Journal of Materials Processing Technology 210 (2010) 1304–1313

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Design and use of a novel sample design for formability testing in pure shear

D.R. Shouler[1], J.M. Allwood*

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK

ARTICLE INFO

Article history:
Received 5 November 2009
Received in revised form 5 February 2010
Accepted 20 March 2010

Keywords:
Shear
Forming limit diagram
Materials testing

ABSTRACT

Existing tests for assessing the formability of sheet metal samples can create strain ratios in the range from uniaxial to biaxial stretching, $-1/2 \le \varepsilon_2/\varepsilon_1 \le 1$. A novel sample design is proposed, with shaped cut-outs in a rectangular sheet specimen, intended to produce with strain ratios in the range, $-1 \le \varepsilon_2/\varepsilon_1 \le 1/2$ in a small zone, while the sample is uniaxially extended. The strain ratio is controlled by changing the geometry of the cut-outs.

The behaviour of the new sample design is examined by finite element modelling showing nearly proportional behaviour in the test zone, with the best results occurring near to pure shear. Two experimental methods are considered for the validation of these predictions: measurement of the distortion of a grid of small circles created on the sample surface by laser-scribing; use of a commercial strain measurement system based on an applied speckle pattern. Both techniques demonstrate that the evolution of experimentally measured strains during the test closely follows that predicted numerically.

The novel sample is applied to test the formability of a range of materials known to be difficult to form. The tests on aluminium alloys Al 2024, Al 7075, Al 2198 and commercially pure titanium demonstrate that significantly enhanced deformation prior to failure is possible with loading near to pure shear. The implication of these results is that it may be possible to design novel forming processes capable of creating more dramatic deformation in "difficult to form" materials through the creation of strain paths close to pure shear.

1. Testing the formability of sheet materials

Formability is a key concern in the design, analysis and operation of manufacturing processes for sheet metal. If formability were a material property of the material, independent of any particular process, the success or failure of a given forming operation could be predicted reliably, and forming processes could be designed or adjusted accordingly. In practice, forming failures may arise from several mechanisms and are dependent on loading history and deformation path, so such a simple characterisation cannot be achieved.

Since the early 1950s, there has been extensive work aiming to find an effective means to collate experimental forming limit data into a format that approximates a material property. This has lead to the creation of forming limit diagrams (FLDs) which show envelopes of allowable forming as a limit curve below which failure should not occur. The earliest example of such a diagram was created by Swift (1952), who plotted major strain against stress ratio in proportional loading. Yoshida and Kuwabara (2007) refer to an alternative representation by Marin et al. (1953) who plots equivalent strain against stress ratio. A further variation, plotting effective strain against strain rate ratio, was proposed by Ferron et al. (1994) who claimed that forming limit curves (FLCs) plotted in this space are independent of strain paths. The most widely used type of FLD plots major versus minor surface strains and was first described by Keeler and Backhofen (1963). FLDs of the type proposed by Keeler and Backhofen can be constructed for any process by comparing the final to the initial surface geometry, but depend on the assumption that the loading has been proportional throughout the process. Without this assumption, the comparison of final to initial geometry cannot be described by a strain measurement, and can only be characterised as a stretch, which could have been achieved by an infinite variety of loading paths. The formability of the sheet within the particular process is recorded as the envelope of all measured strains in non-failed areas of the sheet. This envelope, the FLC, will be consistent across all processes which lead to purely proportional in plane loading. Goodwin (1968) introduced a method of measuring strains in a deforming sheet by pre-printing a grid of interlocking circles on the surface, and this remains commonly in use.

Any destructive forming test that leads to sample deformation with a constant strain ratio can be used to determine a point on the FLC. However several tests have been designed specifically to investigate a range of strain paths by alteration in sample geometry,

* Corresponding author. Tel.: +44 1223 338181; fax: +44 1223 332662.
E-mail addresses: drs39@cam.ac.uk (D.R. Shouler), jma42@cam.ac.uk, engjmpt@hermes.cam.ac.uk (J.M. Allwood).
[1] Tel.: +44 1223 764773.

0924-0136/$ – see front matter © 2010 Published by Elsevier B.V.
doi:10.1016/j.jmatprotec.2010.03.019

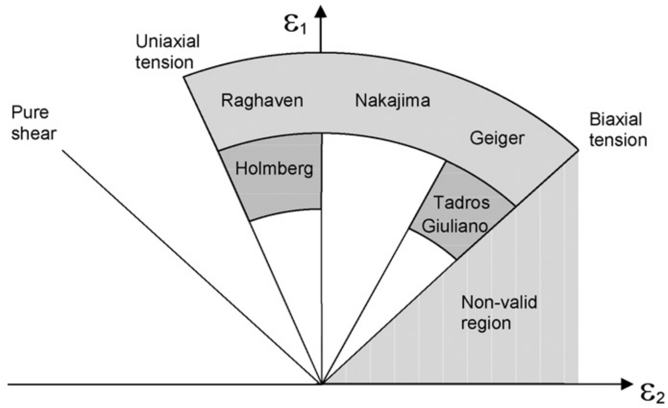

Fig. 1. The range of standard sheet material testing procedures.

and are able to determine forming limits over an arc of the FLD and therefore to produce a segment of the FLC. Some of these tests are summarised in Fig. 1 and discussed below.

Several test apparatus and test designs exist for investigation of the behaviour of a material under biaxial tension, of which the majority require multiple actuators applied to complex cruciform sample designs. However, Marciniak and Kuczynski (1967) described a simpler test designed to achieve biaxial stretching by deep drawing a circular specimen into a flat-bottomed cup. A disc with a circular cutaway is placed between the specimen and the punch to ensure that there is no contact between the central test region of the sample and the apparatus. This test is represented by the line $\varepsilon_1 = \varepsilon_2$ on the FLD. Tadros and Mellor (1978) created a variation on this test in which elliptical cutaways of varying geometry are used to allow mapping of strain ratios in the arc between $1.7\varepsilon_1 = \varepsilon_2$ and $\varepsilon_1 = \varepsilon_2$. Raghavan (1995) proposed a variety of notched samples used with similar cup testing apparatus to extend the range of possible strain ratios in cup testing across the full arc from uniaxial tension and biaxial stretching.

In a summary of testing methodologies, Karthik et al. (2002) list the Erichsen, Olsen and Hecker cup tests which press domes of differing geometries into circular blanks constrained around their perimeter. As in the Marciniak test, a full blank corresponds to a biaxial stretching condition but by changing the width of the samples Nakajima et al. (1972) showed variation in the ratio of principal strains from uniaxial for a thin sample to fully biaxial for a sheet of sufficient width to be clamped completely across the die using a solid dome. The Nakajima test is widely used at present: the test apparatus is simple; sample preparation is now cheap and easy with CNC laser or water-jet cutters; the one test can be used to map the range of surface strains with ratios of ε_2 to ε_1 between 1 and $-1/2$. However, in practice the Nakajima test does not perfectly achieve the intended strain combinations due to sample curvature over the domed punch and friction between the punch surface and the test sample introducing an unwanted additional loading.

The hydraulic bulge test, originally described by Hill (1950), is similar to that of Nakajima, but with the sheet deformed by fluid pressure. This design change avoids friction between the tool and the work piece, so the location of failure is more predicable than in the Nakajima test where it may vary with lubrication and the tolerance to which the apparatus is manufactured. Giuliano et al. (2005) demonstrate the use of bulge testing to assess formability, bulging samples through a variety of elliptical dies. More recently, viscous silicon domes have been used by Gutscher et al. (2004) which are able to deform with the surface of the sheet, offering some of the benefits of the hydraulic test but with simpler apparatus.

Geiger et al. (2005a) have suggested returning to the use of cruciform specimens clamped at the ends of their arms and pressed from beneath by an arrangement of four rollers. In further work Geiger et al. (2005b) show that the same test may be used to map a wider arc of strain space, by varying the length ratio of the cross arms of the sample. This test addresses both of the problems with the Nakajima test, since the test sample remains in plane and not in contact with the apparatus, but at the cost of more complicated apparatus and sample construction. The range of strain ratios achieved by this test is represented in Fig. 1 by the same arc as the Raghaven and Nakajima tests.

Predictive analyses of forming limit curves, reviewed in detail by Allwood and Shouler (2009), have indicated that high formability is exhibited in materials under strain combinations approaching pure shear, however to date, no test has been reported intending to investigate formability across the tensile range $-1 \le \varepsilon_2/\varepsilon_1 \le 1/2$. While several geometries have been proposed for achieving shear only such as McMeeking (1982) examining shear in thin-walled welded tubes and Marciniak and Kolodziejski (1972) who considered shear in a circular sample with the centre twisted relative to the perimeter, variations in strain paths close to this ratio have been largely ignored. In most designs a sheet is held by at least two clamps which translate with a fixed distance between them leading to simple shear. Such experiments designed by Miyauchi (1984) and by Genevois (1992) have been used as part of non-linear strain path experiments using tensile and shear loading alternately by Barlat et al. (2003) and Bouvier et al. (2006), but these experiments cannot be used to generate forming limit curves because they do not produce proportional loading. Tekkaya et al. (1982) proposed an apparatus to vary the strain ratio between uniaxial tension and pure shear by changing the direction of moving clamps, and used the experiments for determining flow curves. However, the dedicated apparatus required is complex and details of the forming limits in these experiments are not given.

A preliminary description of a new test has been presented by Shouler and Allwood (2008) specifically to investigate formability in the remaining unexplored region of the FLD. Details of the design of this test are given in Section 2, a finite element analysis is performed to anticipate the loading achieved as the novel sample geometry is varied, and two appropriate strain measurement techniques considered. In Section 3, the finite element predictions are validated through tests using a variety of loading and measurement techniques. In Section 4, the novel test is applied for the first time to examine the formability of several metals.

2. Design of a formability test for near to pure shear loading

The novel test design proposed by Shouler and Allwood (2008) aims to allow proportional loading across an arc of the strain diagram from $-1 \le \varepsilon_2/\varepsilon_1 \le 1/2$. The test has been designed for use in any existing apparatus able to apply uniaxial tension, including standard tensile testing machines, and cup and dome test equipment. The innovation in this test is in the sample geometry, and is based on cut-outs of specific geometry to cause deformation in small test regions to occur at varying strain ratios. The original sample concept is shown in Fig. 2a, with two test regions aligned to deform in pure shear when the sample is pulled in uniaxial tension as indicated, while the bulkier upper and lower parts of the sample remain undeformed. The test regions as shown were intended to deform in pure shear, but by changing the angle of the test region relative to the global loading, the strain ratio can be altered from -1 to $-1/2$.

In this description and throughout this paper, the effects of anisotropy are ignored. Thus uniaxial tension is referred to as having a strain ratio of $-1/2$ where in anisotropic materials this is not so. Similarly pure shear is said to have a strain ratio of -1. Simple shear, for clarification does not have a strain ratio of -1, but occurs when two parallel edges of a material are moved relative to one