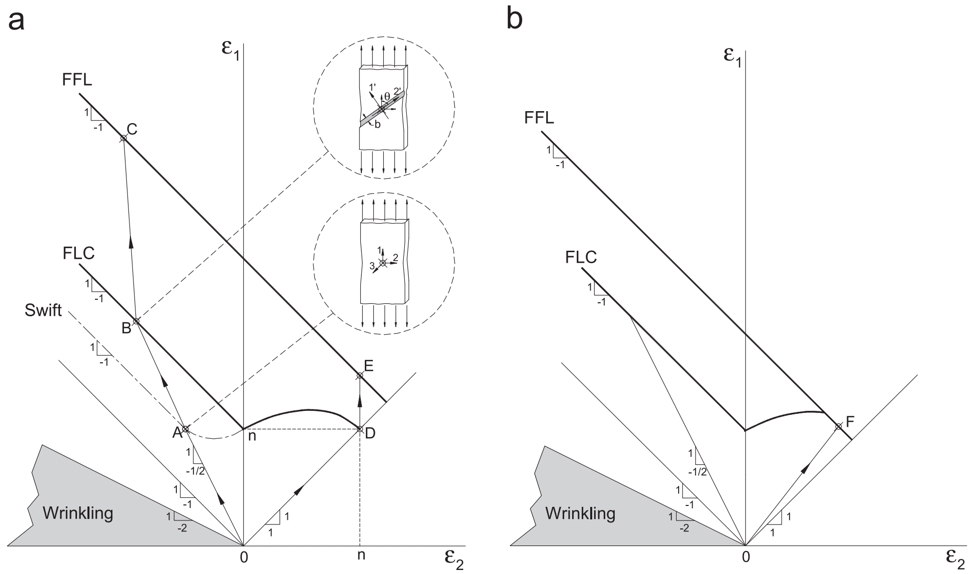

Fig. 1. Sheet metal forming workability in the principal strain space: (a) schematic representation of the forming limit curve (FLC) and of the fracture forming limit line (FFL) and (b) schematic representation of the interaction between fracture and necking in biaxial stretching.

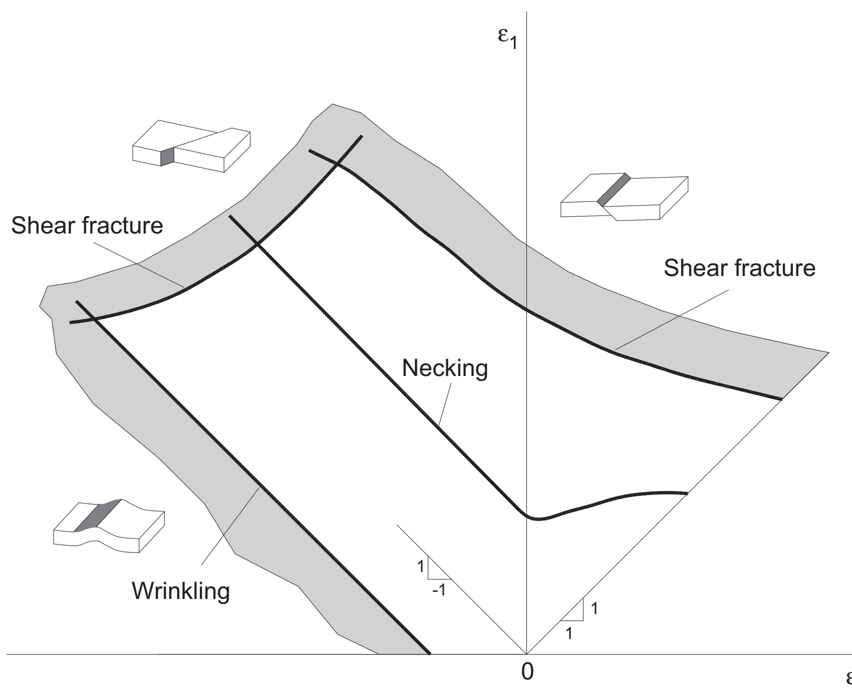

Fig. 2. Schematic forming limits by necking, wrinkling and shear fracture that were suggested by Marciniak [10].

determine limits. Hence the designation 'principal strain space' will be preferentially used throughout the paper.

In the newly developed single point incremental forming (SPIF) process necking is suppressed owing to the particular mode of deformation [9]. Consequently, much greater deformability can be achieved in parts manufactured by SPIF than by traditional sheet metal forming processes. The onset of fracture sets limits in SPIF, not necking.

Depending on the loading path, experiments show that two types of crack are found in all sheet metal forming processes, not only (i) tensile cracks, as found in incremental sheet forming and traditional sheet metal forming processes and described by the tensile fracture limit locus (also known as the 'fracture forming limit line', FFL), but also (ii) in-plane shear cracks that had previously been noted in deep-drawn aluminium alloy cups by Embury and Duncan [8] and which do not lie on the FFL but on a different shear fracture limiting locus in the tension–compression quadrant.

Shear fracture in the principal strain space was originally suggested by Marciniak [10]. Fig. 2 shows his proposed limiting loci for failure always by shear whatever the loading path. The fracture locus in the tension–compression quadrant is new. The fracture locus falling from left to right is similar to the FFL governed by tensile cracking. However, to authors' knowledge, the forming limits suggested in Fig. 2 were never accompanied by any phenomenological model or experimental evidence.

In the case of bulk metal forming, workability is limited by buckling, folding of material over itself, formation of laps or fracture. Buckling takes place when the workpiece fails like a column due to