Advanced Metal Forming and Application of AI in Manufacturing

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Background

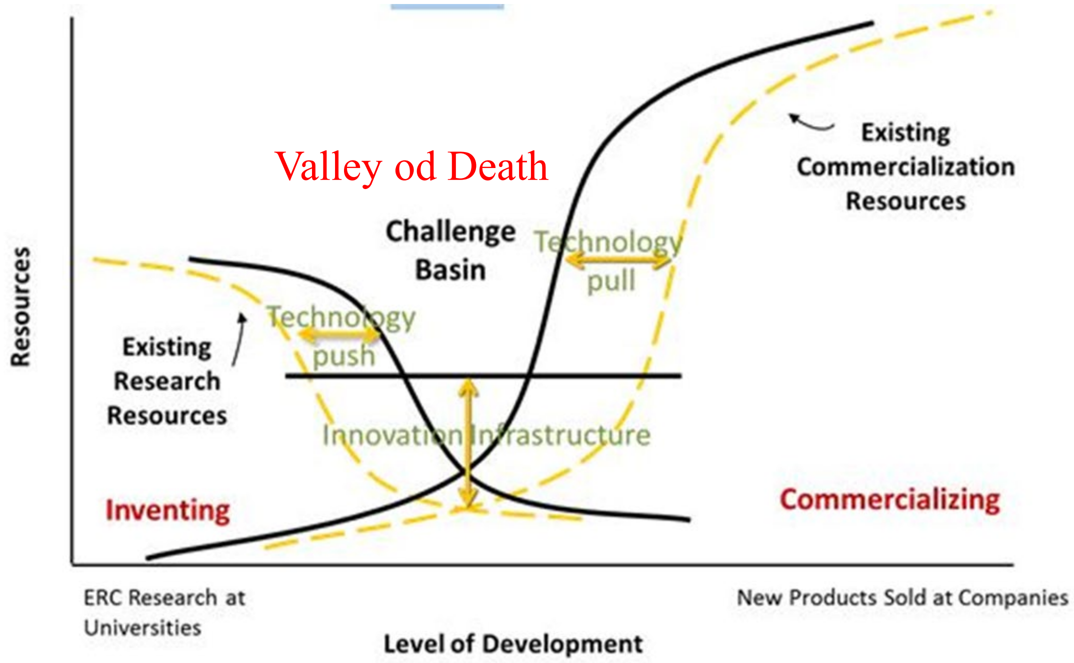
- B. S. Industrial Engineering, Tunghai University, Taiwan
- M. S. Industrial Engineering and Operations Research, Syracuse University, Syracuse, New York
- M. Eng. Manufacturing Engineering, Ph. D. Mechanical Engineering, Northwestern University, Evanston, Illinois
- Research Engineer/Sr. R&D Manager, Weirton Steel Corp. Weirton, West Virginia
- Professor, Department of Engineering Technology and Industrial Distribution, Texas A&M University

Research Interests

- Material Processing/Metal Forming
  - Roll cladding, interference friction welding, forming of polymer coated sheet metal, incremental forming, tube/sheet hydroforming
- Application of AI in Manufacturing
  - Springback control of sheet bending and tube bending
- Additive Manufacturing
  - Metal powder material extrusion, digital light processing of ceramics, selective laser melting for coating, compaction enhanced binder jetting
- Design and Analysis of Lightweight Structures
  - Perforated sheet metal, metallic foam, advanced cell-wall honeycomb

R&D Valley of Death

- Manufacturing Research



Jackson, Deborah J., What is an Innovation Ecosystem?, National Science Foundation, Arlington, VA (http://erc-assoc.org/docs/innovation_ecosystem.pdf), 2012.

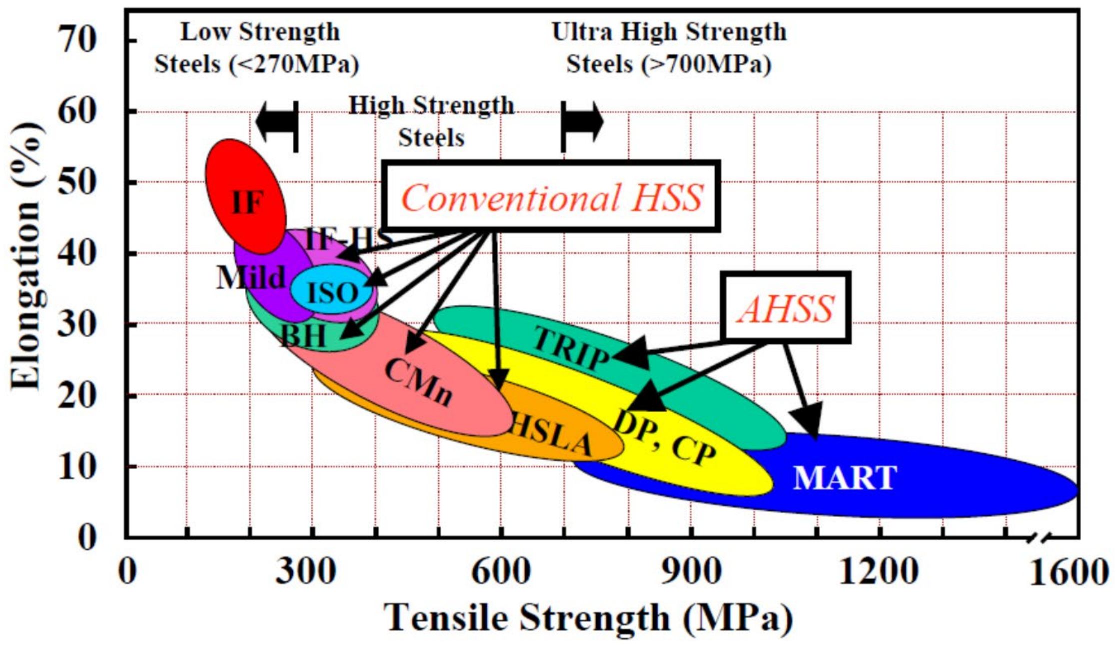
Manufacturing Research

- “Converting materials to useful products”
- Materials and mechanics
- Analytical, numerical and experimental
- Product and process innovation

Edge Cracking of Advanced High Strength Steels

What are Advanced High Strength Steels?

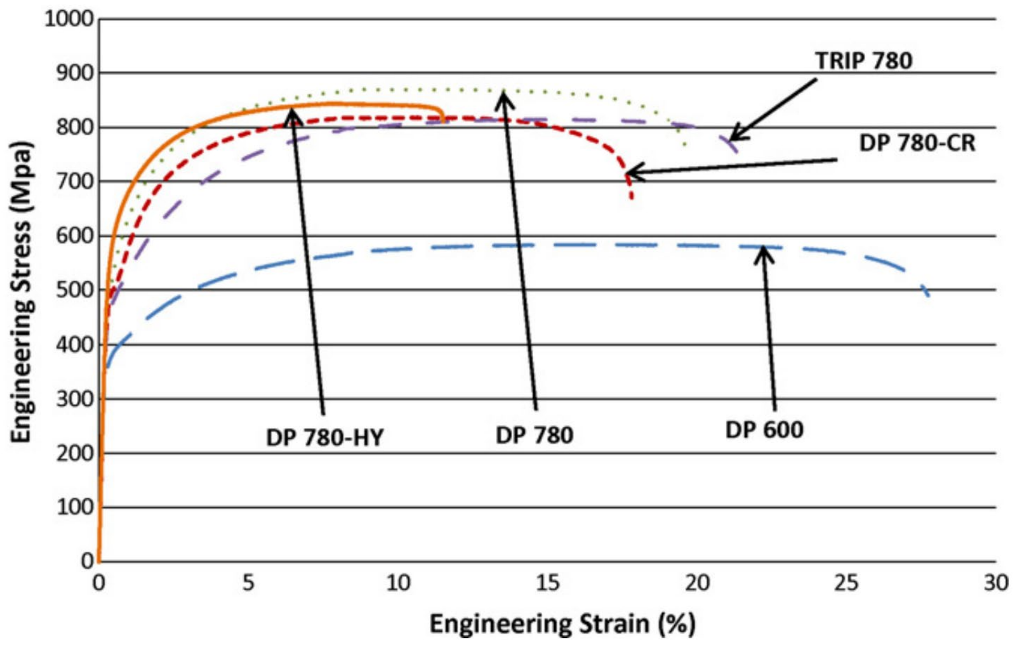
- High yield (300 MPa) and tensile strengths (500 MPa)
- Multi-phase micro-structure
- Light weight, good crash-worthiness
- Preferred in automotive industry for vehicle body manufacturing
- Less formable than conventional steels



E. Billur et al., “Challenges in Forming Advanced High Strength Steels,”NewDevelopments in Sheet Metal Forming, pp. 285–304, 2010.

Challenges in Forming AHSS

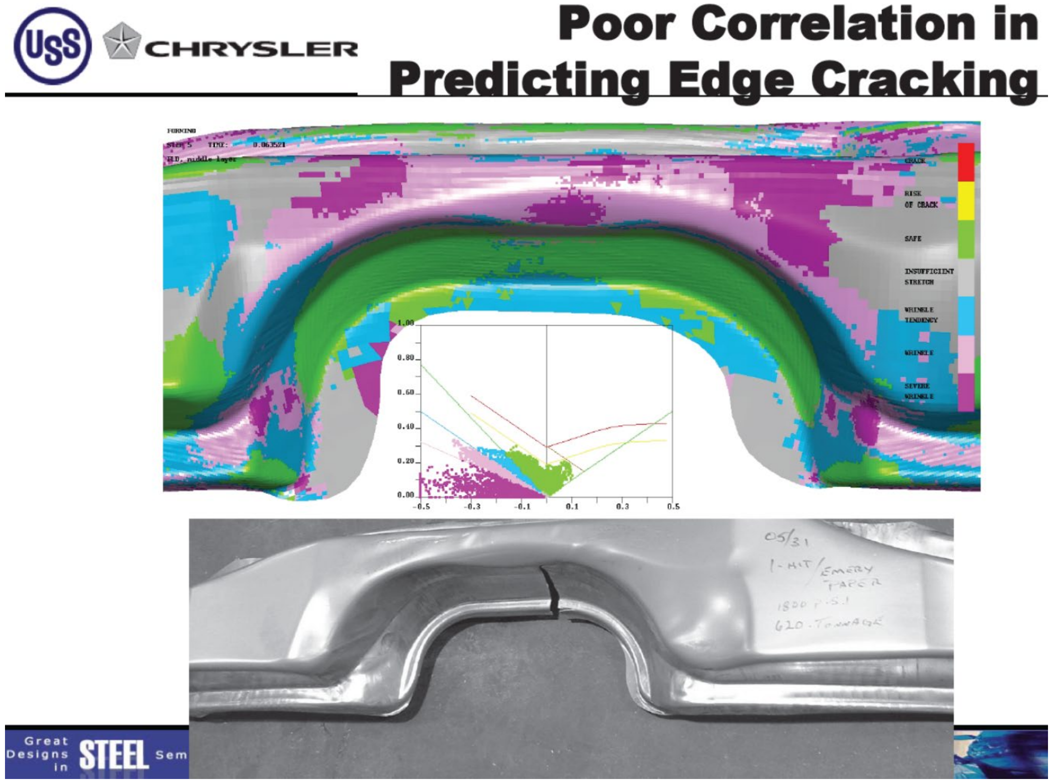
- Poor ductility consequent to higher strength
- Inconsistency in mechanical properties
- Risk of sheet breakage during press forming
- Repeated die adjustments, increased die manufacturing costs



Ming Chen (US Steel), D.J Zhou, (Chrysler), “AHSS Forming Simulation for Shear Fracture an Edge Cracking”

Challenges in Forming AHSS

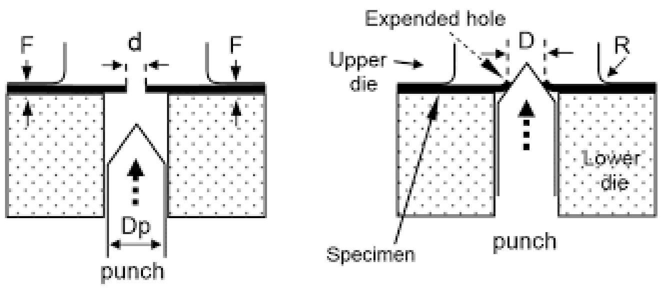
- Tool wear, large spring back
- Lubricants, coatings demand for careful selection.
- Forming limit diagrams (FLDs) cannot predict formability limits reliably
- Prone to cracking at portions of stretch flanging/bending



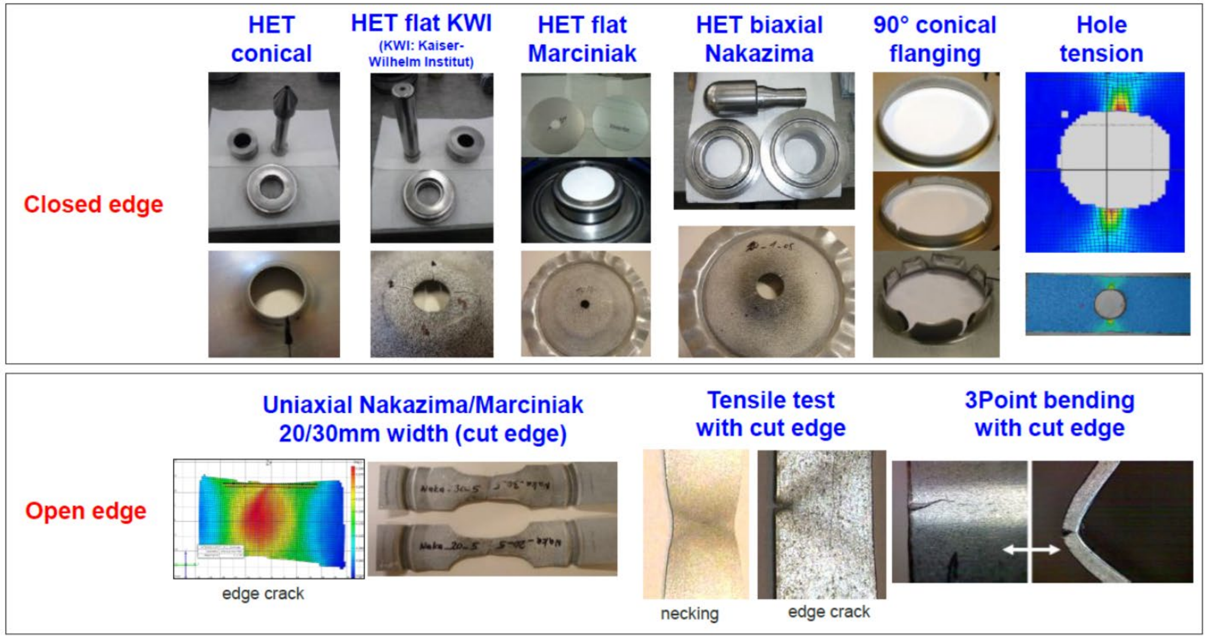
E. Billur et al., "Challenges in Forming Advanced High Strength Steels,"New Developments in Sheet Metal Forming, pp. 285–304, 2010.

Literature Review

- Experiments and new testing methods[2-7]
  - Hole expansion test, modified tensile test, deep drawing and bending tests, notched and central hole specimen tests.
- Effects of process parameters [2-7]
  - Die clearance angle, cutting angle, cutting edge geometry, edge condition.

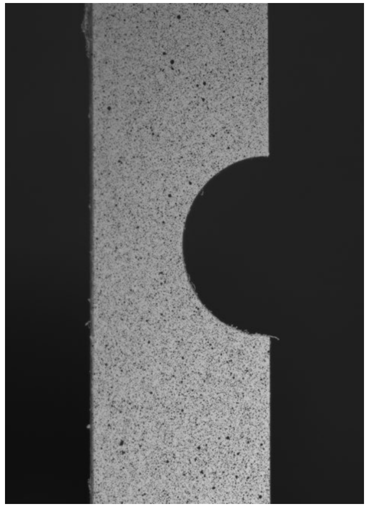


No strain gradient

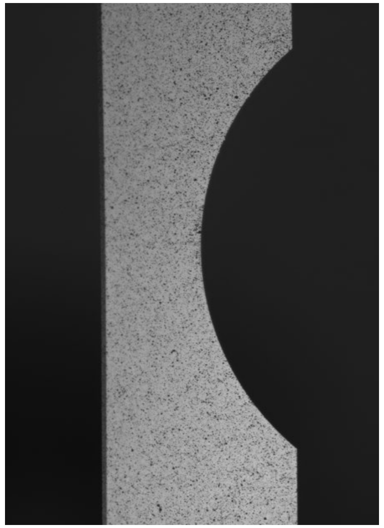


Single Notched Test

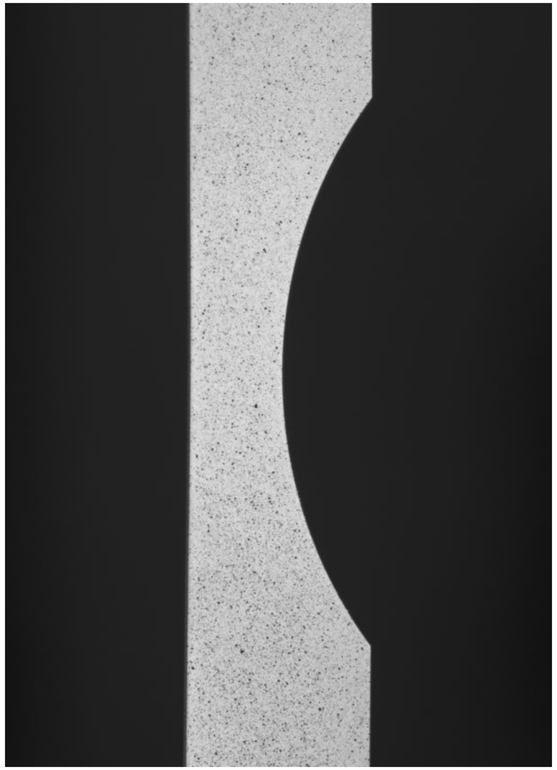
10 mm notch radius

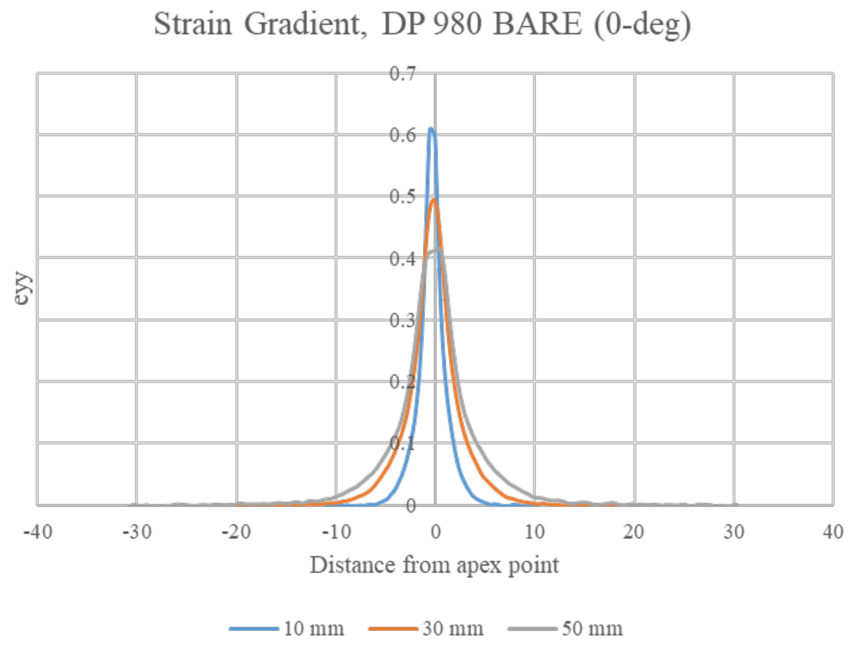


30 mm notch radius



50 mm notch radius

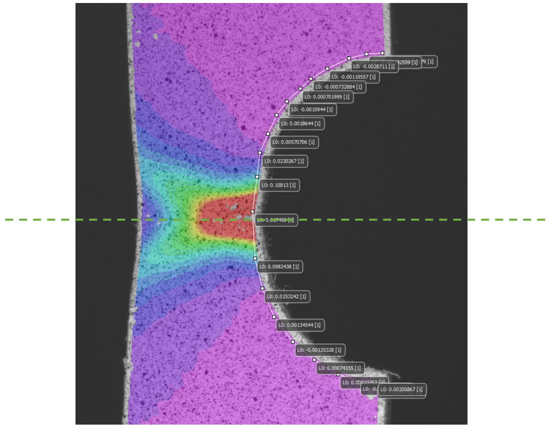


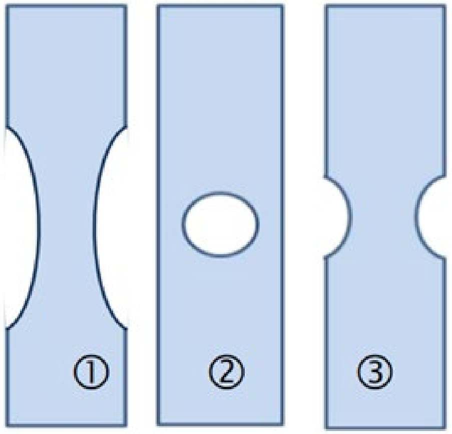


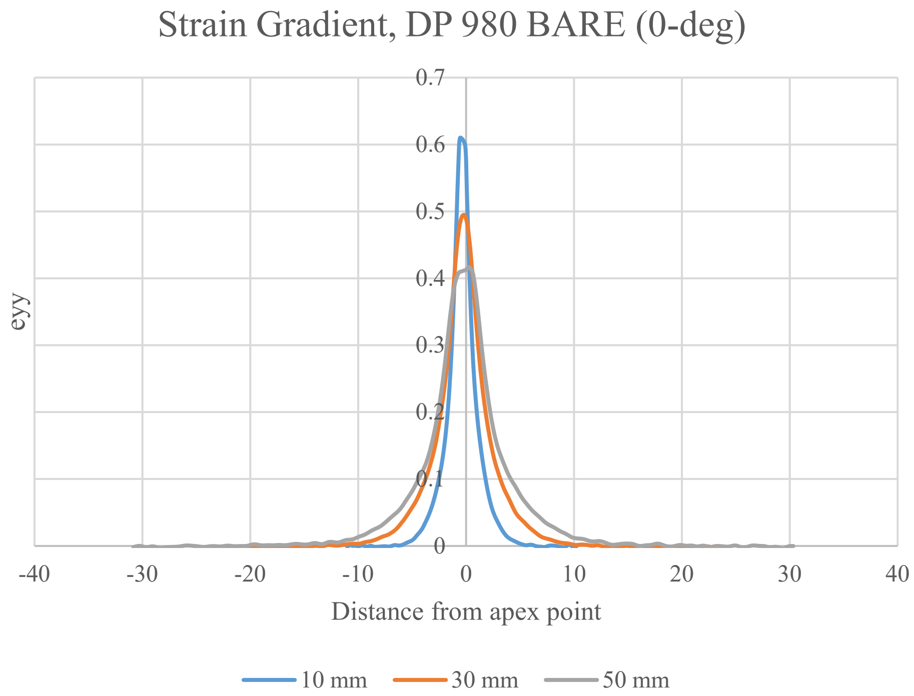
With strain gradient

Experimental Investigation

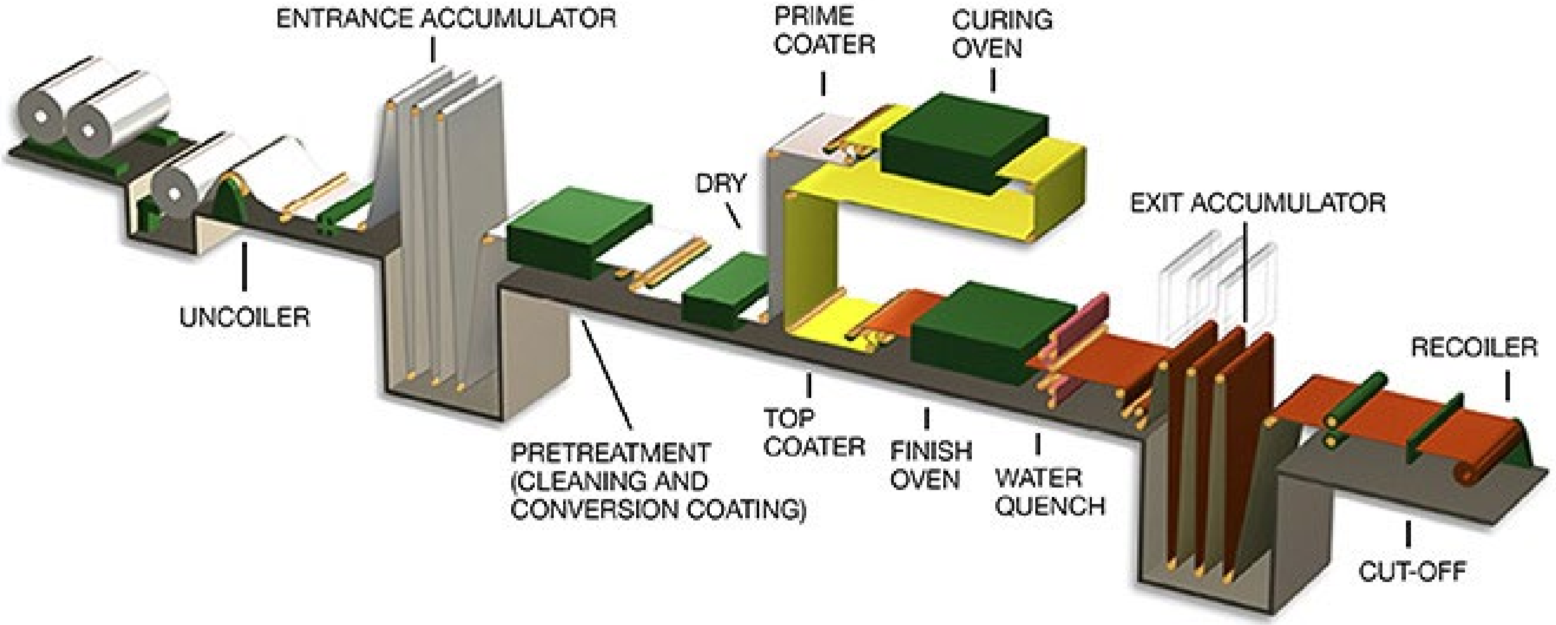
- Strain gradient: 10 mm > 30mm > 50mm
- Higher strain gradient, better formability

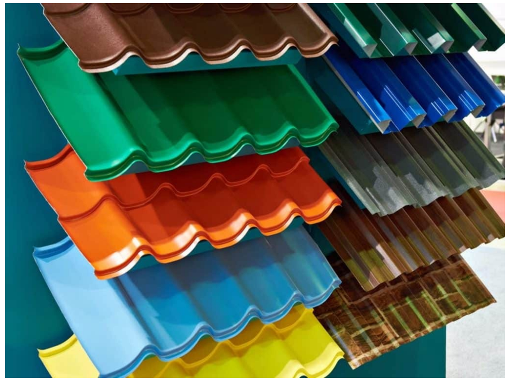






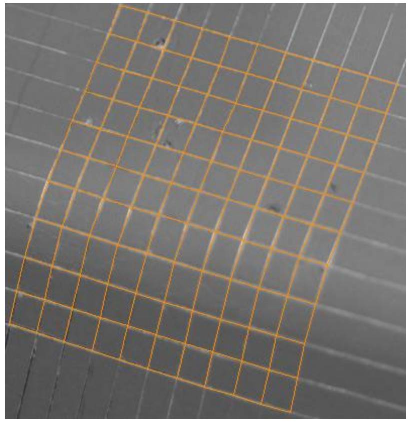
Coil Coated Sheet Metals

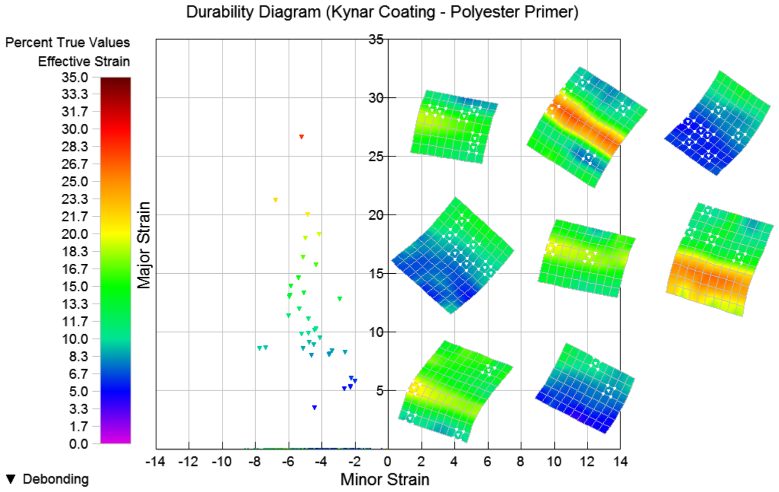


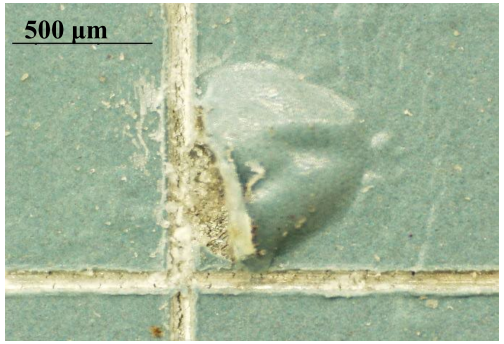


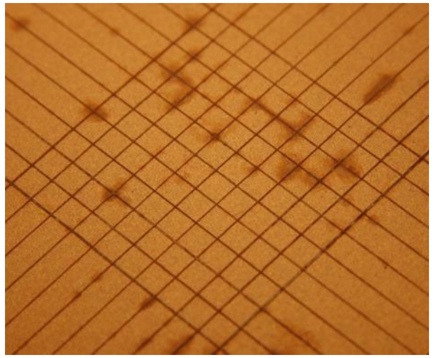
Evaluation of Coating Adhesion

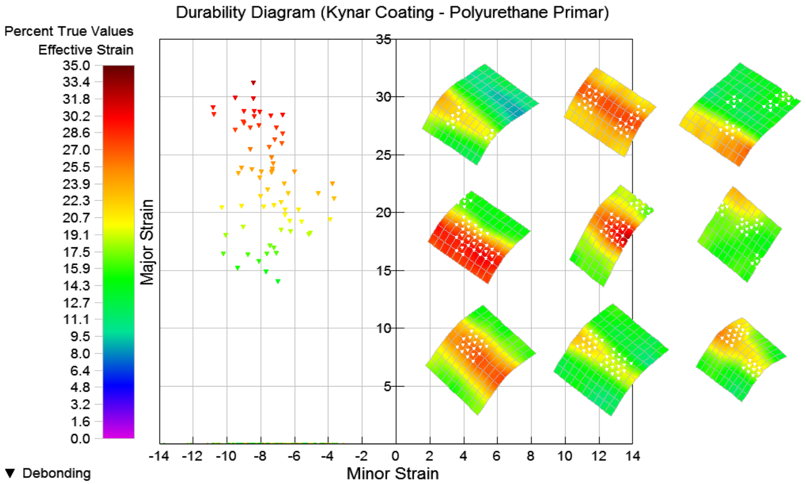
Pre-coat Sheet Metal

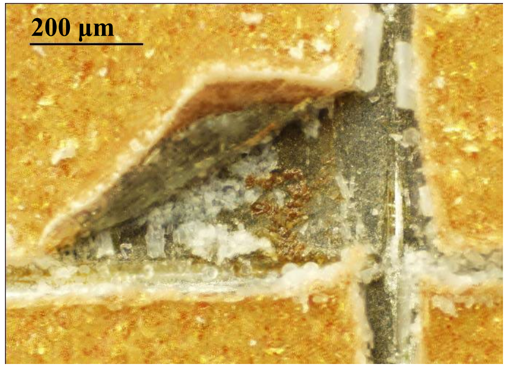




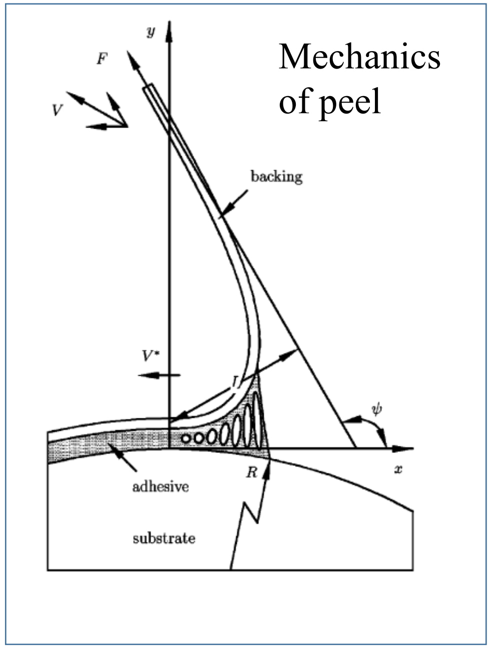








Evaluation of Coating Adhesion

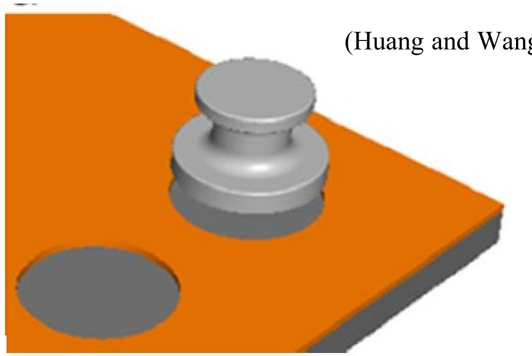


(Zhang and Wang 2009)

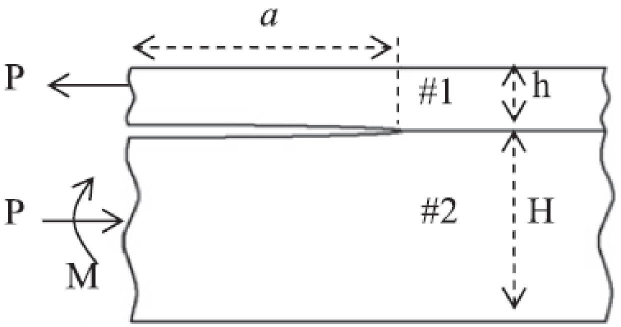
$$G=\frac{1}{2\bar{E}_1}\left(\frac{(-P)^2}{h}+12\frac{(a^2\sigma_{22}/2)^2}{h^3}\right)+\frac{1}{2\bar{E}_2}\left(\frac{(-P)^2}{H}+12\frac{(-M)^2}{H^3}\right)$$

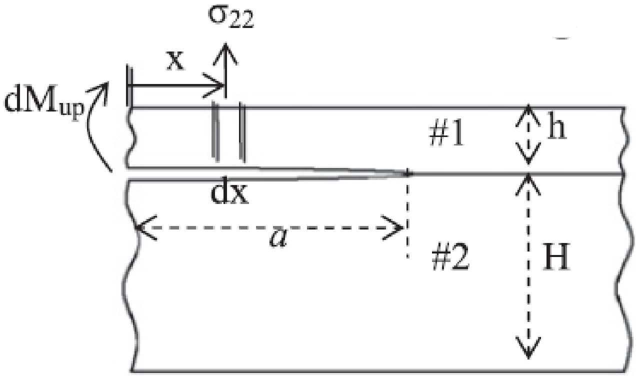
$$G_{\text{initial}}=\frac{1}{2\bar{E}_1}\left(12\frac{(a_0{}^2\sigma_{22\_\text{initial}}/2)^2}{h^3}\right)$$

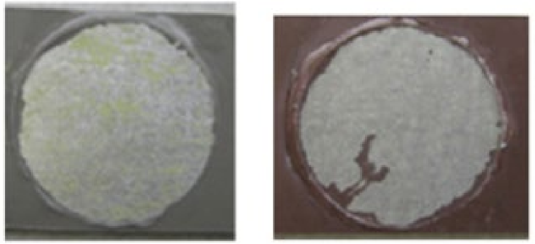
$$G_{\text{new}}=\frac{1}{2\bar{E}_1}\left(\frac{(-P)^2}{h}+12\frac{(a^2\sigma_{22\_\text{new}}/2)^2}{h^3}\right)+\frac{1}{2\bar{E}_2}\left(\frac{(-P)^2}{H}+12\frac{(-M)^2}{H^3}\right)$$

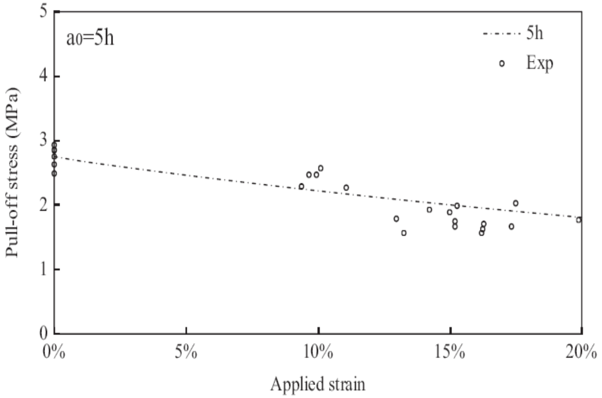


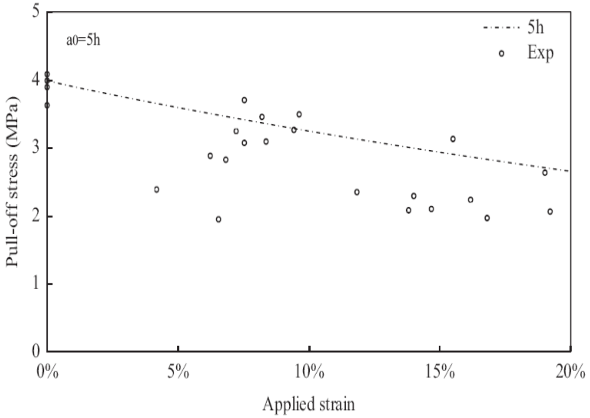
(Huang and Wang 2013)



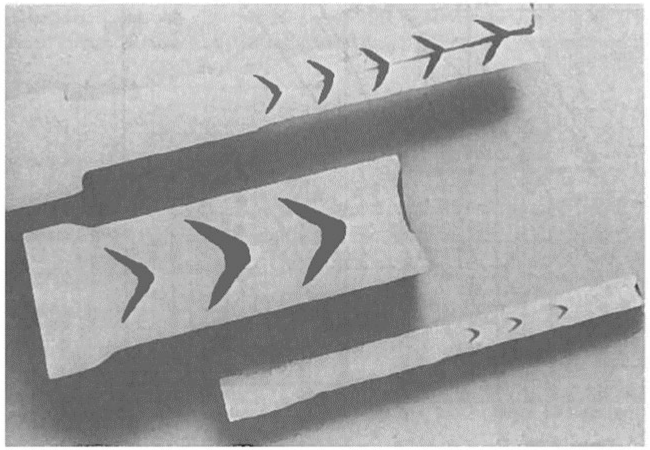


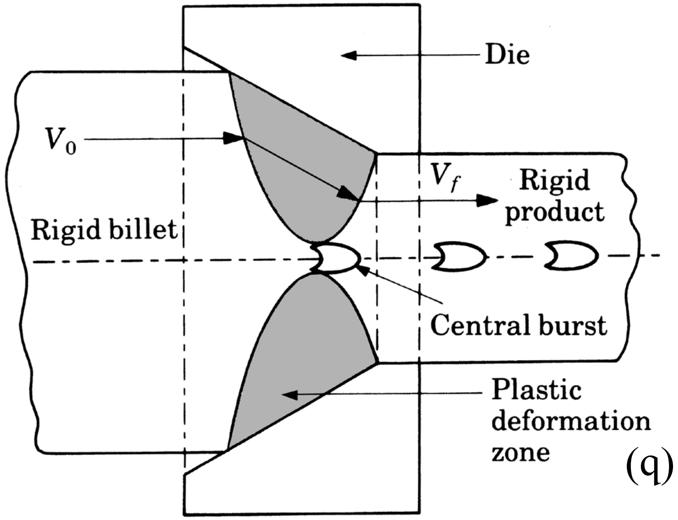


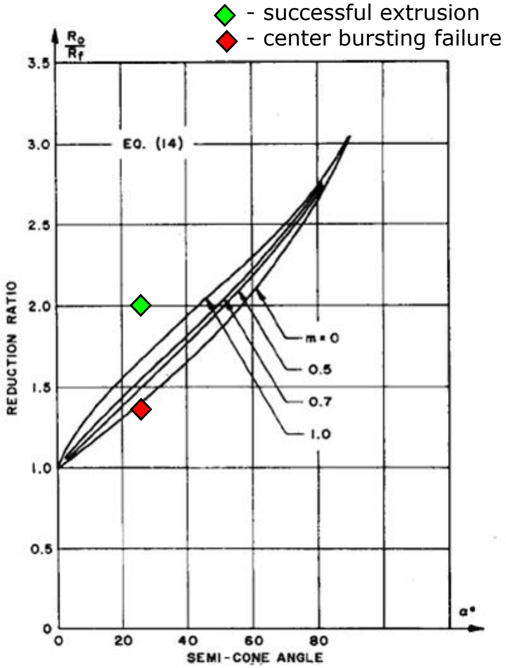




Chevron Cracking in Extrusion

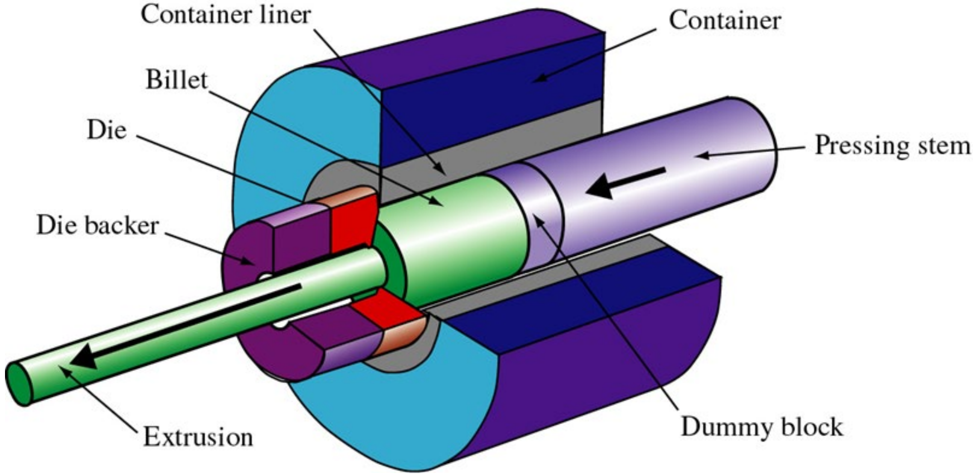


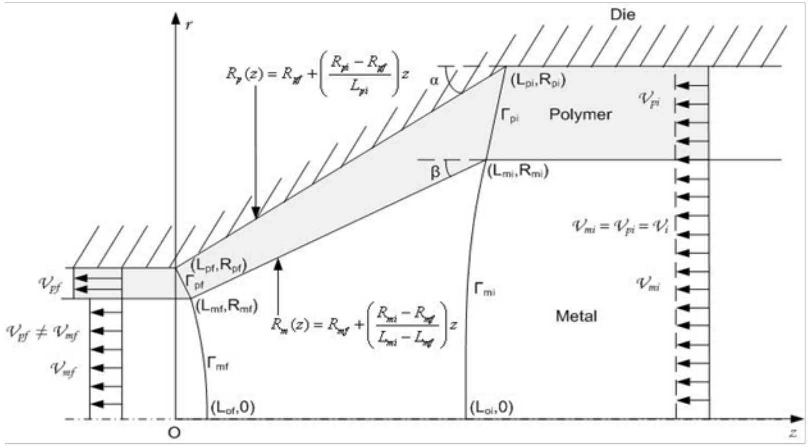


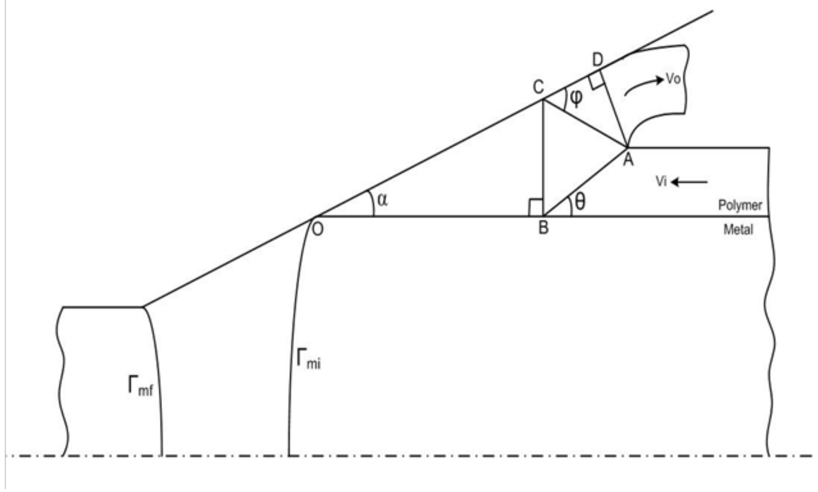


Avitzur, B., 1968, "Analysis of Central Bursting in Extrusion and Wire Drawing," Journal of Engineering for Industry, **90**, pp. 79-91.

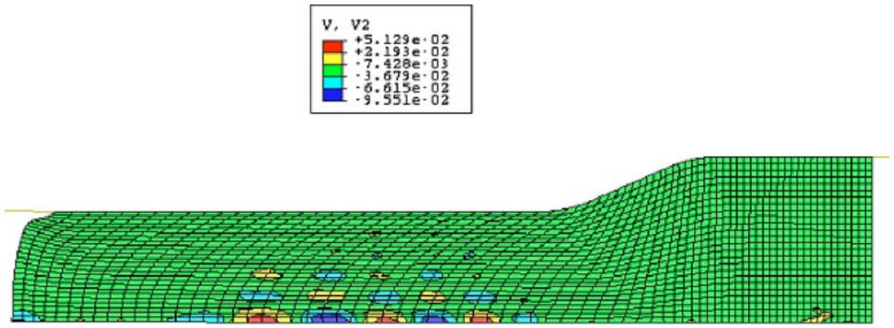
Extrusion of Polymer Coated Metal Rods



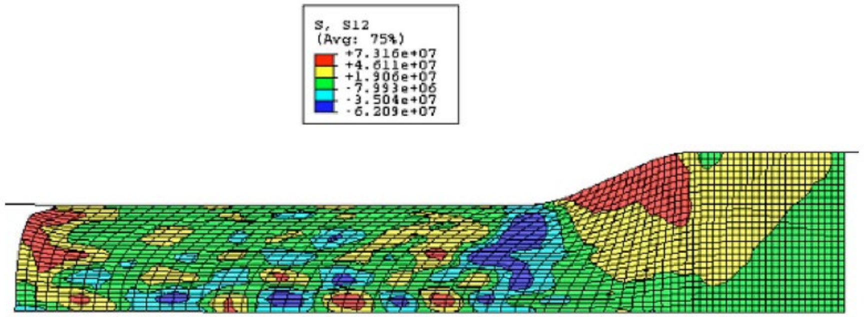




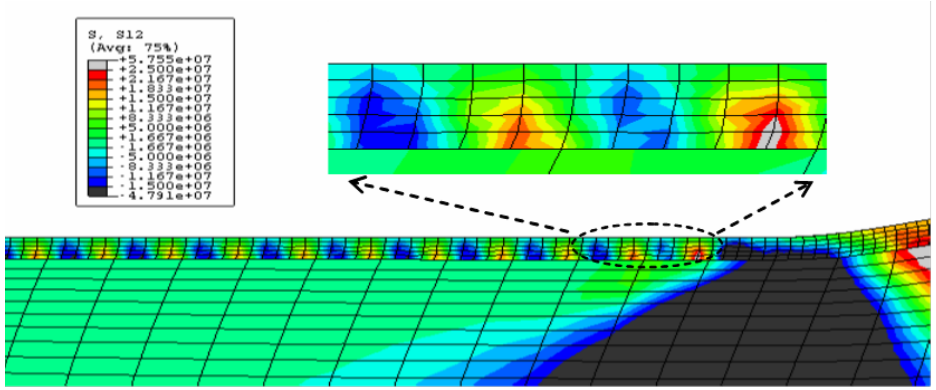
Extrusion of Polymer Coated Metal Rod



(a)



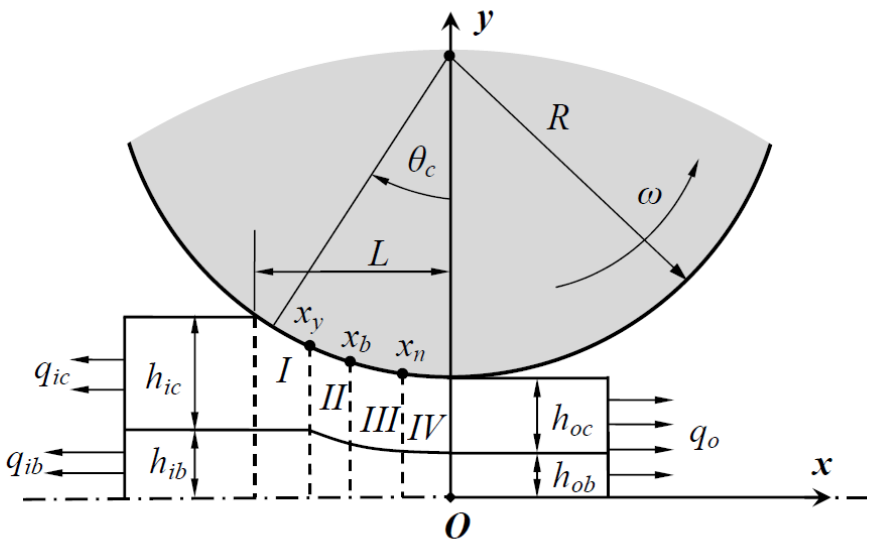
(b)

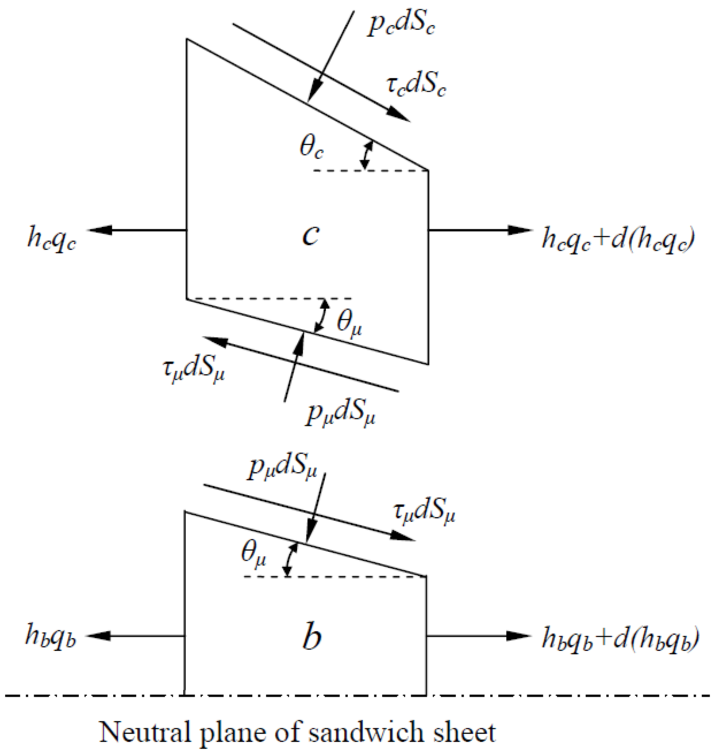


Cold Rolling of Polymer Coated Steel?

Modeling of Roll Bonding Process

A). Macroscopic rolling mechanics





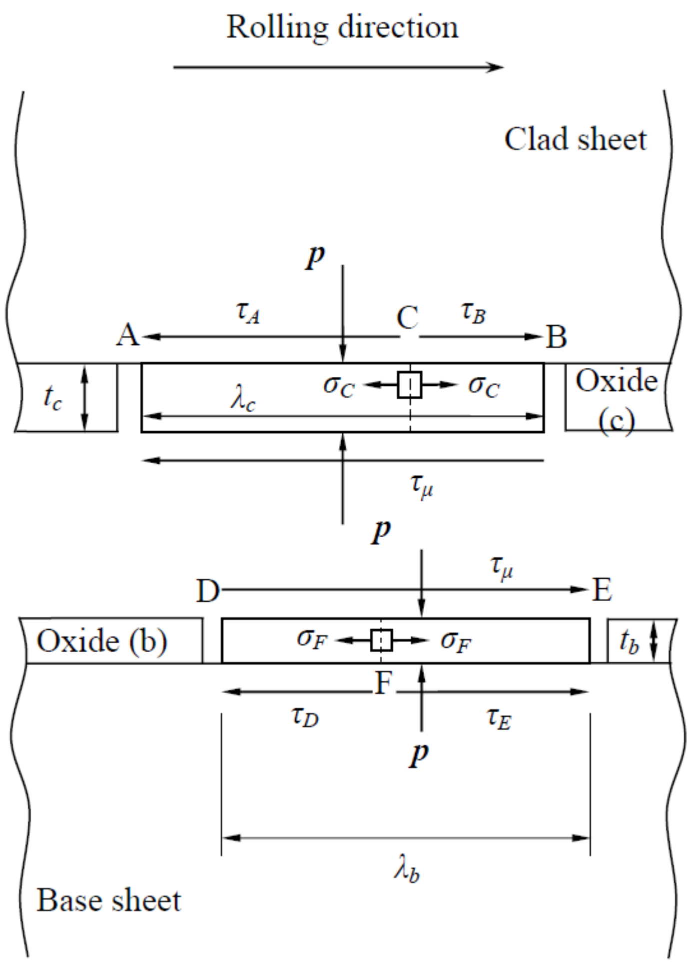
$$\frac{d\left(h_c q_c\right)}{dx} + \tau_c\left(1+\tan^2\theta_c\right) - p\left(\tan\theta_c - \tan\theta_\mu\right) - \tau_\mu\left(1+\tan^2\theta_\mu\right) = 0$$

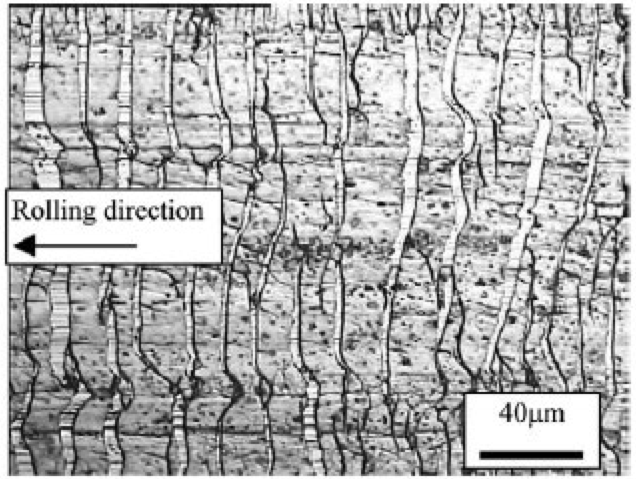
$$\frac{d\left(h_b q_b\right)}{dx} - p\tan\theta_\mu + \tau_\mu\left(1+\tan^2\theta_\mu\right) = 0$$

Modeling of Roll Bonding Process

B). Microscopic oxide film fracture

Open Atmosphere





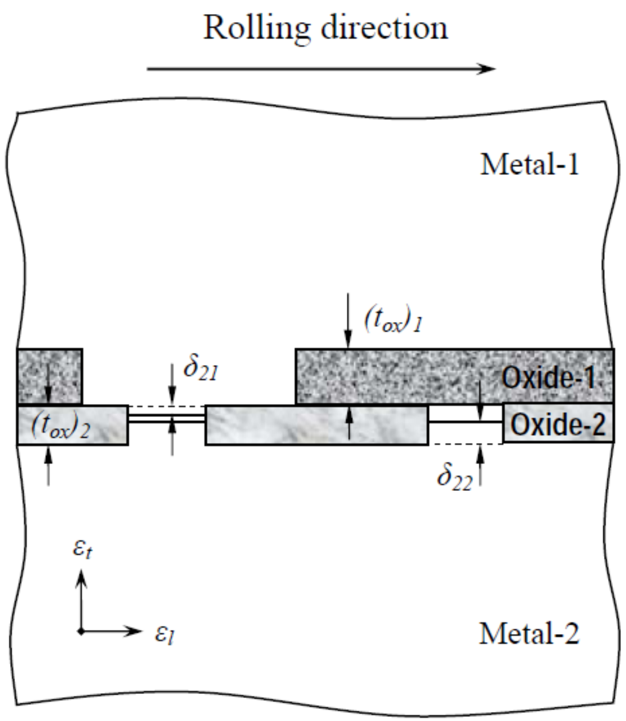
(Le, et al, 2004)

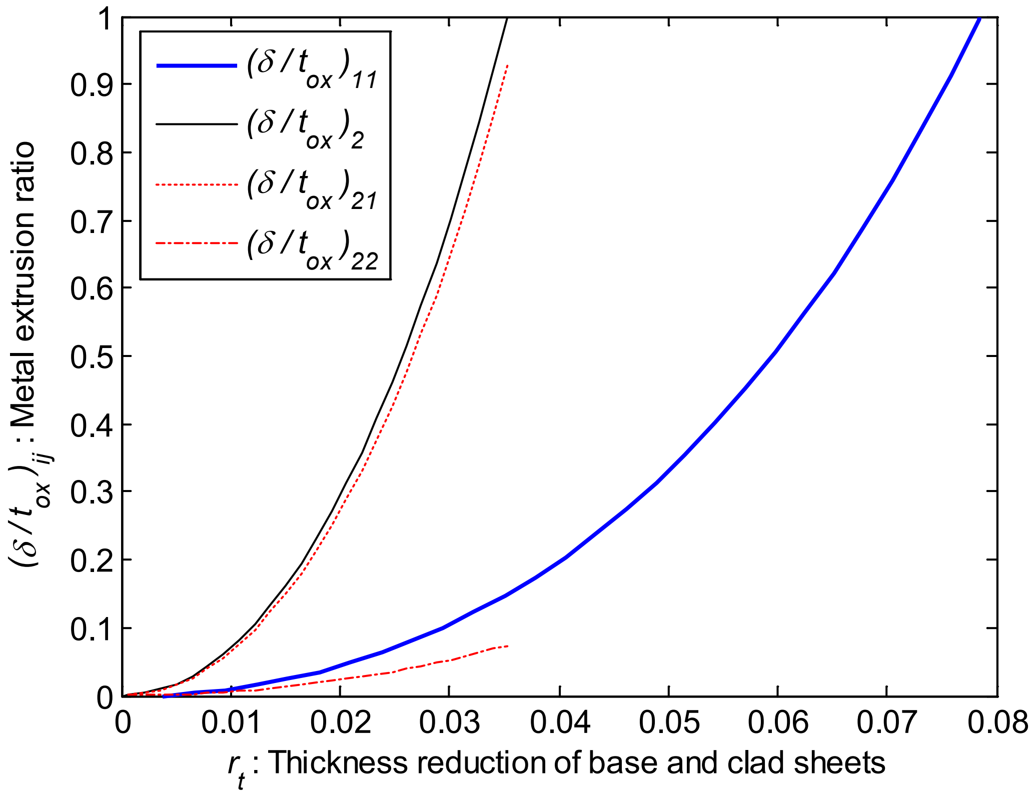
$$\left(\frac{\lambda_c}{t_c}\right)_{\max} = 4\frac{\left(\frac{k_{co}}{k_c}-1\right)}{\left(1-4\mu^2\right)}$$

$$\left(\frac{\lambda_b}{t_b}\right)_{\max} = 4\frac{\left(\frac{k_{bo}}{k_b}-\frac{k_c}{k_b}\right)}{\left(1-4\mu^2\left(\frac{k_c}{k_b}\right)^2\right)}$$

Analytical Results

Metal extrusion:





Diffusion bonding strength model

Fick's law:

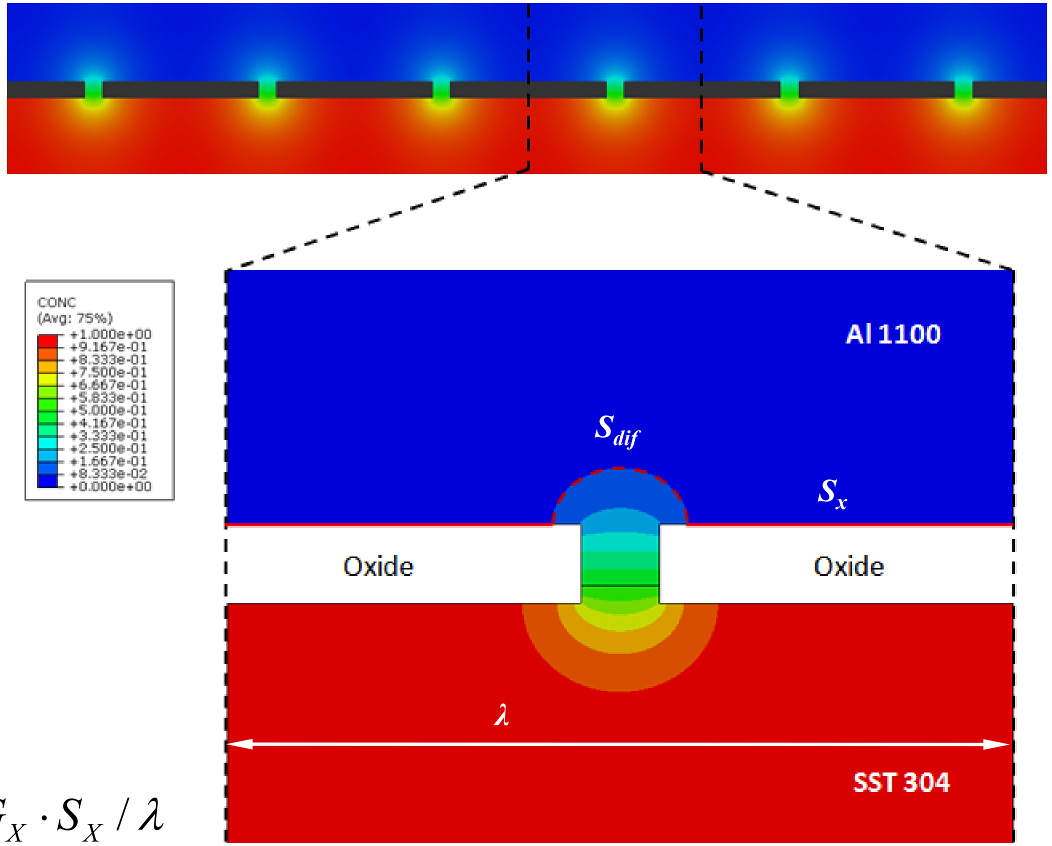
$$\frac{\partial c}{\partial t} = \nabla \cdot (D \nabla c)$$

Mixture rule:

$$G_{dif}(x,y) = G_{Al} + (G_{SST} - G_{Al}) \cdot c(x,y)$$

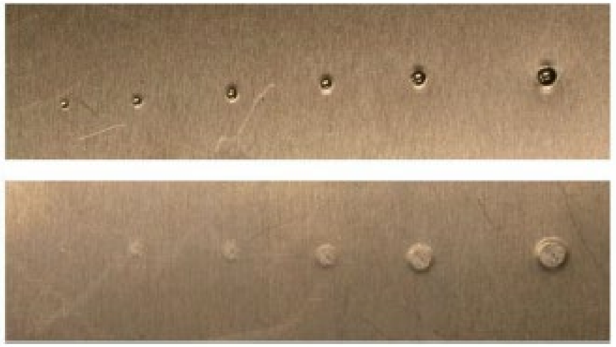
$$f(a, D_0, Q, T, t) = \frac{S_{dif}}{\lambda}$$

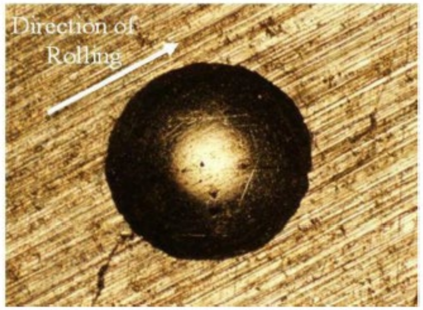
$$G = G_{dif}(\varepsilon_p, T, t) \cdot f(a, D_0, Q, T, t) + G_X \cdot S_X / \lambda$$



Indention Hardness

https://evsmetal.com/2018/10/roll-forming-bending-metal-fabrication.html





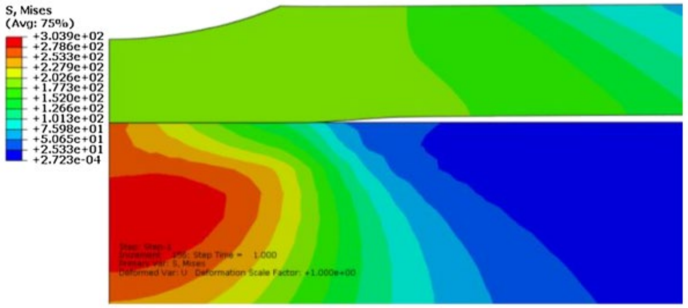


Fig. 9. von Mises stress contour of the indentation on 0.813 mm thick Al 3003-H14 sheet metal.

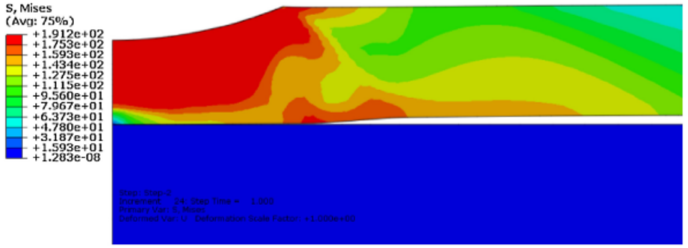


Fig. 10. von Mises stress contour of the indentation on the 0.813 mm thick Al 3003-H14 sheet metal after springback.

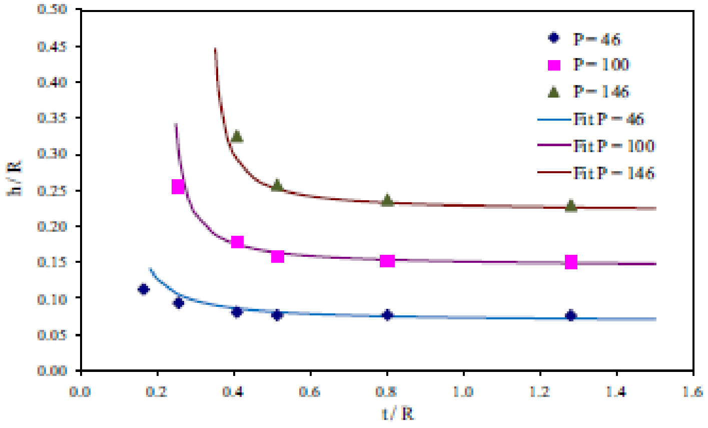


Fig. 17. Comparison of experimental data and fitted curve data for Al 3003-H14.

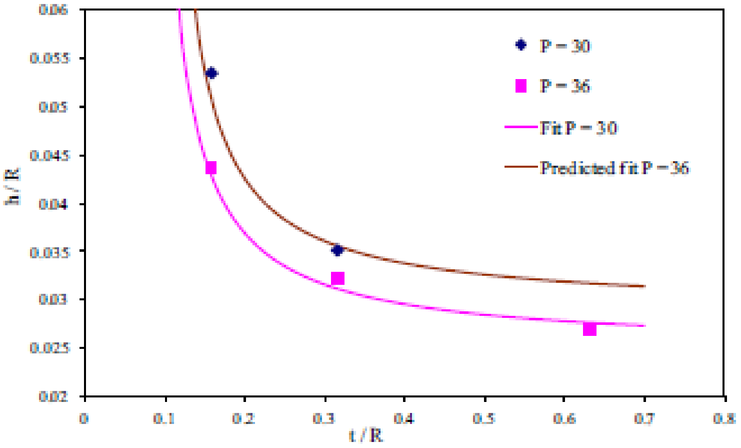


Fig. 19. Confirmation test on 0.5 mm thick 1020 low carbon steel.

Micro Extrusion Forging/Rolling

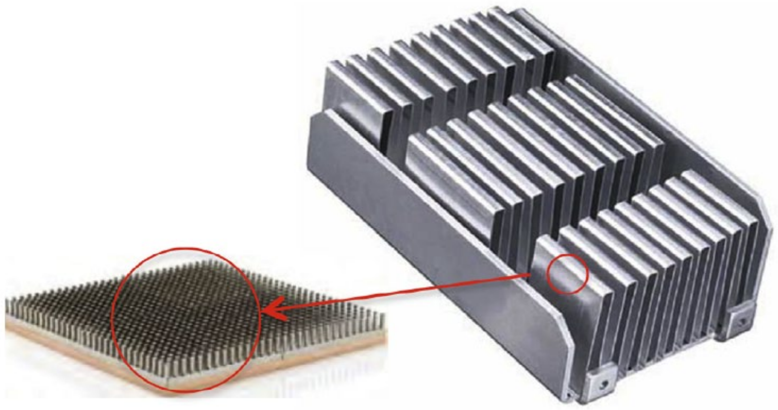
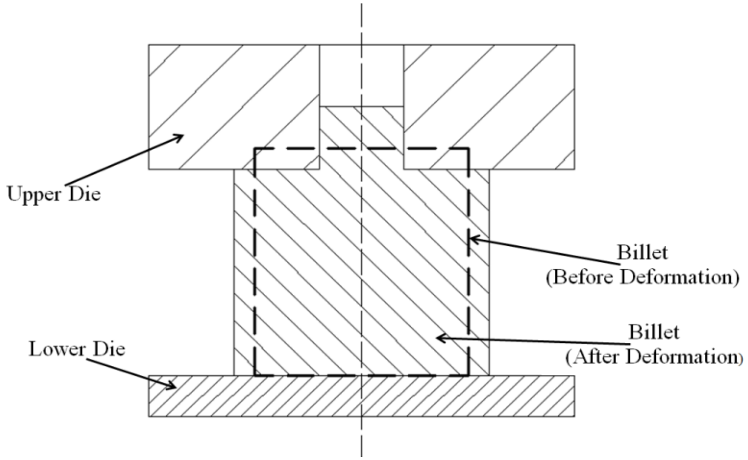
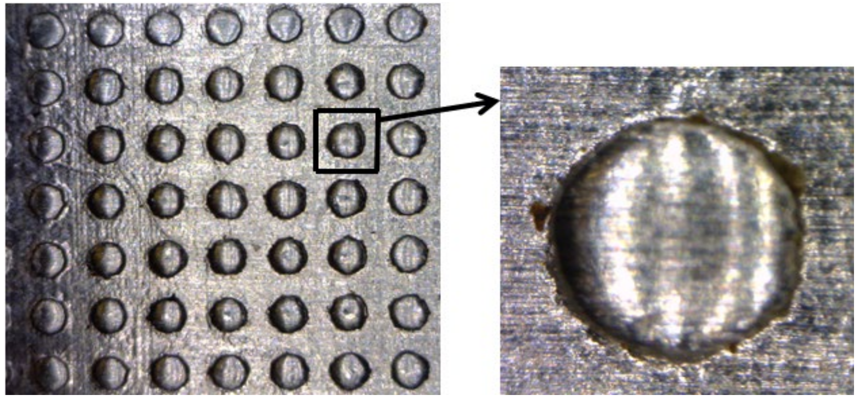
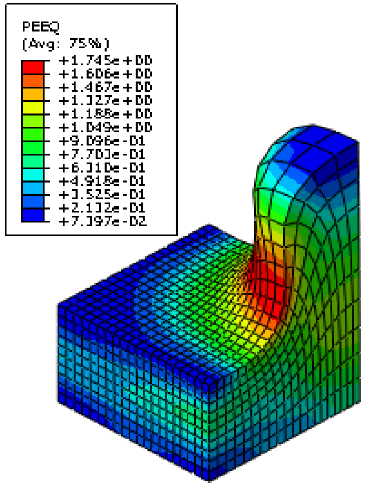


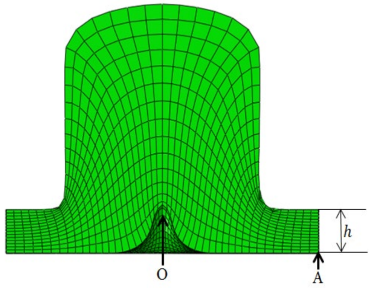
Fig. 1. Low profile pins on folded fin heat sink [1,2].

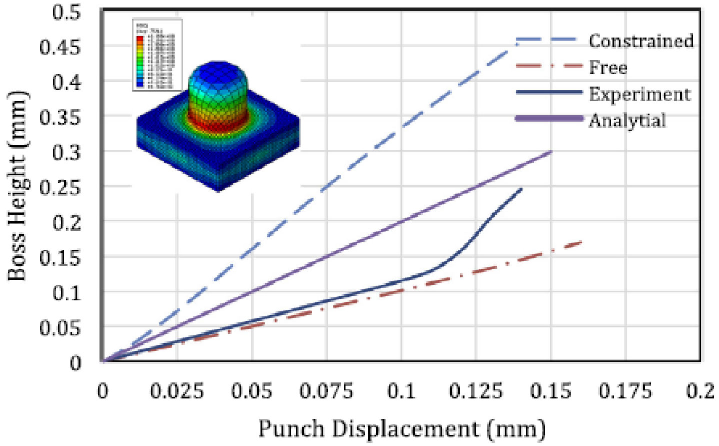




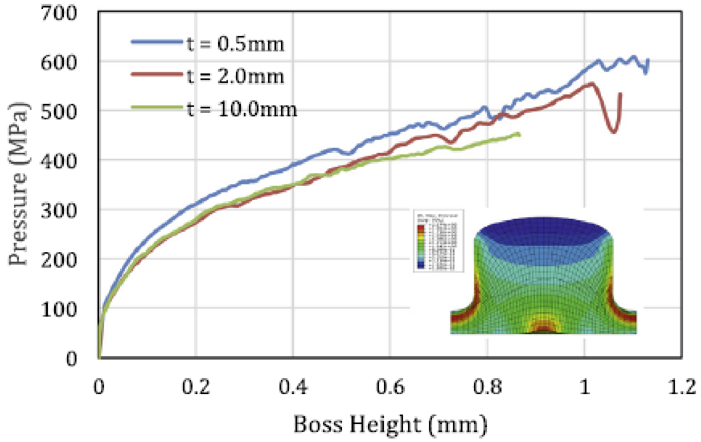
Creating Surface Features

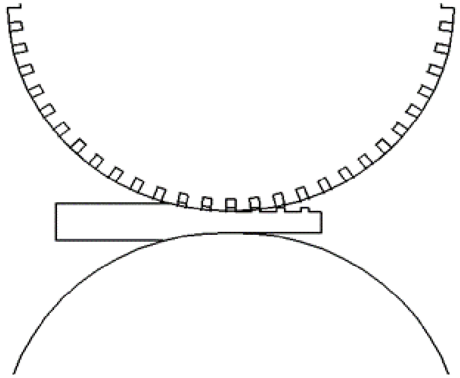


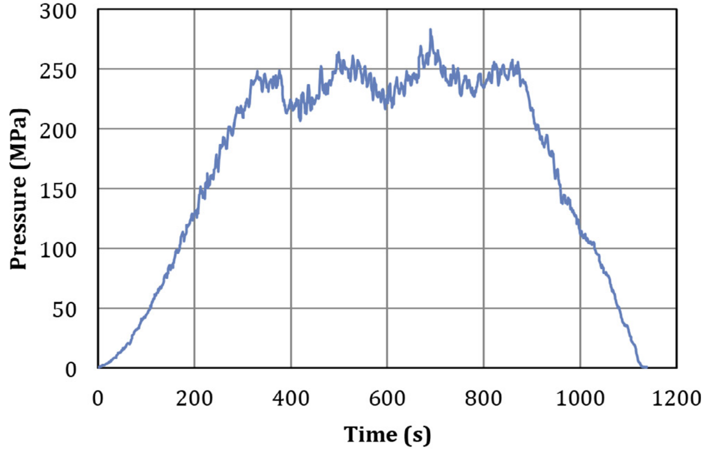


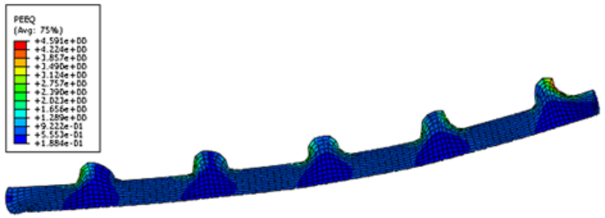


(a)









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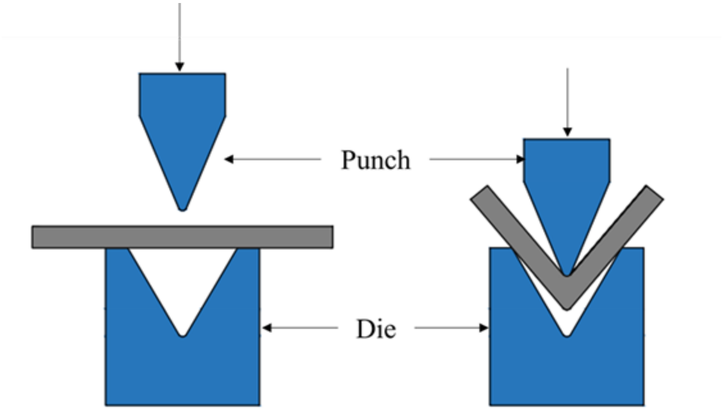
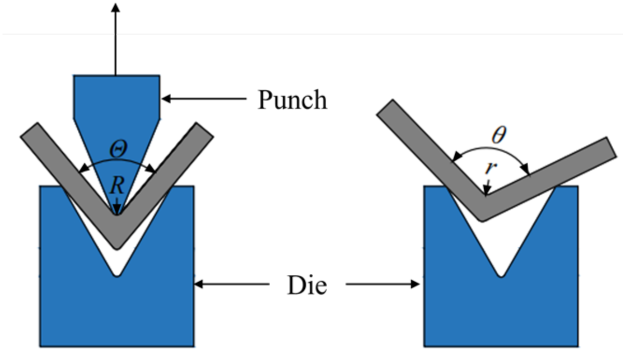
  - Springback control of sheet bending and tube bending
- Additive Manufacturing
  - Metal powder material extrusion, digital light processing of ceramics, selective laser melting for coating, compaction enhanced binder jetting
- Design and Analysis of Lightweight Structures
  - Perforated sheet metal, metallic foam, advanced cell-wall honeycomb

Springback in Sheet Metal Bending

- Press brake bending – forming the pre-determined bend angle by using a punch to press metal sheet into the die
- Springback/elastic recovery upon unloading
- Final (unload) bend angle > initial a bend angle





Springback cannot be eliminated

Springback Predication

- Springback is affected by material properties and sheet thickness
  - Hosford and Caddell

$$\frac{1}{R} - \frac{1}{r} = \left(\frac{6}{2-n}\right)\left[\frac{K'\left(1-\nu^2\right)}{ET}\right]\left(\frac{T}{2R}\right)^n$$

  - Gardiner

$$K' = K\left(\frac{4}{3}\right)^{(n+1)/2}$$

$$\frac{R}{r} = 4\left(\frac{RY}{ET}\right)^3 - 3\left(\frac{RY}{ET}\right) + 1.$$

  - Özdemir, response surface
  - Narayanasamy and Padmanabhan, linear regression
  - Hardt (1993), analytical modeling of punch force

R, initial bend radius

r, final bend radius

Y, yiled strength

E, elastic modulus

ν, Poisson′s ratio

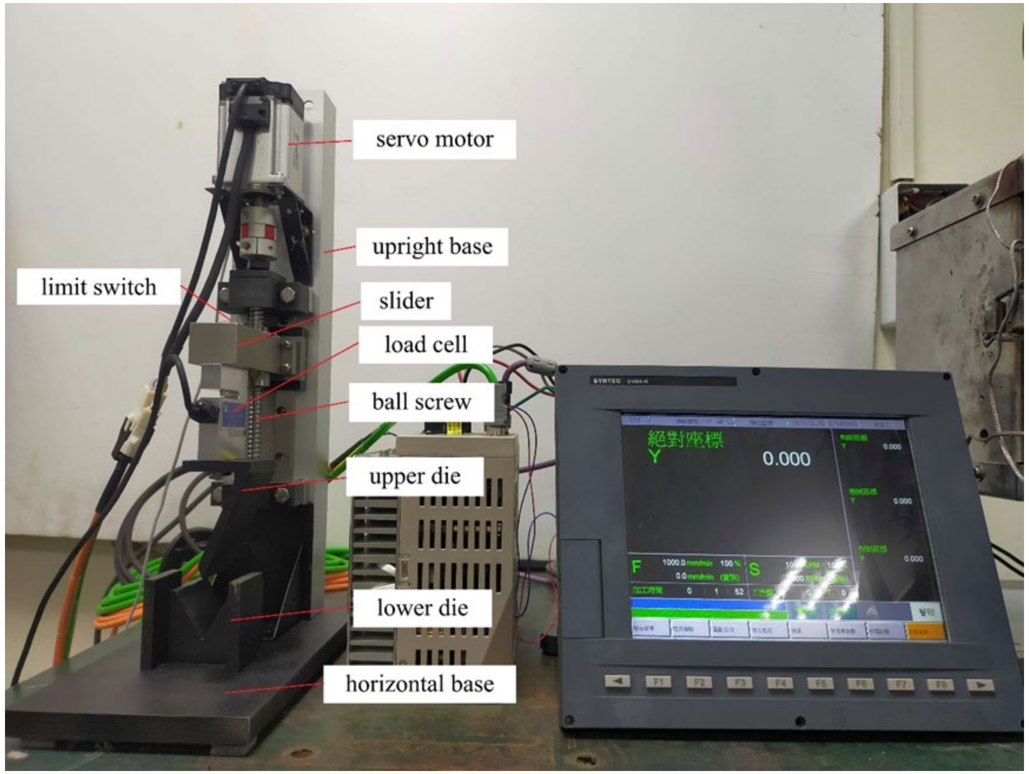
n, strain hardening exponent

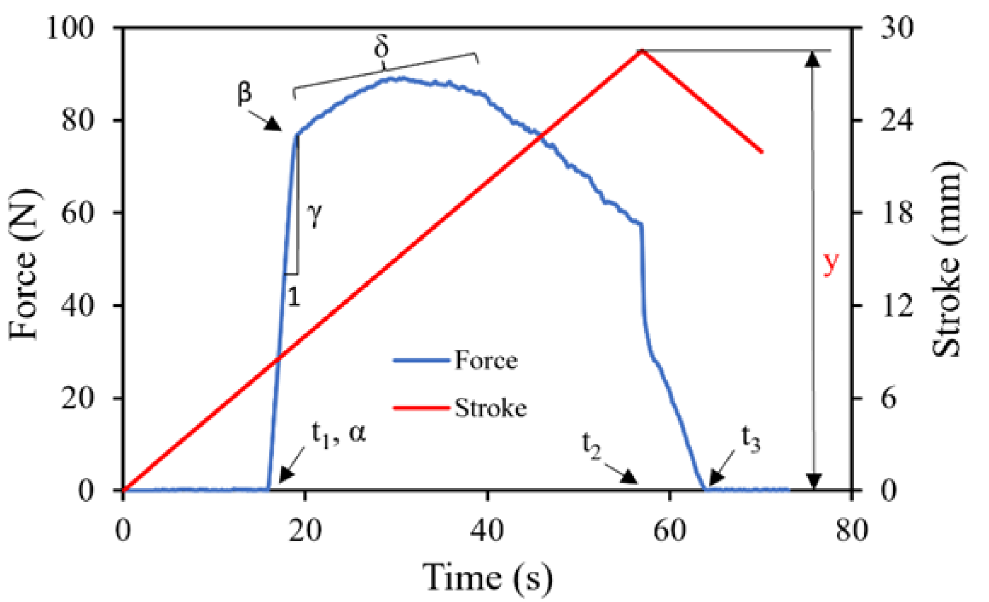
K, strength coefficient

T, thickness

Experimental Setup

α, implies thickness
β, implies yielding
γ, implies elastic modulus
δ, remaining data, implies strain hardening

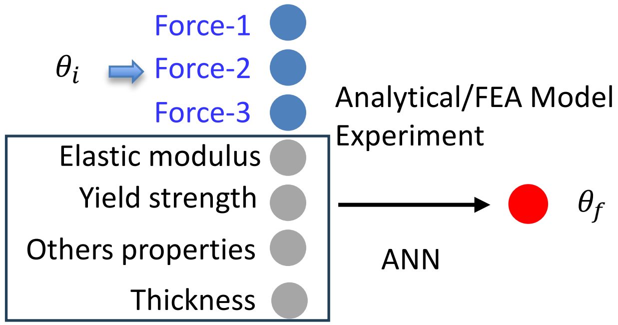


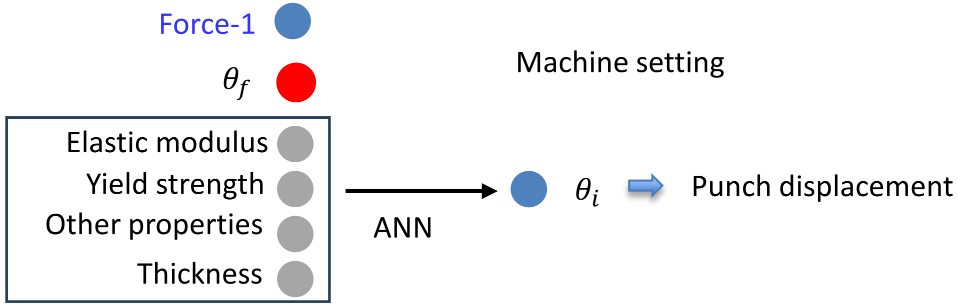


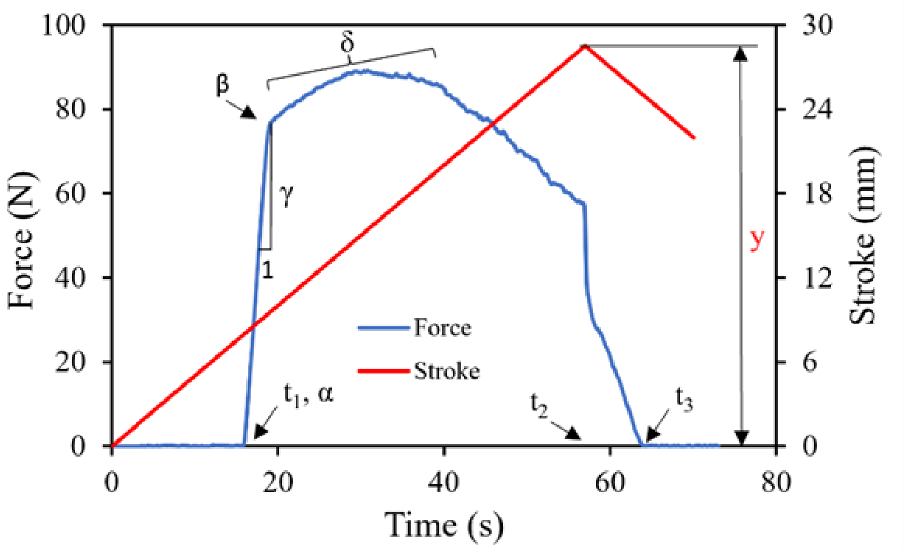
Punch and die radius: 1 mm
Punch travel: 0.5 mm/s
Span: 40 mm
Stroke: 40 mm max.

Load cell: 200 N max.
Sampling: 10 Hz

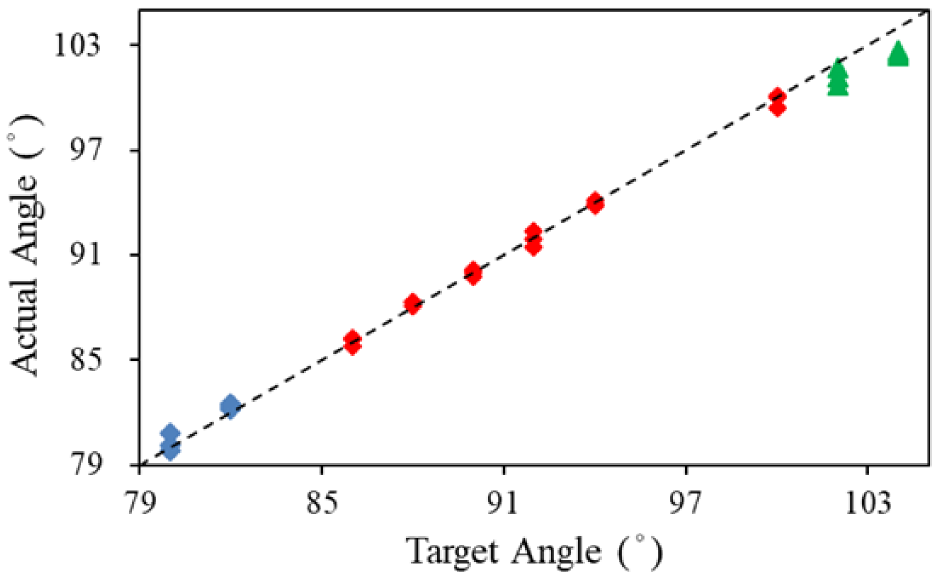
Springback Control





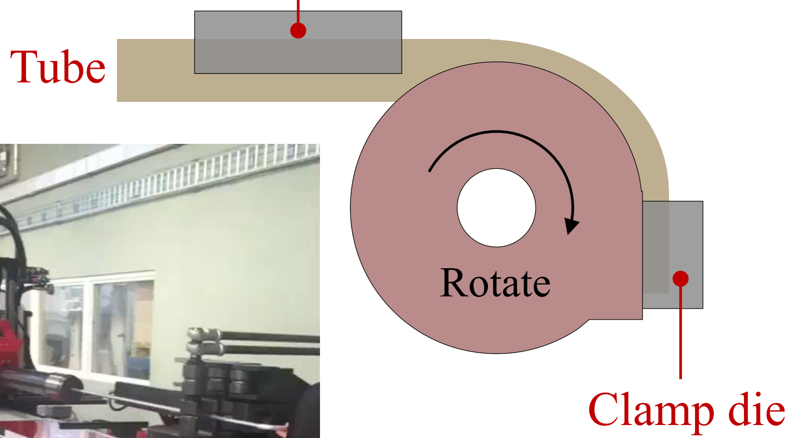


Training range – about 85 to 100 degrees



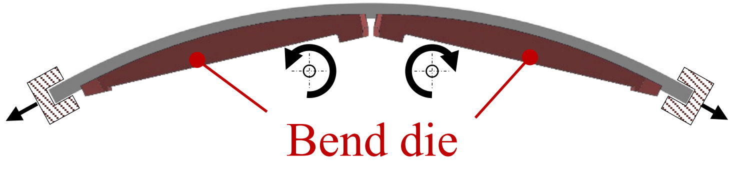
Springback in Tube Bending

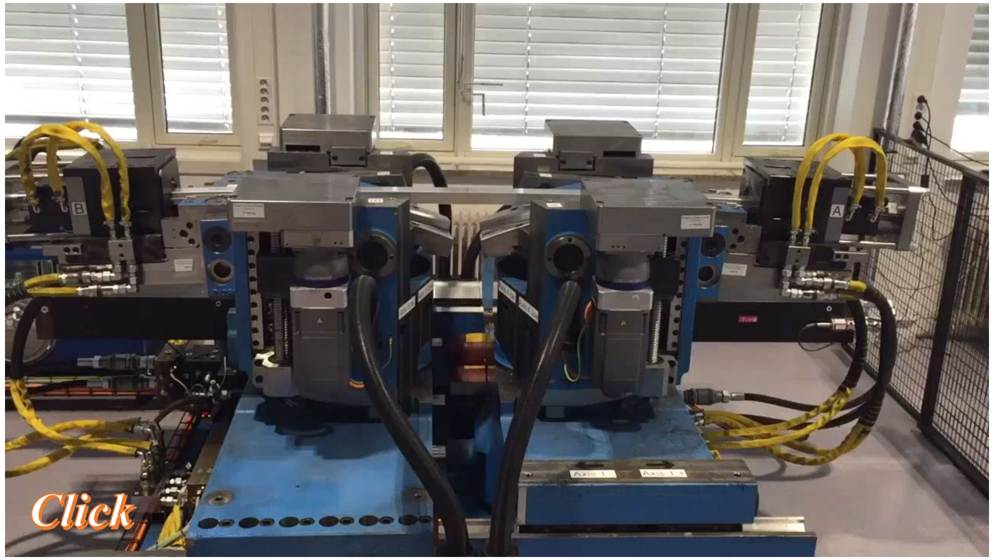
Rotary draw bending (RDB)



Rotary draw bending

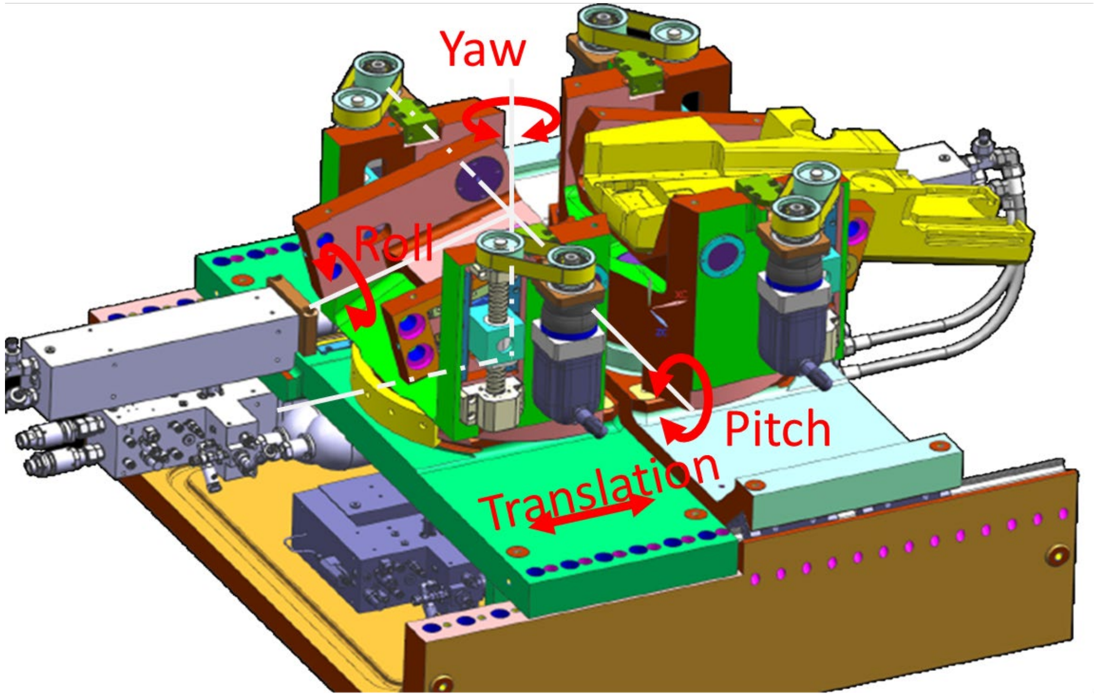
3D Stretch bending

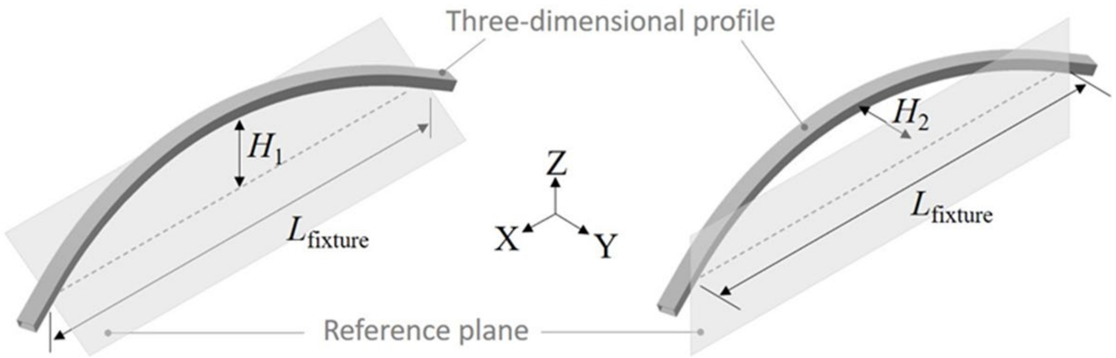




3D stretch bending

Springback in 3D Tube Bending





Generalized springback calculation in 3D stretch bending

- Curvature by Frenet-Serret theorem

$$\begin{bmatrix} T' \\ N' \\ B' \end{bmatrix} = \begin{bmatrix} 0 & \kappa & 0 \\ -\kappa & 0 & \tau \\ 0 & \tau & 0 \end{bmatrix} \begin{bmatrix} T \\ N \\ B \end{bmatrix}, \text{ where } T' = \frac{dT}{ds},\ N' = \frac{dN}{ds},\ \text{and } B' = \frac{dB}{ds}$$

$$\therefore \text{ Curvature, } \kappa = \left\| \frac{dT}{ds} \right\|$$

- Tangent vector decomposition and its change

$$T_i = < T_{i,\mathrm{X}}, T_{i,\mathrm{Y}}, T_{i,\mathrm{Z}} > \rightarrow \begin{cases} T_{i,\mathrm{XY}} = < T_{i,\mathrm{X}}, T_{i,\mathrm{Y}}, 0 > \\ T_{i,\mathrm{XZ}} = < T_{i,\mathrm{X}}, 0, T_{i,\mathrm{Z}} > \end{cases}, \quad \begin{cases} \Delta T_{i,\mathrm{XY}} = T_{i-1,\mathrm{XY}} - T_{i,\mathrm{XY}} \\ \Delta T_{i,\mathrm{XZ}} = T_{i-1,\mathrm{XZ}} - T_{i,\mathrm{XZ}} \end{cases}$$

- Curvatures $\kappa_{i,\mathrm{XY}} = \left\| \frac{\Delta T_{i,\mathrm{XY}}}{s_i} \right\|, \quad \kappa_{i,\mathrm{XZ}} = \left\| \frac{\Delta T_{i,\mathrm{XZ}}}{s_i} \right\|$

- Springback angles of total segments

$$\begin{cases} \Delta\theta_{i,\mathrm{XY}} = \left(\frac{1}{\kappa_{i,\mathrm{XY}}} + h_{bi,\mathrm{XY}}\right) \cdot \theta_{i,\mathrm{XY}} \cdot \Delta\kappa_{i,\mathrm{XY}} \\ \Delta\theta_{i,\mathrm{XZ}} = \left(\frac{1}{\kappa_{i,\mathrm{XZ}}} + h_{bi,\mathrm{XZ}}\right) \cdot \theta_{i,\mathrm{XZ}} \cdot \Delta\kappa_{i,\mathrm{XZ}} \end{cases}, \quad \Delta\theta = \sum_{i=1}^{nn-1} \Delta\theta_i$$

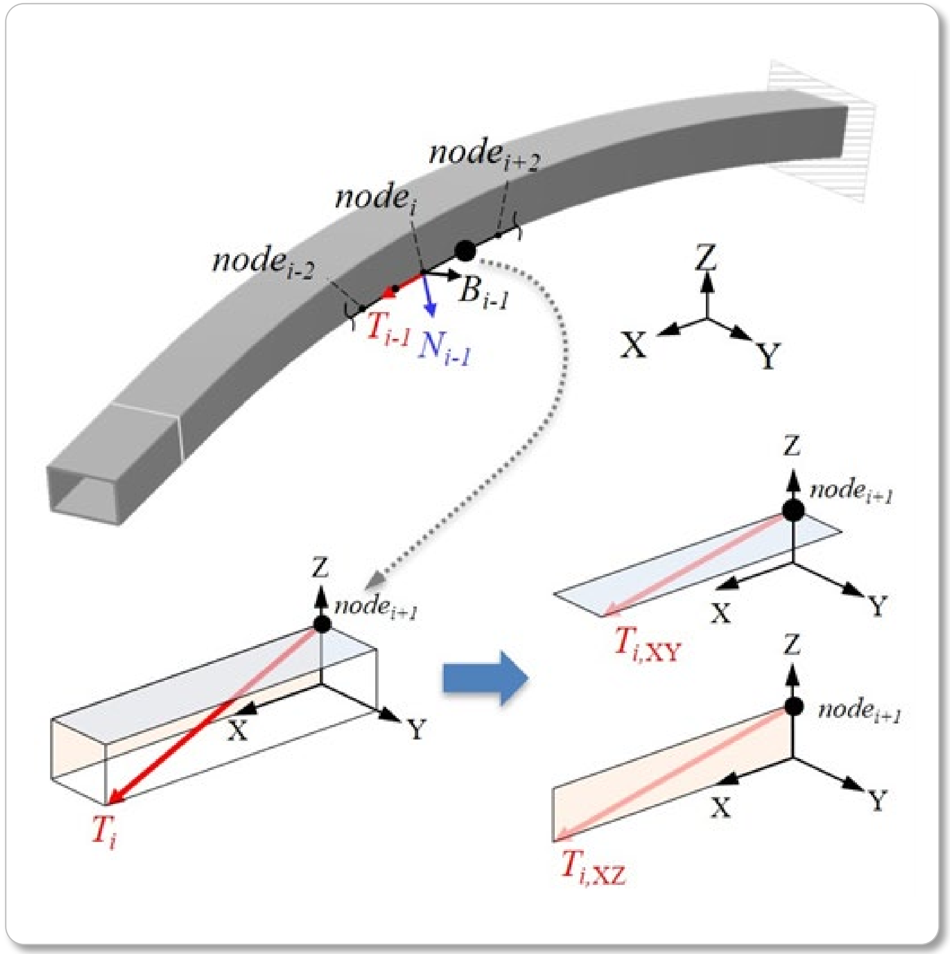
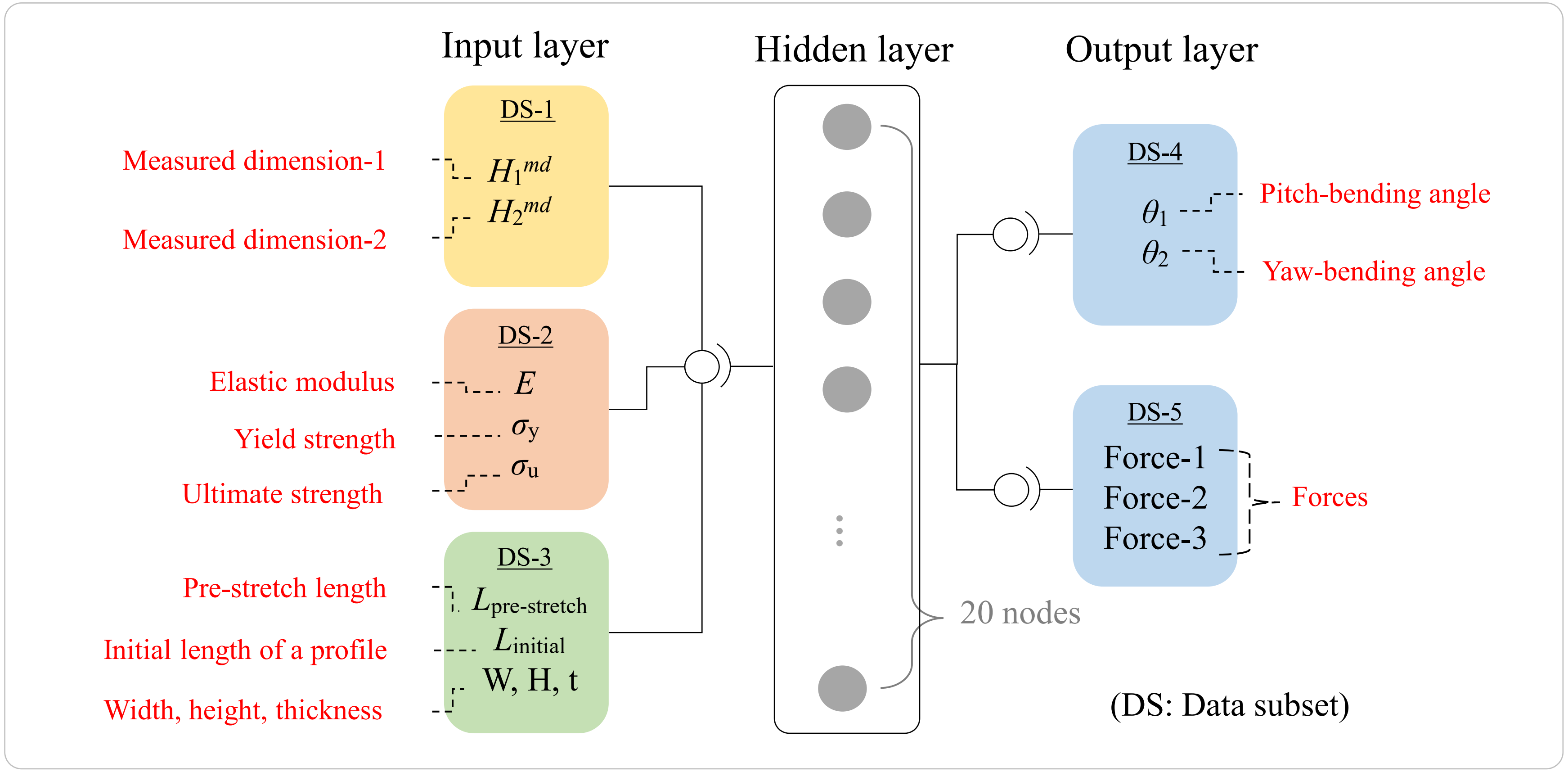


Fig. d-7, Tangent vector decomposition

ANN for springback control

- Analytical model prediction is used to provide supplemental data for training



Experiments – Validation

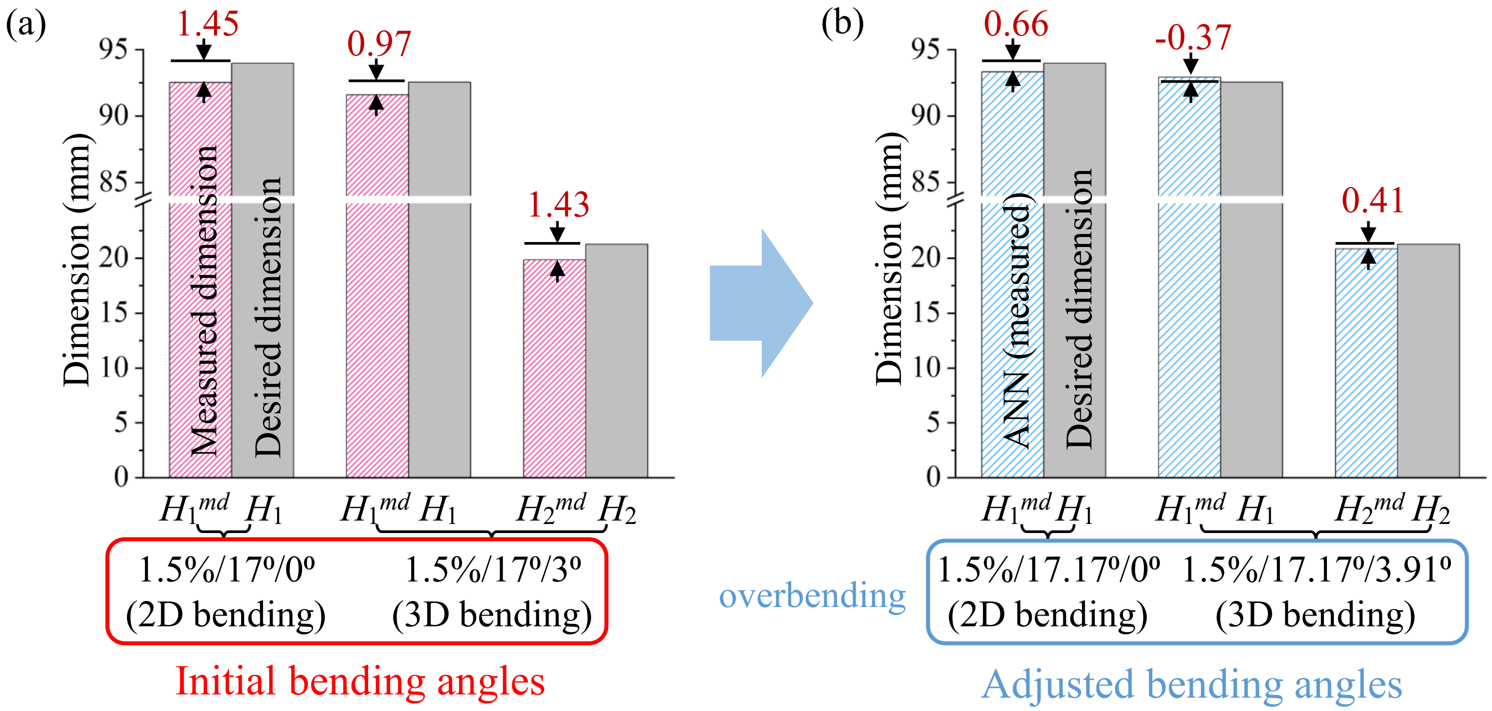


Fig. e-12, Springback, (a) initial bending; (b) adjusted bending by ANN

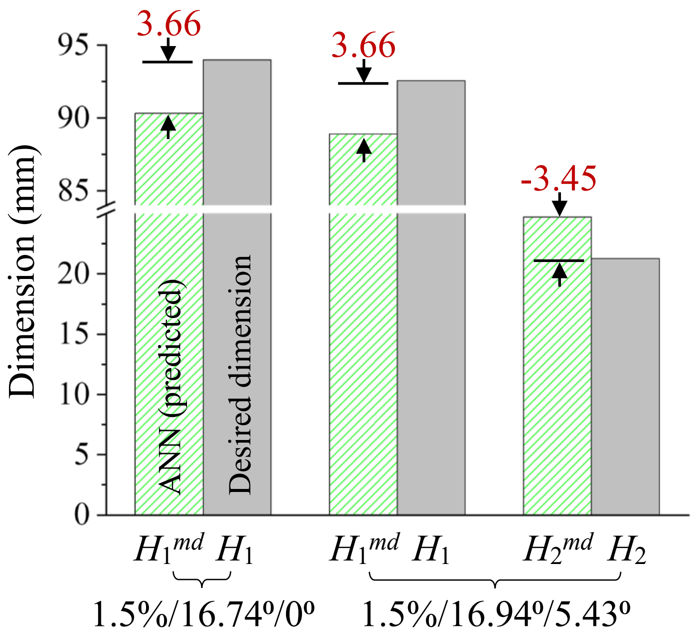
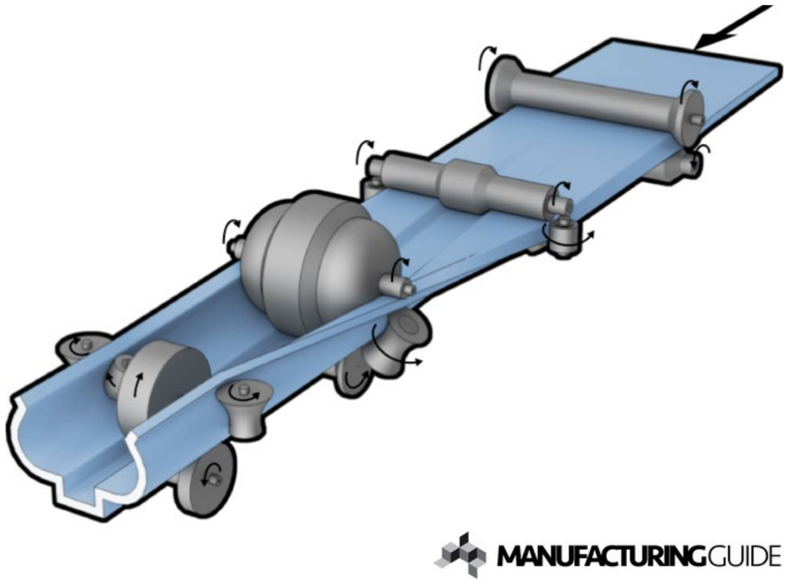
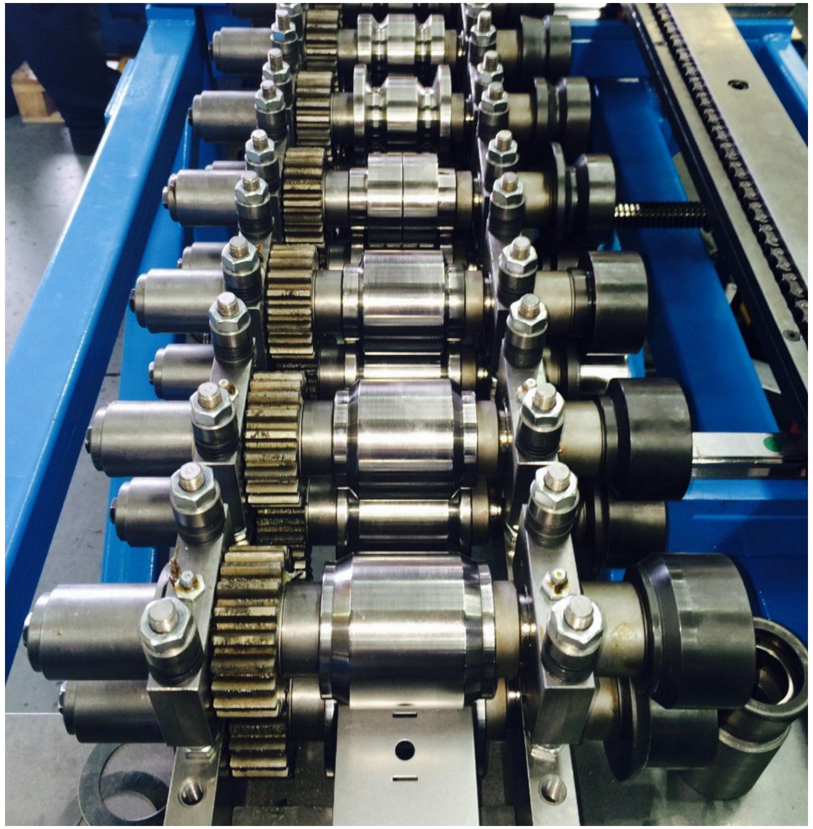


Fig. e-13, Springback by ANN-exp
(ANN trained by only experimental data)

- Initial bending angles are adjusted by the ANN.
  : The ANN with supplementary data sets helps to reduce springback.
- ANN-exp is not effective to improve the geometrical accuracy.
  * ANN-exp: ANN without supplementary data (trained with only 24 experimental data)

Roll Forming





http://bulldog-uk.com/new-machinery/roll-forming/roll-forming-machines

Residual Stress in Roll Forming

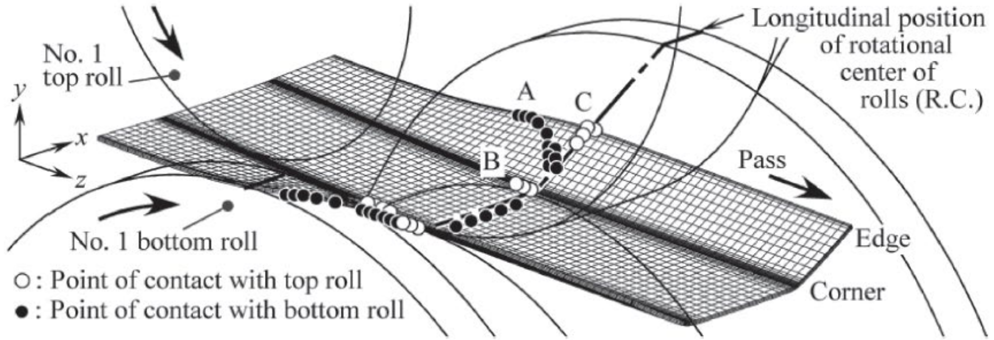
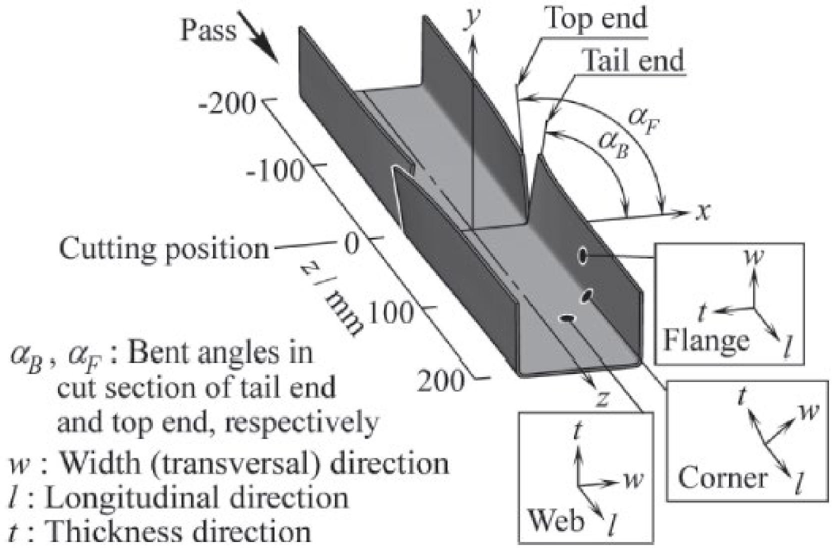


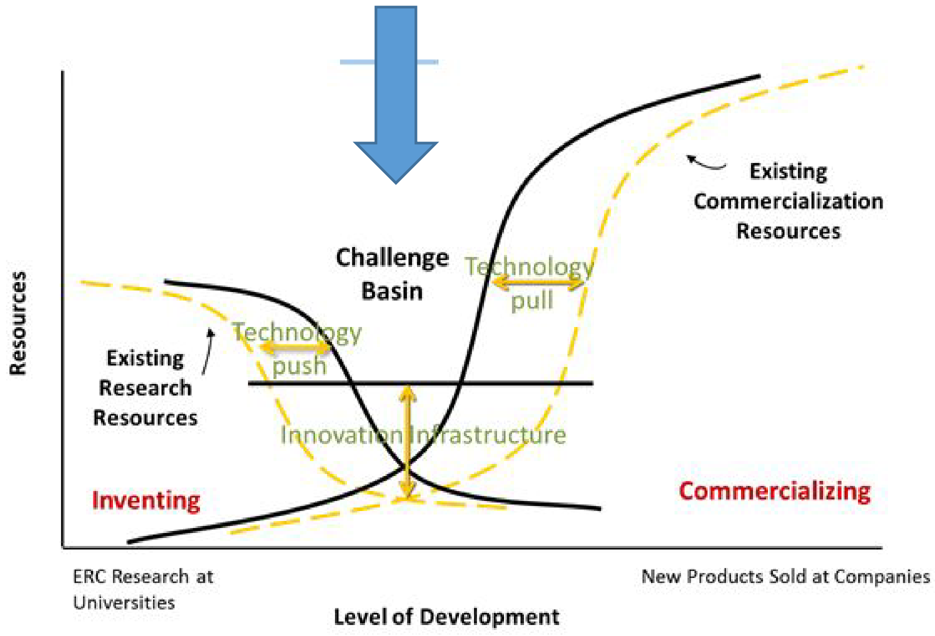
Fig. 8 3-dimensional shape and contact areas of channel steel being formed by No. 1 rolls, simulation results.



Source 1: https://www.jstage.jst.go.jp/article/matertrans/56/2/56_P-M2014842/_article

Summary

- Develop applied engineering knowledge
- Design innovative products and processes
- Address industrial needs



Jackson, Deborah J., What is an Innovation Ecosystem?, National Science Foundation, Arlington, VA (http://erc-assoc.org/docs/innovation_ecosystem.pdf), 2012.

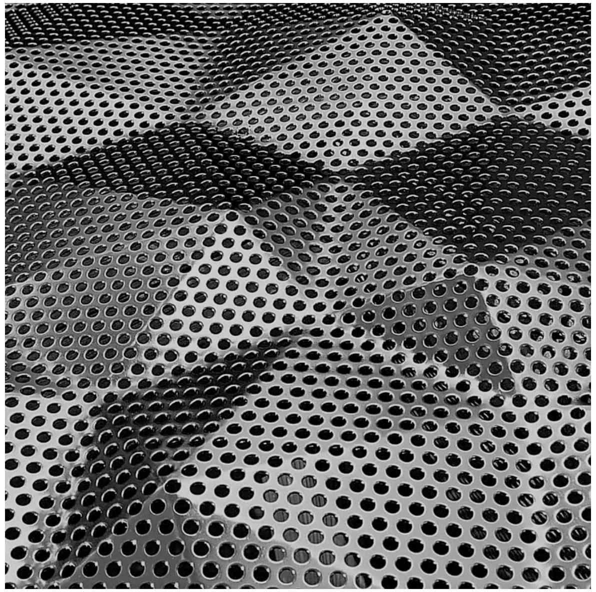
TEXAS A&M UNIVERSITY

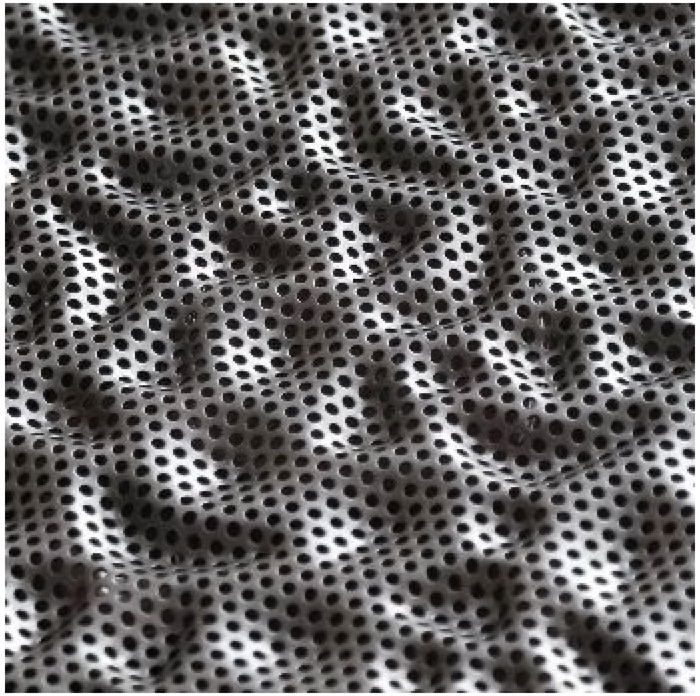
Research Interests

- Material Processing
  - Roll cladding, interference friction welding, forming of polymer coated sheet metal, incremental forming
- Application of AI in Manufacturing
  - Springback control of sheet bending and tube bending
- Additive Manufacturing
  - Metal powder material extrusion, digital light processing of ceramics, selective laser melting for coating, compaction enhanced binder jetting
- Design and analysis of Lightweight Structures
  - Perforated sheet metal, metallic foam, advanced cell-wall honeycomb

Perforated Sheet Metals

- Stamping perforated sheet metals can enhance their functionality and/or aesthetics



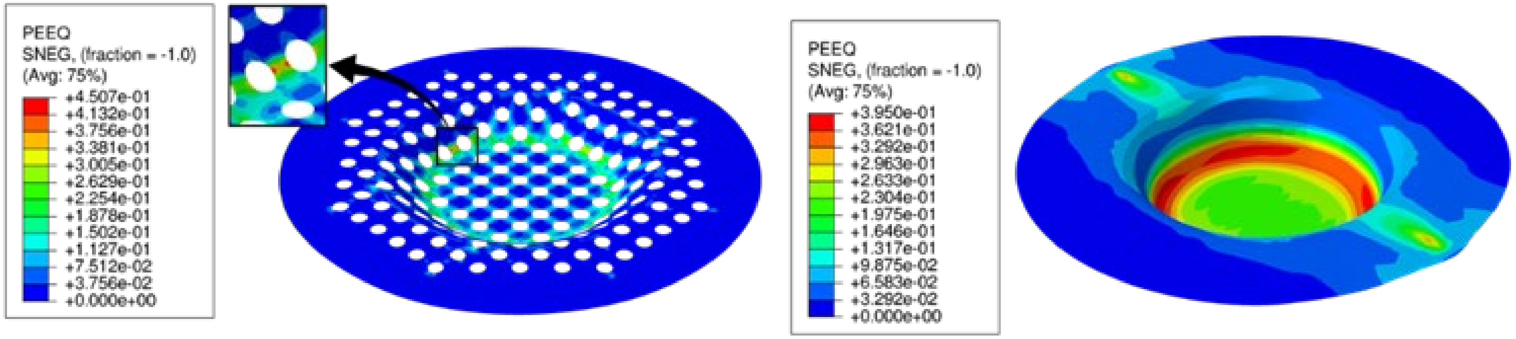


https://sagarsteel58.medium.com/importance-of-perforated-metal-sheet-types-and-specifications-ba457df9984e

https://www.rigidized.com/product/1un-perforated

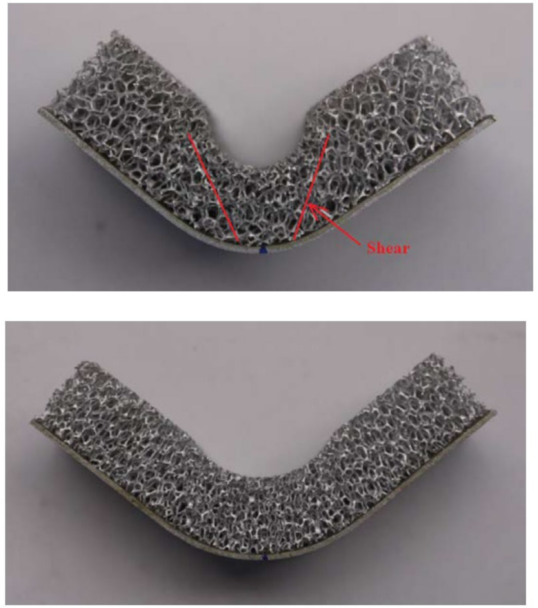
Forming Simulation of PSM

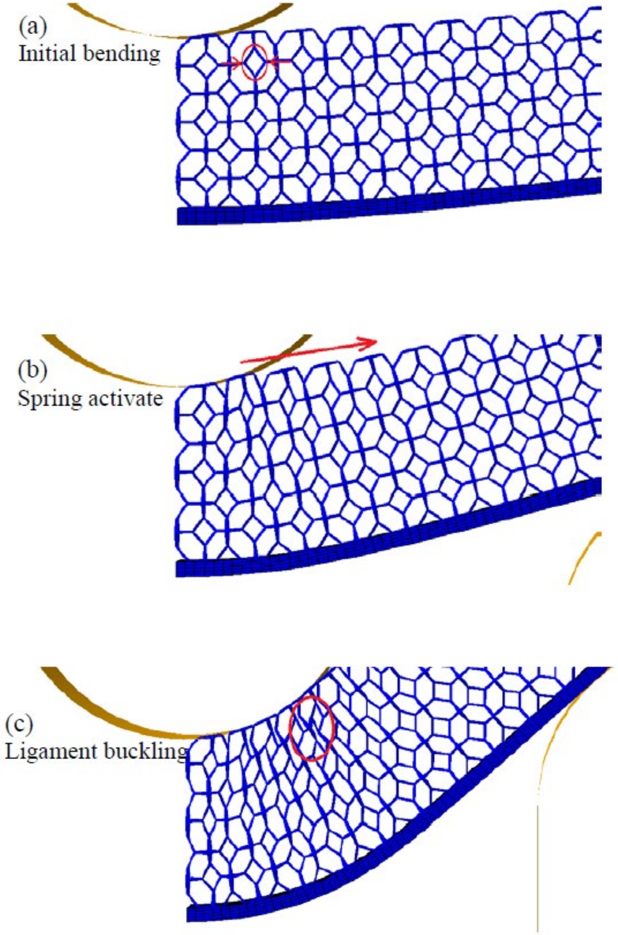
- Perforated Sheet Model
  - Large number of small elements
  - Significant computation time/cost
- Homogenized Sheet Model
  - Reduce number of elements, reduce computation time/cost
  - Need accurate description of PSM's deformation and failure behavior



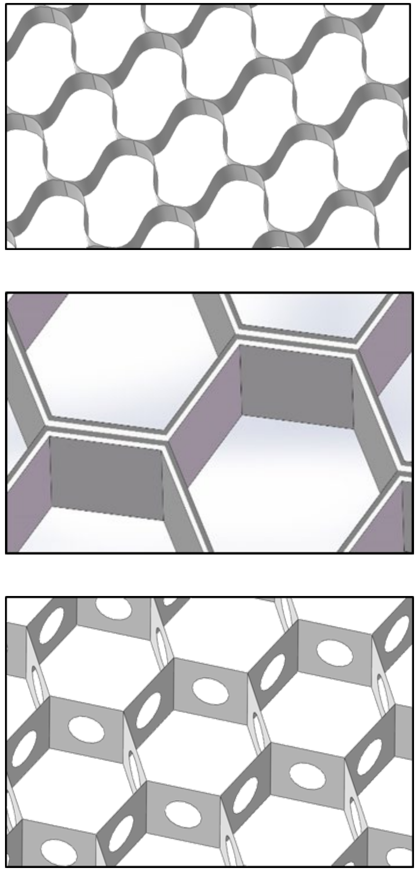
(a) (b)

Deformation of Metallic Foams

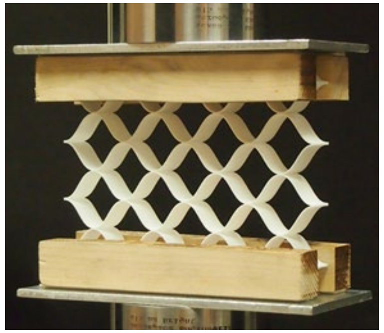


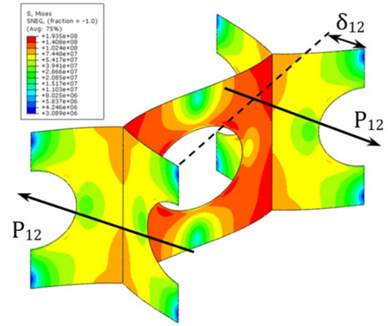


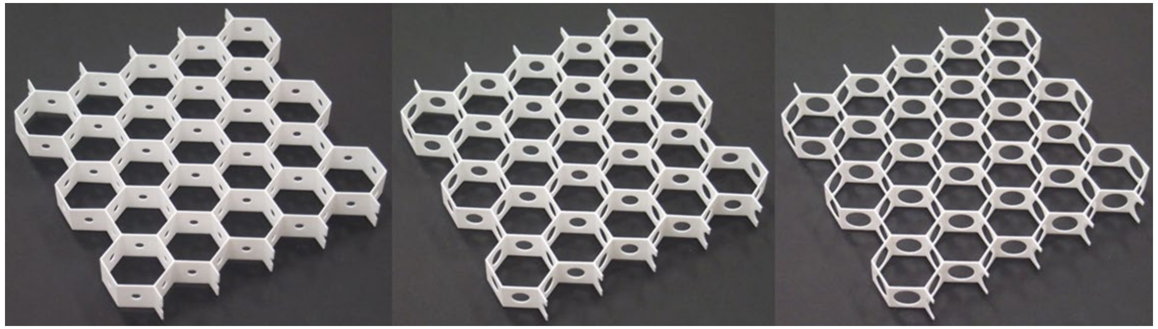
Advanced Cell Wall



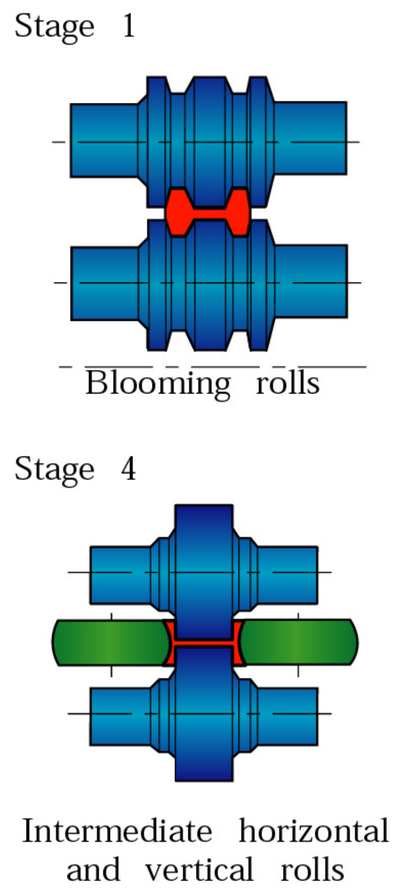
Advanced cell walls

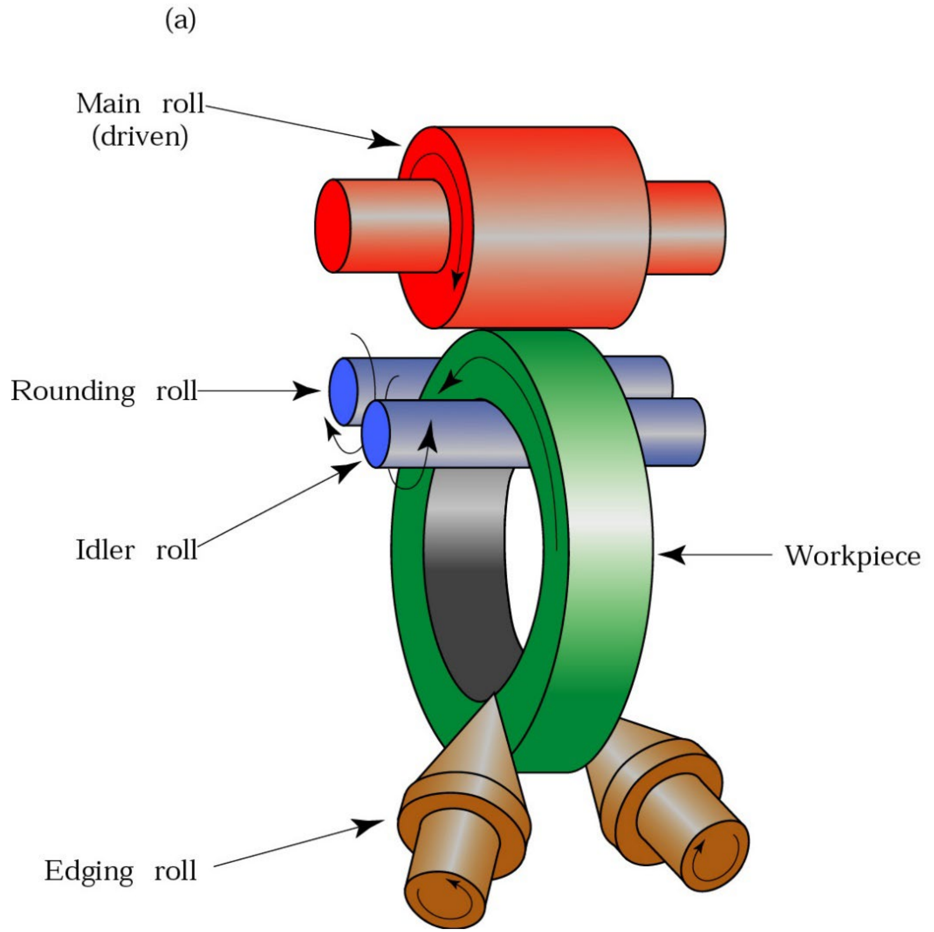






Shape Rolling and Ring Rolling





Roll Bending