Determination of sheet material properties using biaxial bulge tests

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Abstract

Tensile test, conventionally used to determine the flow stress of sheet materials under uniaxial state of stress, is limited to small amount of strain / deformation (due to necking) compared to higher strain/deformation and biaxial state of stress that occur in practical stamping operations. Therefore, in this study, biaxial bulge tests were developed to determine the material properties (flow stress, anisotropy and formability) over a large strain/deformation range. The developed tests were applied to: a) DR210 steel, b) DDS steel, c) AKDQ steel, d) DP600 steel, and e) AL5754-O. The results were validated by comparing FE predictions with experiments in deep drawing of round cups. This study showed that in many, but not all, cases the tensile data, if properly

extrapolated, is adequate for use in FE simulation. However, the bulge test is a better indicator of material formability and quality than the tensile test. This is especially true when material properties are not always consistent and vary from batch to batch, as it is the case with most high strength steels.

1 Introduction

For reliable FE simulations of sheet forming operations, it is necessary to have material data, namely a) constants of the selected yield criterion, b) constants of selected hardening law and c) flow stress of the sheet material. Conventionally, these data are obtained from uniaxial tensile tests and are not sufficient because a) maximum strain obtained in uniaxial tensile test before necking is relatively small and b) the stress state in tensile test is uniaxial while in regular stamping it is biaxial. Therefore, it is necessary to obtain the material properties from a biaxial test, which provides data for large strain range relevant to stamping operations. Circular bulge test has been used to estimate the flow stress of the material in biaxial stress state [1,2,3,4,5]. In this study, a new test was developed to use along with the existing circular bulge test to estimate both the flow stress and the anisotropy constants for the Hill's yield criteria. The flow stress and anisotropy obtained from the bulge test were compared with tensile data and used in FE simulation for validation of the test method.

2 Background on biaxial tests

The elliptical shape of the yield surface under plane stress conditions changes with the anisotropy coefficients in rolling, $r_{0,}$ and transverse, r_{90}, directions (6,7). Therefore, in order to estimate the anisotropic coefficients from the biaxial test, a test method, such as the elliptical bulge test, that induces non-equal biaxial stresses must be considered. In the elliptical bulge test, for a given die geometry, different strain paths can be obtained by changing the relative position of the sheet material. Initially two positions of the sheet with respect to the die were considered, namely a) Elliptical bulge test 1: rolling direction of the sheet coincides with major axis of ellipse (Figure 1), corresponding to stress path (Figure 2), b) Elliptical bulge test 2, transverse direction of the sheet coincides with major axis of ellipse (Figure 1), corresponding to stress path

(Figure 2). In both tests, the principle stress in the sheet coincides with anisotropy axis therefore shear stress ($\tau_{xy} = 0$). Using Hill's 1948 yield criterion, it is possible to obtain the values of the flow stress, $\bar{\sigma}$, and the anisotropy coefficients r_0 and r_{90} from three tests, namely circular bulge test, elliptical bulge test 1 and elliptical bulge test 2. The effect of the shear stress (r_{45}) can be studied by placing the sheet such that the rolling direction of the sheet is at an angle of 45^{o} to the major and minor axis of the die, Figure 1.

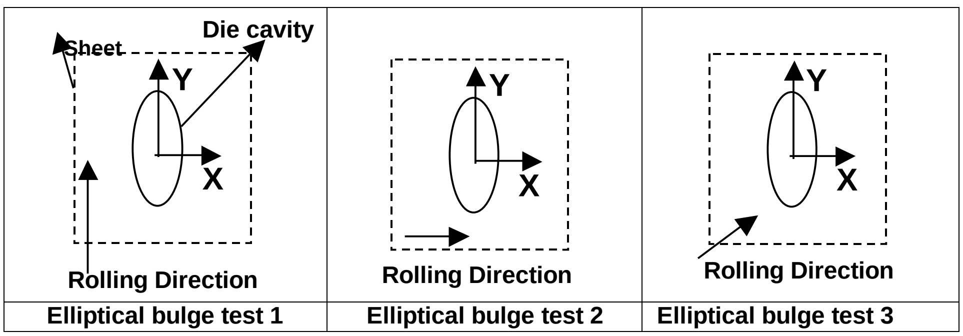


Figure 1: Schematic of positioning of sheet metal with respect to die cavity in the proposed elliptical bulge test

In the elliptical bulge tests, the pressure required to bulge the specimen to a dome height would be different for bulge test 1 and test 2 depending on the anisotropy constants.

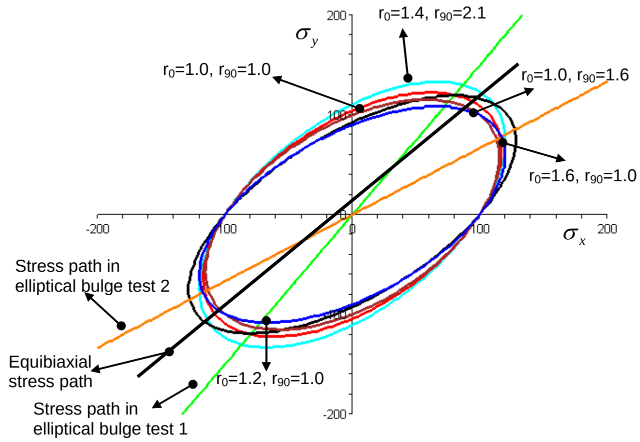


Figure 2: Schematic illustration of the stress path in the elliptical bulge test 1 and elliptical bulge test 2

3 Preliminary FE simulations to validate the test concept

FE simulations were conducted to study the effect of the anisotropy constants on the forming pressure for the elliptical die geometry of major axis to minor axis ratio of 2.0. The material properties for the AKDQ sheet of thickness 0.83 mm were used in the simulation (Table 1). Table 2 shows the simulation matrix considered for this study. The values of each anisotropy coefficient were incremented by 0.2 for each case. In each case, FE simulations of elliptical tests 1, 2 and 3 were conducted.

Table 1: Material properties for AKDQ steel used in the FE simulations

Thickness	K-Value[MPa]	n-Value	Pre-strain
0.83	495	0.183	0.005

Table 2: Simulation matrix to study the influence of anisotropy constants on the forming pressure, bulge height and the thickness at the top of the dome.

Simulations	Anisotropy coefficients		
	R_0	R_{45}	R_{90}

Case A	1.0	1	1
Case B	1.2	1	1
Case C	1	1	1.2
Case D	1	1.2	1

In case A, as expected, the forming pressure necessary to reach a dome height is the same for all the tests. Figure 3. In case B, a higher forming pressure was predicted in the elliptical test 2 when rolling direction of the sheet was kept parallel to the minor axis of the die (Figure 4). In case C, higher forming pressure was observed in the elliptical test 1 and elliptical test 3 compared to elliptical test 2 when rolling direction of the sheet was kept parallel to the major axis of the die (Figure 5). In case D, the forming pressure predicted by FE simulation was the same for both test 1 and test 2 as r_{45} does not influence the yielding behavior of the material when the principal stress coincides with major and minor axis. The difference in the forming pressure between the test 3 and test 1/ test 2 was not significant (Figure 6). The results obtained from these preliminary FE simulations of the various circular and elliptical bulge tests, with different anisotropy coefficients, indicate that it is possible to inversely calculate the anisotropy coefficients from the proposed tests.

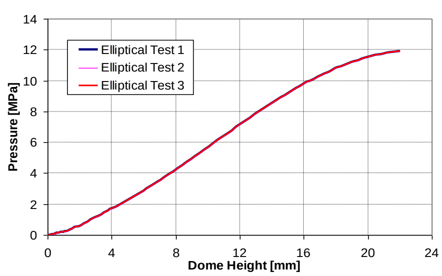


Figure 3: Forming pressure in the elliptical bulge test 1, elliptical bulge test 2 and elliptical bulge test 3 obtained from FE simulation for isotropic case.

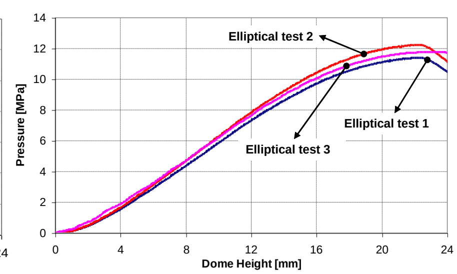


Figure 4: Effect of anisotropy constant along the rolling direction (r_0) on the forming pressure in the elliptical bulge test 1, elliptical bulge test 2 and elliptical bulge test 3

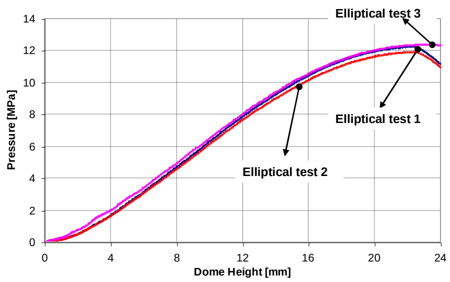


Figure 5: Effect of anisotropy constant along the transverse direction (r_{90}) on the forming pressure in the elliptical bulge test 1, elliptical bulge test 2 and elliptical bulge test 3

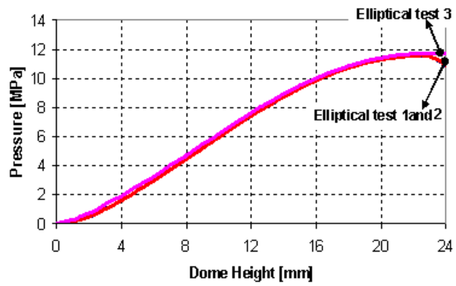


Figure 6: Effect of anisotropy constant along the 45^o to the rolling direction (r_{45}) on the forming pressure in the elliptical bulge test 1, elliptical bulge test 2 and elliptical bulge test 3

4 Test tooling and procedure

4.1 Tool Design

The difference in the forming pressure between the proposed elliptical tests increases with increase in the die ratio (ratio of major axis to minor axis of the ellipse) indicating that die geometry with higher die ratio is good for the elliptical test to determine anisotropy, Figure 7. However, increase in the die ratio decreases the maximum achievable dome height, Figure 8. An earlier study on elliptical bulge test [7] indicated that the maximum achievable strain decreases rapidly beyond the die ratio of 2.0. Therefore, the die ratio of 2.25 that could give a maximum difference in the forming pressure of at least 5 bar and maximum possible dome height of ~ 20 mm for AKDQ material was selected as optimum die geometry in this study.

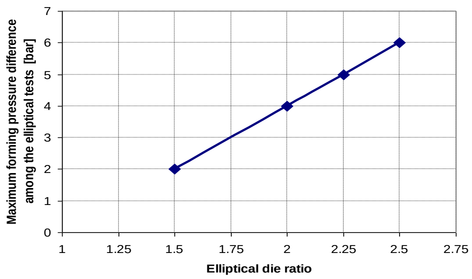


Figure 7: Comparison of the maximum difference in the forming pressure among the three elliptical test predicted by FE simulation for different elliptical die geometries using AKDQ steel sheet material

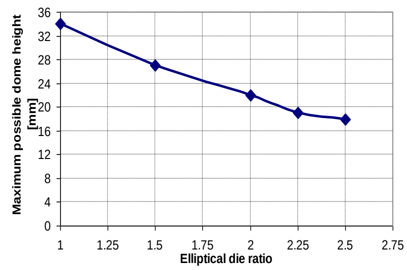


Figure 8: Maximum achievable dome height in the elliptical test predicted by FE simulation for different elliptical die geometries using AKDQ steel sheet material

4.2 Estimation of flow stress and anisotropy from bulge tests

The flow stress along the rolling direction and the anisotropy constants (r_0,r_{90}) were estimated from circular test, elliptical test 1 and 2 measurements. Estimated material properties (flow stress and anisotropy coefficients (r_0,r_{90})) and elliptical test were used to estimate anisotropy constant (r_{45}).Figure 9 shows the flow chart of the methodology used to estimate the material properties. Initially, the anisotropic constants will be assumed to be equal to 1. The unknown anisotropy coefficients (r_0,r_{90}) were estimated by minimizing the least square difference between the flow stress obtained from three tests (circular test, elliptical tests 1 and 2). Modified Newton method with line search was used for the minimization procedure. This procedure was repeated until the anisotropy values converged. The anisotropy constant (r_{45}) was latter estimated by minimizing the least square difference between the flow stress obtained from the elliptical test 3 and the estimated flow stress of the material from circular test, elliptical tests 1 and 2.

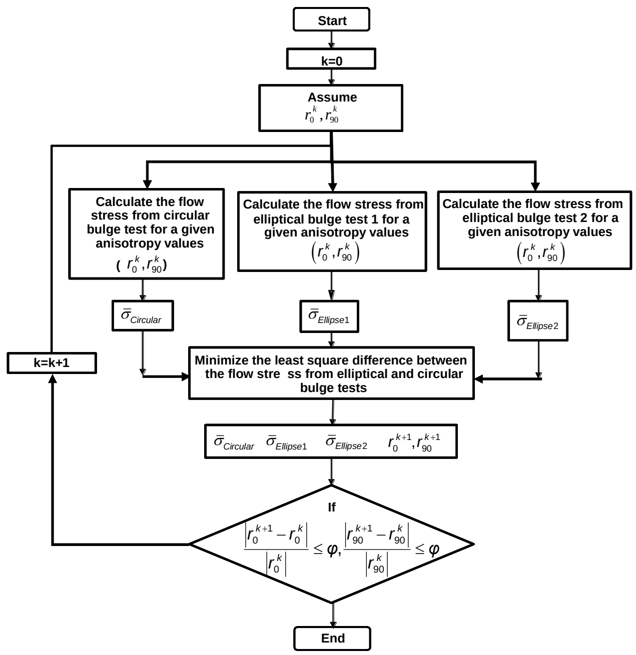


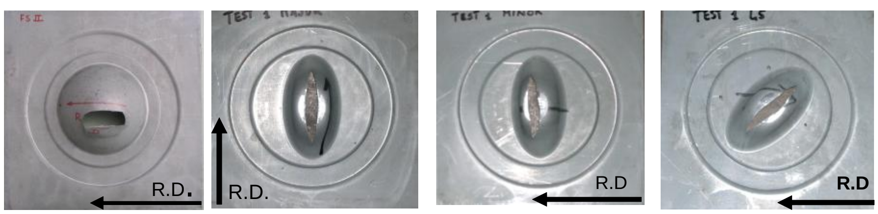
Figure 9: Flow chart illustrating the methodology to estimate the flow stress and anisotropy values (r0,r90,) from the circular and elliptical bulge tests 1 and 2

Bulging of the sheet in the circular die and the elliptical die can be analyzed using the closed form solutions available in the literature based on membrane theory [6,7]. More detailed derivations of these formulas can be obtained in [8]. Calculation of flow stress from bulge test for known anisotropy coefficients ($r_{0,}$ $r_{90,}$ and r_{45}) using the analytical equations requires measurement of pressure, thickness and radius of curvature at the top of the dome at different dome heights. Pressure and dome height can be easily measured real time in the experiment while radius of curvature and thickness are difficult to measure in real time during the tests.

FE simulations of the bulge test indicated that the thickness at the top of the dome at different dome heights and radius of curvature at the top of the dome are functions of only n value ($\sigma = k\varepsilon^n$) and independent of anisotropy values ([5,8]). Therefore a database (of thickness at the top of the dome and radius of curvature along the major and minor axis at different dome heights for different n values) was generated for each of the tests and used in the calculation of flow stress. In the calculations, the flow stress beyond the effective strain of 0.05 was assumed to follow the power law ($\sigma = k\varepsilon^n$).

4.3 Experimental results

The developed bulge tests were used to determine the flow stress and anisotropy of AKDQ steel thickness = 0.83 mm, DR210 steel thickness = 1.00 mm, DDS steel thickness = 0.77 mm, and AL5754-O thickness = 1.3 mm. At least three specimens were tested in each of the proposed tests for each material. Figure 10 shows example specimens after the test for AKDQ steel material. The flow stress and the anisotropy coefficients obtained for the tested materials using developed methodology are given in Figure 11 and Table 3, respectively.



Circular bulge test | Elliptical bulge test 1 | Elliptical bulge test 2 | Elliptical bulge test 3

Figure 10: Deformed AKDQ samples in circular bulge test, elliptical bulge test 1, 2, and 3

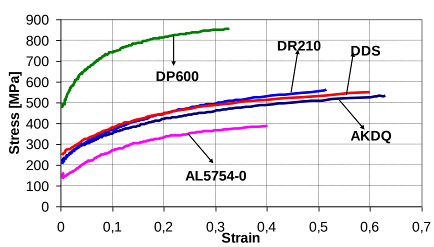


Figure 11: Flow stress of DR210 steel, DP600 steel, AKDQ steel. DDS steel and AL5754-O

	r0	r45	r90
DR210	2.04	2.05	2.32
DP600	1.38	1.20	1.42
AKDQ	1.27	1.00	1.59
DDS	1.32	1.00	1.41
AL5754	1.05	1.00	1.06

Table 3: Anisotropy coefficients of DR210 steel, DP600 steel, AKDQ steel. DDS steel and AL5754-

obtained from the developed bulge tests O obtained from the developed bulge tests

5 Comparison of flow stress and anisotropy data obtained from tensile tests and bulge tests

Tensile tests were conducted at ERC/NSM and at IWU, Chemnitz to estimate the flow stress and the anisotropy of the sheet materials. Figure 12 and Figure 13 show the comparisons for tested materials. It is observed that the flow stress from the bulge test was higher compared to tensile test for the same strain for the tested sheet materials except DP600. The differences could be due to the inability of the yield criterion to accurately model the behavior of sheet material in multi axial stress state. Also, it should be noted that the flow stress can be obtained for much larger strain range (usually twice) in bulge test compared to tensile test. Table 4 shows the comparison of the anisotropy values. The anisotropy values obtained from bulge test were lower compared to the tensile test. This may be due to the fact that in the bulge test the anisotropy values were obtained for strain range of 0.05 to 0.4, while in tensile test it is measured at strain of ~0.2.

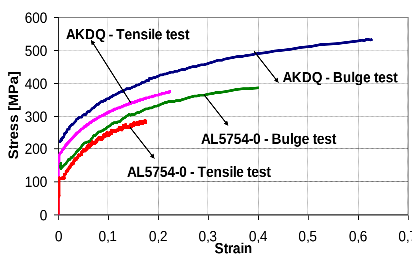


Figure 12: Comparison of flow stress from tensile test and bulge test for AKDQ steel and AL5754-O

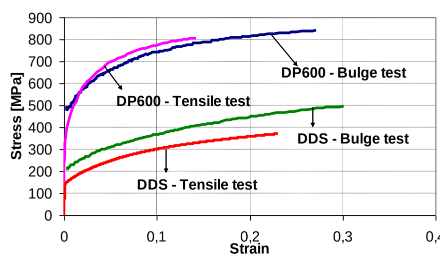


Figure 13: Comparison of flow stress from tensile test and bulge test for DDS steel and DP600

6 Validation of the estimated material properties

The flow stress and the anisotropy values obtained from tensile tests and bulge tests were observed to be different. Therefore, the estimated material properties were used in the FE simulation of a) bulge test and b) the round cup deep drawing process to compare the FE predictions with experimental measurements.

6.1 Bulge test

Figure 14 and Figure 15 show example comparison of pressure versus dome height curves in circular test and elliptical test-1, respectively for the DDS steel material. At higher dome heights, the pressure predicted by FE simulation using bulge test data agrees well with the experiment. FE simulation using tensile test data predicted lower pressure compared to the experiment as the flow stress from tensile test was lower than the bulge test for the same strain. Similar results were also observed for other tested sheet materials as well. Figure 16 and Figure 17 show example comparisons of thinning in circular test and elliptical test-1, respectively, for the DDS steel material. Thinning predicted by FE simulation using bulge test data agrees well with the experiment. FE simulation using tensile test data predicted higher thinning because at higher dome heights (strains), the flow stress input to the FE simulation were extrapolated leading to considerable error in the description of material behavior at higher strains

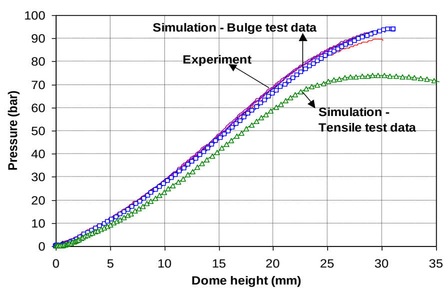


Figure 14: Comparison of pressure versus dome height curve in circular bulge test from experiment with FE simulation using flow stress from tensile test and bulge test

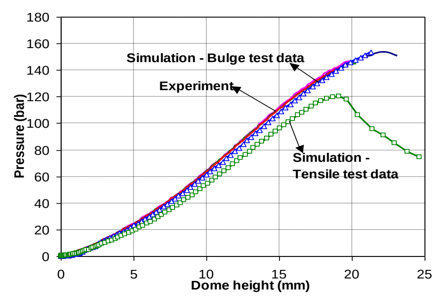


Figure 15: Comparison of pressure versus dome height curve in elliptical bulge test from experiment with FE simulation using flow stress from tensile test and bulge test

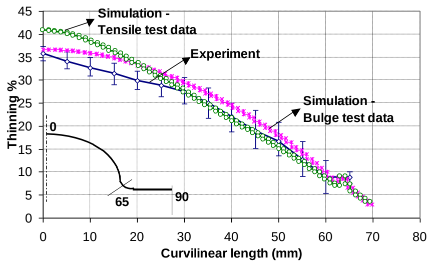


Figure 16: Comparison of thinning in circular bulge test from experiment with FE simulation using flow stress from tensile test and bulge test for dome height of 31.3 mm

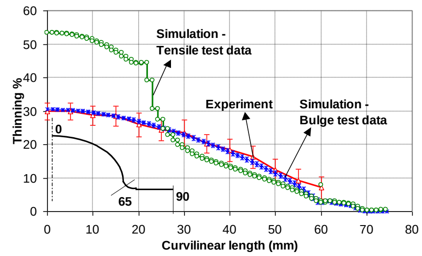


Figure 17: Comparison of thinning in circular bulge test from experiment with FE simulation using flow stress from tensile test and bulge test for dome height of 21.2 mm

6.2 Round cup deep drawing

Round cup (diameter =153 mm, height = 100 mm) deep drawing experiments were conducted using the tested sheet materials. Punch force, draw-in map and the thinning distribution along the rolling direction were compared between experiment and FE simulation. Figure 18, and Figure 19 show example comparisons of the punch force, and the thinning distribution along the rolling direction for DDS sheet material. Punch force predicted by FE simulation using the bulge test data was higher compared to experiments while the punch force predicted using tensile test data was lower compared to the experiment. Higher punch force was observed for the bulge test data compared to tensile test data because a) flow stress from bulge test was higher compared to tensile test data for same strain, and b) anisotropy from bulge test was lower compared to tensile test. Thinning predicted by FE simulation agreed better with experiments while FE simulation using tensile test data predicted less thinning compared to experiment. Less thinning was predicted for tensile test data compared to bulge test data because of higher anisotropy values obtained from tensile test. Similar observations were made for other tested sheet materials as well.

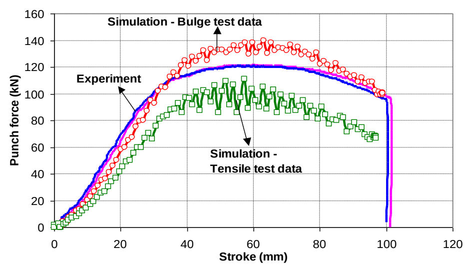


Figure 18: Comparison of punch force from experiment with FE simulation using flow stress from tensile test and bulge test for DDS sheet material

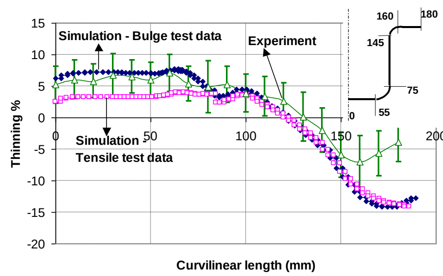


Figure 19: Comparison of thinning along rolling direction from experiment with FE simulation using flow stress from tensile test and bulge test for DDS sheet material

7 Conclusions

It is desirable to have flow stress and anisotropy data, obtained at large stains under biaxial deformation conditions. This data allows more reliable prediction of process variables in stamping operations, by using FEM simulations. In this study, an elliptical bulge test was developed to complement the exitsing circular bulge test to determine the flow stress and anisotropy coefficients of AKDQ steel, DR210 steel, DDS steel, DP600 steel and AL5754-O sheet material. FE predictions were compared with experiments to evaluate the findings. Conclusions drawn from this study are:

1. The flow stress along the rolling direction obtained from the bulge test was higher (~10%) compared to the tensile flow stress for the same strain. However, the strain hardening coefficients, obtained in both tests, were approximately the same. The flow stress could be obtained for much larger strain in bulge test, compared to tensile test.
2. The anisotropy coefficients obtained from bulge test were lower compared to the tensile test.
3. Pressure versus dome height curve, thinning distribution in circular and elliptical bulge tests predicted by FE simulation were compared with experiments. Results show that FE simulation using bulge test data accurately predicts experimental measurements.
4. Punch force, earing in the flange and thinning distribution in round cup deep drawing were predicted by FE simulation. Comparison with experiment indicates

that FE simulation using both the test data does not accurately predicts experimental measurements. This indicates that a closer look is necessary to the assumption made in the representation of the material behaviour to further improve the accuracy of the FE predictions.

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