Advanced Material Testing Methods for Enhancing the Accuracy of Metal Plasticity Models

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FEA of hole expansion forming

Cold rolled ultralow carbon steel sheet
Material models
(cold rolled ultralow carbon steel sheet)

Experimental
- $\varepsilon_0^p = 0.005$
- $\varepsilon_0^p = 0.24$

FEA of hole expansion forming

Cold rolled ultralow carbon steel sheet
FEA of hole expansion forming

This example suggests that ...

- **Accurate material models** must be used to enhance the accuracy of forming simulations, as the definition of the yield condition fully defines the behavior.

- **Accurate material models** can be determined by performing the biaxial stress tests, as the biaxial stress states are typical in real forming operation.
1. Typical stress states in sheet metal forming operations

2. Conventional biaxial stress testing methods for sheet metals

3. Biaxial stress testing methods using cruciform specimens and tubular specimens

4. In-plane tension-compression testing method

Biaxial stress tests are necessary for accurate material modeling!
Contents

1. Typical stress states in sheet metal forming operations
2. Conventional biaxial stress testing methods for sheet metals
3. Biaxial stress testing methods using cruciform specimens and tubular specimens
4. In-plane compression testing method

Conventional biaxial stress tests

Useful to measure the work hardening behavior for a larger strain range than what is achievable by uniaxial tension tests

Pure titanium sheet
Biaxial compression tests using adhesive bonded sheet laminate specimens


Combined tension-shear test for measuring a yield surface in the $\sigma_x-\sigma_y-\sigma_{xy}$ space

Vegter and van den Boogaard (2006)
Mohr and Oswald (2008)
Material testing methods for reproducing the typical stress states in sheet metal forming

**Cruciform specimens in literature**


- Hoferlin et al. (1998)
- Shiratori & Ikegami (1968)
- Müller & Pöhlandt (1996)

Difficult to determine the cross-sectional area for determining biaxial stresses.

**ISO 16842**: 2014 Metallic materials — Sheet and strip — Biaxial tensile testing method using a cruciform test piece


1) \( a < 0.08B \)
   - \( a \): thickness
   - \( B \): side length of gauge area

2) \( N \geq 7, \ L \geq B, \ w_s \leq 0.01B \)
   - \( N \): number of slits
   - \( L \): slit length
   - \( w_s \): slit width

Strain measurement position should be on the centerline at a distance of approximately \( 0.35B \) from the center of the specimen, parallel to the \( \sigma_{\text{max}} \) direction.

Stress measurement error is less than 2%.
Biaxial tensile testing apparatus


Material modeling based on contours of equal plastic work

\[ W_0 = W_x + W_y \]

The material model that accurately reproduces the work contour is an appropriate material model to be used in forming simulations.
Material modeling based on contours of equal plastic work

This was motivated as the shape of a yield locus changes with plastic deformation. In sheet metal forming processes sheet metals go through large plastic deformation. Therefore, modeling the flow stresses as an **average behavior of a material over a deformation range** is likely to be more appropriate than determining an initial yield locus of the material.

Comparison with theoretical yield loci

Comparison with theoretical yield loci for IF steel and A6XXX.

Material testing methods for reproducing the typical stress states in sheet metal forming


A problem of cruciform specimen

Maximum plastic strain: $0.002 \sim 0.05$

A cruciform specimen is effective for a small strain range.

Korkolis (2012)
Fabrication of a tubular specimen

Sheet material → Weld → Bend

Multiaxial tube expansion testing method

Measurement system using DIC

Input to PC $\varepsilon_\phi, \varepsilon_\theta, R_\phi$

Stress calculation

**Measured data**

- **$T$** Axial load
- **$P$** Internal pressure
- **$\varepsilon_\phi$** Axial strain
- **$\varepsilon_\theta$** Circumferential strain
- **$R_\phi$** Bulge curvature

\[
\sigma_\phi = \frac{P\pi(D/2-t)^2 + T}{\pi(D-t)t}
\]

\[
\sigma_\theta = \frac{(R_\phi-t)(D-2t) - (D-t)\sigma_\phi}{2R_\phi-t}
\]

\[
t = t_0 \exp(\varepsilon_\phi + \varepsilon_\theta)
\]

\[
D = D_0 \exp(\varepsilon_\theta)
\]
Linear stress paths

\[ \sigma_x : \sigma_y = 0:1 \quad 1:4 \quad 1:2 \quad 3:4 \quad 1:1 \]

Biaxial stress-strain curves (SPCD)

Hole Expansion Simulation Considering the Differential Hardening of a 6000-series Aluminum Alloy Sheet


Hole expansion forming

Biaxial stress tests

Material modeling

Hole expansion forming

FE simulation

Evaluate the effects of material models on the accuracy of forming simulation.
Contours of equal plastic work

Differential hardening is observed.

Variation of $M$ and $\alpha_i$ with $\varepsilon_0^p$
Hole expansion test apparatus

Hole expansion simulation

- Abaqus/Standard 6.12
- 4-node shell elements (S4R)

Blank Holding Force 60kN

Teflon + Vaseline

No lubricant
Thickness strain in RD

![Graph showing thickness strain in RD](image)

Thickness strain in 90°

![Graph showing thickness strain in 90°](image)
Thickness strain in 45°

![Graph showing thickness strain versus spatial radial coordinate.]

Material testing methods for reproducing the typical stress states in sheet metal forming

The Yld2000-2d yield function is consistent with the measurement.

Material testing methods for reproducing the typical stress states in sheet metal forming


Uniaxial tension

Biaxial tension
(small strain range)

Biaxial tension
(large strain range)

Combined tension-compression

In-plane tension-compression

Experimental methods for applying continuous stress reversals to a sheet specimen.


Yoshida et al. (1998)

G’sell et al. (1983); Hu et al. (1992)

Miyauchi (1984)

Iwata et al. (2001)

Yoshida et al. (2002b)
In-plane uniaxial compression testing jig for a sheet metal


In-plane reverse loading test devise for ultra-thin sheet metals

Test material


- SUS304 (as-rolled)
- 0.3 mm thick
- Electronic spring parts

Difference in springback angle of SUS304 stainless sheets for electronic parts


\[ \Delta \theta = \theta' - \theta \]

16 kinds of stainless steel sheets with different strength

RD-bending

TD-bending

Rolling direction
Difference in springback angle between RD and TD

\[ \Delta \theta = \theta' - \theta \]

This is strange ....

What is the causes of the difference?

\[ \frac{\Delta \theta}{\theta} = \frac{\rho}{EI} M \]

Bending moment \( M \) should be the same if the flow stress is the same for RD and TD.

Is the compressive flow stress the same, if the tensile flow stress is the same?
**Conclusions**

✓ Material models (yield functions) significantly affect the predictive accuracy in sheet metal forming simulations.

✓ Biaxial stress tests and in-plane reverse loading tests are effective for determining appropriate material models for sheet metals.
Thank you for your attention!

July 30 (Mon) — Aug 3 (Fri), 2018

Toyocho, Tokyo