BENCHMARK-1 Hole Expansion of A High Strength Steel Sheet

Chair: Toshihiko Kuwabara (Tokyo University of Agriculture and Technology, Japan)
Co-Chair: Tomoyuki Hakoyama (RIKEN, Japan)
Members: Taiki Maeda (Tokyo University of Agriculture and Technology, Japan)
Chiharu Sekiguchi (Tokyo University of Agriculture and Technology, Japan)

October 2, 2017

1. Overview
The objective of this benchmark (BM1) is to predict the deformation and fracture of a dual phase steel sheet (1.2 mm thickness) with a tensile strength of 980 MPa (DP980) subjected to hole expansion. A circular blank with a central hole (30 mm diameter) fabricated using a wire-electrical discharging machine is used to perform hole expansion forming to a set depth with a circular punch (100 mm diameter), see Fig. 1. Formed parts will be sectioned to measure thickness strain along the hole edge as well as along the three radial directions: 0 (RD), 45 (DD), and 90º (TD) from the rolling direction of the test sample. Additional parts will be formed to “failure”, and the location and timing of the failure will be identified. These measurements will be used to evaluate numerical predictions of the results submitted by benchmark participants prior to the Numisheet 2018 Conference.

Fig. 1 A specimen after hole expansion forming. Material: cold rolled ultralow carbon steel sheet. The punch and die geometry used is the same as that used in this benchmark, see Fig. 2.

2. EXPERIMENTAL PROCEDURE

2.1 Blank material and material data
DP980 (1.2 mm thickness) is considered for this benchmark. Large blanks are trimmed to circular blanks with a diameter of 215 mm. A detailed material characterization for the test sample is shown in Section 4 of this document, which includes the uniaxial and biaxial
tension test data. The data are also available in a separate Excel file (BM1_Material Data) to allow analysts to use their own data fitting algorithms and/or employ alternate material model options.

2.2 Hole Expansion Forming

Figure 2 shows the experimental apparatus used for the hole expansion forming. The punch was 100 mm in diameter and the die and punch profile radii were 15 mm. The initial hole diameter was \( d_0 = 30 \text{ mm} \), fabricated at the center of a circular blank using a wire-electrical discharging machine. The periphery of the blank was clamped using a triangular draw-bead with a diameter of 195 mm. The interface between the blank and punch head was lubricated with Vaseline and 0.3 mm thick Teflon sheet, while no lubricant was applied to the interfaces between the blank and the die/blank-holder. The blank was clamped using a hydraulic cylinder. The punch speed was approximately 0.1 mm/s, and the forming was terminated when the punch stroke reached 15 mm.

Fig. 2 Experimental apparatus for hole expansion experiment. (a) Schematic illustration of the die geometry and specimen used for the hole expansion experiment. All dimensions are in millimeters. (b) Geometry of the male and female beads. (c) Lower die and punch. (d) Setup of a specimen; the center of the specimen is coaxial with that of the punch as it is guided by a cylindrical block that stands at the punch center.
After the hole expansion forming, the sheet thickness along the radial lines at 0 (RD), 45 (DD), and 90° (TD) from the RD, as well as along the hole edge, was measured using a micrometer with a minimum readout of 0.001 mm.

3. **BENCHMARK REPORT**

All results must be reported using the benchmark report template, BM1_Report.xlsx, which can be downloaded from the conference website. The file must be submitted by March 1, 2018, on the website under the “Benchmark Report Submission” tab on the right-sided menu.

3.1 **General description**

Please fill out the information:

A. **Benchmark participant**

   Name, affiliation, address, e-mail, phone-number and fax number

B. **Simulation Software**

   Name of the FEM code, general aspects of the code, basic formulations (implicit or explicit), element/mesh technology, type of elements, element adaptivity information, number of elements (or initial and final number of elements if adaptivity is used), contact property model and friction formulation

**Simulation Hardware**

   CPU type, CPU clock speed, number of cores per CPU, number of CPUs, parallel or shared processing, main memory, operating system and total CPU time

C. **Material model**

   Yield function/Plastic potential, Hardening rule, Stress-Strain Relation, and Failure Model

D. **Remarks**

3.2 **Calculated results**

Please fill out the information:

1. Punch force (kN) vs. punch stroke (mm) up to and a bit beyond the point of maximum load. The zero mm punch stroke is defined at the position when the specimen is just in contact with the punch with zero interface force.

2. Logarithmic thickness plastic strain $\varepsilon^p_z$ at a position of $S = 2$ mm distant from the hole edge in the original blank vs. circumferential coordinate $\theta$ (degree in the original blank), see Fig. 3, at a punch stroke of 15 mm.

3. Logarithmic thickness plastic strain $\varepsilon^p_z$ vs. $S$ (mm), at a punch stroke of 15 mm, for the three radial directions: RD, DD and TD of the original blank, see Fig. 4.

4. Punch stroke at the predicted onset of fracture (within 0.1 mm precision)

5. Location of the predicted onset of fracture, $(\theta \text{ (degree), } S \text{ (mm)})$, in the original blank.
Fig. 3 Definition of the circumferential position, \( \theta \), for the report of logarithmic thickness plastic strain profile along the hole edge. \( \theta \) is defined to be zero at the RD.

Fig. 4 Definition of the position \( S \) (mm) from the hole edge in the original blank for the report of the logarithmic thickness strain profile along the three radial directions: RD, DD and TD

4. UNIAXIAL AND BIAXIAL TENSION TESTS

4.1 UNIAXIAL TENSION DATA

Tensile tests are performed in every fifteen degrees, i.e., 0, 15, 30, 45, 60, 75, and 90\(^{\circ}\), inclined from the rolling direction (RD) of the test sample. The strain rate is approximately \( 5 \times 10^{-1} \text{ s}^{-1} \). Stress–strain curves and \( r \)-values are measured.

Figure 5(a) and (b) shows the plastic-work-based proof stresses, \( \sigma_{0.2(W)} \) and \( \sigma_{1.0(W)} \), and the \( r \)-values measured from the uniaxial tensile tests performed every 15\(^{\circ}\) from the RD. \( \sigma_{0.2(W)} \)
and $\sigma_{1.0(W)}$ are defined as the uniaxial tensile stress at an instant when the same plastic work per unit volume is consumed as that at a tensile strain of $\varepsilon^p_0 = 0.002$ and 0.01, respectively, in the RD, see Appendix. The $r$-values were measured at a nominal tensile strain of 0.1. These data are provided in a separate Excel sheet (BM1_Material Data).

![Graph showing plastic-work-based proof stress and $r$-values](image)

**Fig. 5** Mechanical properties measured using uniaxial tension tests: (a) $\sigma_{0.2(W)}$ and $\sigma_{1.0(W)}$ and (b) $r$-values. The marks show an average of two specimens for each tensile direction.

Figure 6 shows the nominal stress $\sigma_N$ vs. nominal strain $\varepsilon_N$ curves for $\theta = 0, 45,$ and 90°. The number of specimens are two for each tensile direction. The data for the $\sigma_N - \varepsilon_N$ curves are provided in a separate Excel sheet in file BM1_Material_Data.xlsx.

Figure 7 shows the true stress $\sigma$ vs. logarithmic plastic strain $\varepsilon^p$ for $\theta = 0, 45,$ and 90°, compared with those approximated using Swift’s power law. The parameters of Swift’s power law are determined for a strain range of $0.002 < \varepsilon^p < \varepsilon^p_u$, $\varepsilon^p_u$ is the logarithmic plastic strain giving the maximum tensile force. The data for the $\sigma - \varepsilon^p$ curves are provided in a separate Excel sheet in file BM1_Material_Data.xlsx.

Logarithmic plastic strain components in the thickness ($\varepsilon_T^{\text{frac}}$), width ($\varepsilon_W^{\text{frac}}$), and longitudinal ($\varepsilon_L^{\text{frac}}$) directions in the localized necking area of fractured specimens are also measured for $\theta = 0, 45,$ and 90°, see Fig. 8. $\varepsilon_T^{\text{frac}}$ is determined by directly measuring the thickness at the tip of the fracture surface using a tool microscope in an accuracy of 0.001 mm. $\varepsilon_W^{\text{frac}}$ is determined using a DIC system just outside of the localized neck. $\varepsilon_L^{\text{frac}}$ is calculated as $-\varepsilon_T^{\text{frac}} - \varepsilon_W^{\text{frac}}$. The data for $\varepsilon_T^{\text{frac}}$, $\varepsilon_W^{\text{frac}}$, and $\varepsilon_L^{\text{frac}}$ are provided in a separate Excel sheet in file BM1_Material_Data.xlsx.
Fig. 6 Nominal stress vs. nominal strain curves for $\theta = 0, 45,$ and $90^\circ$

Fig. 7 True stress vs. logarithmic plastic strain curves, compared with those approximated using Swift’s power low
4.2 BIAXIAL TENSION DATA

The specimen geometry used in the biaxial tension tests and a method of determining a contour of plastic work are given in Appendix.

Figure 9 shows the stress points that form the contours of plastic work associated with the reference plastic strain of $\varepsilon_0^p = (a) 0.002$ and (b) 0.01; the stress values are normalized by the $\sigma_0$ associated with each work contour. Each data point represents an average of the data measured from two specimens; the difference between these two measured data was less than 1% of the flow stress. The maximum value of $\varepsilon_0^p$, for which the work contour has a full set of stress points measured using cruciform specimens, was $\varepsilon_0^p = 0.012$. The values of the stress points forming the work contours are provided in a separate Excel sheet (BM1_Material Data).

Figure 9 also includes the theoretical yield loci based on the von Mises (Von Mises, 1913), Hill’s quadratic (Hill, 1948), and the Yld2000-2d yield function (Barlat et al., 2003; Yoon et al., 2004) with an exponent of $a = 6$, the value typically suggested for BCC metals. The material

![Figure 9](image_url)
parameters $\alpha_i$ ($i = 1^{-8}$) of the Yld2000-2d yield function were determined using $r_0$, $r_{45}$, $r_{90}$, and $r_b$, and $\sigma_0 / \sigma_0$, $\sigma_{45} / \sigma_0$, $\sigma_{90} / \sigma_0$, and $\sigma_b / \sigma_0$, where $r_0$ and $\sigma_0$ are the $r$-value and uniaxial tensile flow stress measured at an angle $\Theta$ from the RD, respectively, and $r_b$ and $\sigma_b$ are the ratio of the plastic strain rates, $\dot{\varepsilon}_p / \dot{\varepsilon}_p^0$, and the flow stress at a balanced biaxial tension, respectively, associated with a particular value of $\varepsilon_p^0$. The values of $\alpha_i$ ($i = 1^{-8}$) are provided in a separate Excel sheet (BM1_Material Data).

The material parameters of the Hill ’48 yield function were determined using the $r_0$, $r_{45}$, and $r_{90}$.

Figure 10 compares the directions of the plastic strain rates, measured at $\varepsilon_p^0 = 0.002$ and $\varepsilon_p^0 = 0.01$, with those calculated using selected yield functions. The Yld2000-2d yield function with $\alpha=6$ is consistent with the measured data, while those predicted by the von Mises and Hill ’48 yield functions deviate slightly from the measured data. The value of $\beta$ for each stress path is provided in a separate Excel sheet (BM1_Material Data).

![Fig. 10 Directions of the plastic strain rates measured at (a) $\varepsilon_p^0 = 0.002$ and (b) $\varepsilon_p^0 = 0.01$, compared with those calculated using the von Mises, Hill ’48, and the Yld2000-2d yield functions.](image)

APPENDIX: METHOD OF BIAXIAL TENSION TEST

A1 Specimen geometry

Figure A1 shows the geometry of the cruciform specimen used in the biaxial tension tests. The stress measurement error is estimated to be less than 2% when using the cruciform specimen with the geometry and strain measurement positions as shown in Fig. A1 (Hanabusa et al., 2010 and 2013).
Fig. A1 Geometry of the cruciform specimen and the strain measurement positions used in the biaxial tensile tests

**A2 Measurement of contours of plastic work**

Seven linear stress paths, $\sigma_x : \sigma_y = 4:1$, 2:1, 4:3, 1:1, 3:4, 1:2, and 1:4, are applied to the specimens using a servo-controlled biaxial tensile testing machine developed by Kuwabara et al. (1998), where $\sigma_x$ and $\sigma_y$ are the true stress components in the RD and TD of the test sample, respectively. The von Mises’ strain rate is approximately $5 \times 10^{-4}$ s$^{-1}$. Details of the testing procedures are given in ISO 16842 (2014).

Contours of plastic work in the stress space (Hill and Hutchinson, 1992; Hill et al., 1994) are measured to identify a proper material model for the test sample, see Fig. A2. First, the true stress vs. logarithmic plastic strain curve ($\sigma_0 - \varepsilon_p^0$ curve) is measured from the uniaxial tension test for the RD, and is selected as the reference data for work hardening; the plastic work per unit volume $W_0$ associated with selected values of $\varepsilon_p^0$ are determined. Next,

![Diagram](image)

**Fig. A2 Schematic diagrams for the data analysis of the biaxial tension test.** (a) A method for determining the stress points forming a contour of plastic work. (b) The definitions of $\varphi \equiv \arctan(\sigma_y / \sigma_x)$ and $\beta \equiv \arctan(\dot{\varepsilon}_y / \dot{\varepsilon}_x)$.
the stress points that give the same plastic work as $W_0$ are determined from the biaxial tension test data and the uniaxial tension test data in the TD. Consequently, these stress points form a contour of plastic work associated with $\varepsilon_0^p$ in the first quadrant of the $\sigma_x - \sigma_y$ stress space.

Moreover, the direction of the plastic strain rate, \( \beta \equiv \arctan(\dot{\varepsilon}_y^p / \dot{\varepsilon}_x^p) \), is measured for each linear stress path with a loading angle of \( \phi \equiv \arctan(\sigma_y / \sigma_x) \), to check whether the normality flow rule is established for the work contour.

References


