Double-Sided Incremental Forming

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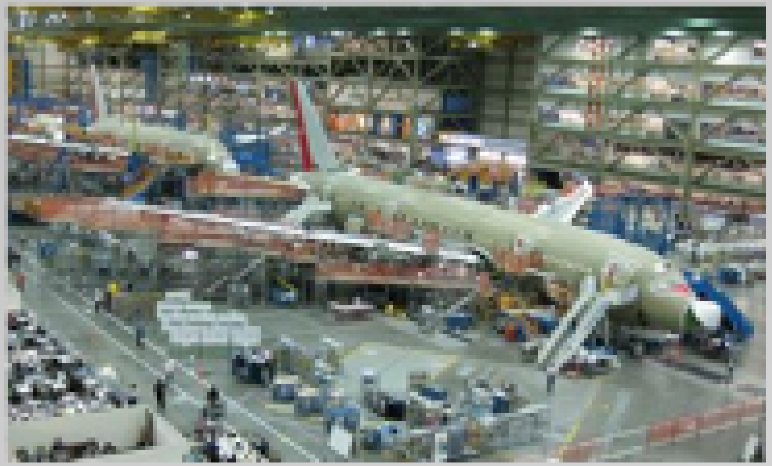
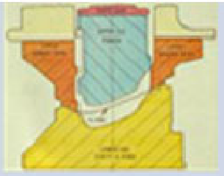
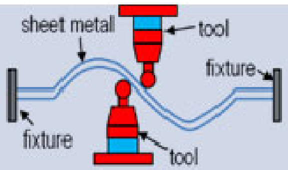
DIELESS FORMING

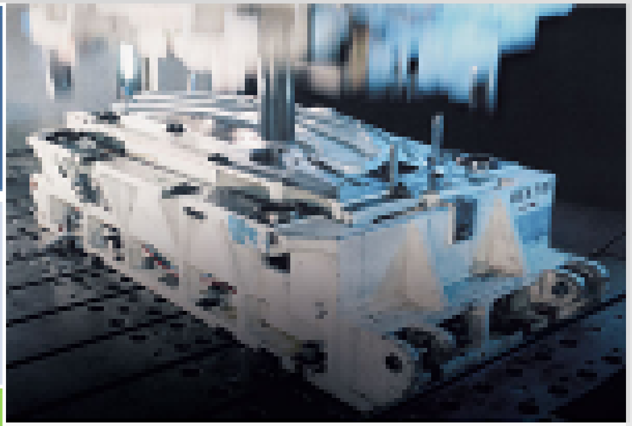
LOW VOLUME SHEET METAL PRODUCTION

AEROSPACE PRODUCTION

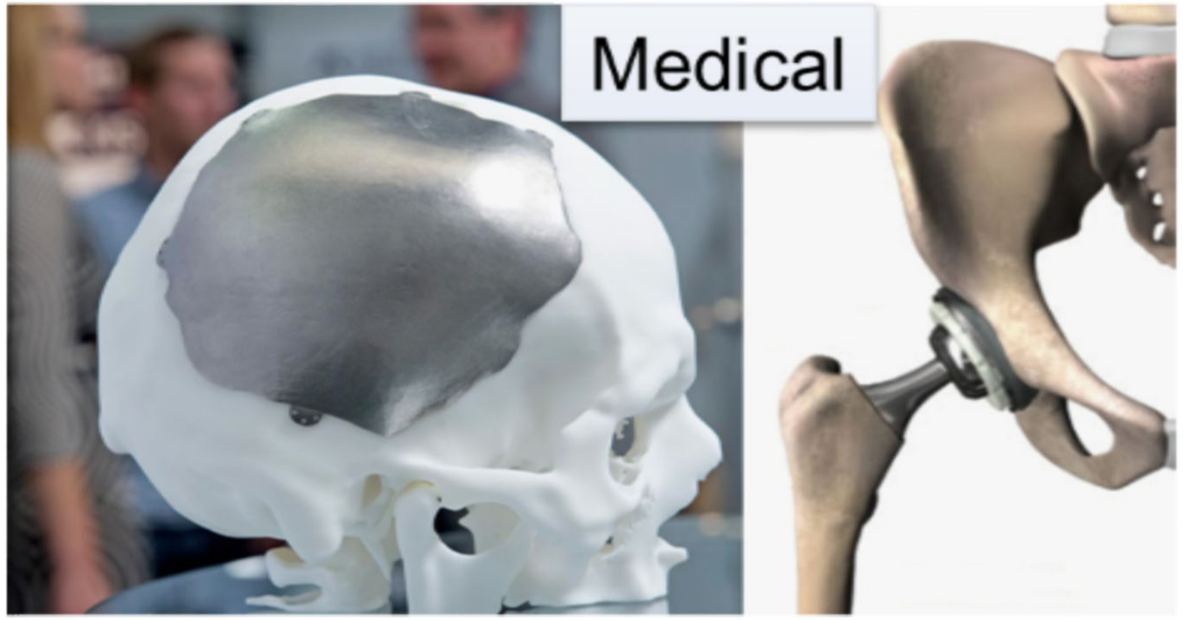


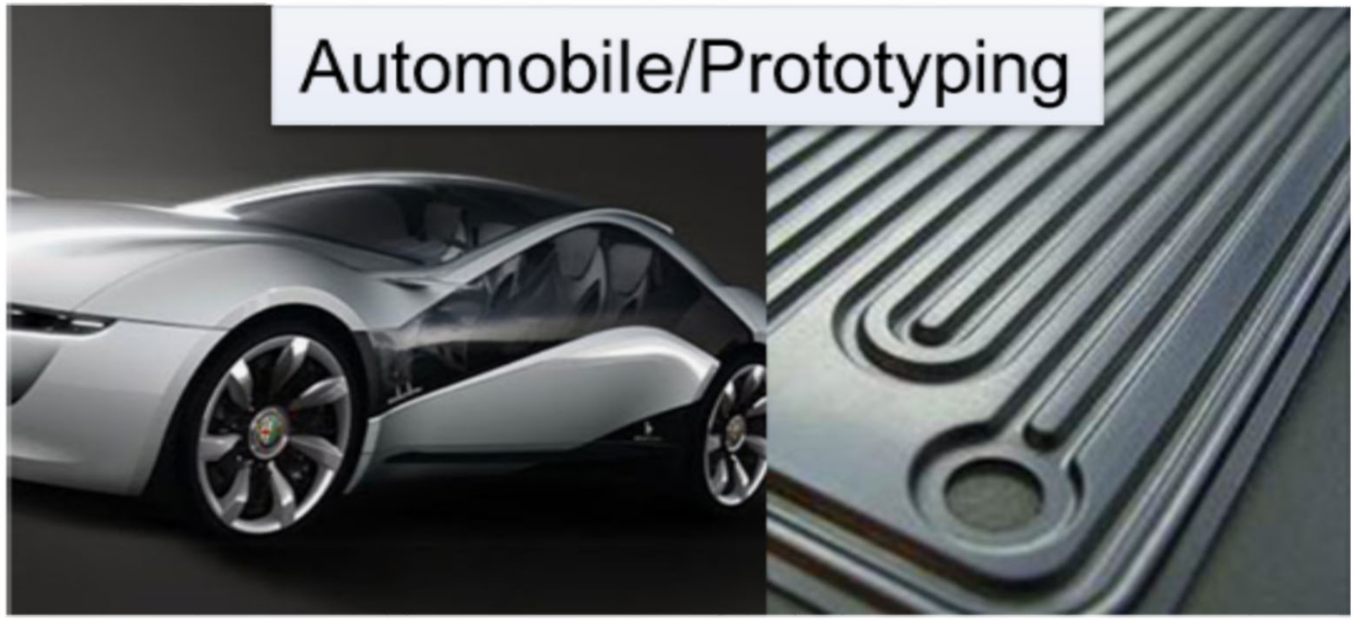
AUTOMOTIVE DESIGN & PROTOTYPING

	TRADITIONAL PROCESSES	DSIF
		
TOOLING COST	\$100K - \$1M	NEGLIGIBLE
DESIGN TO PRODUCTION	8 – 15 WEEKS	< 1 WEEK
FACILITY SIZE & COMPLEXITY	HIGH	LOW
TOOLING STORAGE	REQUIRED	NONE
MATERIAL CHOICE	LIMITED	BROAD

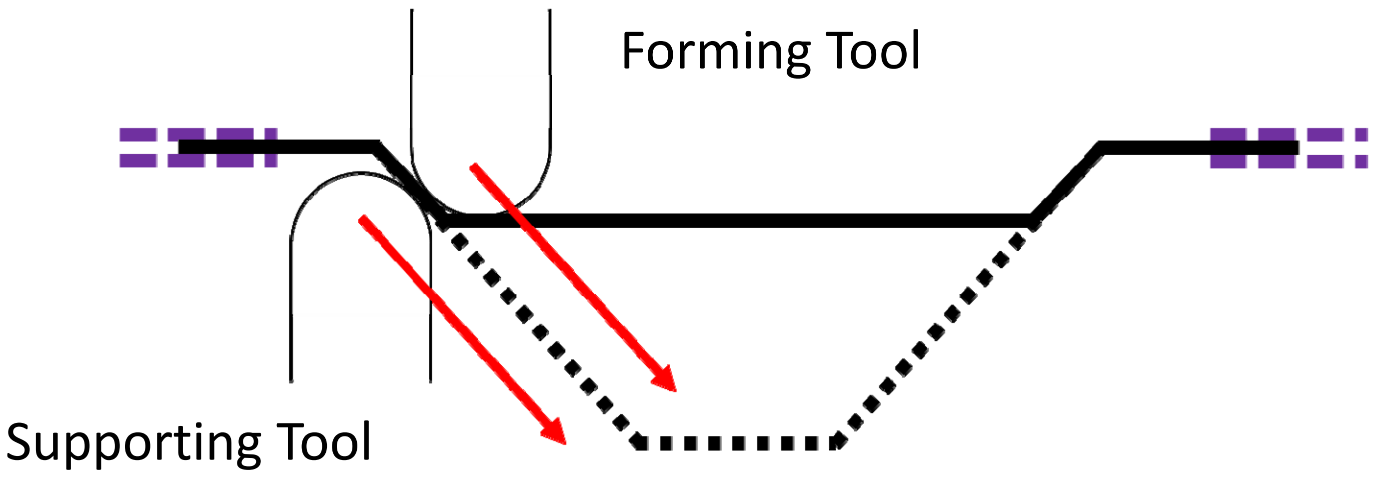


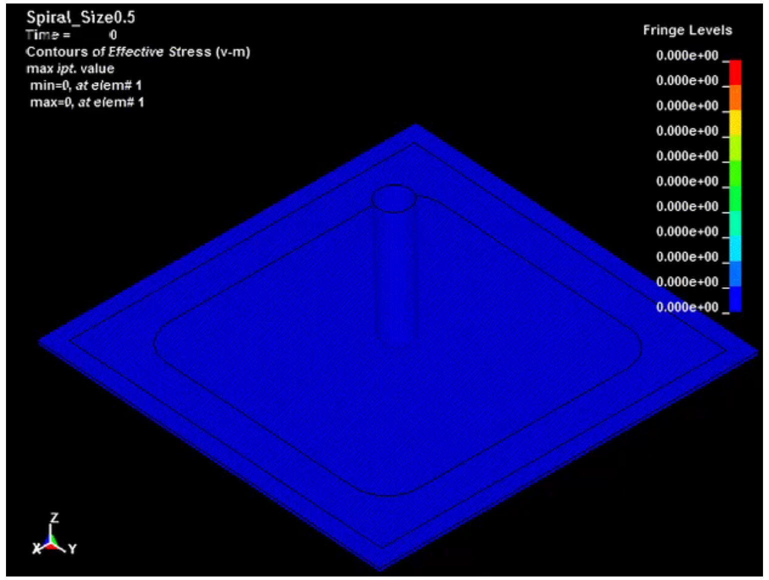
Potential Applications

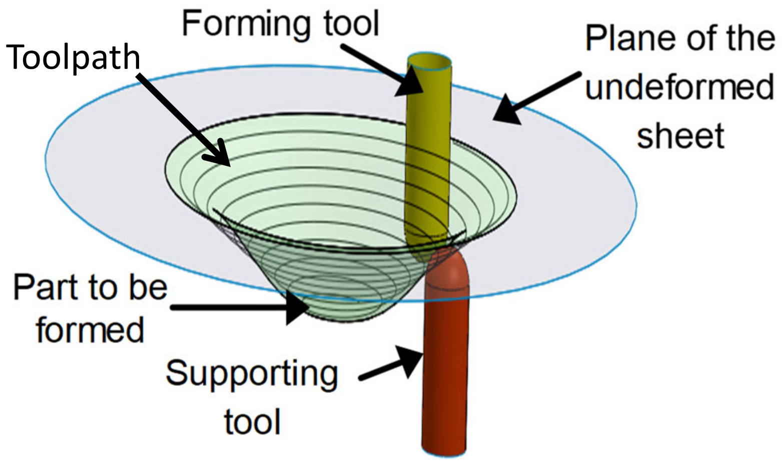




Double-Sided Incremental Forming (DSIF)







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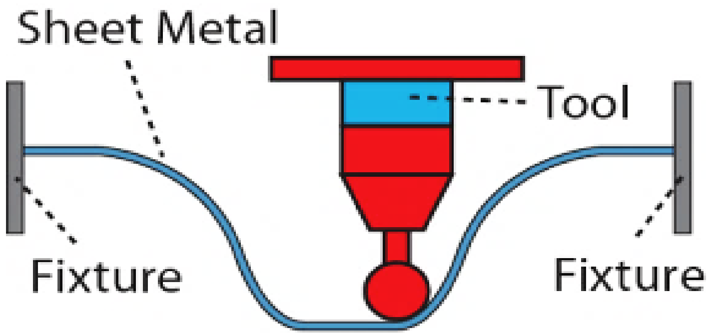
[1] Wang, Y., Huang, Y., Cao, J., and Reddy, N.V.. (2008),International Manufacturing Science and Engineering Conference American Society of Mechanical Engineers.
[2]Malhotra, R., Cao, J., Ren, F., Kiridena, V., Xia, Z. C., & Reddy, N. V. (2011). Journal of Manufacturing Science and Engineering
[3] Zhang, Z., Ren, H., Xu, R., Moser, N., Smith, J., Ndip-Agbor, E., ... & Cao, J. (2015). Journal of Manufacturing Science and Engineering

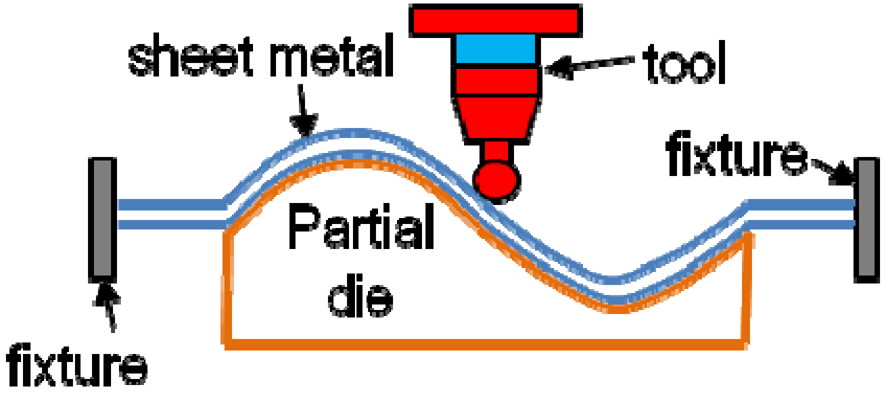
Common Configurations of Incremental Sheet Forming

Single-Point Incremental Forming (SPIF)



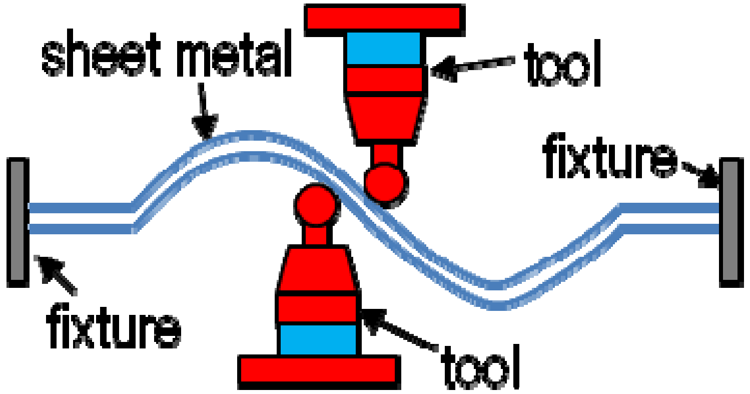
- Highly flexible manufacturing process
- Energy efficient for low-batch production
- High formability

Two-Point Incremental Forming (TPIF)



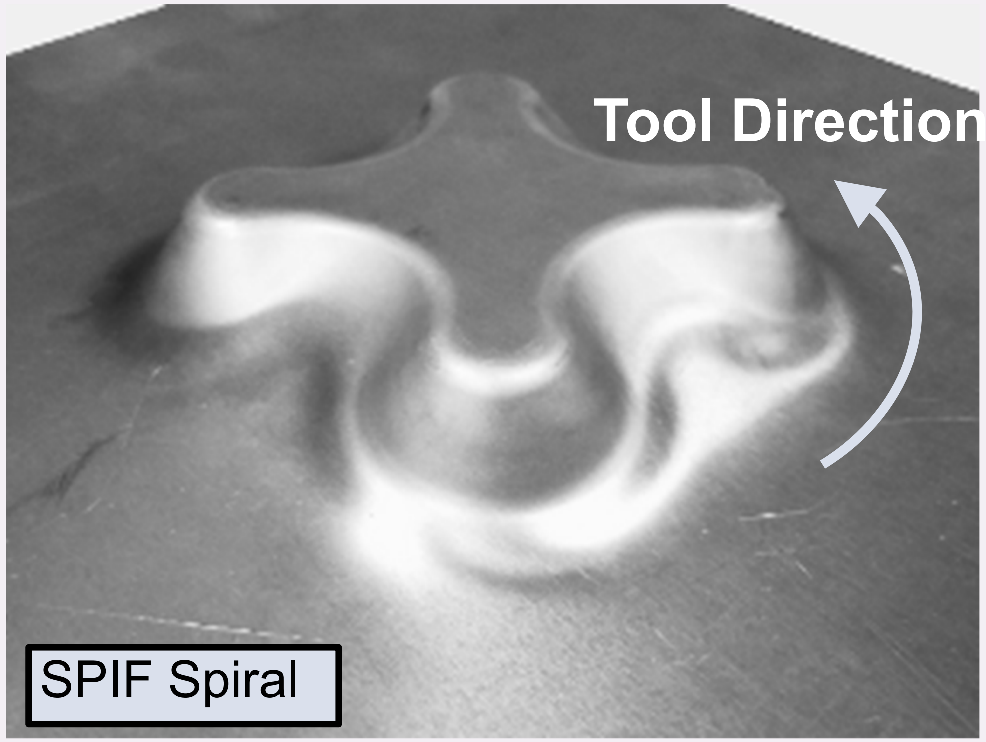
- Utilizes a partial die or support post
- Increased geometric accuracy, but with less flexibility

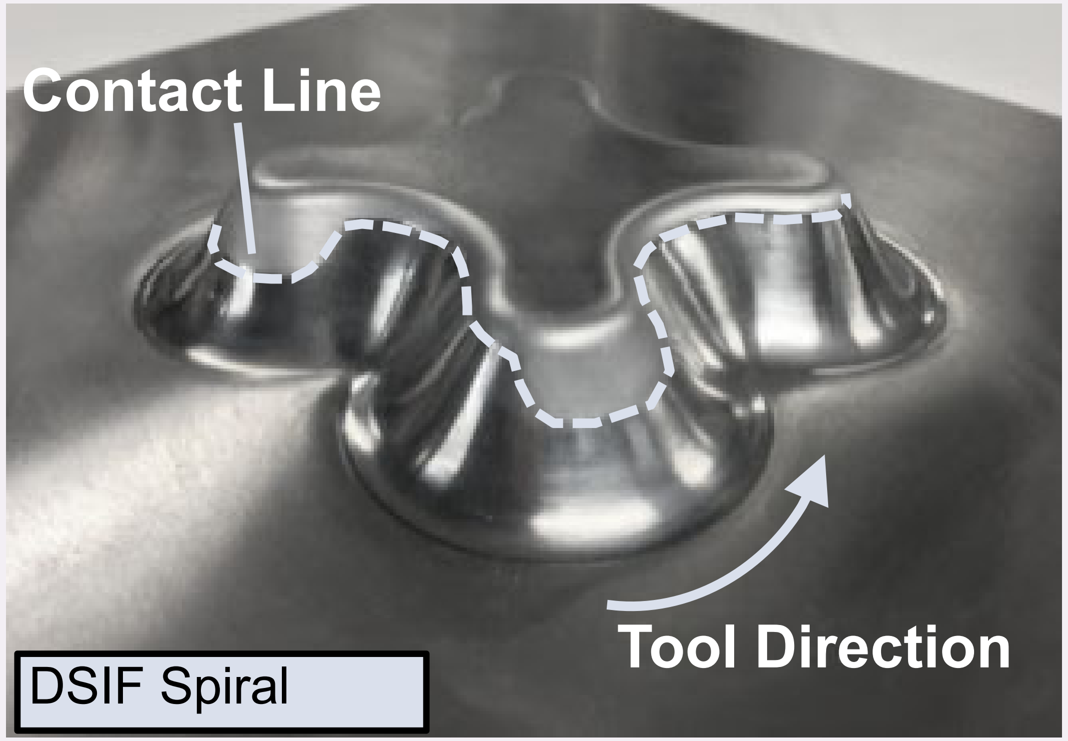
Double-Sided Incremental Forming (DSIF)



- Increased process control and accuracy, and still dieless
- Can form material above and below the sheet

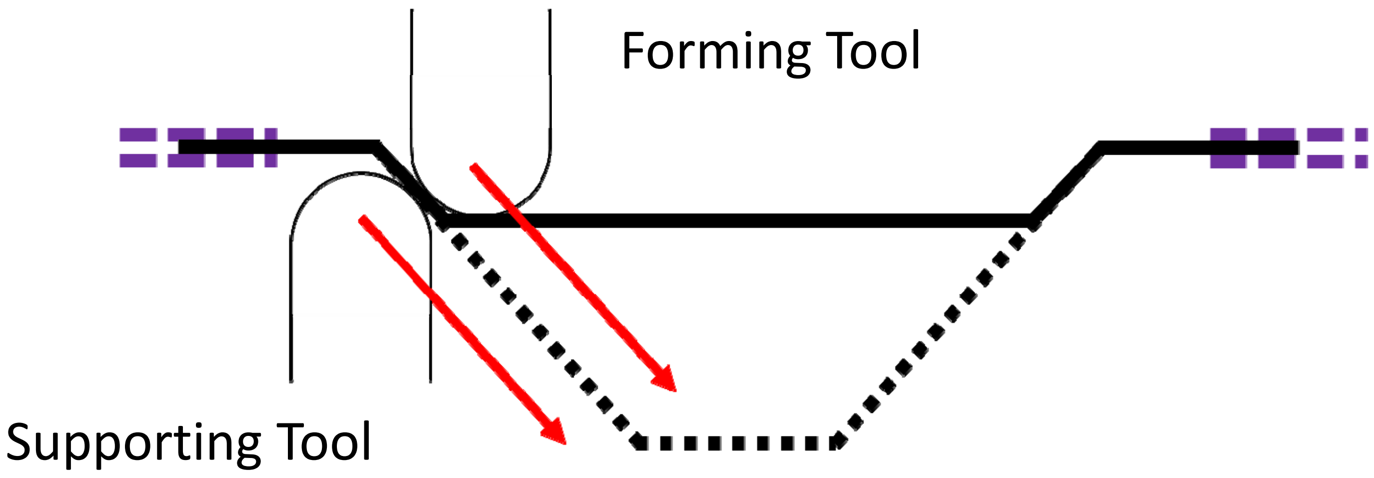
SPIF vs. DSIF

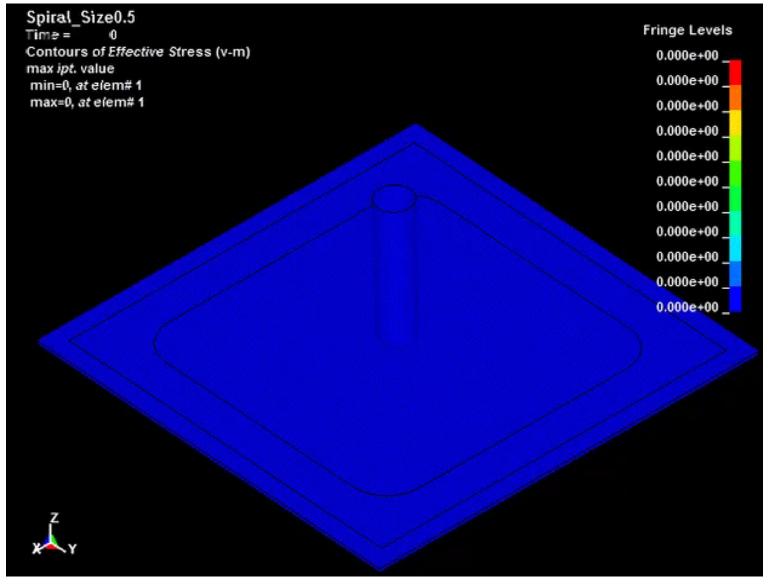


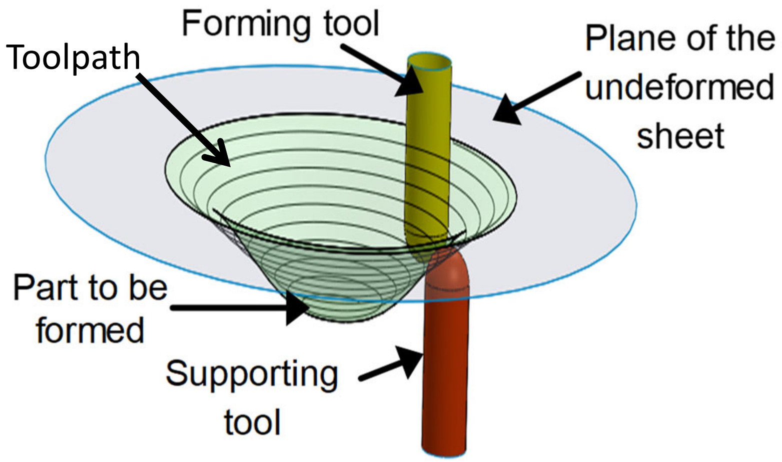


- Significant bending effects cause geometric deviations in concave features when using SPIF.

Double-Sided Incremental Forming (DSIF)







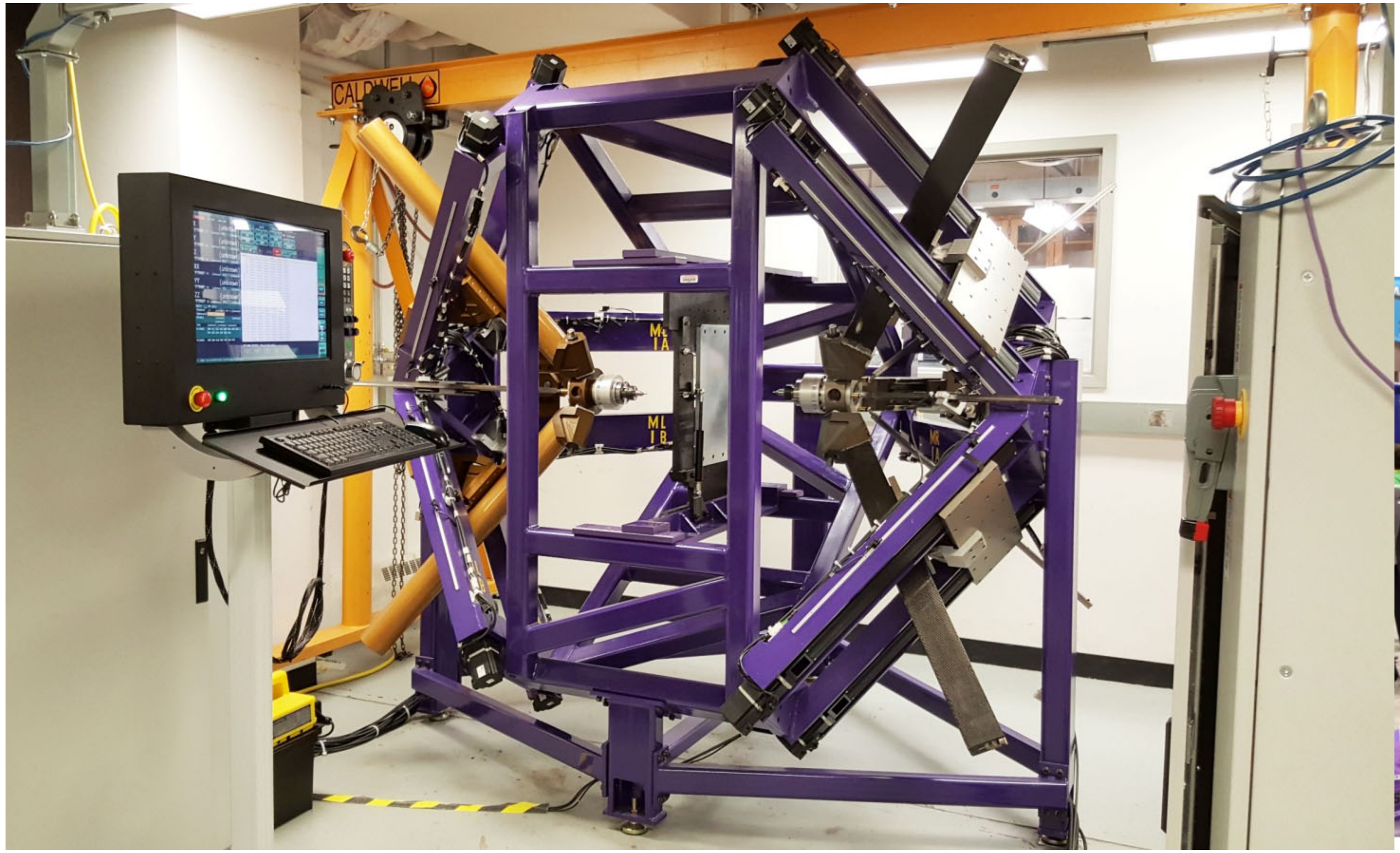
Many applications, such as hole-flanging

Nearly vertical wall angles

Complex features using custom toolpaths

[1] Wang, Y., Huang, Y., Cao, J., and Reddy, N.V.. (2008),International Manufacturing Science and Engineering Conference American Society of Mechanical Engineers.
[2]Malhotra, R., Cao, J., Ren, F., Kiridena, V., Xia, Z. C., & Reddy, N. V. (2011). Journal of Manufacturing Science and Engineering
[3] Zhang, Z., Ren, H., Xu, R., Moser, N., Smith, J., Ndip-Agbor, E., ... & Cao, J. (2015). Journal of Manufacturing Science and Engineering

DSIF Machines

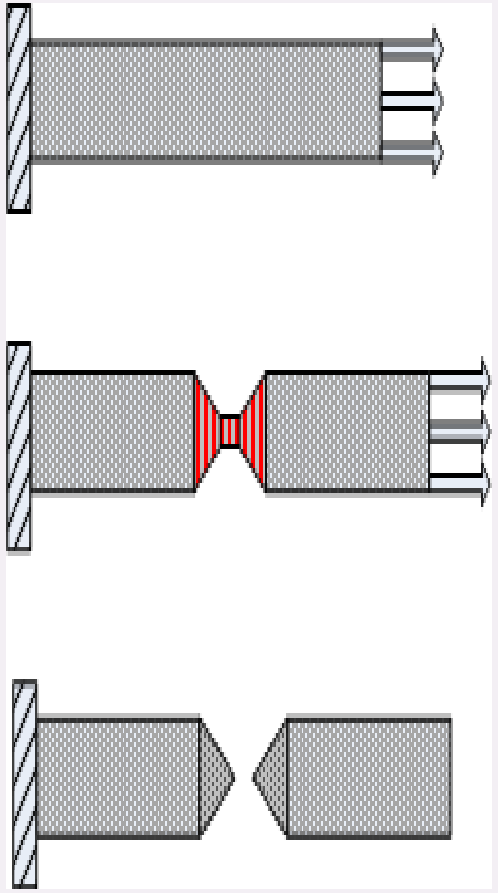


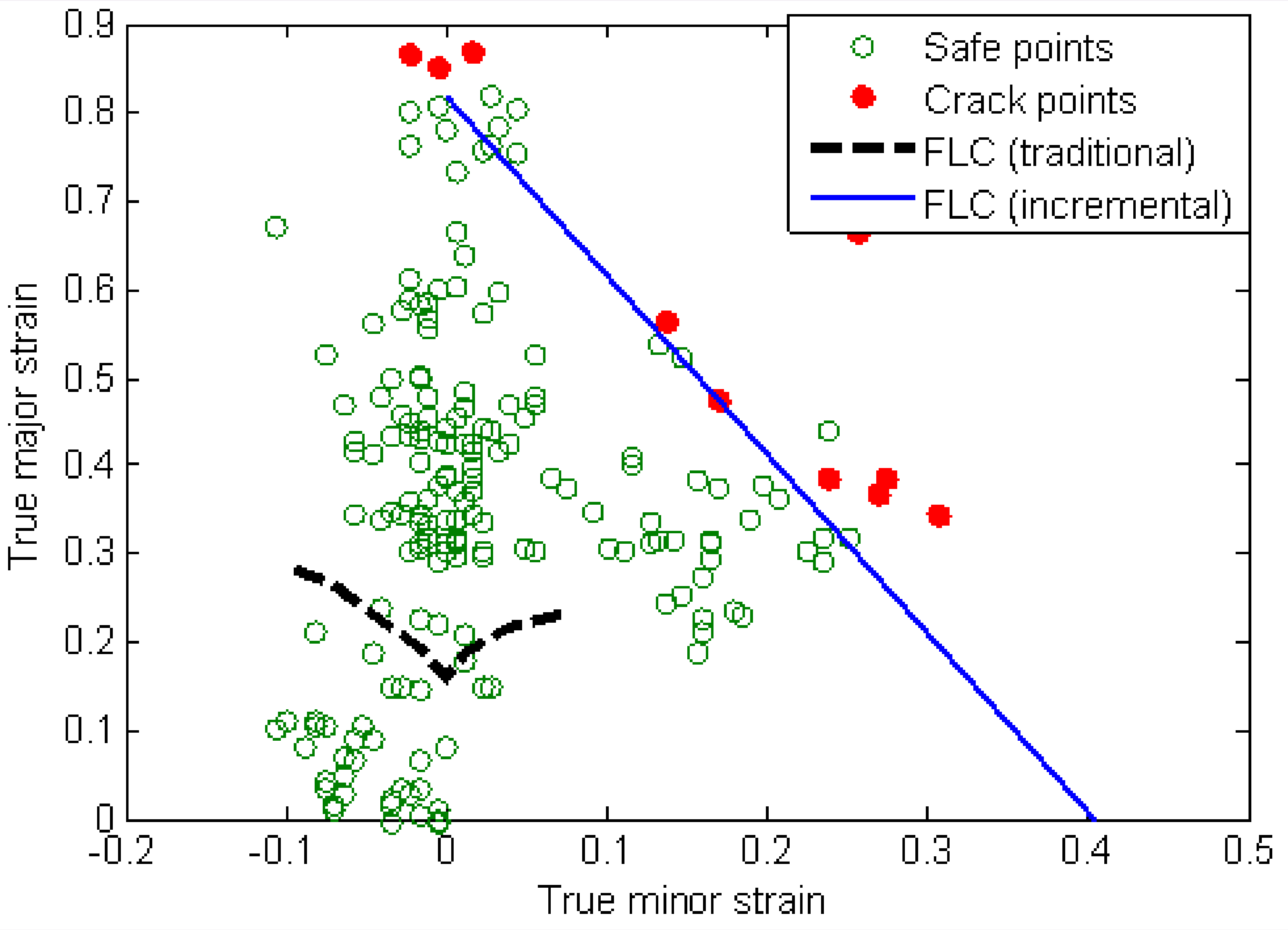
Opportunities and Challenges of IF

- Higher formability
- Geometric accuracy
- Forming sequence and forming time
- Turn-key operation
  - Toolpath code https://youtu.be/fLSOVylJr9o

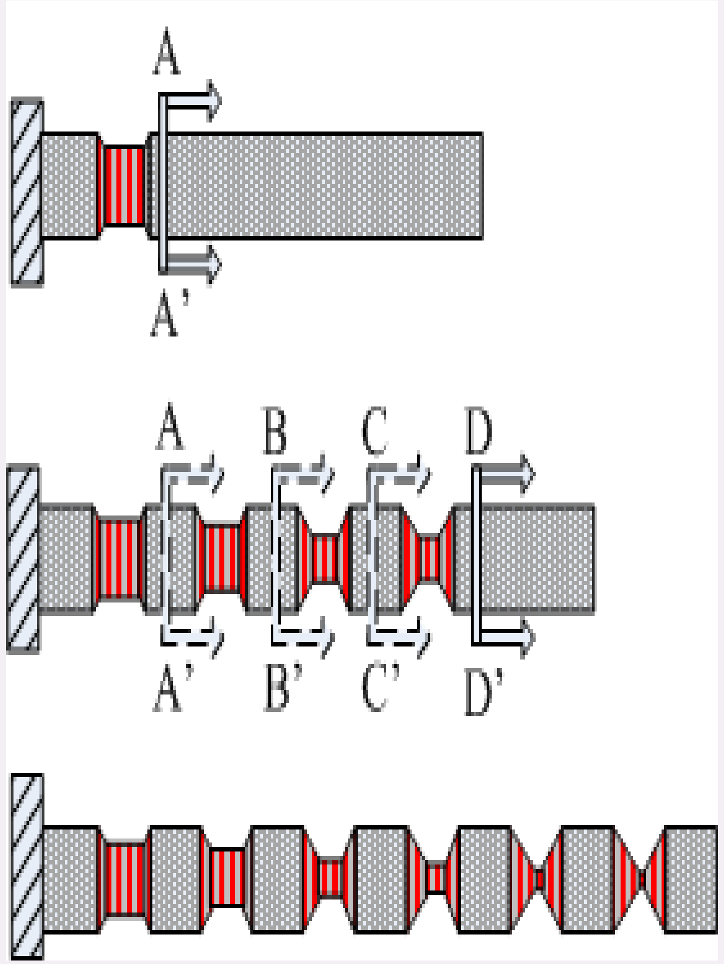
Forming Limits in Incremental Forming

Traditional Forming





Incremental Forming



Cao – NAMRC 2008, JMPT 2012

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Geometric Accuracy

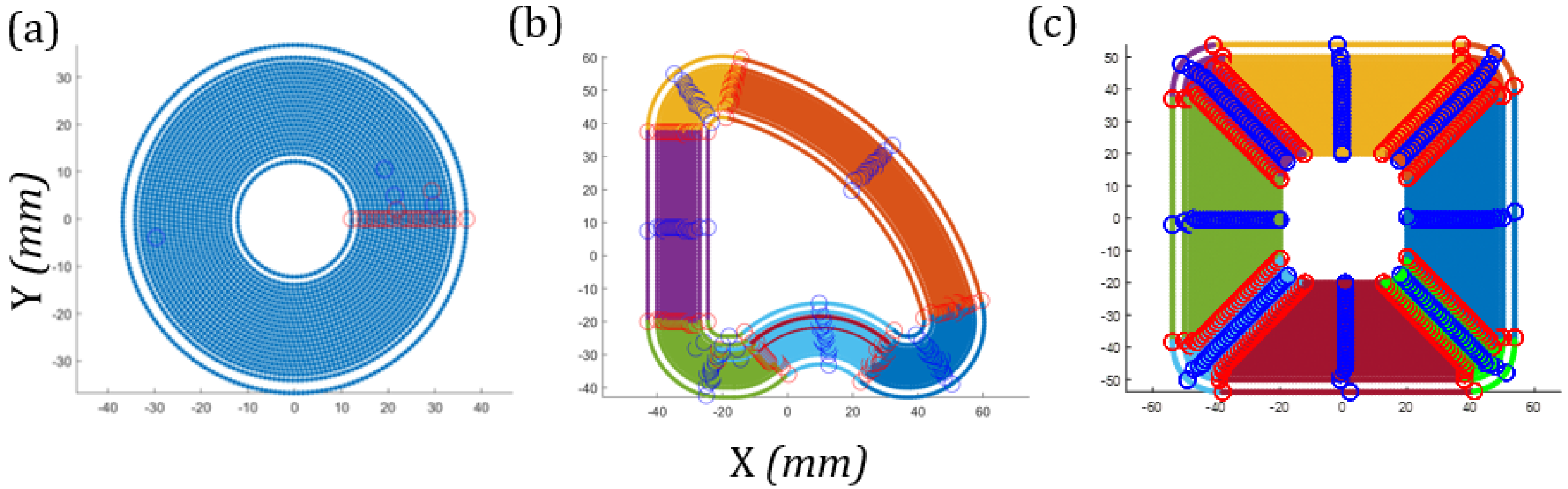

Table 1 Comparison of geometric deviations for the test cases.

Geometry	Cone		Fish fin			Pyramid	
Method	Ref	SC	Ref	SC	SC+FC	Ref	SC+FC
Max. error (mm)	5.7	1.5	5.0	3.0	2.0	4.8	1.2
Avg. error (mm)	3.1	0.8	3.2	1.9	1.2	2.6	0.2

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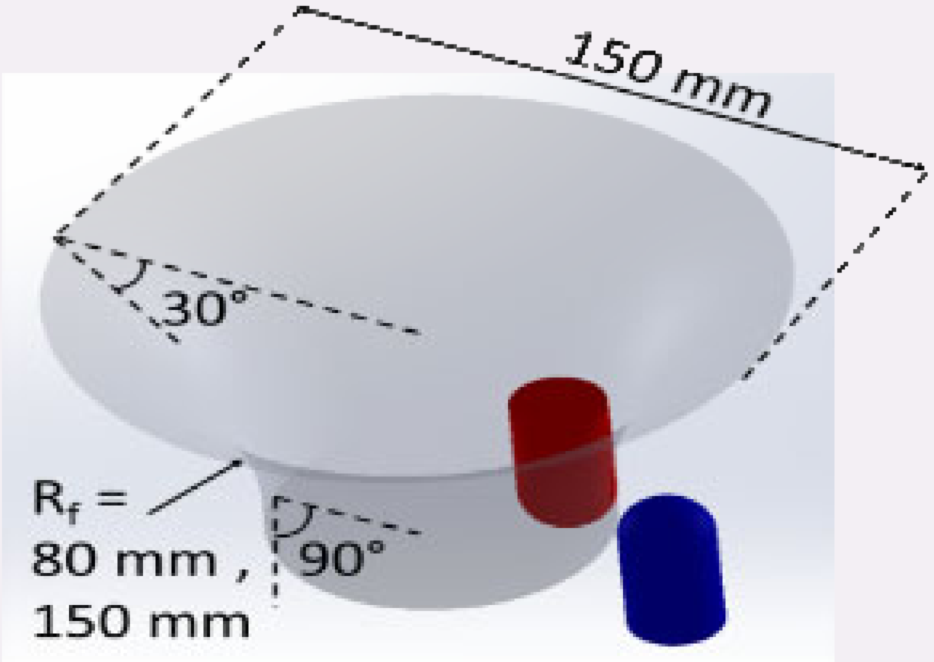
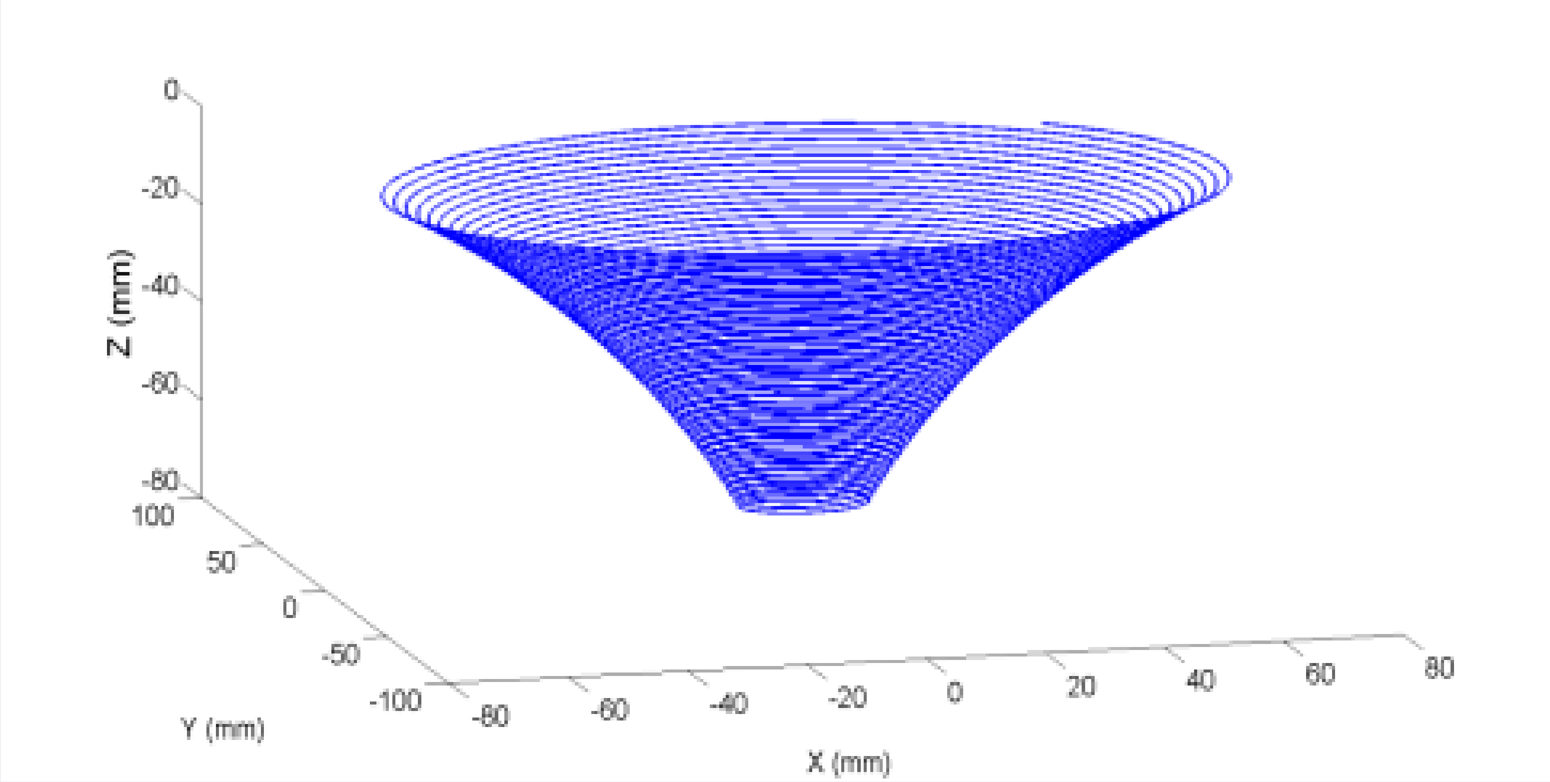
Toolpath Generation

- CAD model for a funnel part



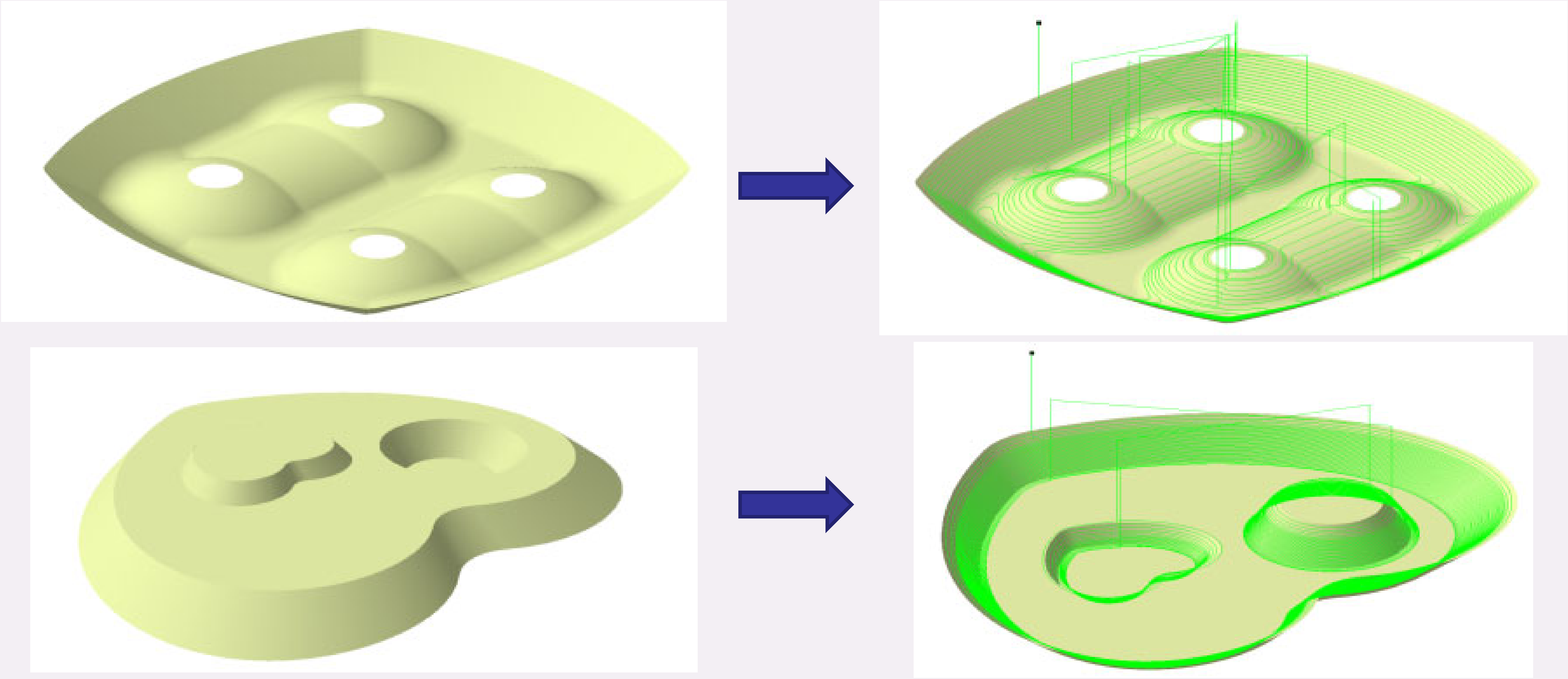
- Inputs:
  - CAD model
  - Tool radius
  - Incremental depth
  - Relative tool position

- Toolpath of the top tool



- Outputs:
  - Points (X,Y and Z) of the tool center

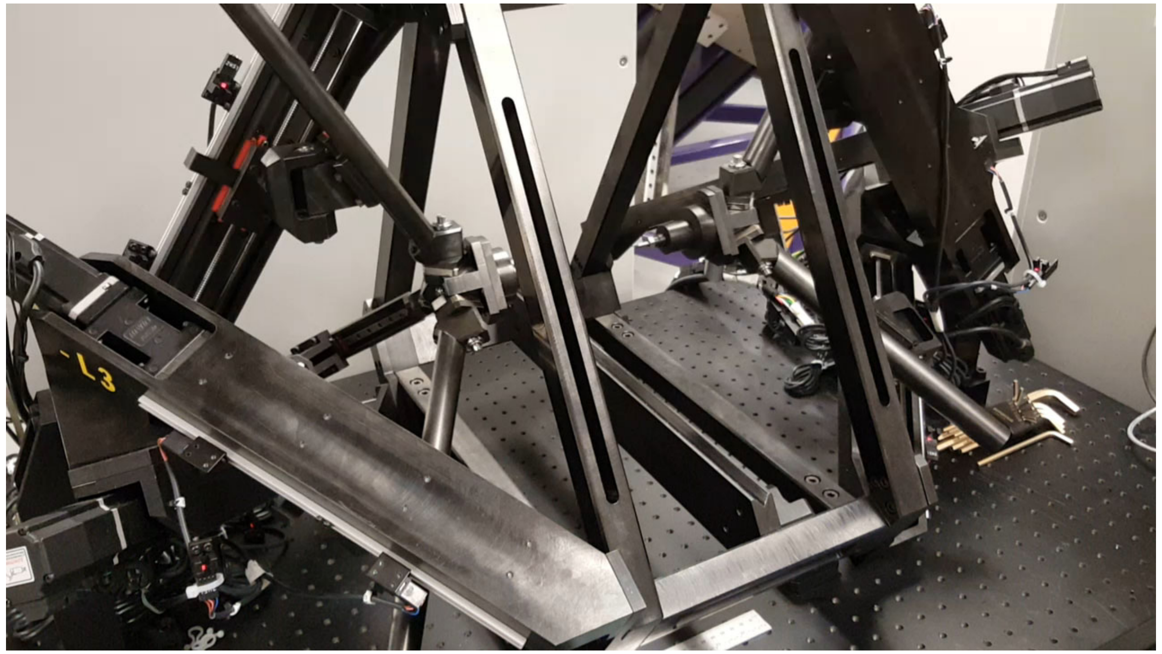
Toolpath Generation



Gen-2 DSIF – Tri-Pyramid Robots

Macro Forming

Micro Forming



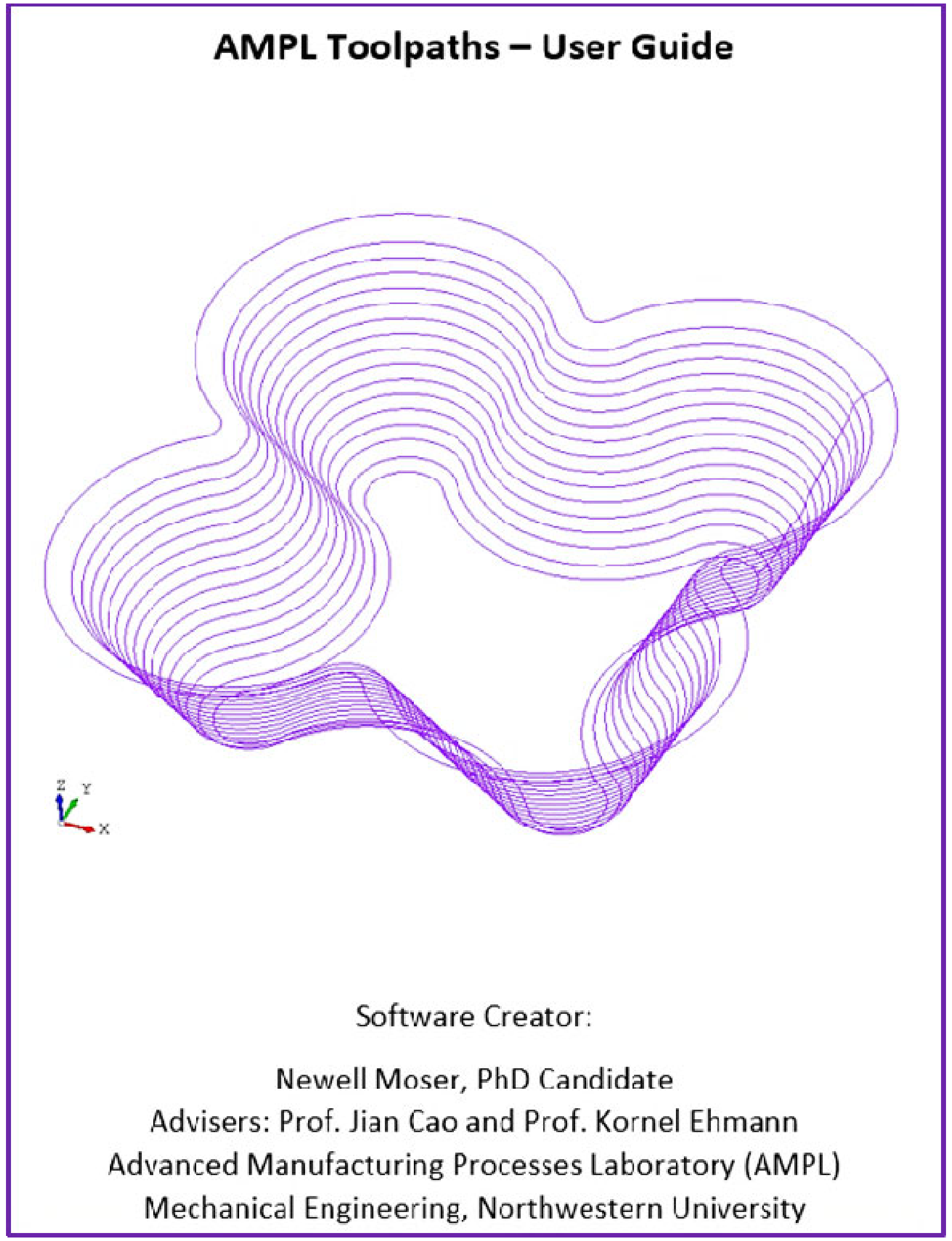
Zeng, Q., Ehmann, K.F. and Cao, J. (2016) “Design of General Kinematrotropic Mechanisms”, Robotics and Computer-Integrated Manufacturing, Vol. 38, pp.67-81

Zeng, Q., Ehmann, K.F. and Cao, J. (2016) “Tri-pyramid Robot: Stiffness Modeling of a 3-DOF Translational Parallel Manipulator”, Robotica

Opportunities and Challenges of IF

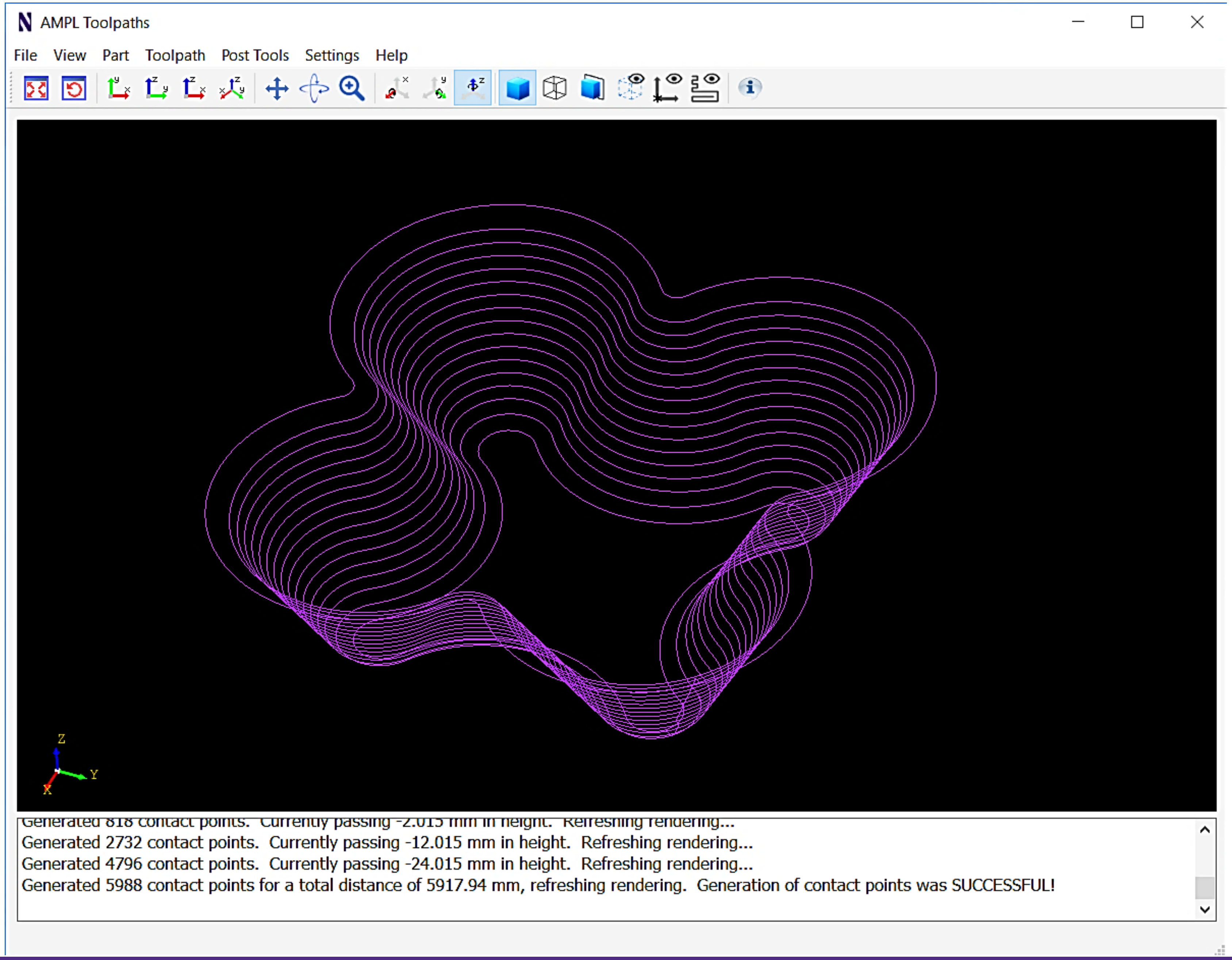
- Higher formability
- Geometric accuracy
- Forming sequence and forming time
- Turn-key operation
    - Toolpath code https://youtu.be/fLSOVylJr9o

In-House C++ Toolpath Generation Software


AMPL Toolpaths – User Guide

Software Creator:

Newell Moser, PhD Candidate
Advisers: Prof. Jian Cao and Prof. Kornel Ehmann
Advanced Manufacturing Processes Laboratory (AMPL)
Mechanical Engineering, Northwestern University



Opportunities and Challenges of IF

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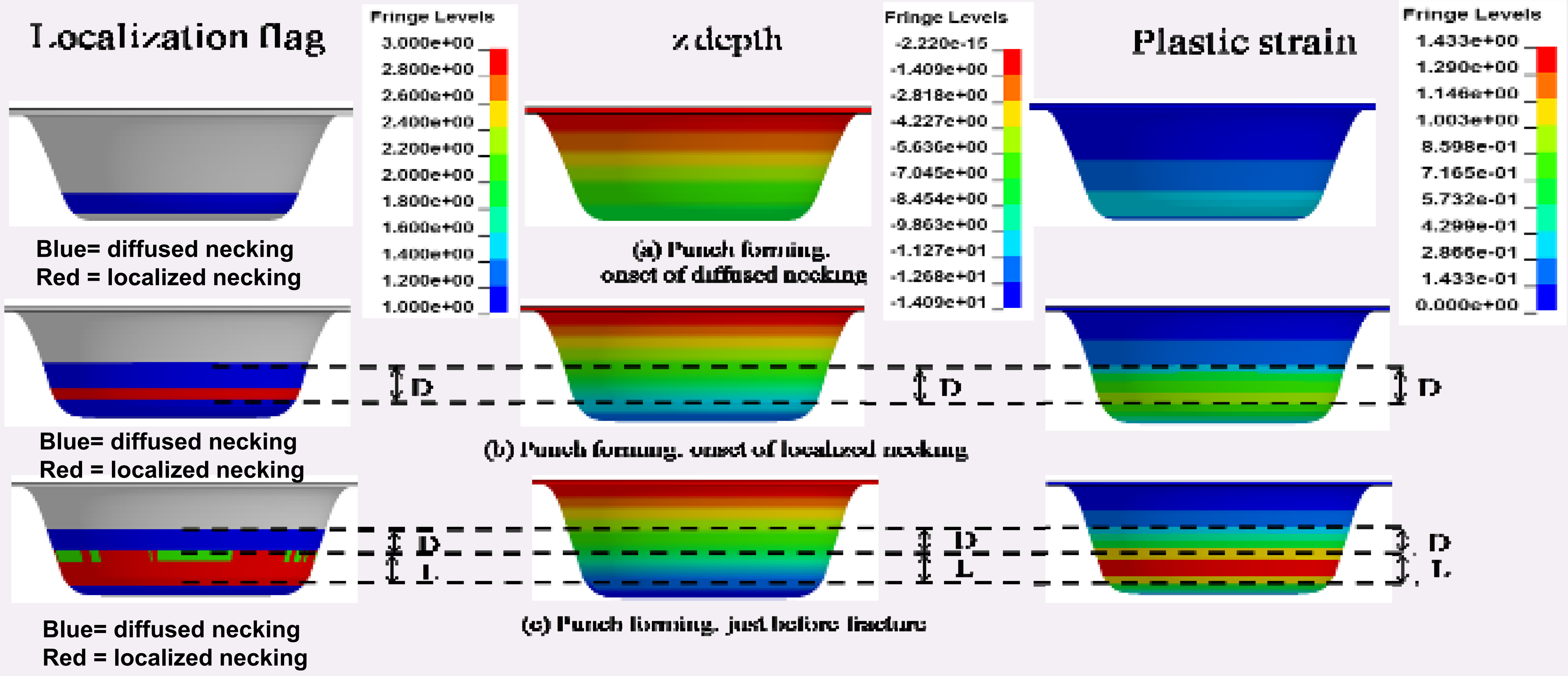
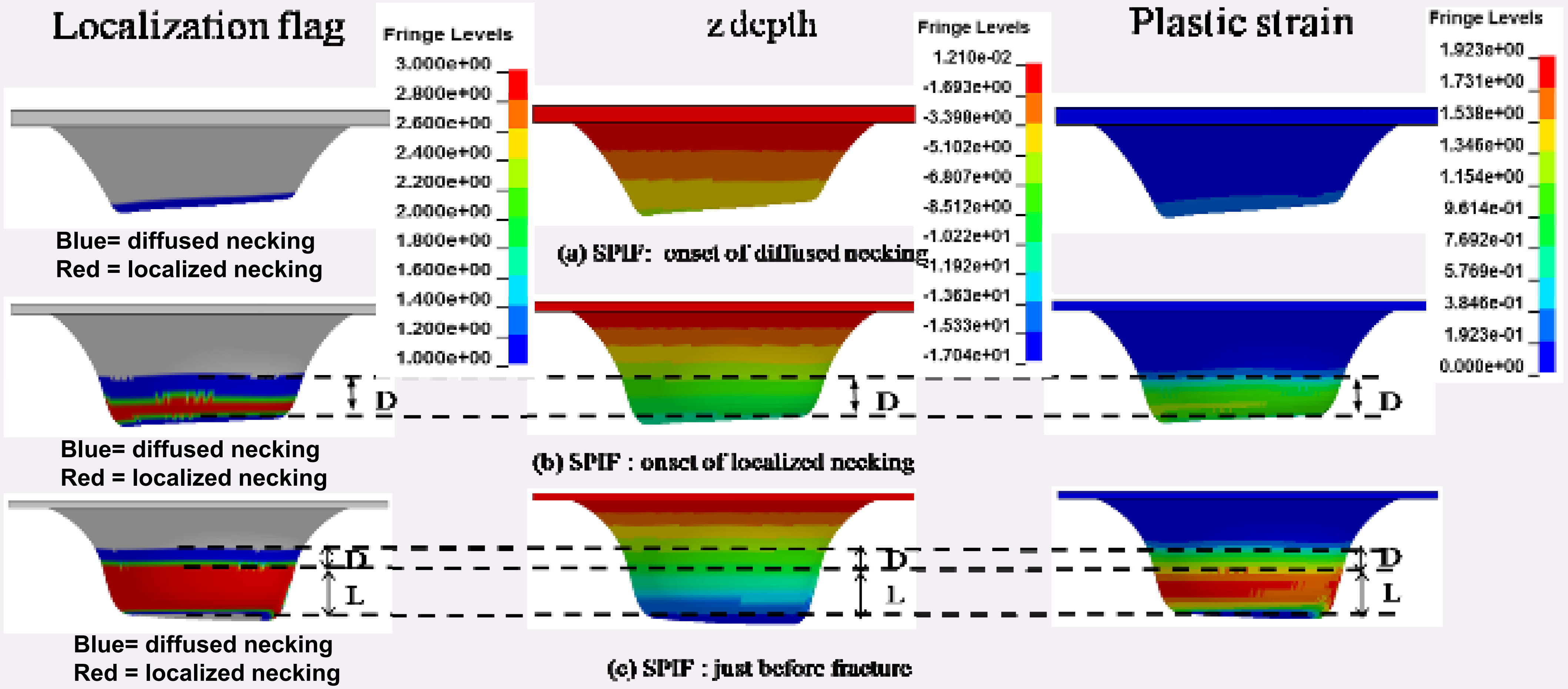
Material Instability: Punch forming



Beginning of (a) Diffused necking at 8.6 *mm* (b) Localized necking at 12.6 *mm* (c) Fracture at 14.09 *mm*

- Deformation is global in nature, so after initial localized necking occurs this unstable material is still actively stretched by the punch
- Therefore the plastic strain gets concentrated in the shear bands which grow rapidly leading to rapid fracture

Material Instability: SPIF

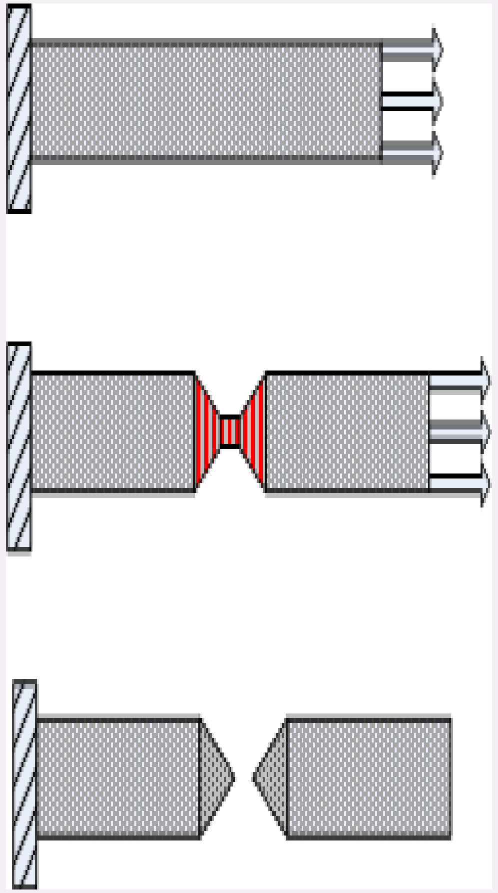


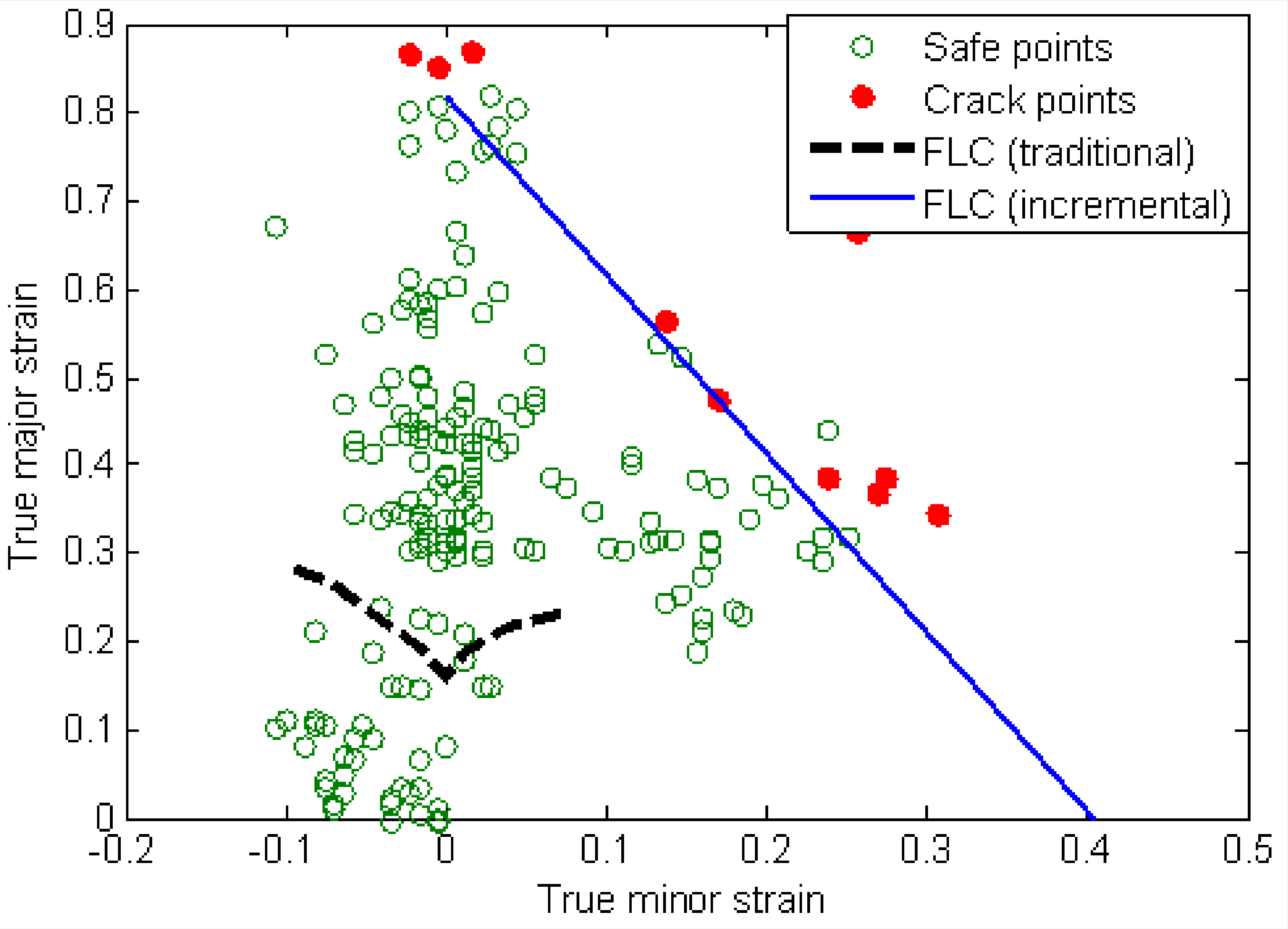
Beginning of (a) Diffused necking at 5.6 *mm* (b) Localized necking at 10.4 *mm* (c) Fracture at 16.9 *mm*

- Deformation is local, so shear bands in previously formed unstable region don't grow as quickly. This previous unstable region takes up some of the plastic strain of the newly formed material in subsequent tool passes
- This allows the newly formed material to take greater amount of plastic strain and reach a greater Z depth without fracture

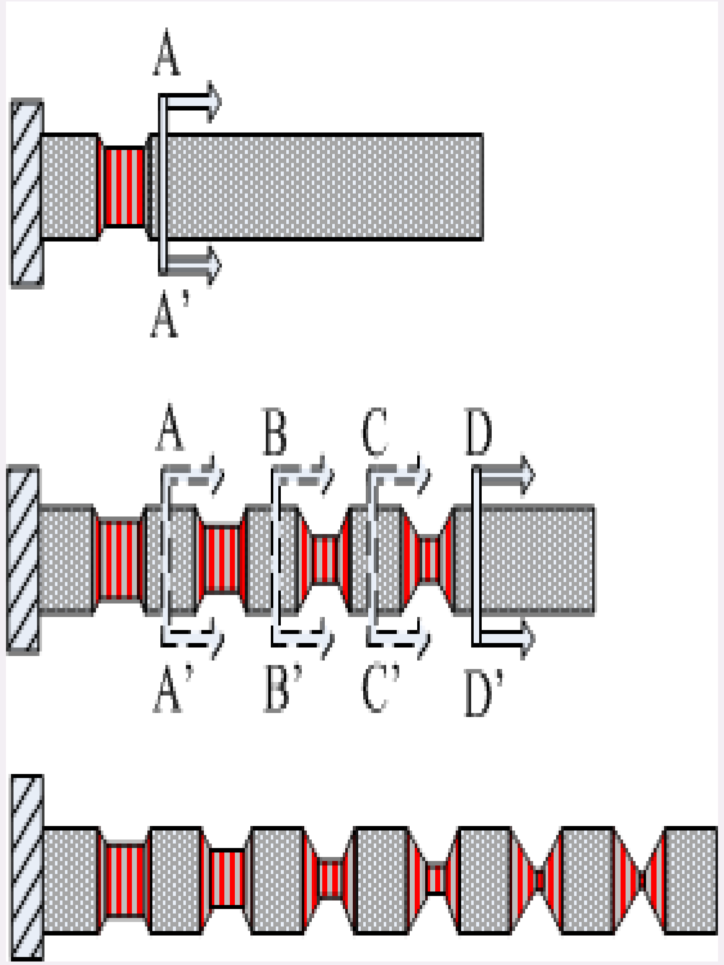
Forming Limits in Incremental Forming

Traditional Forming

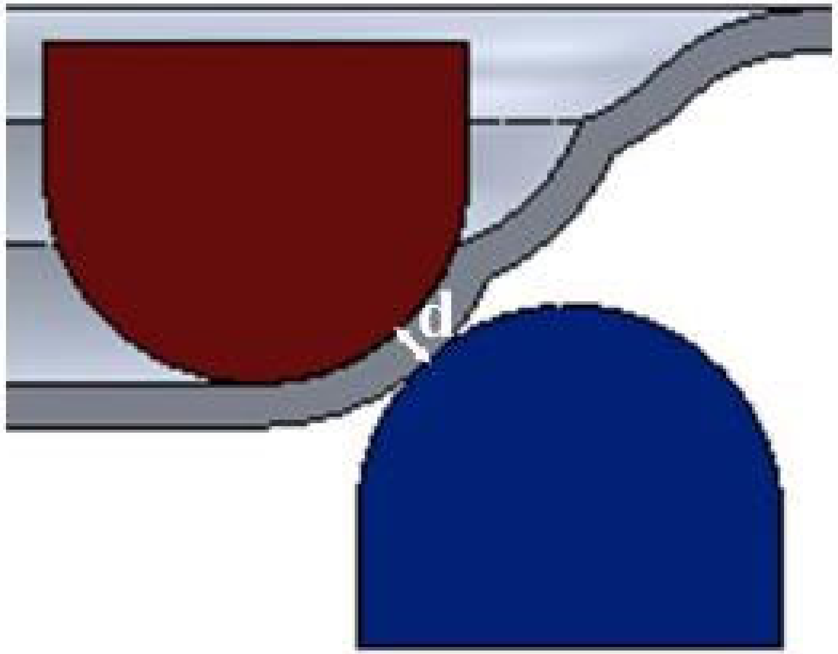




Incremental Forming



Squeeze Factor in DSIF



$$d = s \cdot t_0 \cdot \cos\theta$$

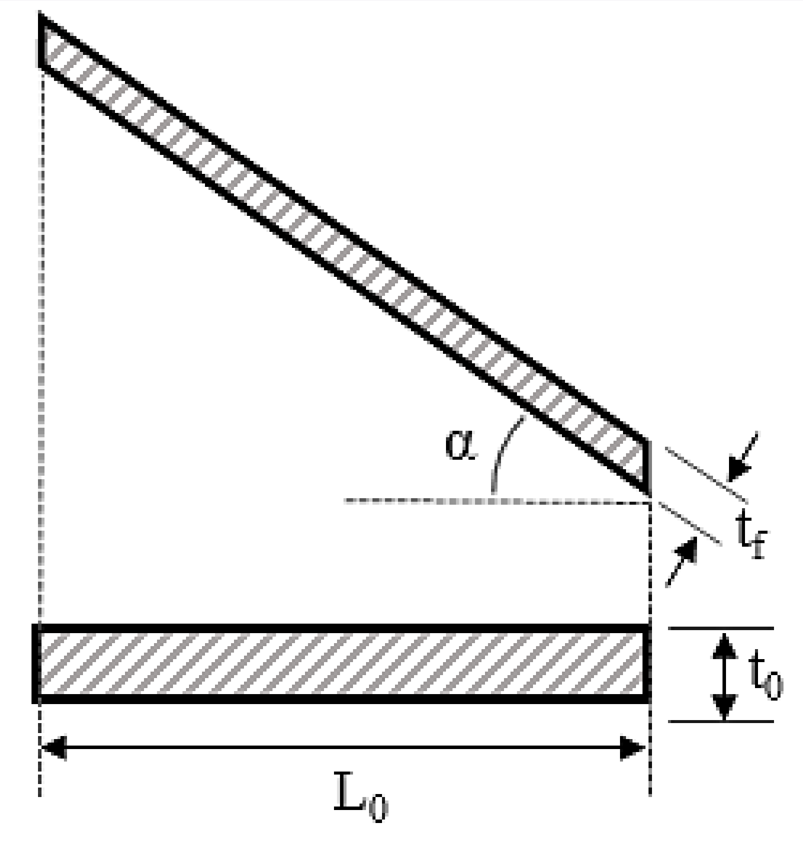
where,

s (squeeze factor) ≤ 1.0

t_0*: original sheet thickness*

θ*: wall angle at local contact point of forming tool*

$[t_0 \cdot \cos\theta]$*: Sine Law thickness*



Sine Law (proposed originally for Shear Spinning)

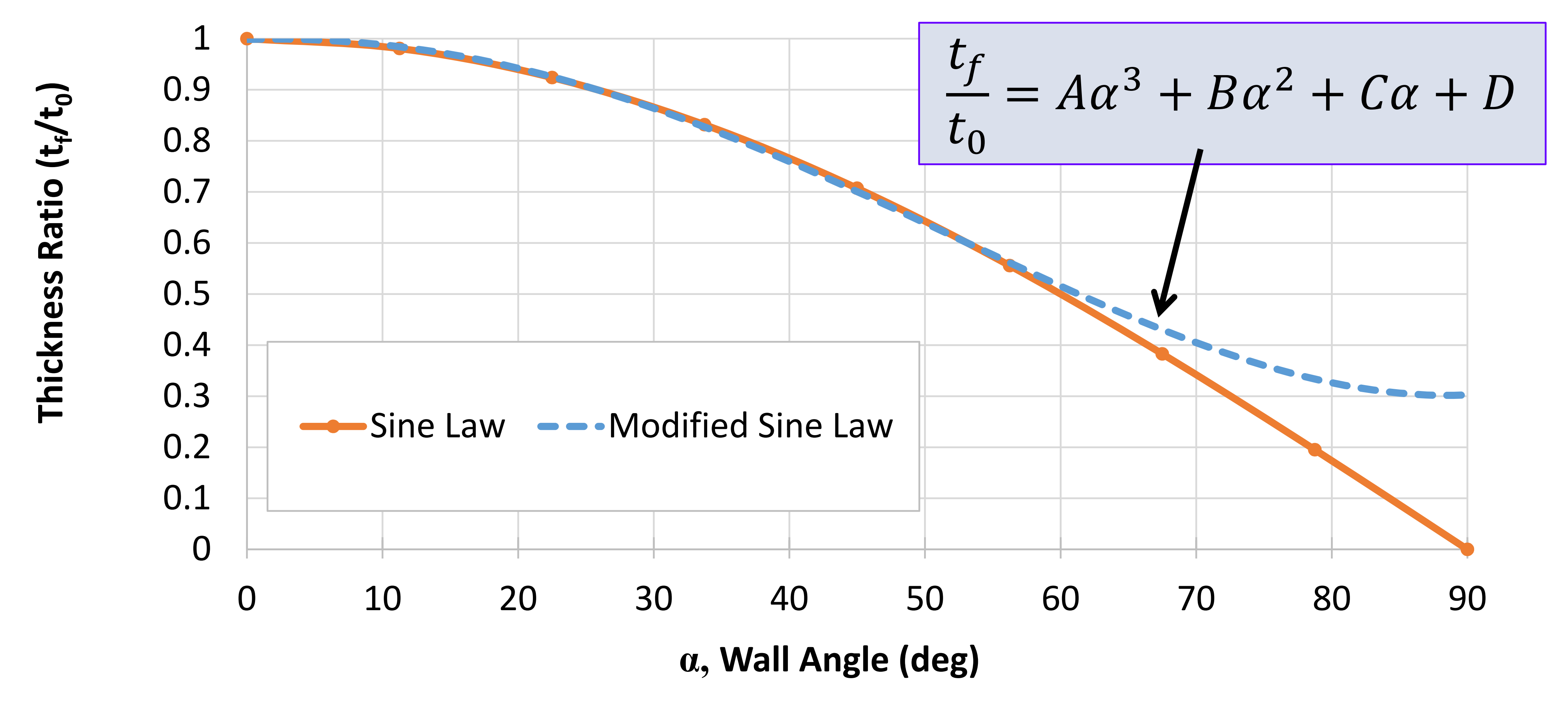
$$t_f = t_0 \sin(90° - \alpha) = t_0 cos\alpha$$

where: α - Wall Angle

Modified Thickness Prediction

Thinning Failure Criterion: $\boldsymbol{\varepsilon_3} \leq \boldsymbol{\varepsilon_f}$

where $\boldsymbol{\varepsilon_f}$ is the thickness strain at the onset of fracture in plane strain conditions

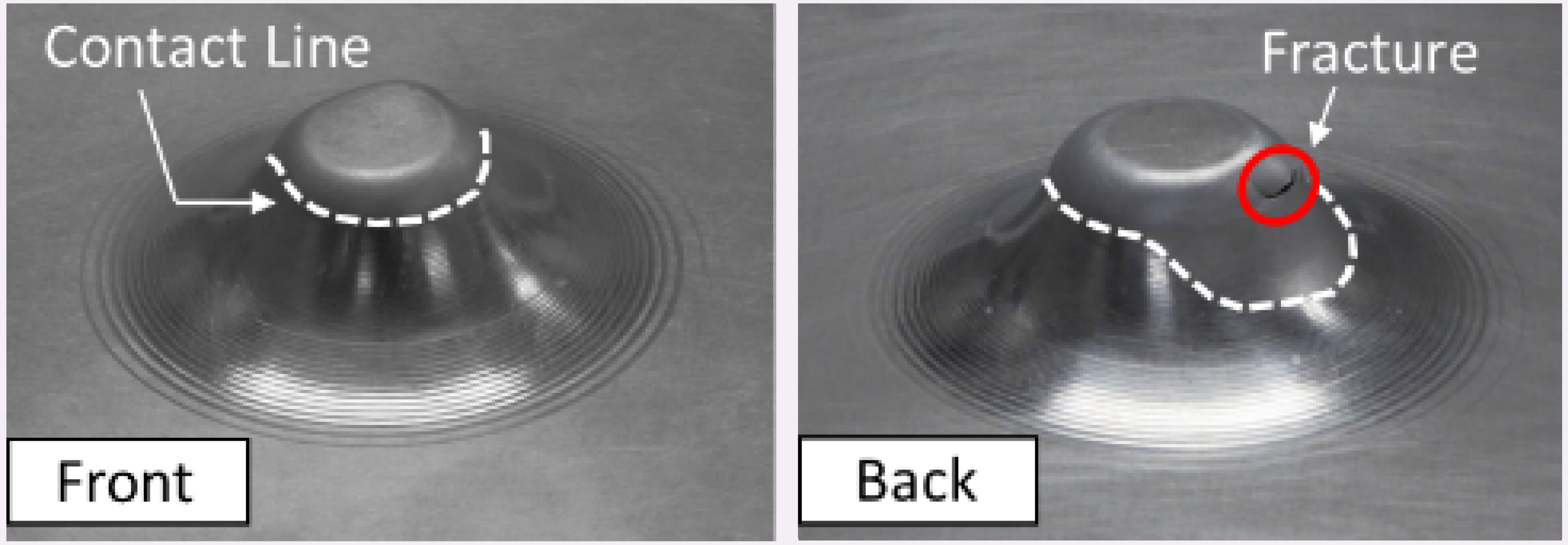


Fracture in DSIF

Shamrock Part (63º Wall Angle)

Objective: To Delay Fracture

Hypothesis: Lost contact leads to earlier fracture

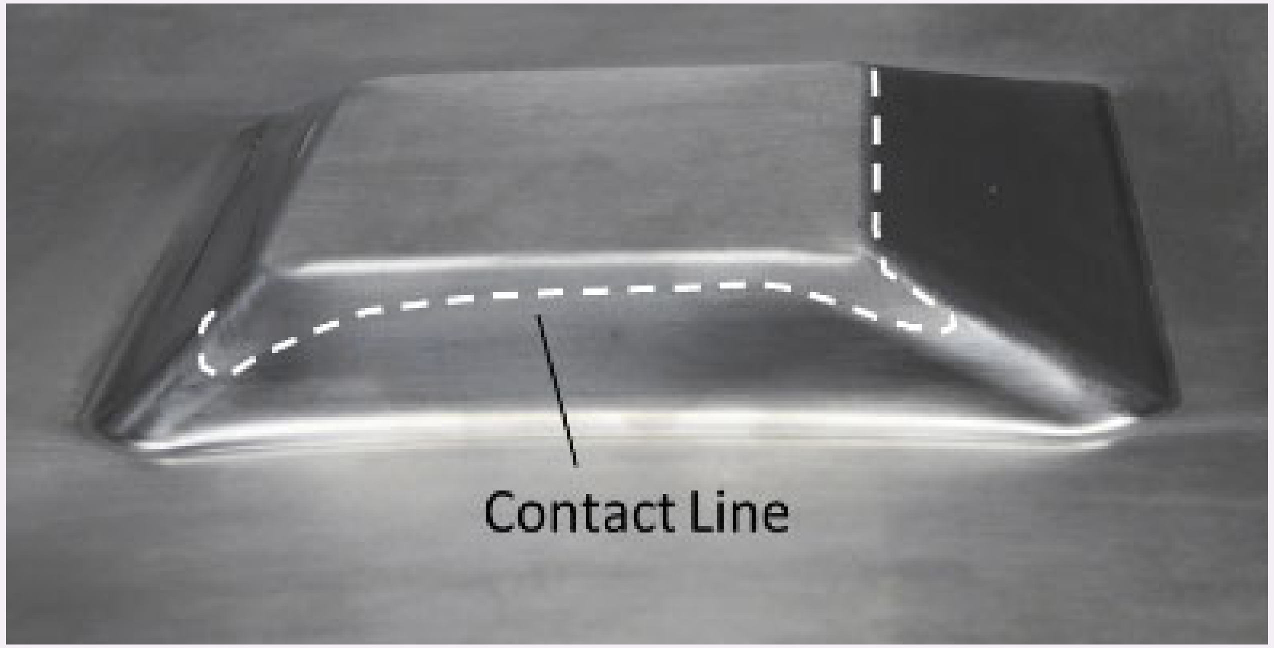


If the supporting tool loses contact with the part:

1. DSIF degenerates to Single-Point Incremental Forming;
2. The stabilizing compressive stress through-the-thickness is lost;
3. Local thinning tends to occur resulting in premature fracture.

Potential Source Causing the Loss of Contact – Inaccurate Thickness Prediction

Truncated pyramid with four different wall angles – Used the Sine Law

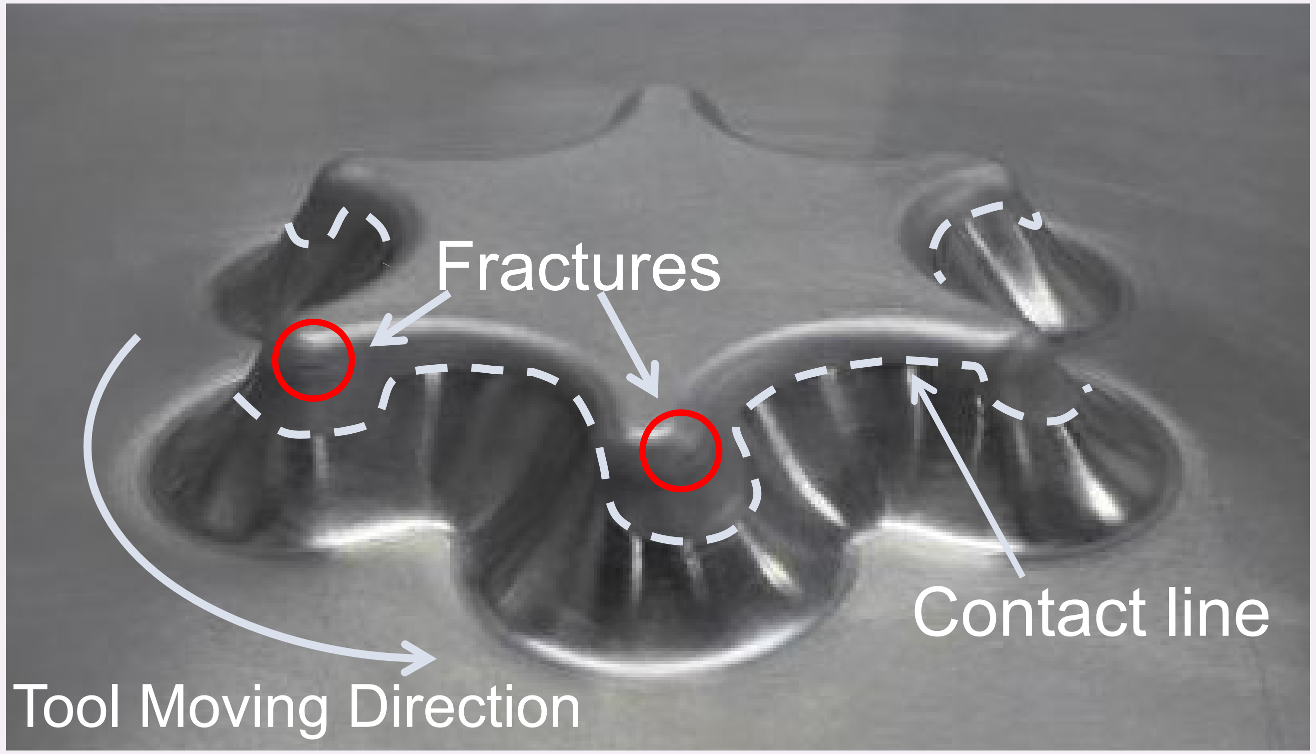


Despite the constant wall angle, the tool gap defined by the Sine Law was not adequate, particularly in transition zones near the corners.

➢ Should consider the in-plane curvature.

and more…

Funnel-Star – Used the Sine Law

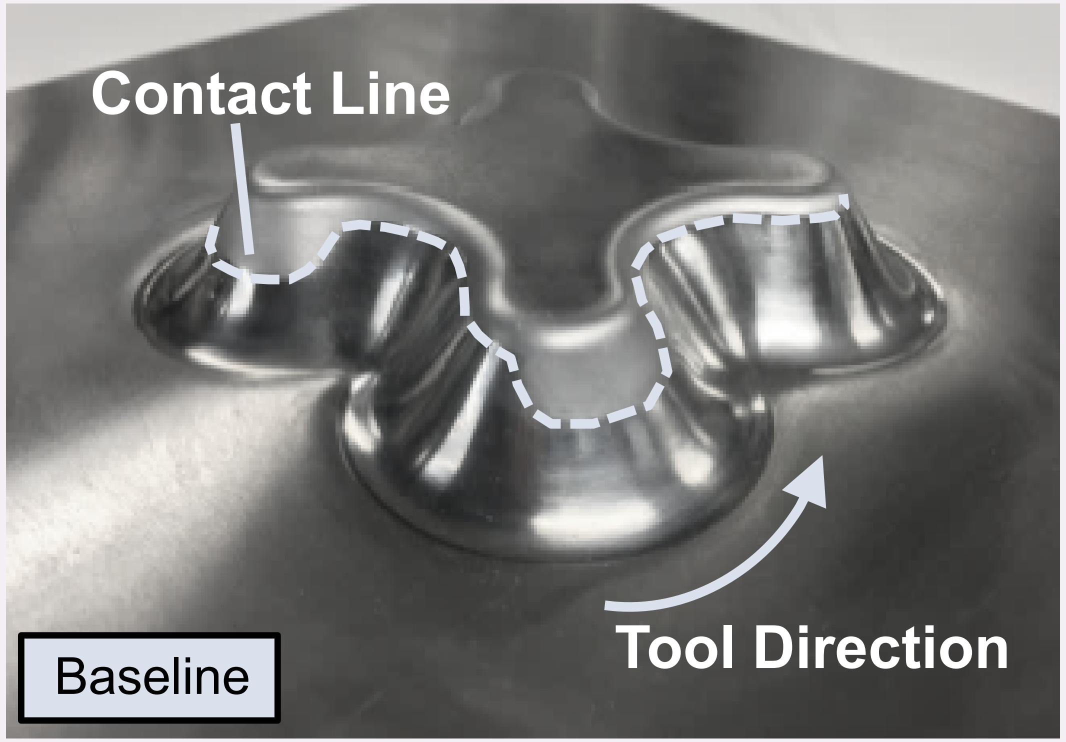


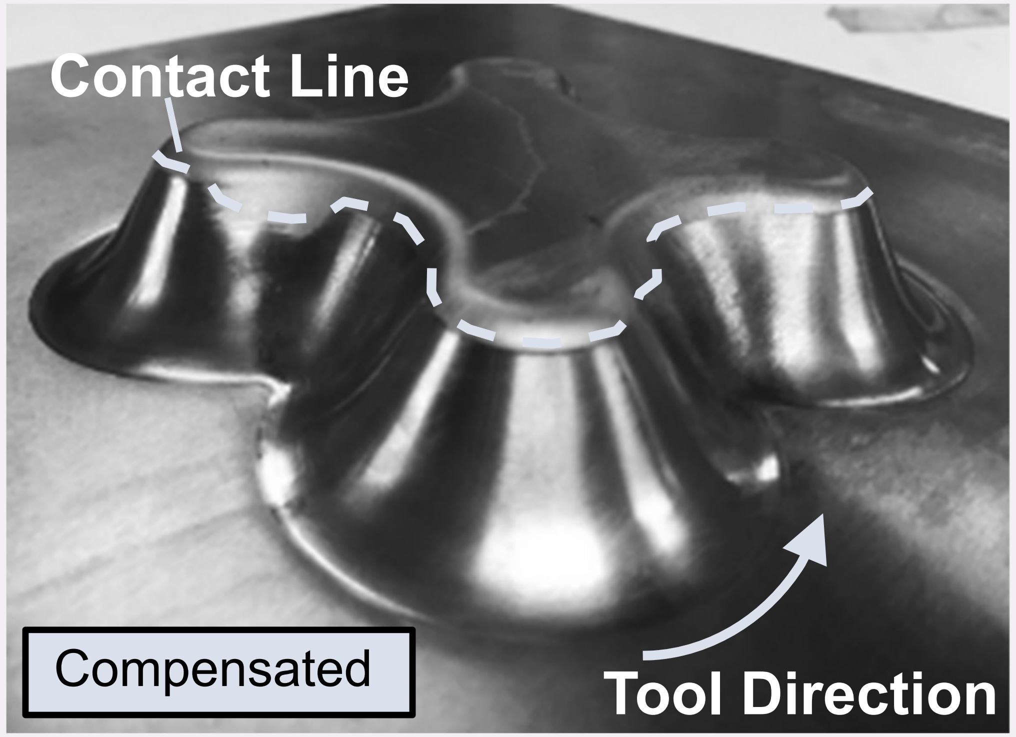
Note the **asymmetry** of contact line; in favor of the tool direction. This asymmetry was present for **ALL** corners of the part.

➢ Should consider the tool moving direction.

Experiment Using the Proposed Correction Function

Shamrock with 60° Wall Angle



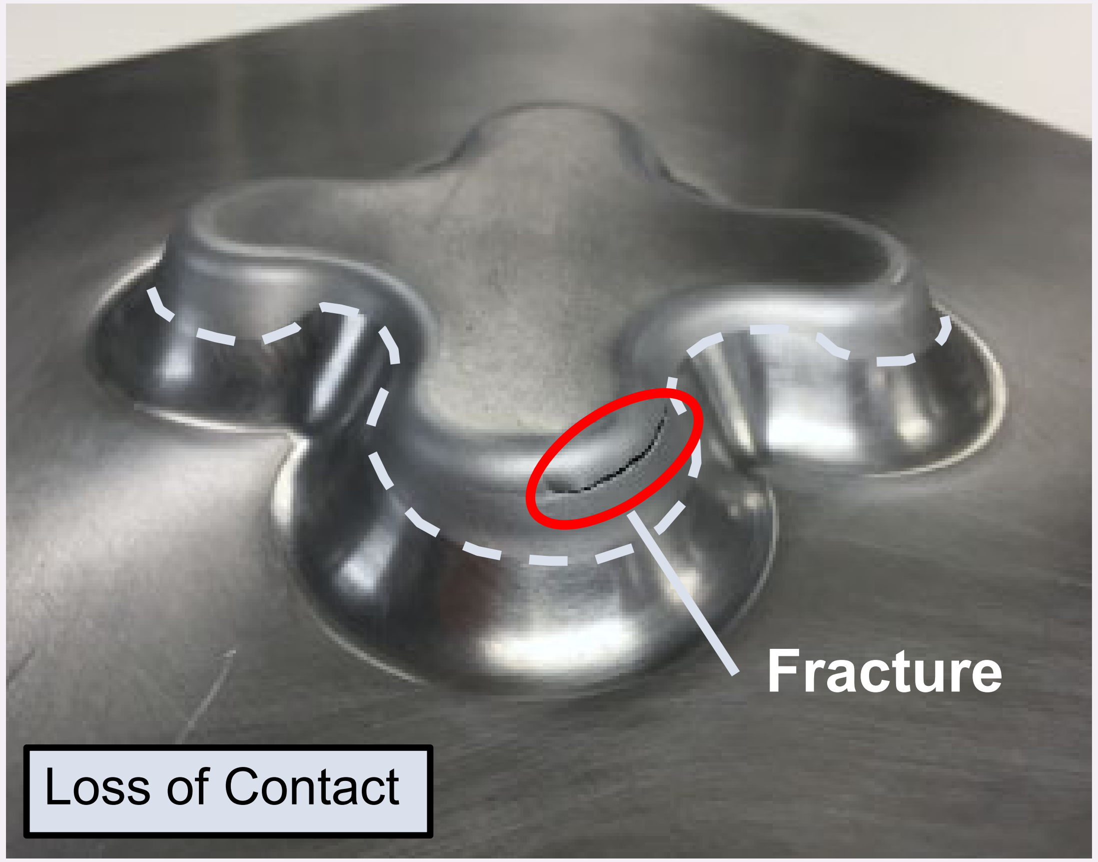


Baseline – Tool gap based on the Sine Law

Compensated – Tool gap based on the proposed correction function

Contact was maintained far better when using the proposed tool gap model.

Verification – Shamrock Part with 65º Wall Angle

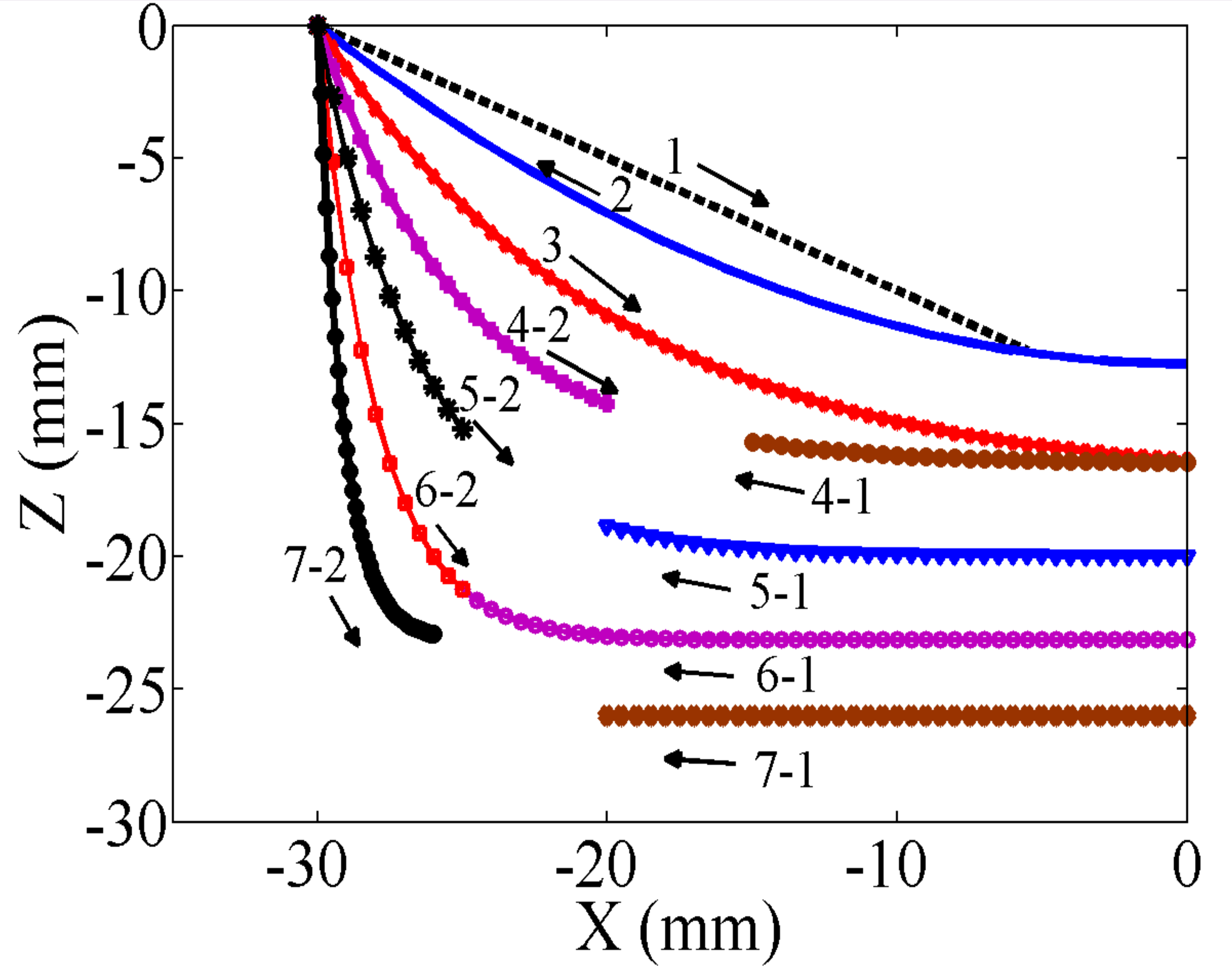


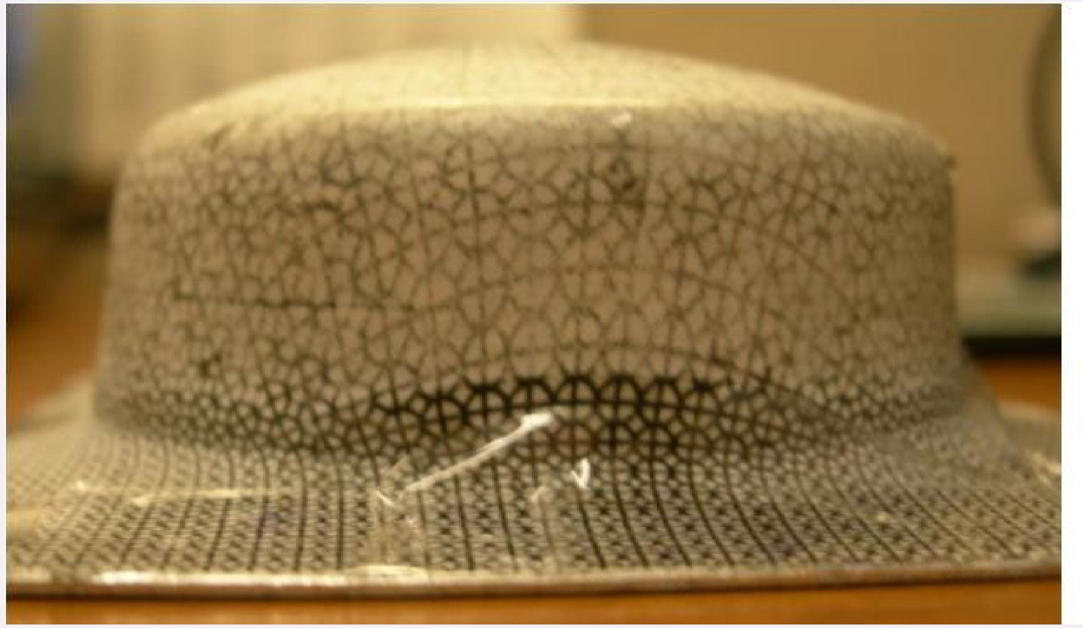
Baseline – Tool gap based on the Sine Law

Compensated – Tool gap based on proposed correction function

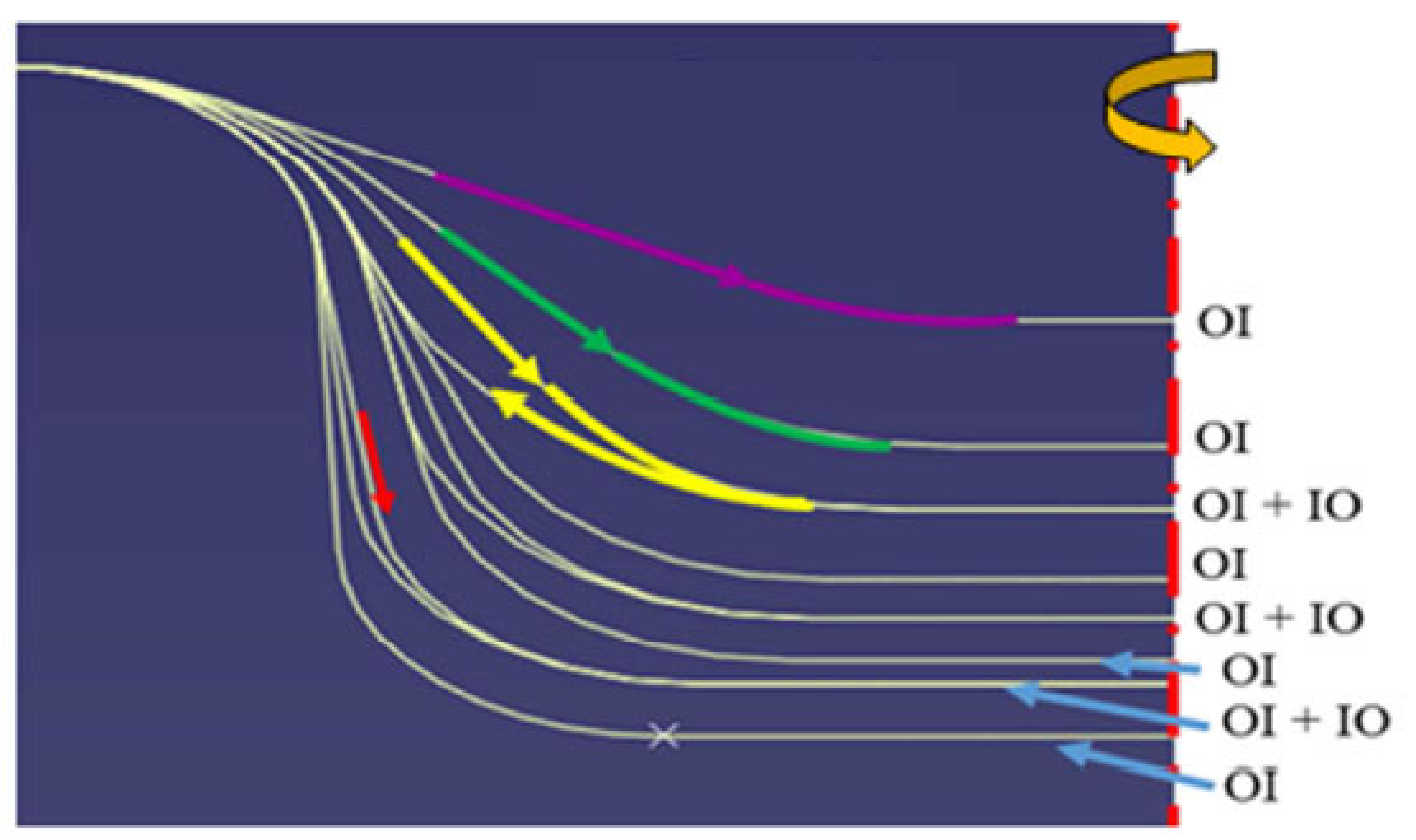
Upon increasing the wall angle, maintaining contact helped to prevent thinning and increased formability.

Multi-pass SPIF



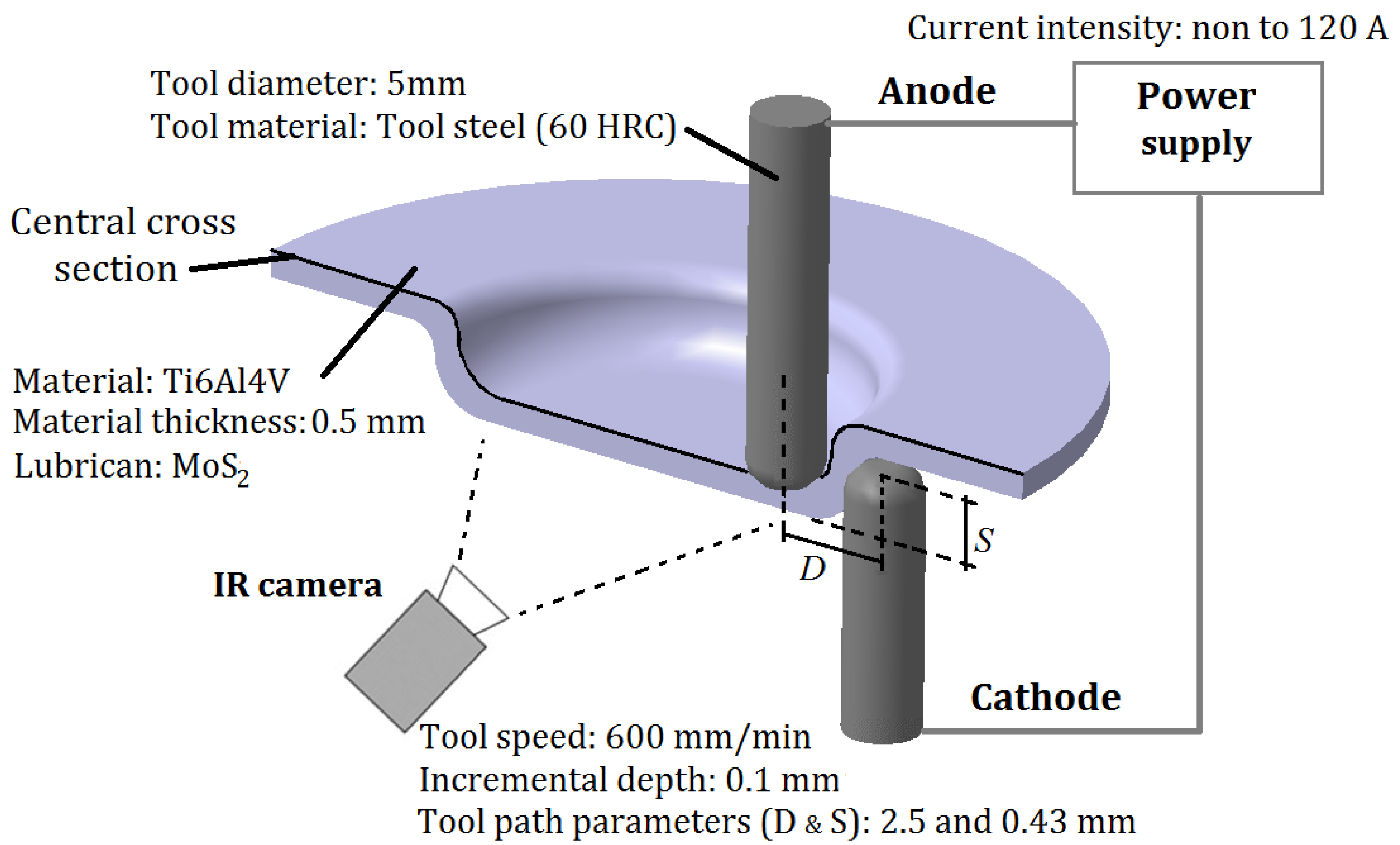


Multi-pass DSIF



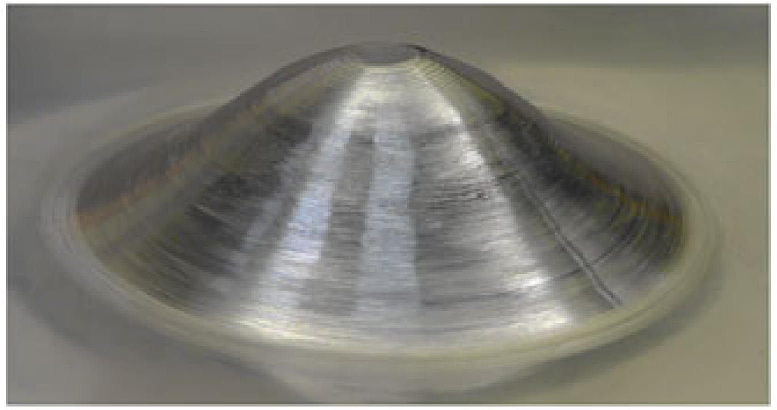
Moser, N. … Cao, J., Key Eng. Materials 2015

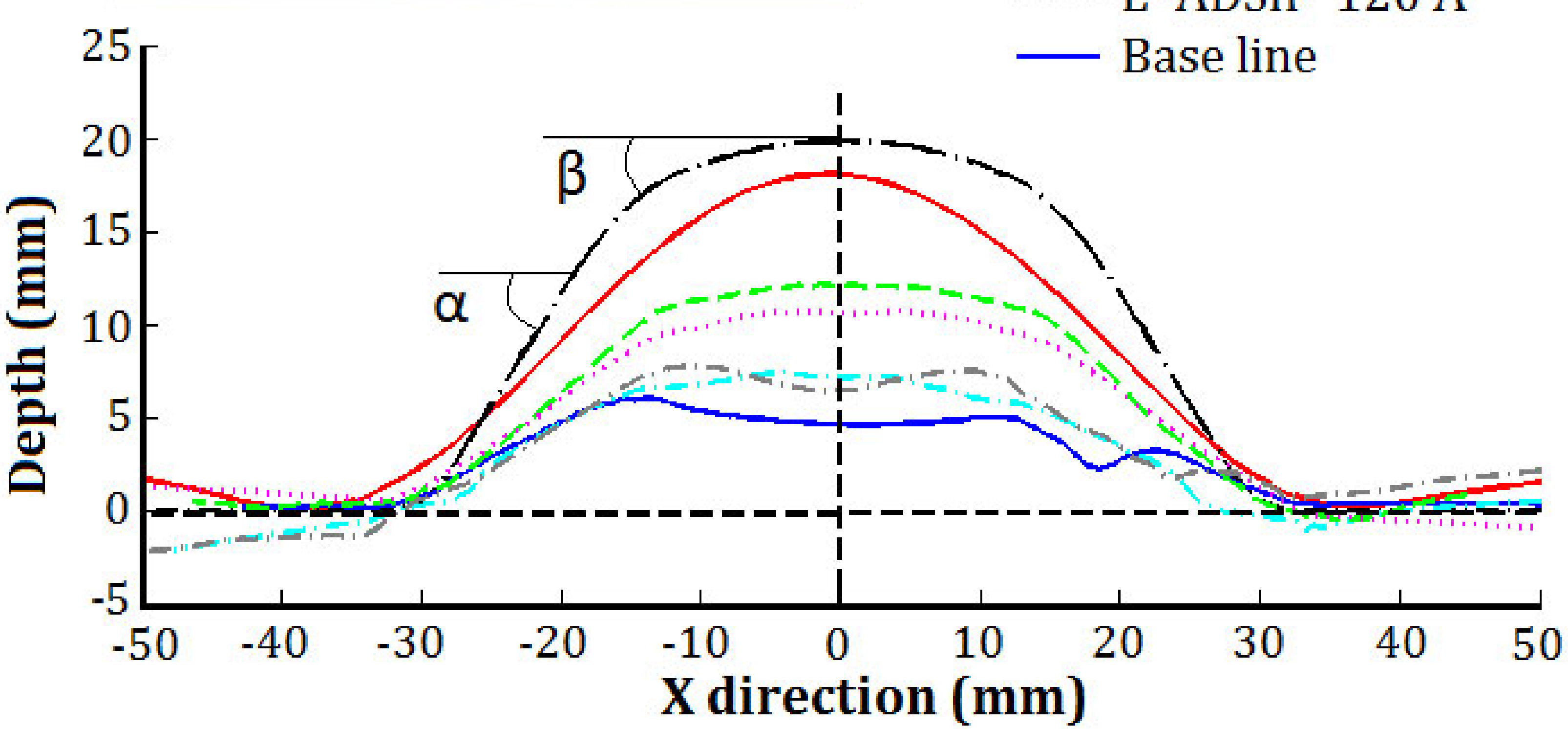
Electrically-Assisted ADSIF (E-ADSIF)



Z. Zhang, A. Gonza, B. Valoppi, A. J. Sa, A. Ghiotti, S. Bruschi, and J. Cao (2016) "A hybrid mixed double-sided incremental forming method for forming Ti6Al4V alloy," CIRP Annals, vol. 65, pp. 4–7, 2016.

Varying the Amperage and Resultant Formability





Forming **Ti6Al4V** in room temperature fractured at the depth of <u>4.58 *mm*</u>

Need to maintain tool contact or else risk sparking/welding, so ADSIF is used.

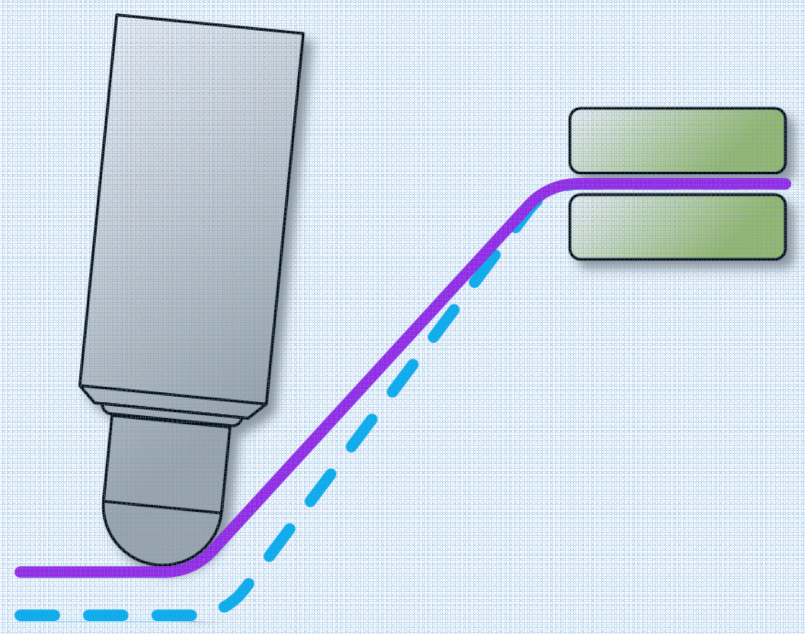
Z. Zhang, A. Gonza, B. Valoppi, A. J. Sa, A. Ghiotti, S. Bruschi, and J. Cao (2016) "A hybrid mixed double-sided incremental forming method for forming Ti6Al4V alloy," CIRP Annals, vol. 65, pp. 4–7, 2016.

Opportunities and Challenges in Incremental Forming

- Higher formability
- Geometric accuracy –
  - System compliance
  - Springback in forming
  - Springback after unclamping
- Forming sequence and forming time

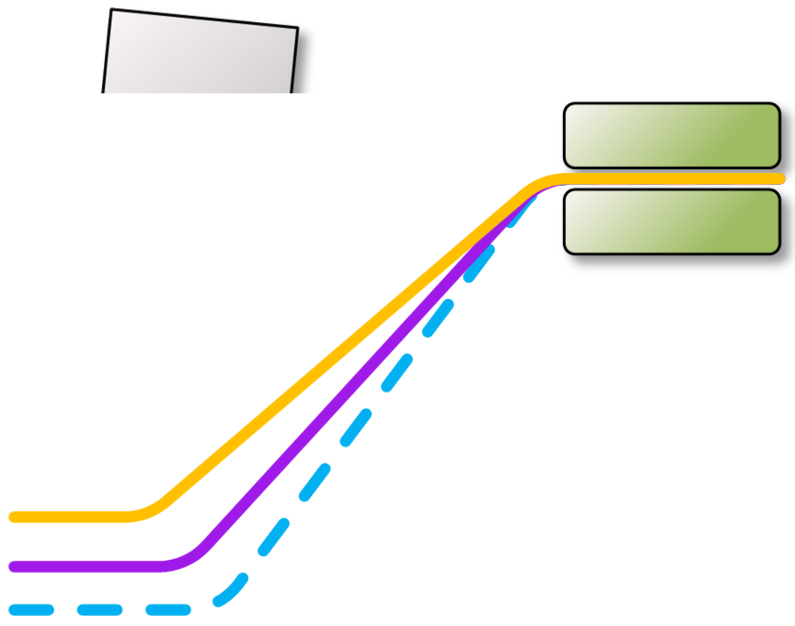
Challenge - Geometric Accuracy

Tool/Machine Deflection

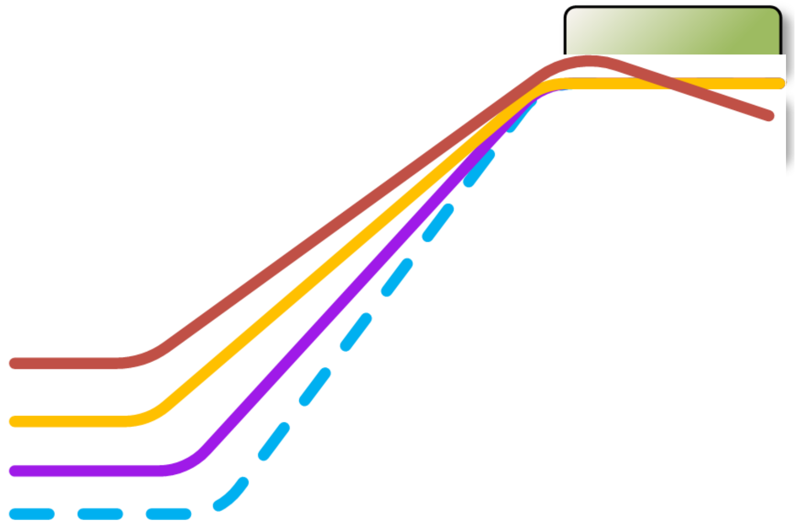


- *requires* ***Compliance Compensation*** *for forming tool*

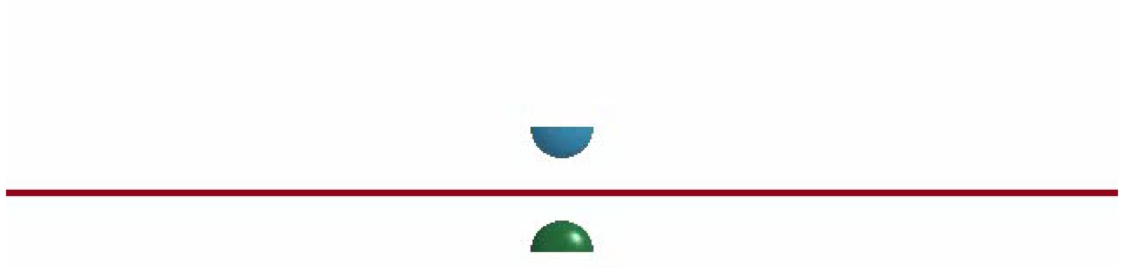
In-process Springback



Post-process Springback

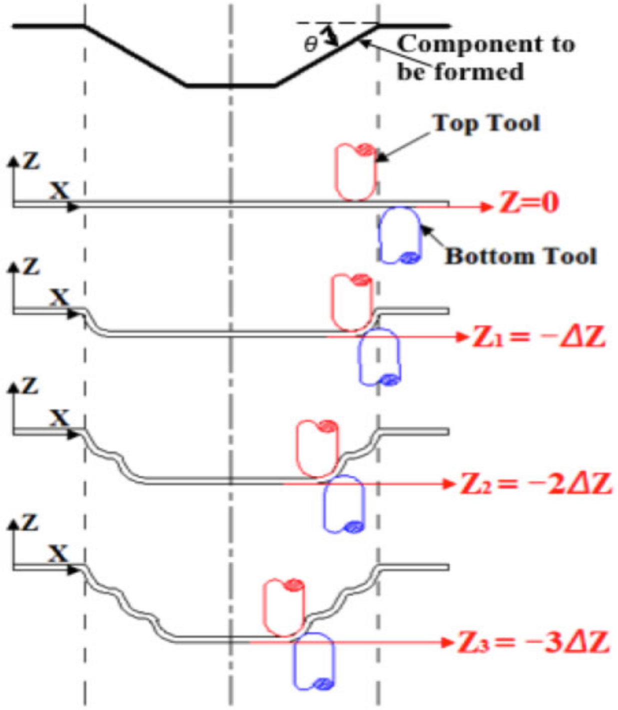


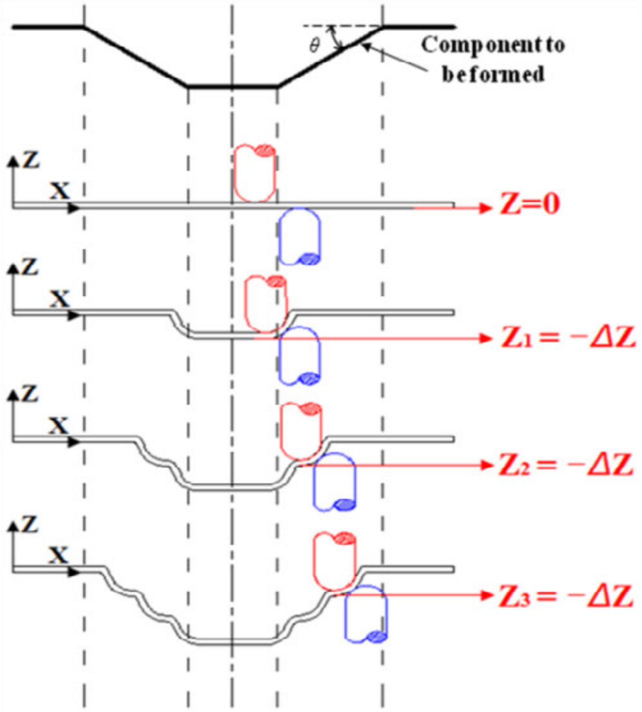
Two Forming Strategies – DSIF and ADSIF



Double-Sided Incremental Forming (DSIF)

Accumulative Double-Sided Incremental Forming (ADSIF)

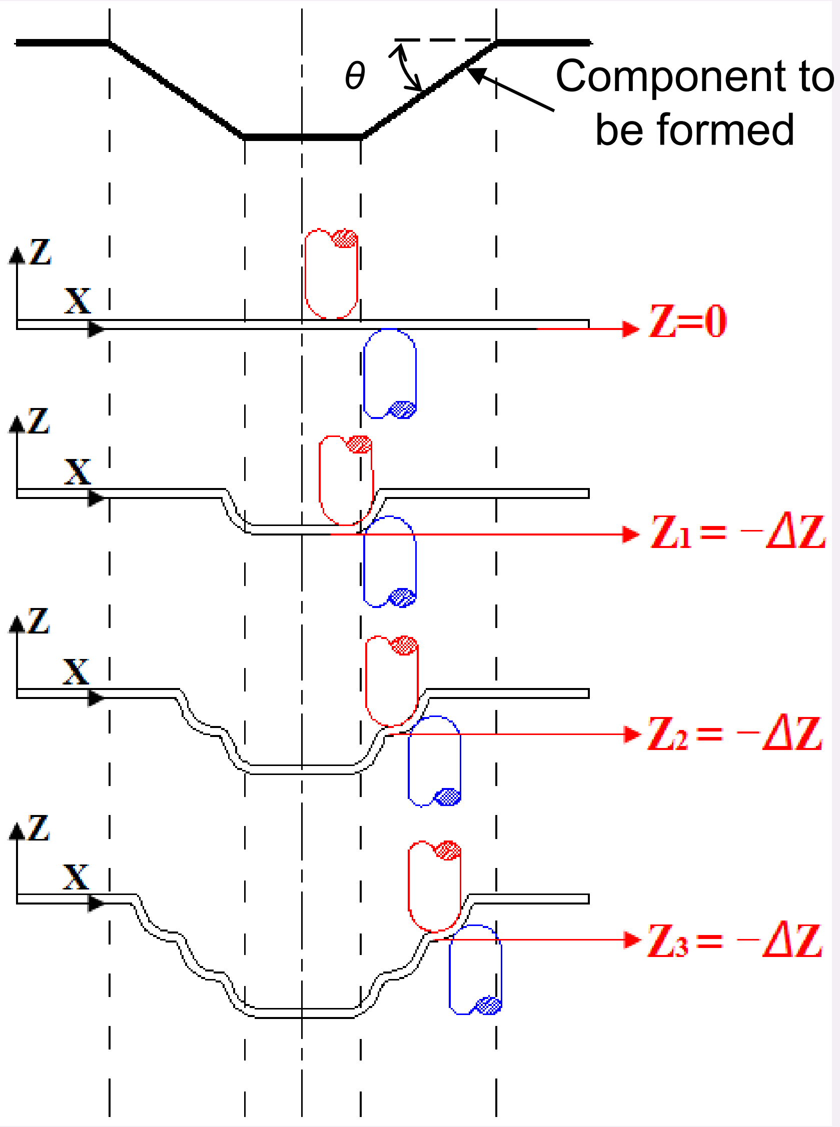




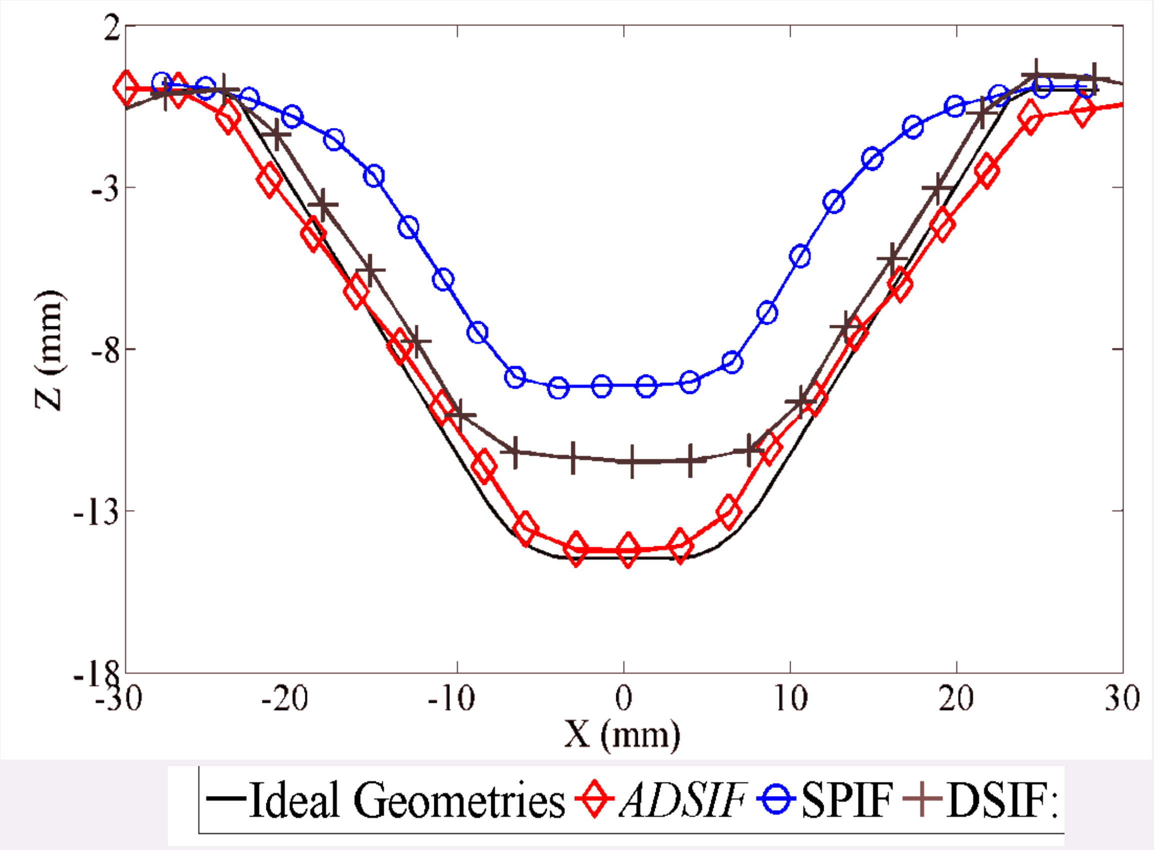
Malhotra, R., Cao, J., Beltran, M., Xu, D., Magargee, J., Kiridena, V., Xia, Z.C. (2012) "Accumulative-DSIF Strategy for Enhancing Process Capabilities in Incremental Forming", CIRP *Annals*

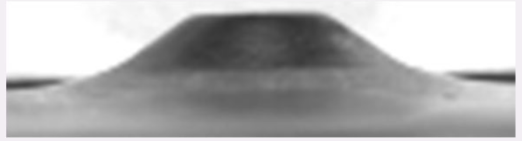
Advantages of ADSIF

Accumulative DSIF (ADSIF)

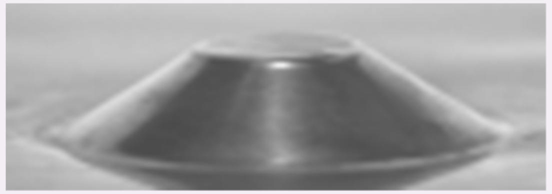


40° cone formed on 0.5 *mm* thick AA2024 sheet

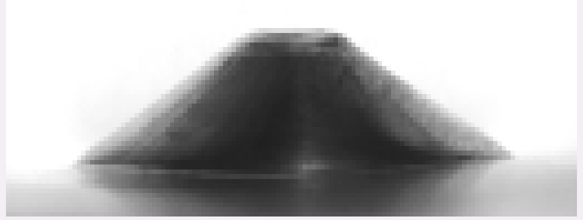




SPIF

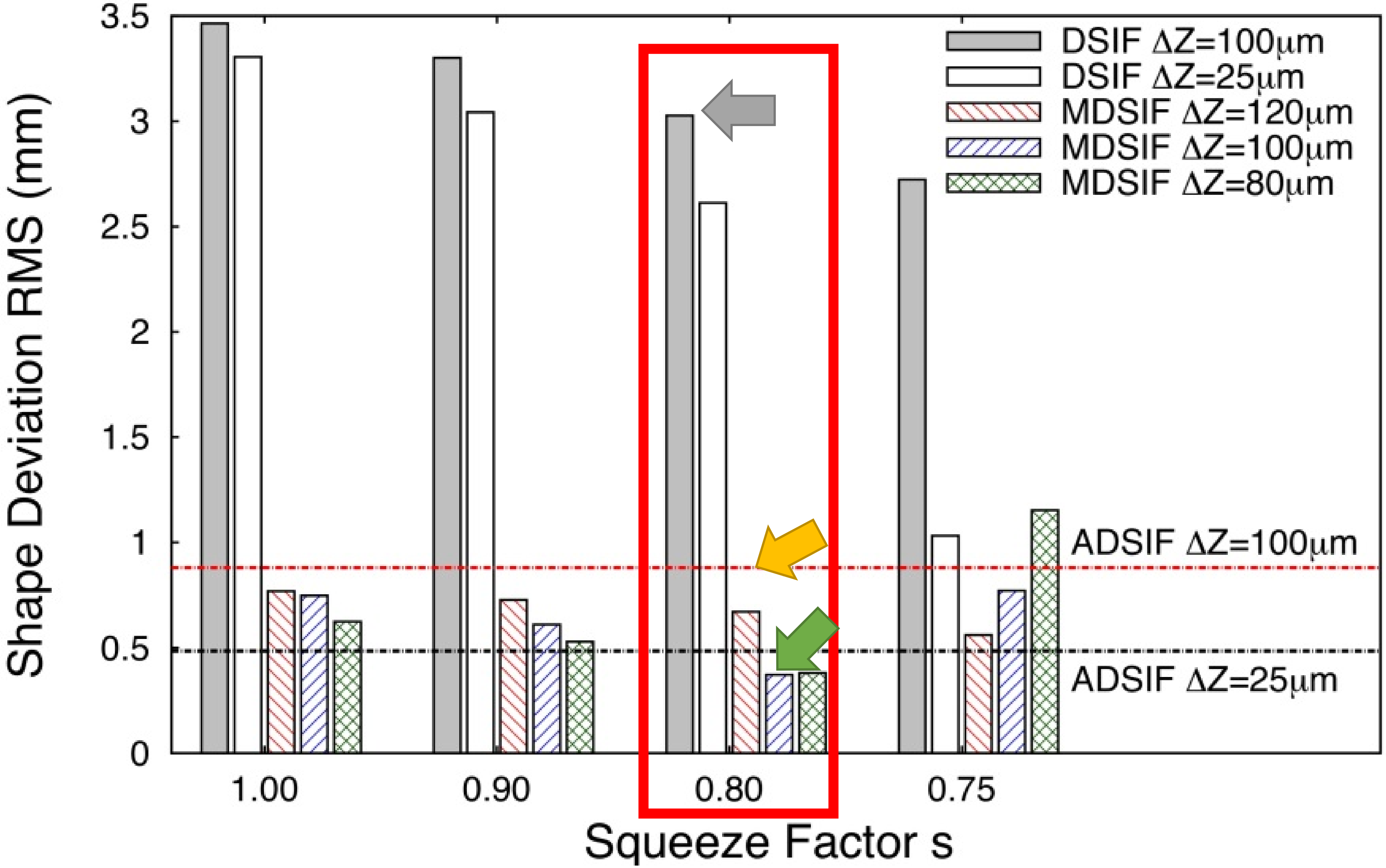


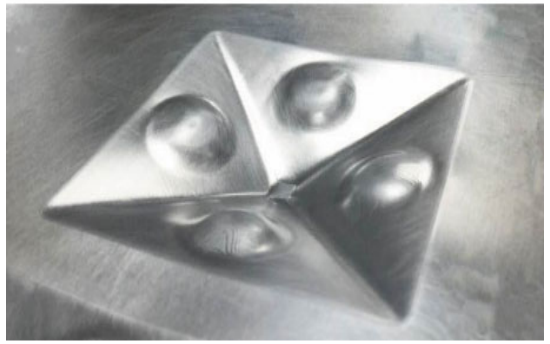
DSIF



ADSIF

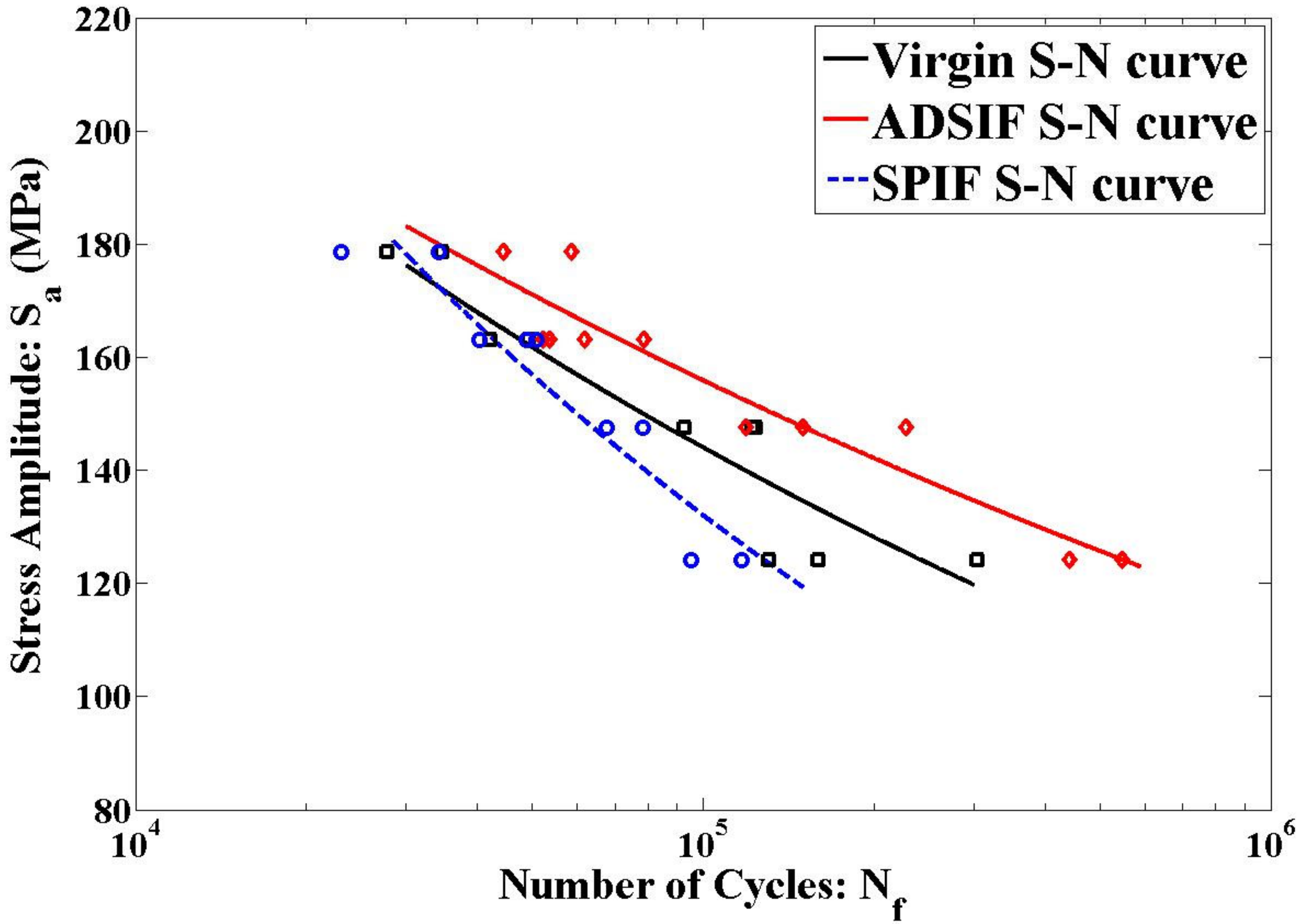
Geometry Comparisons – DSIF, ADSIF, MDSIF (ADSIF+DSIF)

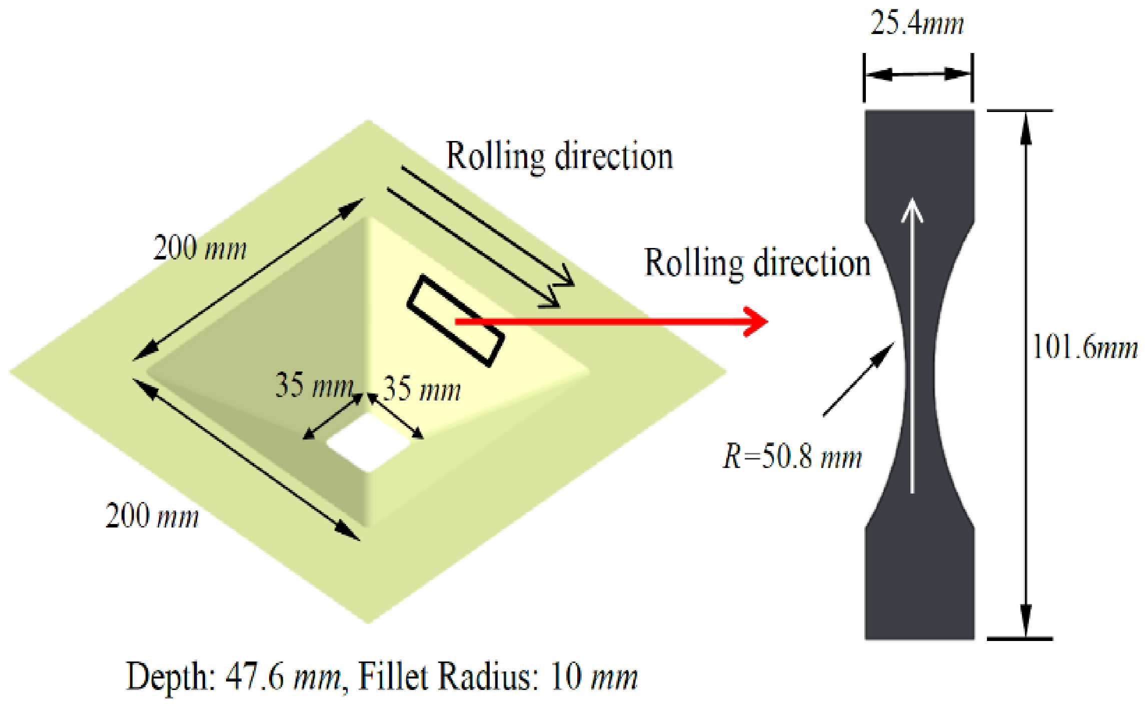




Zhang, Z., Ren, H., Xu, R., Moser, N., Smith, J., Ndip-Agbor, E., Malhotra, R., Xia, Z.C., Ehmann, K.F. and Cao, J. (2015) "A Mixed Double-Sided Incremental Forming Toolpath Strategy for Improved Geometric Accuracy", ASME Journal of Manufacturing Science and Engineering, Vol.137(5), 051007

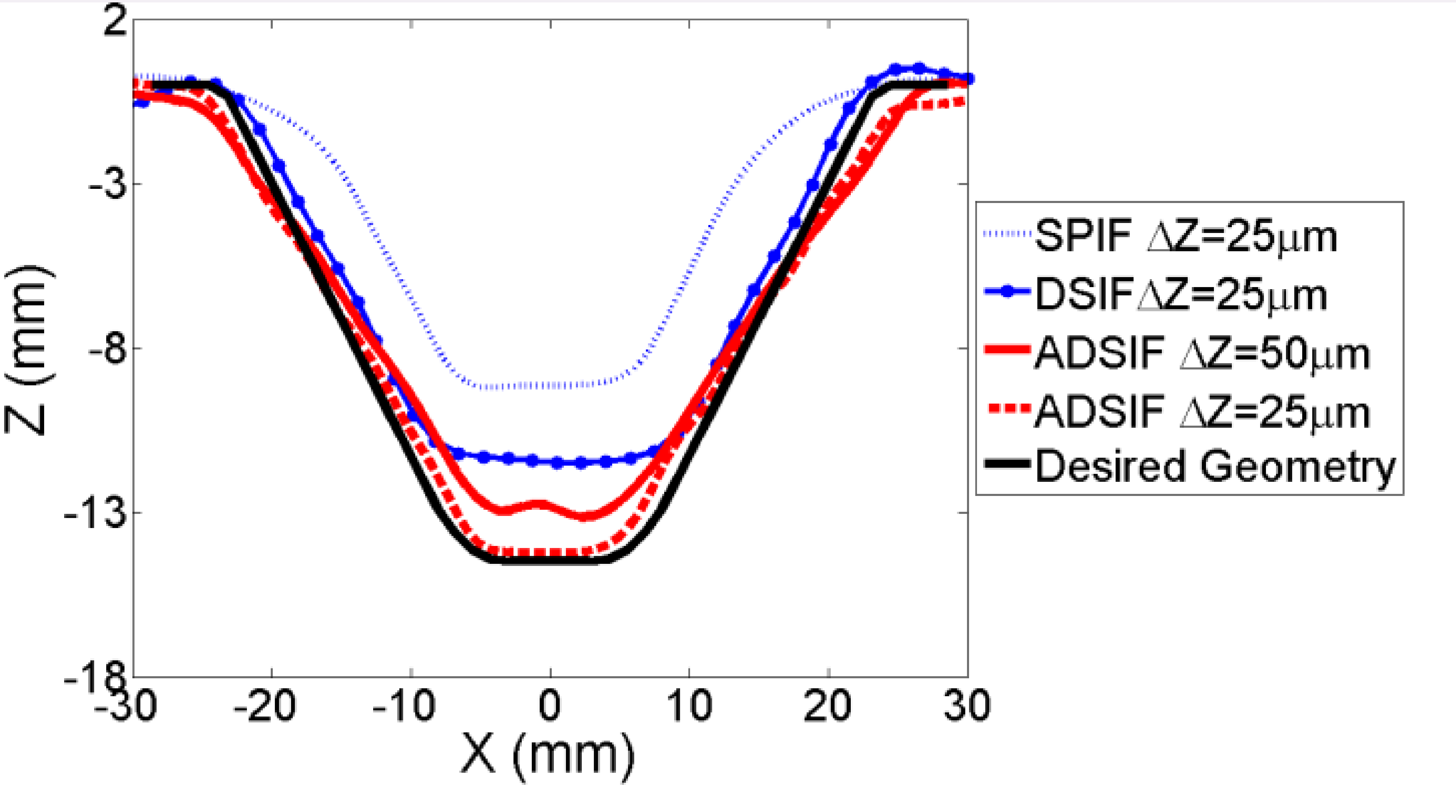
Fatigue Life Comparison





Xu, R., Shi, X.T., Xu, D.K, Malhotra, R. and Cao, J. (2014) “A preliminary study on the fatigue behavior of sheet metal parts formed with accumulative-double-sided incremental forming”, *Manufacturing Letters*, Vol. 2(1), pp. 8-11 + unpublished results

Challenge in ADSIF



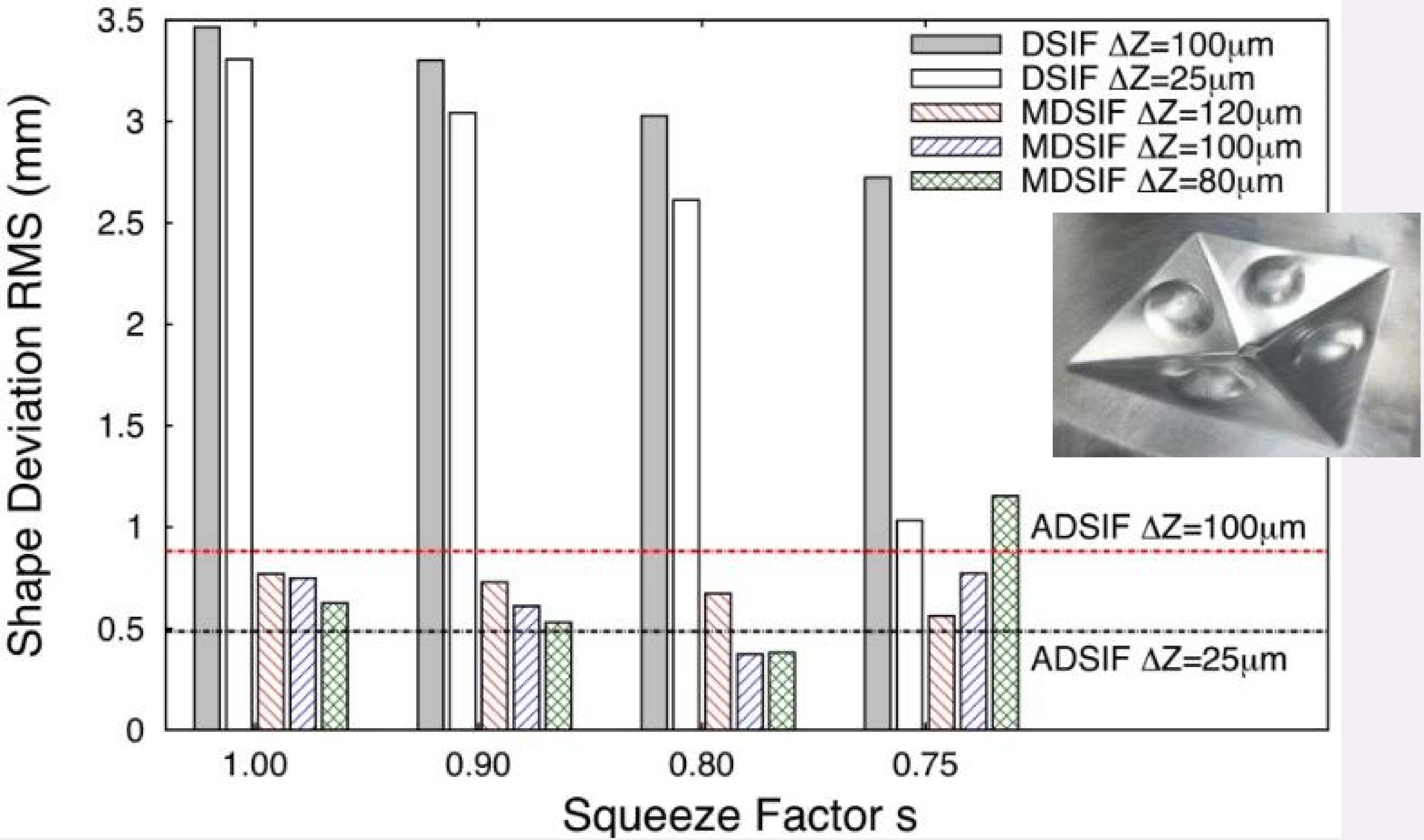
Challenge:

Extremely small incremental depth is needed: 25μm

Forming Strategy: MxDSIF

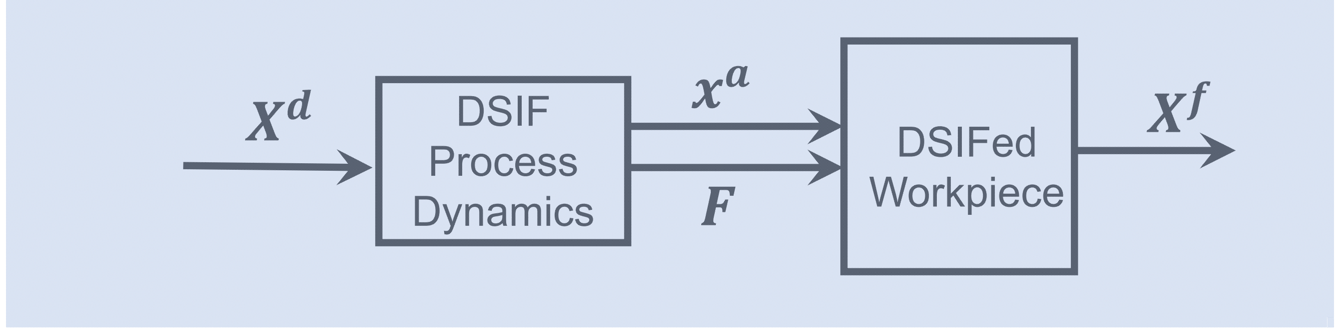
Mixed Toolpath (MxDSIF) = ADSIF + DSIF

TOOLPATH EFFECT

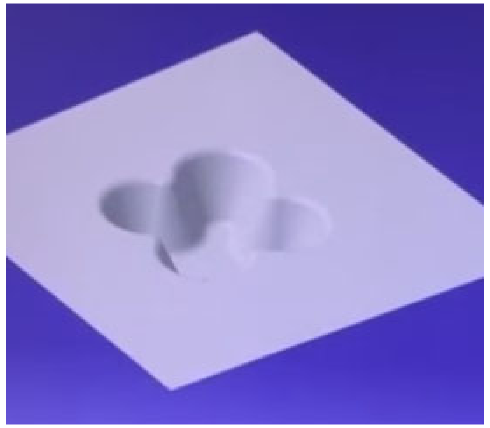


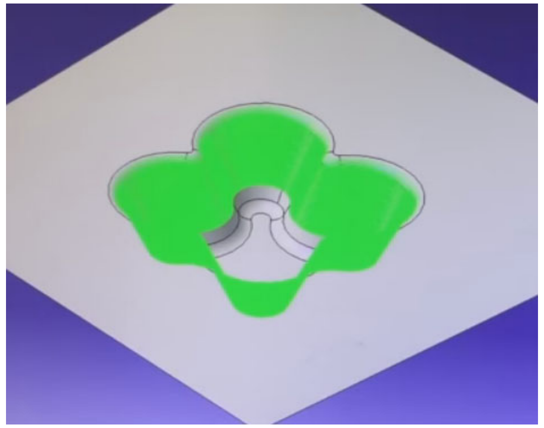
Zhang, Z. … Cao, J., JMSE 2015

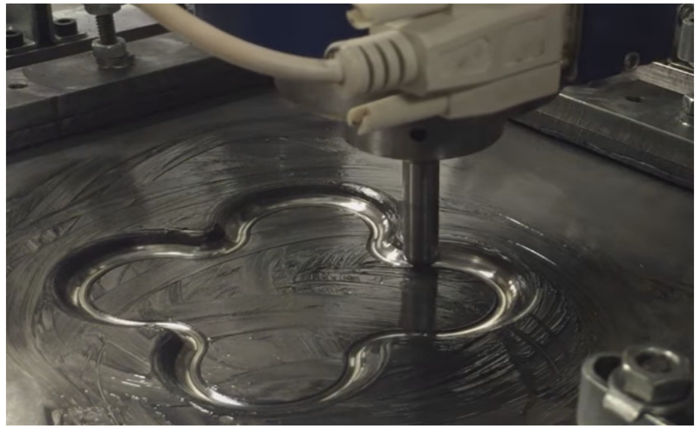
Conventional DSIF Process



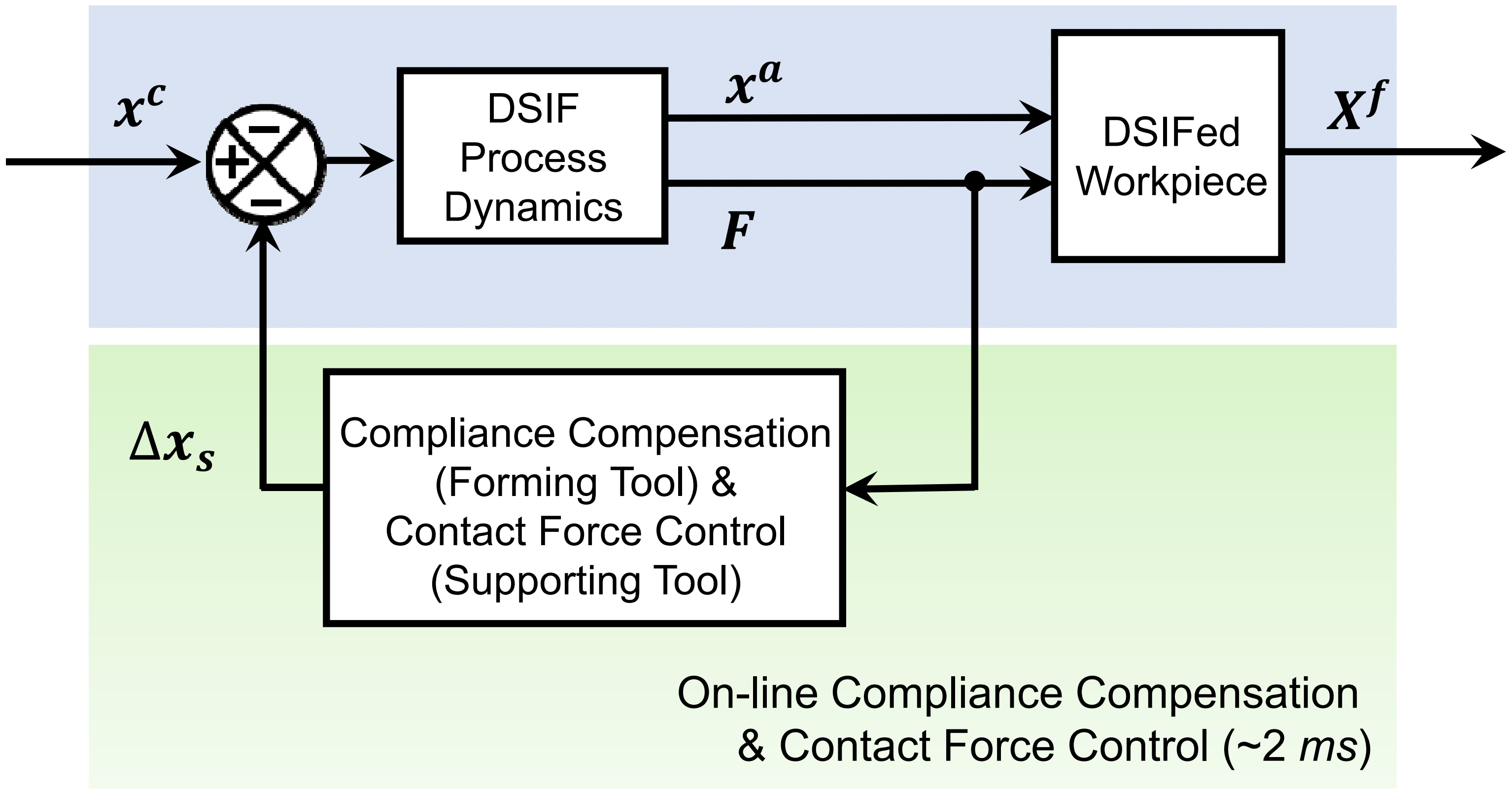
X^d *Desired Part Geometry* → x^a *Actual Tooltip Position*, F *Forming Force* → X^f *Final Part Geometry*



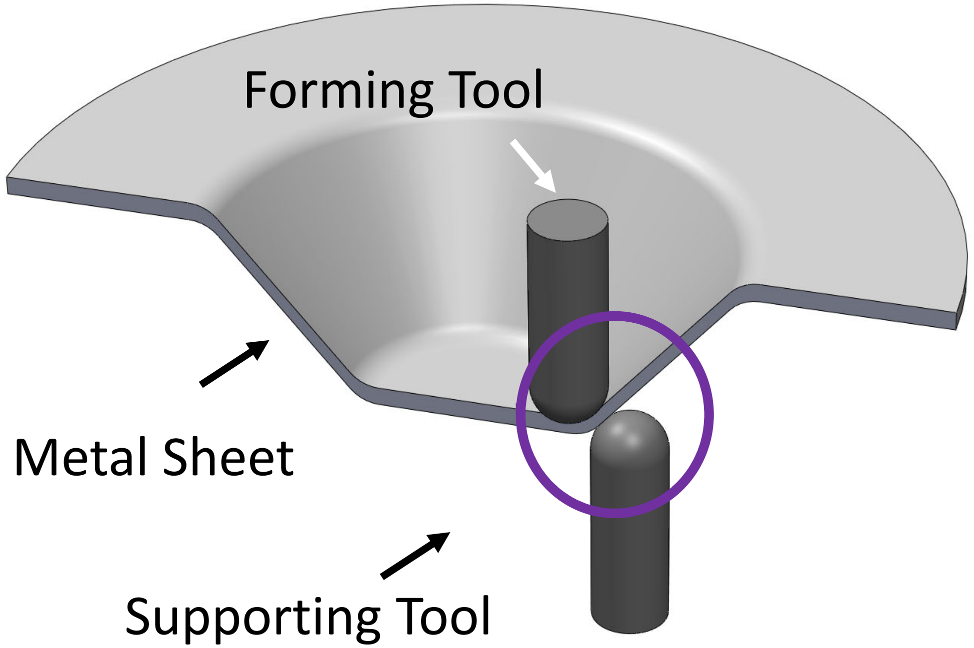


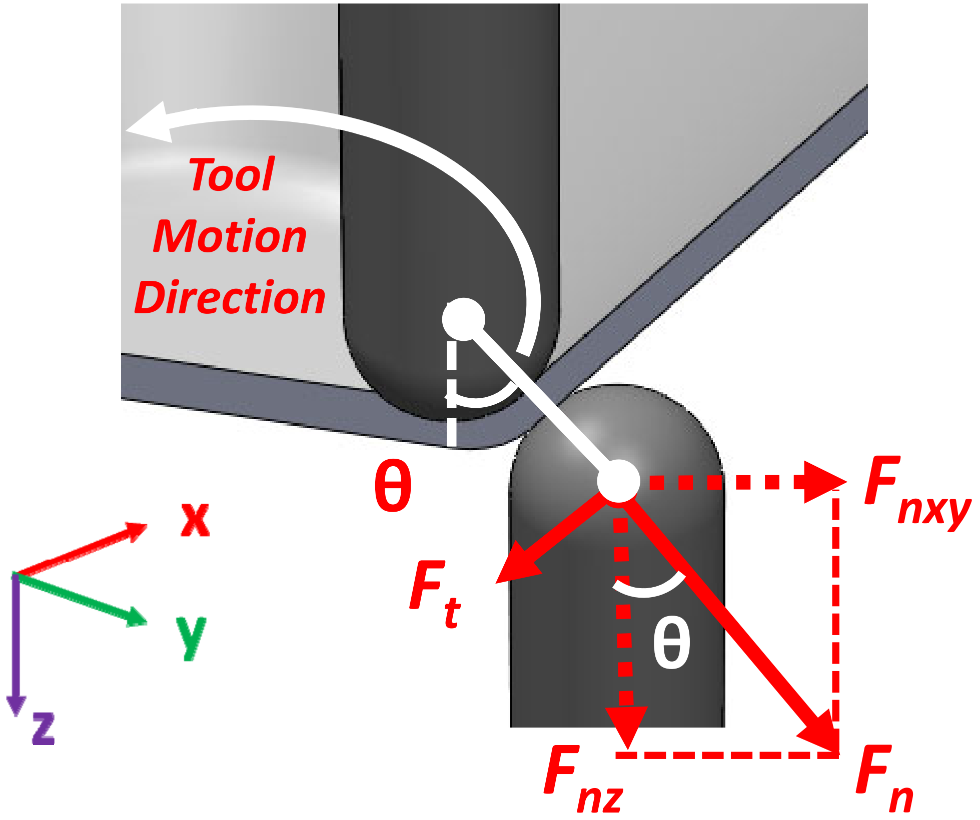


Proposed Control System for DSIF



Force Control Algorithm



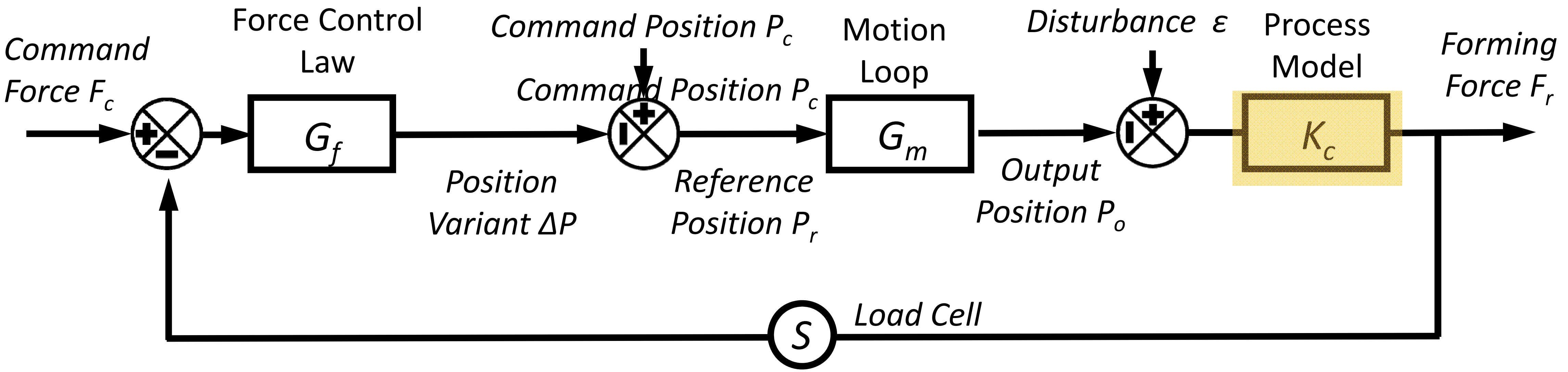


Particularly, we directly control F_{nxy} assuming:

$$F_{nz} = F_{nxy} \cot\theta$$
or
$$F_n = F_{nxy} / \sin\theta$$

Ren, H., Li, F., Moser, N., Leem, D., Li, T., Ehmann, K., & Cao, J. (2018). General contact force control algorithm in double-sided incremental forming. CIRP Annals.

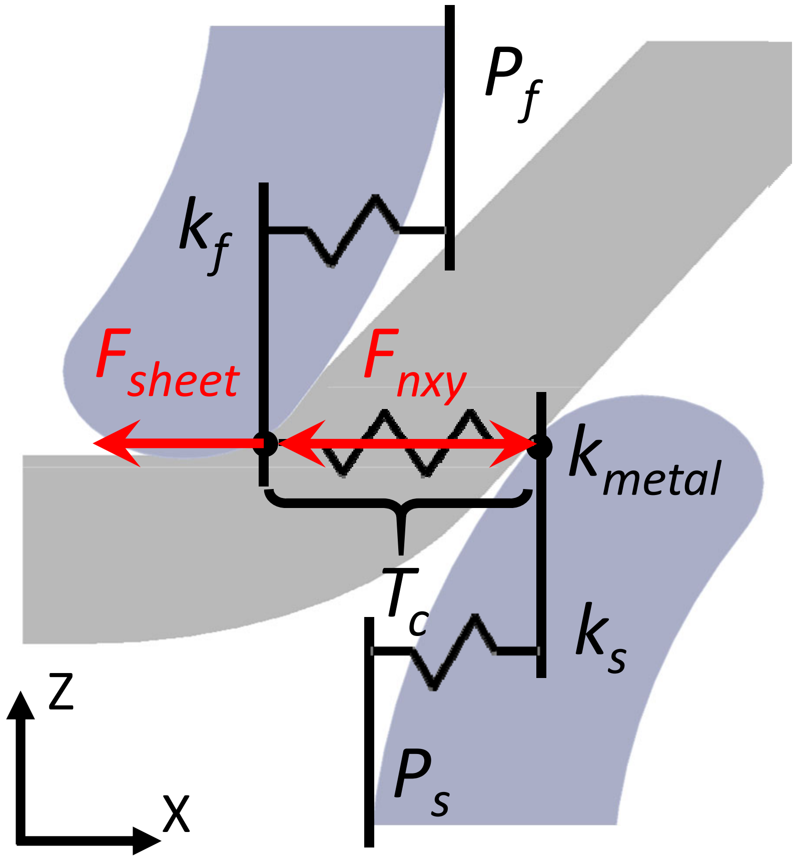
Control Scheme – Explicit Force Control



A principal characteristic of this explicit force control scheme is that the force control signal only acts as a modifier to the commanded position signal and, consequently, does not require direct interference with the inner position control loop, G_m.

[1] Volpe, R., & Khosla, P. (1993). IEEE Transactions on Automatic Control

Determination of the Process Model



P_f, P_s : controller output tool position

F_{nxy} : normal contact force in x-y plane

F_{sheet} : sheet force on forming tool

k_f, k_s : tool and machine stiffness

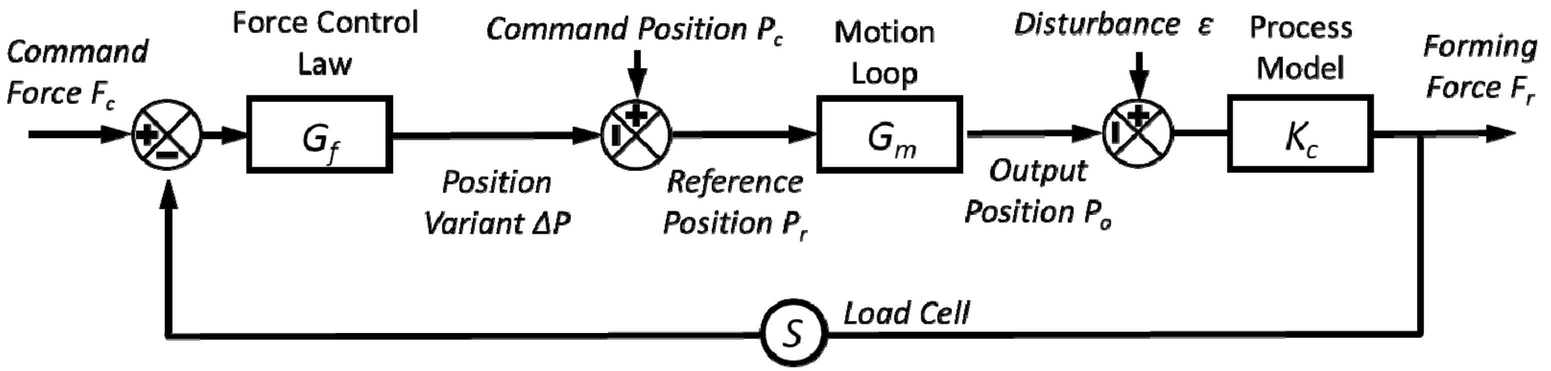
k_{metal} : squeezing stiffness for sheet metal

T_c : horizontal sheet thickness

$$F_r = K_c(\varepsilon - P_s),$$

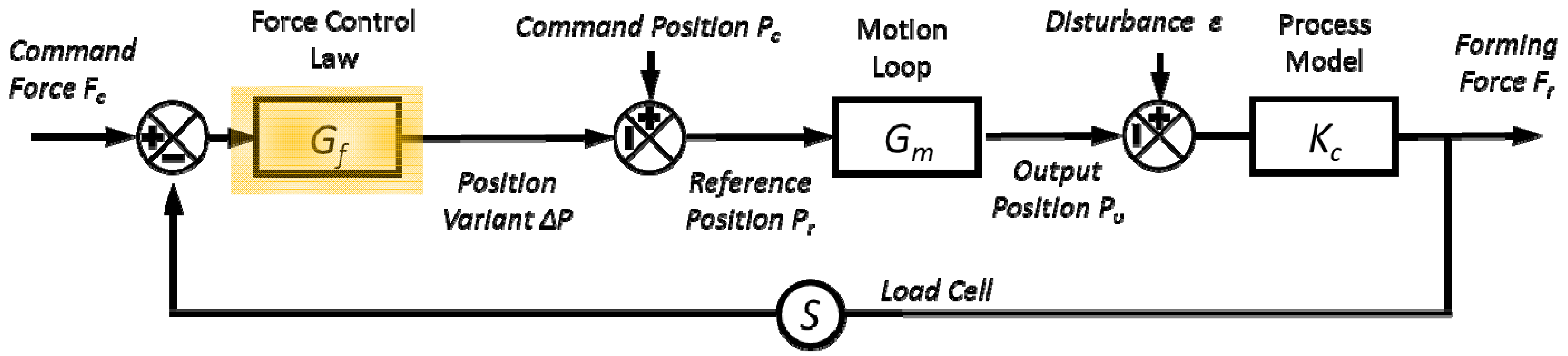
$$K_c = 1/\left(\frac{1}{k_f} + \frac{1}{k_{metal}} + \frac{1}{k_s}\right)$$

$$\varepsilon = -F_{sheet}/k_f + P_f + T_c$$



Ren, H., Li, F., Moser, N., Leem, D., Li, T., Ehmann, K., & Cao, J. (2018). General contact force control algorithm in double-sided incremental forming. CIRP Annals.

Control Scheme – Explicit Force Control



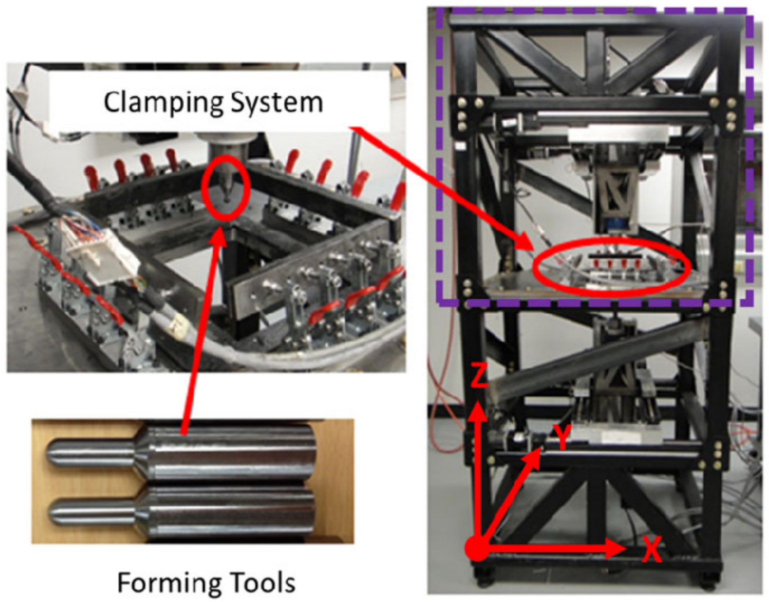
$$F_r = \frac{G_f G_m K_c}{1+G_f G_m K_c} F_c + \frac{G_m K_c}{1+G_f G_m K_c} P_c + \frac{K_c}{1+G_f G_m K_c} \varepsilon$$

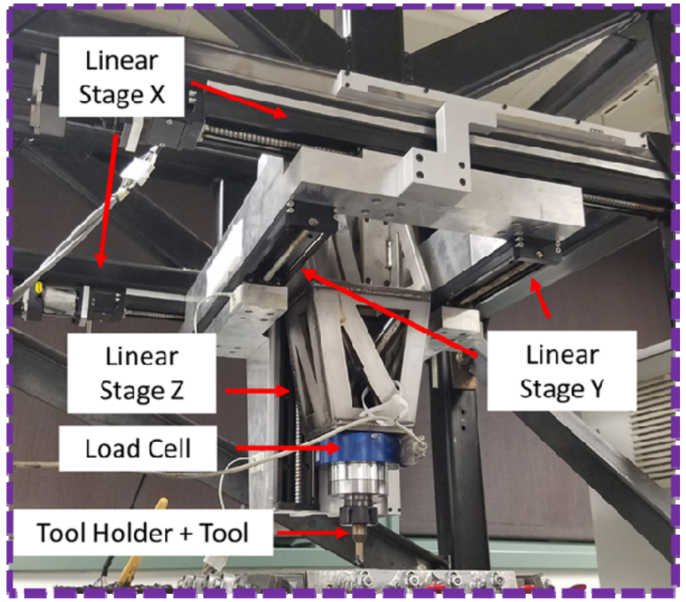
- To guarantee the possibility of implementing the control algorithm in most standard controllers, a simple integral controller (K_i/s) is proposed for G_f.
- The advantages of integral control are its low pass nature and zero steady state error for a constant desired force and a disturbance, ε, for a given *Kc*.

$$\lim_{s\to 0}\left(\frac{G_f G_m K_c}{1+G_f G_m K_c}\right) = 1, \lim_{s\to 0}\left(\frac{G_m K_c}{1+G_f G_m K_c}\right) = 0, \lim_{s\to 0}\left(\frac{K_c}{1+G_f G_m K_c}\right) = 0$$

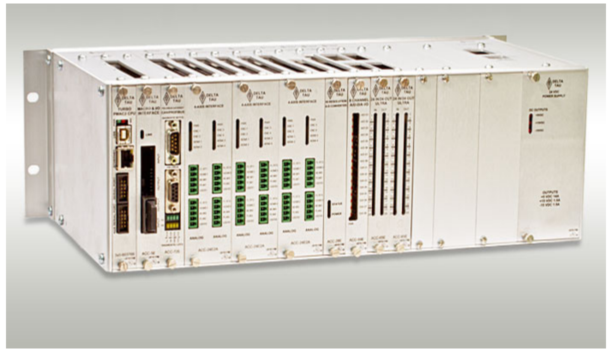
Ren, H., Li, F., Moser, N., Leem, D., Li, T., Ehmann, K., & Cao, J. (2018). General contact force control algorithm in double-sided incremental forming. CIRP Annals.

DSIF Machine System at Northwestern University





Turbo PMAC Controller
80 MHz DSP56303 CPU
~ 10 Mb Memory

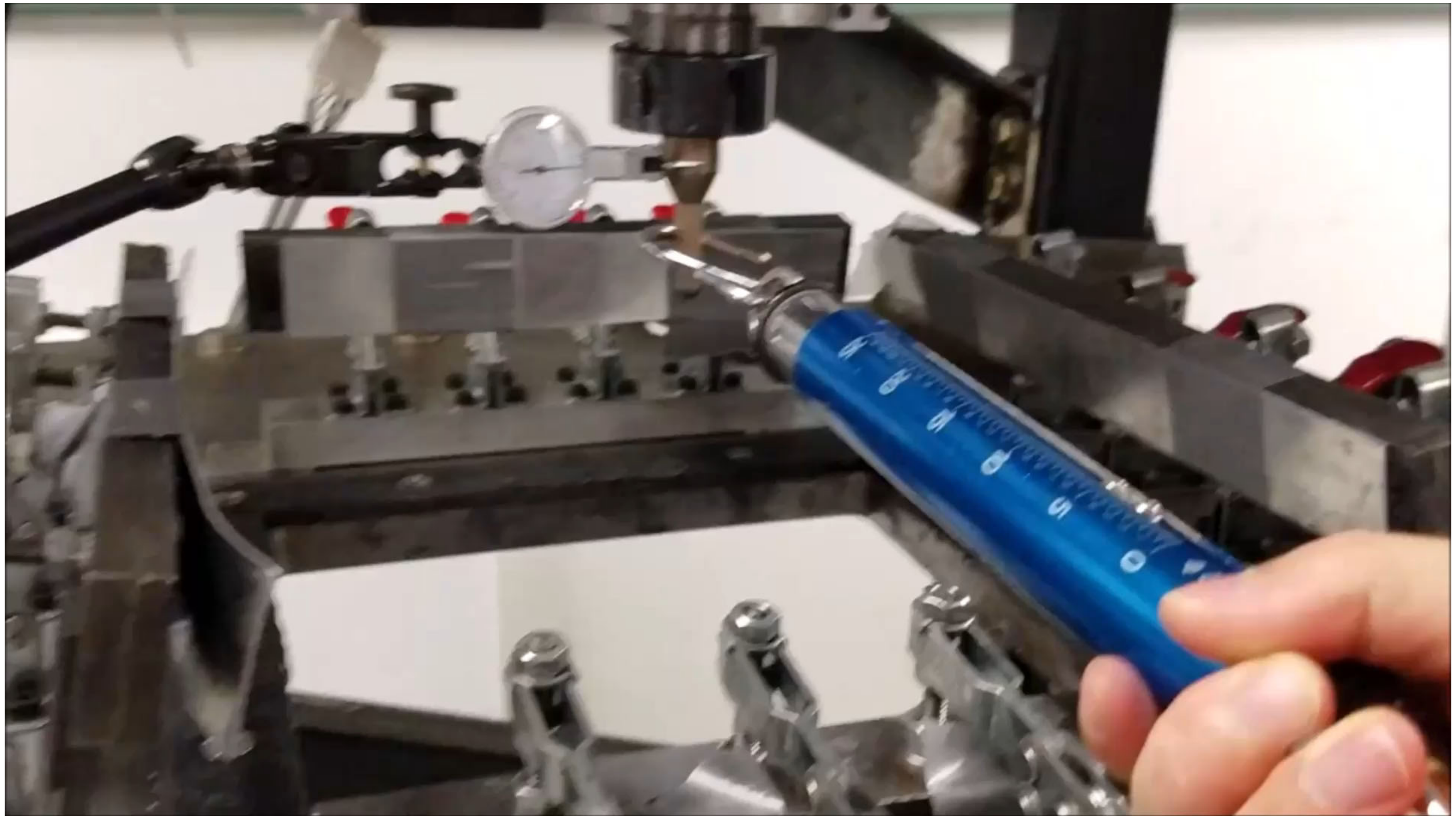


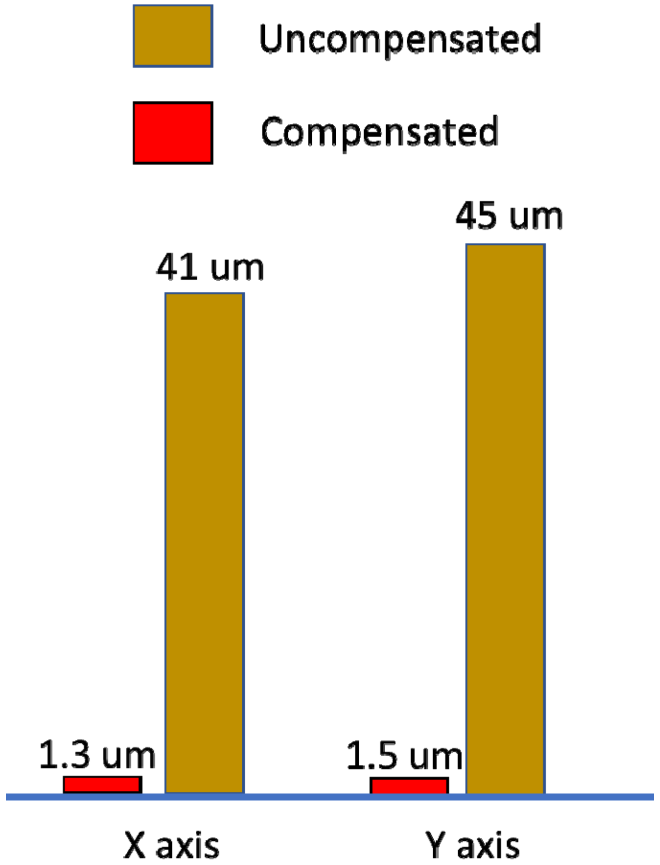
Parameters	Value
Total Motor	10
Maximum Tool Speed	9.6 *mm/s*
Load Cell Resolution	1 *N*
Servo Frequency	2.2 *kHz*
Linear Position Error	< 12 μm / $\pm$100 *mm*
Circular Position Error	< 15 μm *for R = 50 mm*

Stiffness	Value (N/um)
X - forming	0.98
Y - forming	1.11
Z- forming	6.67
X- Supporting	0.91
Y - Supporting	0.76
Z- Supporting	6.67
Metal (AA5754-O)	~20.0
K_c (X)	0.46
K_c (Y)	0.44
K_c (Z)	2.86

Ren, H., Li, F., Moser, N., Leem, D., Li, T., Ehmann, K., & Cao, J. (2018). General contact force control algorithm in double-sided incremental forming. CIRP Annals.

Experimental Verification – Compliance Compensation

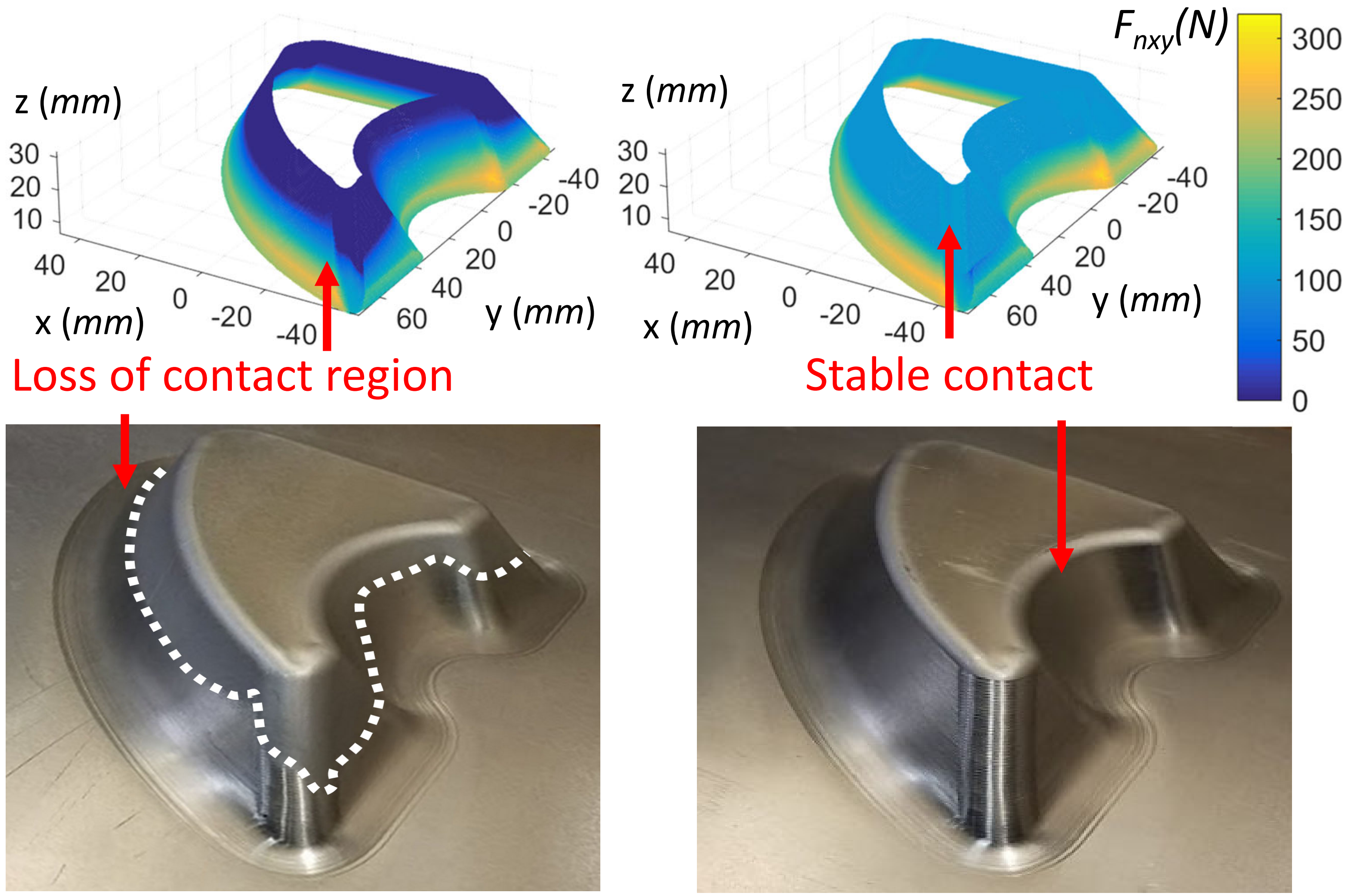


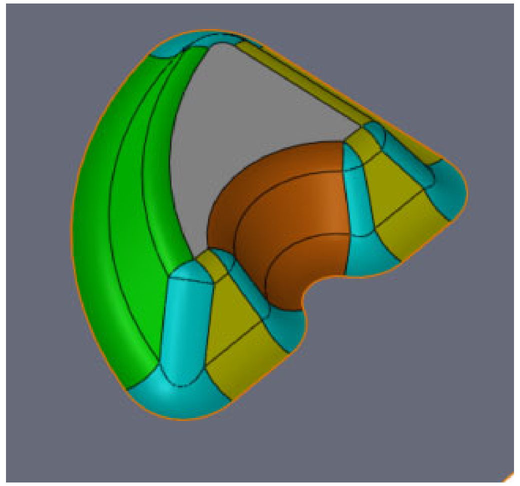


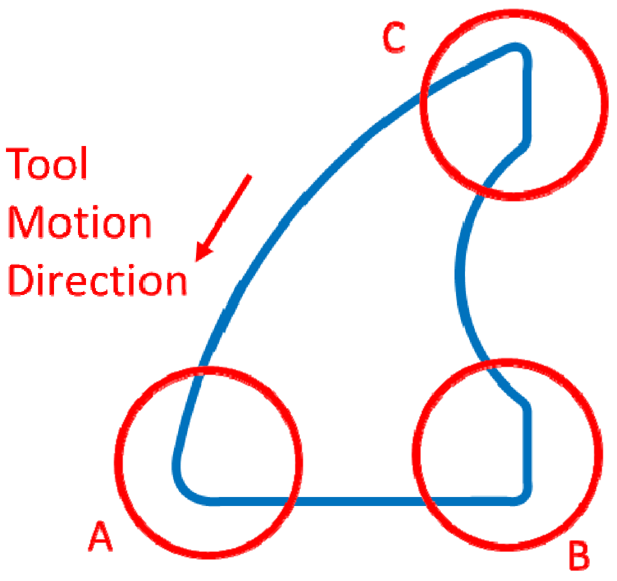
Dial indicator reading under a 100 N pulling force (for X and Y Axes)

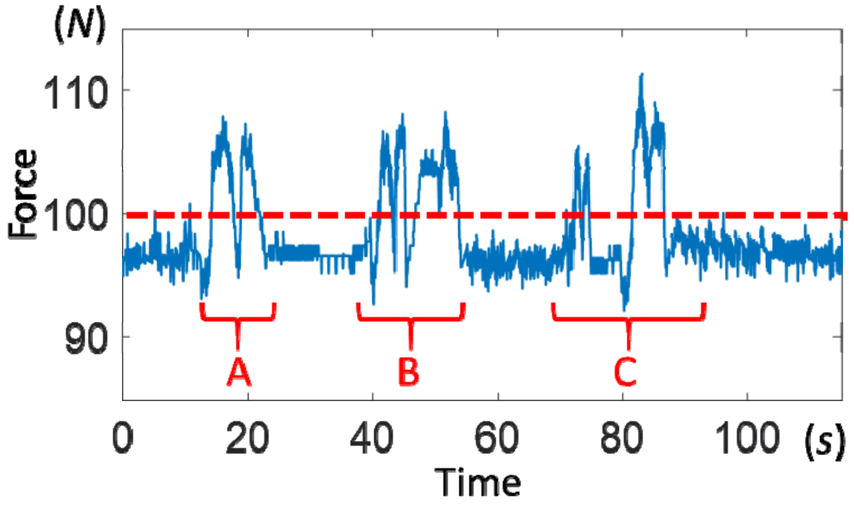
Ren, H., Li, F., Moser, N., Leem, D., Li, T., Ehmann, K., & Cao, J. (2018). General contact force control algorithm in double-sided incremental forming. CIRP Annals.

Force Control for the Complex Geometry





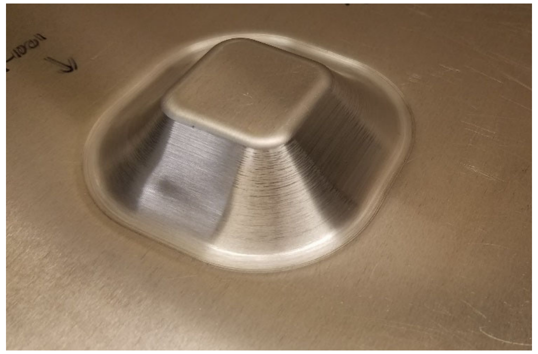


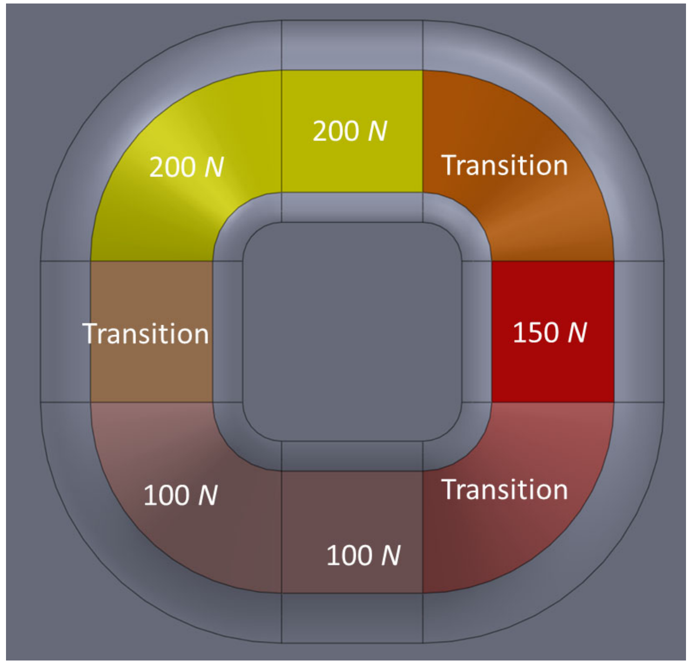


* AA1100-O, 1 mm thick, 5 mm radius tool

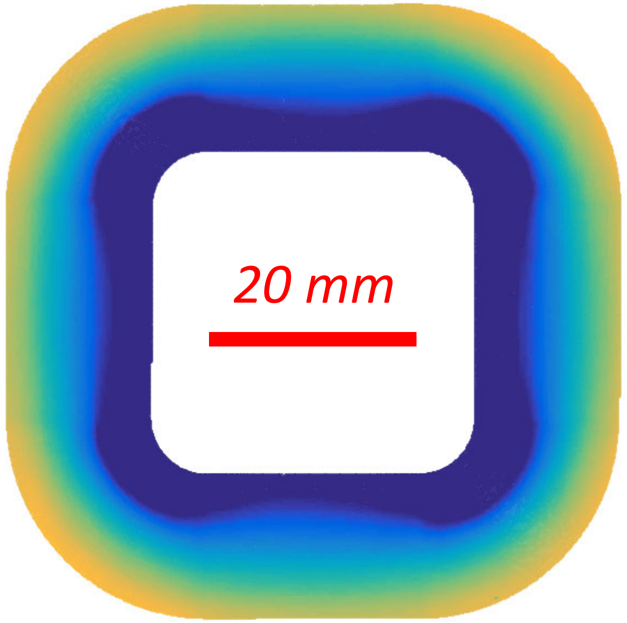
Ren, H., Li, F., Moser, N., Leem, D., Li, T., Ehmann, K., & Cao, J. (2018). General contact force control algorithm in double-sided incremental forming. CIRP Annals.

Complex Command Contact Force





- AA5754-O, 1 mm thick, 5 mm radius tool



F_{nxy} without Force Control

F_{nxy} with Force Control

Ren, H., Li, F., Moser, N., Leem, D., Li, T., Ehmann, K., & Cao, J. (2018). General contact force control algorithm in double-sided incremental forming. CIRP Annals.

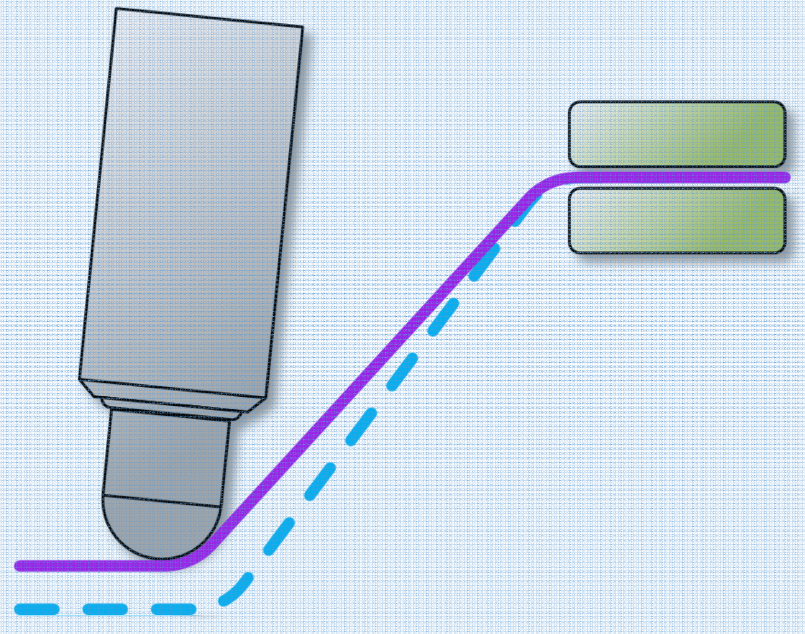
Conducted Experiments to Examine Applicability

Test Case	A	B	C	D	E	F	G
Shape	Funnel	Funnel	Cone	Fin	Pyramid	Funnel	Cone
Aluminum Alloy	1100-O	5754-O	2024-T3	1100-O	5754-O	1100-O	5754-O
Strategy	DSIF	DSIF	ADSIF	DSIF	DSIF	DSIF	DSIF
Sheet Thickness	1.0 mm	1.0 mm	0.5 mm	1.0 mm	1.0 mm	1.0 mm	1.0 mm
Tool Radius	4.5 mm	5.0 mm	2.5 mm	5.0 mm	5.0 mm	4.5 mm	5.0 mm
Inc. Depth	0.5 mm	0.5 mm	0.1 mm	0.5 mm	0.2 mm	0.5 mm	0.2 mm
Command F_{nxy}	120 N	200 N	180 N	100 N	100-200 N	120 N	350 N
Wall Angle ϕ	≥50°	≥65°	40°	60°	45°	≥60°	55°
Tool Speed	5 mm/s	5 mm/s	5 mm/s	5 mm/s	5 mm/s	8 mm/s	5 mm/s

* Force control error was kept less than ±10 N for all cases

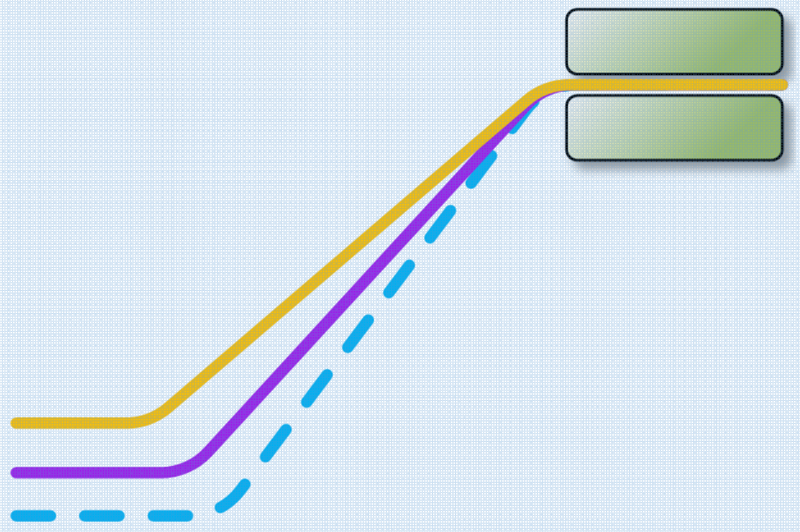
Challenge - Geometric Accuracy

Tool/Machine Deflection



- *requires **Compliance Compensation** for forming tool*

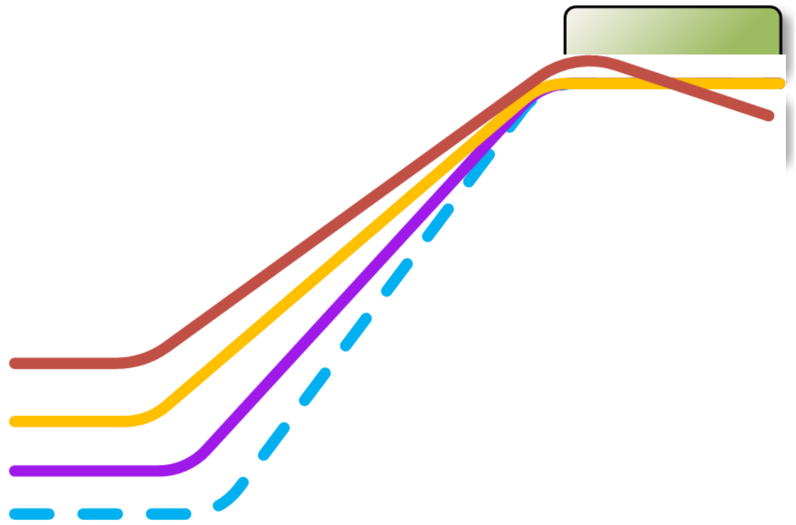
In-process Springback



- *requires **Springback Compensation***

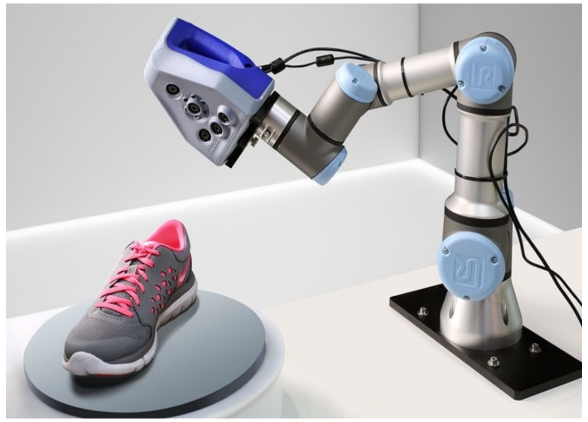
Can we enhance the functions of tooling?

Post-process Springback

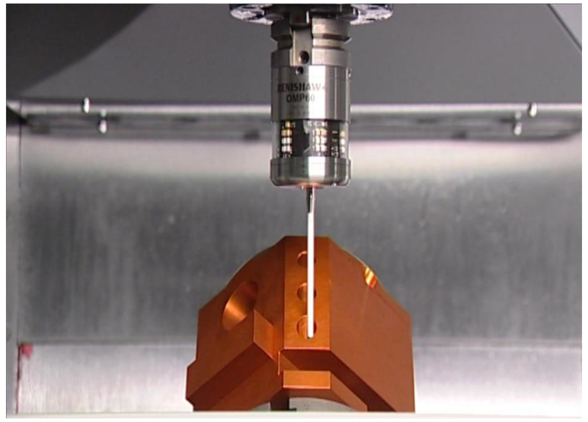


Ren, H., Xie, J., Liao, S., Leem, D., Ehmann, K. and Cao, J. (2019) "In-situ springback compensation in incremental sheet forming", CIRP Annals, Vol. 68(1).

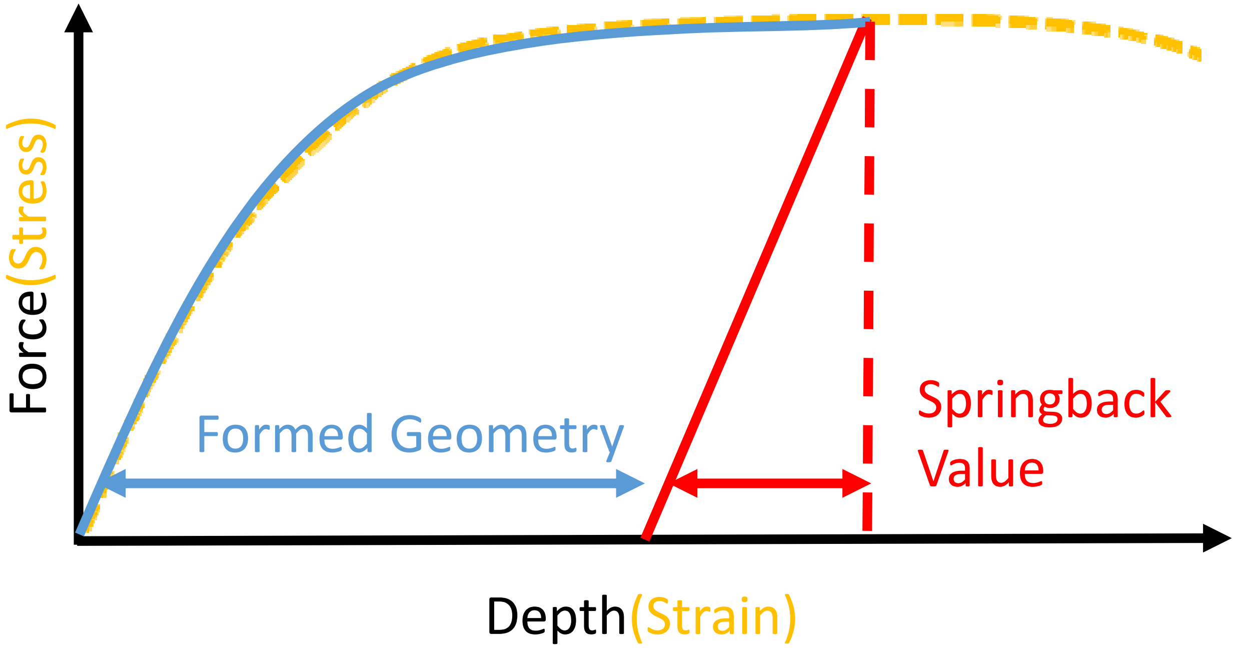
Springback Measurement – Smart Tooling



- Accuracy vs price
- Surface texturing requirement
- Space requirement



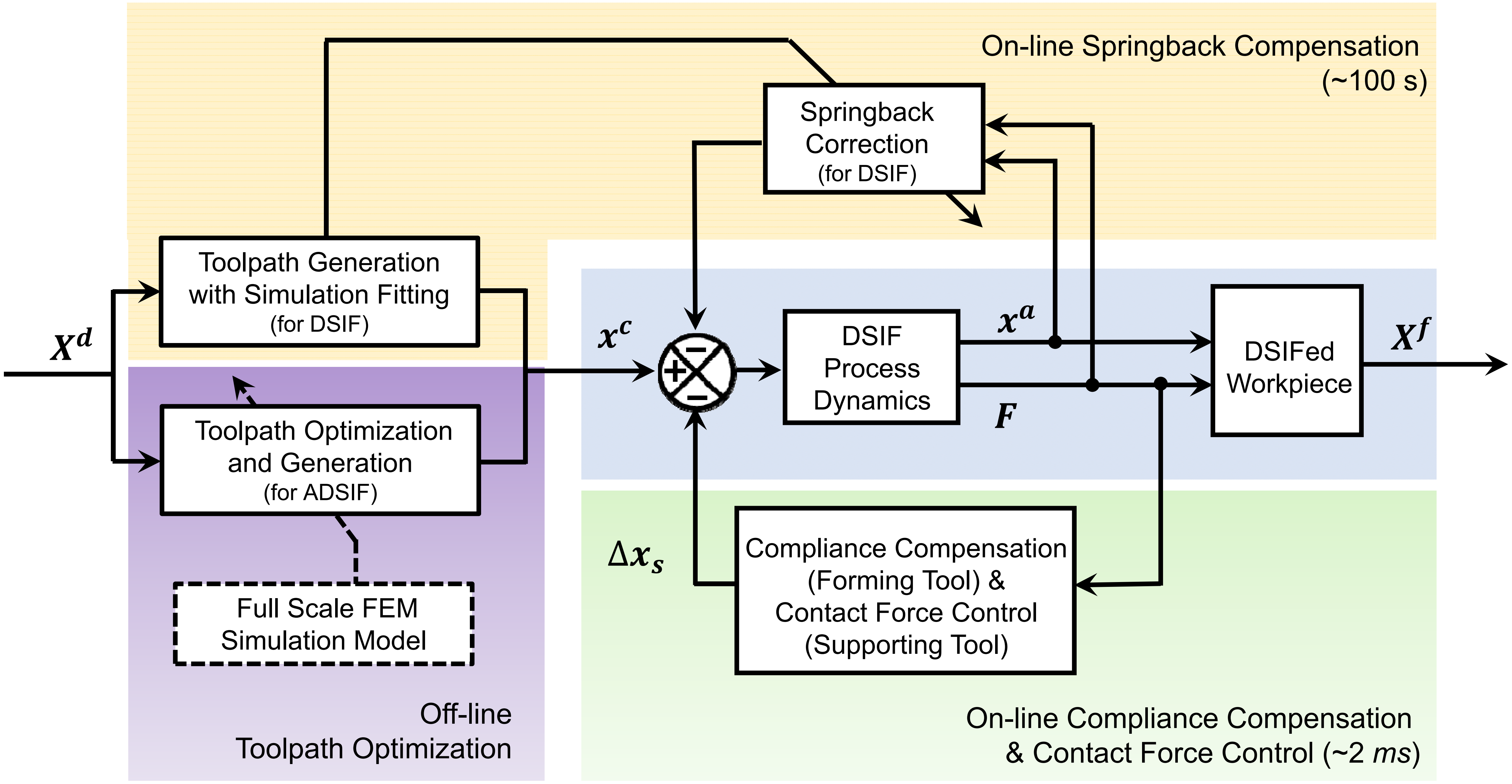
- Speed
- Tool exchangeability
- Space requirement



- Springback is the elastic response of the formed sheet due to the change of the forming force;
- The forming force can be easily measured online;

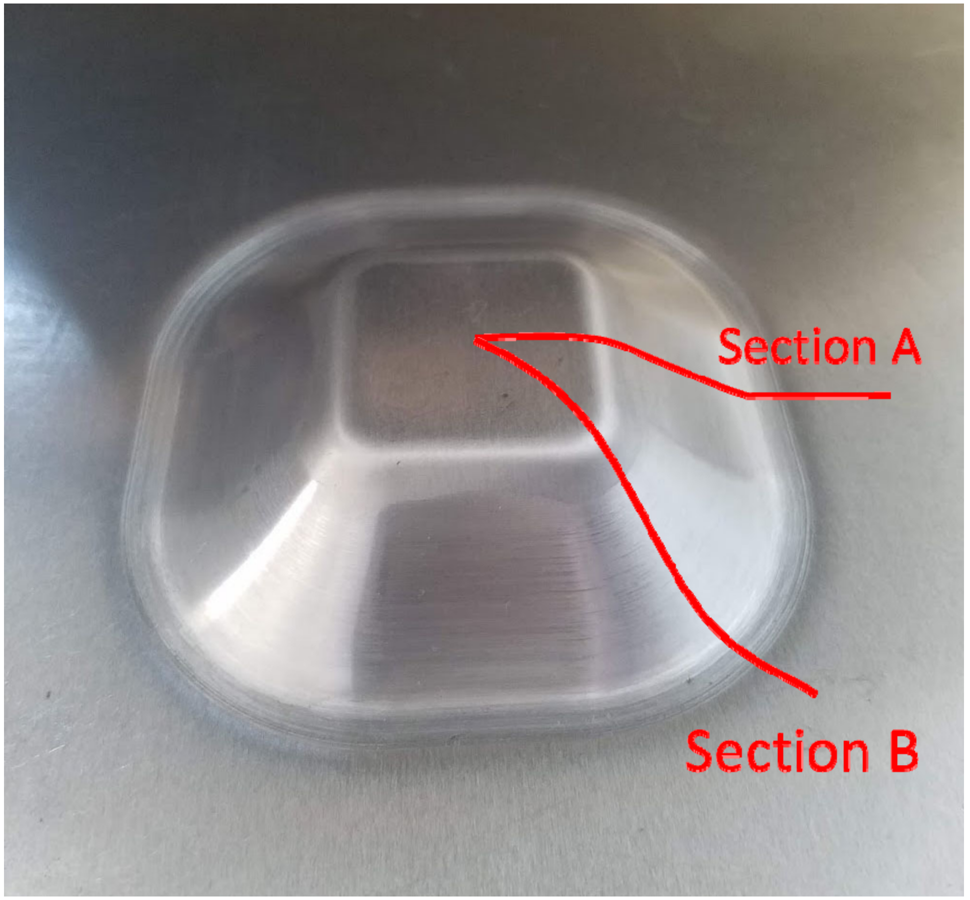
Ren, H., Xie, J., Liao, S., Leem, D., Ehmann, K. and Cao, J. (2019) “In-situ springback compensation in incremental sheet forming”, CIRP Annals, Vol. 68(1).

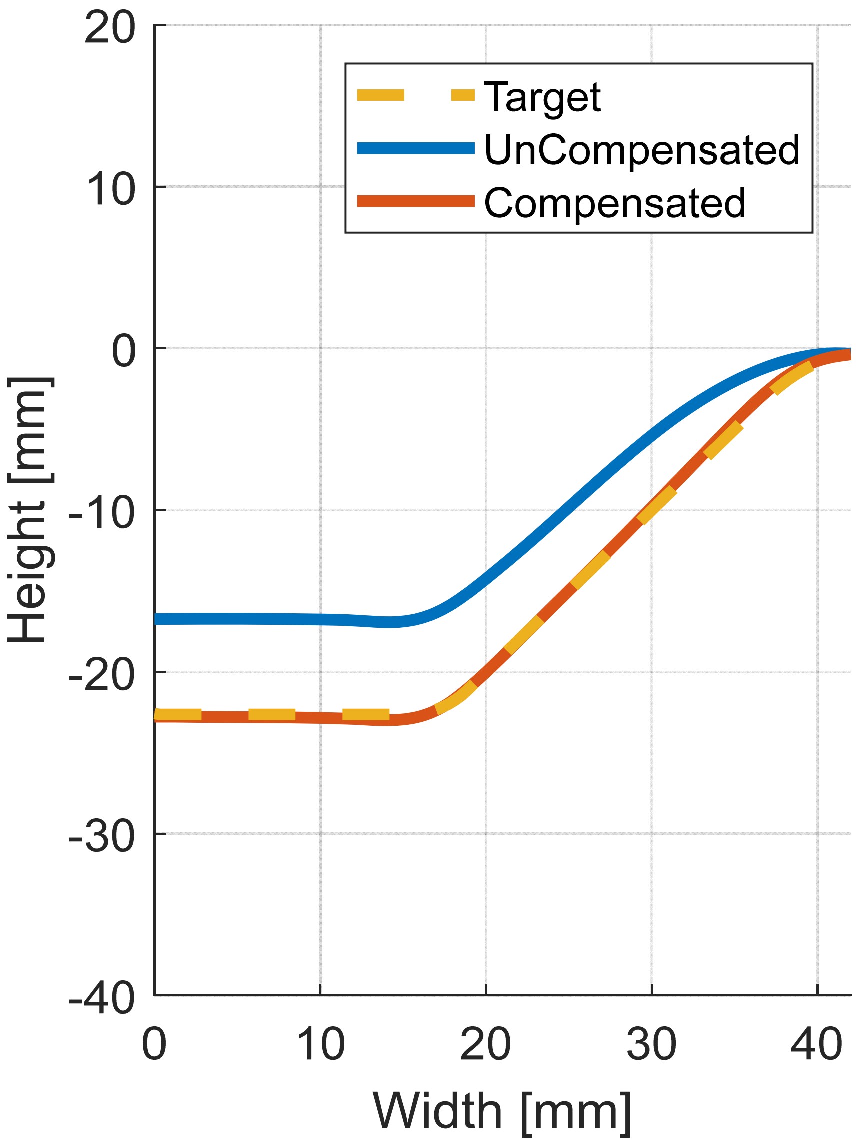
Proposed Control System for DSIF



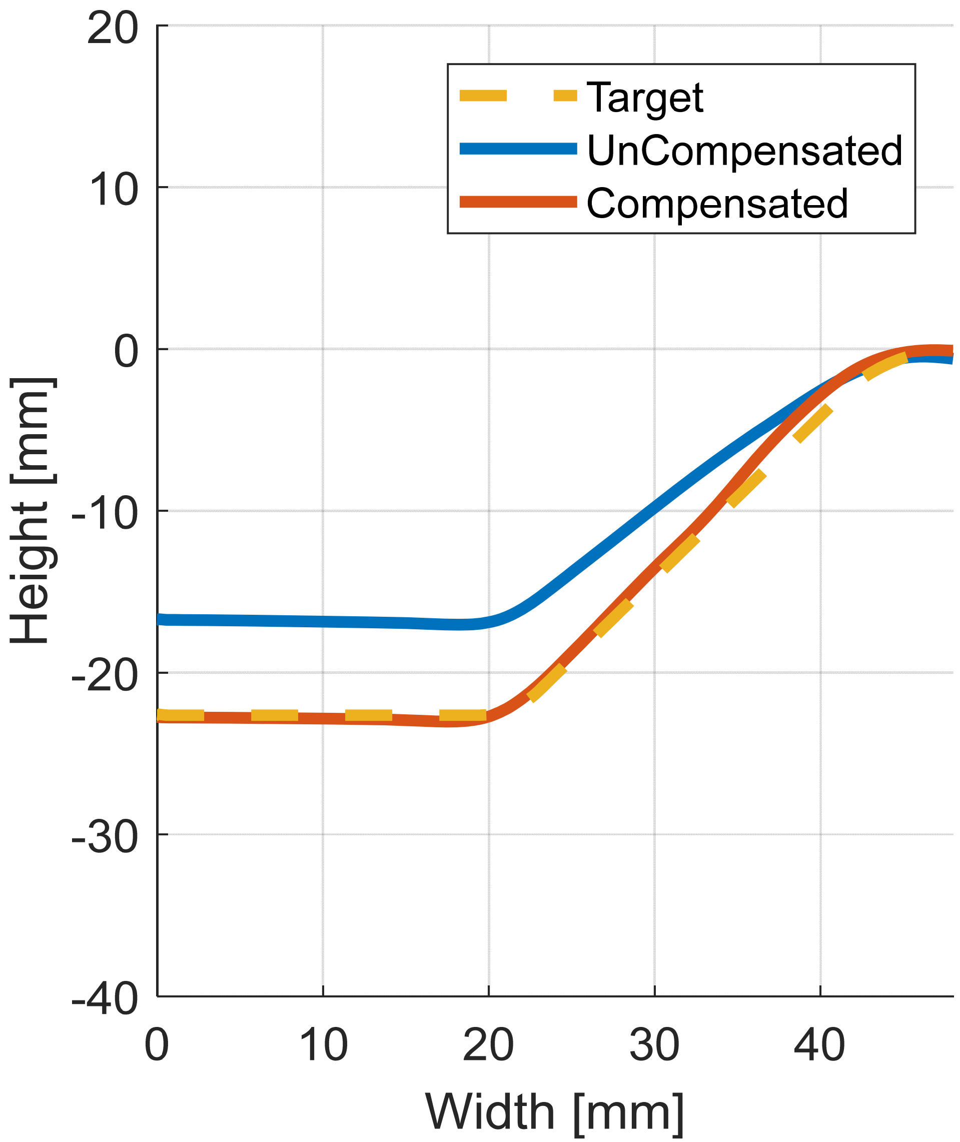
Ren, H., Xie, J., Liao, S., Leem, D., Ehmann, K. and Cao, J. (2019) “In-situ springback compensation in incremental sheet forming”, CIRP Annals, Vol. 68(1).

Experimental Verification





Section A



Section B

Ren, H., Xie, J., Liao, S., Leem, D., Ehmann, K. and Cao, J. (2019) "In-situ springback compensation in incremental sheet forming", CIRP Annals, Vol. 68(1).

Geometric Accuracy

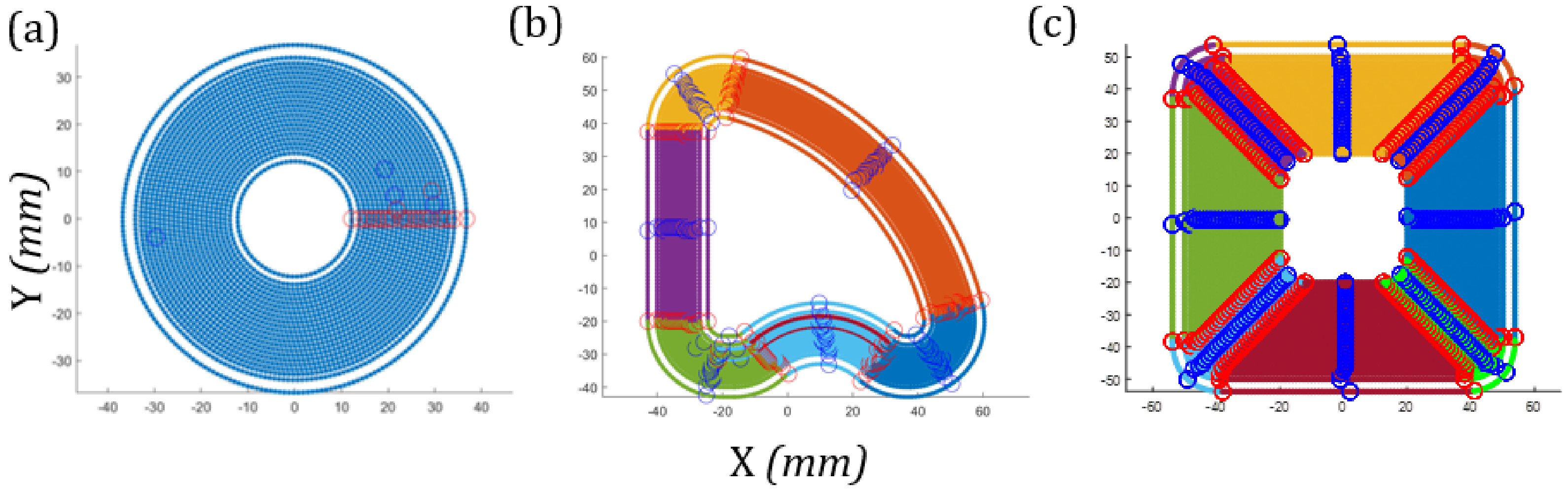


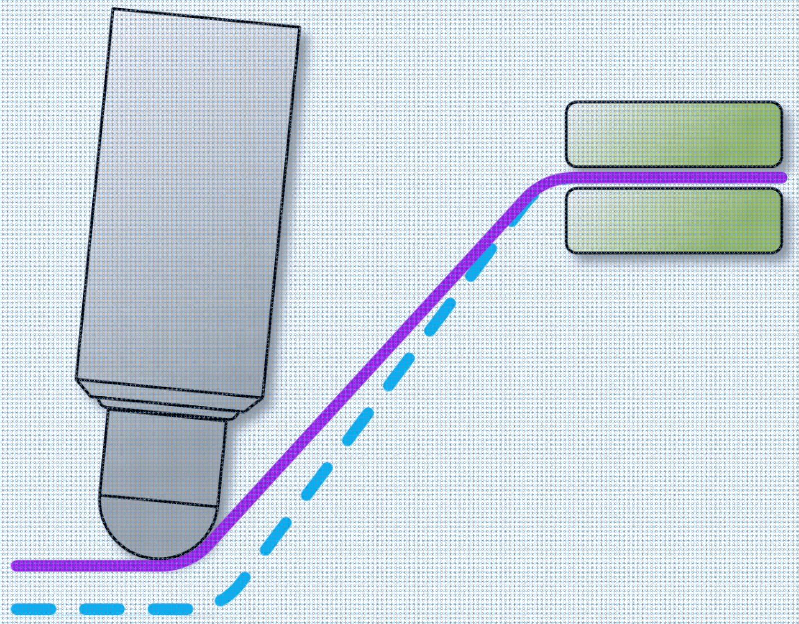
Table 1 Comparison of geometric deviations for the test cases.

Geometry	Cone		Fish fin			Pyramid	
Method	Ref	SC	Ref	SC	SC+FC	Ref	SC+FC
Max. error (mm)	5.7	1.5	5.0	3.0	2.0	4.8	1.2
Avg. error (mm)	3.1	0.8	3.2	1.9	1.2	2.6	0.2

Ren, H., Xie, J., Liao, S., Leem, D., Ehmann, K. and Cao, J. (2019) “In-situ springback compensation in incremental sheet forming”, CIRP Annals, Vol. 68(1).

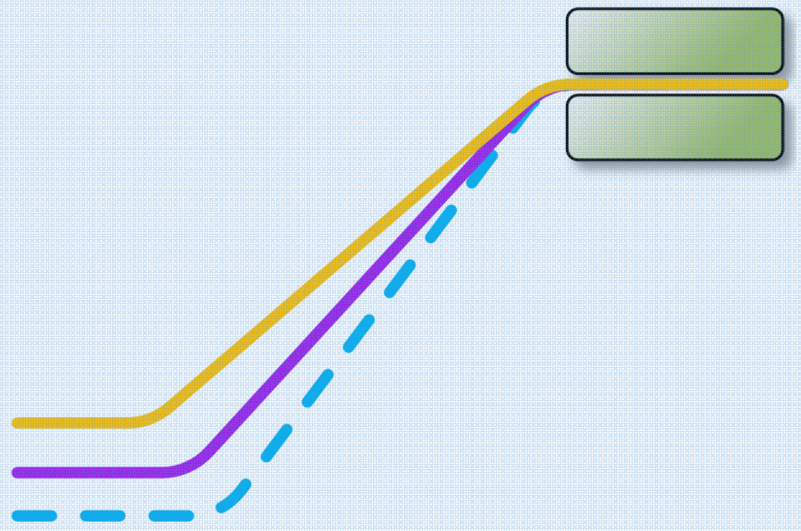
Challenge - Geometric Accuracy

Tool/Machine Deflection



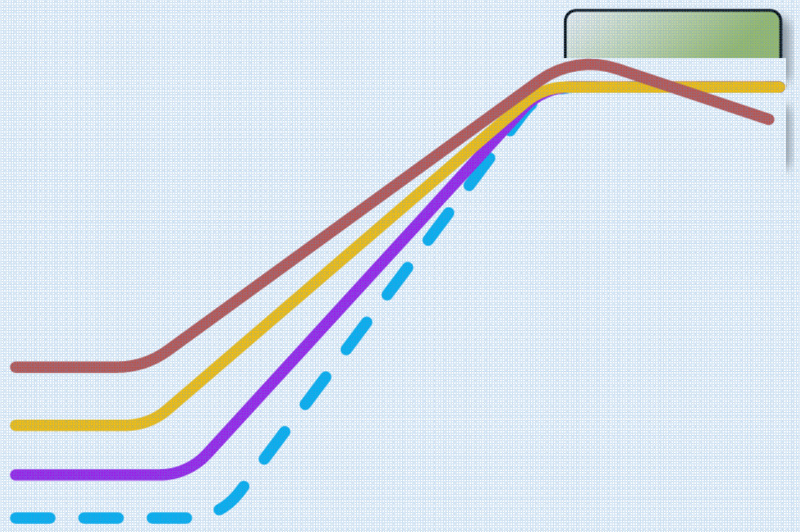
- *requires **Compliance Compensation** for forming tool*

In-process Springback



- *requires **Springback Compensation***

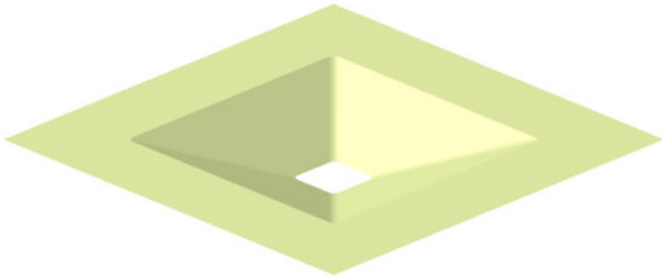
Post-process Springback



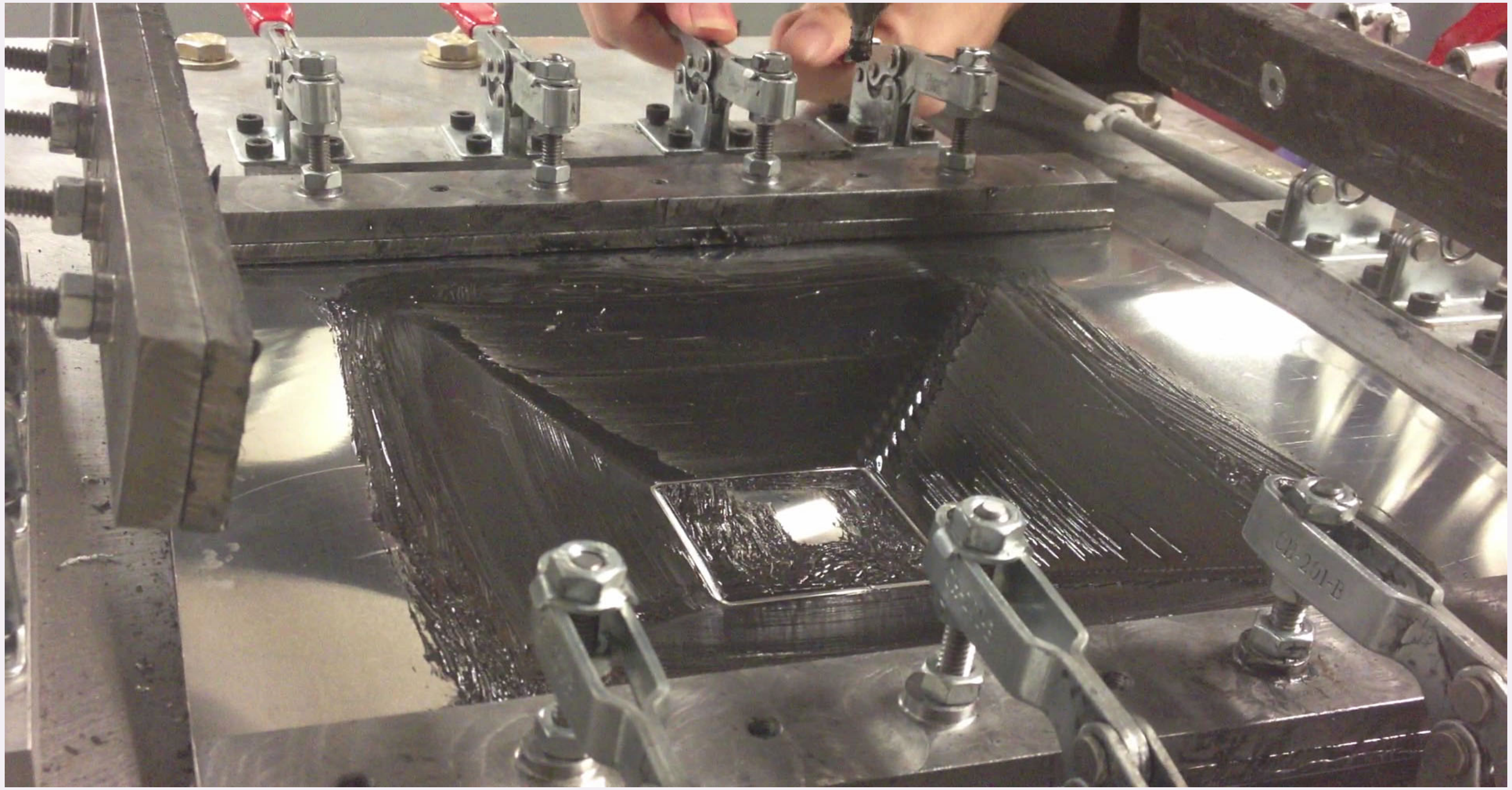
- *requires **Post-annealing***

Ren, H., Xie, J., Liao, S., Leem, D., Ehmann, K. and Cao, J. (2019) “In-situ springback compensation in incremental sheet forming”, CIRP Annals, Vol. 68(1).

Springback Reduction



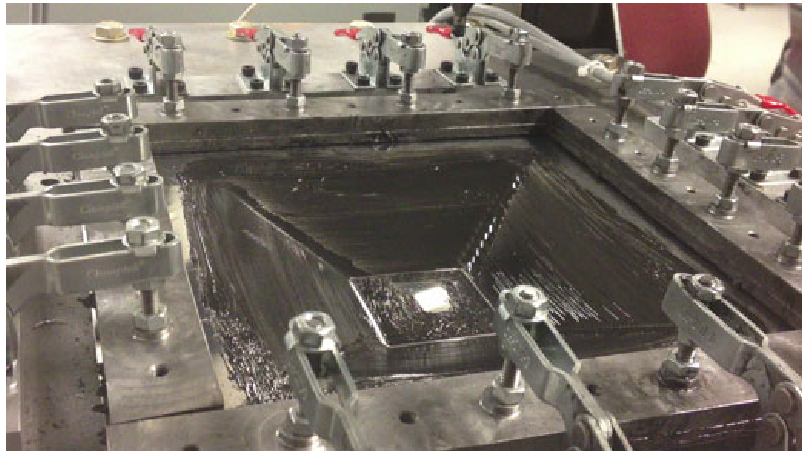
- A universal method to significantly reduce springback due to unclamping



Springback Reduction from Thermal Stress Relief

- Stage 1

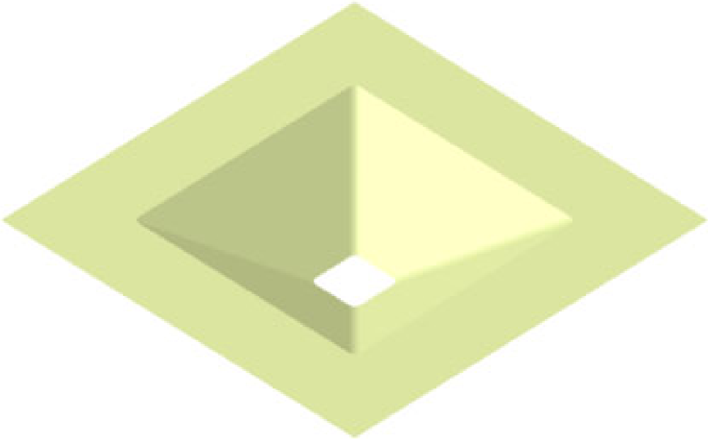
Original part within the machine clamp



- Stage 2

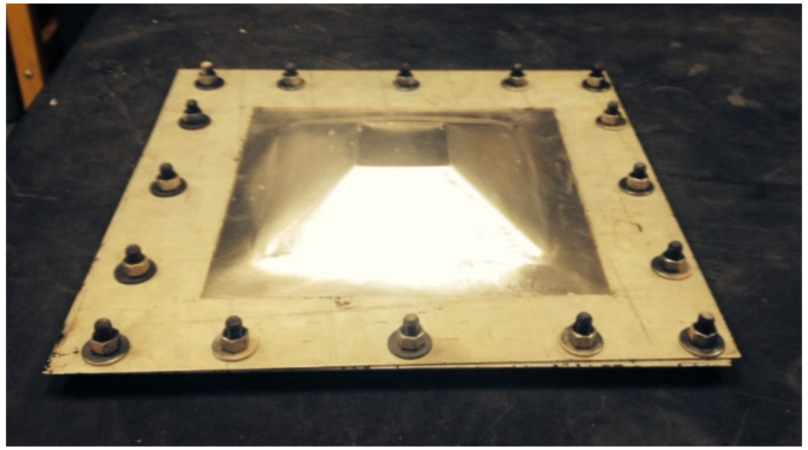
Freestanding original part

Target geometry
(truncated pyramid)



- Stage 3

Original part within the portable clamp



- Stage 4

Freestanding annealed part

Zhang, Z., Zhang, H., Shi, Y., Moser, N., Ren, H., Ehmann, K.F. and Cao, J. (2016) “Springback Reduction by Annealing for Incremental Sheet Forming”, NAMRC 44, June 27- July 1, 2016, Blacksburg, Virginia, USA.

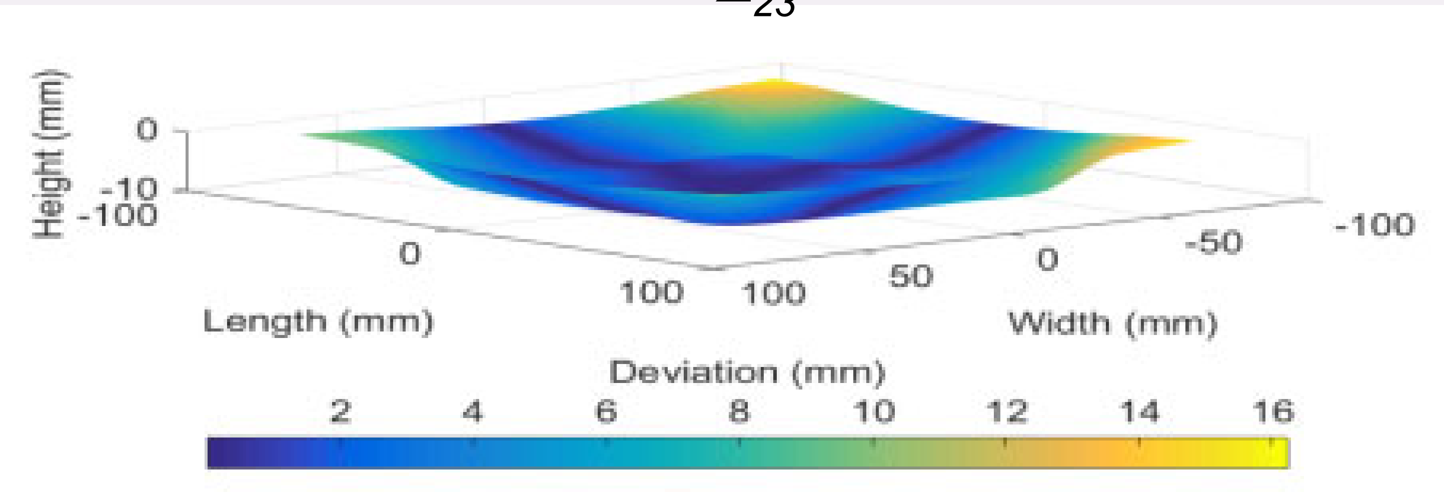
Springback Evaluation

- Assume: Stage 1 = Stage 3
- Inner surface scanned by Romer Absolute Arm with an integrated laser scanner

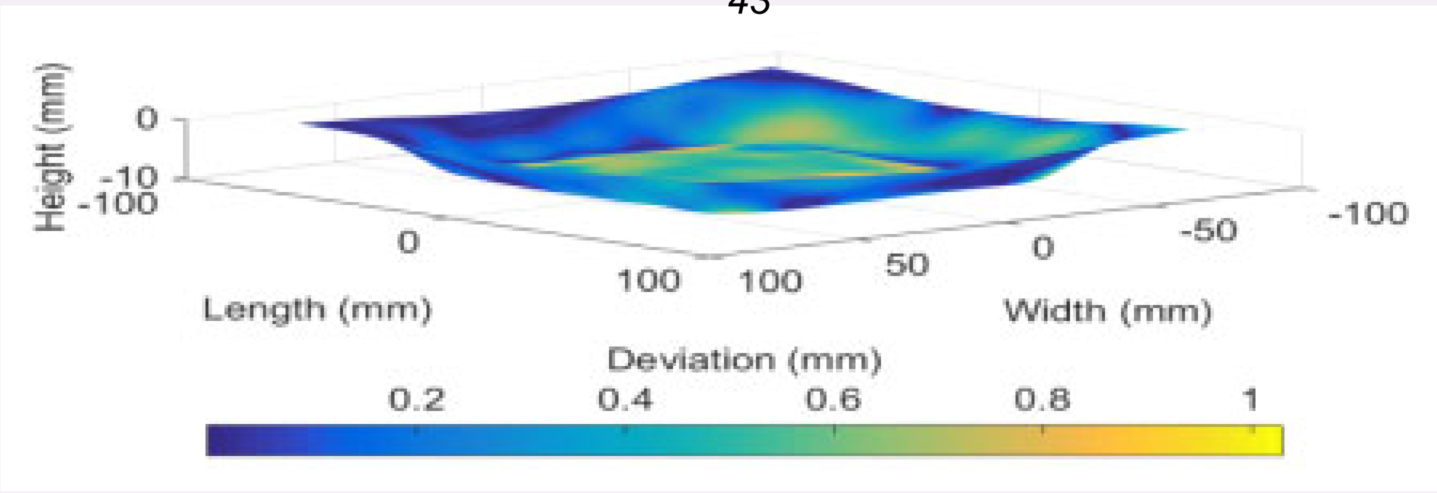
  - Stage 2

  - Stage 4

  - Δ_{23}

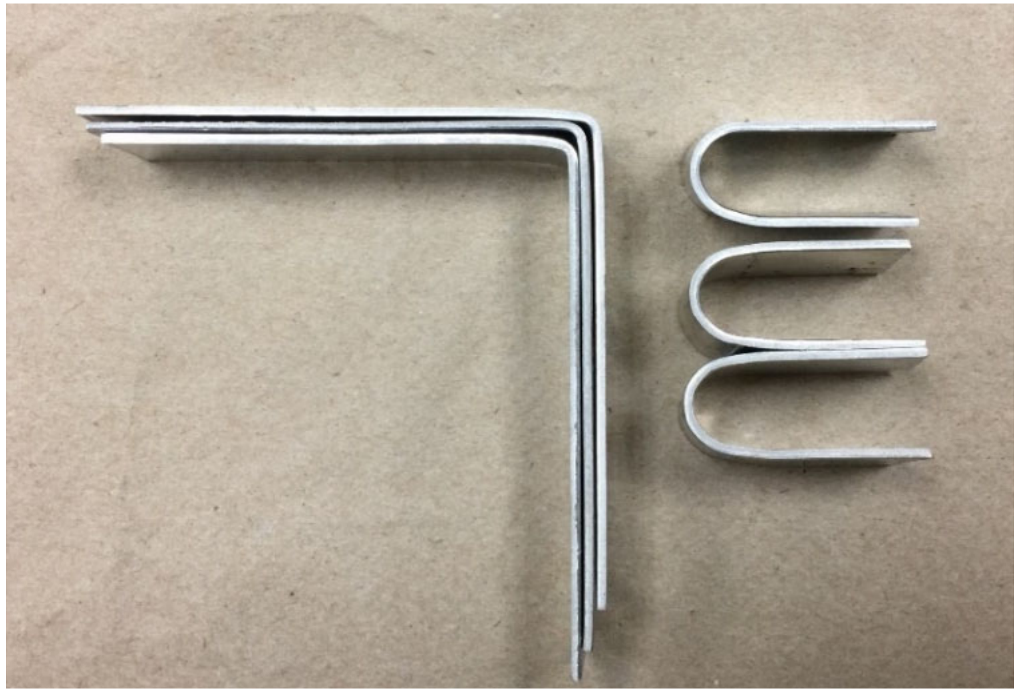


  - Δ_{43}



Bending and Annealing

- Two different bending angles & four different annealing parameter sets



Annealing Parameter		Angle for 90° Bending Tests (°)	Angle for 0° Bending Tests (°)
Temp. (℃)	Time (hr)		
RT	NA	100.2 ± 0.3	17.2 ± 0.9
170	1	90.2 ± 0.8	0 ± 0
130	1	93.3 ± 0.8	0.9 ± 0.2
250	0.5	92.8 ± 0.4	1.1 ± 0.6

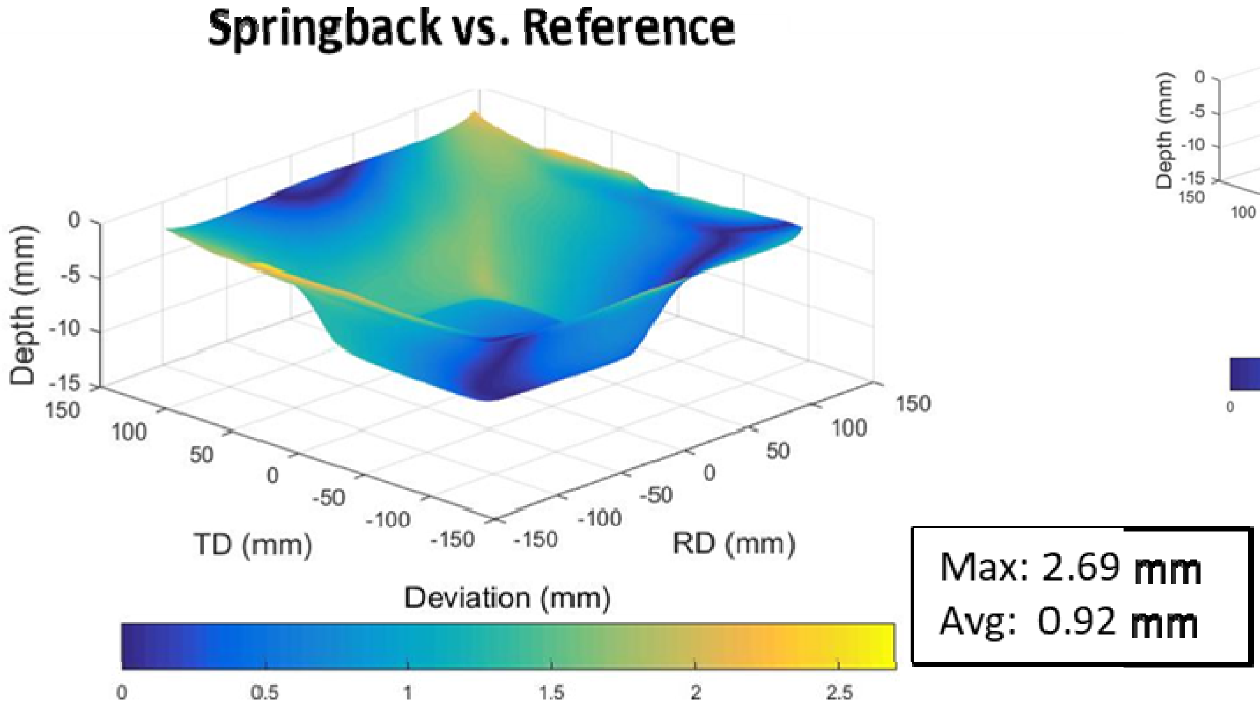
Selected parameters

Standard stress relive annealing for AA7075-O (SAE AMS2770)

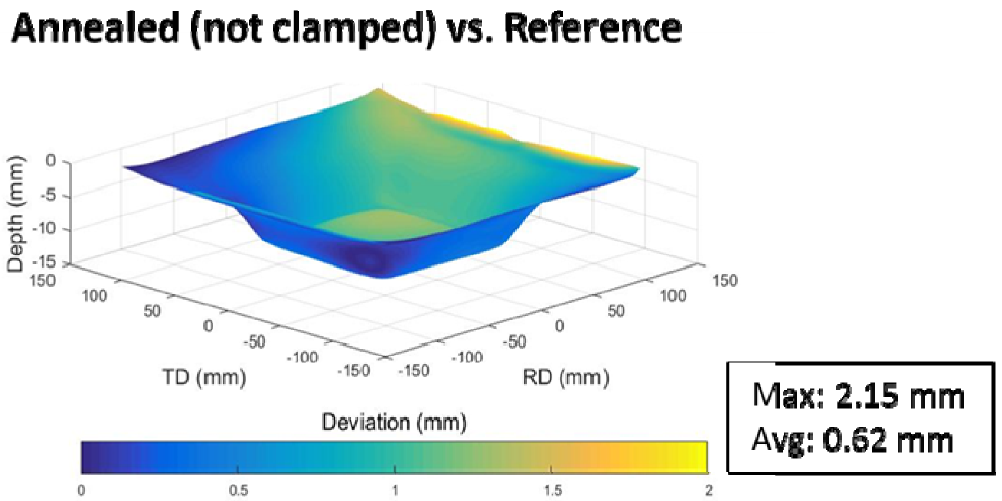
1) Temperature: 333-349℃
2) Heat for 2 hrs
3) Air cool to RT

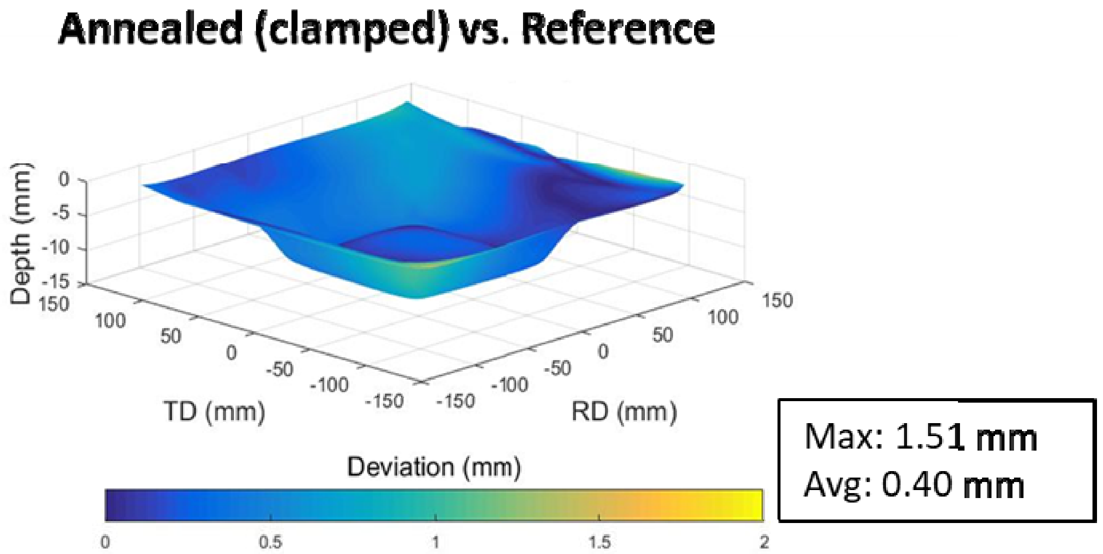
Validation of the Selected Parameters

- 3D geometrical deviation map of a part with springback



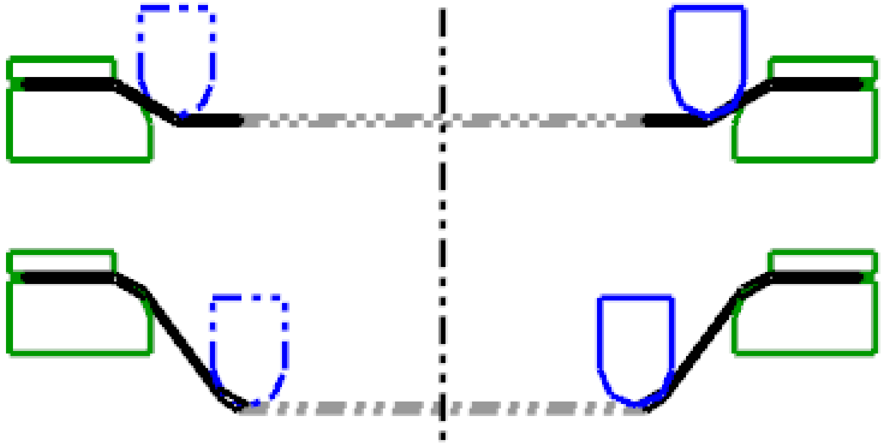
- Geometrical deviation map of the two different annealed cases

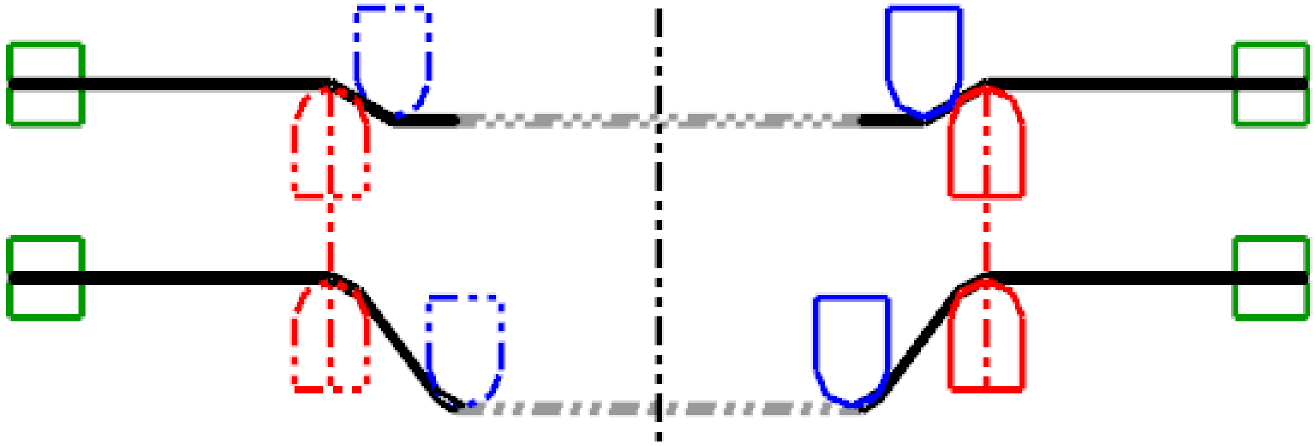




Single-sided incremental hole flanging

Dieless double-sided incremental hole flanging (Current work)





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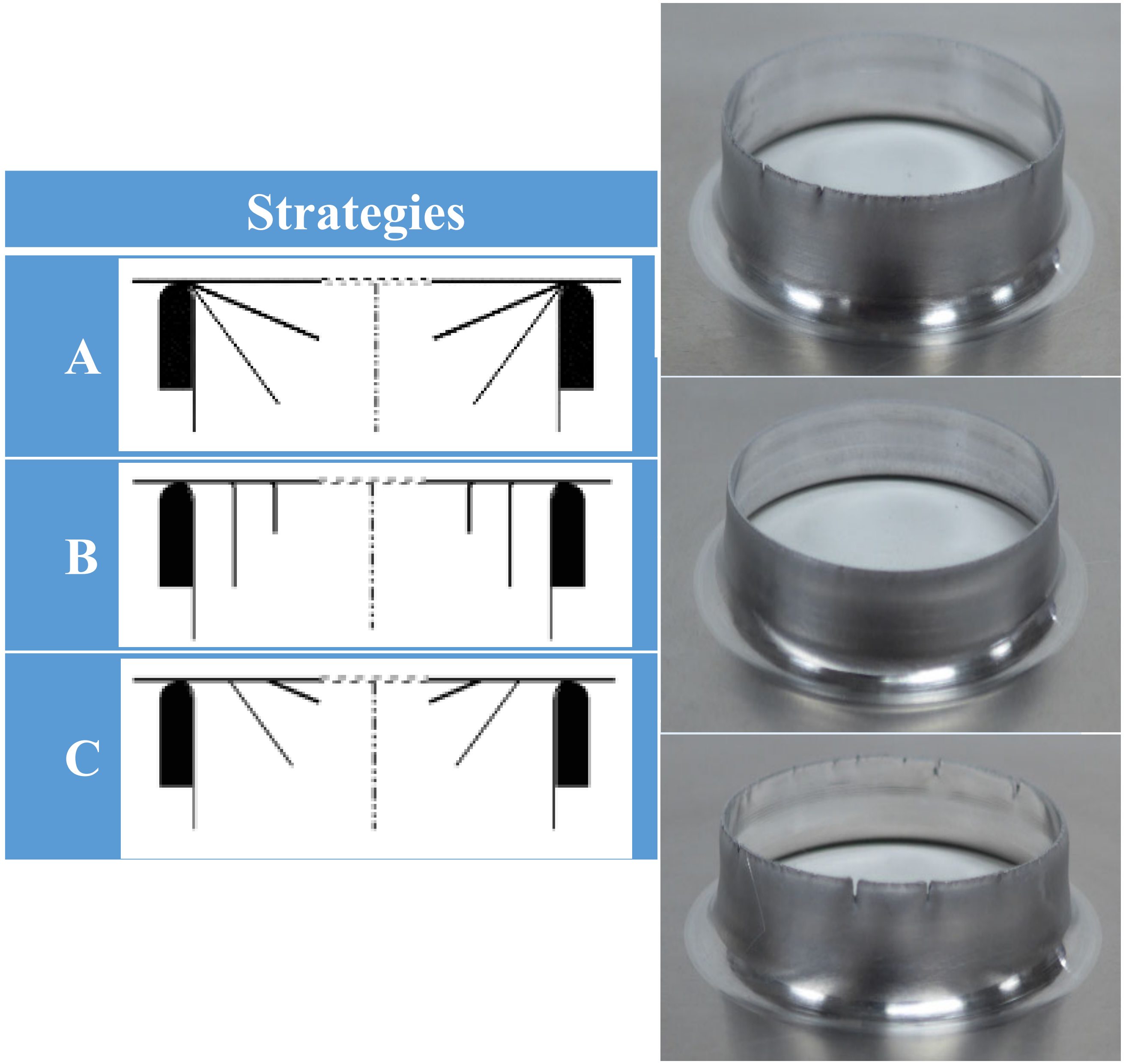
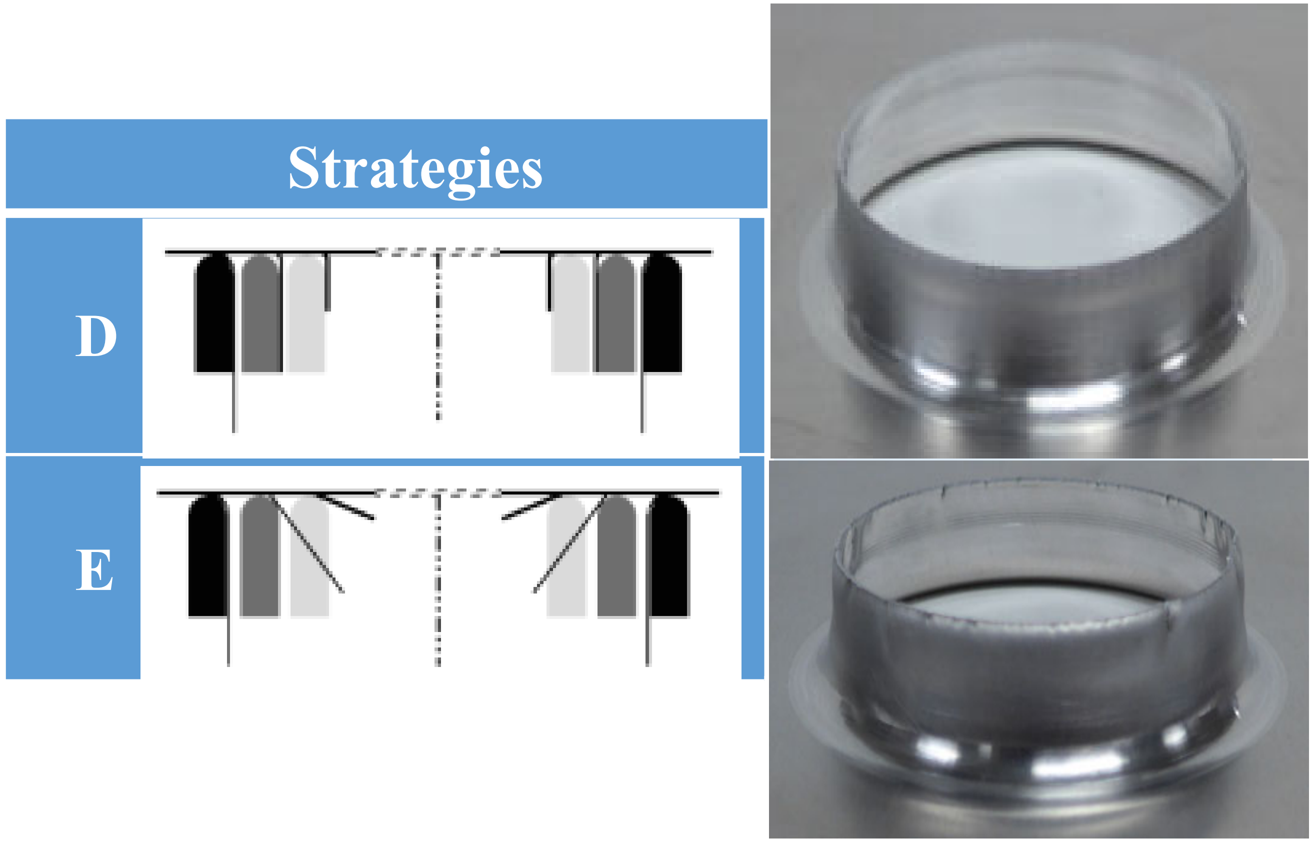
Huan Zhang, Zixuan Zhang, Huaqing Ren, Newell Moser, Jian Cao. Dieless double-sided incremental hole-flanging with different toolpath strategies. MSEC 2016-8829

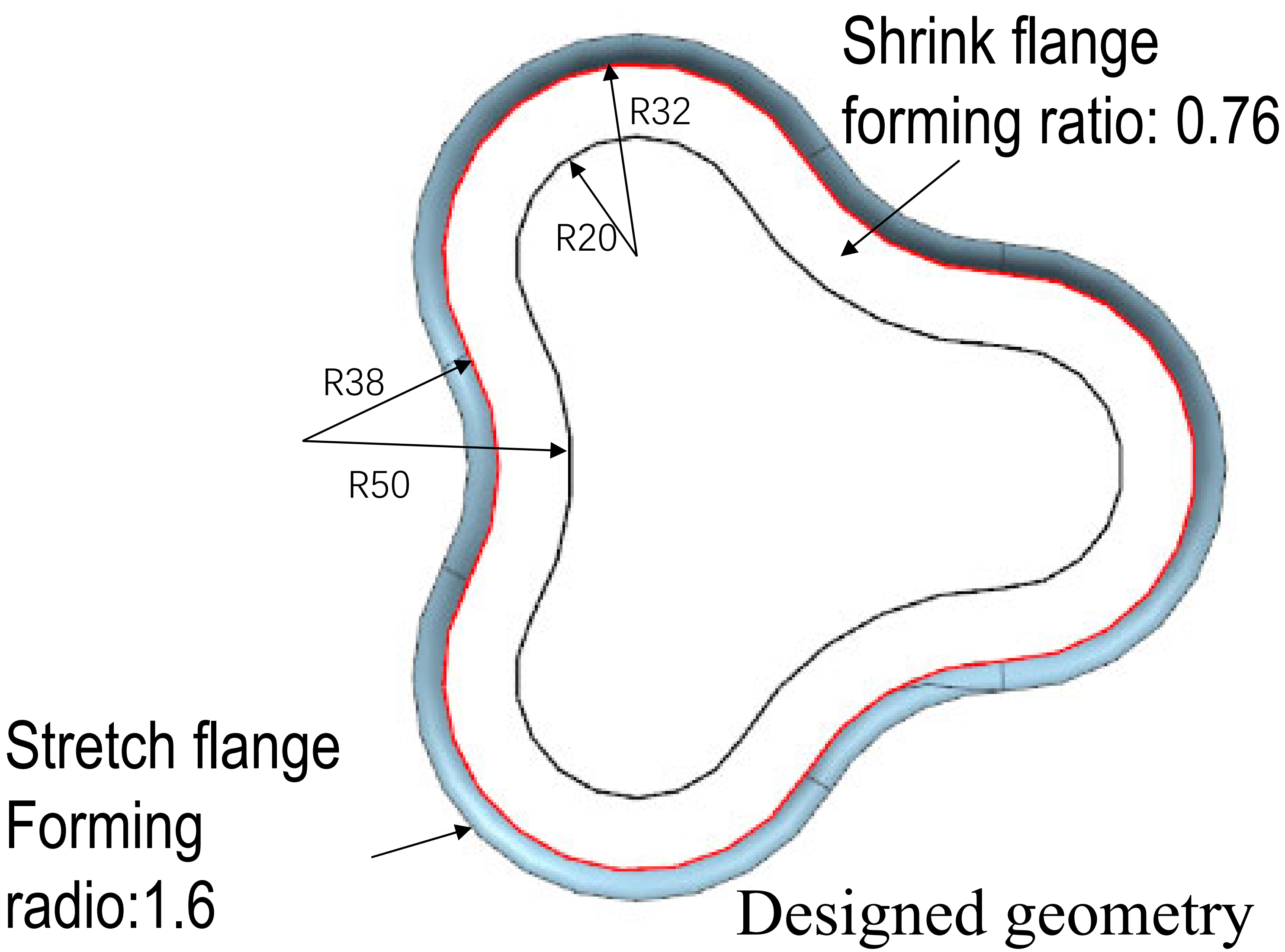
Experimental Results



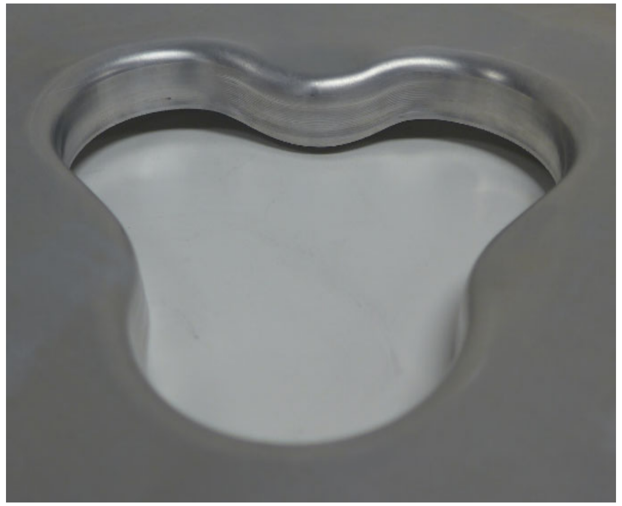


Zhang, H. … Cao, J., MSEC 2016

Asymmetric hole flanging experiment



Designed geometry



Achieved part

Thank You

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Zilin Jiang

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NIST National Institute of Standards and Technology U.S. Department of Commerce

AMPL Advanced Manufacturing Processes Laboratory
AMPL.MECH.NORTHWESTERN.EDU

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Questions

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