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Equal Channel Angular Extrusion Process for Grain Refinement in Hypermesh and Abaqus

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Overview on Equal Channel Angular Extrusion Process for Grain Refinement

- Equal Channel Angular Extrusion ("ECAE") was first conceived by V.M. Segal in 1972.[Segal 20]
- ECAE is a plastic deformation process that utilizes simple shear on a work-piece (a/k/a a billet) to produce different structures and textures in the work-piece.[Segal 95]
- A common set-up for ECAE is shown in FIG. 1.
- As shown in FIG. 1, a tool includes two channels with the equal, uniform cross-sections, A.[Segal 95] The channels are connected and arranged at an angle, 2φ.[Segal 95] A work-piece having a cross-section nearly equal to the cross-section of the channel is placed in one channel.[Segal 95] A punch presses the work-piece through the first channel and on through the second channel.[Segal 95] The work-piece moves through the two channels as a rigid body.[Segal 95] However, deformation occurs by simple shear in a crossing plane, O-O, between the two channels.[Segal 95]

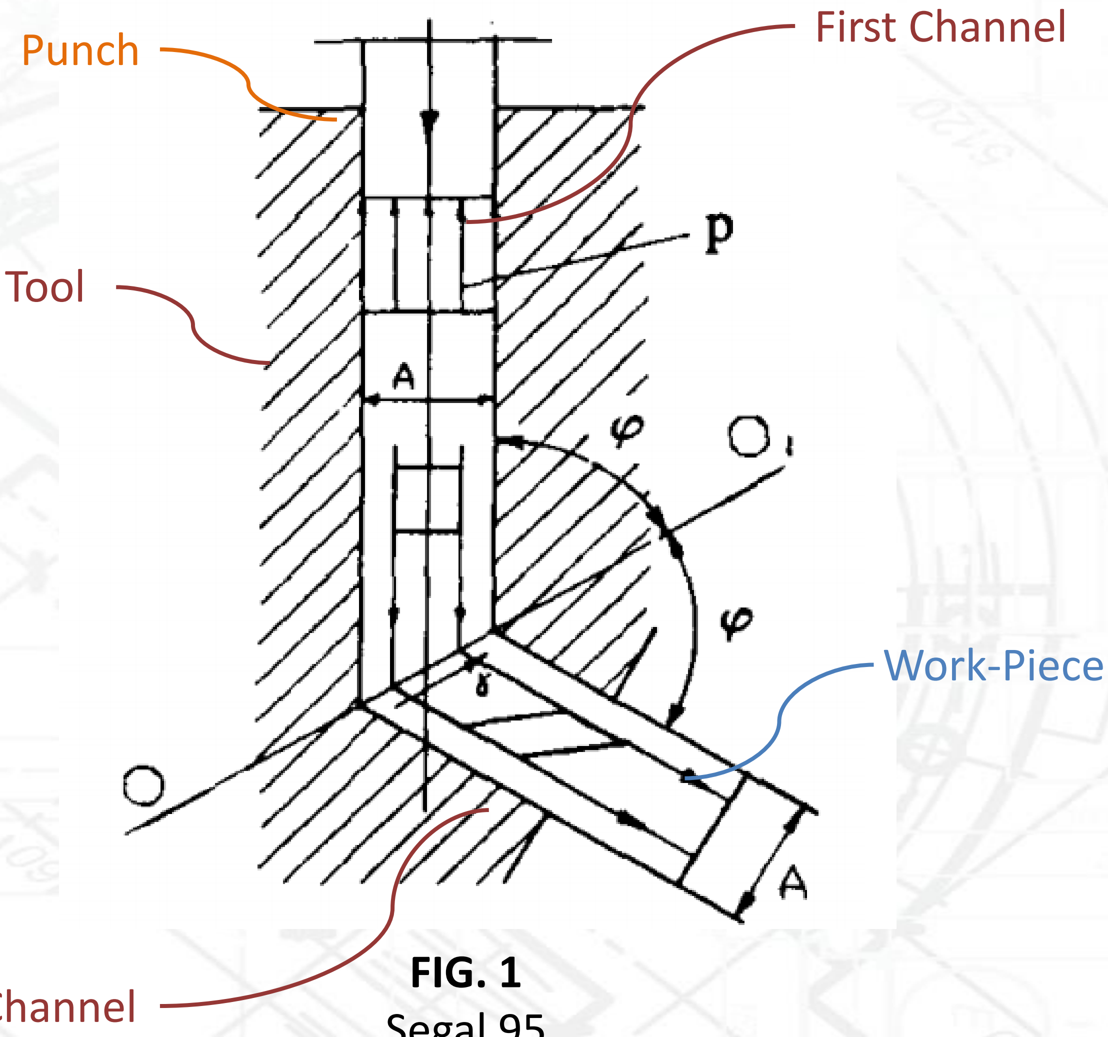

FIG. 1
Segal 95

Overview on Equal Channel Angular Extrusion Process for Grain Refinement

- What are some benefits of ECAE?
- From Segal 95,
  - uniform structure and properties throughout the work-piece
  - a larger equivalent deformation per pass
  - extremely large total effective deformation after multiple passes
  - no appreciable change of the work-piece cross-section
  - relatively low pressures and loads are sufficient for ECAE
  - the creation of special structures and textures are possible because of:
    - strict control over the direction of shear, the homogenous stress-strain state, the capacity for extremely large deformations in massive products and the opportunity to modify the shear plane and direction during a multiple extrusion sequence
  - the stimulation of specific mechanisms of structure formation and phase transformation are possible in ECAE.

Overview on Equal Channel Angular Extrusion Process for Grain Refinement

FIG. 2A: Example of Grain-Size/Microstructure of Work-Piece Original State, Segal 95

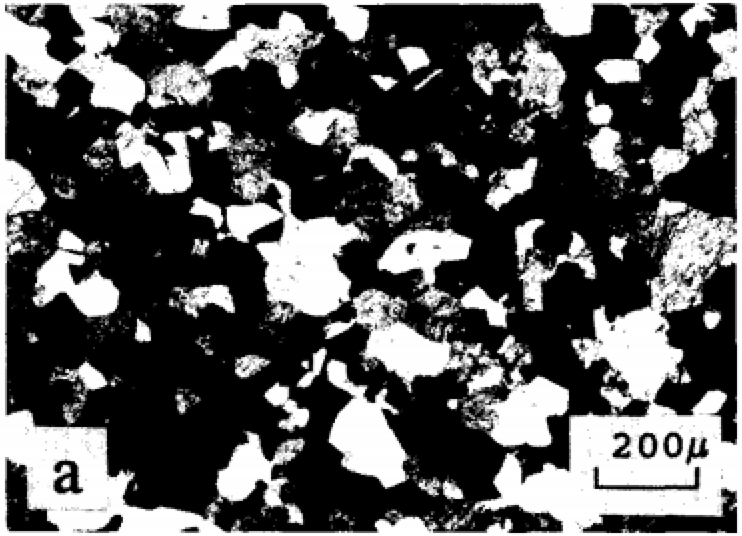

FIG. 2B: Example of Grain-Size/Microstructure of Work-Piece After 4 Passes in ECAE, Segal 95

Note: The approach in 3B is Route A—where the same end of the work-piece is first fed into the first channel.

Overview on Equal Channel Angular Extrusion Process for Grain Refinement

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- Segal 95 identifies that punch pressure, P, divided by flow stress of material, Y, is equal to strain intensity, $\Delta\varepsilon_i$, which in turn is equal to a value based on the angle, 2φ, between the channels.

$$\frac{p}{Y} = \Delta\,\epsilon_i = \frac{2}{3^{1/2}}\ \text{cotan}\phi \qquad (1)$$

- Segal 95 identifies that total strain intensity is equal to the number of passes, N, multiplied by strain intensity, $\Delta\varepsilon_i$.

$$\epsilon_n = N\Delta\epsilon_i \qquad (2)$$

- Segal 95 identifies when pass orientation of the work-piece (i.e., same end is consistently first fed into the first channel) is kept the same, the total shear after N passes is equation (3).

$$\gamma = \tan\psi = 2N\ \text{cotan}\phi = \epsilon_N/3^{1/2} \qquad (3)$$

Overview on Equal Channel Angular Extrusion Process for Grain Refinement

- Iwahashi 96 introduced curvature into ECAE, as shown in FIG. 2. The first channel and the second channel may be joined by a curved section having an angle, Ψ.
- Note: The angle between the two channels in Iwahashi 96 is designated as Φ, not 2Φ as in Segal 95.

- In response to the curvature, Iwashashi 96 developed equation (4) for total strain, which is based on knowing the number of passes, the angle between the channels, and angle associated with the curvature.

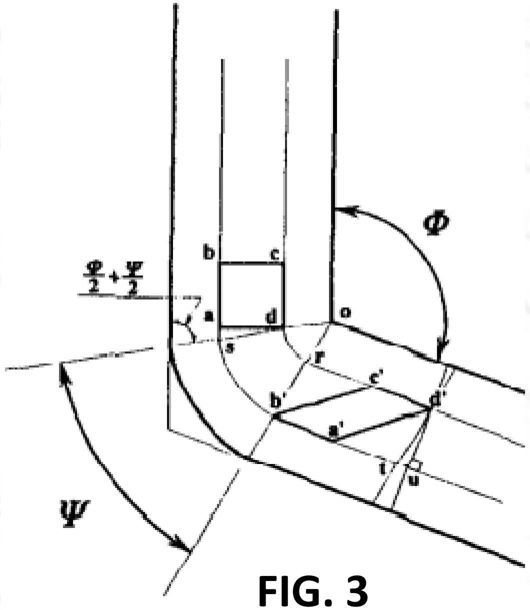


FIG. 3
Iwahashi 96

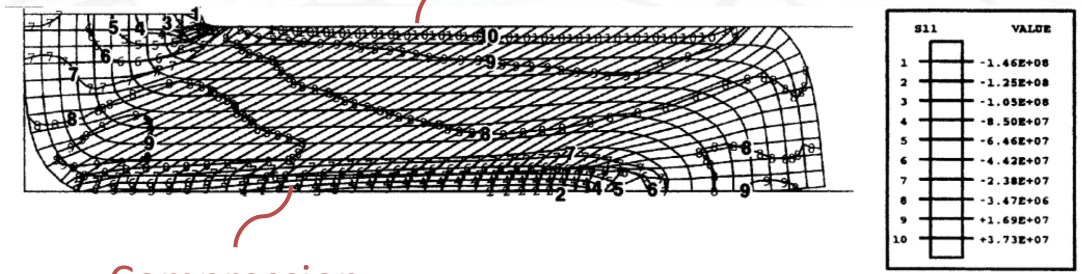
$$\varepsilon_N = N\left[\frac{2\cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right) + \Psi \operatorname{cosec}\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)}{\sqrt{3}}\right] \qquad (4)$$

ECAE Finite Element Examples: Sue 99

- Sue 99 utilizes Abaqus to investigate modeling stress and strain in ECAE for a polymer. See FIGs. 4A and 4B.
- In Sue 99, while the tool/channels are shown having a 90 degree angle, a curvature is nevertheless artificially inserted into the work-piece to address a singularity issue.
- Sue 99 simplifies ECAE to a two-dimensional plane-strain problem. Friction is applied. Sue 99 found that the shear plane is about 30deg, as opposed to the predicted 45deg.

Tension

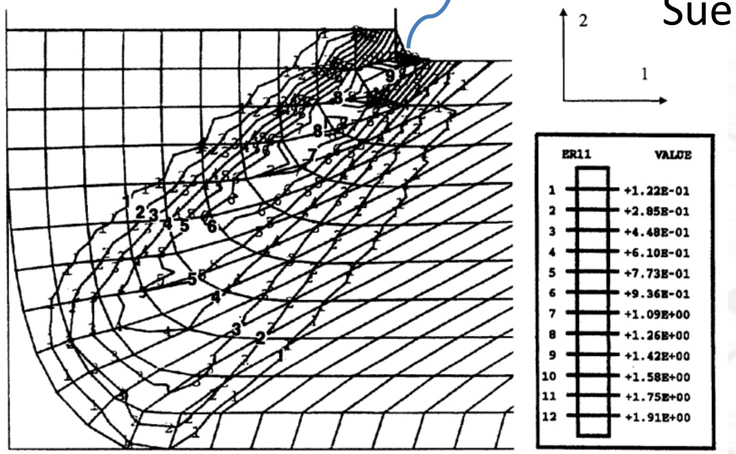
FIG. 4A
Sue 99



Compression

High Shear Strain

FIG. 4B
Sue 99



ECAE Finite Element Examples: Suh 2001

- Suh 2001 utilizes Abaqus software to investigate Iwashashi 96 total strain formula.
- Suh 2001 simplified to two-dimension plane strain, assumed the tool and ram were rigid, and neglected friction.
- Suh 2001 found that when the curvature angle, Ψ, is 0, homogeneous shear deformation occurs on the whole cross-section of the work-piece, which matches the theoretical model proposed in Iwashashi 96. See FIG. 5A. As Ψ increases, the upper part of the work-piece is comparatively uniform and tracks the theoretical value for plastic strain, but the lower part does not. See FIG. 5B.

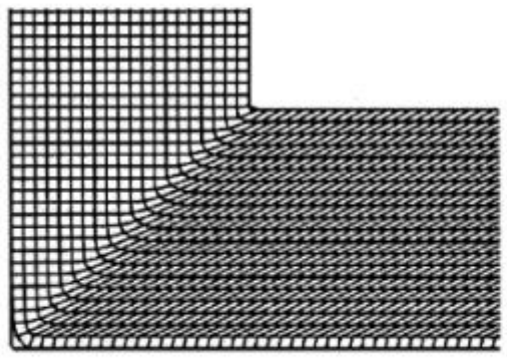


FIG. 5A: Ψ = 0
Suh 2001

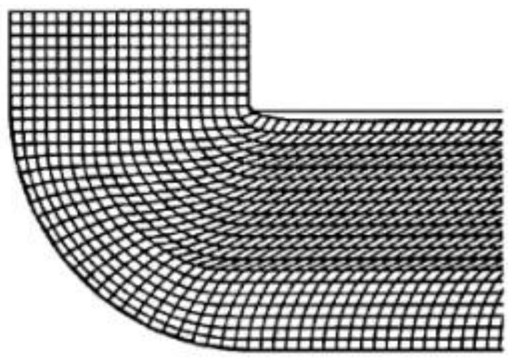


FIG. 5B: Ψ and Φ = 90
Suh 2001

ECAE Finite Element Examples: Kalidindi 09

- Kalidindi 09 utilizes Abaqus to propose a new way of modeling ECAE, particularly crystallographic texture evolution.
- Kalidindi 09 utilizes material streamlines, a, b, and c, to consider the deformation of the work-piece. See FIG. 5. As can be gleaned by FIG. 6A, far away from the shear plane O-O, the material streamlines are assumed to be parallel. Near O-O, however, “the streamlines are assumed to lie on a set of perfect quarter-circles, whose radii increase linearly while matching the radii of the top and bottom surfaces of the ECAE dies at the two extremes.
- Kalidindi 09 utilizes 4,800 C3D8 elements. Two approaches are used to model grain morphologies: each element is assumed to correspond to one crystal; grains elongated to produce a brick wall pattern. See FIG. 6B. Both approaches appeared to produce similar results.

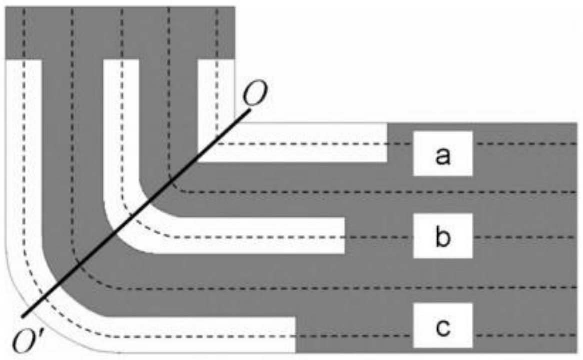


FIG. 6A

Kalidindi 09

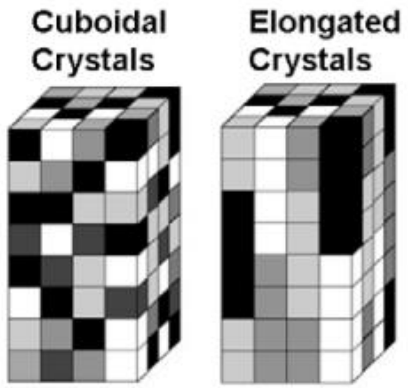
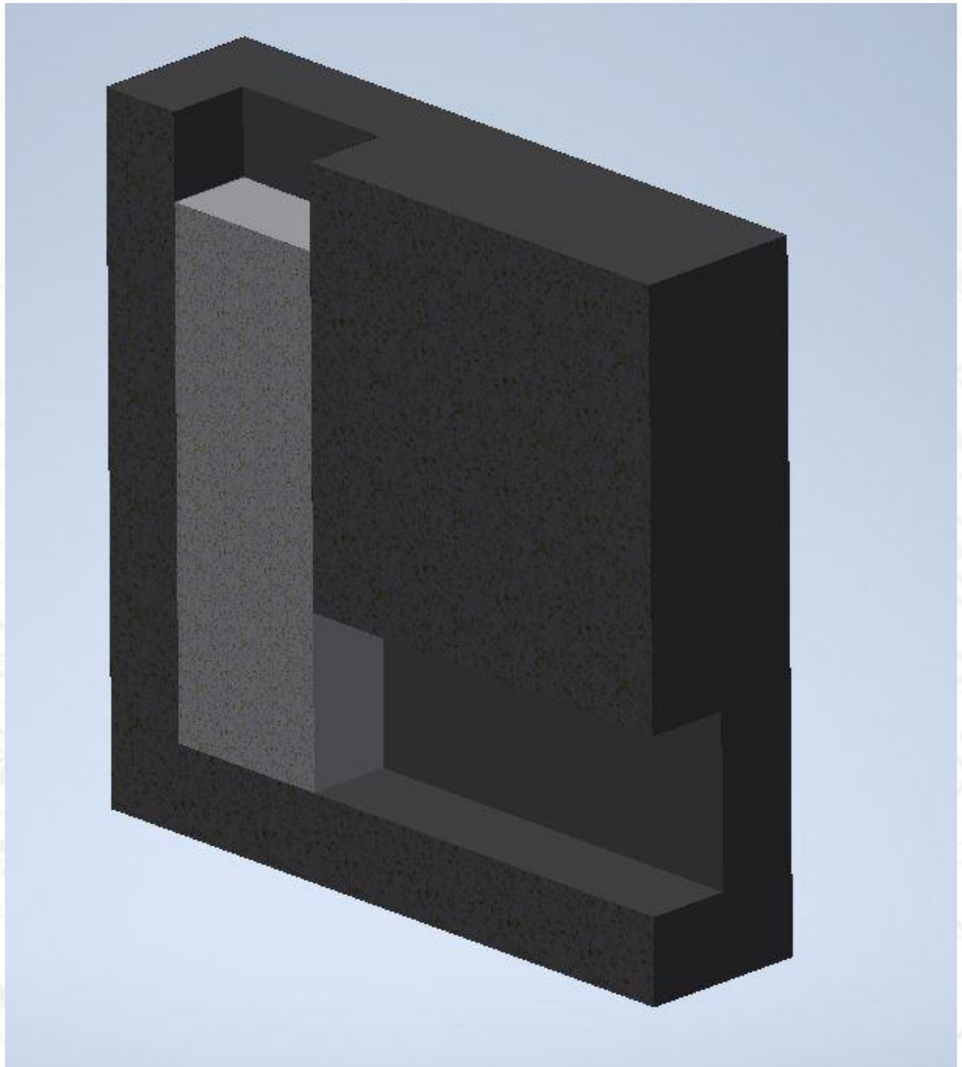


FIG. 6B

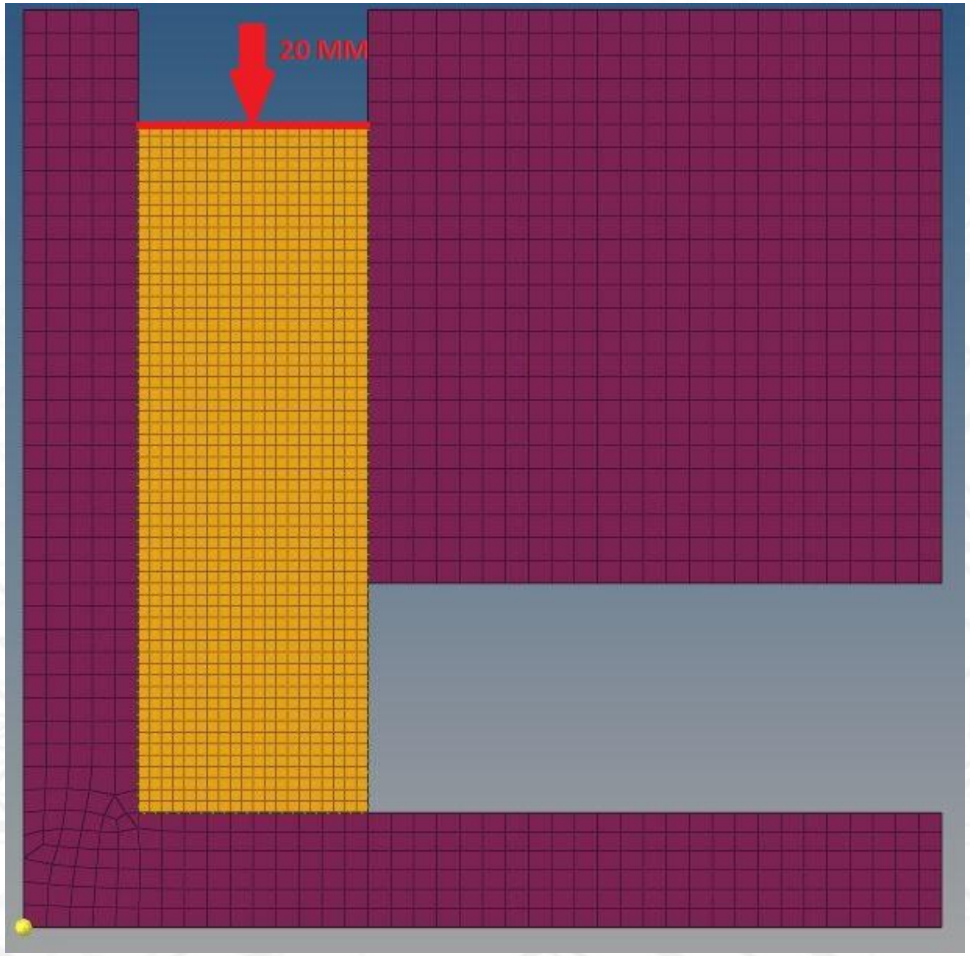
Kalidindi 09

Model



- Model
  - Billet 30 x 10 x 1 MM (in most cases)
  - No clearance in die
  - Billet completely enclosed in die

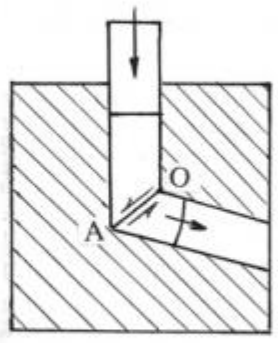
Model



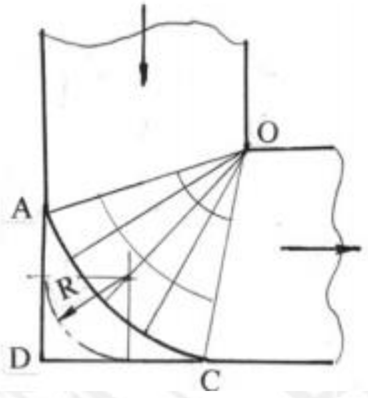
- Mesh
  - 2D solid section
  - CPE4 elements
  - Top of billet displaced 20 MM into die
  - Die completely constrained
  - Plane stress/strain thickness added in Abaqus
  - Entire model subjected to temperature (when applicable)

Task 1-1: Relationship Between Friction Coefficient and Plastic Strain Per Pass and Uniformity of Strain

- **Ideal Case:** Simple shear is uniform across the shear plane/slip line when there is no friction.[Segal 20]
- **Reality:** Friction between the work-piece and channels is present—even when a lubricant is used.[Segal 20] The presence of friction changes the single slip line to a slip region/central fan.[Segal 20] The angle of the central fan is dependent on friction.[Segal 20] Greater the friction, greater the angle.[Segal 20] Additionally, the greater the friction, the less uniform the simple shear is across the work-piece.[Segal 20]
  - Compare ideal (frictionless) slip line A-O to reality (friction) central fan A-O-C.

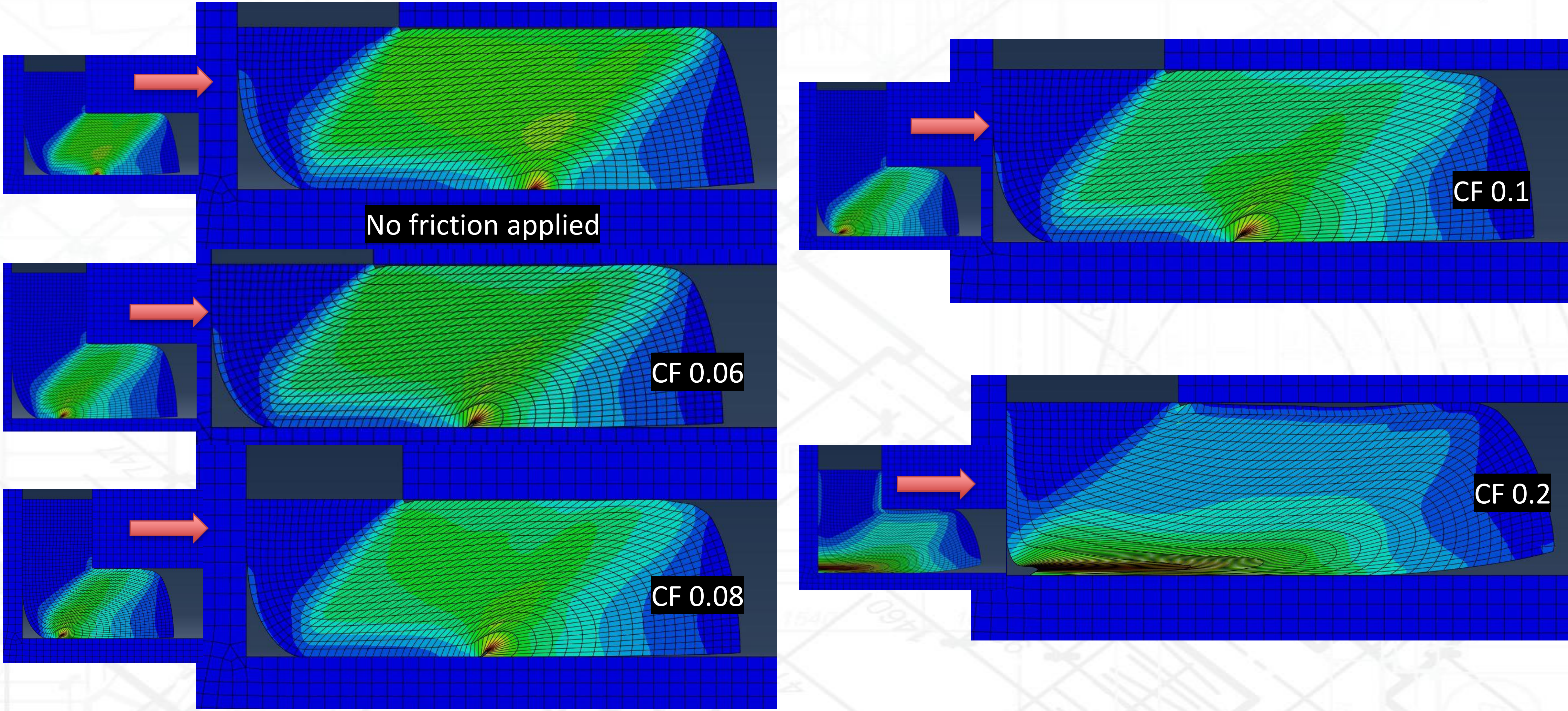


Ideal Case
Segal 20

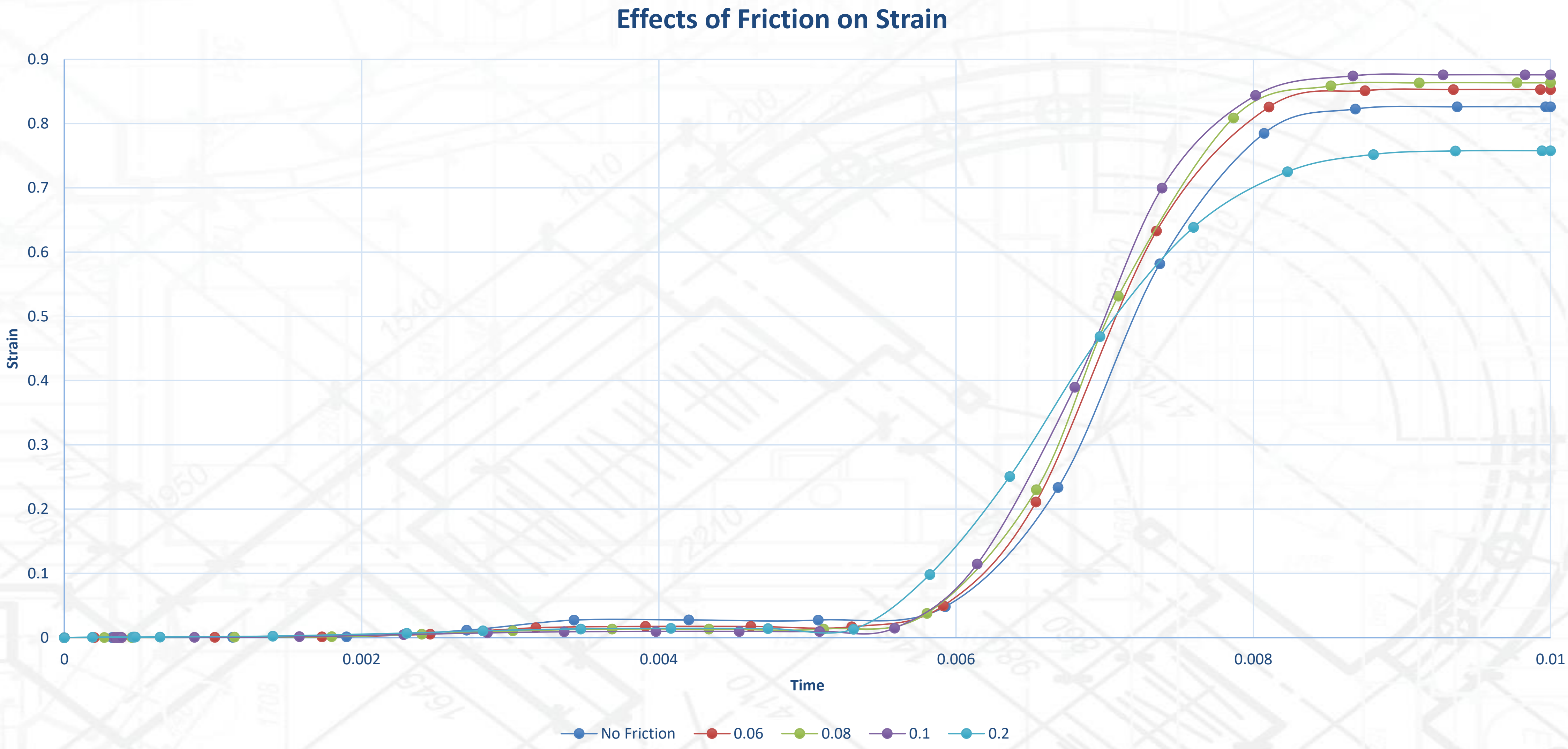


Reality Case
Segal 20

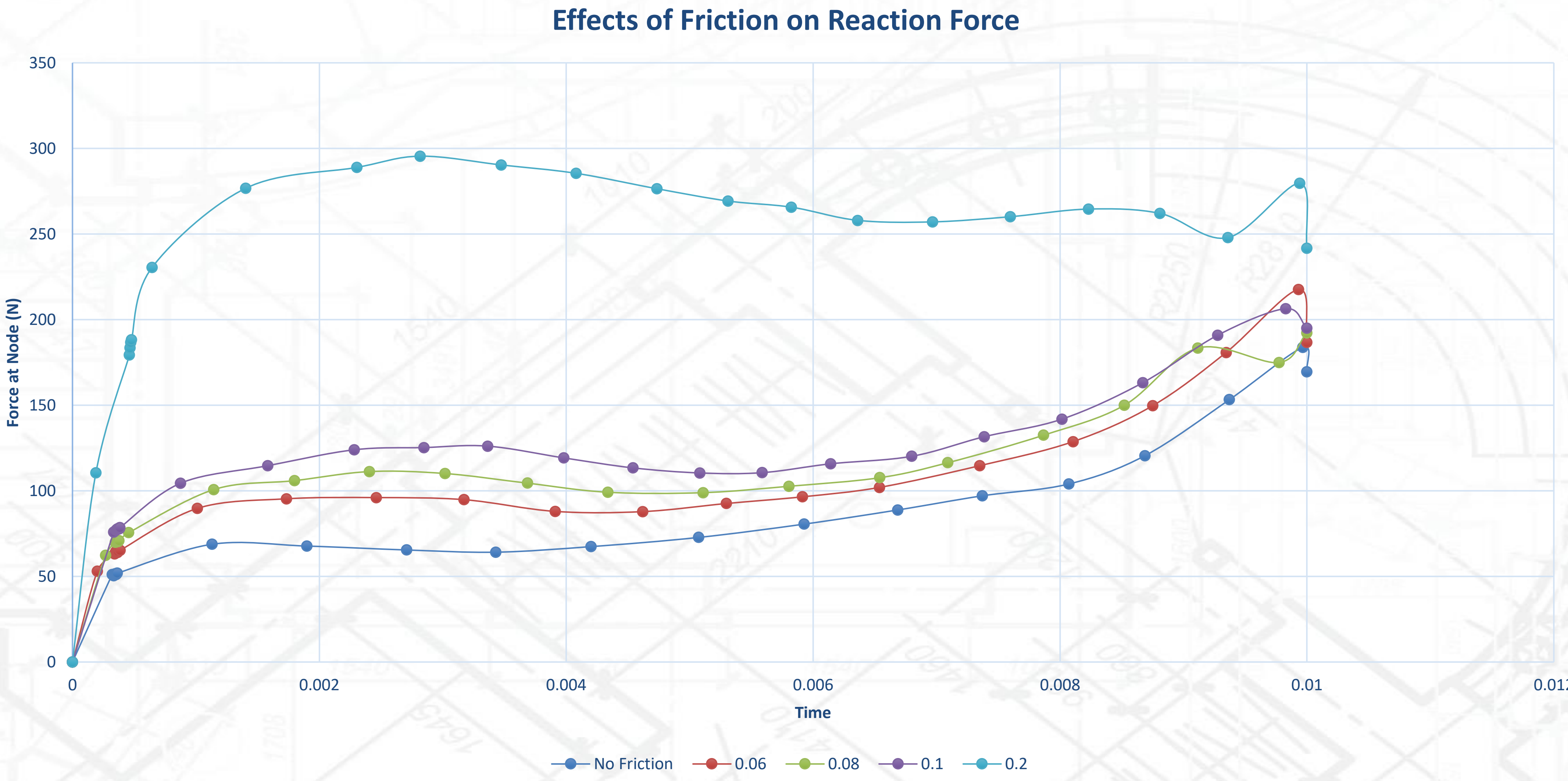
Task 1-1: Relationship Between Friction Coefficient and Plastic Strain Per Pass and Uniformity of Strain



Task 1-1: Relationship Between Friction Coefficient and Plastic Strain Per Pass and Uniformity of Strain



Task 1-1: Relationship Between Friction Coefficient and Plastic Strain Per Pass and Uniformity of Strain



Task 1-2: Effect of Channel Angle Change from 90 to 120 on Plastic Deformation

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- From equation (1), strain intensity, $\Delta\varepsilon_i$, is dependent on the angle between the first channel and the second channel.[Segal 20]
- As seen in Segal 95, the strain intensity decreases when the angle is changed from 90deg to 120deg.
- From equation (4), the relationship between shear strain and the angle can also be seen.[Iwahashi 96] As the angle changes from 90 to 120, the shear strain decreases.

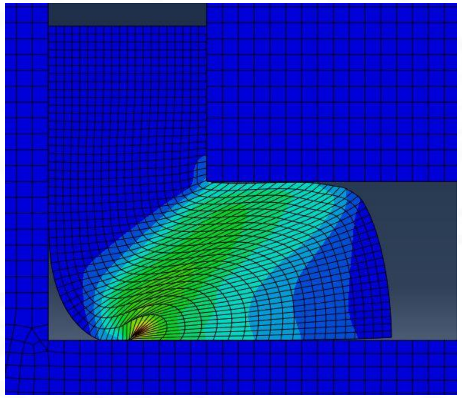
Tool angle (2ϕ)	Punch pressure to flow stress ratio (p/Y)	Incremental strain intensity ($\Delta\epsilon_i$)
150°	0.31	0.31
120°	0.68	0.68
90°	1.15	1.15

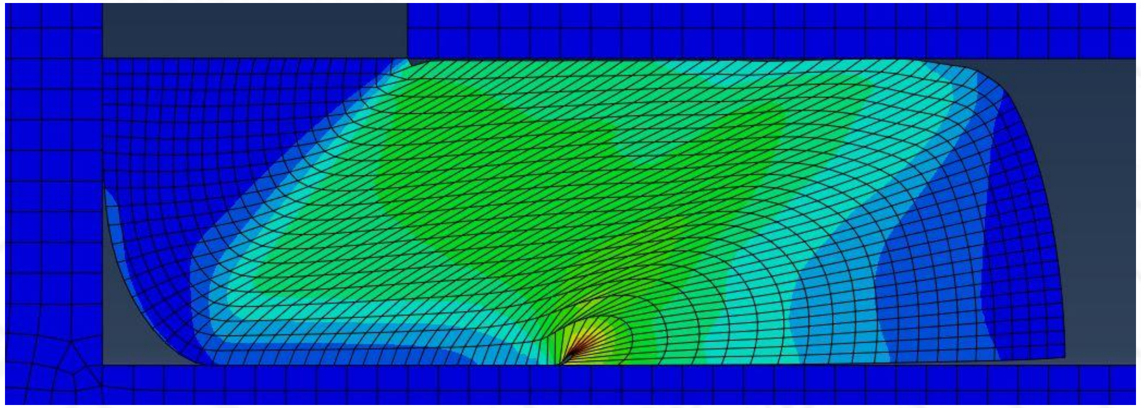
Tool Angle Comparison
Segal 95

$$\varepsilon_{90} = \frac{2\cot\frac{90deg}{2}}{\sqrt{3}} = \frac{2}{\sqrt{3}}$$

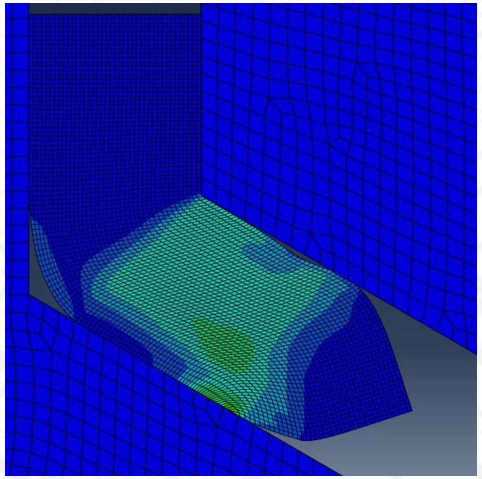
$$\varepsilon_{120} = \frac{2\cot\frac{120deg}{2}}{\sqrt{3}} = \frac{1.1547}{\sqrt{3}}$$

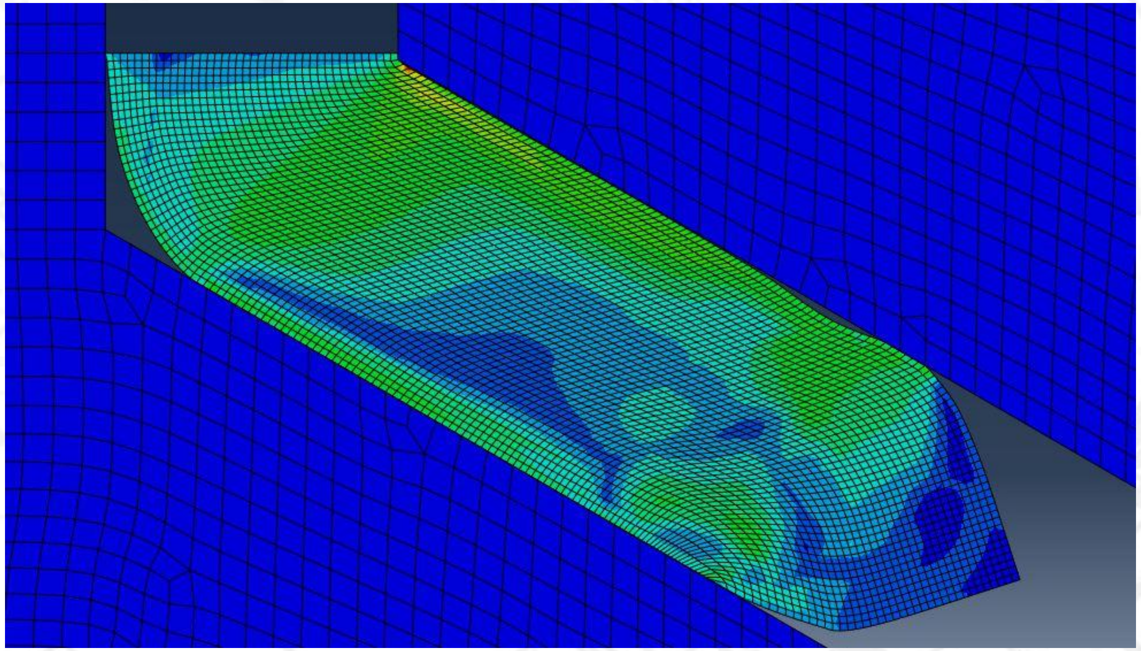
Task 1-2: Effect of Channel Angle Change from 90 to 120 on Plastic Deformation





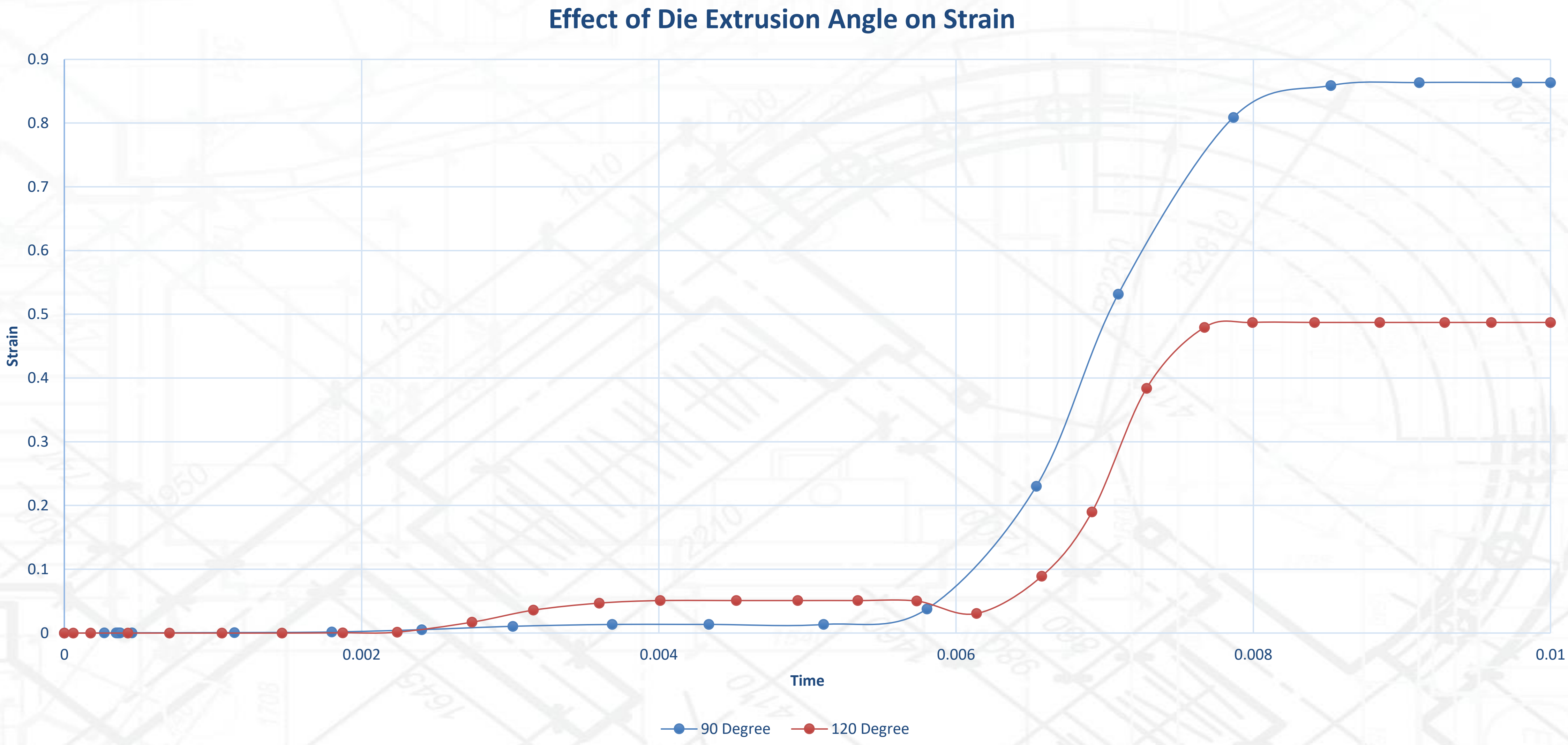
90 Degree



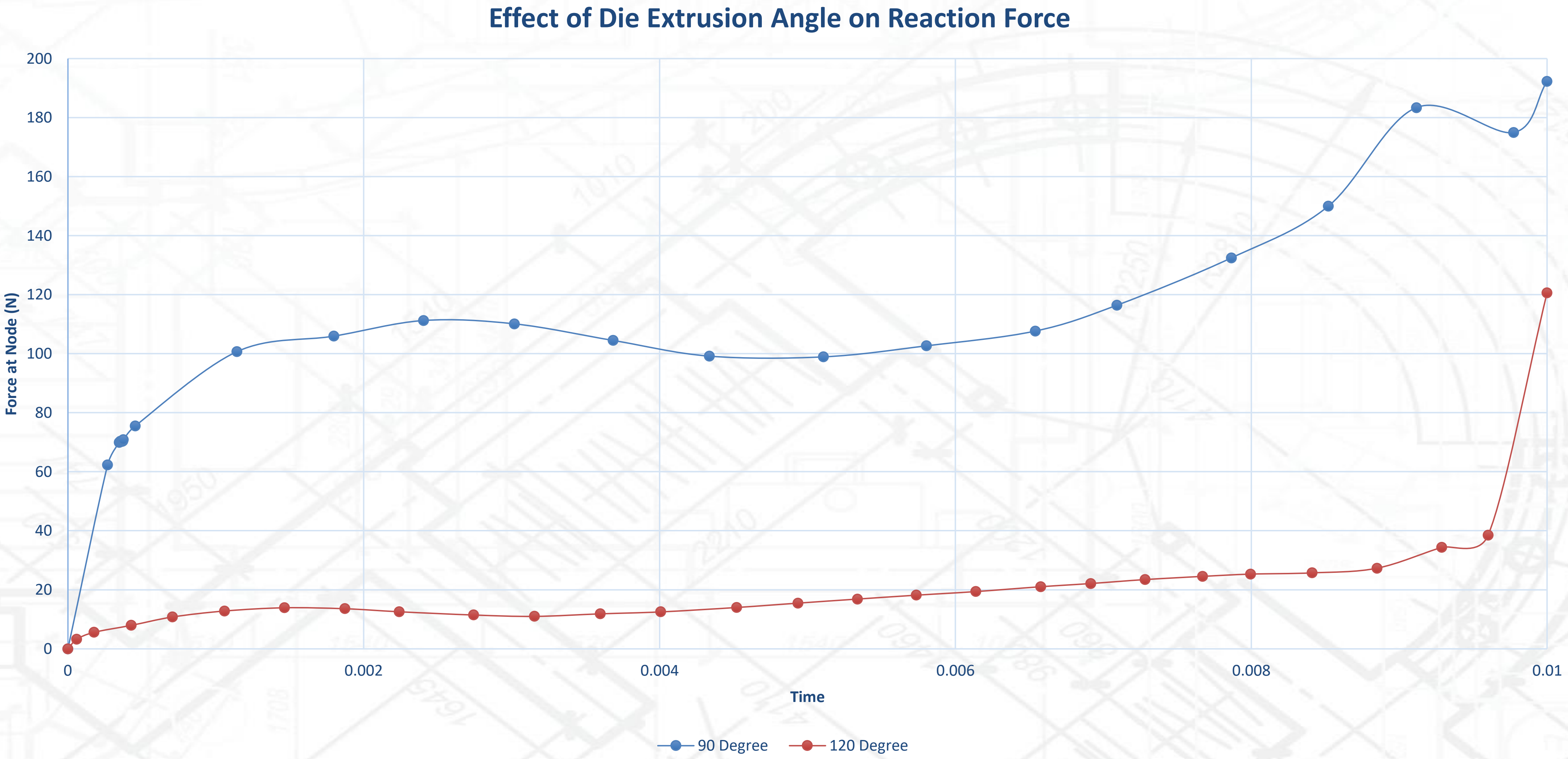


120 Degree

Task 1-2: Effect of Channel Angle Change from 90 to 120 on Plastic Deformation

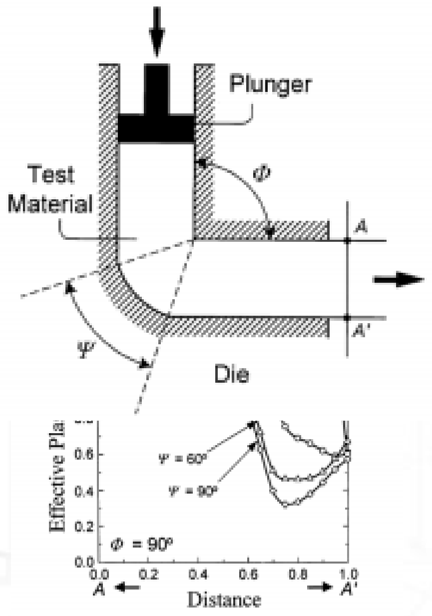


Task 1-2: Effect of Channel Angle Change from 90 to 120 on Plastic Deformation



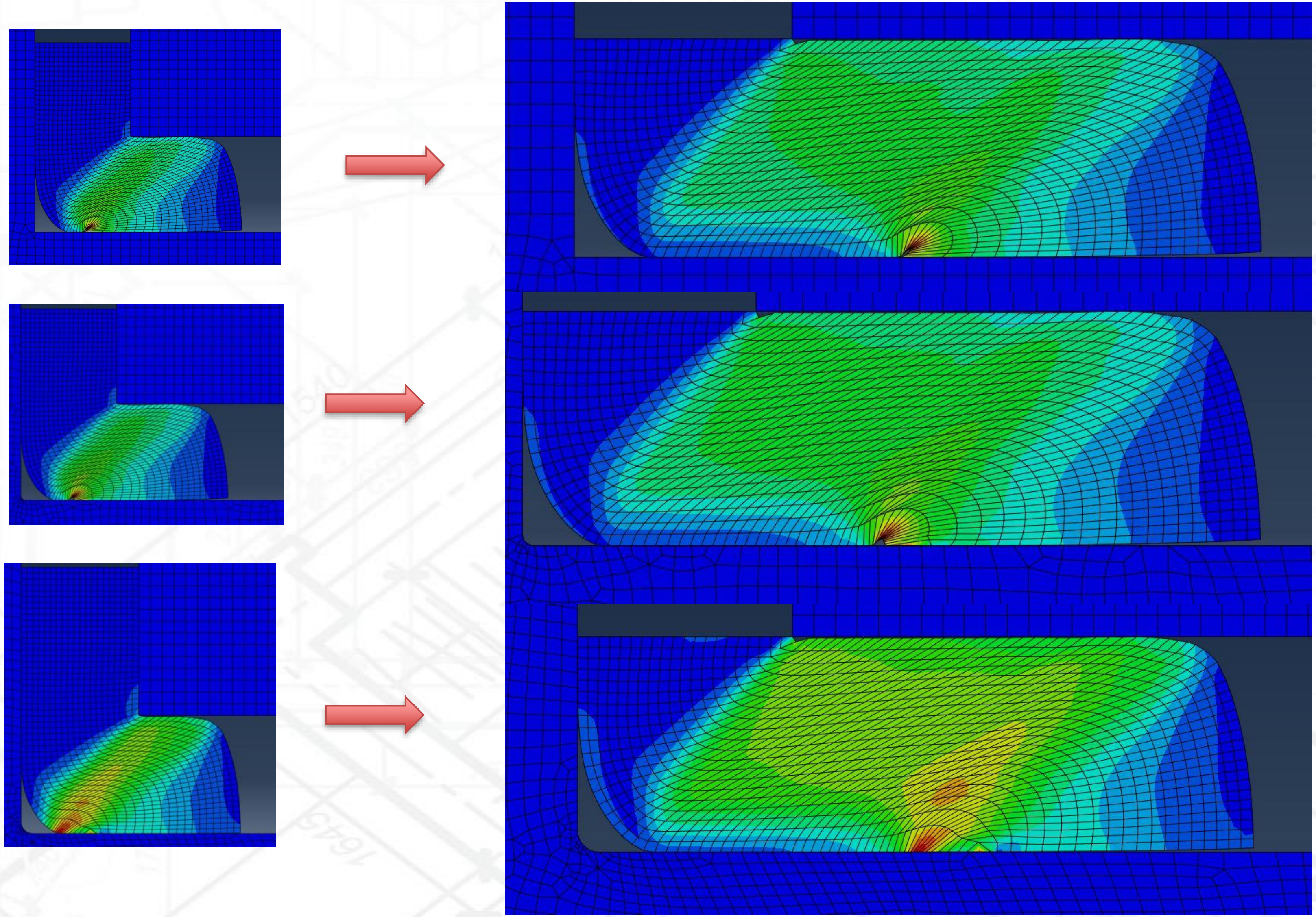
Task 1-3: Effects of Radius of Corner Fillet

- As Iwahashi 96 shows, the radius of the corner fillet impacts shear strain. This is due to the angle of curvature, ψ, formed for the radius. Thus the shear strain is not only dependent on the angle between the first and the second channel, but also the angle of curvature for the radius. This can be seen in equation (4).
- Suh 2001 studied Iwahashi 96's findings from a finite element perspective:
  - When ψ = 0deg, shear deformation largely tracks Iwahasi 96, and when friction is ignored, such is largely uniform through the work-piece.
  - When ψ increases, the lower-region of the work pieces deforms differently than the upper-region. Thus non-uniform shear deformation grows as ψ increases.



Shear Strain through Work-Piece Based on ψ
Suh 2001

Task 1-3: Effects of Radius of Corner Fillet

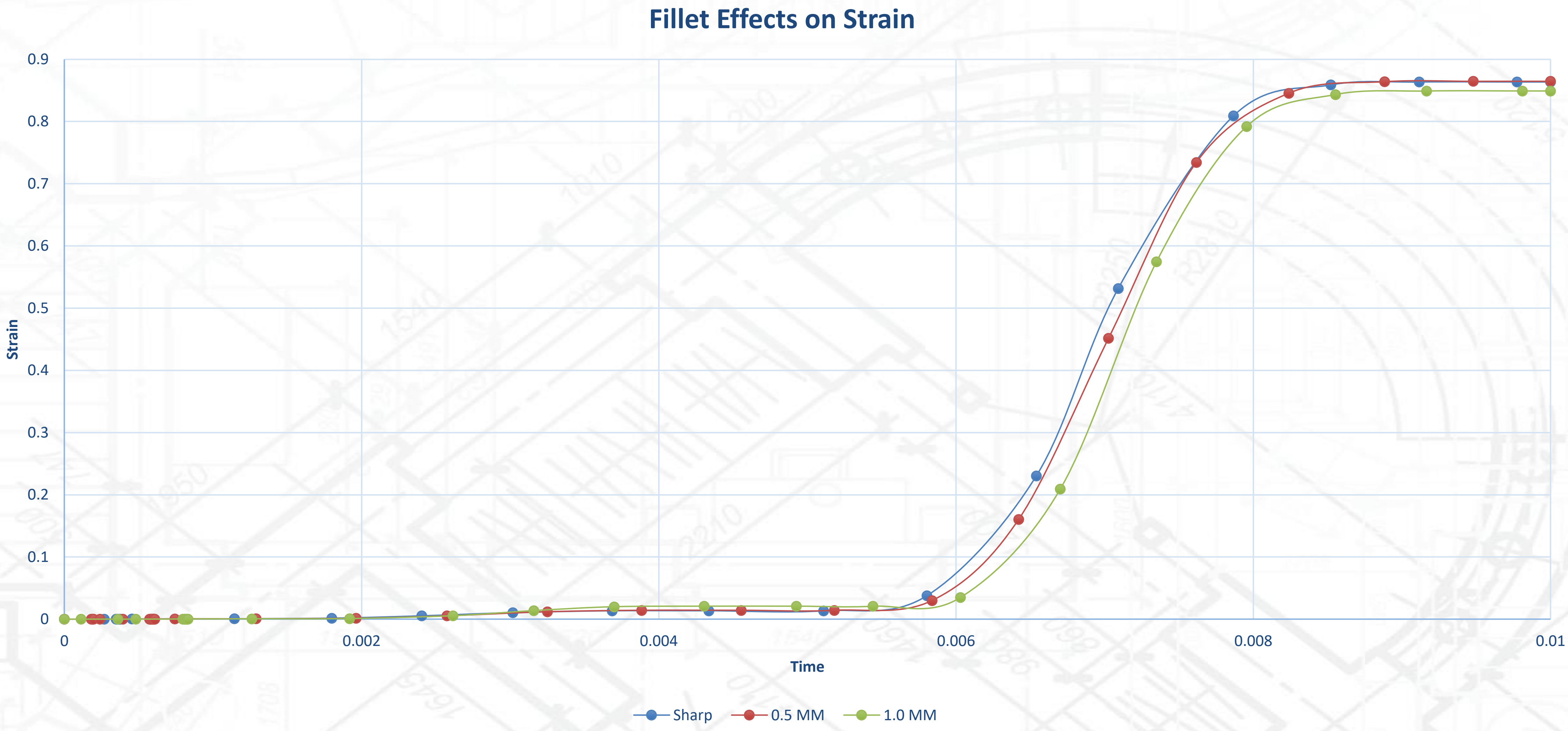


Sharp Corner

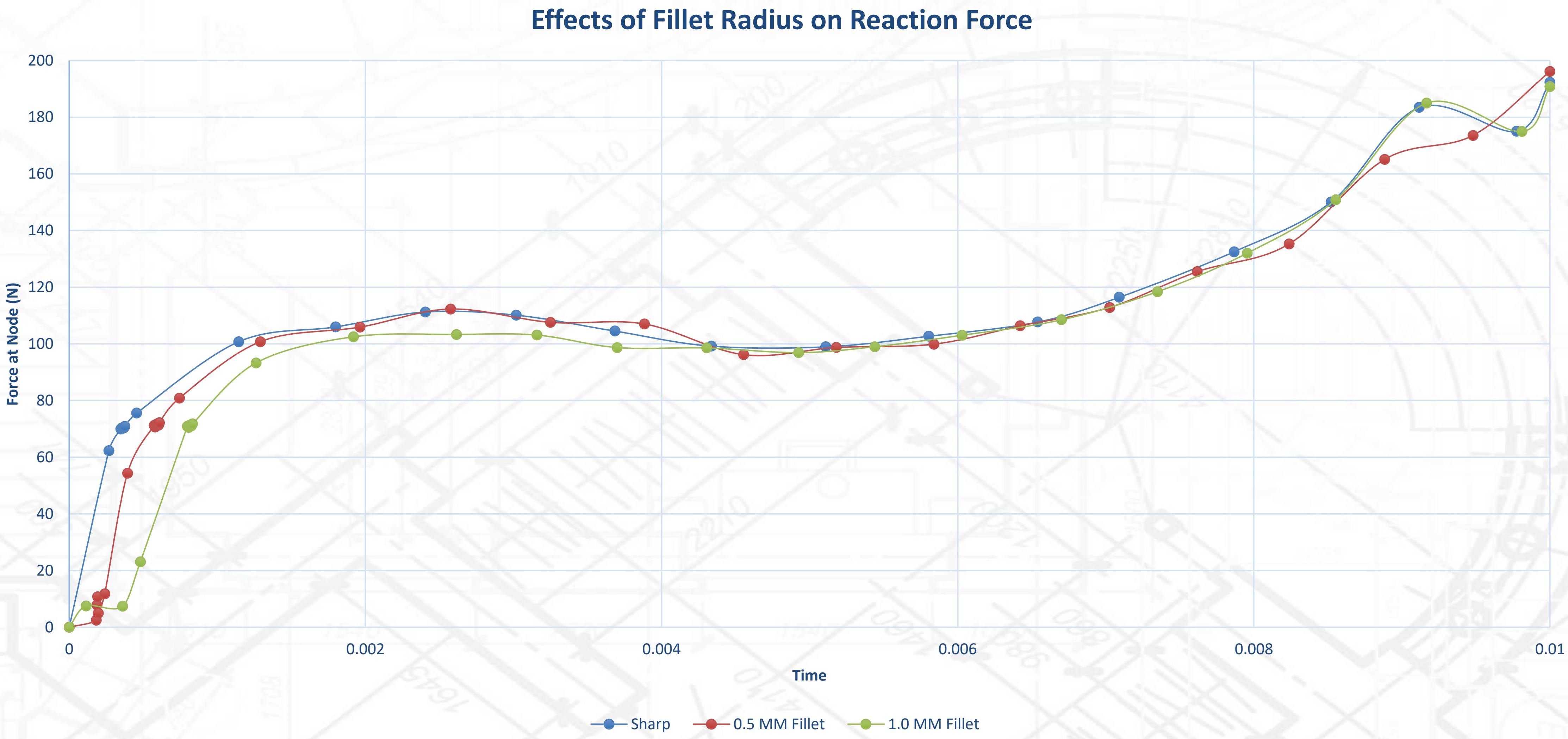
0.5 MM Fillet

1.0 MM Fillet

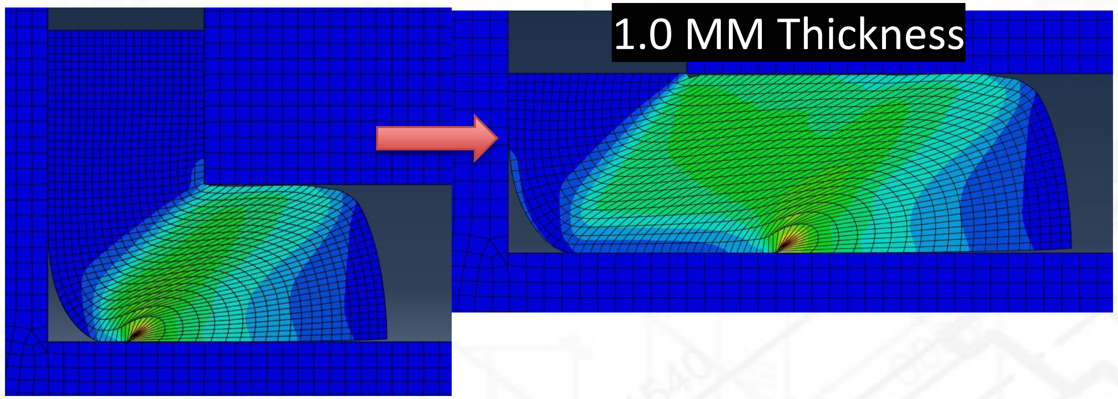
Task 1-3: Effects of Radius of Corner Fillet

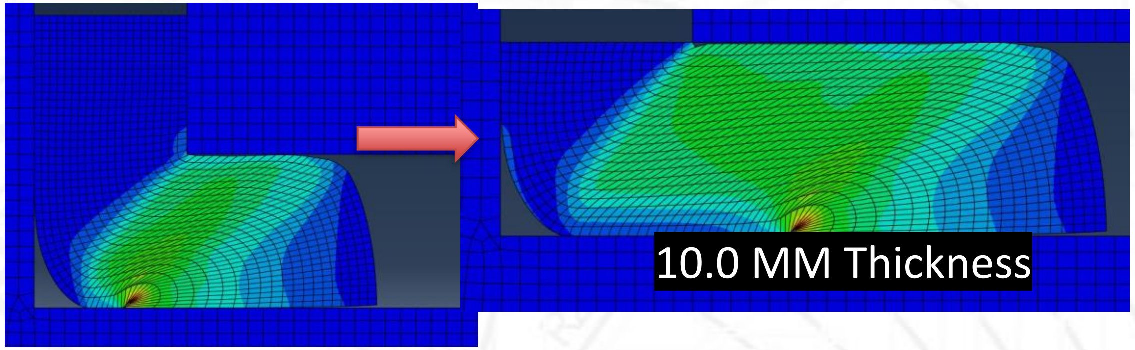


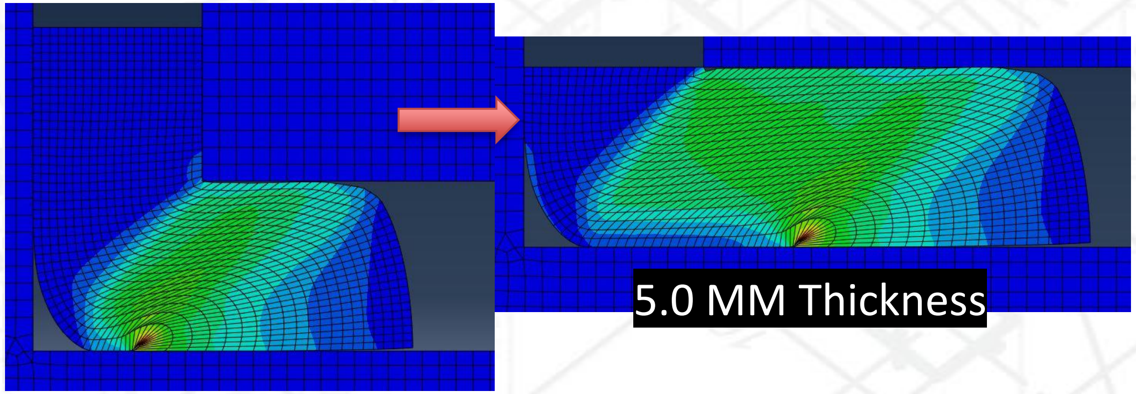
Task 1-3: Effects of Radius of Corner Fillet

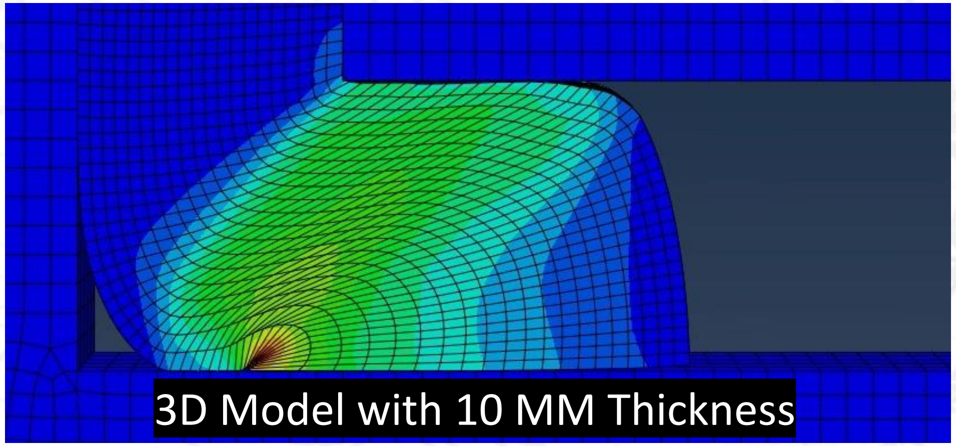


Task 1-4: Comparison of Widths to Thicknesses and 2D v. 3D

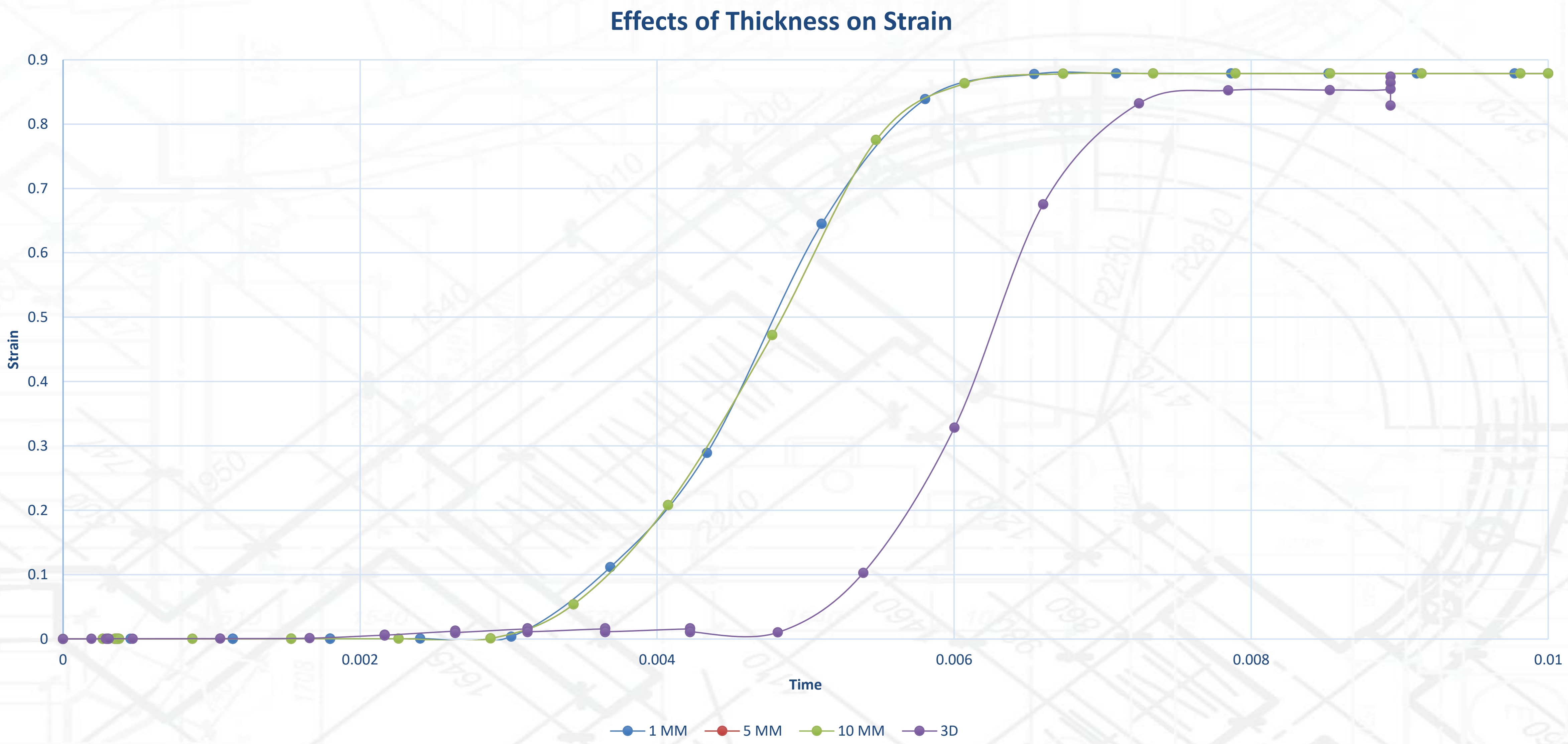








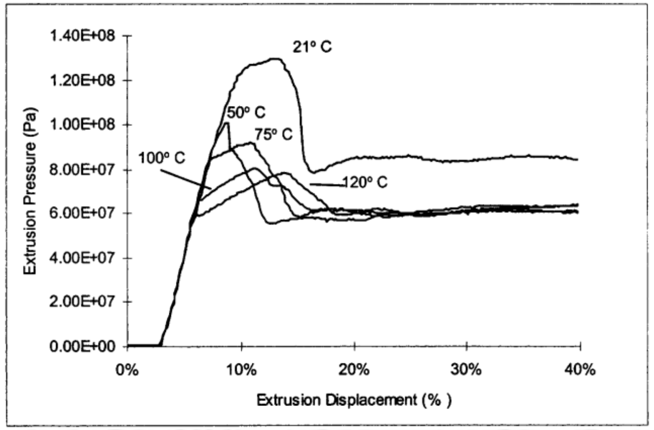
Task 1-4: Comparison of Widths to Thicknesses and 2D v. 3D



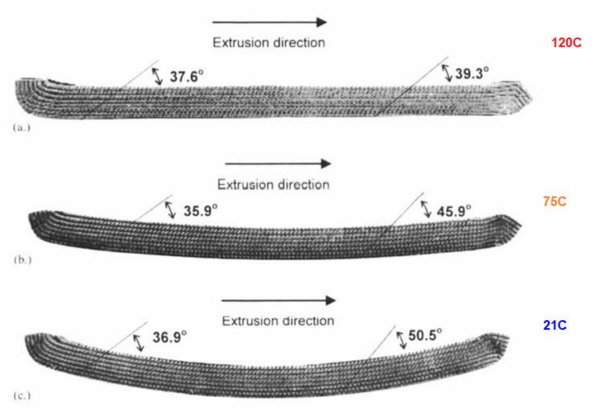
Task 1-4: Comparison of Widths to Thicknesses and 2D v. 3D

Task 1-5: Effect on Temperature on ECAE

- Depending on the material, particularly the properties thereof, temperature may have a profound effect on the work-piece.
- For example, Sue 99 found that for polymers increasing the temperature, while staying below Tg, generally reduces the extrusion pressure. Additionally, increasing the temperature reduces warpage.



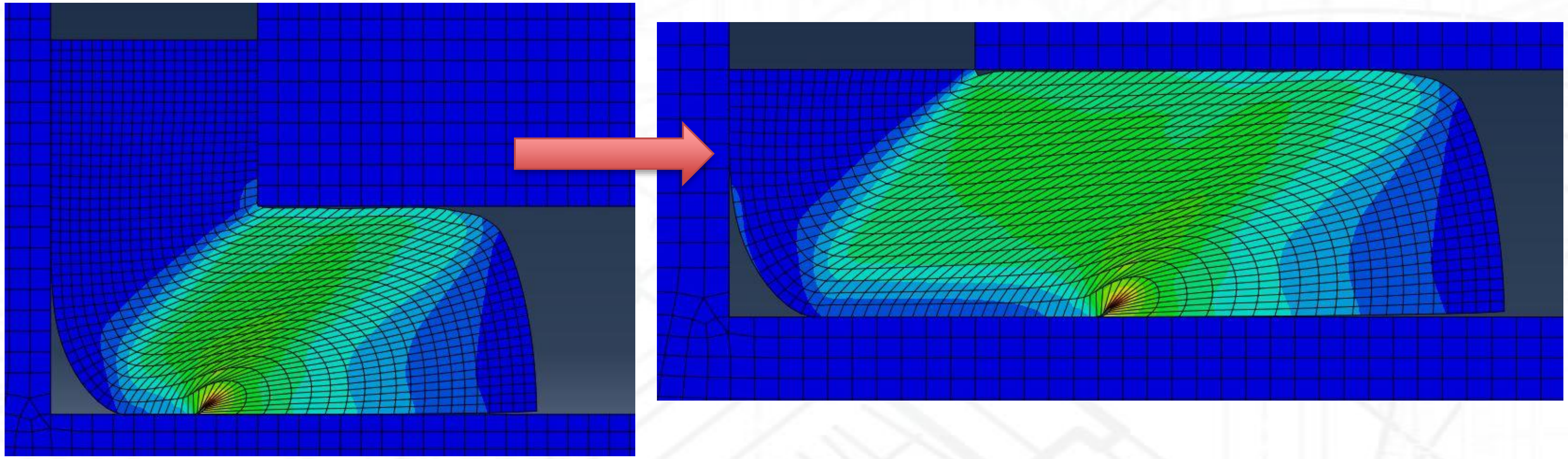
Pressure v. Displacement
Sue 99



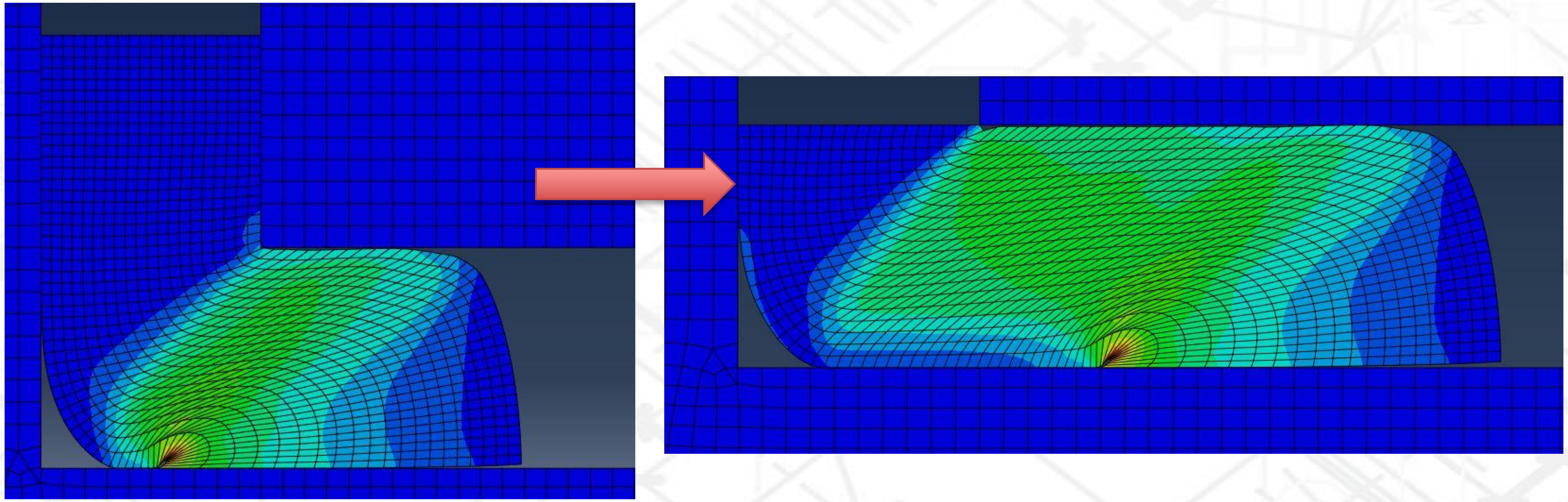
Warpage
Sue 99

Note: Each of the above runs in Sue 99 were performed at the same feed rate.

Task 1-5: Effect on Temperature on ECAE

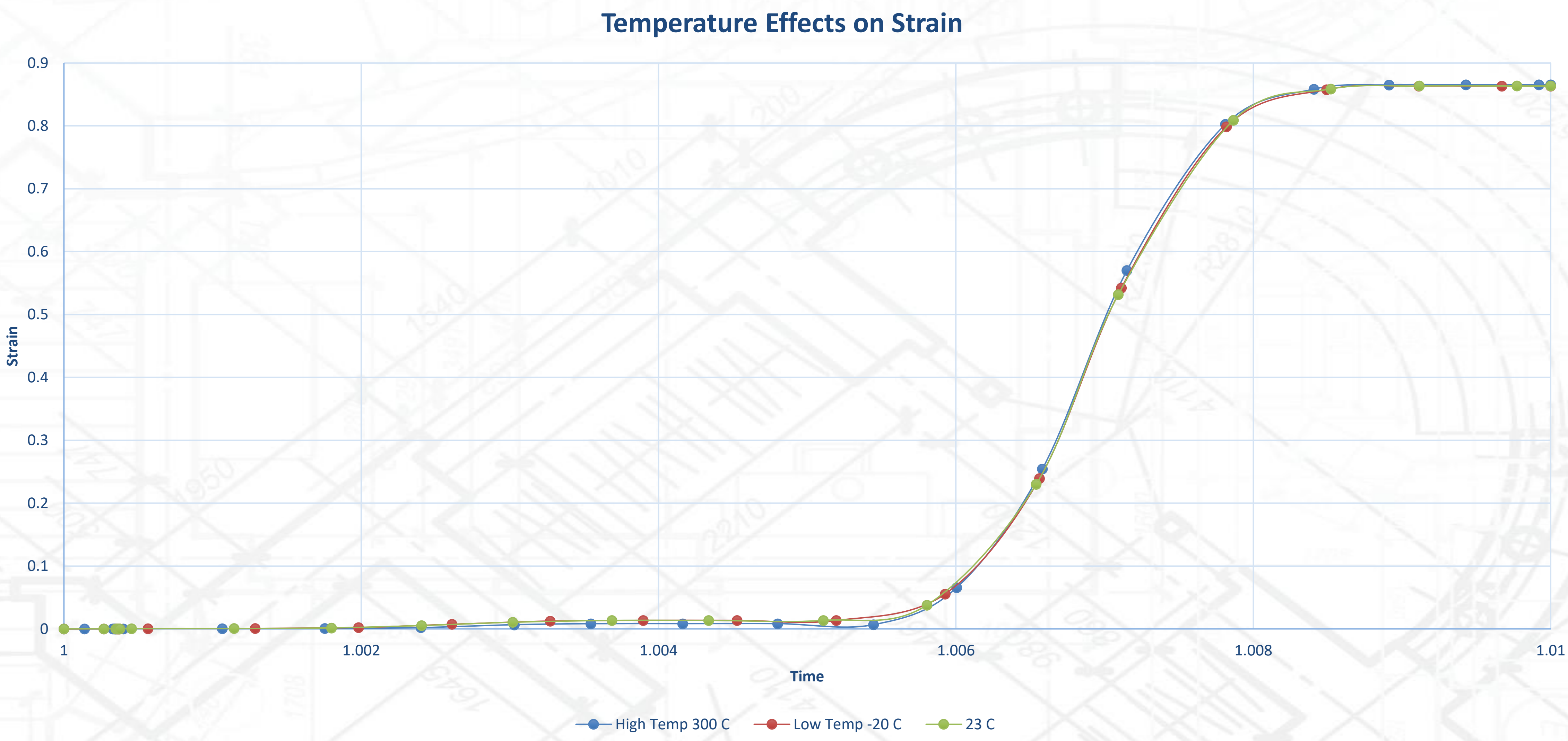


300 C (High temperature)
Oven temperature

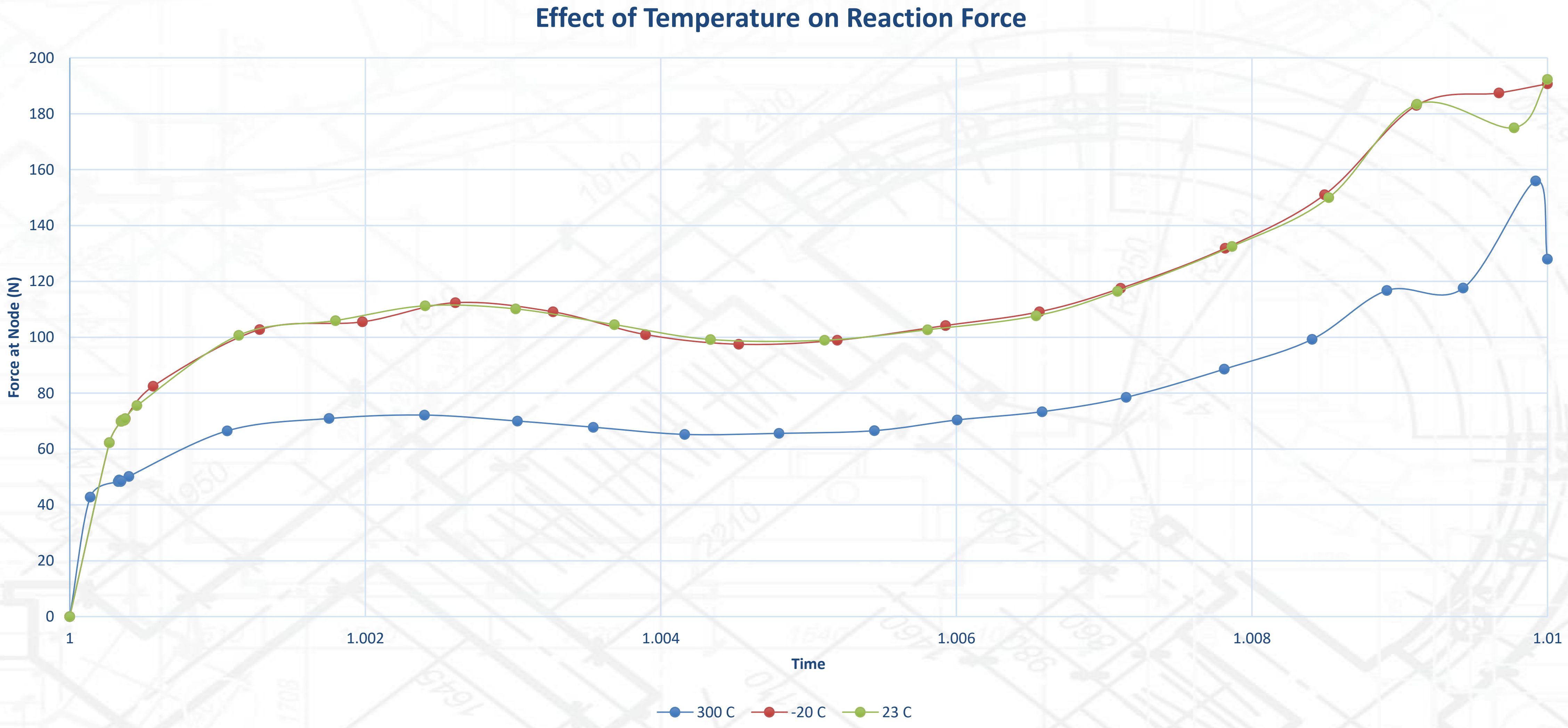


-20 C (Low temperature)
Freezer temperature

Task 1-5: Effect on Temperature on ECAE



Task 1-5: Effect on Temperature on ECAE



References

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2. Vladimir Segal, *Equal-Channel Angular Extrusion (ECAE): From a Laboratory Curiosity to an Industrial Technology*, in *Metals* (2020) (referred to herein as “Segal 20”).
3. Yoshinori Iwahashi et al., *Principle of Equal-Channel Angular Pressing for the Processing of Ultra-Fine Grained Materials*, in *Scripta Materialia*, vol. 35, no. 2, 143-146 (1996) (referred to herein as “Iwahashi 96”).
4. Hung-Jue Sue et al., *Simple Shear Plastic Deformation Behavior of Polycarbonate Plate Due to the Equal Channel Angular Extrusion Porcess. I: Finite Element Methods Modeling*, in *Polymer Engineering and Science*, vol. 39, no. 12, 2505-2515 (Dec. 1999) (referred to herein as “Sue 99”).
5. Jin-Yoo Suh et al., *Finite Element Analysis of Material Flow in Equal Channel Angular Pressing*, in *Scripta Materialia (*2001) (referred to herein as “Suh 2001”).
6. Surya R. Kalidindi at al., *Modeling Texture Evolution in Equal Channel Angular Extrusion Using Crystal Plasticity Finite Element Models*, in *International Journal of Plasticity* 768-779 (2009) (referred to herein as “Kalidindi 09”).