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Determination of biaxial flow stress using frictionless dome test

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Abstract

The frictionless dome test can be used to evaluate formability and determine the flow stress curve of sheet materials under biaxial forming conditions. The flow stress curve, obtained from the frictionless dome test can be determined up to larger strains than in tensile test. As a result the need for extrapolation of the stress-strain curve is reduced. The objectives of this study are to (a) for a given sheet material determine *K* and *n* values in Hollomon's Law $(\sigma = K\varepsilon^n)$ by using experimental punch force vs. stroke curve and (b) develop the computer program, "PRODOME", to automate the calculation of *K* and *n* values.

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Keywords: Biaxial flow stress; Frictionless dome test; Sheet material properties

1. Introduction

Industry uses the finite element method (FEM) widely for process design to predict metal flow and defects in sheet metal stamping. The accuracy of the input data affects the accuracy of the results from FEM. The conventional method to determine the flow stress curve (true stress/strain curve) is the tensile test. In the tensile test, the deformation is uniaxial and does not fully represent the deformation strains seen in automotive stamping applications. In addition, because of early necking, the flow stress data from the uniaxial tensile test is limited to

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low strains. Thus, it is necessary to extrapolate the flow stress curves obtained from tensile tests to be used in FEM of complex parts with high strains. This extrapolation may introduce errors.

Through alternative tests (i.e. Viscous Pressure Bulge Test, and Frictionless Dome Test) it is possible to obtain the biaxial stress-strain conditions that occur in stamping and can be implemented into the FEM. In production environments, especially at smaller companies, the conventional hydraulic bulge test may not be practical to use to evaluate the characteristics (flow stress, formability) of the incoming sheet material. Therefore, work is in progress to develop an analysis to expand the application of the well-known Limited Dome Height (LDH) test, to conduct a Frictionless Dome Test, to obtain biaxial flow stress data.

In this application, it is necessary to use “perfect” lubrication between the solid punch and the sheet sample in order to obtain the fracture at the apex of the bulge. The dome height (or punch stroke) and the deformation force, measured during the test, are used to obtain the flow stress curve, using FE based inverse analysis. Fig. 1 illustrates the frictionless dome test being used to calculate flow stress for sheet samples, where (a) is the schematic with tooling dimensions used in experiments and simulations and (b) is the measured experimental punch force-stroke curve used in analysis. Fig. 2 is the output (flow stress) from the method developed in this paper compared with tensile test results.

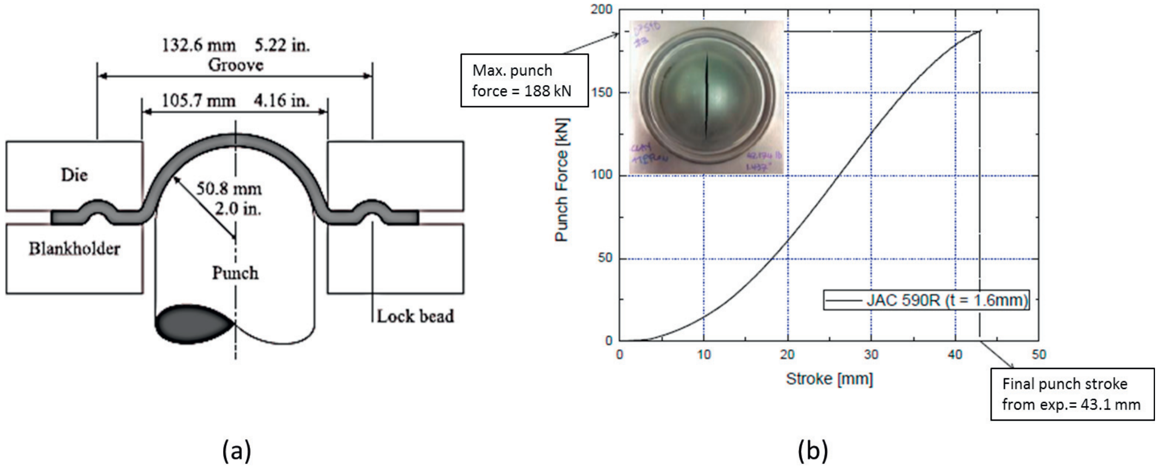

Fig. 1. (a) Schematic of dome test, from Grote and Antonsson (2009), (b) experimental punch force vs. stroke for JAC 590R (t=1.6mm), from Yoon et al. (2012).

2. Background/objectives

By using the dome test with proper lubrication (coefficient of friction nearly 0), it is proposed that the biaxial flow stress can be obtained for sheet metal alloys. The stress-strain condition (flow stress) will be similar to those seen during the bulge test, however the tooling, experiments, and calculations are much simpler for the frictionless dome test. Also, many companies already have existing dome test tooling which could be utilized for testing, as opposed to requiring the design and build of complicated bulge test tooling.

By using the frictionless dome test, it is possible to determine (a) flow stress under biaxial deformation, (b) formability under biaxial stretch and (c) a flow stress equation in Hollomon’s Law ($\sigma = K\varepsilon^n$) that provide reliable input data on mechanical properties of sheet materials to conduct FE simulations of metal flow in stamping.

The overall objective of this study is to determine flow stress curves (determining K and n values in Hollomon’s law, $\sigma = K\varepsilon^n$) of sheet metal, by using the frictionless dome test which is easier to use in industry than the bulge test.

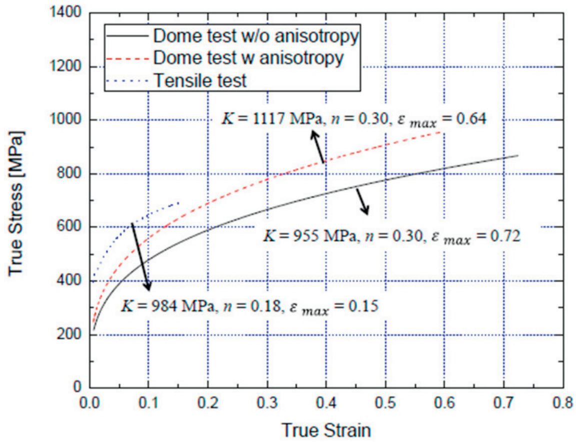

Fig. 2. Calculated flow stress for JAC 590R (t = 1.6mm), from Yoon et al. (2012).

3. Development of the code PRODOME

Cho et al. (2003) used inverse analysis methodology to determine the flow stress and the interface friction. PAM-STAMP FE software was used in all simulations. The same procedure was applied as illustrated in Figure 3:

1) The data points on experimental punch force vs. stroke curve were obtained from the tests, conducted at Honda R&D and POSCO.
2) Material is assumed to follow Hollomon's Law *($\sigma = K\varepsilon^n$)* where *K* is strength coefficient and *n* is strain hardening exponent. FE simulations were conducted for constant *K* (1000 MPa) and several *n* values (from 0.06 to 0.6) by using the same tool geometry, used in the experiments, provided by Honda and Interlaken (who built the test machine for the dome test). Punch forces were calculated as a function of punch stroke.
3) After obtaining punch force vs. stroke curves from experiments and FE simulations, each curve was normalized by dividing the force at various stroke positions by the punch force at the maximum experimental stroke. Normalization of the punch force vs. stroke curve on both experiment and FE simulation was done to eliminate the effect of *K* on the magnitude of the punch force vs. stroke curve. Thus, the. *n* value only affects the shape of the punch force vs. stroke curve.
4) *n* values were determined by a numerical method discussed by Yoon et al. (2012) which brought the minimum difference *(Δn)* between normalized experimental punch force vs. stroke curve and normalized FE punch force vs. stroke curve originally used by Cho et al. (2005).
5) *K* does not affect shape of the punch force vs. punch stroke curve but affects the magnitude of the punch force vs. stroke curve. Since FE simulations were done with *K* = 1000 MPa, *K* value can be calculated by an equation. Since initial thickness t_0 of the sheet sample in FE simulation model was *1 mm*, maximum punch force from FE simulation should be multiplied by the initial sheet thickness as discussed by Yoon et al. (2012).

A MATLAB code was written to perform the outlined analysis. The routine performs the calculations comparing the experimental data input into the program with the simulation based database. Thus, the K and n, and therefore flow stress, is determined. The developed MATLAB code is called "PRODOME".

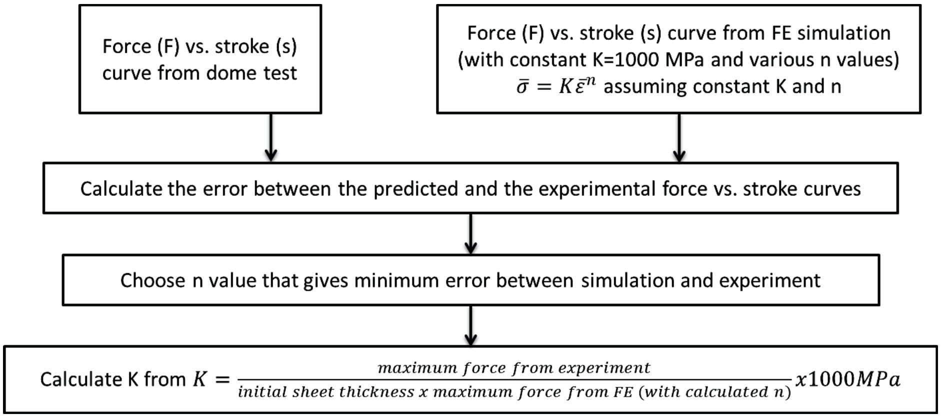

Fig. 3. Flow chart of inverse analysis methodology. (Note: Software PAM-STAMP was used in FE simulations)

4. Incomplete data at start of dome test

In some cases, it was difficult to measure the load-stroke curve, at the start of the frictionless dome test. Thus, depending on experimental set-up, the load-stroke curve from the dome test may not be complete. In some experiments, the punch stroke, before ~5kN of punch force, was reached, but the data was not recorded. Thus, a portion of the data set was missing and made the use of PRODOME inaccurate.

Therefore, it was necessary to correct the load-stroke curve by calculating the missing section of the dome test data, using FEM. Thus, the missing portion of the experimental curve can be estimated, completing the data set and allowing for use of PRODOME to calculate the flow stress. This method was applied in three steps:

1) Estimate the load-stroke of the dome test using DEFORM-2D up until the punch force is equal to ~5kN (the point after which experimental data exists). This was done with two different assumptions: a) the flow stress is equal to the tensile test results for K and n (i.e. $\sigma = K\varepsilon^n$) and b) the flow stress is assumed to be constant, for the calculations, and has a value equal to that of the material's yield strength (i.e. $\sigma = YS$).
2) Combine the calculated (<5kN) and experimental (>5kN) load-stroke curves.
3) Use PRODOME to calculate K and n values for the Hollomon Law fit of the dome test data.

5. Results

Approximately 15 different steels and two Aluminum alloys were used to validate the frictionless dome test. As examples, Figure 4 shows the comparison of the flow stress curves, obtained with the frictionless dome test, bulge test, and tensile test, for Al 5182-O, JAC 270E, TRIP 980, and TRIP 1180.

It is seen that the results correlate fairly well. K and n values (in $\sigma = K\varepsilon^n$) were also calculated for all tested materials. With higher strain values in frictionless dome test, a larger set of data points was used to obtain K and n. Hence, it is expected that these values are different than the corresponding coefficients, obtained by curve fitting with the tensile data, since tensile test uses a smaller range of stress-strain data to obtain K and n.

It should also be noted that for the higher grade steels, a constant K and n may not properly describe the flow stress. Thus, variable K and n may need to be determined in such cases. The current data correction method (simulation of the initial 5kN of the load-stroke curve) seems to give satisfactory results, and is very simple and quick to implement (usually within an hour: to simulate the dome test, combine the simulated and experimental load-stroke curves, and to use PRODOME to calculate the flow stress). Thus, the modification/completion of the experimental load-stroke curve by using FEA allows for dome test analysis even for incomplete experimental data.

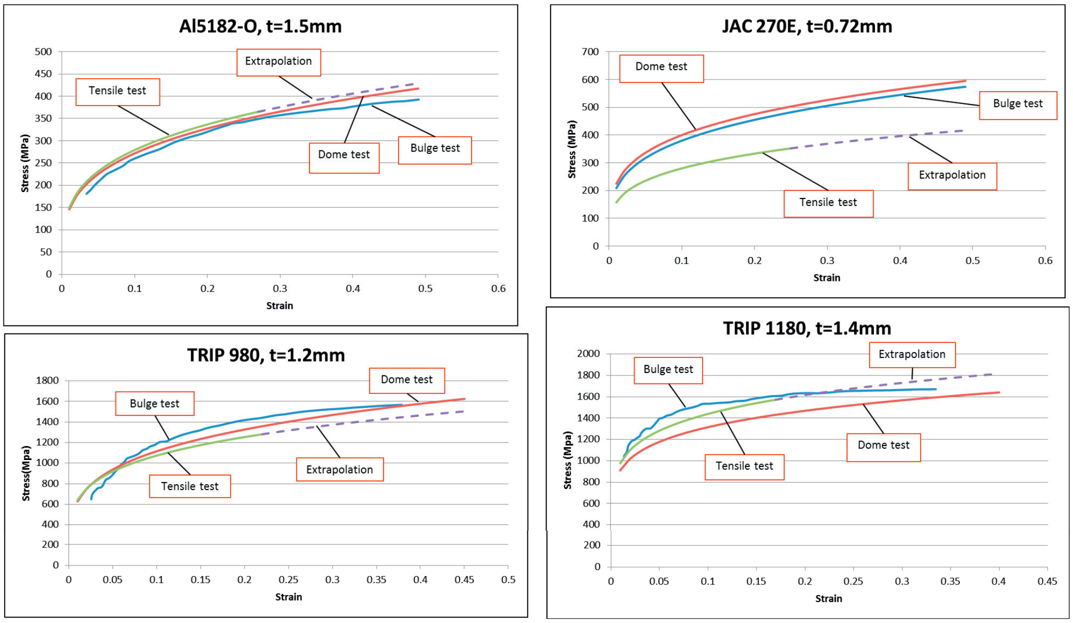

Fig. 4. Comparison of frictionless dome, bulge, and tensile tests for selected materials.

6. Summary and future work

In this study, a relatively simple method has been developed to obtain the flow stress of sheet materials under biaxial forming conditions. The test method is called "Frictionless Dome Test" and it is an expansion of the well-known Limited Dome Height test by using the "best" possible lubrication between the spherical punch and the sheet sample. Thus, friction is nearly eliminated.

The load-stroke curve, obtained from the Frictionless Dome Test and the FEM based inverse analysis are used to estimate the flow stress curve. Thus, Frictionless Dome Test gives results similar to the hydraulic bulge test, but it is simpler to use by industry.

In the present study, it was assumed that the flow stress curve could be represented by constant K and n values to describe the entire curve. This assumption may not hold for some materials, where the n value changes with strain. Work is in progress to use Frictionless Dome Test to determine values of n that vary with strain so that a more realistic representation of the true stress-strain curve can be obtained for materials, such as AHSS, that do not follow the Hollomon's Law.

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