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Journal of Materials Processing Technology 146 (2004) 1–7

Journal of Materials Processing Technology

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Determination of flow stress for sheet metal forming using the viscous pressure bulge (VPB) test

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Abstract

In sheet metal forming operations the mechanical properties of the sheet material (i.e. flow stress or stress–strain curve) greatly influence metal flow and product quality. Therefore, accurate determination of the flow stress is of paramount importance in process simulation via finite element method (FEM). In this paper the use of the viscous pressure bulge (VPB) test for determination of flow stress under biaxial state of stress is discussed. With the VPB test, larger strains, which are relevant for stamping operations, can be achieved compared to the standard tensile test used to-date. In this study, FEM simulations and experiments have been performed in order to study the interrelationship of the geometric and material variables such as dome wall thinning, dome radius, dome height, strain hardening index, material strength coefficient, and anisotropy. From the study a robust method to determine the flow stress under biaxial deformation conditions using a viscous material as pressure medium has been developed.

Keywords: Sheet metal forming; Formability; Flow stress; FEM

1. Background

The deformation properties of sheet material are determined using a standard tensile test which gives the ultimate tensile strength (UTS), the yield strength (*Y*), the maximum percent elongation and, if needed, the reduction in area at rupture (*R*). The tensile test is simple and inexpensive to conduct, but it has limitations because it only provides the stress–strain behavior of the sheet material under uniaxial deformation conditions. In contrast, during stamping operations the material deforms under biaxial conditions of deformation. Under the biaxial tensile this state of stress, the true strain level may reach a magnitude of about 0.7 or more. With the standard tensile test, however, the true strain level can hardly reach 0.3. Therefore, in process simulations via finite element method (FEM), the tensile test stress–strain (σ–ε) curve, often expressed as $\bar{\sigma} = K\bar{\varepsilon}^n$ (*K* the strength coefficient, *n* the coefficient of strain hardening), must be extrapolated. This may cause significant errors in process simulations using FE codes.

The objective of this study was to develop a practical flow stress determination procedure using the hydraulic bulge test principle where viscous material is used as a pressure medium instead of a hydraulic fluid. In the development of this method, analytical investigations and simulations concerning the hydraulic bulge were carried out. To verify the developed method, experiments with different materials have been conducted. The flow stress curve of these materials have been evaluated with the viscous pressure bulge (VPB) test and compared with the results obtained from the tensile test.

2. Theoretical investigation

2.1. Membrane theory

The membrane theory is commonly used to determine the flow stress curve with the hydraulic bulge test [1,2] (Fig. 1). The membrane theory neglects bending stresses. Thus, it is only applicable for thin sheets and gives for the bulge test the following relationship between stresses, sheet geometry and bulge pressure:

$$\frac{\sigma_1}{R_1} + \frac{\sigma_2}{R_2} = \frac{p}{t} \qquad (1)$$

where σ_1 and σ_2 are the principle stresses on the sheet surface, R_1 and R_2 are the corresponding radii of the curved surface, p the hydraulic pressure, and t the sheet thickness.

For the axisymmetric case of the hydraulic bulge test, $\sigma = \sigma_1 = \sigma_2$ and the radius of the dome is $R_\mathrm{d} = R_1 = R_2$.

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doi:10.1016/S0924-0136(03)00838-0

Nomenclature

d_c	diameter of the cavity
h_d	dome height
K	material strength coefficient
n	strain hardening coefficient
p	hydraulic pressure
r	anisotropy value
R_c	radius of the fillet of the cavity
R_d	radius at the apex of the dome
R_1, R_2	radii of the curved surface
t	sheet material thickness
t_d	thickness at the apex of the dome
t_0	initial sheet thickness

Greek letters

$\bar{\varepsilon}$	effective strain
$\bar{\sigma}$	effective stress
σ_n	normal stress
σ_1, σ_2	principal stresses

Therefore, Eq. (1) can be simplified to:

$$\sigma = \frac{pR_d}{2t_d} \tag{2}$$

where t_d is the thickness at the top of the dome. In hydraulic bulge testing, pressure is applied on the internal sheet surface. No normal forces act on the outer sheet surface. Therefore, the average stress, σ_n, in the sheet normal to the sheet surface is:

$$\sigma_n = \tfrac{1}{2}(-p+0) = \tfrac{1}{2}(-p) \tag{3}$$

The effective stress, $\bar{\sigma}$, can be calculated by Tresca's plastic flow criterion:

$$\bar{\sigma} = \sigma_{max} - \sigma_{min} = \frac{pR_d}{2t_d} - \frac{-p}{2} \tag{4}$$

or

$$\bar{\sigma} = \frac{p}{2}\left(\frac{R_d}{t_d}+1\right) \tag{5}$$

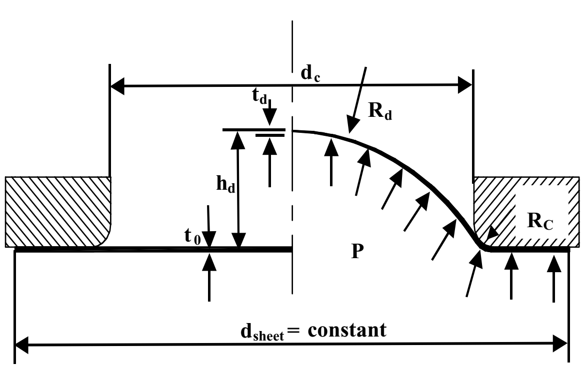

Fig. 1. Geometry of the bulge test.

The effective strain, $\bar{\varepsilon}$, can be calculated for the hydraulic bulge test using the sheet thickness:

$$\bar{\varepsilon} = -\varepsilon_t = \ln\left(\frac{t_d}{t_0}\right) \tag{6}$$

From Eqs. (4) and (5), it can be seen that four variables are needed to determine the flow stress of a material: (a) instantaneous radius of curvature, R_d; (b) instantaneous wall thickness at the apex of the dome, t_d; (c) instantaneous dome height; (d) pressure, p. Gologranc [2] successfully determined a flow stress curve using instrumentation that allowed all four variables to be measured. The handling of fluid and the complex instrumentation to measure all the variables indicate that this procedure may be expensive and complicated. Therefore, in the present study research was carried out to develop analytical methods for determining the radius of curvature and wall thickness at the apex of the dome.

2.2. Calculation of the radius at the top of the dome

The radius at the top of the dome can be calculated by assuming that the dome is spherical and that there is not a fillet in the cavity of the die:

$$R_d = \frac{d_c^2 + 4h_d^2}{8h_d} \tag{7}$$

where d_c is the diameter of the cavity, and h_d the dome height. Considering that there is a fillet in the cavity, R_c, and assuming that the dome is spherical, the radius of the dome can be calculated by:

$$R_d = \frac{((d_c/2)+R_c)^2 + h_d^2 - 2R_c h_d}{2h_d} \tag{8}$$

Panknin [1] investigated the hydraulic bulge test experimentally, measuring the radius at the top of the dome of the bulged samples with radii gages. He also calculated the radius at the apex of the dome using the dome height, assuming that the dome is a part of a sphere and considering the fillet in the cavity of the die. The calculated radius agreed well with experimental values for dome heights, normalized by the diameter of the cavity, of up to $h_d/d_c = 0.28$. For larger dome heights, the radius of the dome determined experimentally was found to be up to 10% smaller than the calculated one. Gologranc [2] had similar results with his experiments.

2.3. Calculation of the thickness at the apex of the dome

Hill [3] investigated analytical methods to describe the deformation in the hydraulic bulge test. In his calculations he assumed that the locus of each point on the sheet is a circle during the deformation. With this assumption the thickness at the top of the dome can be calculated by the following equation:

$$t_d = t_0\left(\frac{1}{1+(2h_d/d_c)^2}\right)^2 \tag{9}$$

This equation was improved by Chakrabarty and Alexander [4] who considered the strain hardening coefficient, n, in the equation:

$$t_d = t_0 \left(\frac{1}{1 + (2h_d/d_c)^2} \right)^{2-n} \quad (10)$$

Panknin [1] conducted hydraulic bulge experiments with materials with different strain hardening index, n, and found that the strain hardening index has significant influence on the dome height and thickness at the top of the dome. He found that the thickness distribution is more uniform in materials with larger strain hardening. This means that a material with larger strain hardening has, at the same dome height, a larger thickness at the top of the dome. Gologranc [2] had the same results with his experimental investigation. He found that the thickness at the top of the dome differs considerably between Eq. (9) and the experimental results. The bulge test was investigated also by Johnson and Duncan [5] and Rees [6].

2.4. FEM approach

The ERC/NSM has developed a tooling for flow stress determination as shown in Fig. 2.

This tooling provides an online measurement of dome height and pressure. The pressure to bulge the specimens is raised by using viscous medium instead of fluid, making the tooling design simple and easy to use. The instantaneous radius of curvature, R_d, and wall thickness at the top of the dome is obtained by the aid of FEM.

The tooling (Fig. 2) is designed for a double action hydraulic press. The upper die is connected to the slide of the press and the lower die is connected to the cushion of the press. The punch in the lower die is fixed with the press table and therefore stationary. At the beginning, the tooling is open and the blank sheet is placed between the upper and the lower dies. Then dies are closed to clamp the blank material and the slide moves down together with the entire die set. Consequently, the viscous medium is pressurized by the stationary punch and the sheet is bulged by the viscous medium flowing into the upper die. The sheet is deformed until its forming limit is reached and it bursts. The tooling is equipped with a lock-bead to ensure that no material from the periphery of the blank is drawn into the cavity.

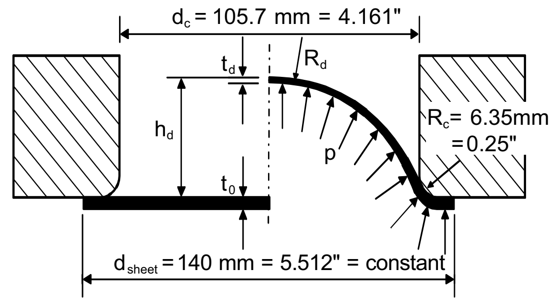

Fig. 3. Geometry of the simulated bulging test.

The wall thickness at the apex of the dome is obtained via FEM. In the development of the procedures to determine the flow stress, FEA was conducted to study the interrelationship between the geometrical and material variables. The main focus was to investigate the influence of: (a) strain hardening index; (b) anisotropy; (c) material strength coefficient on the deformation behavior. A dynamic explicit commercial FE code, PAMSTAMP was used. The geometrical model of the simulation is shown in Fig. 3. The sheet metal on the flange is fixed so that it cannot be drawn into the cavity.

The flow stress of sheet metals can be described by the power law ($\bar{\sigma} = K\bar{\varepsilon}^n$). In the FE simulations the flow stress curve from aluminum killed deep drawing quality (AKDQ) steel was used. The specifications for this material were: sheet thickness $= 0.83$ mm (0.033 in.), strength coefficient, $K = 495$ MPa (71800 Psi), strain hardening index, $n = 0.183$. Since the geometry of the hydraulic bulge test is axisymmetric only a quarter of the geometry was modeled.

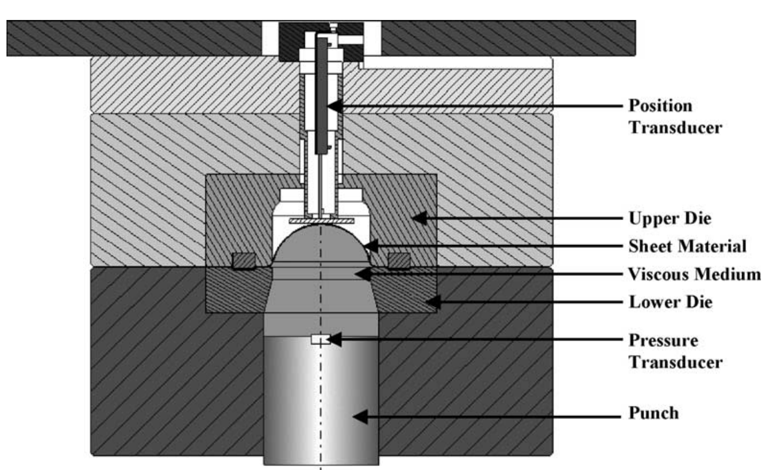

Fig. 2. Sketch of tooling used in the VPB test.

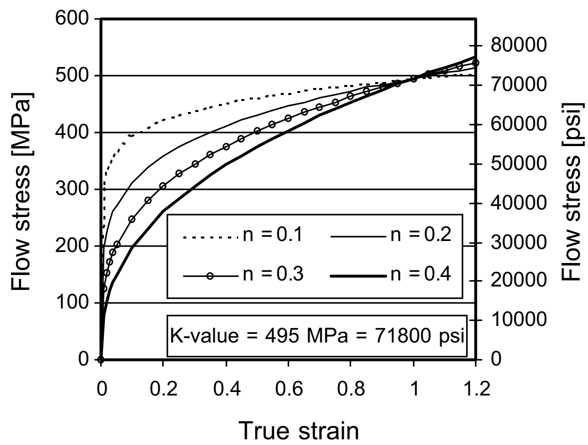

Fig. 4. Flow stress curves ($\bar{\sigma} = K\bar{\varepsilon}^n$) for constant k and various n-values.

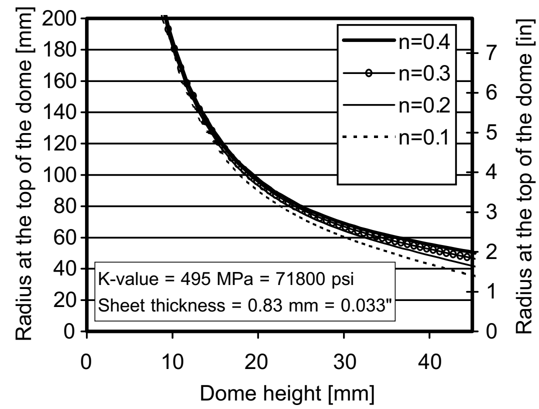

Fig. 6. Radius at the top of the dome versus dome height for constant k and various n-values.

2.4.1. *Influence of the material strength coefficient, K, on deformation*

With a constant strain hardening index, n, the K-value varies linearly with stresses. Therefore, K-value has no influence on the deformation under VPB forming, i.e., at a constant dome height the change in K-value does not influence the geometric variables such as wall thickness distribution and dome radius.

2.4.2. *Influence of the n-value on deformation*

To investigate the influence of the n-value on the deformation in the VPB test, simulations were run with different n-values between 0.1 and 0.4. The flow stress curves that were used in the simulation are shown in Fig. 4. All curves intersect at a true strain equal to 1 because the K-value is the same for all curves. The flow stress curves with larger n-value have larger gradients.

The thickness at the top of the dome versus the dome height is plotted in Fig. 5 for different n-values. The n-value has a considerable influence on the thinning at the top of the dome. For large n-values, the thinning at the top of the dome is less than for small n-values. Fig. 6 shows that the n-value has a small influence on the radius at the top of the dome at constant dome height. The radius at the top of the dome is smaller for smaller n-values because the deformation is localized at the center of the dome. The FE simulations have also shown that the change in the thickness ($t = 0.83$ and 2 mm) of the blank material has no significant effect on the dome height.

2.4.3. *Influence of the anisotropy on deformation*

Anisotropy of sheet metals can be described by the r-value as follows:

$$r = \frac{\varepsilon_w}{\varepsilon_t} \tag{11}$$

The r-value can be obtained by the tensile test. The r-value describes the ratio of the strains in the direction of the width (ε_w) and thickness (ε_t). An isotropic material has an r-value equal to 1. A material with a larger r-value will thin less during the tensile test. FE simulations were run with three different r-values ($r = 0.6$, 1 and 1.6) to investigate if anisotropy has an influence on the deformation during the hydraulic bulge test. As shown in Fig. 7, the simulation results show that the r-value has a very small influence on the correlation between the dome wall thickness at the apex of the dome

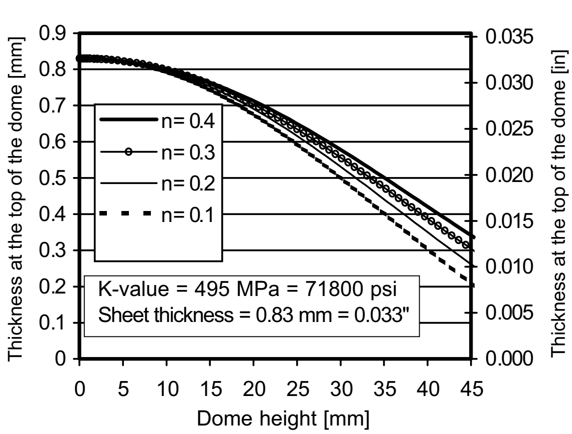

Fig. 5. Thickness at the top of the dome versus dome height for constant k and various n-values.

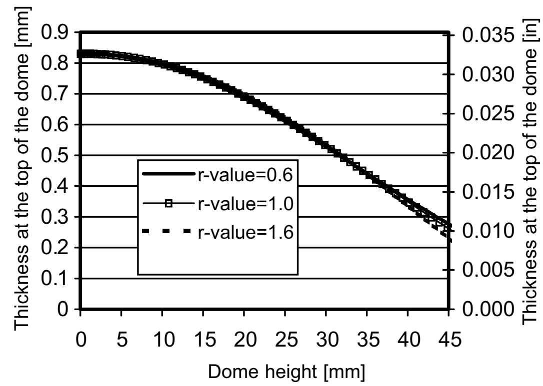

Fig. 7. Thickness at the top of the dome versus dome height for various r-values.

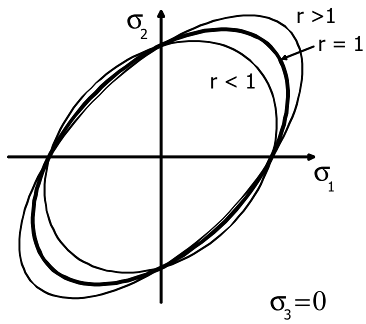

Fig. 8. Yield loci.

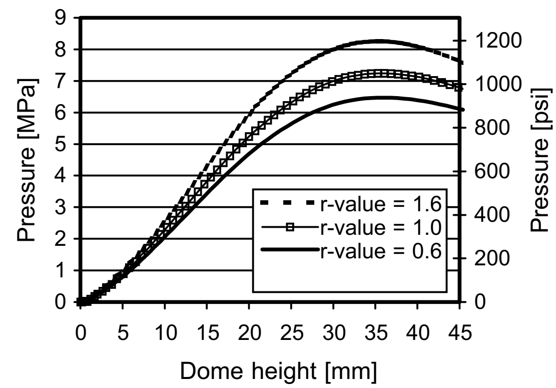

Fig. 9. Hydraulic pressure versus dome height for different *r*-values.

and the dome height. FE simulations have also shown that anisotropy has no significant effect on the radius at the apex of the dome.

Although in the previous discussion we have found no effect of anisotropy on geometrical variables of the deforming dome, the yield locus (see Fig. 8) shows the effect of anisotropy on the stress.

If the *r*-value changes, the yield locus is transformed as shown in Fig. 8. For tensile test conditions, flow stress remains the same ($\sigma_2 = \sigma_3 = 0$). However, for biaxial bulging conditions the flow stress changes considerably ($\sigma_1 = \sigma_2, \sigma_3 = 0$). This phenomenon can also be observed from the FE simulations (Fig. 9), where the hydraulic pressure increases with increasing *r*-value.

2.4.4. Determination of flow stress

For the determination of the flow stress curve, it is necessary to know the radius and the thickness at the top of the dome during the deformation The radius and the thickness are calculated as a function of the dome height and the *n*-value by using a database, which was created by FEM.

The procedure to determine the flow stress is shown in Fig. 10. This database has been created using the data from Figs. 5 and 6 for different *n*-values. It should be noted that a database for different *n*-values is only created once. Once created, the database can be used for any material. As discussed in Section 2.4.1, the *K*-value does not influence the geometric variables.

As shown in the flow chart (Fig. 10) determination of the flow stress start by assigning an initial *n*-value. Then the flow stress curve and the *K*- and *n*-values ($\bar{\sigma} = K\bar{\varepsilon}^n$) are calculated. This *n*-value is then used to calculate the thickness and the radius at the top of the dome and flow stress curve again. Iteration is continued until the difference between the new and the previous *n*-value is less than 0.001.

2.5. Experiments

The VPB experiments were conducted with the tooling described in Section 2.4. The press used for these experiments was a 160 t hydraulic press with a hydraulic NC cushion. The maximum cushion force of the press is 100 t.

2.5.1. Test parameters and materials

The tested materials were AKDQ steel, high strength (HS) steel, and aluminum AA 6111. These materials were used because they are widely used for stamping parts.

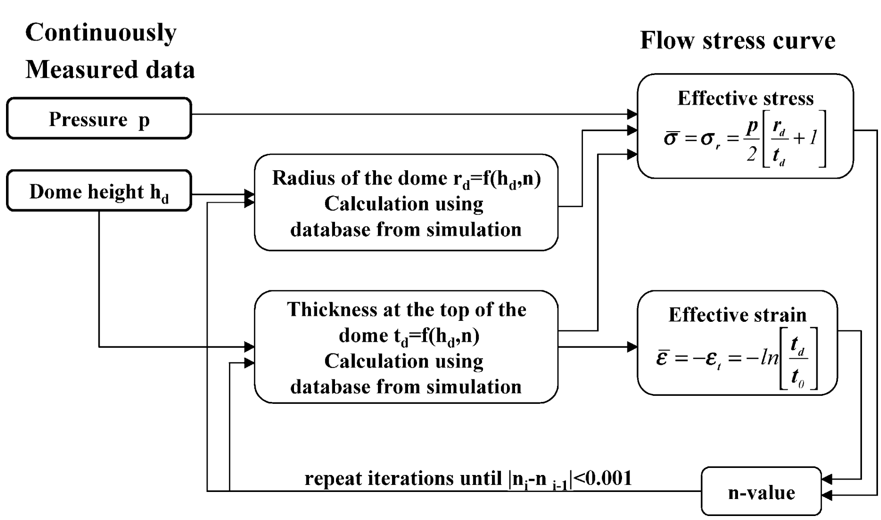

Fig. 10. Determination of flow stress curve.

Table 1
Parameters used in the viscous bulge test

	Metric	British
Test duration	∼43 s	
Ram speed	0.9 mm/s	0.04 in./s
Clamping force	800 kN	3500000 lbf
Diameter of the cavity in the upper die	105.7 mm	4.16 in.
Radius of the fillet of the cavity	6.4 mm	0.25 in.
Size of the test sample	250 mm × 250 mm	10 in. × 10 in.

The blank sheet thicknesses were 0.83 mm (0.033 in.) for AKDQ and HS steel, and 1.04 mm (0.041) for AA 6111. In Table 1 the parameters for the hydraulic bulge test are shown. The speed of the ram was set to a low speed of 0.9 mm/s (0.04 in./s). A clamping force of 800 kN (3,500,000 lbf) along with the lock-bead to ensure that the material is not drawn into the cavity in the die was used. Fig. 11 shows the tested samples.

2.5.2. Flow stress curve determined by VPB and tensile test

The flow stress curves obtained at low strain rates for AKDQ steel, HS steel and aluminum AA 6111 were evaluated by the VPB and tensile tests (strain rate in both test was about 0.02 s^{-1}). The main difference between these two tests is the stress state, i.e., uniaxial in the tensile test and biaxial in the hydraulic bulge test. Localized necking occurs for most materials in a tensile test at effective strains between 0.2 and 0.4. In VPB tests, localized necking occurs at effective strains between 0.5 and 0.8. Figs. 12–14 show that the VPB test attains a higher strain level as compared to the tensile test before material fractures.

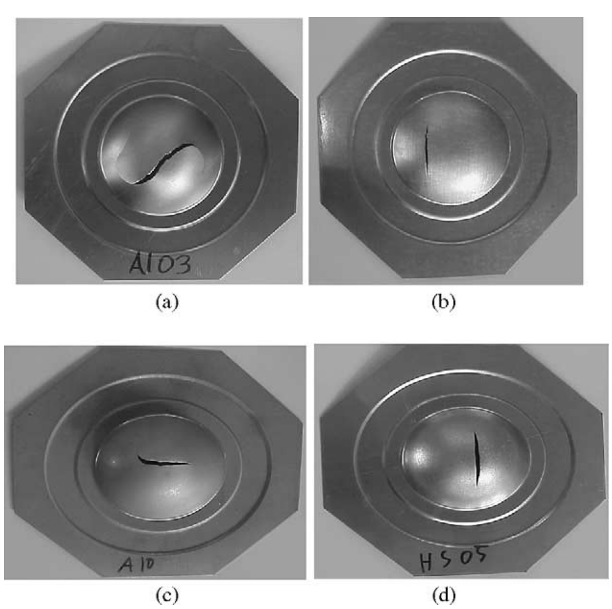

Fig. 11. Bulged samples: (a) AKDQ steel; (b) HS steel; (c) aluminum AA 6111; (d) ferritic stainless steel.

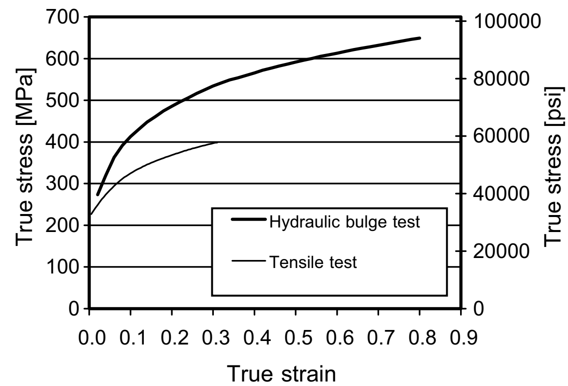

Fig. 12. Flow stress curves of AKDQ steel.

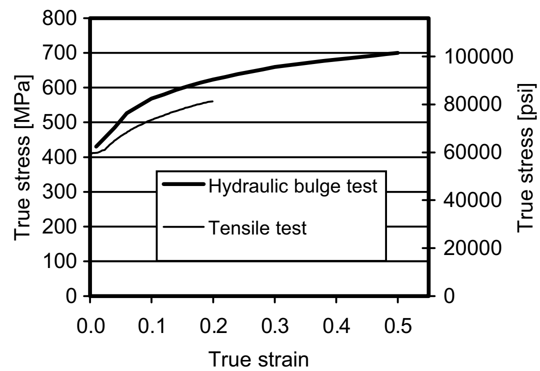

Fig. 13. Flow stress curves of HS steel.

For AKDQ steel, the flow stress determined using the VPB test is much larger than the one determined by the tensile test (Fig. 12). The difference is between 10 and 35% and increases with strain. Fig. 13 shows the flow stress curves for HS steel determined by the VPB test and the tensile test.

In these tests the maximum difference is 12%. The flow stress curves for aluminum determined from the VPB and tensile test are very similar (Fig. 14). The maximum difference is 6%. These experimental results show that the flow

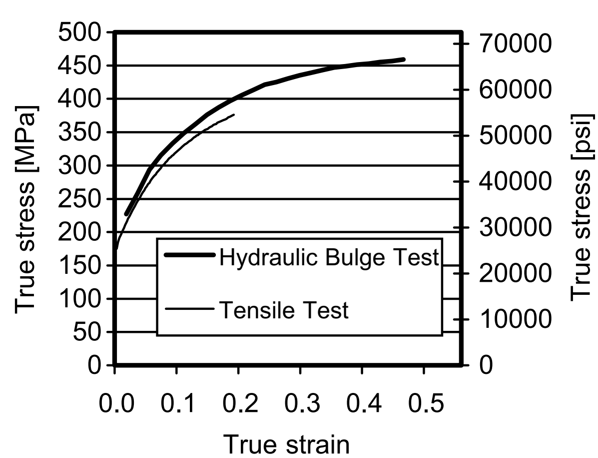

Fig. 14. Flow stress curves of aluminum AA 6111.

stress curve in a biaxial stress state can be considerably different from that obtained in an uniaxial state of stress.

2.6. Summary and conclusions

The VPB test is a material test for sheet metal to evaluate formability and determine the flow stress curve. Due to the biaxial state of stress induced in this test, the maximum achievable strain before necking is much larger than in the tensile test. Therefore, the flow stress curve can be determined up to larger strains than in the tensile test. This is important for process simulations using FE analysis.

The FE simulations have demonstrated that only the n-value of the material has a significant influence on the dome height and thickness at the apex of the dome [$t_{\mathrm{d}} = f(h_{\mathrm{d}}, n)$], as well as on the correlation between dome height and radius at the top of the dome [$R_{\mathrm{d}} = f(h_{\mathrm{d}}, n)$]. This has made possible the application of FEM to generate a single database that can be used to determine the radius and wall thickness at the apex of the dome. Hence, simplifying the determination of flow stress via VPB test. Furthermore, the use of viscous material instead of fluid as a pressure medium has made the VPB test simple and easy to evaluate the formability of sheet metals. The use of a viscous material as a pressure medium, however, has a disadvantage. At high deformation velocities, the viscous material is strain rate dependent. Therefore, the pressure readings do not represent purely the hydrostatic pressure but also include the “stiffening” or the pressure increase of viscosity of the viscous material with strain rate. At low deformation speeds, as used here, this effect is negligible.

The study has also shown that the flow stress curves from the tensile and VPB tests can differ considerably, especially for AKDQ steel.

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