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Accurate determination of flow curves using the bulge test with optical measuring systems

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ABSTRACT

Optical measuring systems provide much more detail on the deformation of the blank in the bulge test than classical mechanical measuring systems. Within the practical limitations of mechanical measuring systems the shape of the bulged surface has been approximated by a sphere. The additional information that is available from optical measuring systems allows a more accurate description of the bulged surface and in general a more accurate determination of the stress and strain state at the pole. A detailed analysis is presented of all assumptions and simplifications in the evaluation of the test and their contribution to the accuracy of the result. It is shown that higher accuracy can be achieved by fitting the surface coordinates to an ellipsoid shape function. With this fit and by considering the local strain data to approximate the curvature for the midplane, the flow curve is retrieved with very high accuracy. The accuracy of the evaluation procedure is assessed by numerical experiments, using surface coordinates that were obtained from finite element calculations. The new accurate evaluation method has been tried for a variety of yield loci and hardening curves. A realistic level of measurement noise has been applied on the nodal coordinates of the finite element results per time step to demonstrate the robustness of the fitting procedure.

Numerical experiments with strong planar anisotropic properties show a deviation from the assumed balanced biaxial stress state. Despite the fact that the stresses in different directions are not equal, it is proven that the obtained flow curve is an accurate representation of the work hardening behaviour in this non-balanced biaxial stress state.

A final draft of an international standard on the determination of biaxial stress–strain curves by means of the hydraulic bulge test with optical measuring systems (ISO 16808) has been published. This paper will discuss the recommendations of that standard and compare the results for a steel (DC06) and aluminium (AA5182) example with the proposed procedure in this paper.

1. Introduction

The work hardening behaviour of sheet metal under biaxial stress is often examined by means of the hydraulic bulge test. A uniform blank is placed under a die with circular aperture and is completely clamped around the perimeter by a blank holder. An increasing pressure is applied by a fluid to one side of the blank, causing it to bulge through the aperture (Fig. 1).

The true stress at the pole position can be calculated from the applied fluid pressure and the local radius of curvature and thickness using the equilibrium equation for thin membranes. It is often assumed that the stress state at the pole position is balanced biaxial. Aretz and Keller (2011) showed by numerical analysis that this is in general not the case. That conclusion is refined in this paper with respect to the validity of the established stress–strain curve.

An advantage of the hydraulic bulge test is the large strain range before instability. The flow curve can be determined far beyond the uniform elongation limit of the tensile test. That ability in combination with the opportunities of new optical measuring systems has led to an increasing interest in the bulge test. A detailed understanding of the test and the evaluation method of test results is therefore very important.

Hill (1950) was the first to publish a theory on the varying shape of the bulge and the distribution of strain, depending on the

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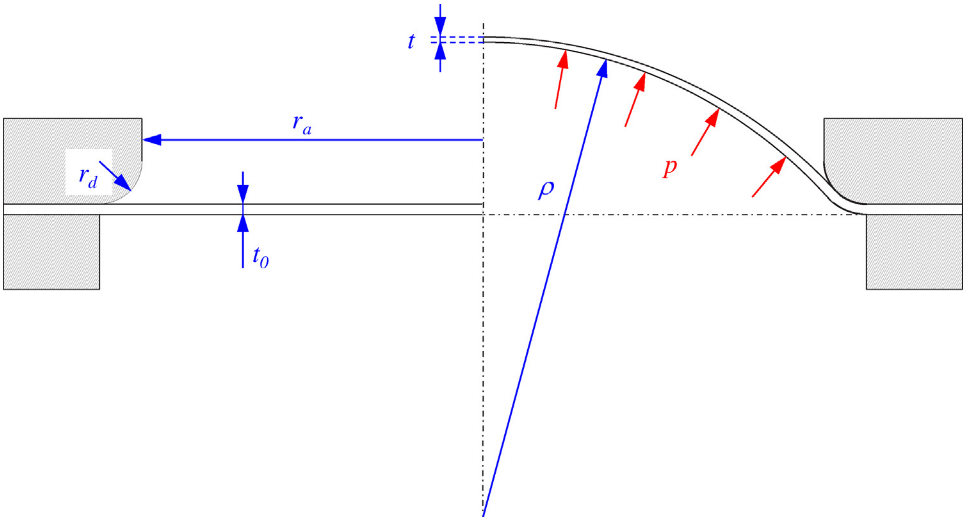

Fig. 1. Bulge test with initial (left) and pressurized blank (right).

material properties. His basic equations, that only assume planar isotropy, have formed a sound theoretical starting point for many researchers. Hill's special solution assumes a circular arc for the full curvature within the die aperture without considering a die radius (r_d in Fig. 1). This allowed a calculation based on the height of the pole position and geometrical data of the test. Despite the known limitations Hill found that the results he obtained for the stress–strain curve were in good agreement with experiments up to strains of 0.4. This procedure with a measurement of the pole height and the fluid pressure as the only process variables, has been refined over the years. Panknin (1959) showed the importance of including the die radius in the calculation of the curvature. Several authors developed pragmatic equations for the thickness at the pole position. Lăzărescu et al. (2011) recently published a refinement of an equation that was initially due to Kruglov et al. (2002). Results are good but current measurement techniques allow more accurate solutions.

The paper by Young et al. (1981) describes a procedure for a more direct measurement of the curvature and strain at the pole position using a spherometer and an extensometer. This procedure has enhanced the applicability and exchangeability of bulge test results. A three point spherometer measures the height difference between the pole and three positions at a fixed radius. The radius of curvature of the (assumed) sphere at the pole follows from a simple geometrical equation. An extensometer measures the increased diameter of two points close to the pole in one material orientation. With the known radius of curvature the strain at the pole can be closely approximated. Santos et al. (2010) describe a recently developed bulge tester using this procedure. The positions of the three points for the spherometer and the initial diameter for the extensometer have been optimized using finite element simulations. A claimed advantage is a stable and smooth evaluated flow curve. Bleck and Blumbach (2005) describe an optical system that operates according to the same procedure. The spherometer is replaced by a laser cross hair. The laser sensors can measure the shape of the bulge in the directions of the laser lines. The calculation of the radii of curvature (typically in rolling direction, RD, and transverse direction, TD) is based on the height difference of points at a fixed difference from the pole. The extensometer is replaced by a single camera system and an applied grid on the blank. The maximum error in the stress–strain determination is stated to be less than 5%.

Mutrux et al. (2008) describe an optical system using two cameras and a 2 mm grid, resulting in a 3D image of the bulge. The points that form a cross through the pole are used for the evaluation. In particular the need to fit to multiple points to reduce the influence of noise is noted. The points are fitted to a sphere for the determination of the radius of curvature. It is also noted that not only the noise, but also the average value of the radius changes when more points are considered. In other words: the shape is not a perfect sphere. Keller et al. (2009) describe an optical 3D system that is used by the German IDDRG Working Group as a reference for an ISO proposal. A speckle pattern is applied to the blank. The optical system determines for each facet, a virtual square specified in pixel dimensions, the 3D coordinates and surface strain. The facets form a regular pattern that describes the bulged surface. The amount of data that is available in 3D optical measuring systems allows fitting of the bulged surface to different shape functions. Peters et al. (2011) fit the surface coordinates to a spheroidal equation. In addition some refinements are added to the procedure. The radius of curvature that is established for the outer surface of the bulge is reduced by half the thickness at the pole, giving the assumed radius for the midplane. The surface strains are corrected for bending and the thickness strain is corrected for elastic components. The procedure is tested on simulation results with superposed noise, using isotropic material properties. The accuracy is stated to be better than classical evaluation methods, but not fully accurate. Volk et al. (2011) fit the surface coordinates to a paraboloid equation. Other refinements to the evaluation method are not mentioned. Results are in good agreement with expectation. An important remark is made on the influence of strain rate sensitivity, which should not be neglected in the interpretation of experimental results. A similar remark was made by Mulder et al. (2012) on dynamic effects in general, i.e. strain rate and temperature, when comparing different experimental techniques.

Using numerical simulation Gutscher et al. (2004) investigated the influence of material properties. They varied the work hardening coefficient (n-value) and the strain ratio (r-value) but always within the context of planar isotropy. Güner et al. (2009) investigated the influence of geometrical dimensions (aperture radius, die shoulder radius) for three different materials on the accuracy of the determined flow curves. One of the conclusions is that the sphere fit of the surface introduces a systematic error and other mathematical equations should be considered. Lemoine et al. (2011) investigated the ratio between sheet thickness and aperture radius. They also found a systematic deviation from the input curve using a sphere fit and suggested to improve the evaluation procedure.