International Seminar on Metal Plasticity, 19 June, 2017
Sapienza - Università di Roma, Rome, Italy

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

Toshihiko KUWABARA
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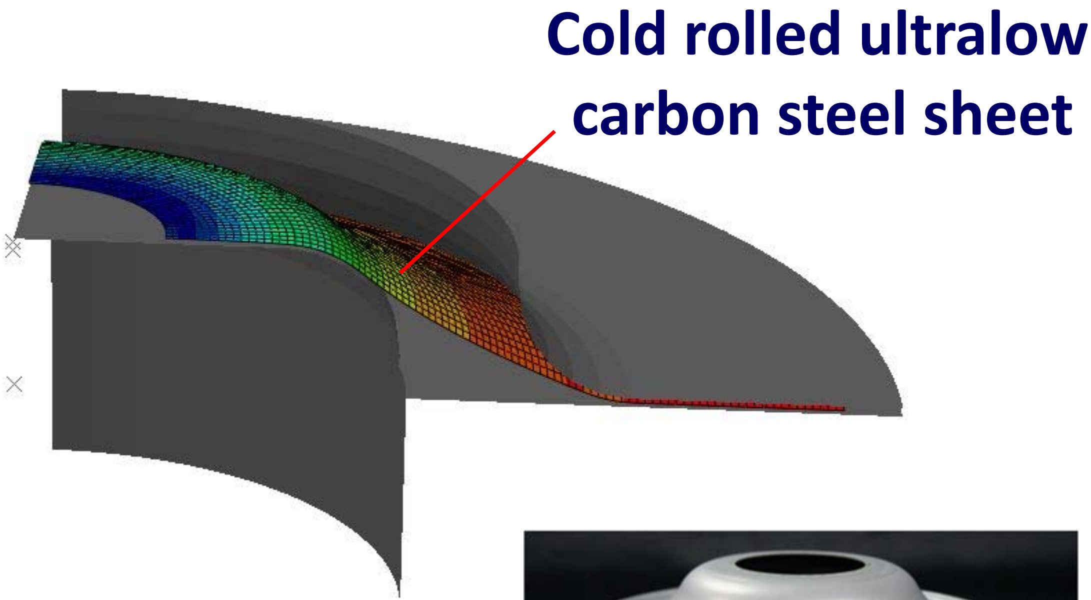
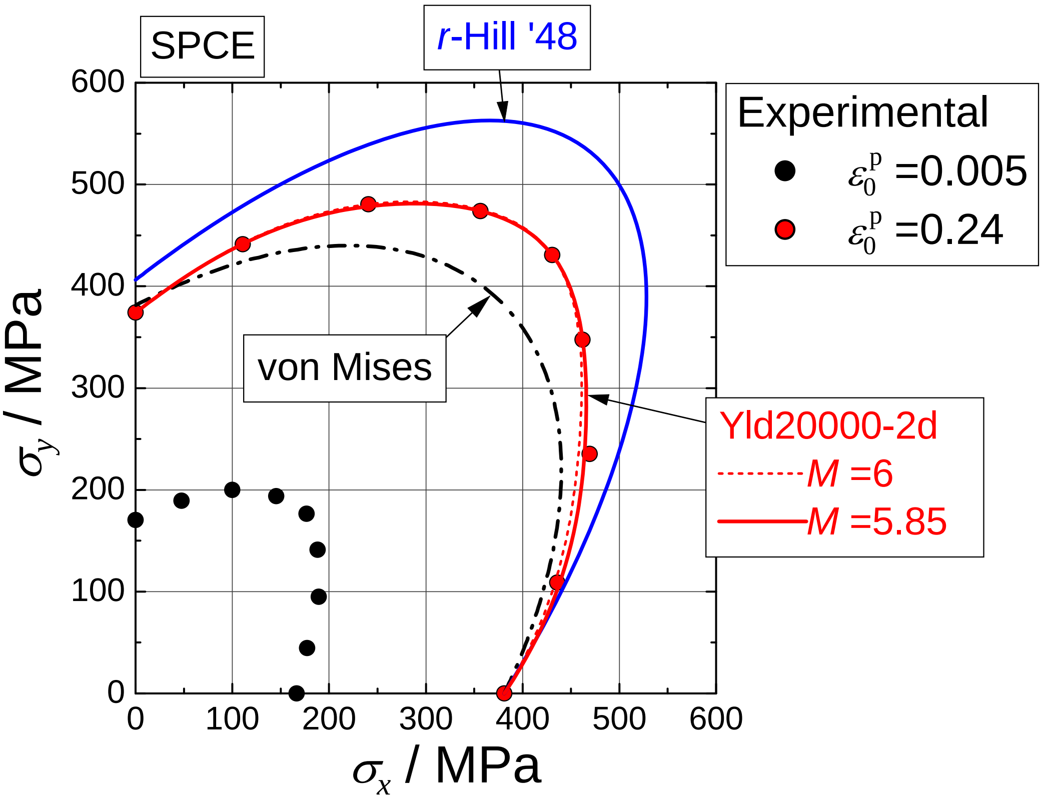
FEA of hole expansion forming

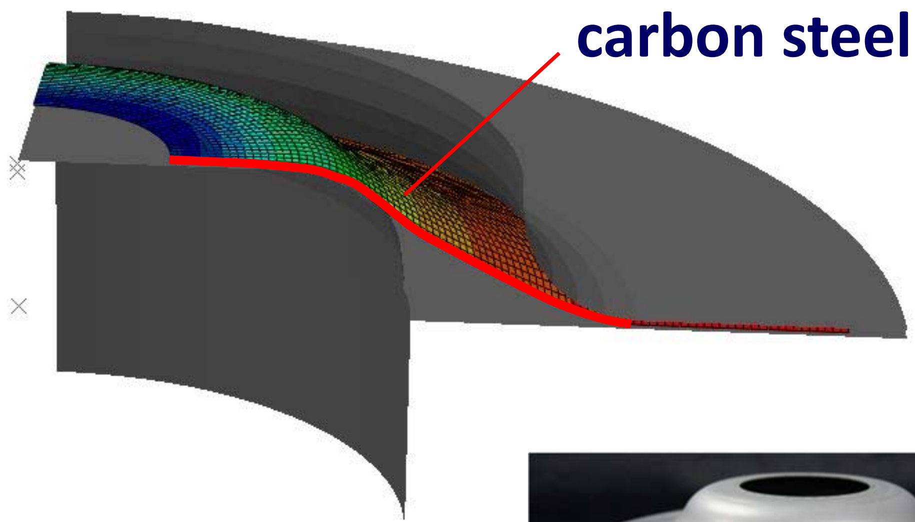


Material models (cold rolled ultralow carbon steel sheet)

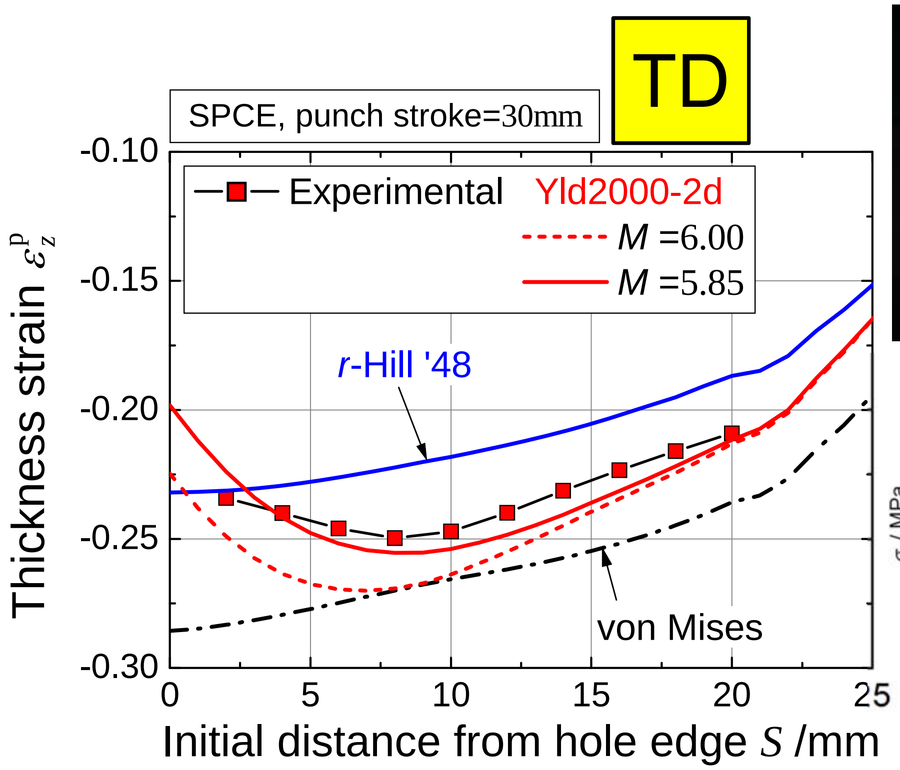


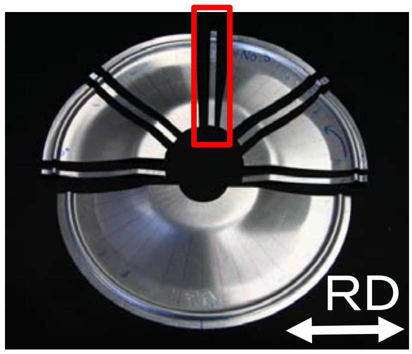
FEA of hole expansion forming

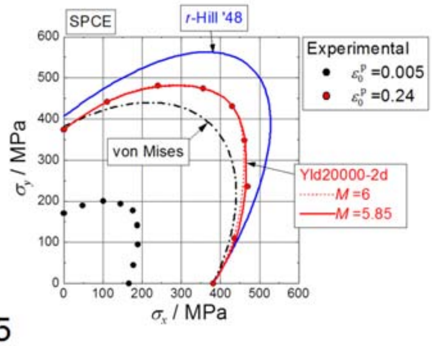
Cold rolled ultralow carbon steel sheet



FEA of hole expansion forming







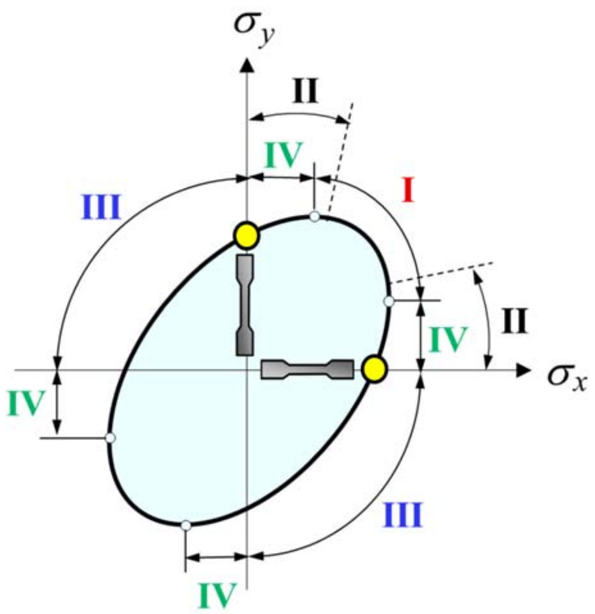
This example suggests that …

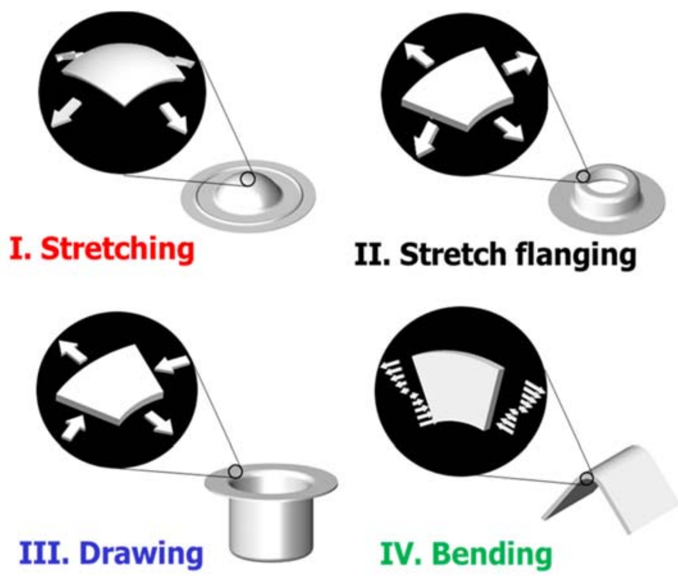
- ***Accurate material models*** must be used to enhance the accuracy of forming simulations, **as the definition of the yield condition fully defines the behavior.**
- ***Accurate material models*** can be determined by performing the ***biaxial stress tests***, as the biaxial stress states are typical in real forming operation.

Contents

Typical stress states in sheet metal forming processes

Kuwabara, T.: Biaxial Stress Testing Methods for Sheet Metals. In *Comprehensive Materials Processing;* Van Tyne, C. J., Ed.; Elsevier Ltd., 2014; Vol. 1, pp 95–111.



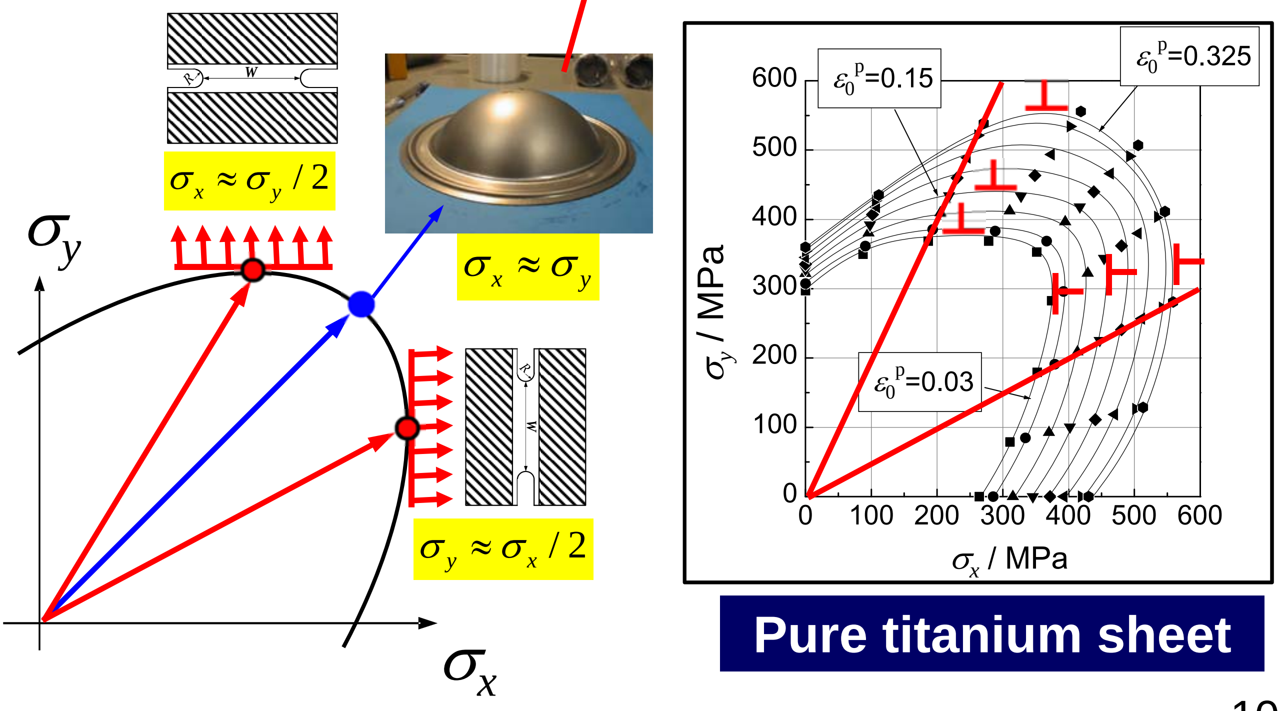


Biaxial stress tests are necessary for accurate material modeling!

Contents

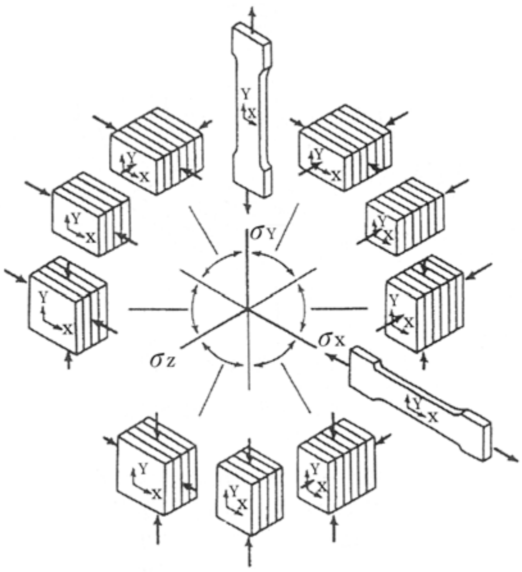
Conventional biaxial stress tests

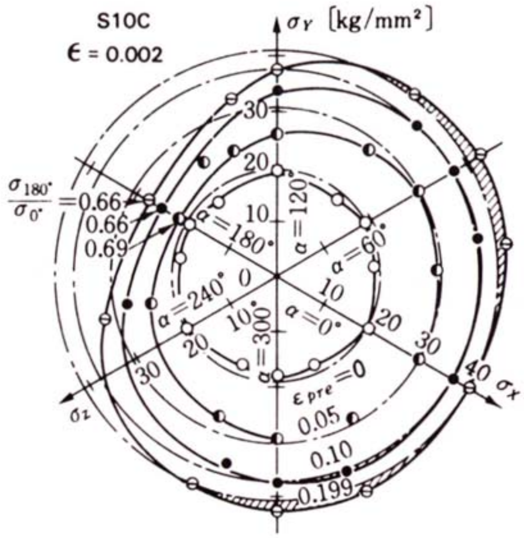
Useful to measure the work hardening behavior for a larger strain range than what is achievable by uniaxial tension tests



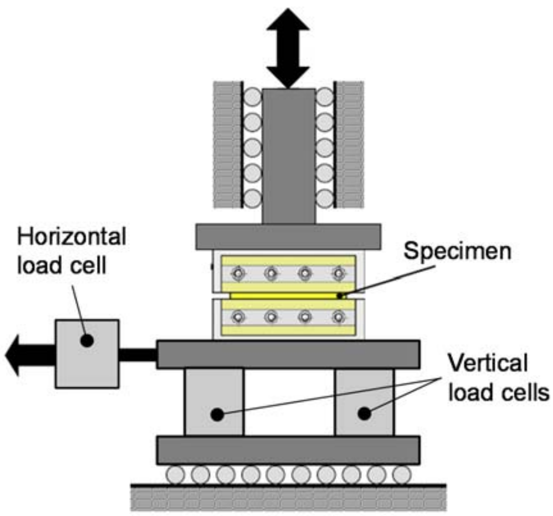
Biaxial compression tests using adhesive bonded sheet laminate specimens

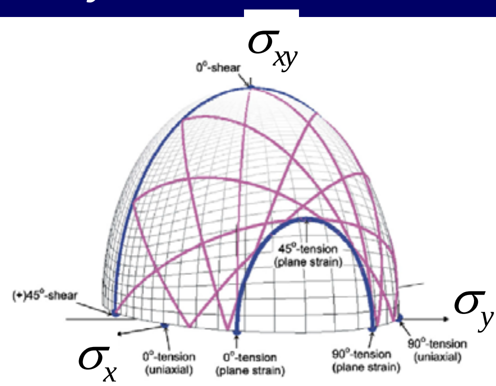
Tozawa, Y., 1978. In: Koistinen, D.P., Wang, N-.M., (Eds.), Mechanics of Sheet Metal Forming. Plenum Press, New York, pp. 81-110.

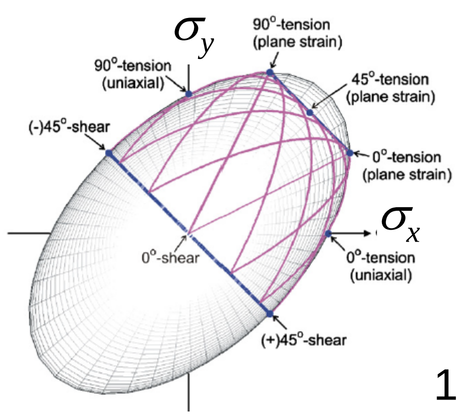




Combined tension-shear test for measuring a yield surface in the σ_x-σ_y-σ_{xy} space







Vegter and van den Boogaard (2006)

Mohr and Oswald (2008)

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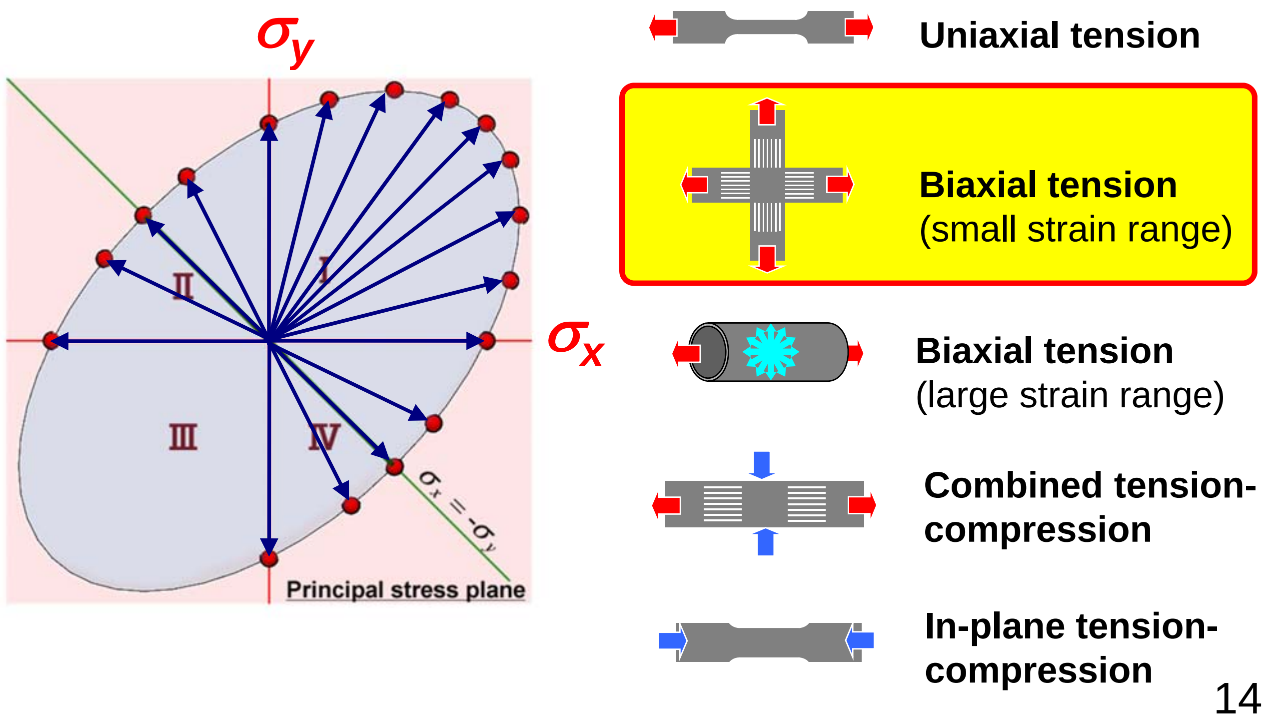
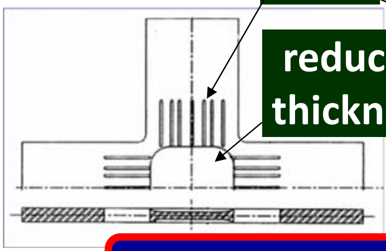


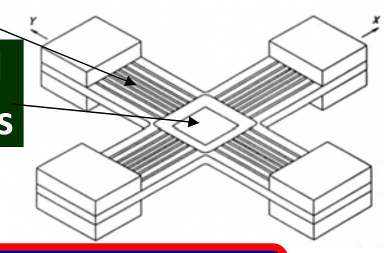
Cruciform specimens in literature

Kuwabara, T., Int. J. Plasticity, 23-3 (2007), 385-419.

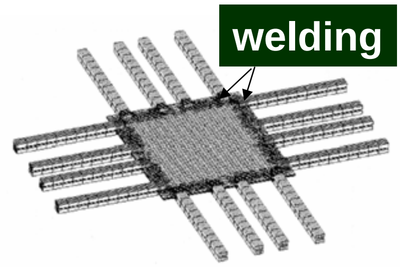
slits

reduced thickness





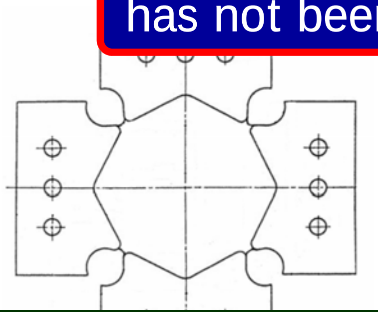
Ferr … 994)

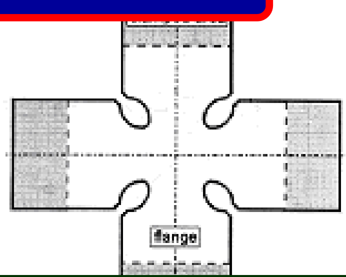


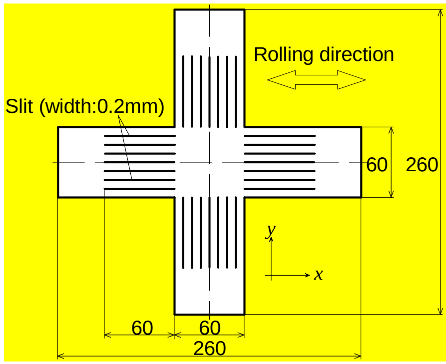
welding

Hoferlin et al. (1998)

Stress measurement error has not been evaluated.







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

6)

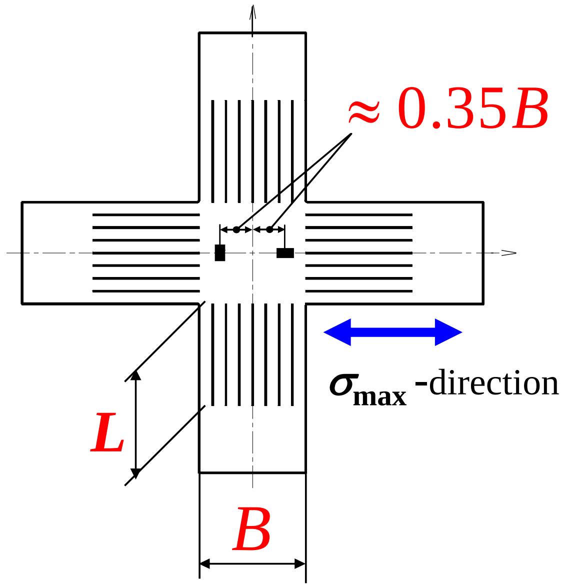
Kuwabara et al. (1998)

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

Hanabusa et al., J. Mater. Processing Technol., 213 (2013), 961-970.

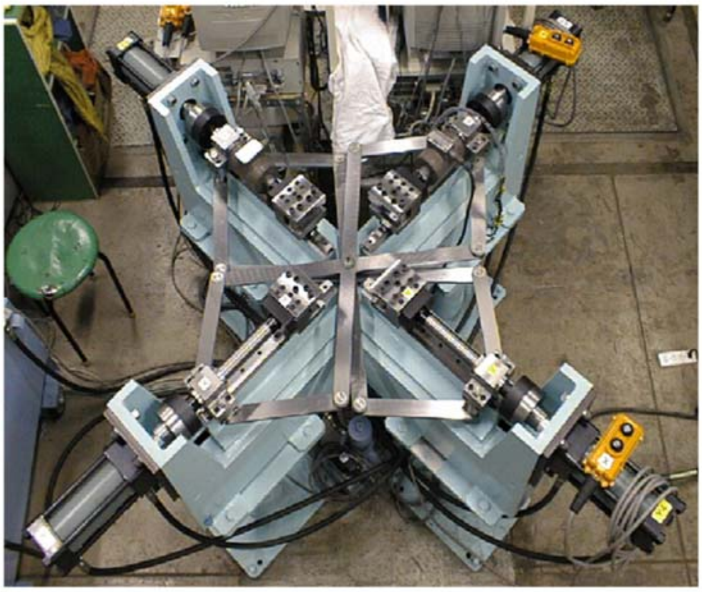
1) $a < 0.08B$
   a: thickness
   B: side length of gauge area
2) $N \geq 7$, $L \geq B$, $w_s \leq 0.01B$
   N: number of slits, L: slit length, w_s: slit width

Strain measurement position should be on the centerline at a distance of approximately **0.35*B*** from the center of the specimen, parallel to the σ_{max} direction.

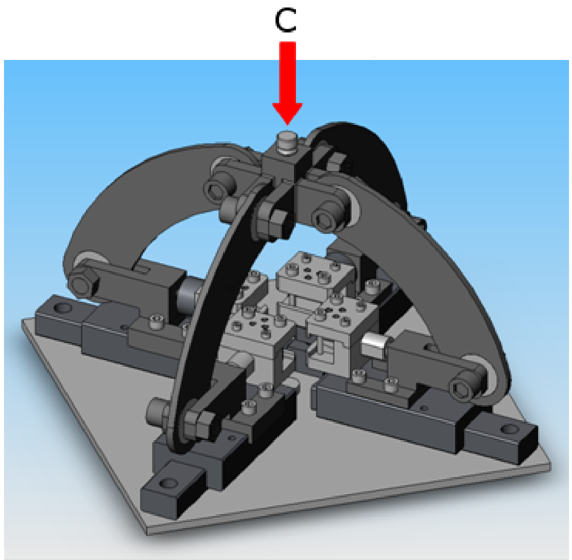


Stress measurement error is less than 2 %.

Biaxial tensile testing apparatus

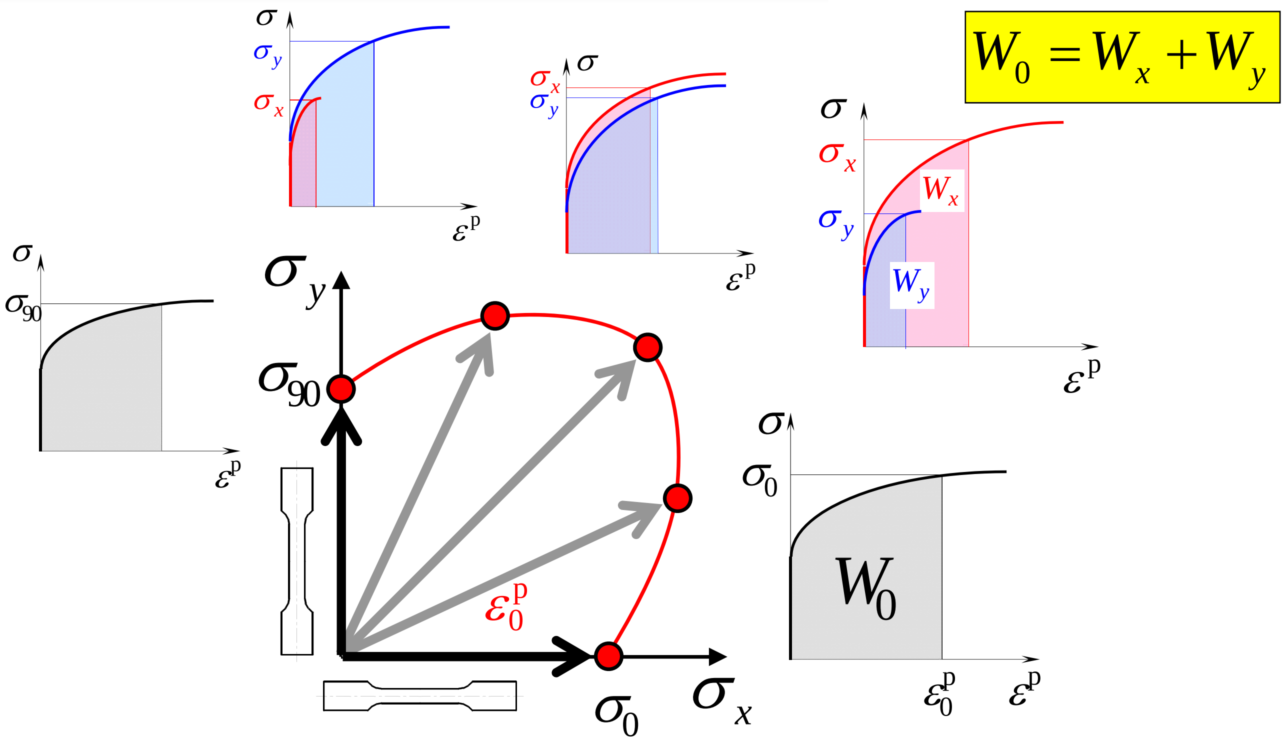


Kuwabara et al. (1998)



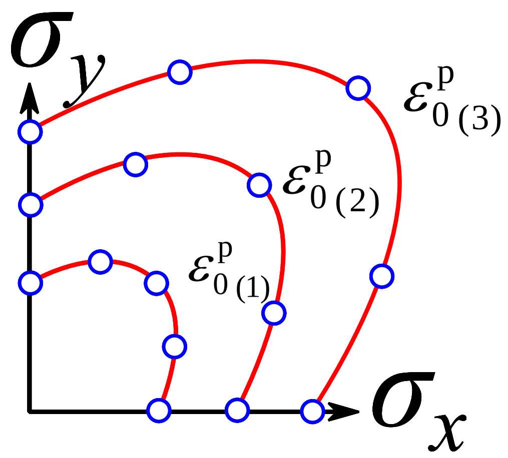
Takahashi et al. (2010)

Material modeling based on contours of equal plastic work



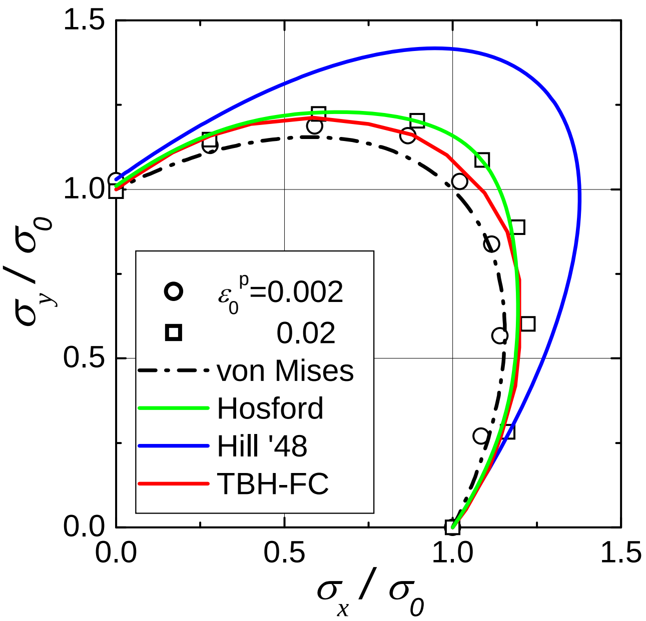
The material model that accurately reproduces the work contour is an appropriate material model to be used in forming simulations.

Material modeling based on contours of equal plastic work

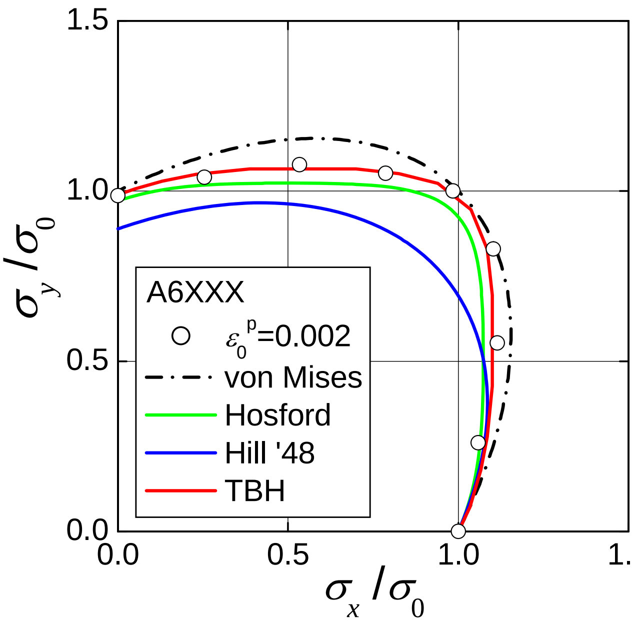


This was motivated as the shape of a yield locus changes with plastic deformation.
In sheet metal forming processes sheet metals go through large plastic deformation. Therefore, modeling the flow stresses as ***an average behavior of a material over a deformation range*** is likely to be more appropriate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

Comparison with theoretical yield loci



IF steel[1]



A6XXX[2]

[1]Kuwabara et al.: Acta Mater., 50/14 (2002), 3717-3729.
[2]Kuwabara, Van Bael: Proc. 4th NUMISHEET, (1999), pp.85-90.

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

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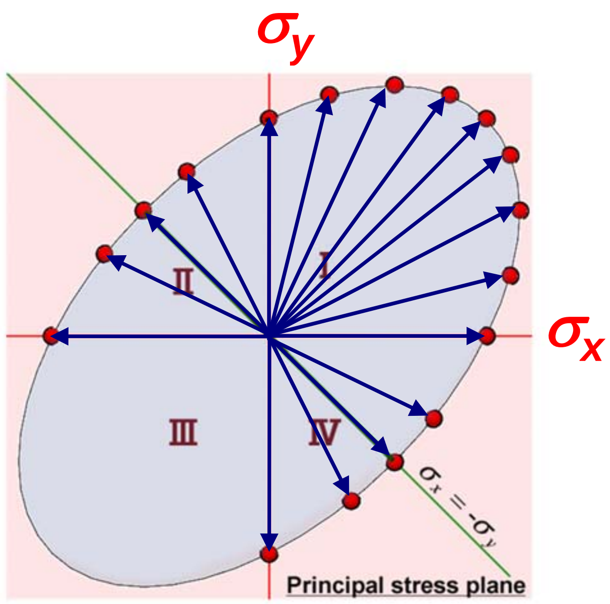
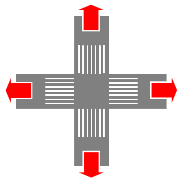
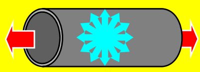


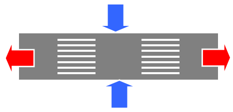
Uniaxial tension



Biaxial tension
(small strain range)



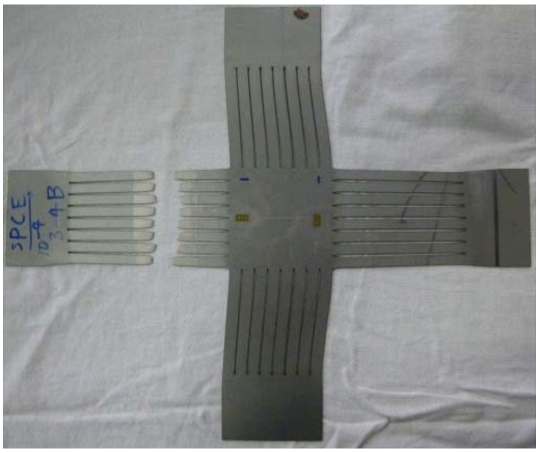
Biaxial tension
(large strain range)



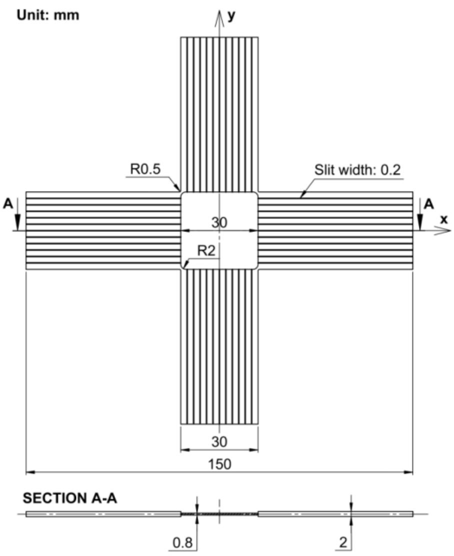
Combined tension-compression

In-plane tension-compression

A problem of cruciform specimen



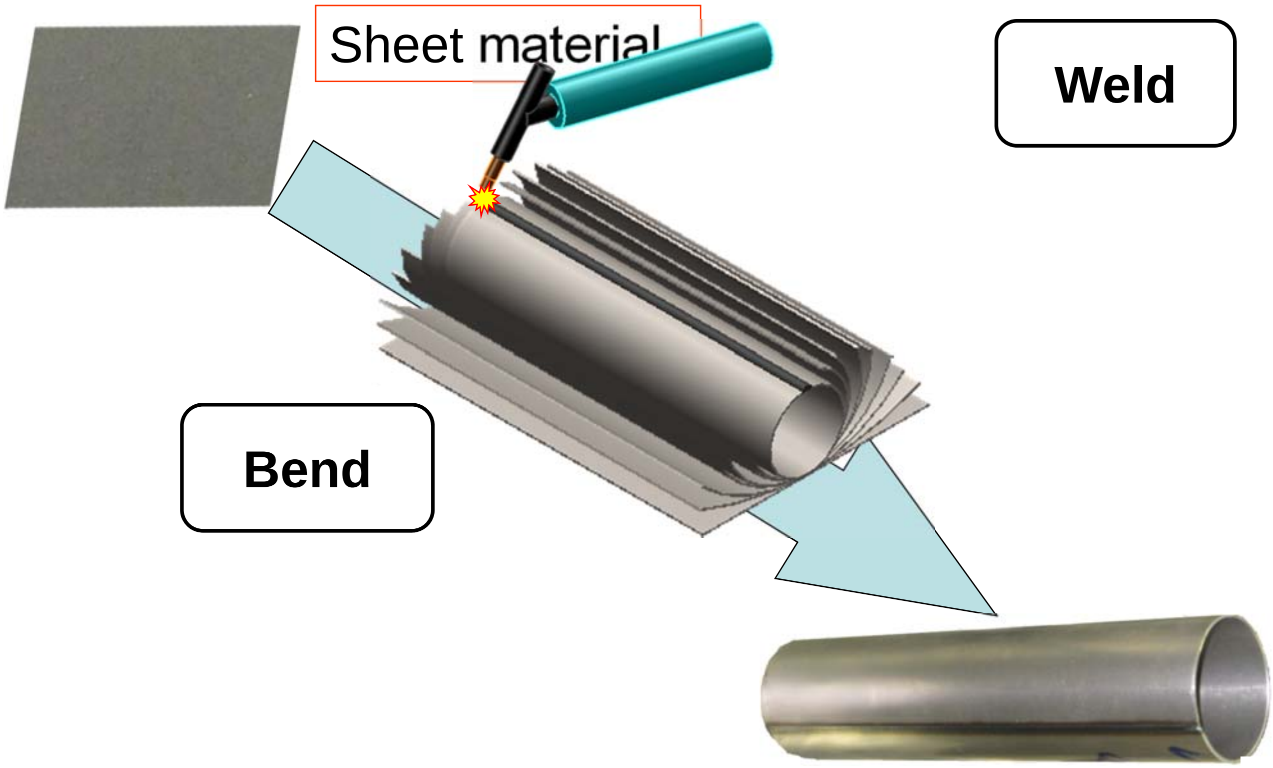
Maximum plastic strain:
0.002 ~ 0.05



Korkolis (2012)

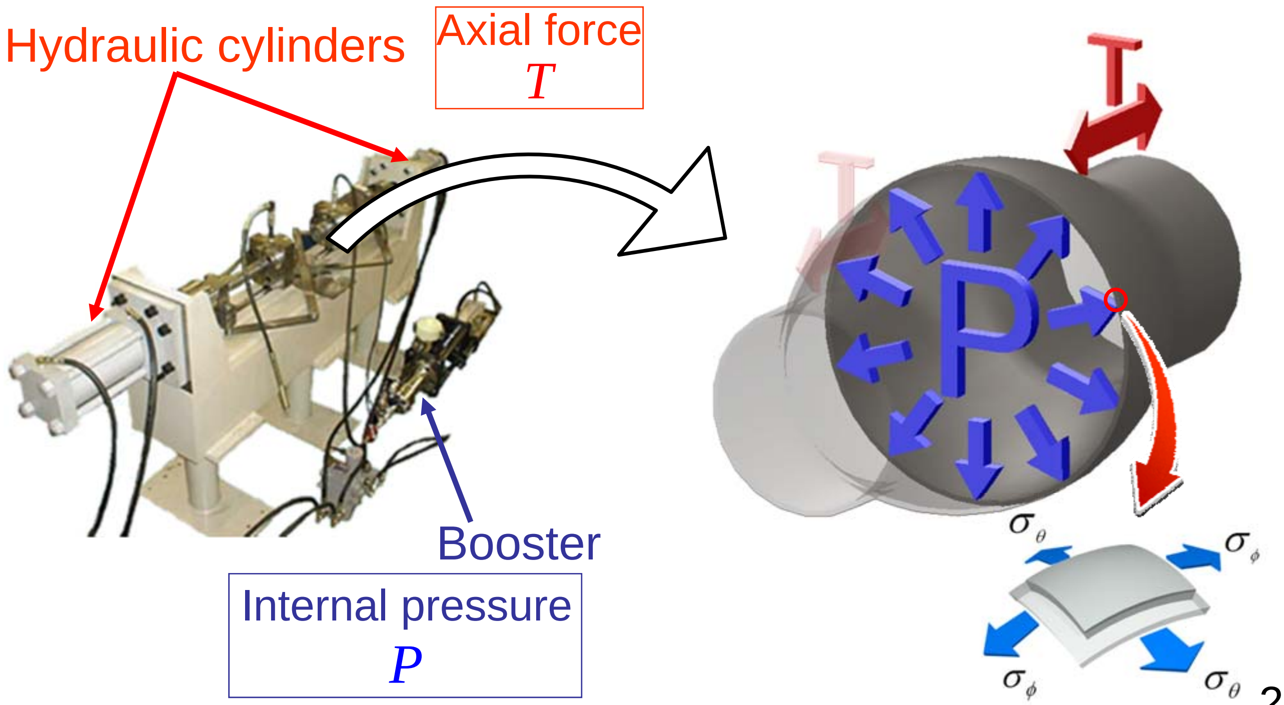
A cruciform specimen is effective for a small strain range.

Fabrication of a tubular specimen

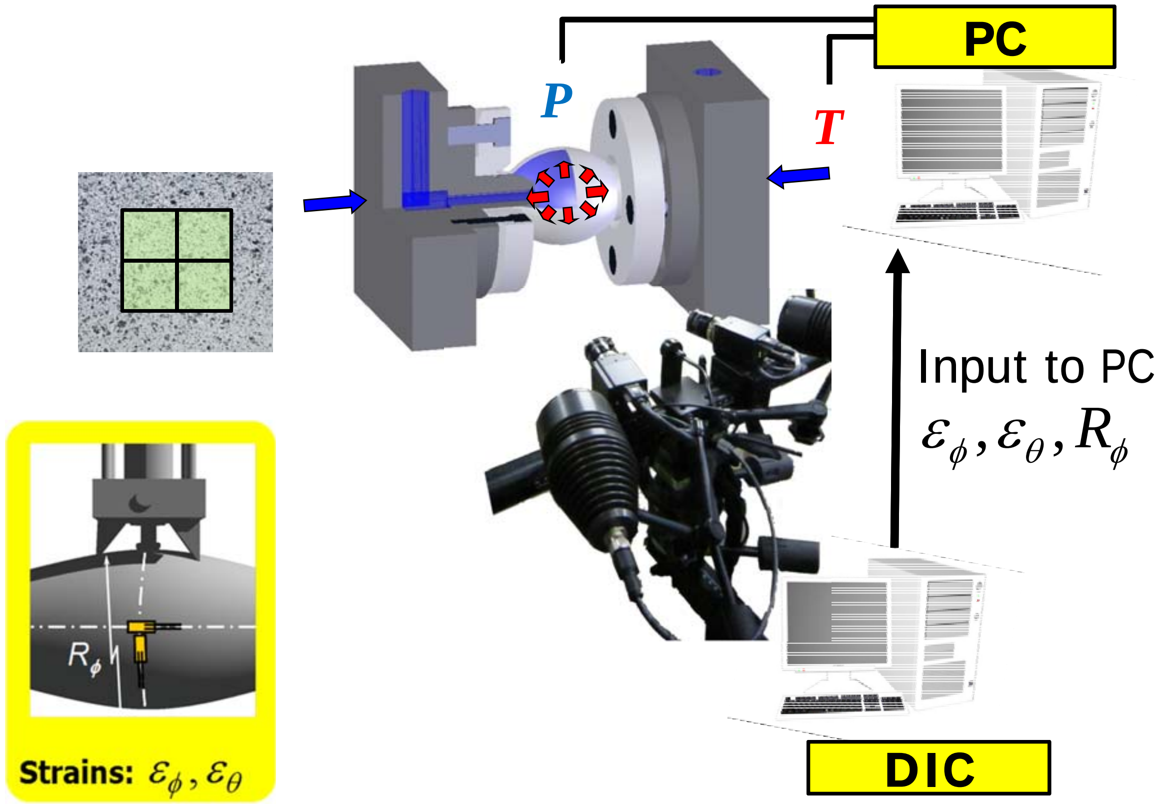


Multiaxial tube expansion testing method

Kuwabara, T., et al., Int. J. Plasticity, 21-1 (2005), 101-117.
Kuwabara, T. and Sugawara, F., Int. J. Plasticity, 45 (2013), 103-118.



Measurement system using DIC



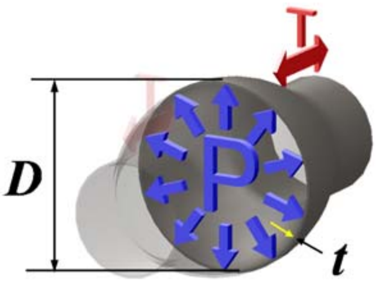
Stress calculation

Measured data

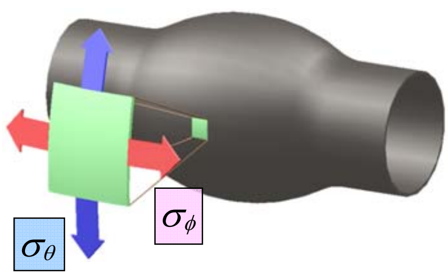
- T **Axial load**
- P **Internal pressure**
- ε_ϕ **Axial strain**
- ε_θ **Circumferential strain**
- R_ϕ **Bulge curvature**

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

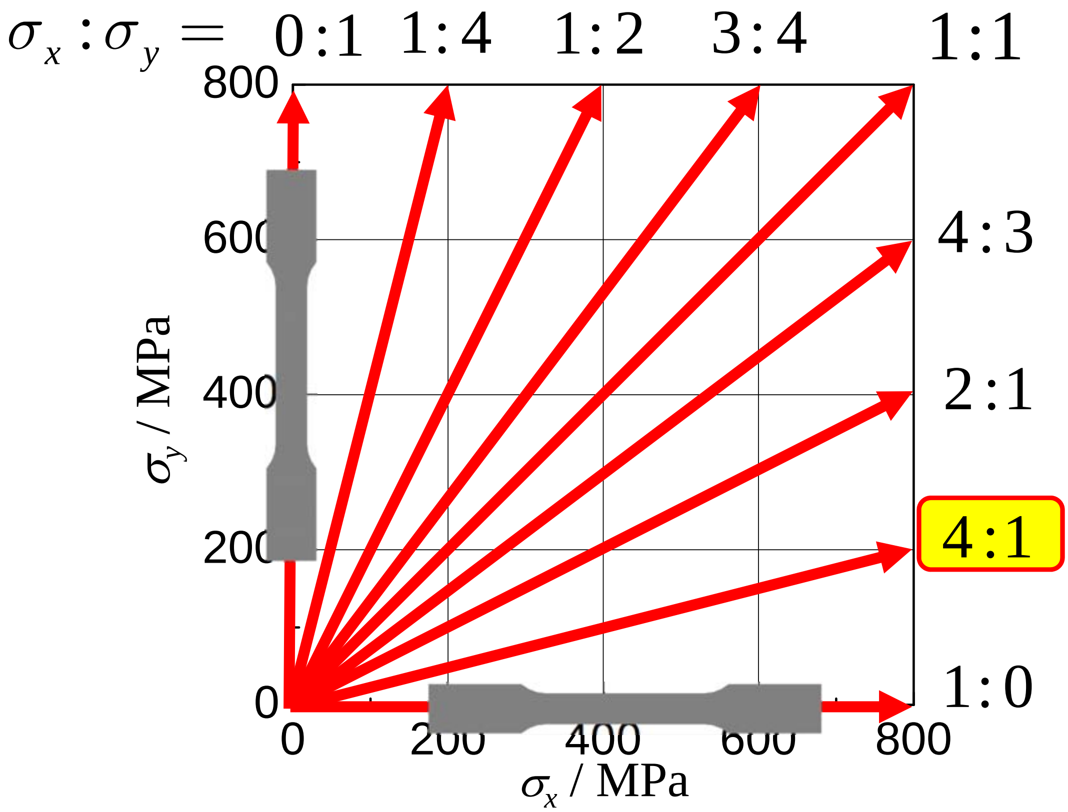
$$\sigma_\theta = \frac{(R_\phi - t)(D-2t)}{(2R_\phi - t)t}P - \frac{D-t}{2R_\phi - t}\sigma_\phi$$



$$t = t_0 \exp(\varepsilon_\phi + \varepsilon_\theta)$$
$$D = D_0 \exp(\varepsilon_\theta)$$

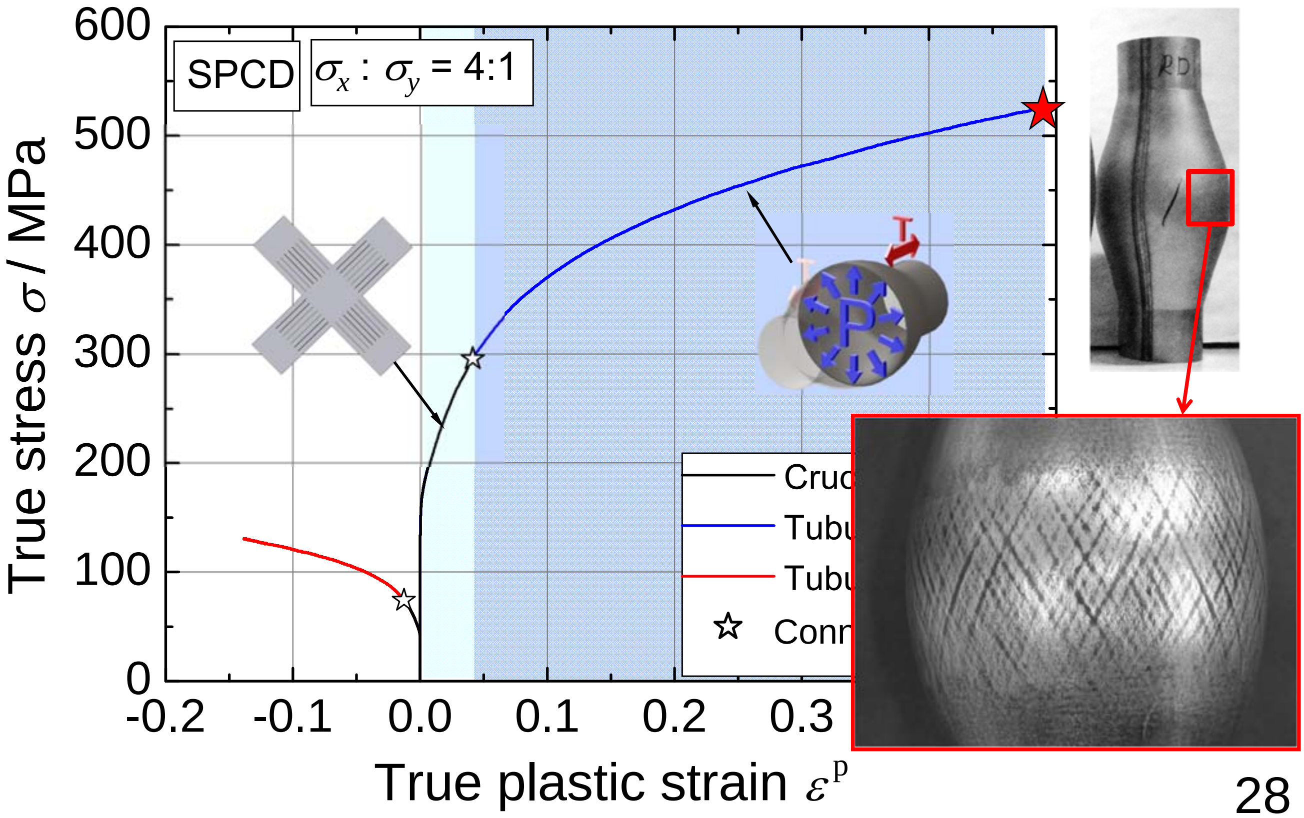


Linear stress paths



Biaxial stress-strain curves（SPCD）

Kuwabara, T. and Sugawara, F., Int. J. Plasticity, 45 (2013), 103-118.

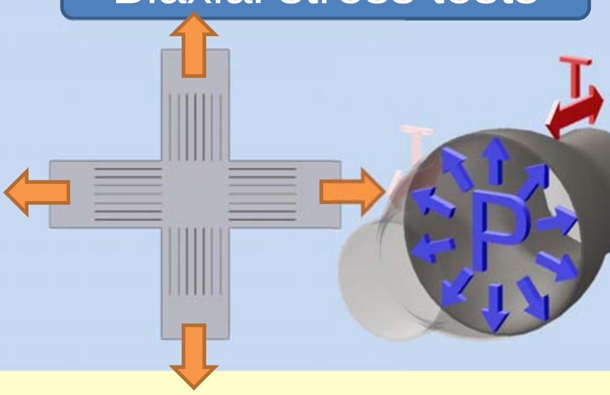


Hole Expansion Simulation Considering the Differential Hardening of a 6000-series Aluminum Alloy Sheet

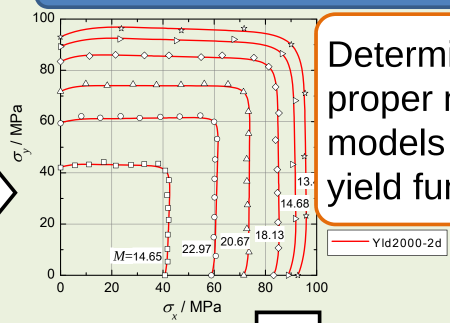
Kuwabara, T., Mori, T., Asano, M., Hakoyama, T., Barlat, F.: Material modeling of 6016-O and 6016-T4 aluminum alloy sheets and application to hole expansion forming simulation. Int. J. Plasticity, 93 (2017), 164–186.

Hole expansion forming

Biaxial stress tests



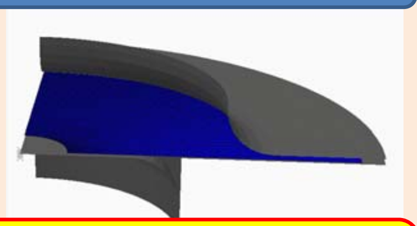
Material modeling



Determine proper material models using yield functions

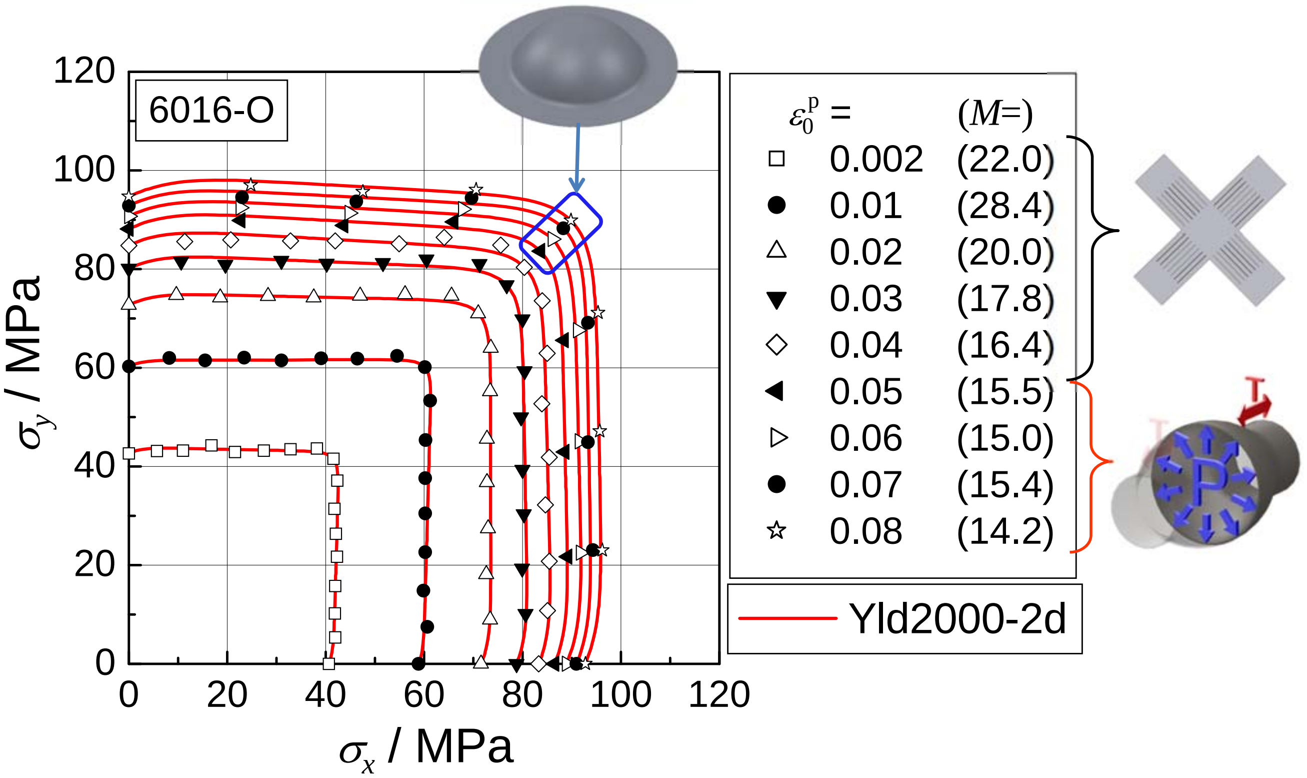
Hole expansion forming

FE simulation



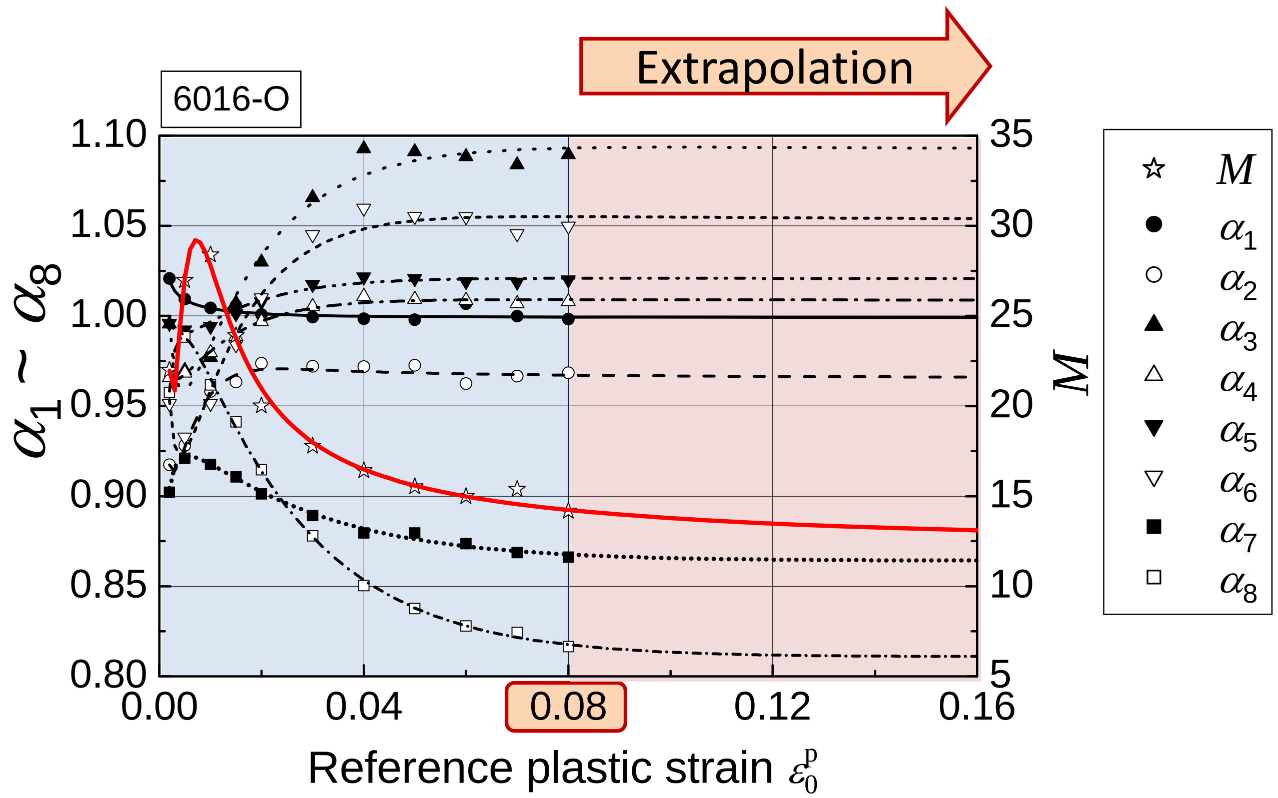
Evaluate the effects of material models on the accuracy of forming simulation.

Contours of equal plastic work

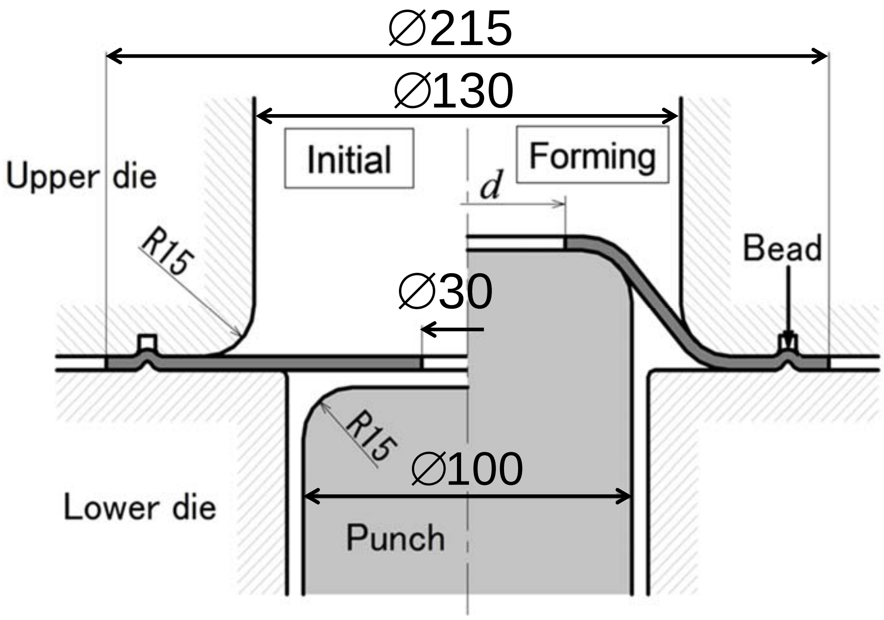


Differential hardening is observed.

Variation of M and α_i with ε_0^p

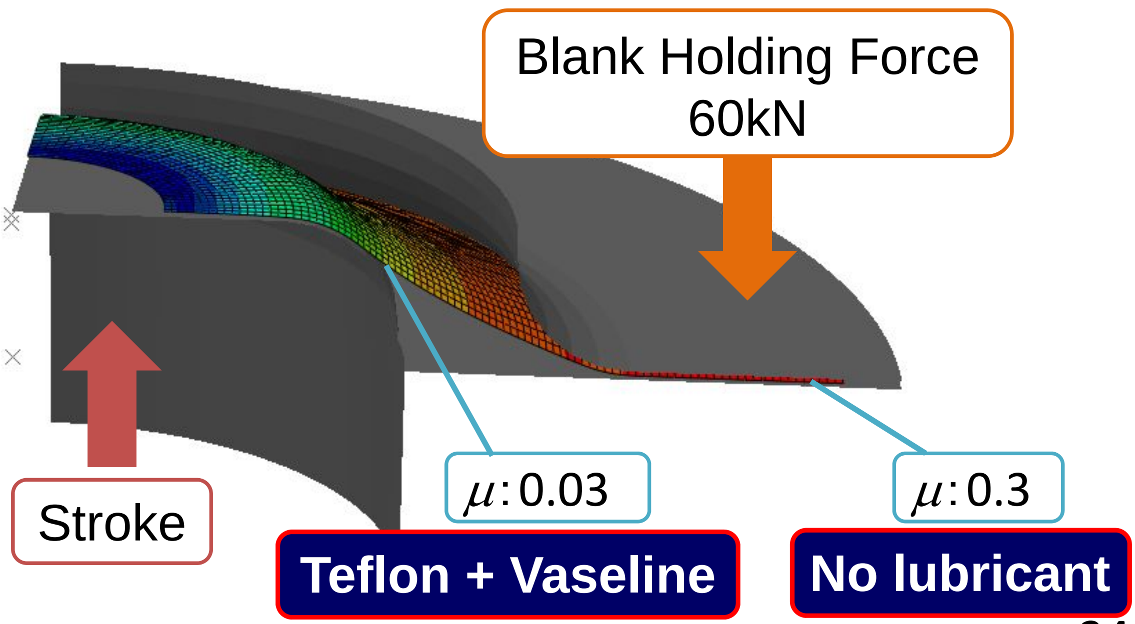


Hole expansion test apparatus

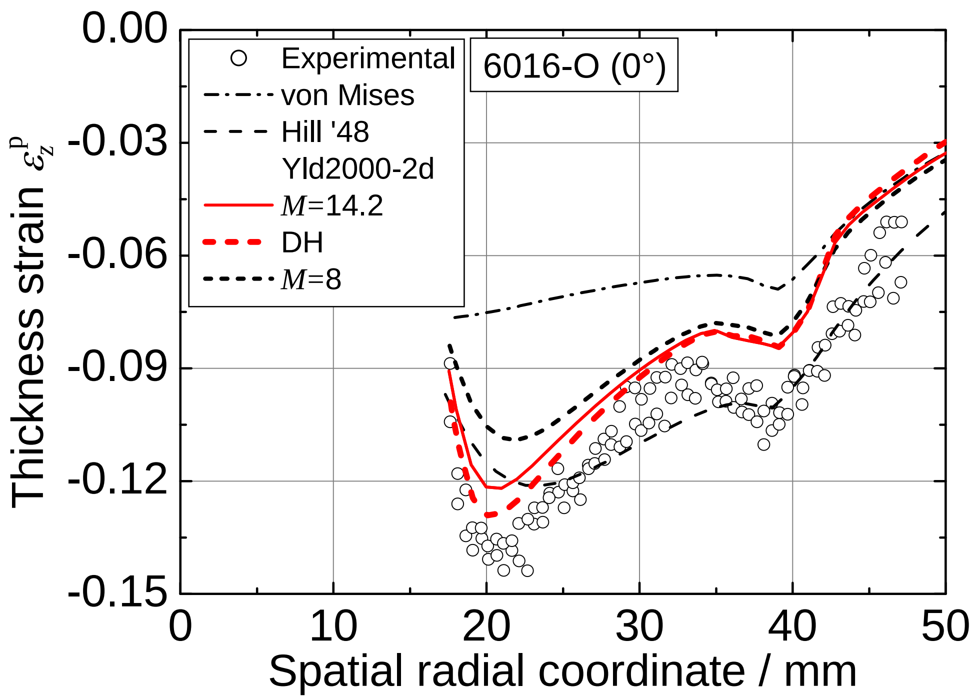


Hole expansion simulation

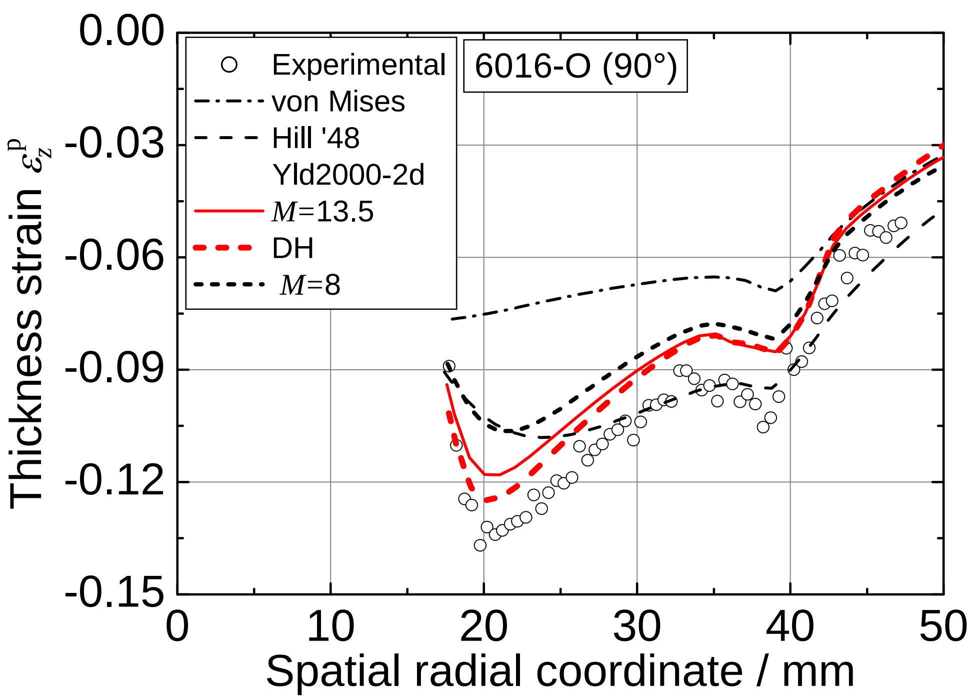
- Abaqus/Standard 6.12
- 4-node shell elements（S4R）



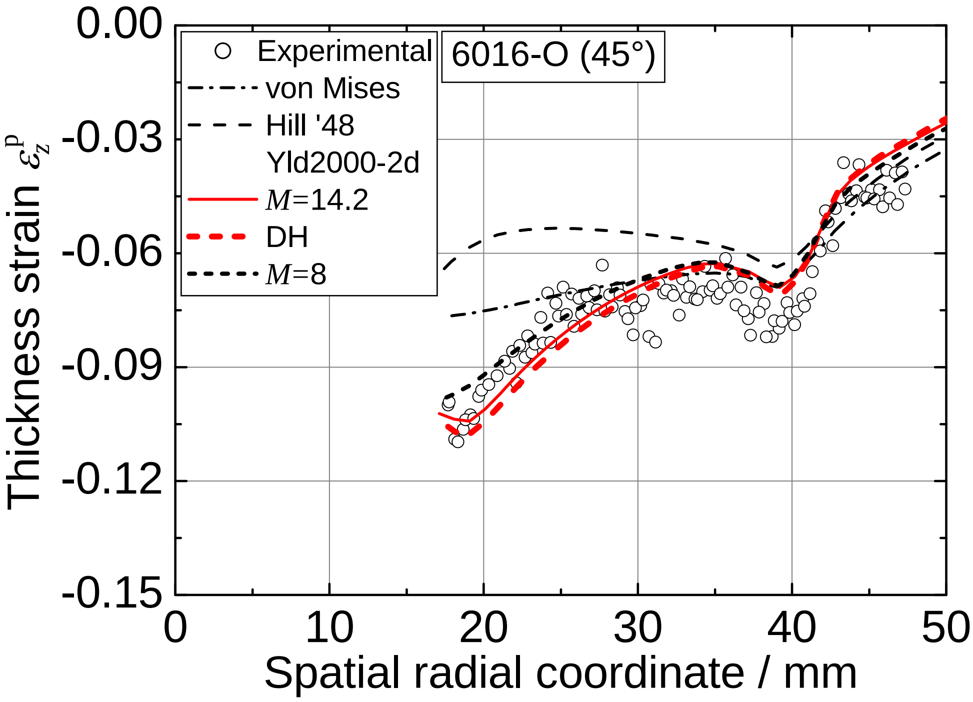
Thickness strain in RD

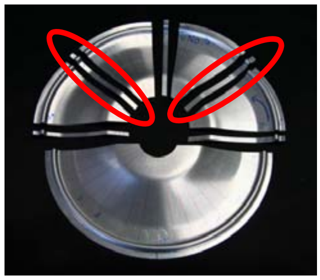


Thickness strain in 90°



Thickness strain in 45°





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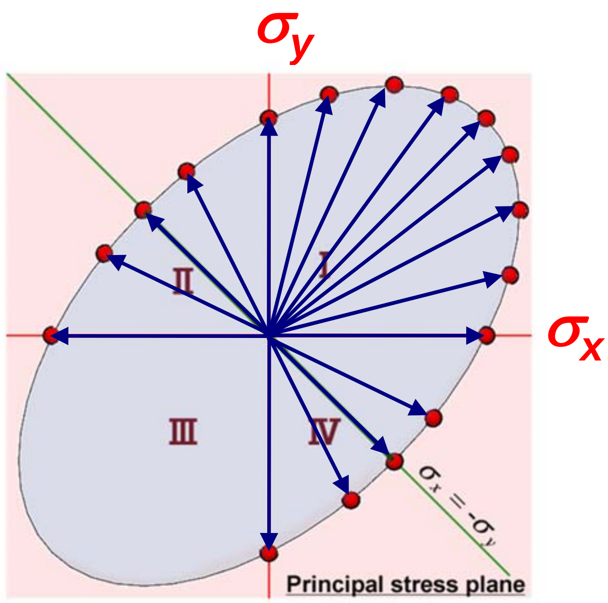
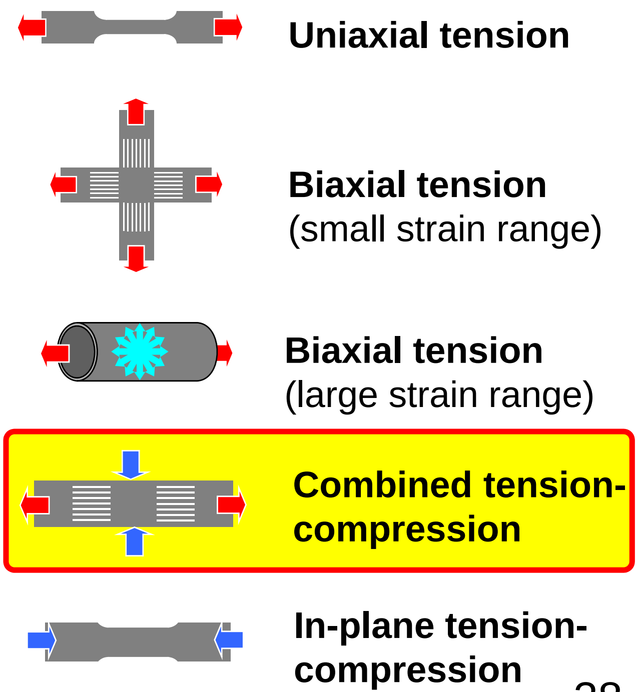
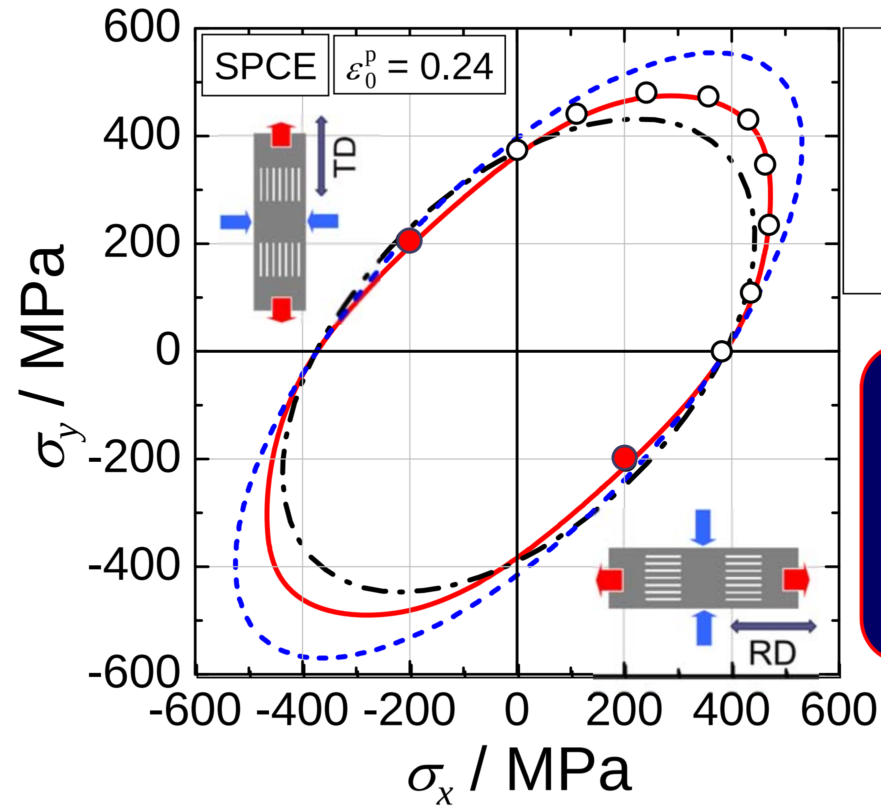


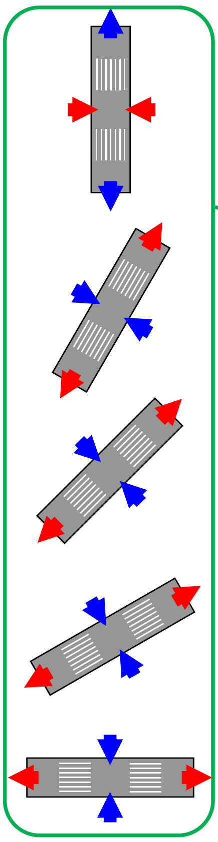


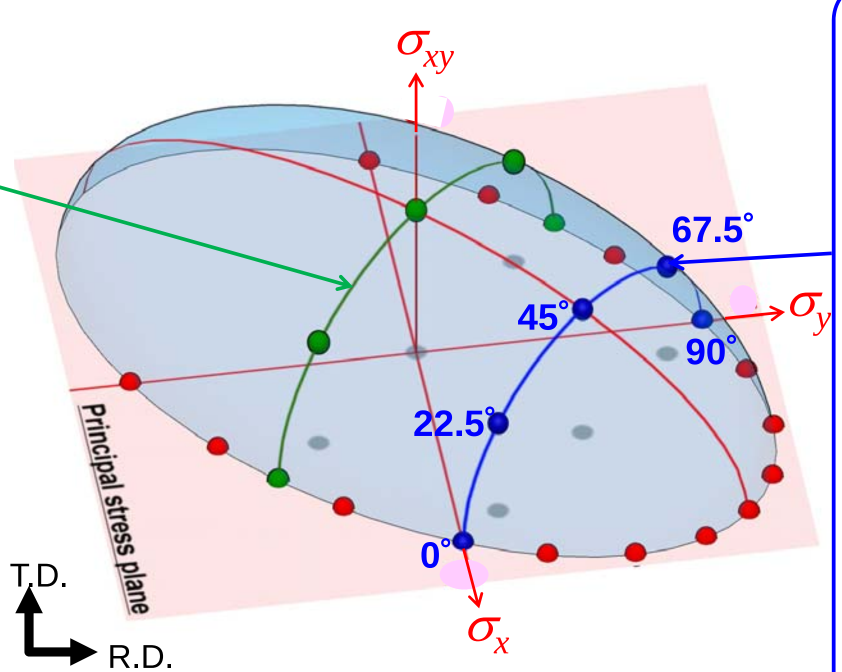
Contour of plastic work (Ultralow carbon steel sheet)

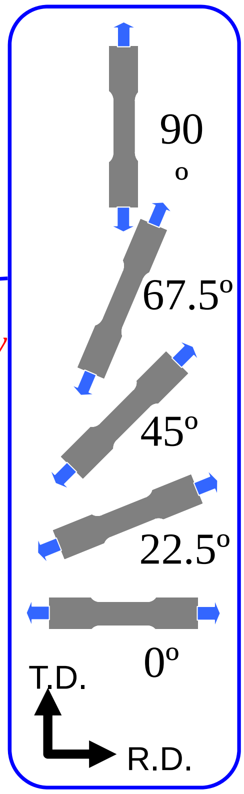


The Yld2000-2d yield function is consistent with the measurement.

Yield surface in σ_x-σ_y-σ_{xy} space







Kuwabara, T., Methods for determining yield surfaces of sheet metals, J. JSTP **57** (2016), 934-939.

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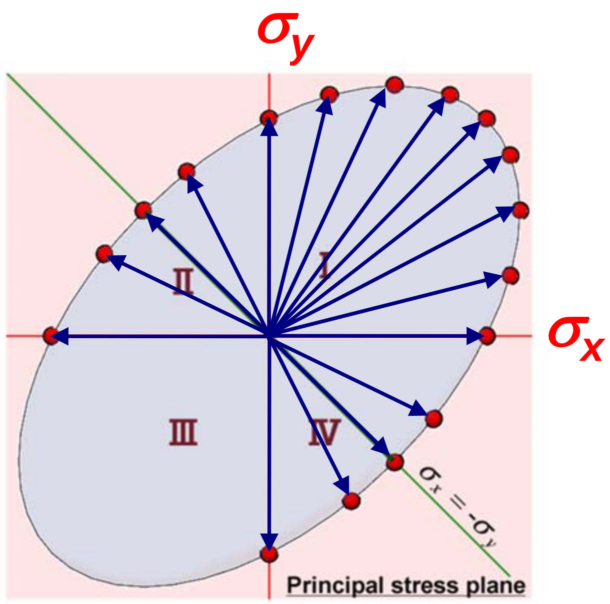
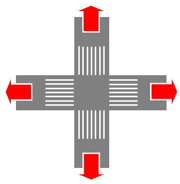
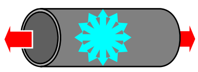


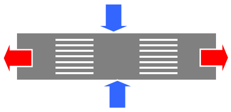
Uniaxial tension



Biaxial tension
(small strain range)



Biaxial tension
(large strain range)

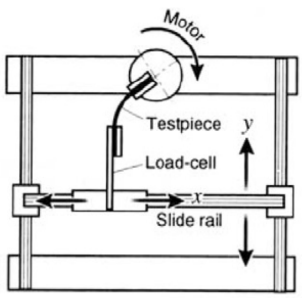


Combined tension-compression

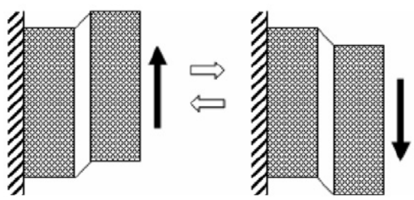
In-plane tension-compression

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

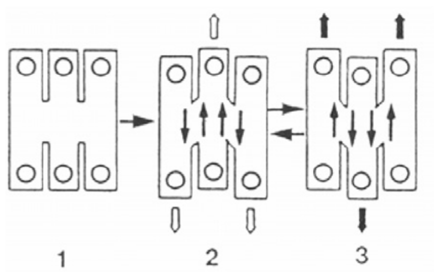
Kuwabara, T., Int. J. Plasticity, 23-3 (2007), 385-419.



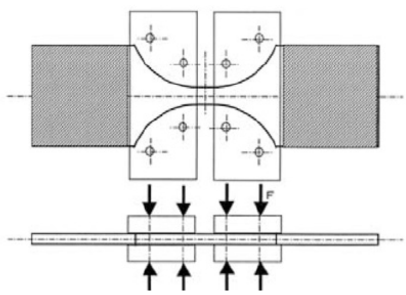
Yoshida et al. (1998)



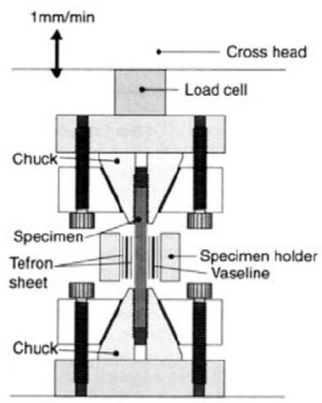
G'sell et al. (1983); Hu et al. (1992)



Miyauchi (1984)



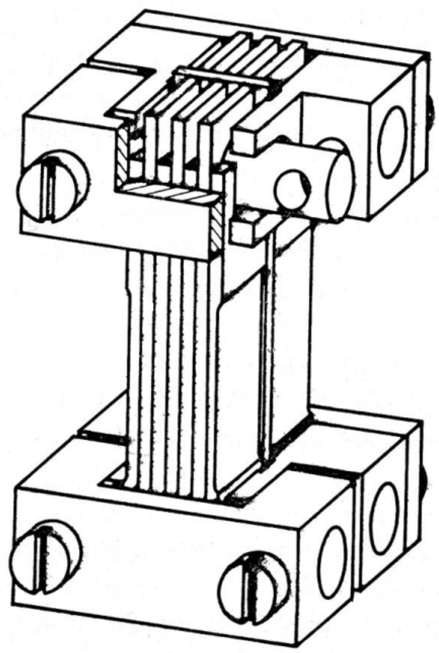
Iwata et al. (2001)



Yoshida et al. (2002b)

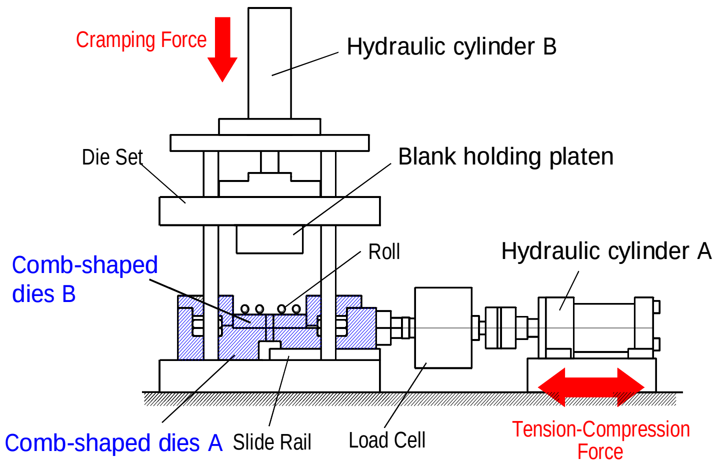
In-plane uniaxial compression testing jig for a sheet metal

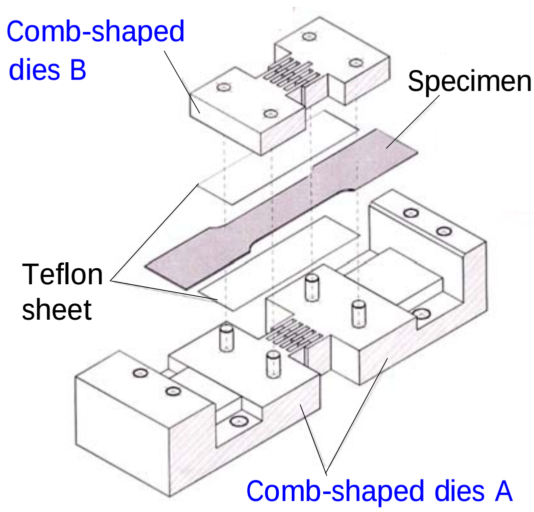
Dietrich, L., Turski, K., 1978. Rozprawy Inzynierskie 26, 91-99. (in Polish)

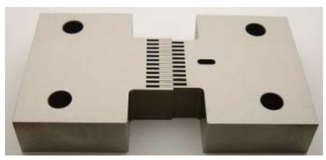


In-plane reverse loading test devise for ultra-thin sheet metals

Kuwabara, T., et al., Int. J. Plasticity, 25 (2009), 1759-1776.





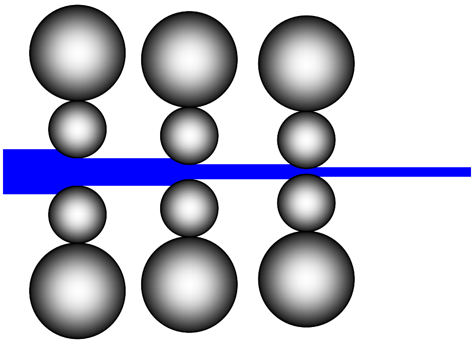


Width of teeth: 1.3mm

$\dot{\varepsilon} = (6-7)\times 10^{-5}\,/\mathrm{s}$

Test material

Kuwabara, T., et al., *Tetsu-to-Hagané*, 95-11 (2009), 732-739.



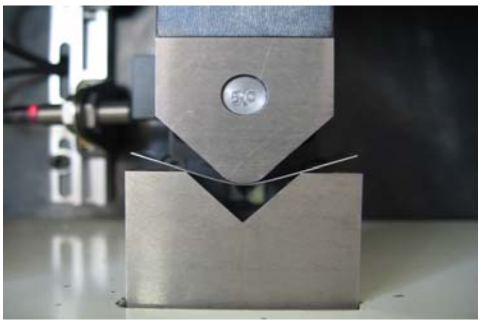
- **SUS304 (as-rolled)**

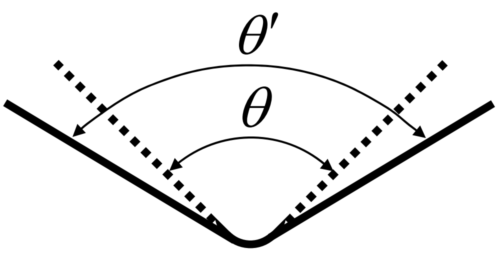
  0.3 mm thick

  Electronic spring parts

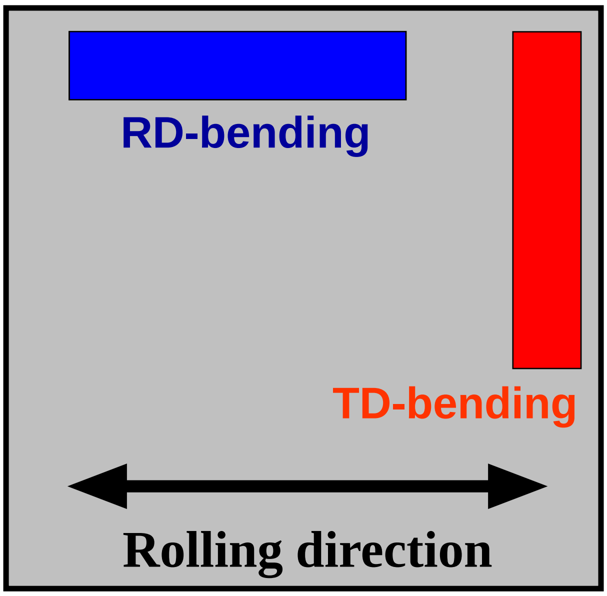
Difference in springback angle of SUS304 stainless sheets for electronic parts

Kuwabara, T., et al., *Tetsu-to-Hagané*, 95-11 (2009), 732-739.



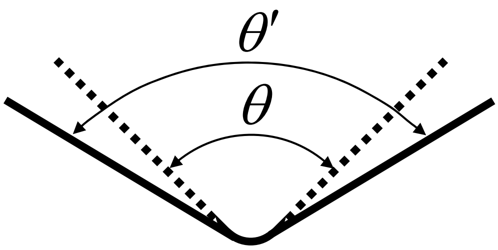


$$\Delta\theta = \theta' - \theta$$

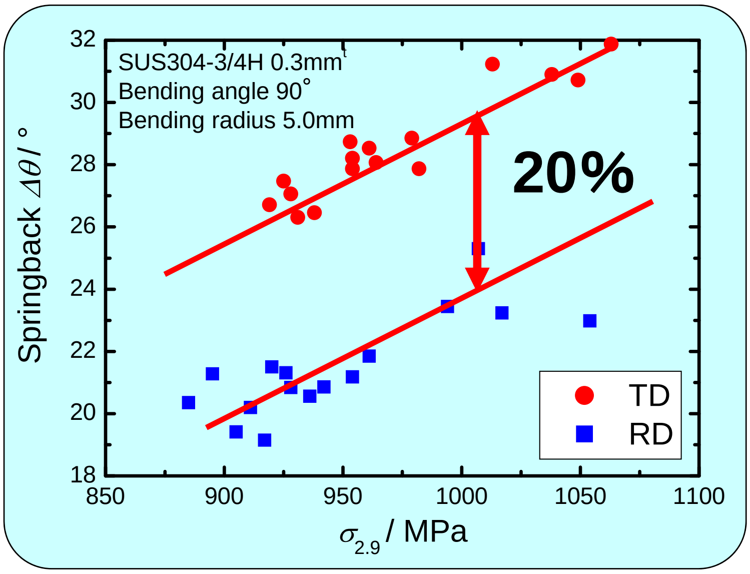


16 kinds of stainless steel sheets with different strength

Difference in springback angle between RD and TD



$$\Delta\theta = \theta' - \theta$$

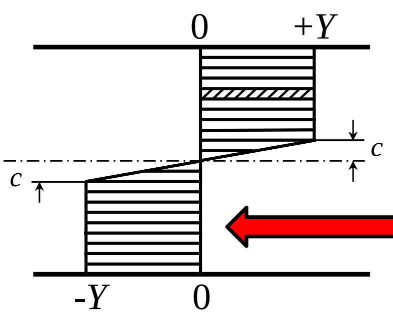


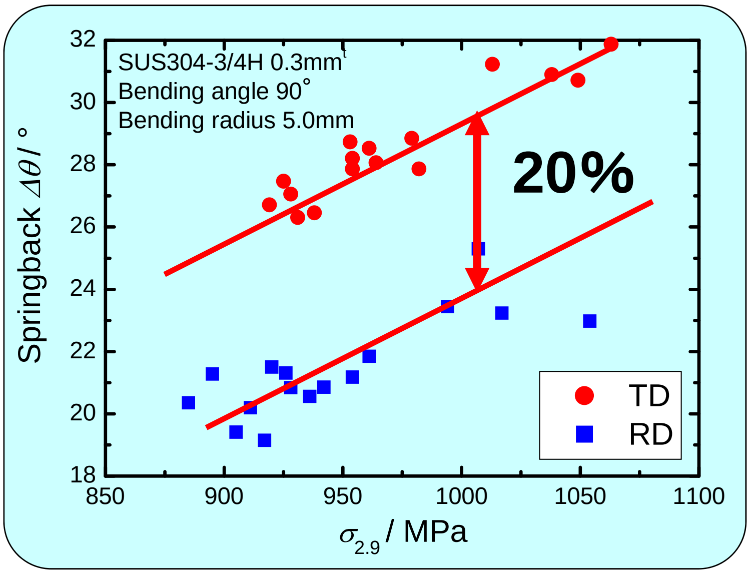
This is strange ....

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.***

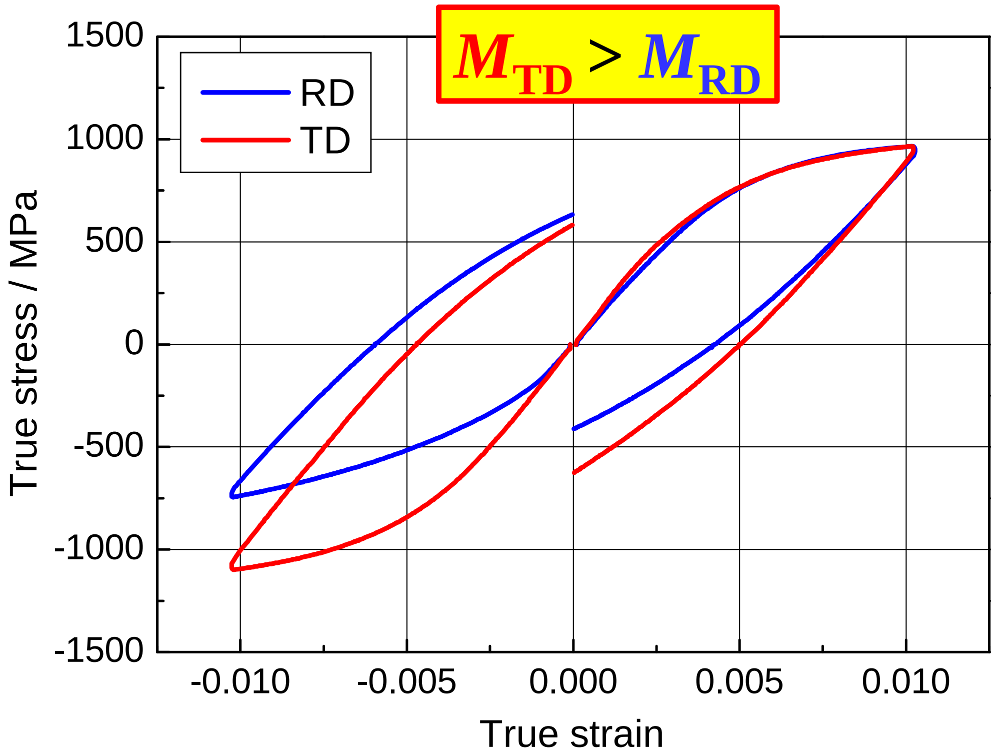




Is the compressive flow stress the same, if the tensile flow stress is the same?

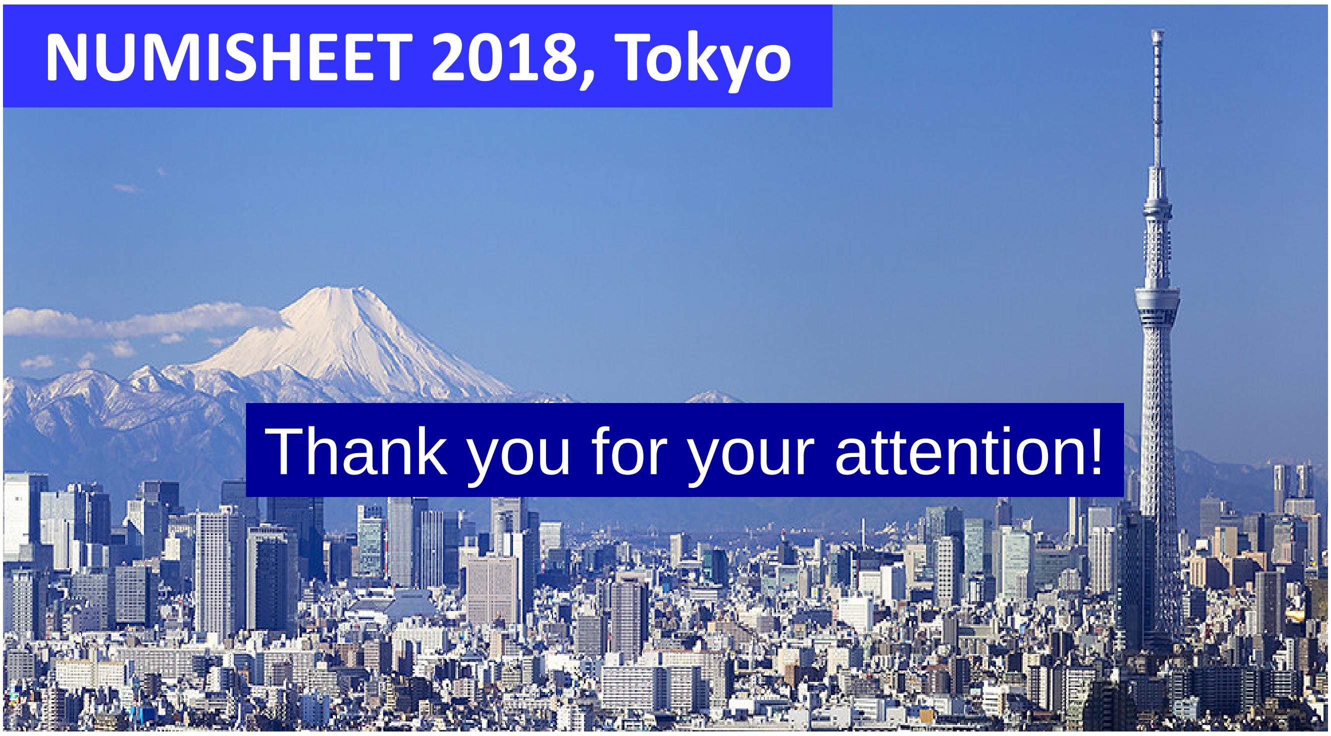
Difference in flow stresses (RD vs. TD)

Kuwabara, T., et al., *Tetsu-to-Hagané*, 95-11 (2009), 732-739.



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.**



- July 30 (Mon) — Aug 3 (Fri), 2018
- Toyocho, Tokyo