Journal of Materials Processing Technology 235 (2016) 121–133

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Experimental and numerical investigation of a strain rate controlled hydraulic bulge test of sheet metal

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ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 4 April 2016
Accepted 17 April 2016
Available online 23 April 2016

Keywords:
Metal forming
Material characterization
Hydraulic bulge test
Constant strain rate

ABSTRACT

An exact characterization of the material behavior is required to identify material laws, e.g. yield criteria or isotropic hardening laws, for an accurate numerical design of forming operations. For instance, the hydraulic bulge test is carried out to determine the material behavior under biaxial stretching. In case of strain rate sensitive materials, as aluminum alloys or mild steels, the influence of the strain rate is important and a constant strain rate during the test is necessary for reliable results. In this contribution, a hydraulic bulge test setup is presented, which allows an online detection of the local strain to control the hydraulic pressure for an almost constant strain rate during the test. Moreover, the difference of the material behavior between strain rate controlled bulge tests and bulge tests with commonly used constant hydraulic cylinder speed is investigated for the aluminum alloy AA5182-O, the deep drawing steel DX54 and the advanced high strength steel HCT980X. Additionally, the influence of the hardening behavior on the numerical results of the hydraulic bulge test is exemplarily investigated for AA5182-O.

1. Introduction

In sheet metal forming, the knowledge of the material behavior is essential for a robust and high quality numerical design of the forming process. Within the field of scale components in the automotive or aviation sector, a predominant biaxial stress state prevails, which is not detected during a standard uniaxial tensile test (Altan et al., 2008). Therefore, the viscous pressure bulge test (VPB) is developed to determine the plastic behavior of sheet metal under biaxial stretching (Hill, 1950). The VPB can be divided in three types of bulge testing regarding the used forming medium. The first category uses a pneumatic pressure bulge test (PBT) setup as mentioned by Abu-Farha et al. (2008). Other test setups use water pressure (WPB) as depicted by Gologranc (1975). The most commonly used version of the viscous pressure bulge test is the hydraulic bulge test (HBT) presented by Mellor (1956), which uses a hydraulic oil to form the specific dome under biaxial stretching. To convert the pressure into the biaxial stress, the membran theory first described by Panknin (1959) is used. Primarily, the VPB is used to characterize the biaxial flow stress by the use of the membrane theory as specified by Gutscher et al. (2004). Besides the calculation of the stress from the introduced pressure, the local strains are mostly detected with the help of digital image correlation (DIC) and a three dimensional optical strain measurement system as described by Keller et al. (2009). Marinho et al. (2013) investigated the difference between the indirect DIC method and a direct ultrasound pulse-echo method to detect the thickness reduction during testing. They received a good correlation between both methods with a difference of about 0.5% of the thickness reduction. With the possibility of strain detection, flow curves to higher limiting strains can be detected in the frictionless bulge test than in the uniaxial tensile test, where early necking occurs as described in Nasser et al. (2010) in case of a dual-phase steel DP780-HY. Additionally, Güner et al. (2009a,b) found out that an optical measurement is crucial to receive accurate flow curves because of the sensitivity of the analytical approach on the radius of curvature at the pole.

For a better comparison of the test results of the bulge test, a standardization of the test is done in the newly developed DIN EN ISO (2014), where the specimen of the hydraulic bulge test consist of a circular blank. It is denoted that the die diameter should not go below a die to blank thickness ratio of 33. Experimental and numerical investigations of Güner et al. (2009a,b) indicate to use larger diameter than 100.0 mm for obtaining the required resolution of an optical strain measurement.

However, in most cases a constant forming velocity, a constant volume flow rate, is realized due to the challenges of realizing a

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http://dx.doi.org/10.1016/j.jmatprotec.2016.04.022
0924-0136/

Table 1
Nomenclature of important abbreviations.

Abbreviations	Designation
HBT	hydraulic bulge test
CSR	hydraulic bulge test with constant strain rate
CVR	Hydraulic bulge test with constant volume flow rate
UNI	uniaxial tensile test
CSR-HS	numerical results for HBT with constant strain rate and flow curve according to Hockett-Sherby hardening law directly determined from experimental results
CSR-SW-Y2000	numerical results for HBT with constant strain rate and flow curve according to Swift hardening law determined from equivalent flow curve according to Yld2000-2d
CSR-HS-Y2000	numerical results for HBT with constant strain rate and flow curve according to Hockett-Sherby hardening law determined from equivalent flow curve according to Yld2000-2d
UNI-HS-Y2000	numerical results for HBT with constant strain rate and flow curve according to Hockett-Sherby hardening law determined from uniaxial tensile tests
CVR-HS-Y2000	numerical results for HBT with constant volume flow rate and flow curve according to Hockett-Sherby hardening law determined from equivalent flow curve according to Yld2000-2d
CSR-HS-Y2000 + 5%	numerical results for HBT with constant volume flow rate and flow curve according to Hockett-Sherby hardening law determined from equivalent flow curve according to Yld2000-2d with an 5% increased biaxial yield stress σ_b
CSR-HS-Y2000-5%	numerical results for HBT with constant volume flow rate and flow curve according to Hockett-Sherby hardening law determined from equivalent flow curve according to Yld2000-2d with an 5% decreased biaxial yield stress σ_b

strain rate controlled test setup. A possible solution for constant strain rates during the VPB is given by Banabic et al. (2005), who identified and implemented a pressure vs. time curve model for controlling the volume flow rate. Though, the expected strain rate needs to be calculated before testing, while material differences and microstructural effects can lead to a deviation of the strain rate during testing. A second, online, version of a strain controlled system is presented by Alaca et al. (2008). The displacement is measured by a laser sensor and converted to the corresponding strains with the help of the plane-strain formulation. In addition, a control algorithm for the bulge test is presented. Anyhow, the equipment of the laser sensor is positioned directly across the specimen, while no local strain measurement system can be further added to detect the local strain distribution or the onset of necking in case of determining the forming limit.

In this contribution, a strain rate controlled hydraulic bulge test (HBT) is presented using an optical measurement system for a closed-loop control of the hydraulic unit with the input of the true strain gradient as A/D signals detected during the bulge test. Moreover, the influence of a constant strain rate on the pressure vs. time curve and the biaxial flow curve is investigated for a mild steel DX54, an advanced high strength steel HCT980X and an aluminum alloy AA5182-O in comparison to conventional tests with constant volume flow rate. To evaluate the effect of the obtained flow curves with and without strain rate control, a numerical analysis is performed for AA5182-O. The determined flow curves are assessed regarding the strain rate, the equivalent strain and the evolution of the maximum dome height. In addition, the impact of the biaxial beginning of plastic yielding σ_b on the numerical results, the evolution of the equivalent strain, the strain rate and the dome height is observed.

2. Abbreviated terms

The present contribution deals with some abbreviations. For a better traceability, the abbreviations of the figures and tfigures and their explanations are given in Table 1.

3. Experimental approach

3.1. Materials and specimen preparation

Hydraulic bulge tests are carried out to characterize the biaxial flow stress of sheet metals. The investigations are done for three important groups of materials represented by a mild steel DX54, an advanced high strength steel HCT980X and an aluminum alloy AA5182-O. The initial sheet thicknesses t_0 are 1.0 mm and 1.5 mm for DX54 and HCT980X and 1.2 mm in case of AA5182-O. The specimen consist of a circular blank with a diameter of 495.0 mm, which are extracted by laser cutting (TruLaser Cell 7020, Trumpf GmbH + Co., KG) with two notches in 0° to the rolling direction (R.D.) for a robust alignment of the specimen in the lower tool of the test setup. The blank is clamped from a diameter of 495.0 mm to a diameter of 250.0 mm. Due to a sufficient width of the clamping area regarding the die diameter, no influence of the heat-affected zone is expected. Furthermore, a stochastic pattern is coated in the relevant middle area of the specimen for the DIC measurement and the strain rate control system.

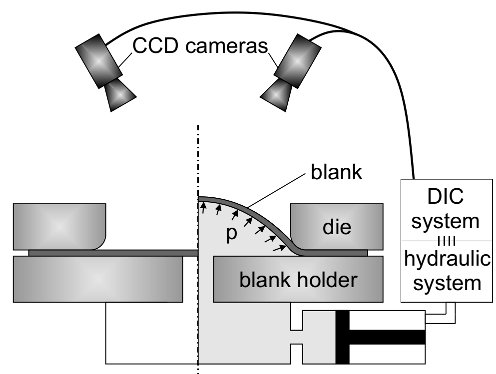

Fig. 1. Principal of HBT with closed-loop control system.

3.2. Experimental setup with closed loop control

The setup of the hydraulic bulge test with closed loop control by means of an optical DIC system is schematically seen in Fig. 1.

The hydraulic bulge test tool is mounted in a triple acting hydraulic drawing press (HPDZb 630, Hydrap) with a nominal press force of 6300 kn. The tool consists of an upper and a lower tool part. The upper tool contains the interchangeable die, the optical measurement system and safety glasses with a thickness of 1.0 mm to protect the optical measurement systems from oil splatter and damaging. The die diameter is 200.0 mm with a die radius of 25.0 mm to reduce bending effects, which can occur with small die radii. For a 3D optical strain measurement, two CCD cameras with a resolution of 5 megapixels are directly integrated in the tool with a camera angle of almost 30° to the center of the blank. The lower tool is composed of the inlay area with two pins for centering the specimen, the oil feed, the attachments of the hydraulic system