International Journal of Solids and Structures 82 (2016) 70–84

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Effects of anisotropy on material hardening and burst in the bulge test

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ARTICLE INFO

Article history:
Received 9 September 2015
Revised 20 November 2015
Available online 19 December 2015

Keywords:
Hydraulic bulge test
Anisotropy
Material stress–strain
Burst

ABSTRACT

The hydraulic bulge test provides a means for testing sheet metal under a nearly equibiaxial stress state. Failure is delayed, allowing measurement of the material response at significantly larger strains than in the traditional uniaxial test. This study uses experiment and analysis to develop a methodology for incorporating anisotropy in the extraction of the material stress–strain response from a bulge test. A custom six-inch bulge testing facility is used to test aluminum alloy discs to failure. The curvature and strains at the apex of the bulge are monitored via stereo digital image correlation (DIC). Anisotropy is modeled via the 18-parameter non-quadratic yield function of Barlat et al. (2005), which is calibrated through independent tests on specimens from the same sheet as the bulge test specimens. The extraction of the material response uses the measured deformation at the apex and a flow rule based on the calibrated yield function. An equibiaxial state of stress or strain at the apex is not assumed. The extracted material response and the anisotropic yield function are subsequently used to simulate numerically the bulge test using solid elements. The results illustrate the effect of anisotropy on the extracted material stress–strain response and on the onset of localization that precedes failure.

1. Introduction

The hydraulic bulge test has long been viewed as an essential complement to standard uniaxial tension tests in the material characterization of sheet metal. In its simplest form the test involves a circular disc clamped at the edge that is inflated with hydraulic pressure. The nearly-equibiaxial stress state at the apex delays the onset of failure by localized instability so that the material response to strain levels that are significantly larger than those of uniaxial tension tests can be established. Successful execution of this task requires first measurement of the local radius and strain at the apex, and second a flow rule appropriate for the material.

Early measurements of the radius and strain at the bulge apex were manual and cumbersome (Mellor, 1956), and often required interrupting the test (e.g., Ranta-Eskola, 1979). Measurements became automated and continuous by the introduction of a spherometer to measure the radius of the apex of the bulge combined with an extensometer mounted in the same device (Young et al., 1981). These innovations enabled the wider use of the bulge test in sheet metal material characterization (e.g., Santos et al., 2010). The test is also used to establish failure under equibiaxial stress states (e.g., Swift, 1952). Furthermore modified bulge tests employing elliptical shapes are used to develop forming limit diagrams at various biaxial stress states (e.g., Yousef et al., 1970; Rees, 1995).

The recent advent of more-advanced deformation diagnostic techniques has further simplified the acquisition of these measurements (e.g., Dziallach et al., 2007; Rana et al. 2010; Koc et al., 2011). The development of digital image correlation (DIC) has provided perhaps the most direct technique for continuous monitoring of the surface strains and shape of the apex (e.g., Vucetic et al., 2011; Friebe et al., 2013—see also Lazarescu et al., 2013; Mulder et al., 2015).

Hill's (1950) insightful solution of an axisymmetric membrane bulge related the height of the bulge to the induced strain and for a long time was the standard tool for extracting the material response from the bulge test (see also Chakrabarty and Alexander, 1970). However, the influence of factors such as the bulge radius-to-thickness ratio and through thickness effects (e.g., Lemoine et al., 2011; Friebe et al., 2013; Mulder et al., 2015), and effects of different hardening behavior and anisotropy (e.g., Bramley and Mellor, 1966; Rees, 1995; Aretz and Keller, 2011) have remained issues of concern until today[1].

In this paper we take what we consider a holistic approach to the analysis of the bulge test. We present experimental results

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[1] The literature on the bulge test is vast so we have limited citations to only documents that we have found useful in our work

http://dx.doi.org/10.1016/j.ijsolstr.2015.12.012
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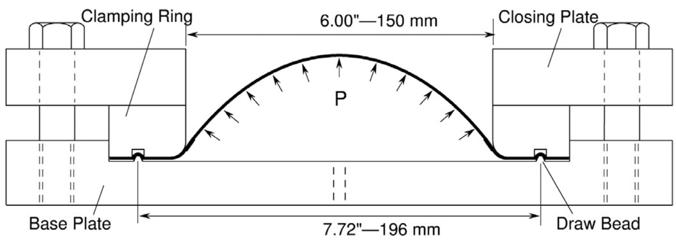

Fig. 1. Cross section of hydraulic bulge testing device.

from a bulge test on an Al-2024-T3 sheet metal with a wall thickness of 0.040 in (1.02 mm) using a 6 in (150 mm) custom bulge testing setup. DIC is used to monitor the deformation and shape of the bulge during the test. The anisotropy of the sheet is established through a separate set of experiments that are used to calibrate the Barlat et al. (2005) non-quadratic anisotropic yield function. The stress–strain response of the material is extracted from the measurements of the bulge test using the measured strains and radii of curvature at the apex. The stress state at the apex is not assumed to be equibiaxial and consequently the extraction process involves iterative solution of the relevant field equations. In keeping with our past thesis that extracted material responses are influenced by the constitutive model adopted (Tardif and Kyriakides, 2012), stress–strain responses are also extracted for the isotropic yield functions of von Mises and Hosford with an exponent of 8.

The bulge test is subsequently simulated numerically using a fully 3-D, solid finite element model in which the three constitutive models and corresponding stress–strain responses are incorporated. The objective is to demonstrate the effect of the constitutive model on the bulging response and failure.

2. Experimental

2.1. Hydraulic bulge tester and data acquisition

The bulge tests were performed in a custom-built hydraulic bulge testing facility with a six-inch diameter test section shown schematically in Fig. 1 (design influenced by the Kuwabara facility shown in Fig. 6 of Yanaga et al., 2012). It consists of a circular 4140 steel base that is 1.25 in (32 mm) thick and 13 in (330 mm) in diameter. A 0.400 in (10.2 mm) deep recess with a 9.0 in (229 mm) diameter is machined into the plate in order to receive the circular disc specimen. The base plate has a 7.72 in (196 mm) diameter draw bead machined into it, and the disc is clamped by pressing a clamping ring with a mating recess groove against it. Thus the 7.72 in (196 mm) can be considered to be the dimension of the deforming part of the disc. A closing plate is placed above the clamping ring, and clamping is achieved by tightening eight bolts that thread into the base plate. Successful operation of the facility required customizing the geometry of the mating groove to the disc thickness using a finite element model of the system. Other important setup parameters include the extent and uniformity of the clamping to the disc specimen, as even small deviations from axisymmetry at the boundaries can influence the stress state at the apex.

The system is pressurized with a light oil using a custom servo-hydraulic pressurization system shown schematically in Fig. 2. It consists of a pressure booster with a capacity of 59 in^3 (0.97 l) that multiplies standard 3000 psi (207 bar) pressure to a maximum of 10,000 psi (690 bar). The booster operates as a closed loop system using an MTS 407 controller/conditioner that enables either "pressure" or "volume" control. The pressure is monitored with a pressure transducer and the volume with an LVDT, both operated through the controller. The bulge experiments were performed under volume control.

The deformation of the bulge is monitored via stereo digital image correlation (DIC). This is enabled by spray painting on the specimen a coarse black speckle pattern on a white undercoat. Our system consists of two 5 MP digital cameras equipped with 50 mm lenses. The camera configuration and aperture setting (f/16) we selected provide a 2.8 in (70 mm) of depth of field and a 3.1 × 2.6 in (80 × 65 mm) measuring area. The DIC system was run on a common time base with the LabVIEW data acquisition system that recorded the pressure and LVDT displacement. Images were acquired at 3 s intervals during the test.

Following the test, deformations were calculated from the DIC images with GOM ARAMIS v6.3 (ARAMIS, 2011). A facet size of 75 × 75 pixels (~0.11 × 0.11 in–2.8 × 2.8 mm) and a facet spacing of 8 pixels (0.01 in–0.25 mm) were found to produce optimal accuracy of the deformation at the apex of the bulge. The deformations will be presented in terms of a Cartesian coordinate system in which (x', y') are aligned to the sheet's rolling and transverse directions respectively, and z' is the normal to a best-fit plane of the undeformed surface of the disc.

2.2. Results from a typical bulge experiment

Results from a typical bulge experiment are now used to illustrate the performance of the facility. The 9-inch (228 mm) discs were cut out of larger sheets of commercially available Al-2024-T3

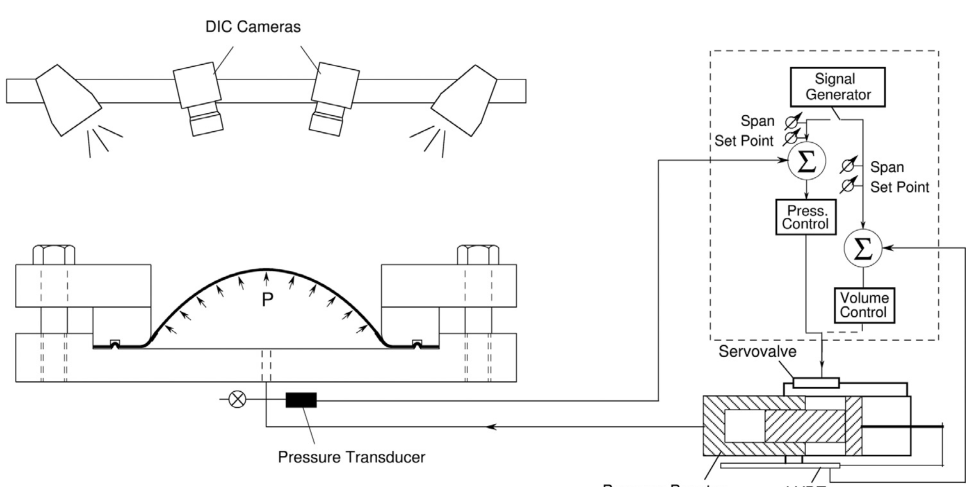

Fig. 2. Schematic of the bulge testing facility; includes the bulge tester, the pressurizing unit, and the DIC system.