International Journal of Plasticity 25 (2009) 1207–1230

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Generalised forming limit diagrams showing increased forming limits with non-planar stress states

Julian M. Allwood *, Daniel R. Shouler

Department of Engineering, University of Cambridge, Mill Lane, Cambridge CB2 1RX, United Kingdom

A R T I C L E   I N F O

Article history:
Received 27 July 2007
Received in final revised form 6 November 2008
Available online 19 November 2008

Keywords:
A. Ductility
C. Mechanical testing
C. Stability and bifurcation
Forming limit diagrams

A B S T R A C T

The forming limit diagram and its associated analytical and experimental techniques has been widely used for 40 years with the assumption that sheet deformation occurs in plane-stress. Some hydro-forming type processes induce significant normal stress across the workpiece and this has led to a small number of extended formability analyses. However, recent work on the incremental sheet forming process which is known to give higher formability than conventional sheet pressing has shown that the repeated passage of a tool over the sheet leads to significant through-thickness shear strains being induced in the workpiece. Accordingly this paper explores the forming limits of sheet forming processes which induce any possible proportional loading, including all six components of the symmetric stress tensor. Marciniak and Kuczyinski's famous (1967) analysis is extended to allow such loading, and a new generalised forming limit diagram (GFLD) is proposed to allow visual representation of the resulting forming limit strains. The GFLD demonstrates that forming limits can be increased significantly by both normal compressive stress and through-thickness shear. This increased formability is confirmed by experiments on a specially designed 'linear paddle testing' apparatus in which a conventional uniaxial test is augmented by the action of a paddle that 'strokes' the sample while also applying a normal force. Tests on the rig show that the paddle action leads to enhanced engineering strains at failure up to 300%. The insight gained in this paper is significant for process analysts, as it may explain existing discrepancies between prediction and experience of forming limits, and is important for designers who may be able to use it to expand process operating windows.

* Corresponding author. Tel.: +44 1223 338181; fax: +44 1223 338076.
E-mail address: jma42@cam.ac.uk (J.M. Allwood).

0749-6419/$ - see front matter
doi:10.1016/j.ijplas.2008.11.001

1. Introduction

The forming limit diagram (FLD) is used to record estimates of the strains experienced by a particular material in one or more forming processes. The logic of the diagram is illustrated in Fig. 1 which potentially shows both thinning and thickening changes to the sheet. Once a range of surface strains before and after failure of a particular process have been identified a forming limit curve (FLC) can be drawn on the diagram. The FLC is the envelope of all recorded un-failed strain states, where failure is generally defined as the onset of necking. The hope of such curves is that they can largely be treated as a material property, so that the same curve can be used for the same sheet material being deformed in different processes.

The FLD and the many models that have been developed to predict FLCs for particular materials assume that sheet forming processes occur under loading which leads to a state of plane-stress. For some well established processes such as hydro-forming, this is not perfectly true, and a small body of work has begun to examine the effect of normal compressive stresses on the formability of sheet metals. However the principal motivation of this paper arises from recent work by the authors on the mechanics of incremental sheet forming (ISF). This process, invented in the early 1990s in Japan, is a flexible sheet forming process in which a small hemispherical tool moves under computer control over a sheet clamped around its edges. A simple schematic of the process is illustrated in Fig. 2a and a photograph of the Cambridge ISF machine (described in Allwood et al., 2005) is given in Fig. 2b. As the tool moves, it creates a small localised indent in the sheet, and by choosing an appropriate tool path, the sheet can be formed to a variety of shapes – so the process aims to be a sheet forming equivalent to a CNC machining process. In fact, the accuracy of the ISF process is limited, and it is still under development (Jeswiet et al., 2005, review developments in the area) but one feature of the process that has caused great interest is that it leads to greater forming limits than conventional sheet pressing operations. Allwood et al. (2007), reporting experiments in which lines were scribed on both upper and lower surfaces of the workpiece and measured before and after deformation, have demonstrated that the ISF process induces significant through-thickness shear strains in the sheet. The key result of these experiments is re-created in Fig. 3 showing through-thickness strain developing in the direction parallel to tool motion. In a preliminary analysis, they demonstrated that including a proportional shear stress in a model used to predict FLCs led to a significant increase in predicted formability.

The motivation of this paper is to build on this insight to propose a generalised forming limit diagram accounting for the possibility that all six components of the stress and strain tensors in sheet forming may be non-zero. Section 2 provides a review of developments in both forming limit dia-

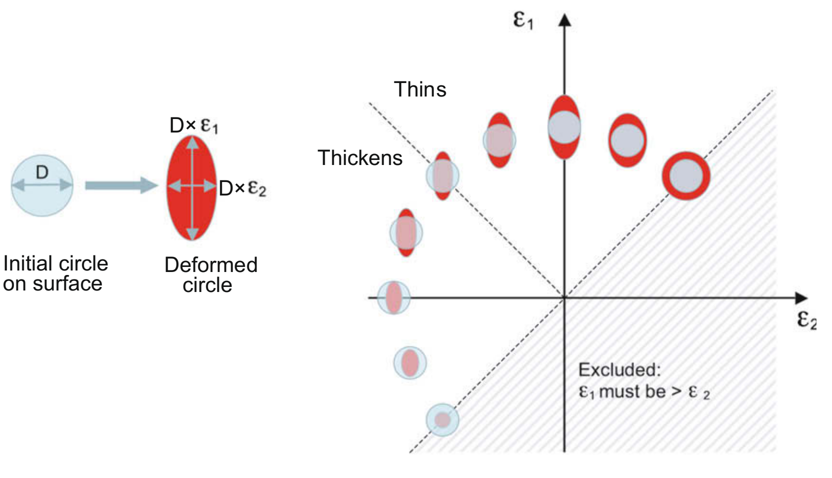

Fig. 1. The conventional forming limit diagram.