FADI-AMT
Advanced Material Testing

Formability Testing for Determining the FLC_0 for Mg e-Form Plus (Batch-4) Sheets @ 200 ˚C and Different Strain Rates

Report Submitted to USAMP

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Materials

Designations

- *One material was received; the material was given an internal FADI-AMT designation (these are designations used internally for: (1) consistency of labeling data files and test samples (2) to maintain privacy since we test/analyze many materials by many suppliers).*

- *Material label for the magnesium sheets provided by USAMP for this project is:*
    - *M20: Magnesium e-Form Plus Batch-4 (~1.18mm thick sheets)*

Materials and Tests

Designations

- *Test Label Format:* ***M**α**_**β**(**γ**)-**τ**-SR**δ**-**$\zeta\psi$*

***M** : Magnesium Alloy*

α : Material Number (20)

β : Test Type (UT: Uniaxial Tension, PST: Plane-Strain Tension, BBT: Balanced Biaxial Tension, FLC: Forming Limit Curve Testing)

γ : Test Approach (for FLC(MS-OP): FLC Testing via Mechanical Stretching using an Out-Of-Plane Punch)

τ : Test Temperature (RT or 200C)

***SR**: Strain rate*

δ : Nominal Strain Rate Value (0.01, 0.1 & 1 s^{-1})

ζ : Orientation (TD)

ψ : Test Repeat Number (1, 2, 3, …)

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Thickness Measurements

- *Thickness measurements were taken at different locations across the provided blanks; the recorded measurements are shown below.*

Thickness Measurements (mm) ▶	***Thickness Measurements (mm)***											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	***Avg.***	*STD*
M20 (Magnesium e-Form Plus Batch-4)	*1.181*	*1.182*	*1.181*	*1.184*	*1.187*	*1.183*	*1.181*	*1.187*	*1.180*	*1.181*	***1.183***	*0.0063*

Testing Overview

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Testing Overview

I) FLC @ 23 ˚C and 0.01 s^{-1}: Test Matrix

- *Several types of tests were performed in this project as follows:*

I) FLC(MS-OP) @ Room Temperature:

This is conventional formability testing via the Nakajima out-of-plane approach; testing was performed at room temperature at a quasi-static rate in order to establish the baseline behavior of the material.

Materials Tested	Test Temperature (˚C)	Strain Rate (s^{-1})	Sample Geometry	Tested Samples (Reported)
M20 (Magnesium e-Form Plus Batch-4)	RT (23)	0.01	MS-OP (UT)	3 [3 more were added*] (6)
			MS-OP (PST)	3 [5 more were added] (8)
			MS-OP (BBT)	3 [4 more were added] (6)

*Extremely high scatter was noted in the results, thus additional test samples were added.

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Testing Overview

II) FLC @ 200 ˚C & Different Strain Rates: Test Matrix

- *Several types of tests were performed in this project as follows:*

II) FLC (Different Approaches) @ 200 ˚C & Different Strain Rates:

IIA) Uniaxial Tension @ 200 ˚C & Different Strain Rates:

These are custom uniaxial tension tests performed using a special sample geometry and with grips specifically designed for high temperature deformation; testing was performed first to obtain the flow curves of the material at different strain rates, and then to obtain the FLC points corresponding to the uniaxial loading case.

Materials Tested	Test Temperature (˚C)	Strain Rate (s^{-1})	Sample Geometry	Tested Samples (Reported)
M20 (Magnesium e-Form Plus Batch-4)	200	0.01	UT-MR (Custom sub-sized sample for testing at higher-than ambient temperatures and different strain rates)	5 (4)
		0.1		5 (5)
		1		5 (4)

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Testing Overview

II) FLC @ 200 ˚C & Different Strain Rates: Test Matrix

- *Several types of tests were performed in this project as follows:*

II) FLC (Different Approaches) @ 200 ˚C & Different Strain Rates:

IIB) Plane-Strain Tension @ 200 ˚C & Different Strain Rates:

These are custom pull tests performed using a special sample geometry (designed to achieve near-PST deformation) and with grips specifically designed for high temperature deformation; testing was performed to obtain the FLC points corresponding to the plane-strain loading case (as close as possible).

Materials Tested	Test Temperature (˚C)	Strain Rate (s^{-1})	Sample Geometry	Tested Samples (Reported)
M20 (Magnesium e-Form Plus Batch-4)	200	0.01	PST-III (Custom pull sample with the right length-width ration to achieve near-PST deformation)	3 [3 more were added*] (6)
		0.1		3 [3 more were added] (5)
		1		3 [3 more were added] (6)

**High scatter was noted in the results, thus additional test samples were added.*

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Testing Overview

II) FLC @ 200 ˚C & Different Strain Rates: Test Matrix

- *Several types of tests were performed in this project as follows:*

II) FLC (Different Approaches) @ 200 ˚C & Different Strain Rates:

IIC) Balanced Biaxial Tension @ 200 ˚C & Different Strain Rates:

These are custom pneumatic bulge tests performed using a special die assembly designed for testing at higher-than-ambient temperatures; testing was performed to obtain the FLC points corresponding to the balanced biaxial loading case.

Materials Tested	Test Temperature (˚C)	Strain Rate (s^{-1})	Sample Geometry	Tested Samples (Reported)
M20 (Magnesium e-Form Plus Batch-4)	200	0.01	Square blank	5 (4)
		0.1		5 (3)
		1		5 (3)

Testing Details

FLC Testing @ Room Temperature (Nakajima)

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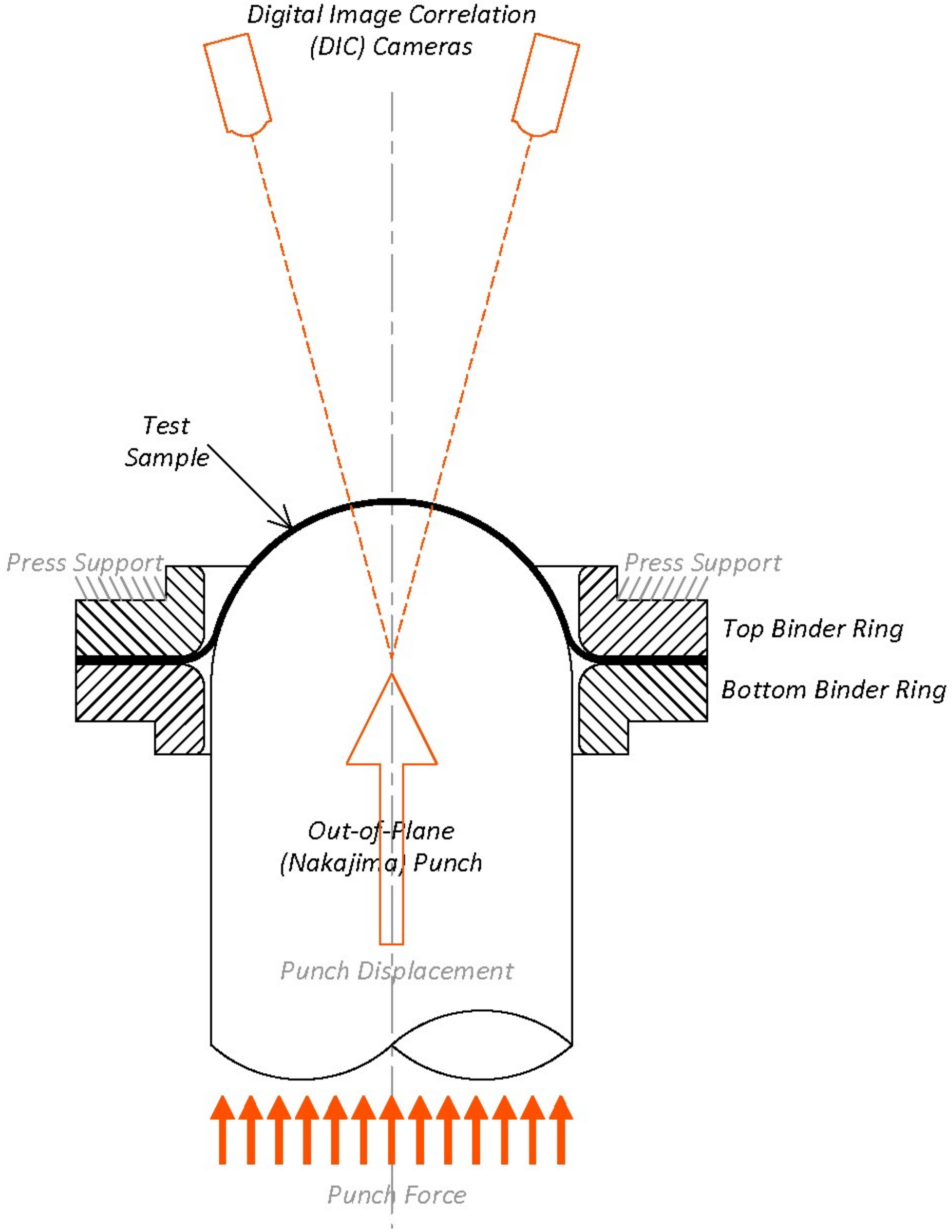
Formability Tests (Nakajima)

Setup and Approach

Setup Schematic ►

Formability testing via mechanical stretching using a ball punch (Nakajima).



Formability Tests (Nakajima)

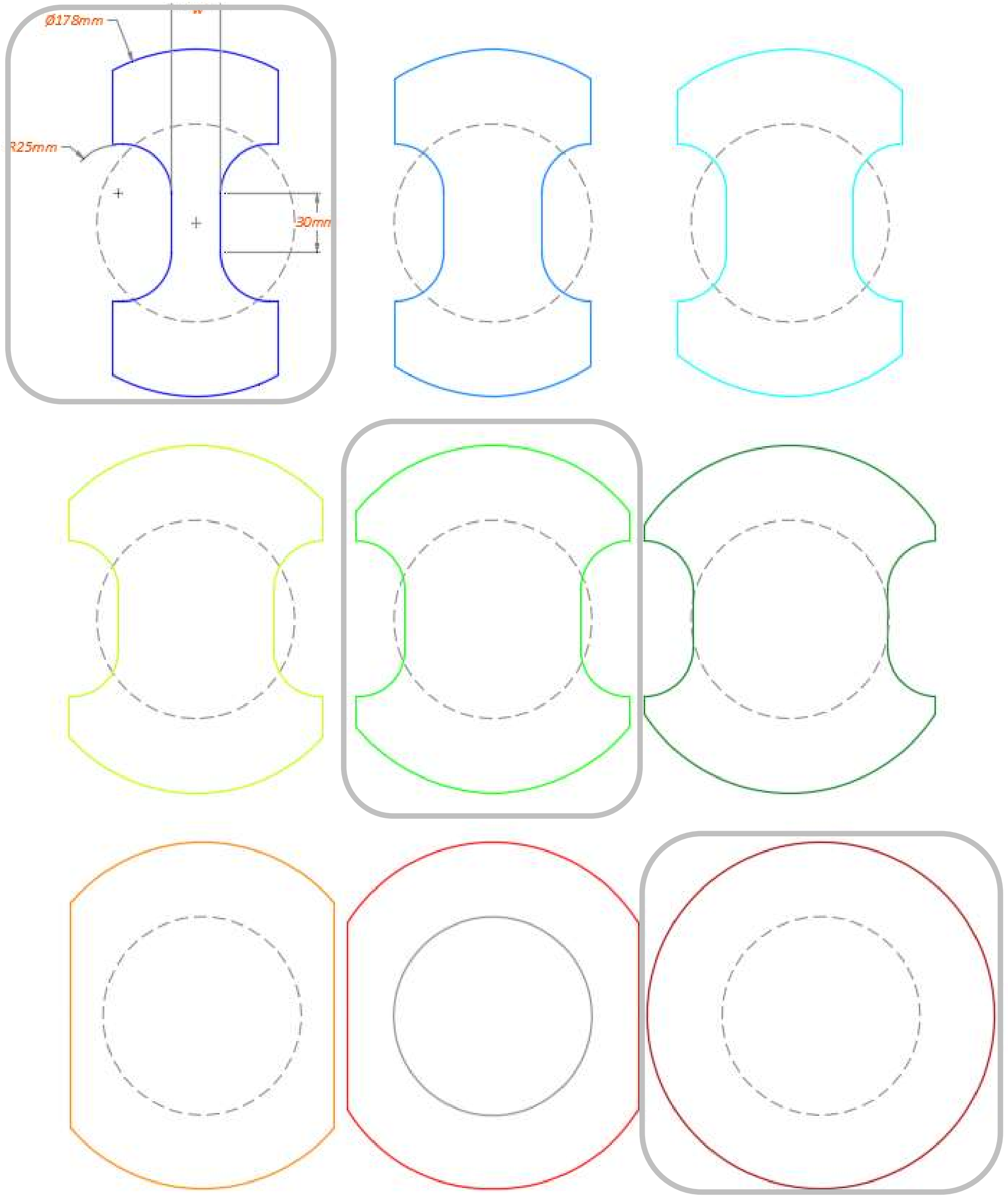
Setup and Approach

Setup Schematic:

Formability testing via mechanical stretching using a ball punch (Nakajima).

Approach:

Several test samples with different geometries can be used to impose different loading paths on the material. Three geometries have been identified here to obtain the three main loading paths and thus the critical points on the FLC: uniaxial tension (UT), plane strain tension (green) and balanced biaxial tension (red) ▶

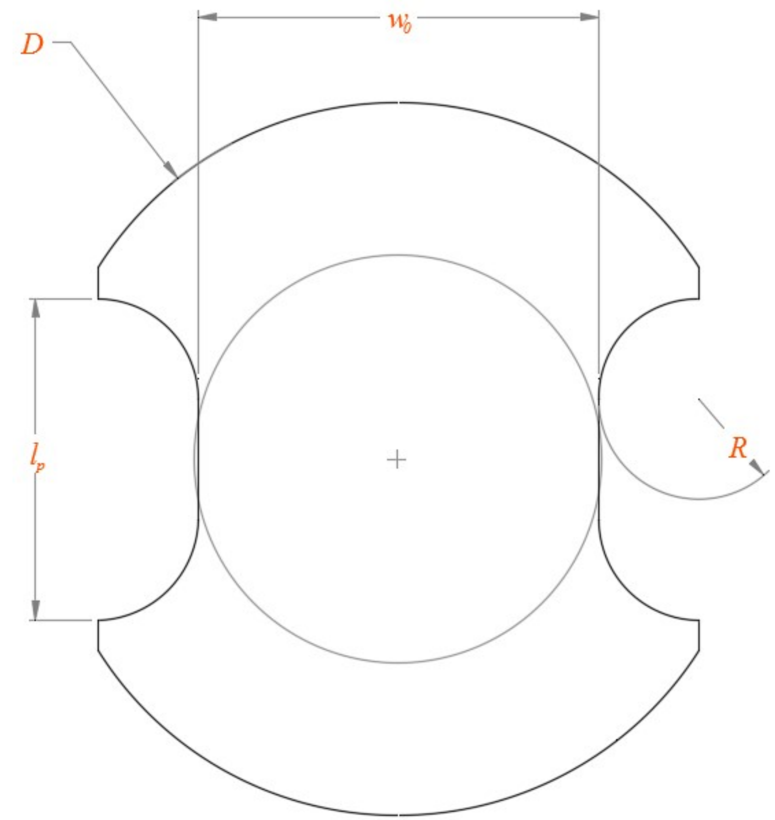


Experimental Details

Test and DIC System Parameters

Test Parameters and Conditions :

- *Test Sample Geometry: Custom geometry for mechanical stretching by Nakajima ball punch testing (FADI-AMT MS-OP_VIII)*
- *Deformation Area (Punch Size): ~101.4mm.*
- *Test Samples: multiple samples (UT, PST and BBT) were cut out of the provided sheets in the TD orientation; samples were cut by waterjet.*
- *Testing was performed at room temperature.*
- *Target strain rate: ~0.01 s^{-1}*
- *Testing was performed using a hydraulic press equipped with a custom mechanical stretching setup. A standard 2-camera system was used for optical non-contact strain measurements (for 3D DIC).*
- *Camera frame rates: Variable (2-20)*
- *A minimum of three samples were tested per condition.*



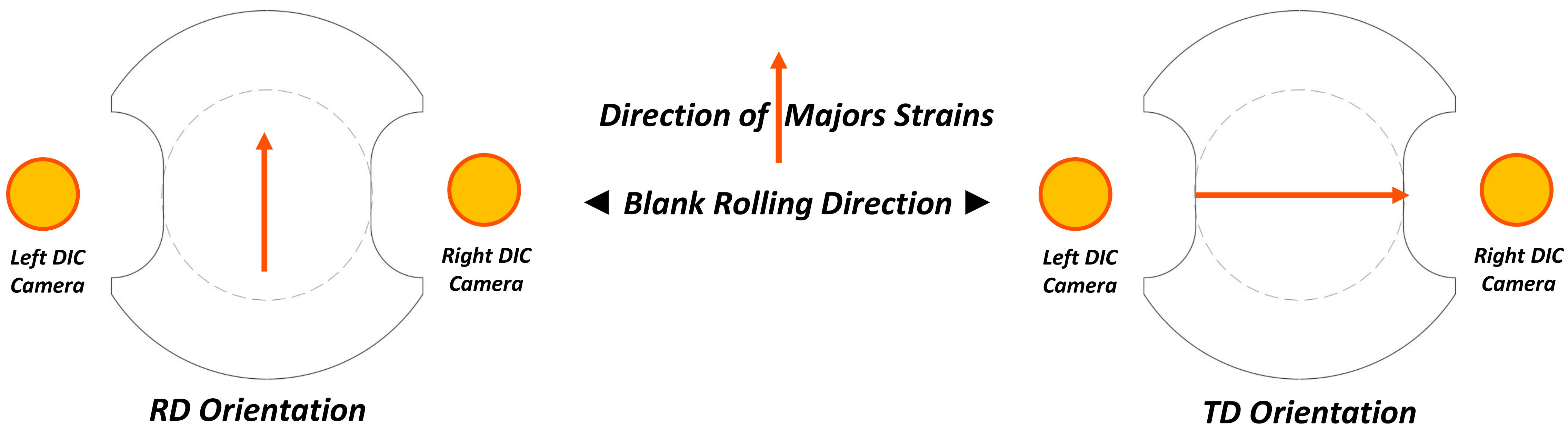
Digital Image Correlation (DIC) :

- *All strain measurements were done based on DIC of recorded images.*
- *The GOM ARAMIS software was used for processing the images.*
- *Pixel resolution of the measurements: ~**45 microns/pixel***

Experimental Details
Other

Orientations ▶

Below is a schematic of the RD and TD orientations (for BBT sample, there is no difference between the two):

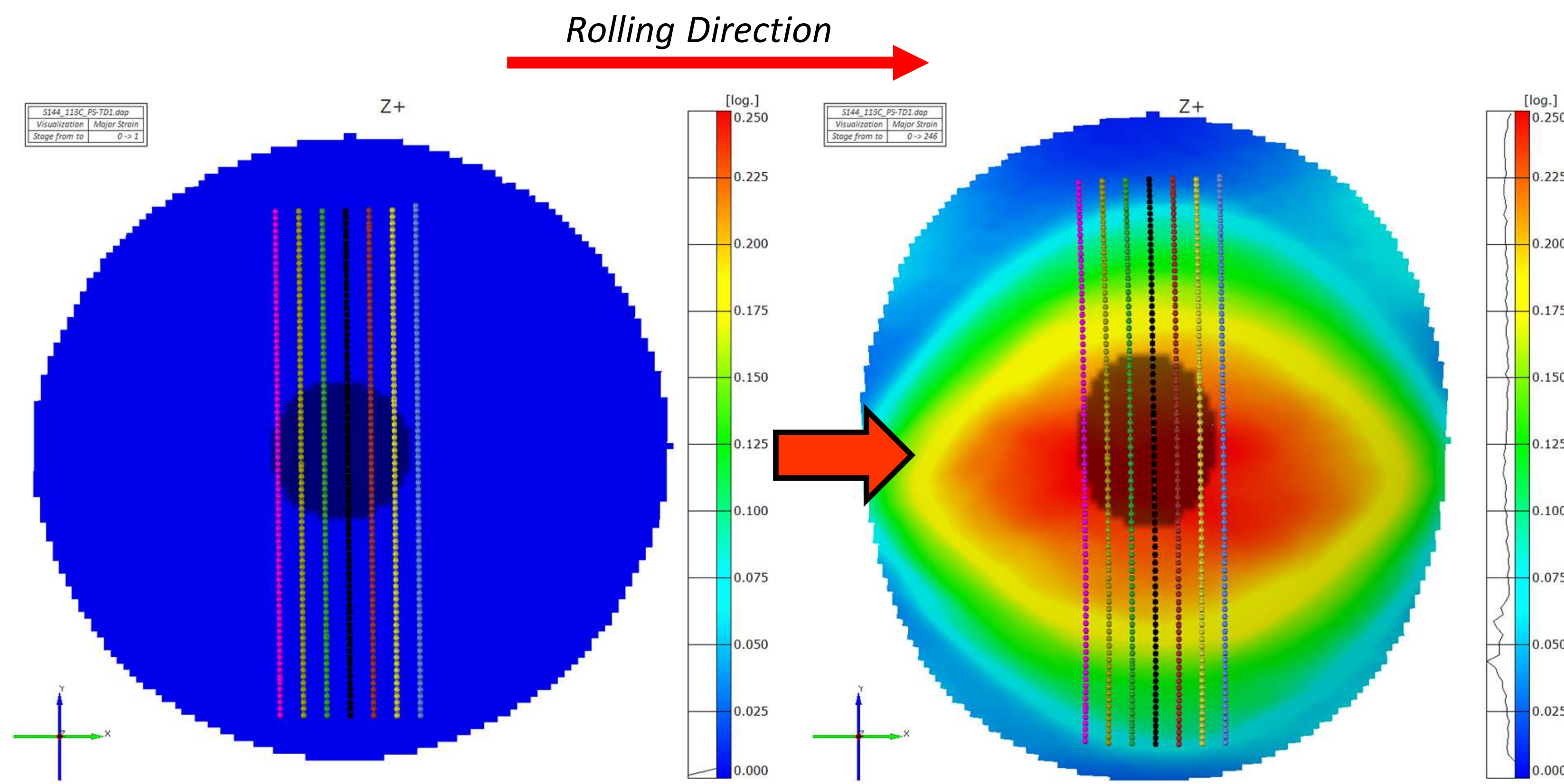


DIC Analysis

DIC Analysis Parameters and Details

DIC Post-Processing Analysis:

- *Surface strains (major vs minor strains) were averaged over a ~ϕ3mm diameter circle close to the apex of the deformed sample _ for constructing the strain path.*
- *5 sections were imposed on each sample in a vertical orientation (all samples failed along the RD).*
- *FLC points were extracted per the ISO-12004 standard, using the section-based method.*



Before *After*

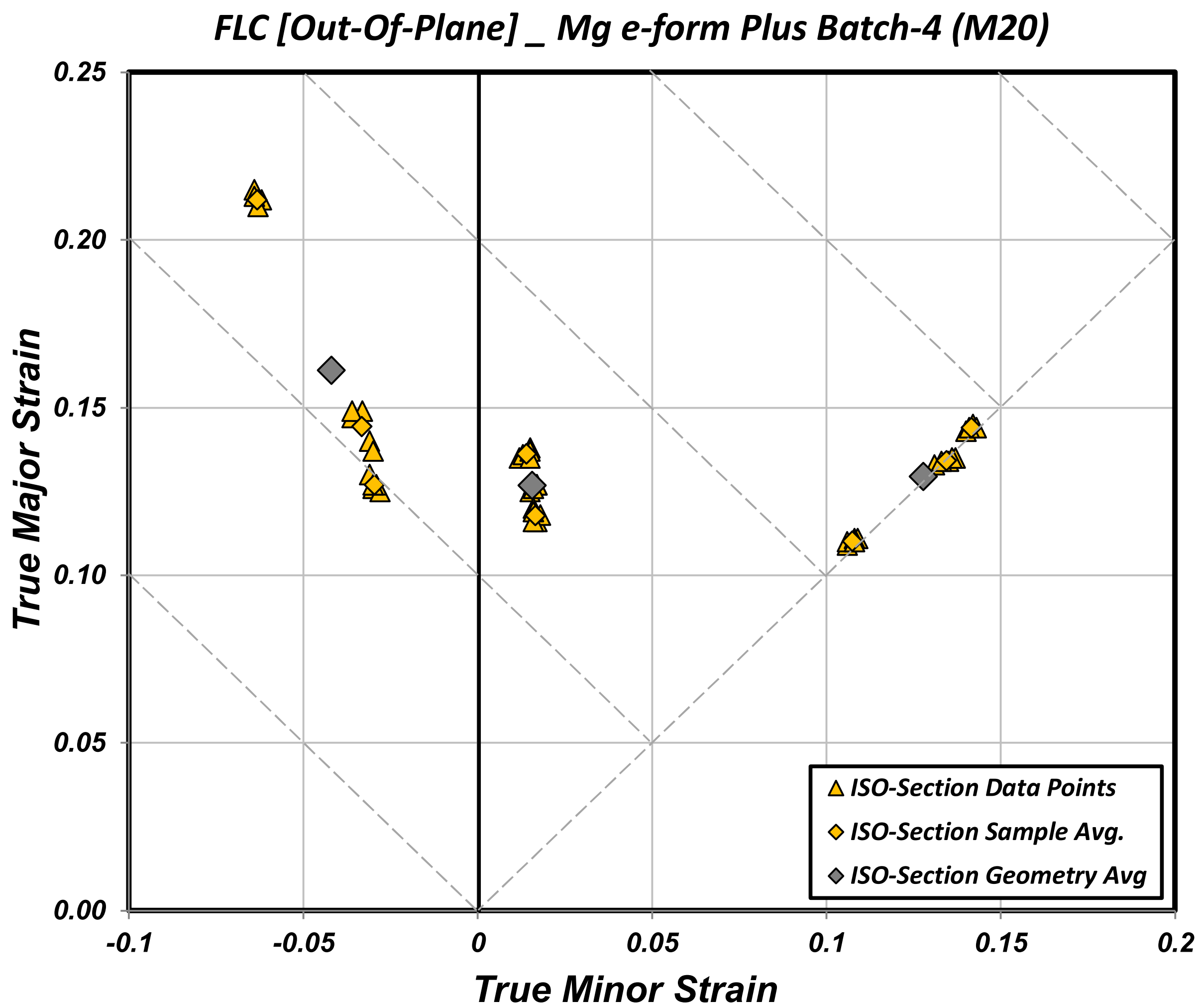
Test Results

FLC Testing @ Room Temperature (Nakajima)

Results

FLC @ 23 ˚C and 0.01 s^{-1}

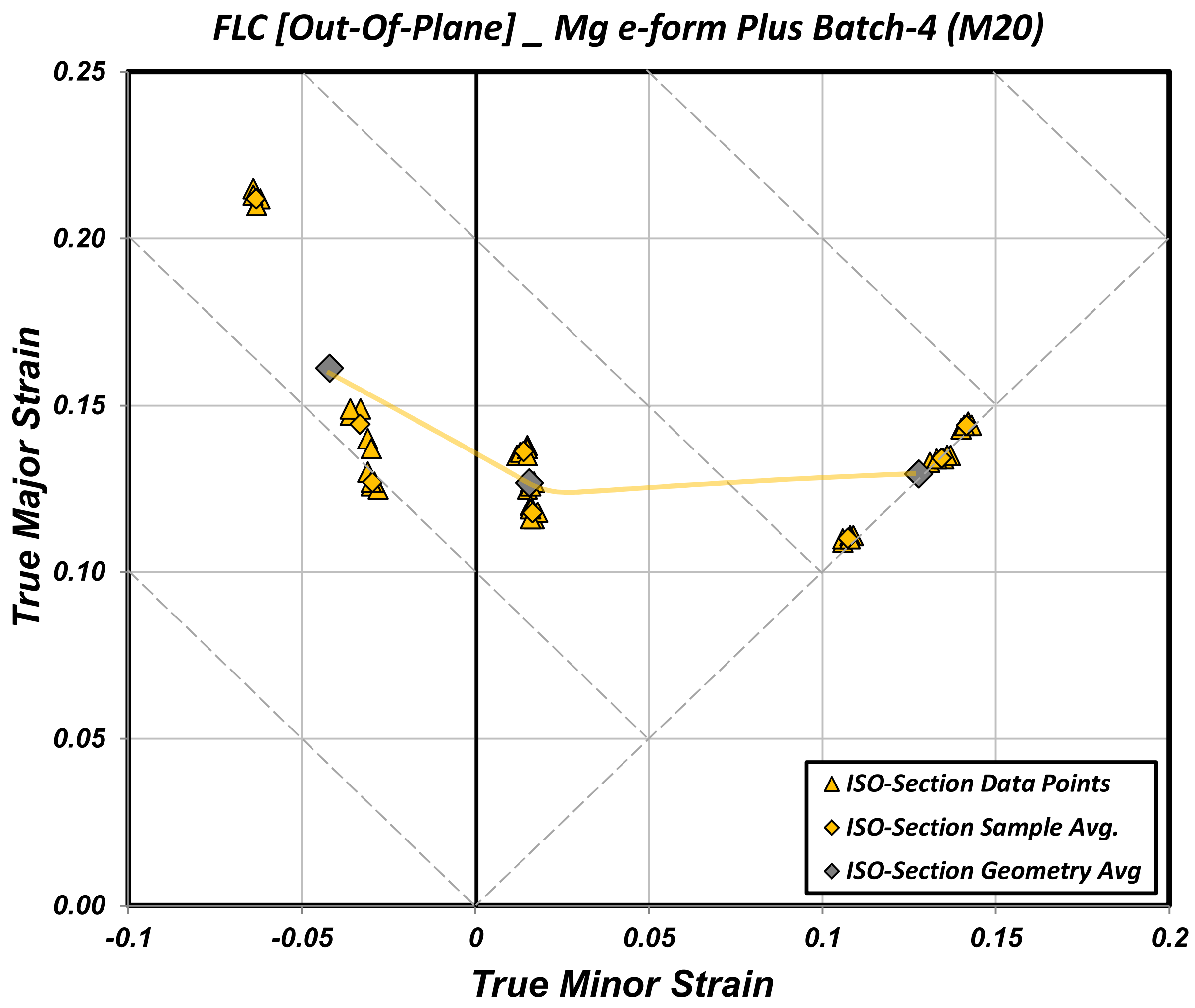
- *The extracted FLC points are shown below; as noted, great amount of scatter was seen based on three repeats per condition; this was an unusual amount of scatter that makes it difficult to construct a reliable FLC.*



Results

FLC @ 23 ˚C and 0.01 s^{-1}

- *The extracted FLC points are shown below; as noted, great amount of scatter was seen based on three repeats per condition; this was an unusual amount of scatter that makes it difficult to construct a reliable FLC.*
- *Below is an attempt to connect the points and shape an FLC!*



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Results

FLC @ 23 ˚C and 0.01 s^{-1}

- *The extracted FLC points are shown below; as noted, great amount of scatter was seen based on three repeats per condition; this was an unusual amount of scatter that makes it difficult to construct a reliable FLC.*
- *Below is an attempt to connect the points and shape an FLC!*

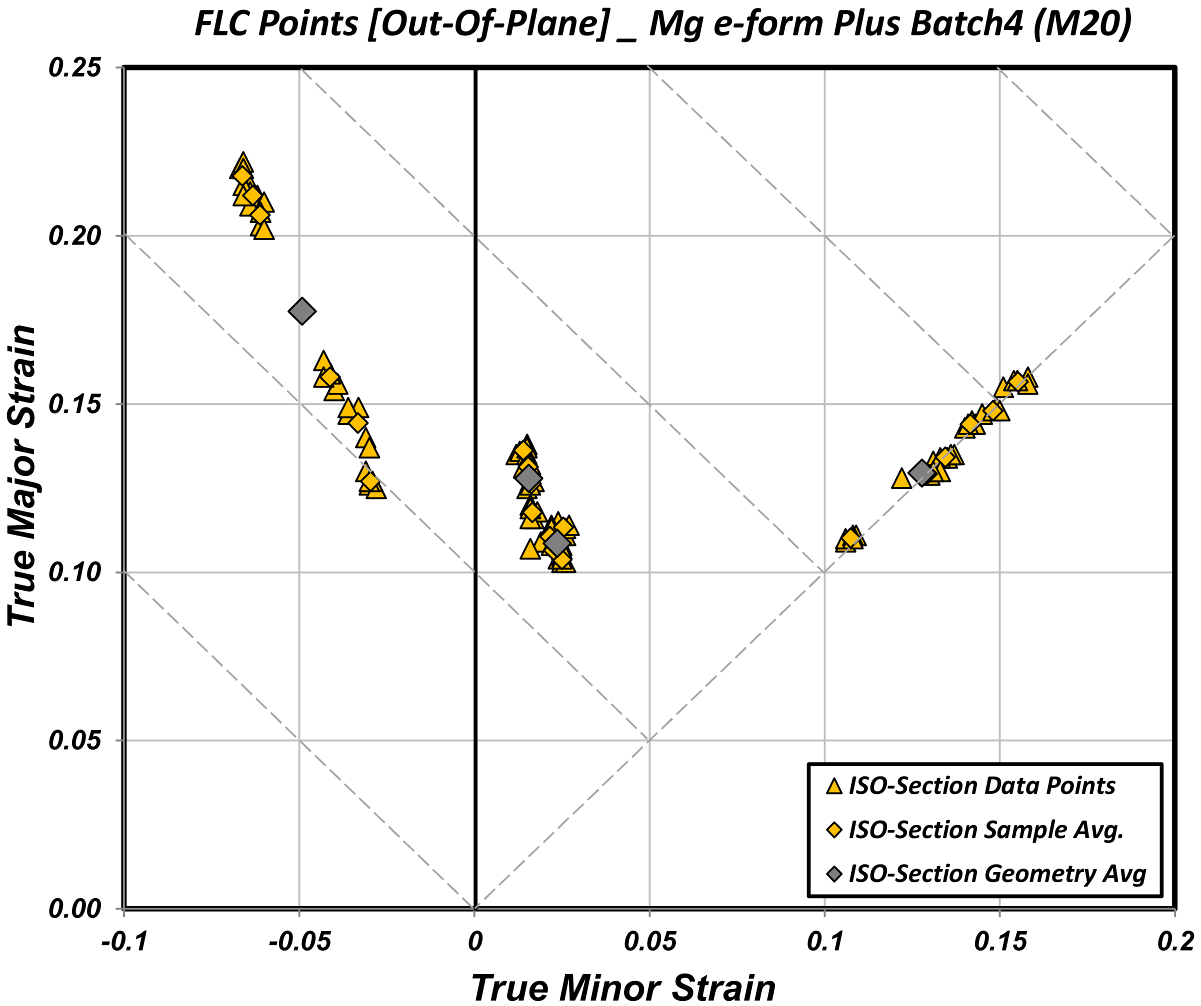
Due to the high scatter, it was decided to increase the number of tests per condition as summarized below. For PST in particular, a second sample geometry was added to check for the robustness of the results.

Materials Tested	Test Temperature (˚C)	Strain Rate (s^{-1})	Sample Geometry	Tested Samples (Reported)
M20 (Magnesium e-Form Plus Batch-4)	RT (23)	0.01	MS-OP (UT)	3 [3 more were added*] (6)
			MS-OP (PST)	3 [5 more were added] (8)
			MS-OP (BBT)	3 [4 more were added] (6)

Results

FLC @ 23 ˚C and 0.01 s^{-1}

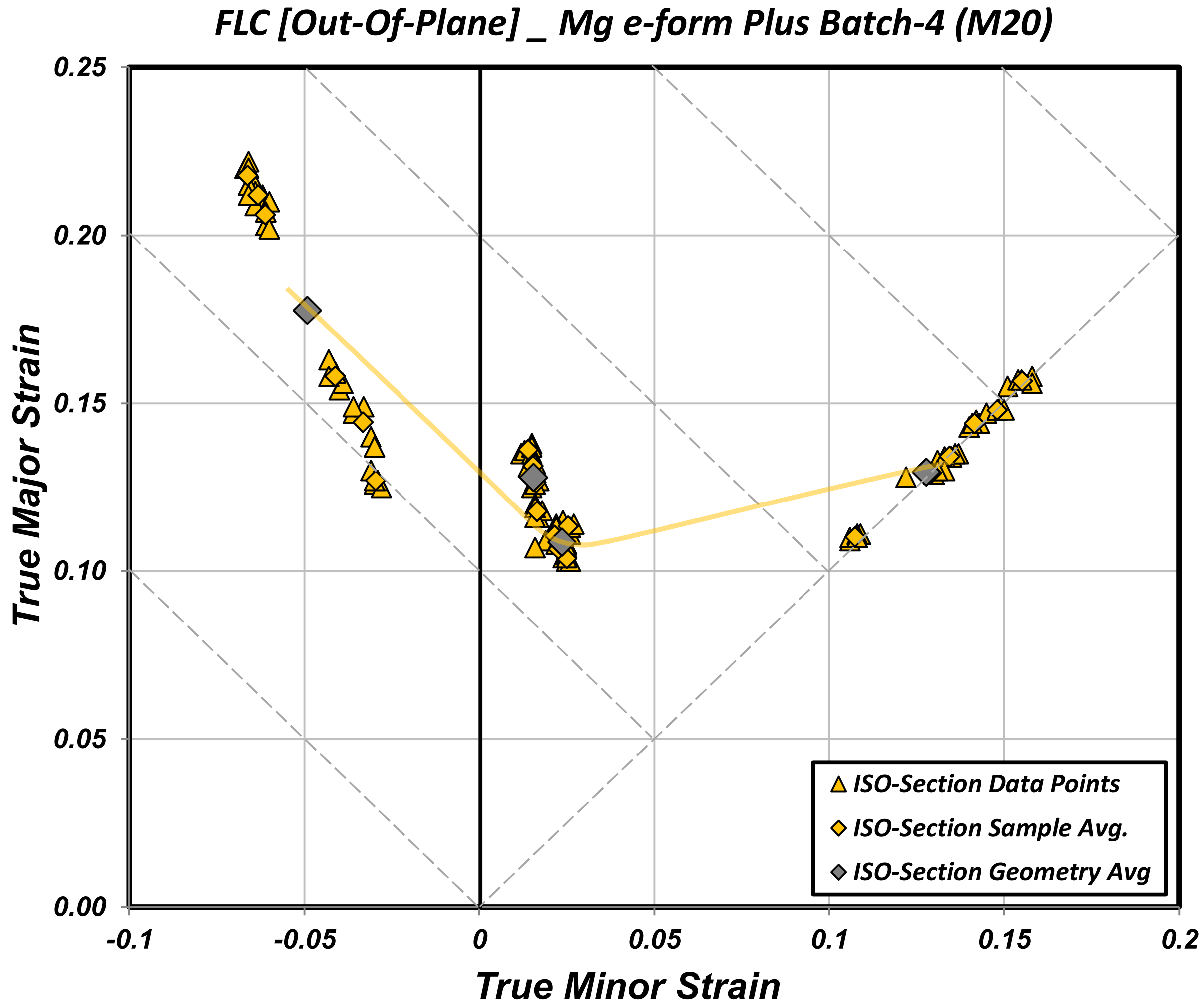
- The updated FLC points are shown below; as noted, the scatter is still high and the new points spread in a similar way over a large domain.
- The scatter is highest for the UT loading case, then for the BBT; the scatter is reasonable for the PST condition!



Results

FLC @ 23 ˚C and 0.01 s^{-1}

- *An FLC was constructed by simply connecting the geometry average points, and the outcome is shown below.*
- *The high scatter seems to be driven by the material (similar levels of scatter were noted in all the other tests at 200C, as will be shown in the subsequent sections)*



Testing Details

FLC Testing @ 200 ˚C and Different Strain Rates

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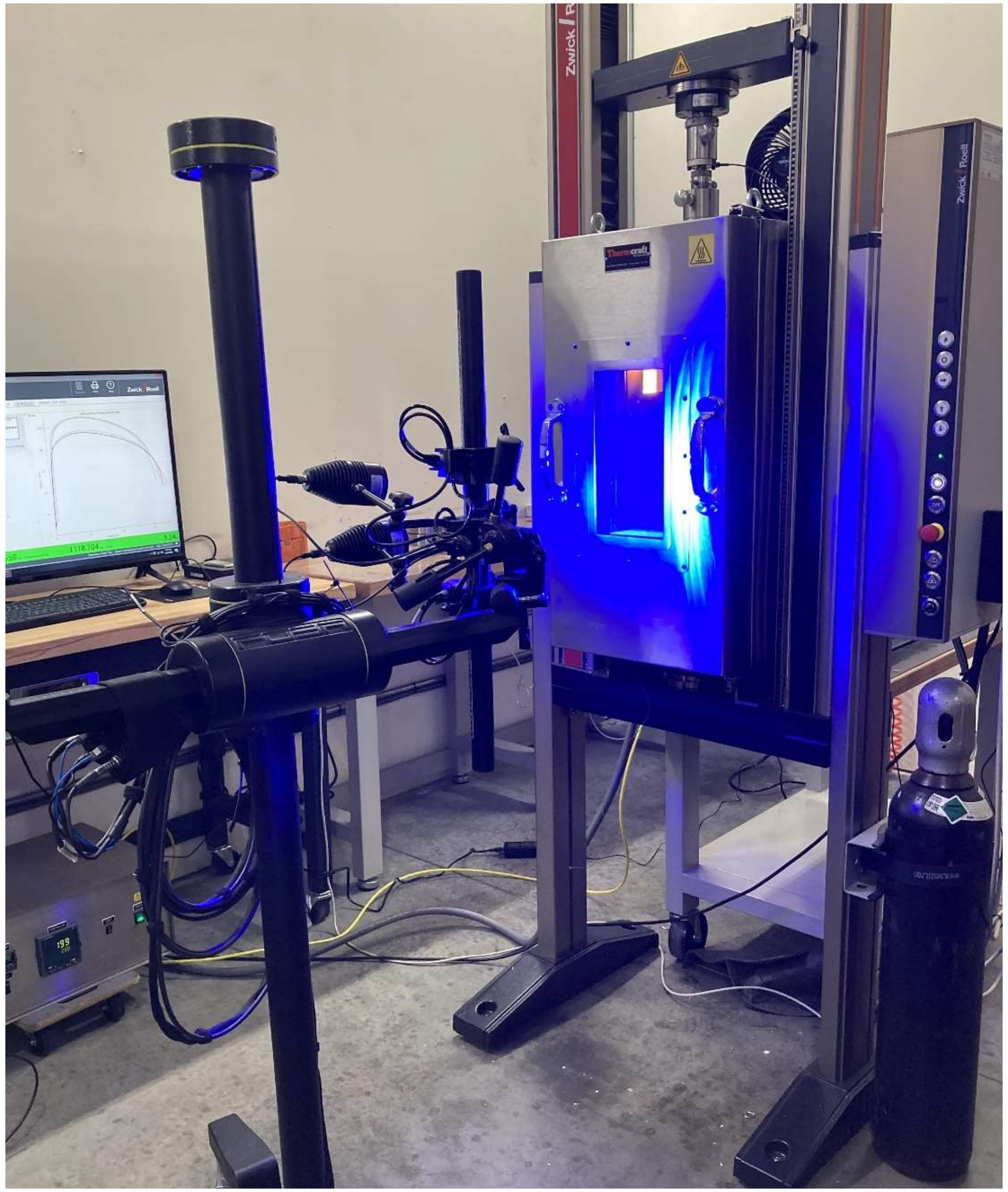
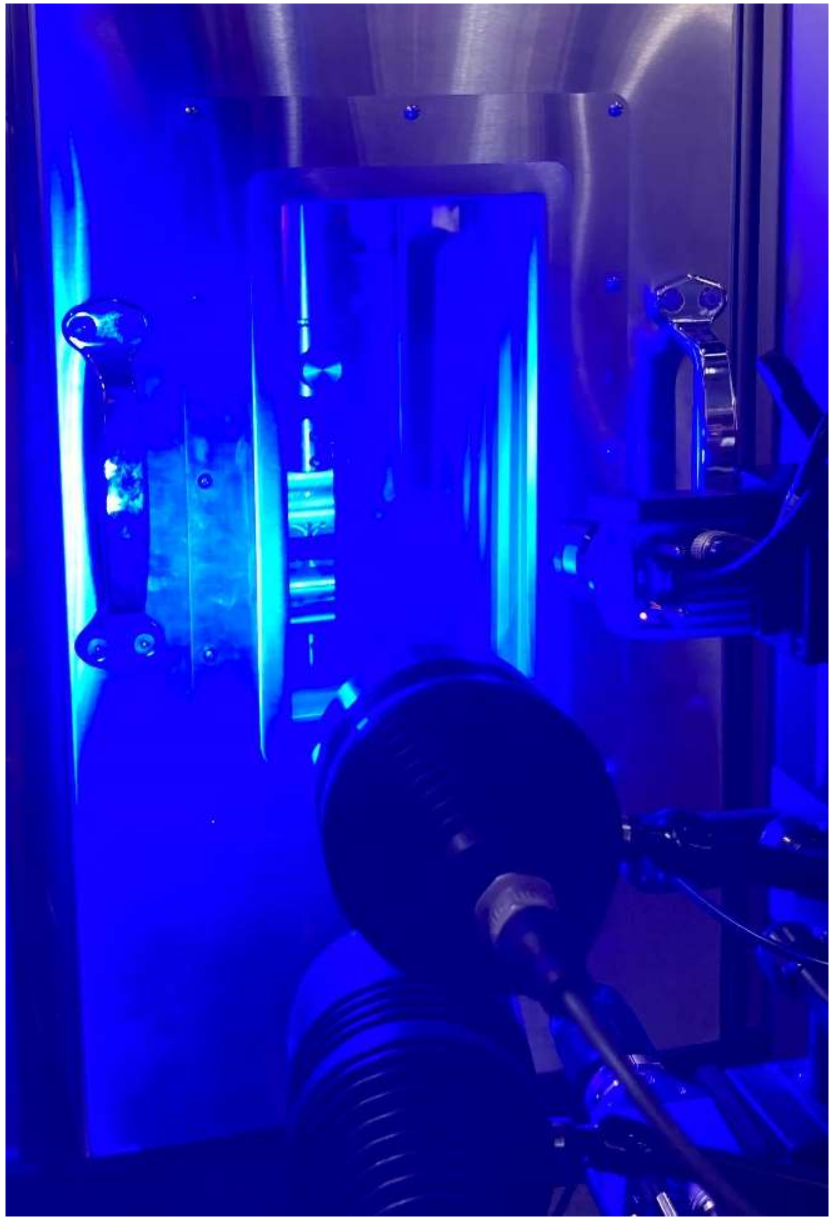
Uniaxial & Plane-Strain Tension Testing @ 200 ˚C

Setup (IIA+IIB)





Uniaxial & Plane-Strain Tension Testing @ 200 ˚C

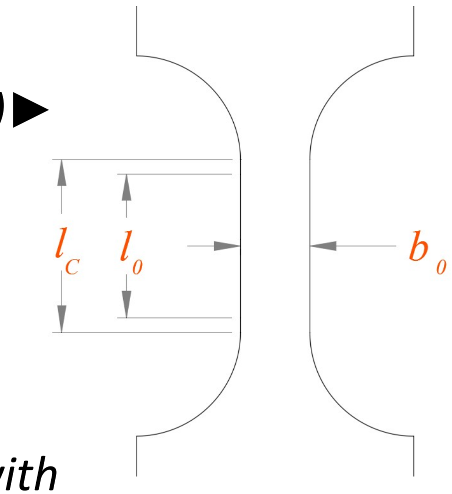
Setup (IIA+IIB)

Experimental Details (Setup-IIA)

Test and DIC System Parameters

Test Parameters and Conditions :

- *Test Sample Geometry: Custom Subsized based for multi-rate testing (FADI-AMT UT-XII7)*▶
- *Deformation Gage Area: ~15mm x ~4mm.*
- *Test Samples: Samples were cut in the TD orientation by wire EDM.*
- *Testing was performed at 200 ˚C.*
- *Target strain rates: ~0.01, 0.1 & 1s^{-1}*
- *Testing was performed using a fast low capacity standard electromechanical load frame with either a standard DIC camera or a single high speed camera for HS-2D DIC strain measurements.*
- *Testing was performed at a near-constant speed that corresponds to the desired strain rate. (under displacement control). Higher accelerations (for 1 s^{-1}) were used to achieve the desired speeds. No slack adaptor was used but rather the design of the grips permits acceleration to the desired speed before engagement with the test sample.*
- *Camera frame rates: variable _ up to 1000fps.*



Digital Image Correlation (DIC) :

- *All strain measurements were done based on DIC of recorded images.*
- *The GOM ARAMIS software was used for processing and post processing the images.*
- *Pixel resolution of the measurements:* ***NA microns/pixel***

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Experimental Details (Setup-IIA)

Test Matrix

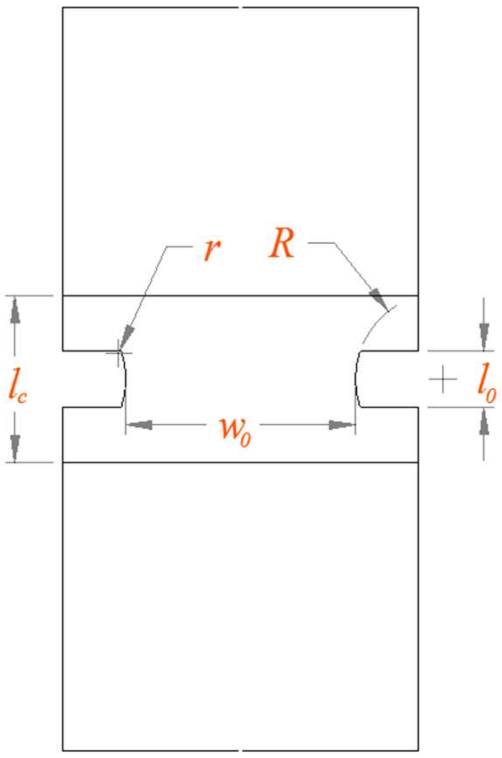
Materials Tested	Test Temperature (˚C)	Strain Rate (s^{-1})	Sample Geometry	Tested Samples (Reported)
M20 (Magnesium e-Form Plus Batch-4)	200	0.01	UT-MR (Custom sub-sized sample for testing at higher-than ambient temperatures and different strain rates)	5 (4)
		0.1		5 (5)
		1		5 (4)

Experimental Details (Setup-IIB)

Test and DIC System Parameters

Test Parameters and Conditions :

- Test Sample Geometry: custom geometry for PST deformation (FADI-AMT PST-III7).
- Deformation Gage Area: NA.
- Test Samples: Samples were cut in the TD orientation by wire EDM.
- Testing was performed at 200 ˚C.
- Target strain rates: ~0.01, 0.1 & 1s^{-1}
- Testing was performed using a fast low-capacity standard electromechanical load frame with either a standard DIC camera or a single high speed camera for HS-2D DIC strain measurements.
- Testing was performed at a near-constant speed that corresponds to the desired strain rate. (under displacement control). Higher accelerations (for 1 s^{-1}) were used to achieve the desired speeds. No slack adaptor was used but rather the design of the grips permits acceleration to the desired speed before engagement with the test sample.
- Camera frame rates: variable _ up to 1000fps.



Digital Image Correlation (DIC) :

- All strain measurements were done based on DIC of recorded images.
- The GOM ARAMIS software was used for processing and post processing the images.
- Pixel resolution of the measurements: **NA microns/pixel**

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Experimental Details (Setup-IIB)

Test Matrix

<table>
<tr><th>Materials Tested</th><th>Test Temperature (˚C)</th><th>Strain Rate (s^{-1})</th><th>Sample Geometry</th><th>Tested Samples (Reported)</th></tr>
<tr><td rowspan="3">M20 (Magnesium e-Form Plus Batch-4)</td><td rowspan="3">200</td><td>0.01</td><td rowspan="3">PST-III (Custom pull sample with the right length-width ration to achieve near-PST deformation)</td><td>3 [3 more were added*] (6)</td></tr>
<tr><td>0.1</td><td>3 [3 more were added] (5)</td></tr>
<tr><td>1</td><td>3 [3 more were added] (6)</td></tr>
</table>

Pneumatic Bulge Testing (Balanced Biaxial)

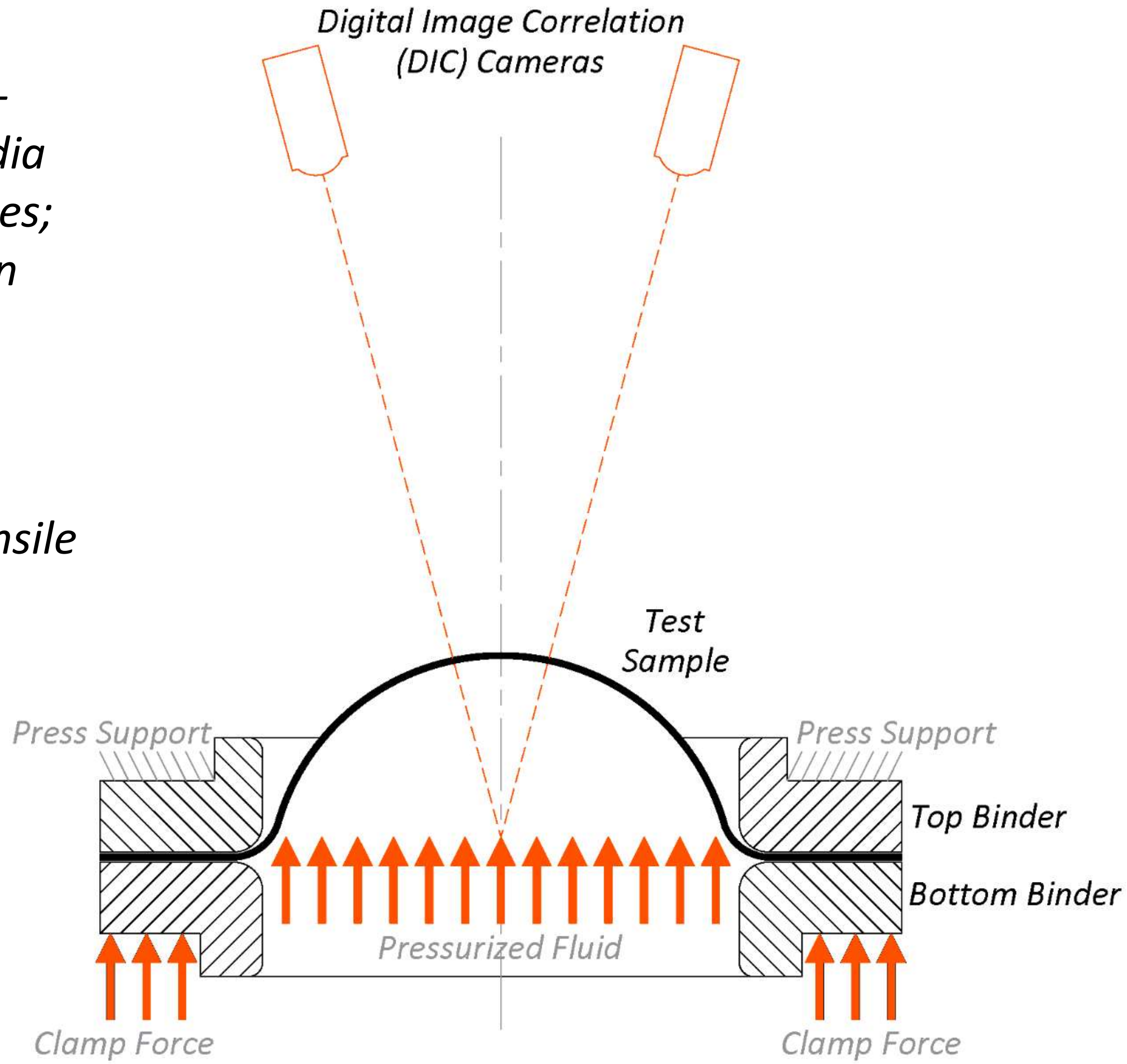
Setup (IIC) and Approach

Setup Schematic ▶

Friction-free test in which the material is exposed to out-of-plane balanced biaxial deformation until failure (bulge media here is gas to accommodate the relatively high temperatures; FS mirrors were used to enable camera view of deformation zone).

Approach:

A circular die insert was used to induce balanced biaxial tensile (BBT) deformation on the material.



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Experimental Details (Setup-IIC)

Test and DIC System Parameters

Test Parameters and Conditions :

- *Test Sample Geometry: Square blank (~160x160mm)*
- *Deformation Gage Area: Φ=~100mm [Bulge Cavity].*
- *Test Samples: Samples were prepared by shearing*
- *Testing was performed at 200 ˚C.*
- *Target strain rates: ~0.01, 0.1 & 1s^{-1}*
- *Testing was performed using a universal testing machine fitted with a custom pneumatic bulge forming setup (FADI-AMT Bulge-50), and two cameras (for 3D DIC strain measurements).*
- *Testing was performed by ramping pressure to achieve the desired overall deformation rate.*
- *Camera frame rate: variable _ 4 to 1000 fps.*
- *A minimum of three samples were tested per condition.*

Digital Image Correlation (DIC) :

- *All strain measurements were done based on DIC of recorded images.*
- *The GOM ARAMIS software was used for processing and post processing the images.*
- *Pixel resolution of the measurements: ~**65 microns/pixel***

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Experimental Details (Setup-IIC)

Test Matrix

Materials Tested	Test Temperature (˚C)	Strain Rate (s^{-1})	Sample Geometry	Tested Samples (Reported)
M20 (Magnesium e-Form Plus Batch-4)	200	0.01	Square blank	5 (4)
		0.1		5 (3)
		1		5 (3)

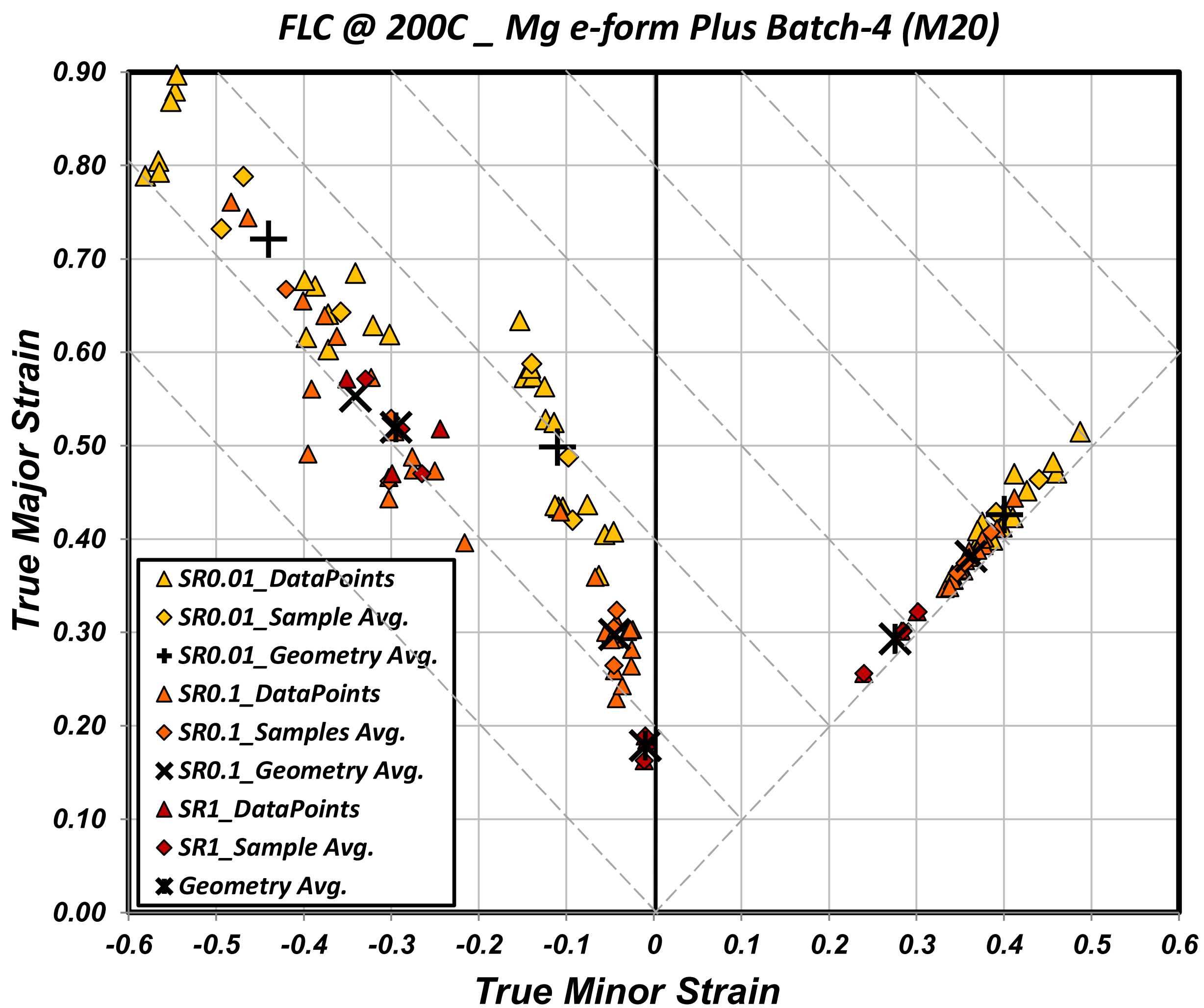
Test Results

FLC Testing @ 200 ˚C and Different Strain Rates

Results

FLC @ 200 ˚C and Different Strain Rates

- *The extracted FLC points shown below clearly indicate a great issue with data scatter, even greater than the one noted earlier at room temperature.*



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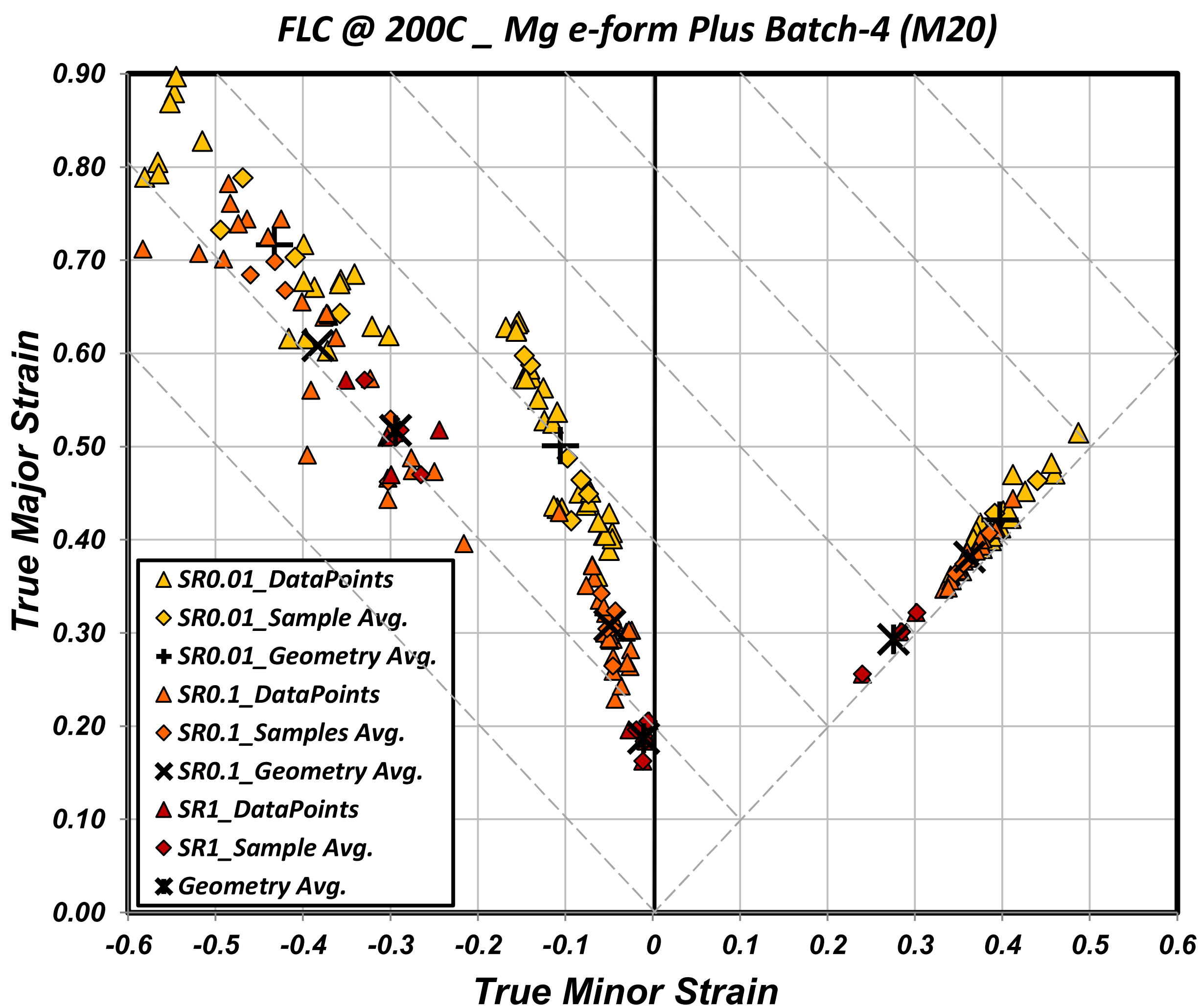
Results

FLC @ 200 ˚C and Different Strain Rates

- Additional samples were therefore tested and additional points were added to the FLC as shown below; this does not reduce the scatter but it was an attempt to increase the robustness of the results.
- Scatter is highest for the UT loading case …



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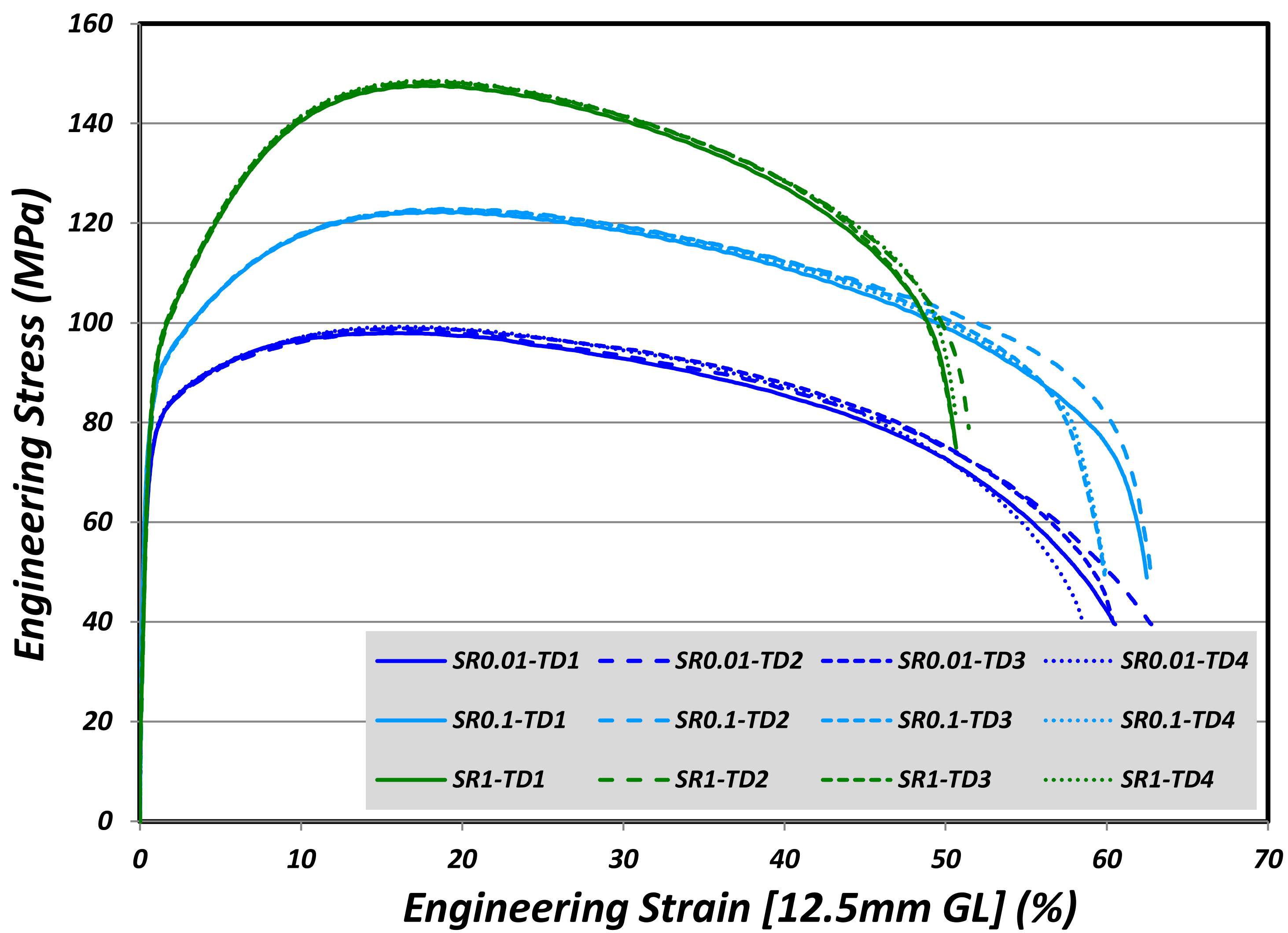
Results

Uniaxial Tension @ 200 ˚C and Different Strain Rates

- *Interestingly, the uniaxial tension curves were extremely repeatable for all three strain rates, as shown below.*



Results

Uniaxial Tension @ 200 ˚C and Different Strain Rates

- *Interestingly, the uniaxial tension curves were extremely repeatable for all three strain rates, as shown below.*
- *This indicates that the scatter in the FLC data is either driven by 1) non-homogeneity of strain localization in the material, or 2) the way FLC points are extracted (algorithms for extracting FLC points).*
- *Considering (2), this is the same approach used extensively before with many materials and it is typically robust and only leads to scatter due to material non-homogeneity. The fact that uniaxial tension and plane-strain tension sample were used here (rather than the conventional Nakajima samples) could play a role, but recall that the same scatter was noted in the Nakajima testing at room temperature, and thus all of these items combined lead us to believe that this response is primarily driven by the material itself!*

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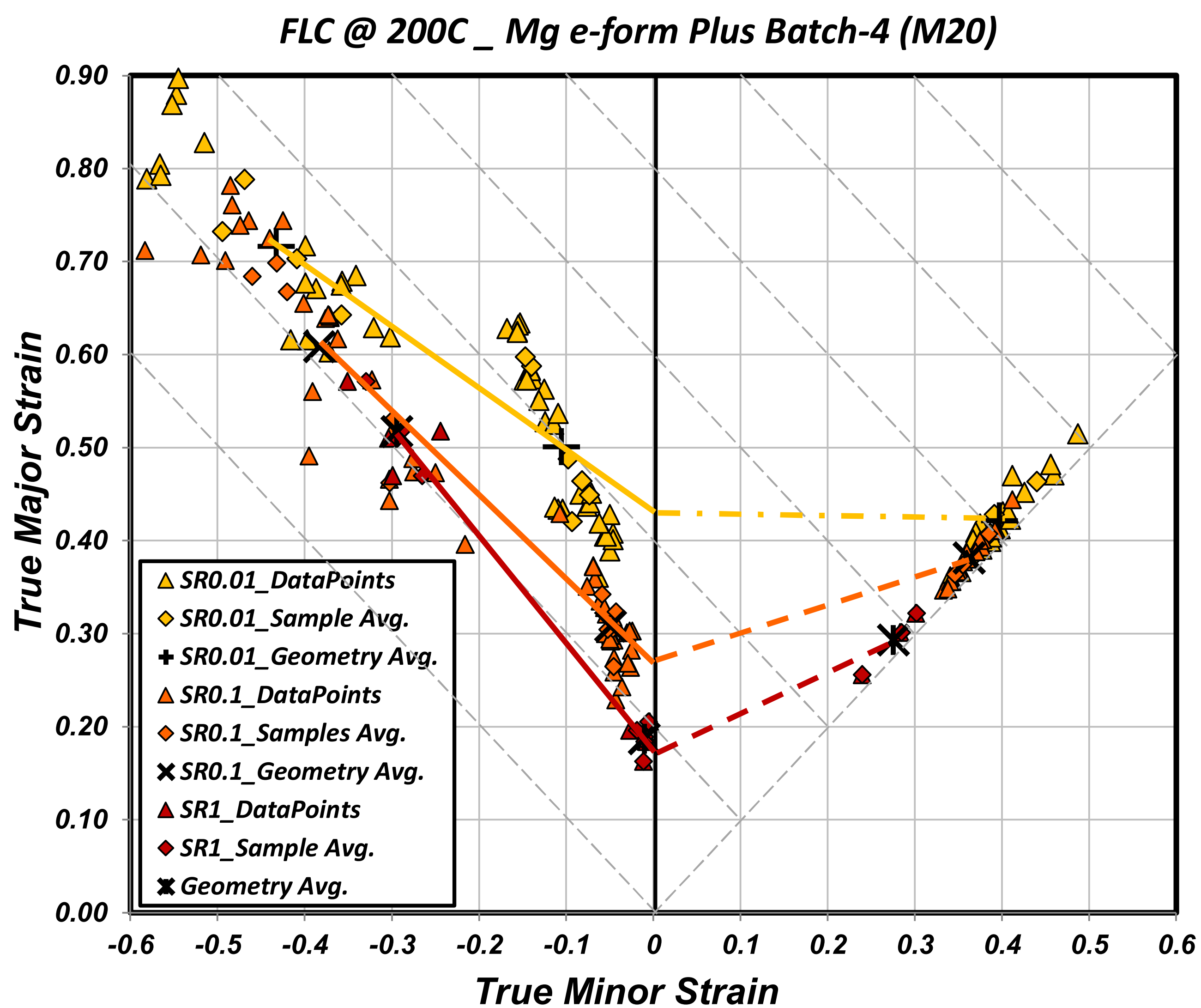
Results

FLC @ 200 ˚C and Different Strain Rates

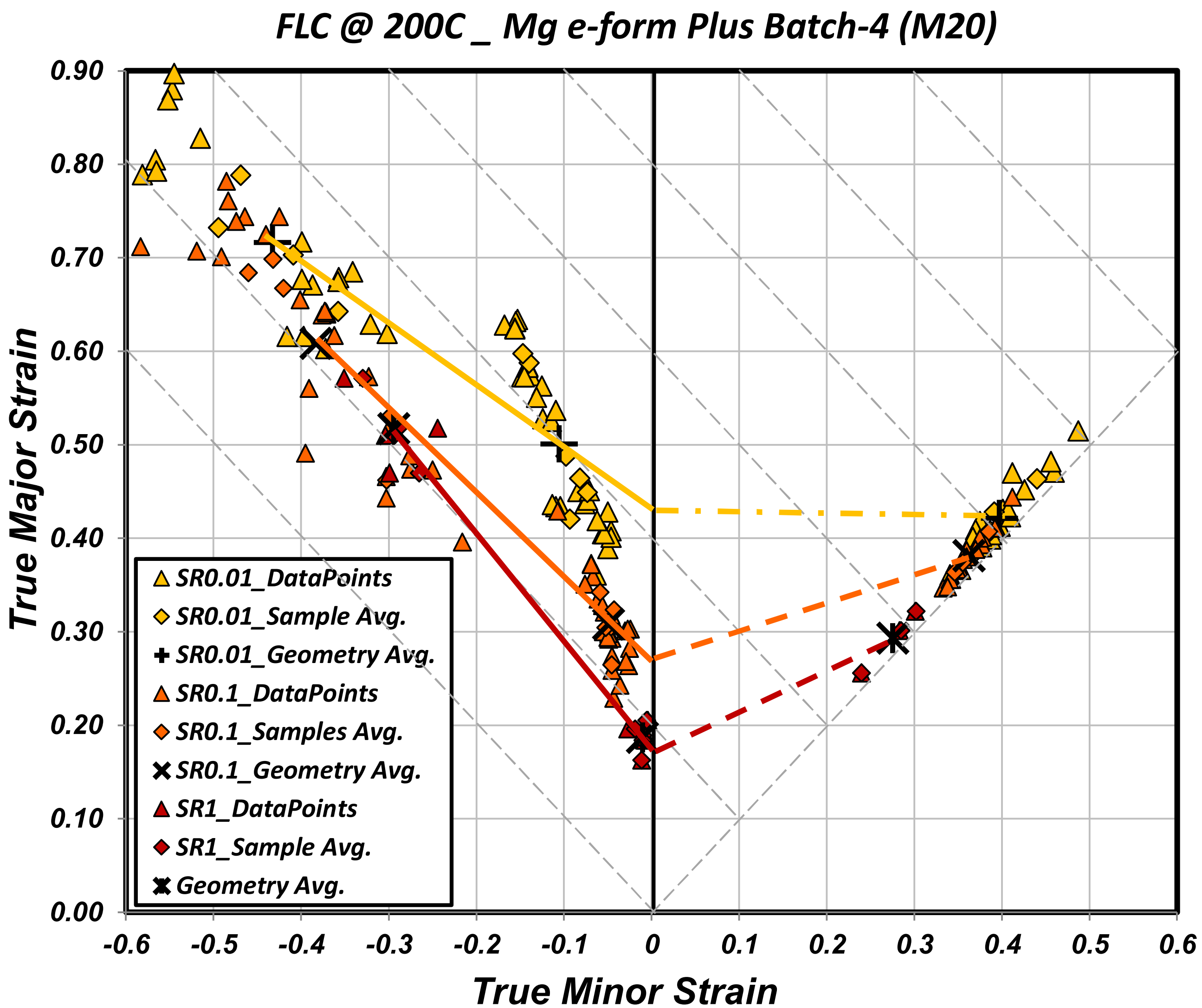
- Using the collected data points, the below FLCs at different strain rates were drawn. It was not possible to perform any further iterations or developments given the limited project time!



Results

FLC @ 200 ˚C and Different Strain Rates

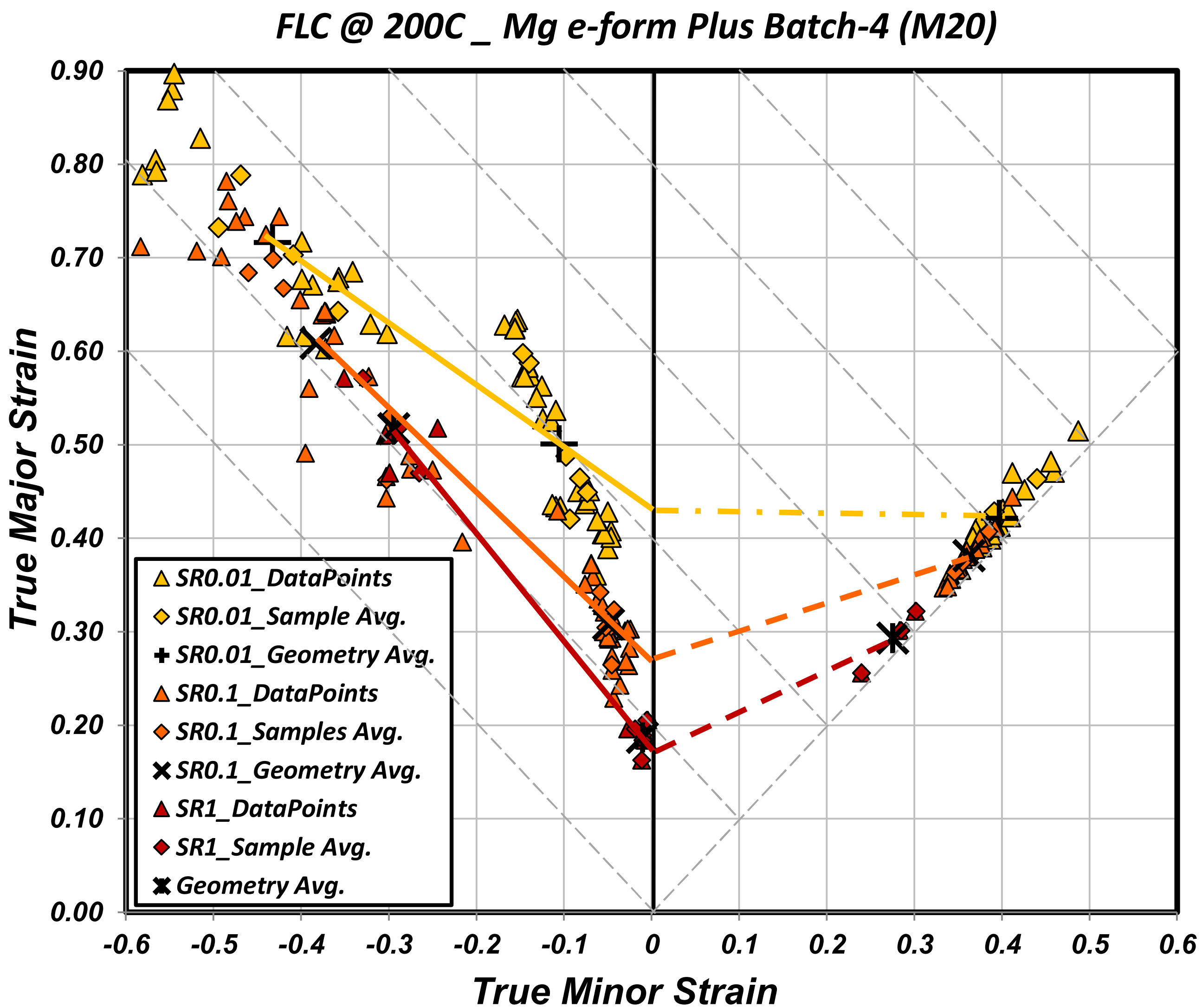
➢ *Based on the outcome reported here, we can draw a general conclusion that higher strain rate drives the formability of the material down as clearly shown by the FLC plots.*



Results

FLC @ 200 ˚C and Different Strain Rates

- *The scatter in the PST results is less than that for the UT case, and thus the results below show how FLC_0 drops with strain rate as indicated (note that deviations in the results improve for the higher strain rate of 1 s^{-1})*



Other

Attachments

Attachments to this report:

- *Excel files (one per test type) containing the test parameters, all raw data (testing machine outputs and DIC-extracted measurements), plots of all relevant measurements, and summary of extracted failure strains.*
- *Detailed sample DIC videos, one per testing condition, each showing the evolution of full-field Major or Mises strains across the tested sample, coupled with the actual position on the stress/strain or load/dome-height curve.*

Other:

- *NA*

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Thank you!