

GREAT DESIGNS IN **STEEL**

GENERATING HIGH QUALITY MATERIAL CARDS THROUGH ROBOT-ASSISTED TESTING

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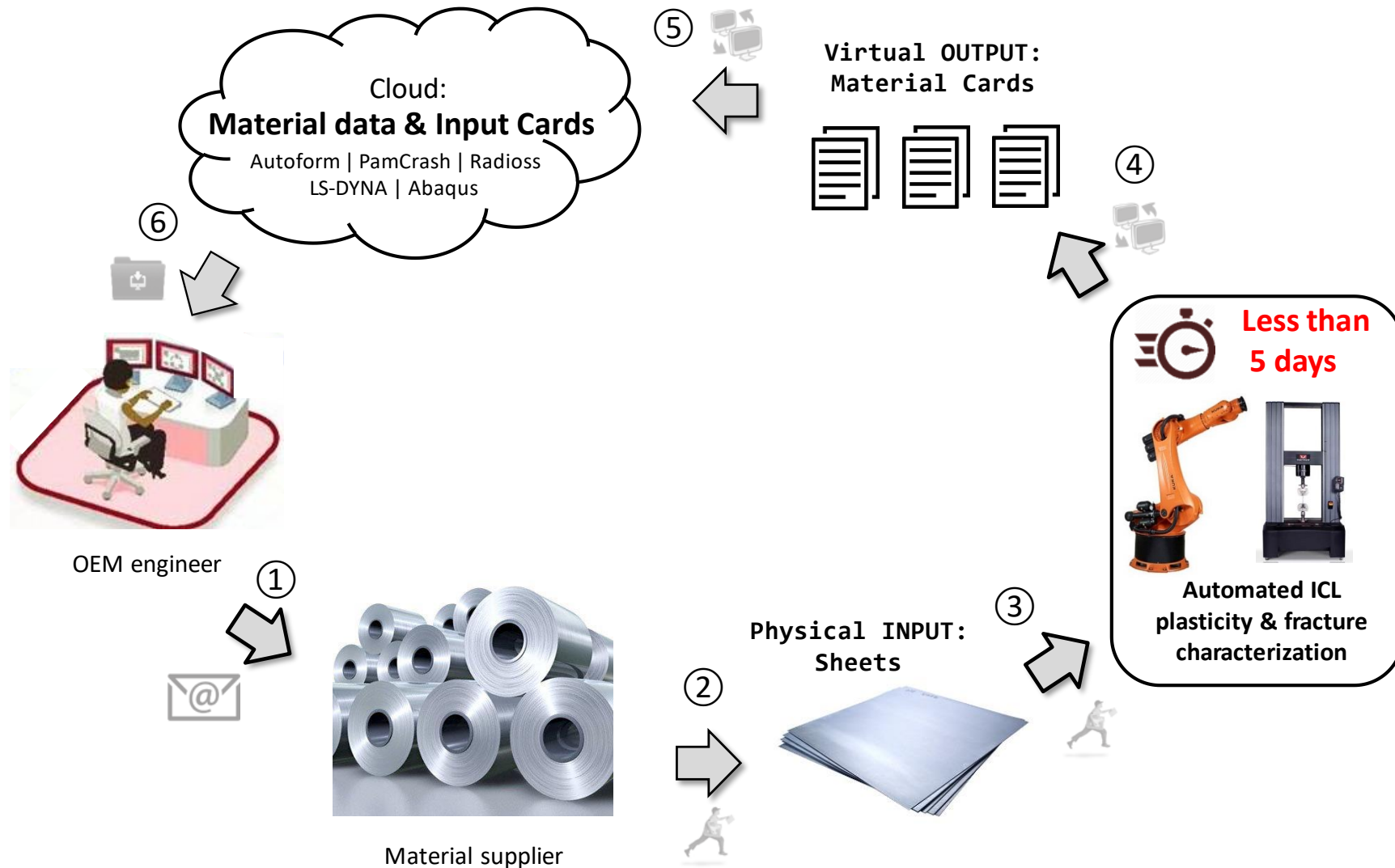
Our Philosophy

We develop robotic systems to perform mechanical experiments with the objective of

- (i) increasing their reliability
- (ii) speeding-up R&D cycles
- (iii) reducing costs
- (iv) archiving know-how.

Our Vision

- Rapid Generation of Material Cards for Finite Element Software based on Reliable Experiments

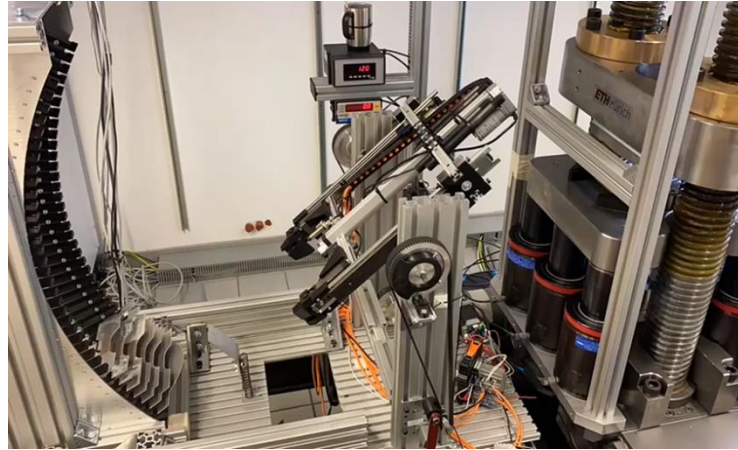


Automated Testing Systems

Autom. 25kN UTM



Autom. Nakazima



Automated 50kN UTM

- Symmetric
- Slow & Intermediate SR (0.001/s-1/s)
- Surround DIC
- Low energy consumption (<2kW during test)

2017

2018

2019

2020

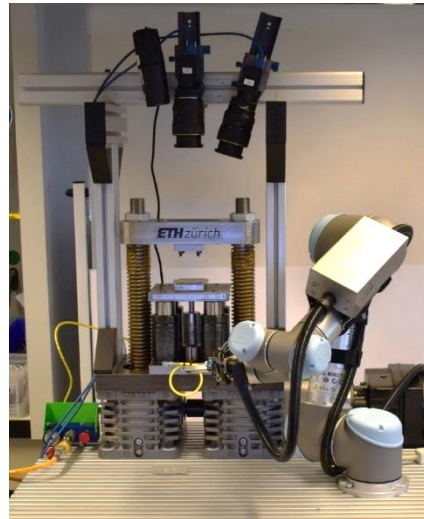
2021

2022

2023

2024.....

Autom. Mini-Punch / Mini-Nakazima



Automation of Split Hopkinson Bars Systems

Experimental Need for Plasticity Characterization

- Yield surface: Hill'48

$$f(\boldsymbol{\sigma}, k) = \bar{\sigma}_{Hill'48} - k[\bar{\boldsymbol{\varepsilon}}_p] = 0$$

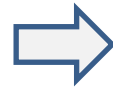
- Flow rule (Hill'48):

$$d\boldsymbol{\varepsilon}_p = d\lambda \frac{\partial g_{Hill}}{\partial \boldsymbol{\sigma}}$$

- Isotropic hardening law



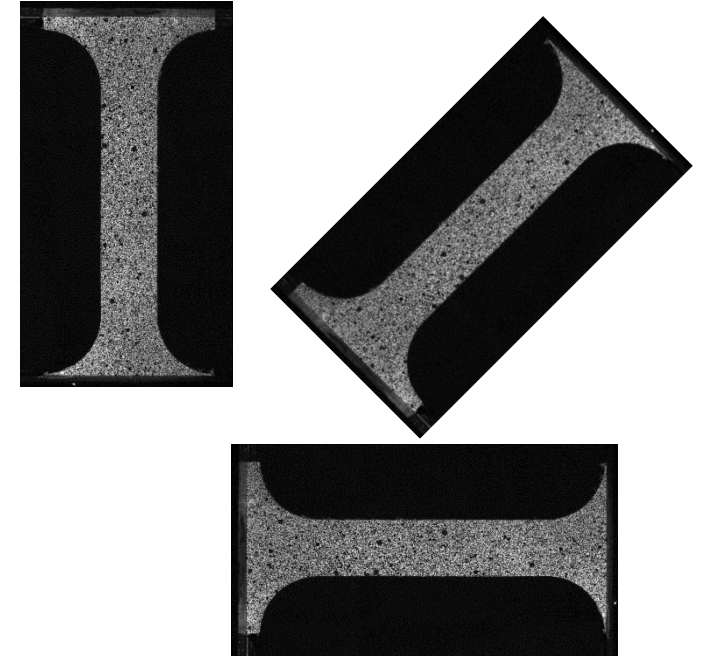
Yield stress ratios for at least 3 material directions



Lankford ratios for at least 3 material directions



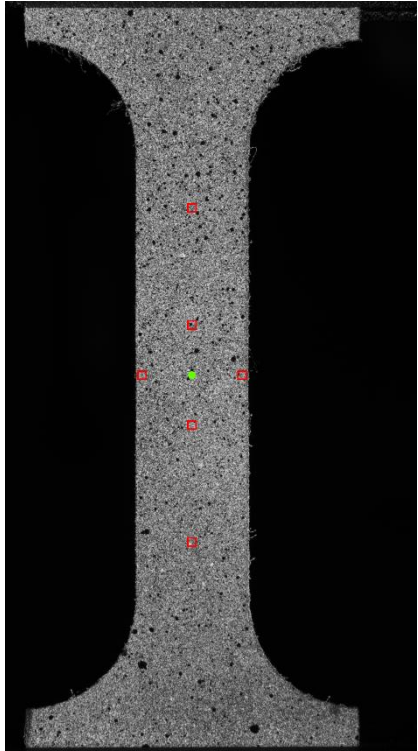
One experiment reaching very large strains



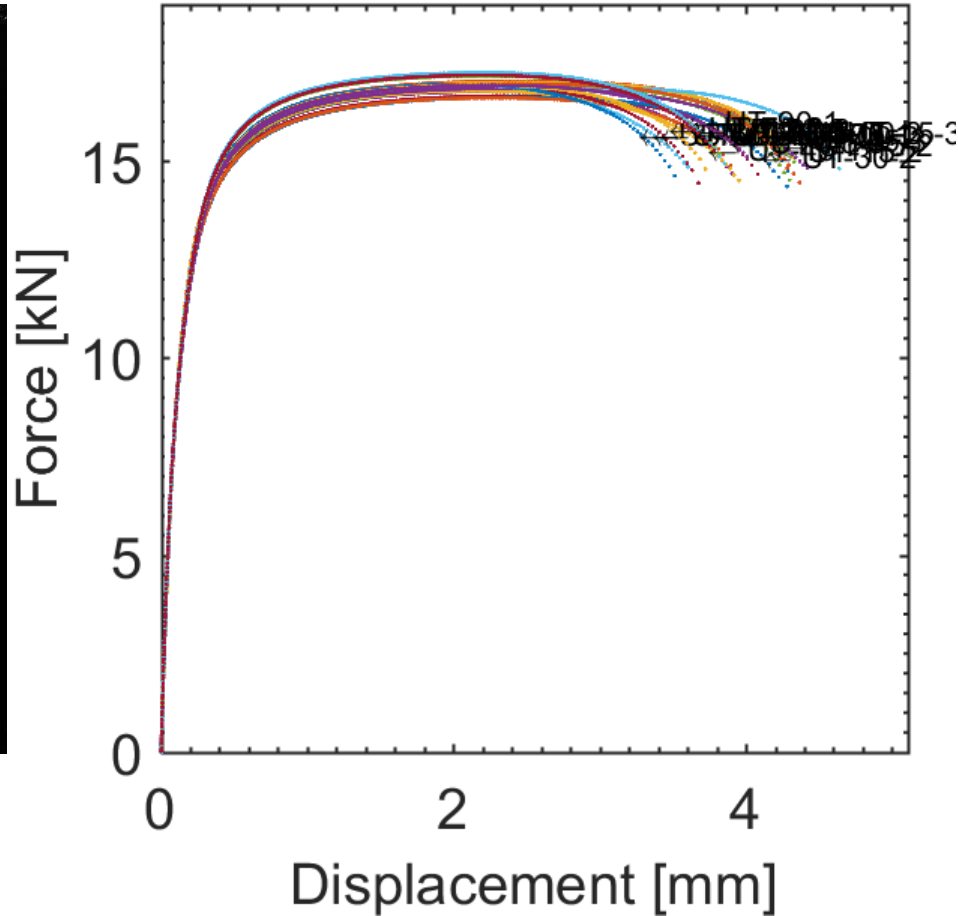
Automated Universal Testing Frame



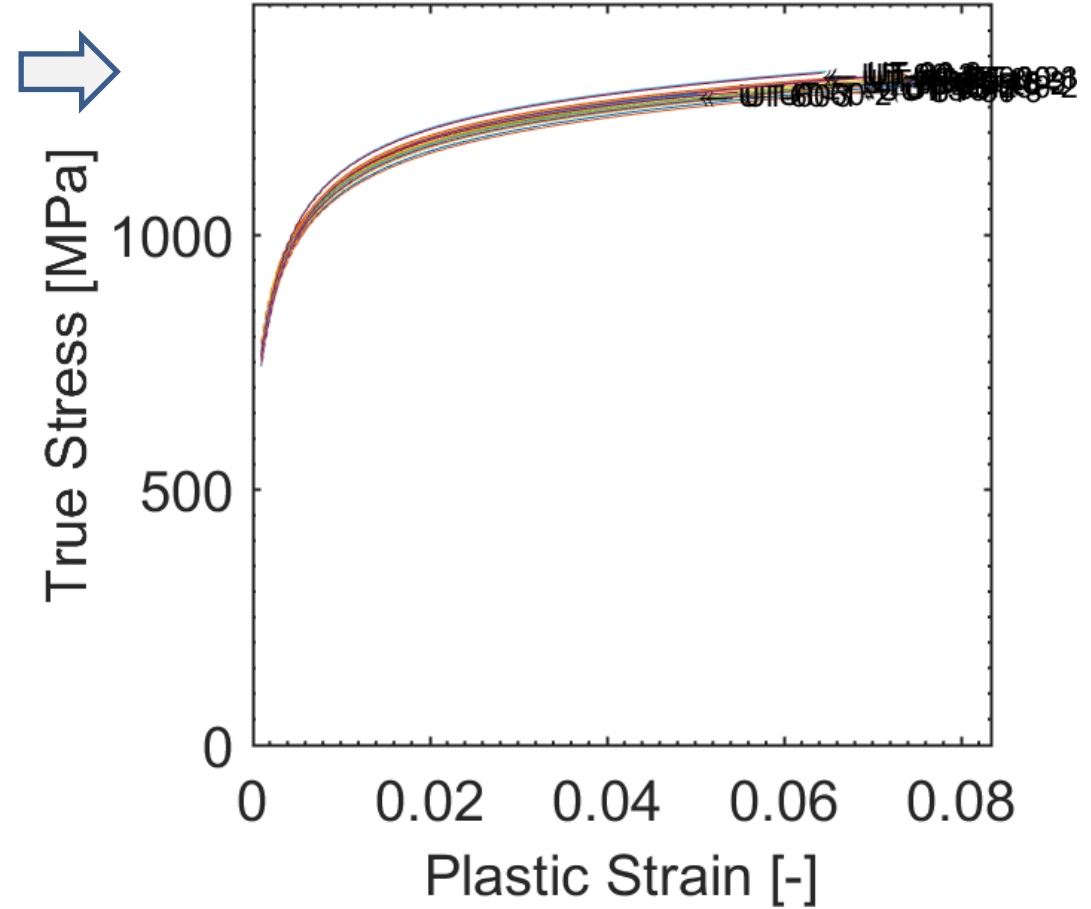
Automated Postprocessing (incl. DIC)



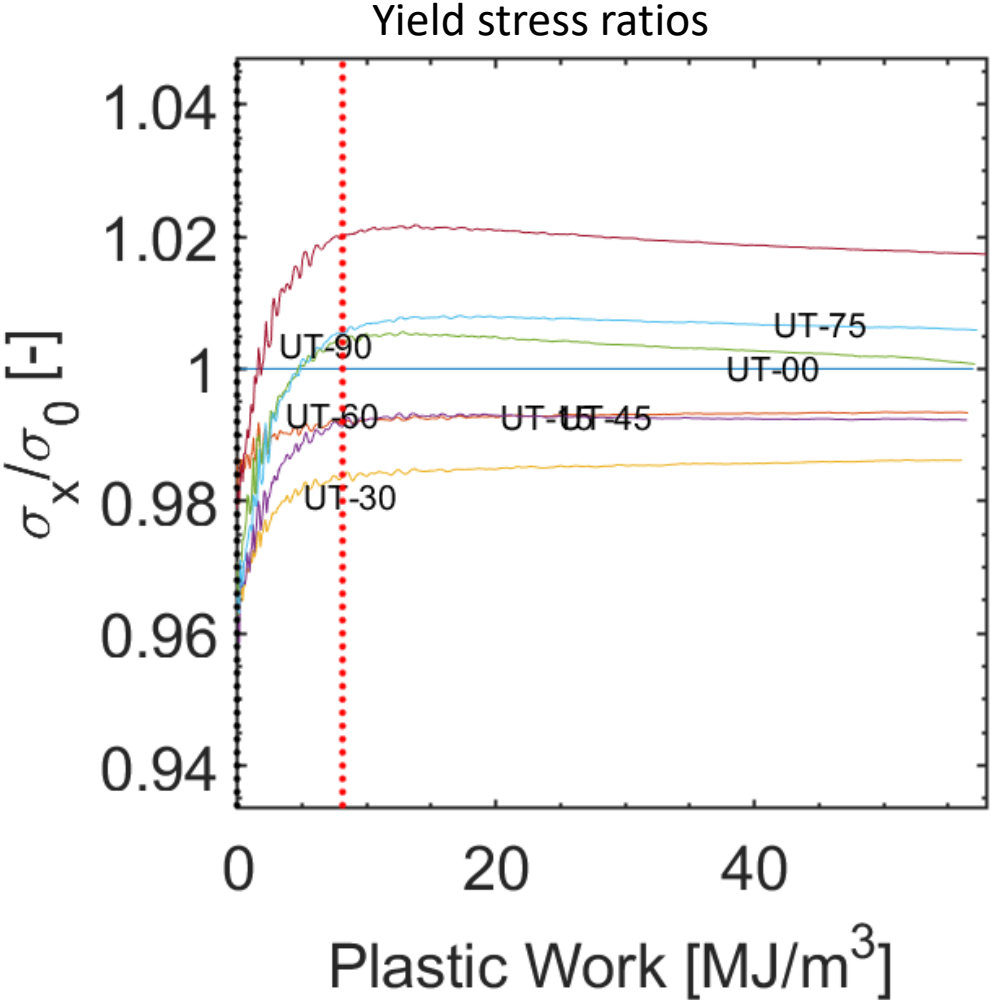
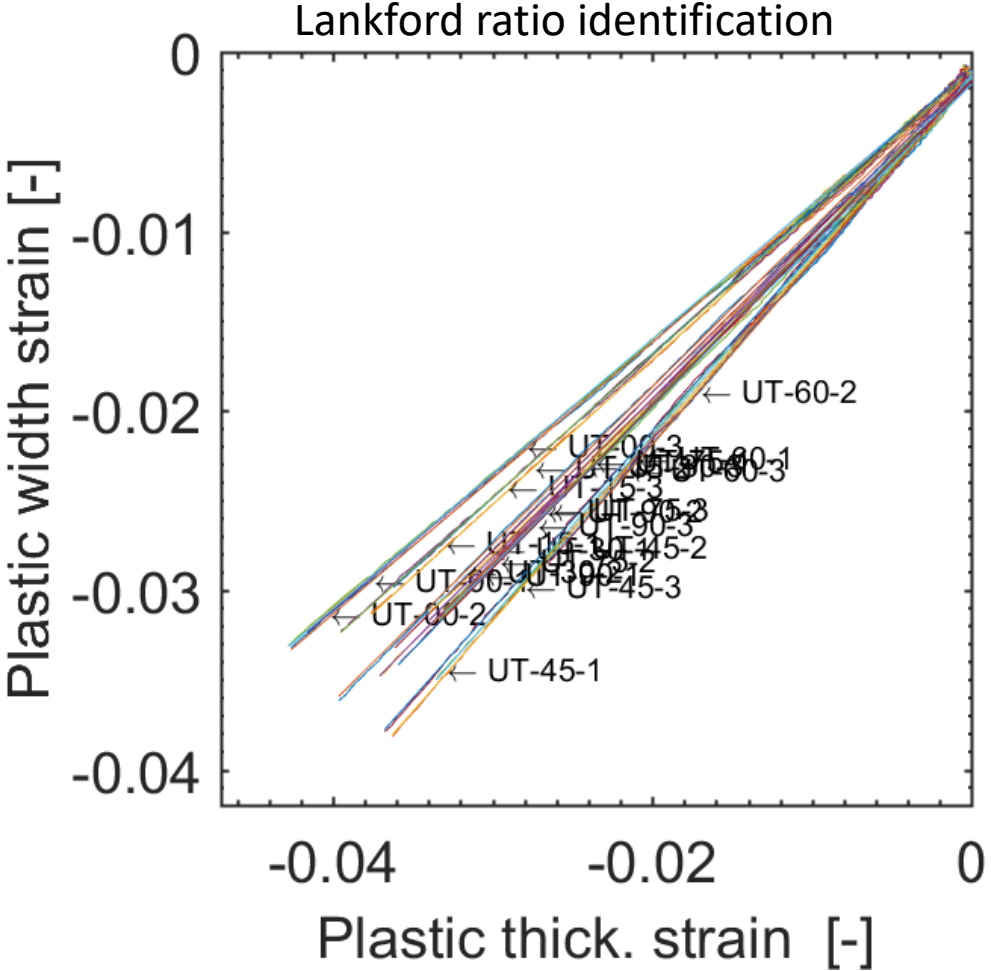
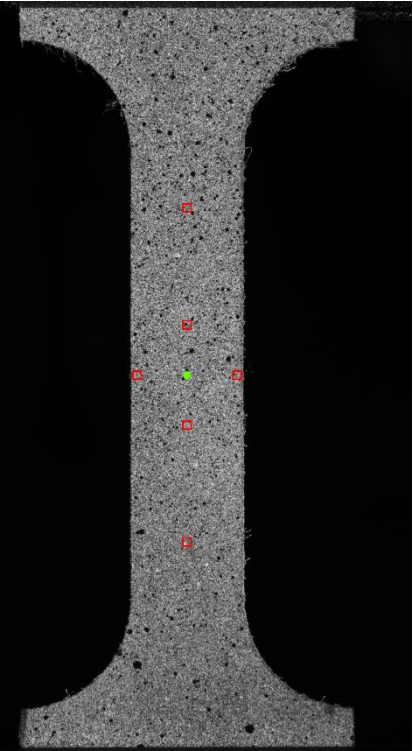
Force-displacement curves



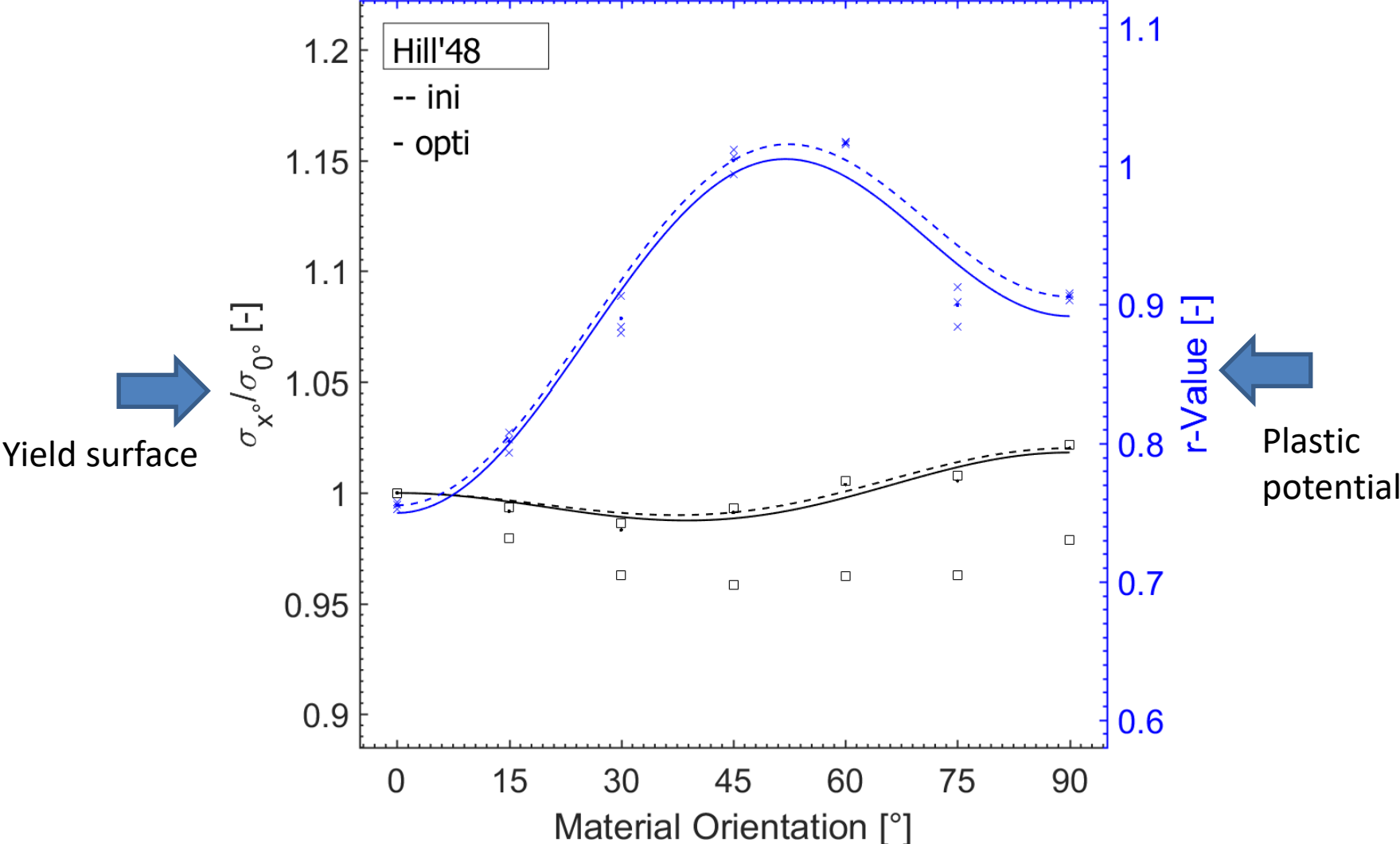
True stress-strain curves



Automated Postprocessing

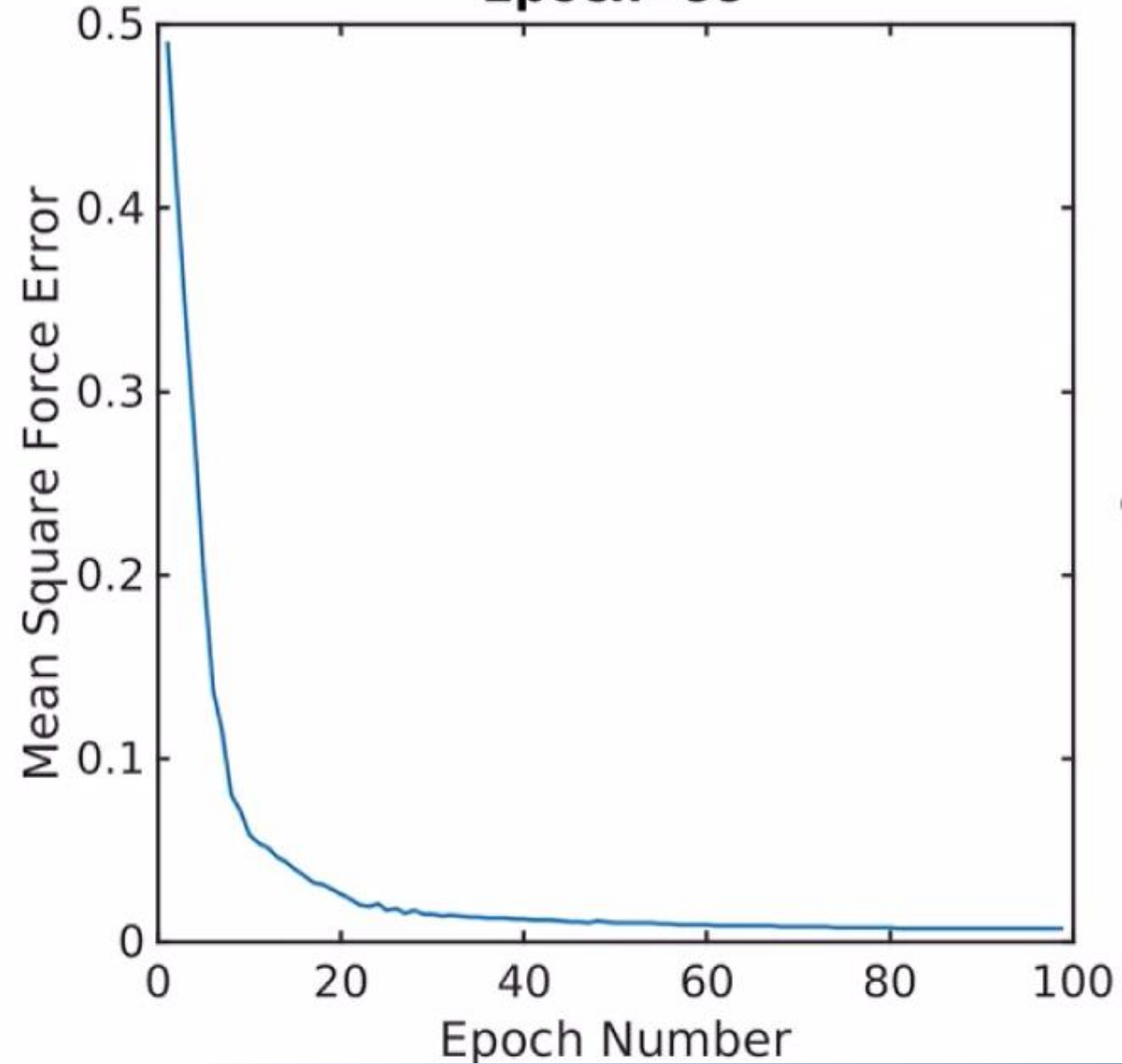
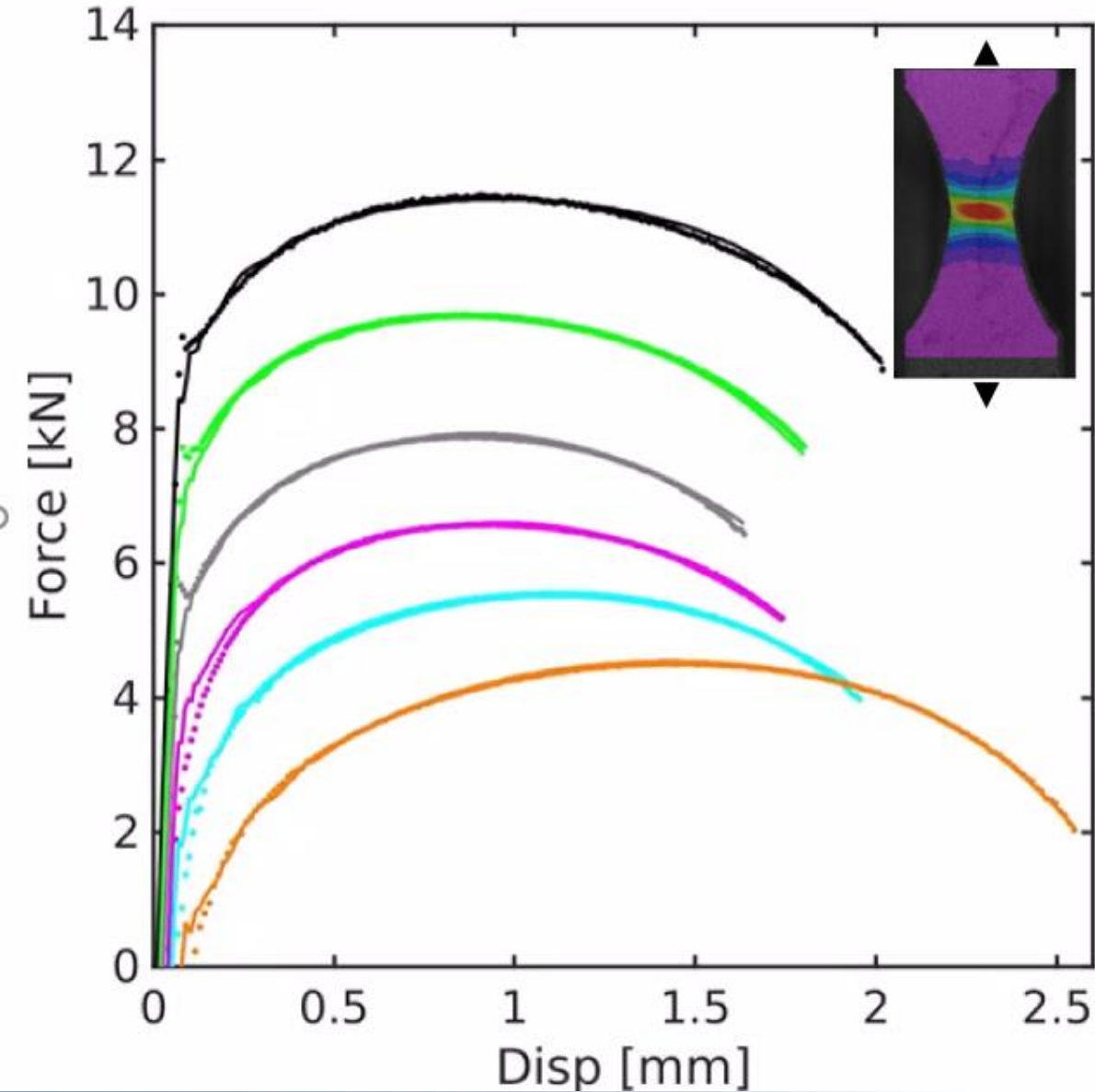


Automated Postprocessing



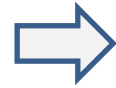
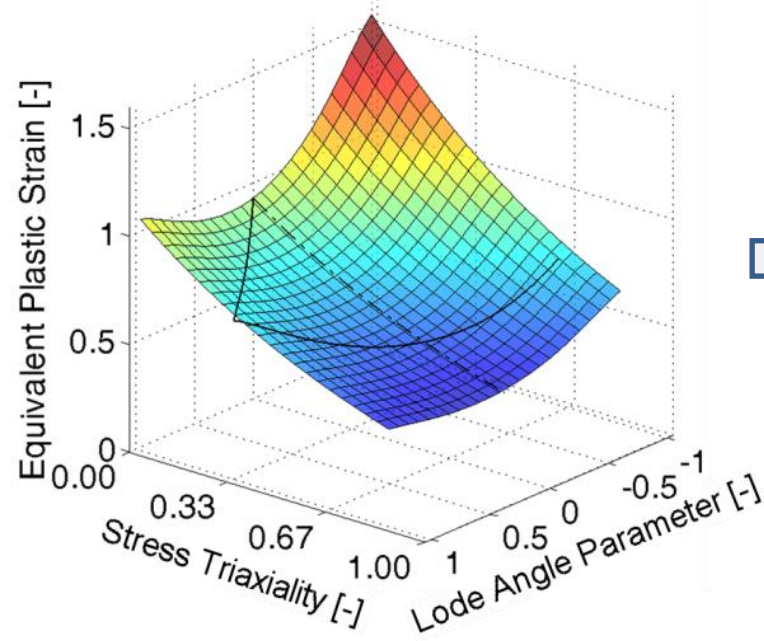
Machine Learning-based Hardening Law Identification

Epoch=99

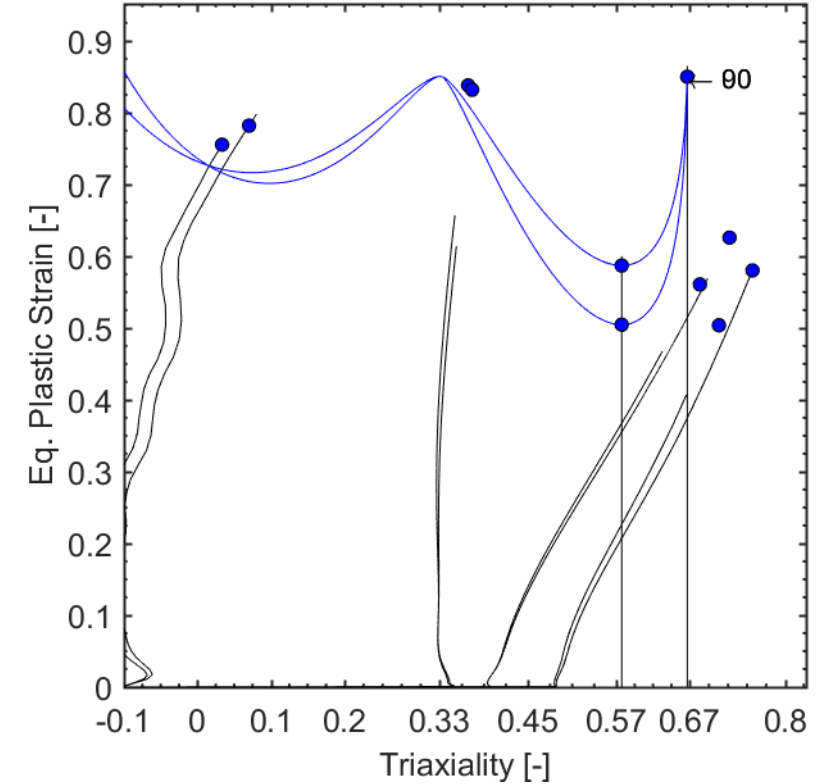


Experimental Need for Fracture Characterization

- Hosford-Coulomb fracture locus



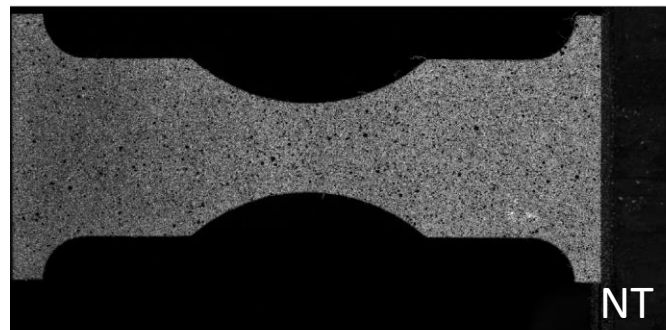
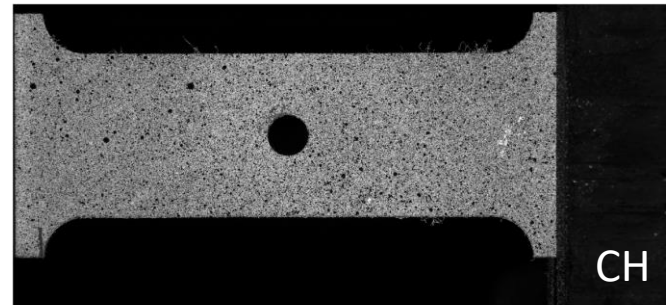
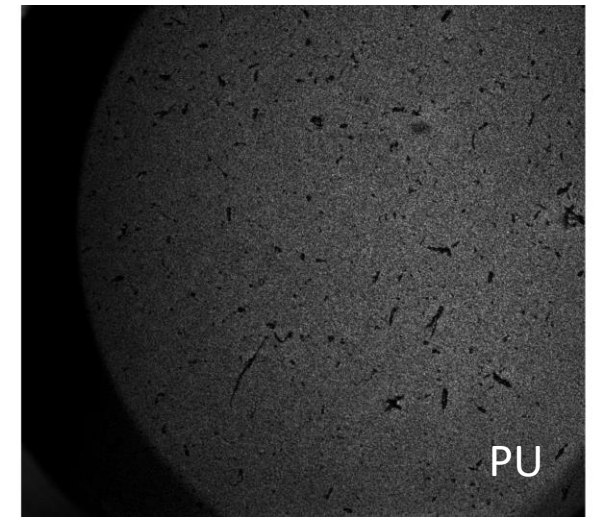
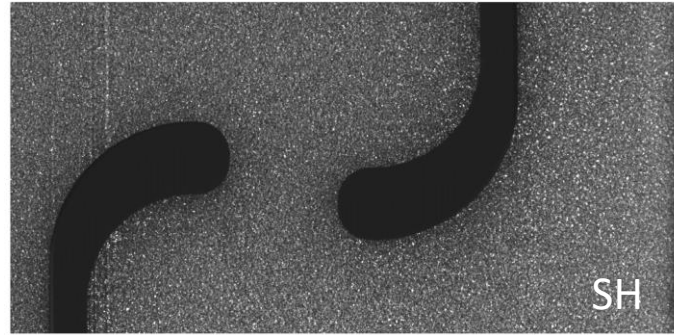
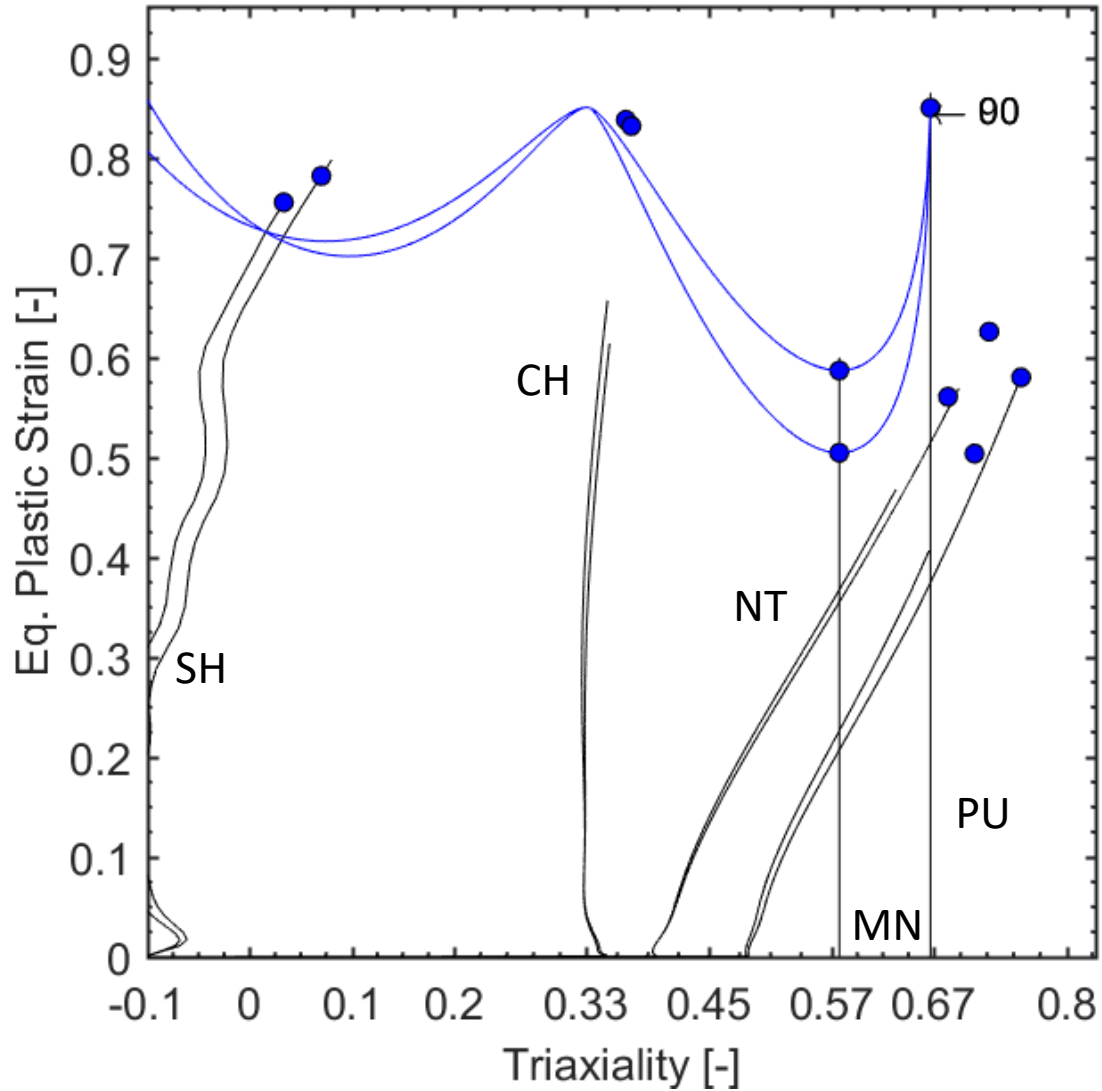
Fracture experiments for at least 3 different stress states



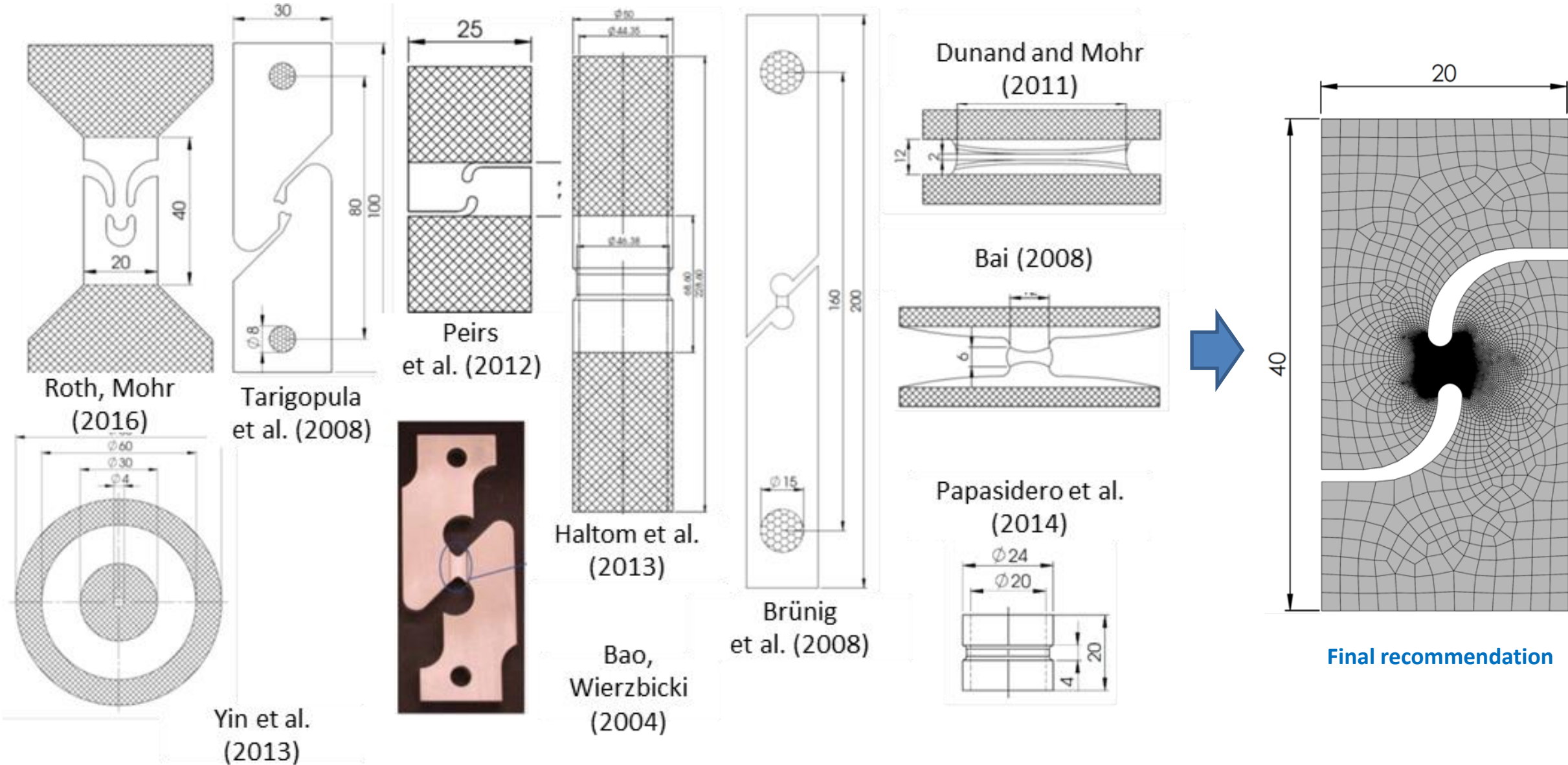
- Effect of anisotropy

Repeat all experiments for at least three different material orientations

Automated Fracture Testing



Research Completed before Automating

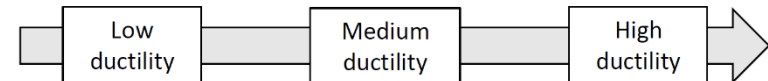
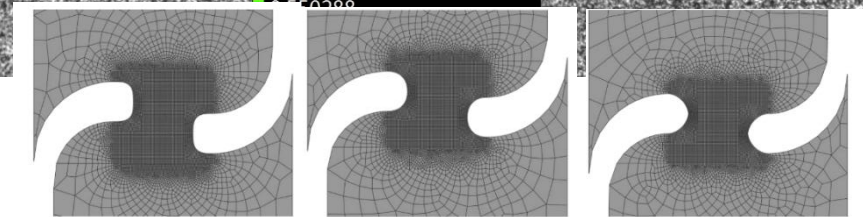
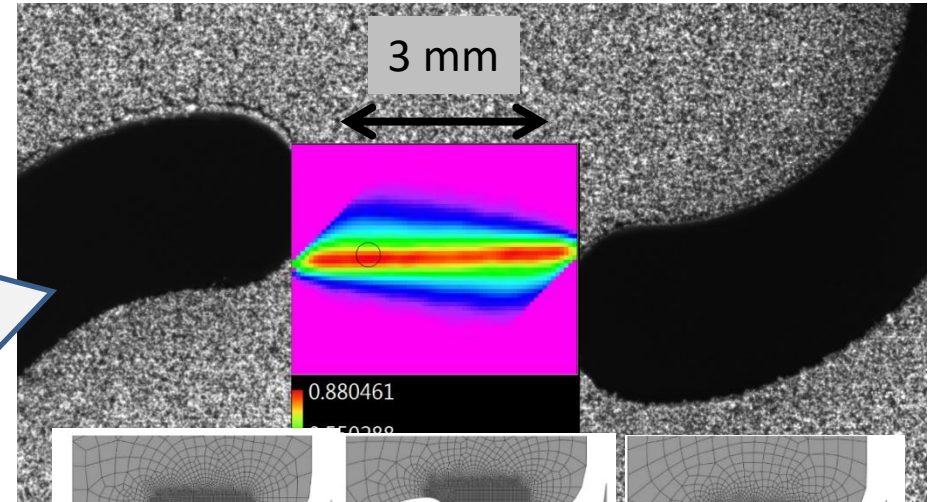


Experimental Details Matter



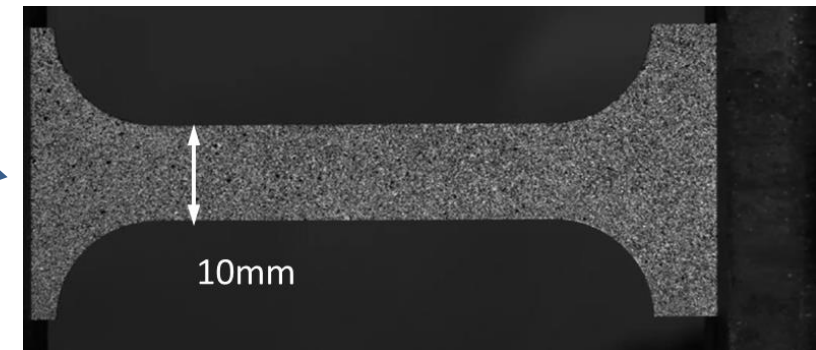
High resolution

Resolution: 7.2 $\mu\text{m}/\text{pixel}$
Speckle size: 3-5 pixels
Subset size: 29 by 29 pixels

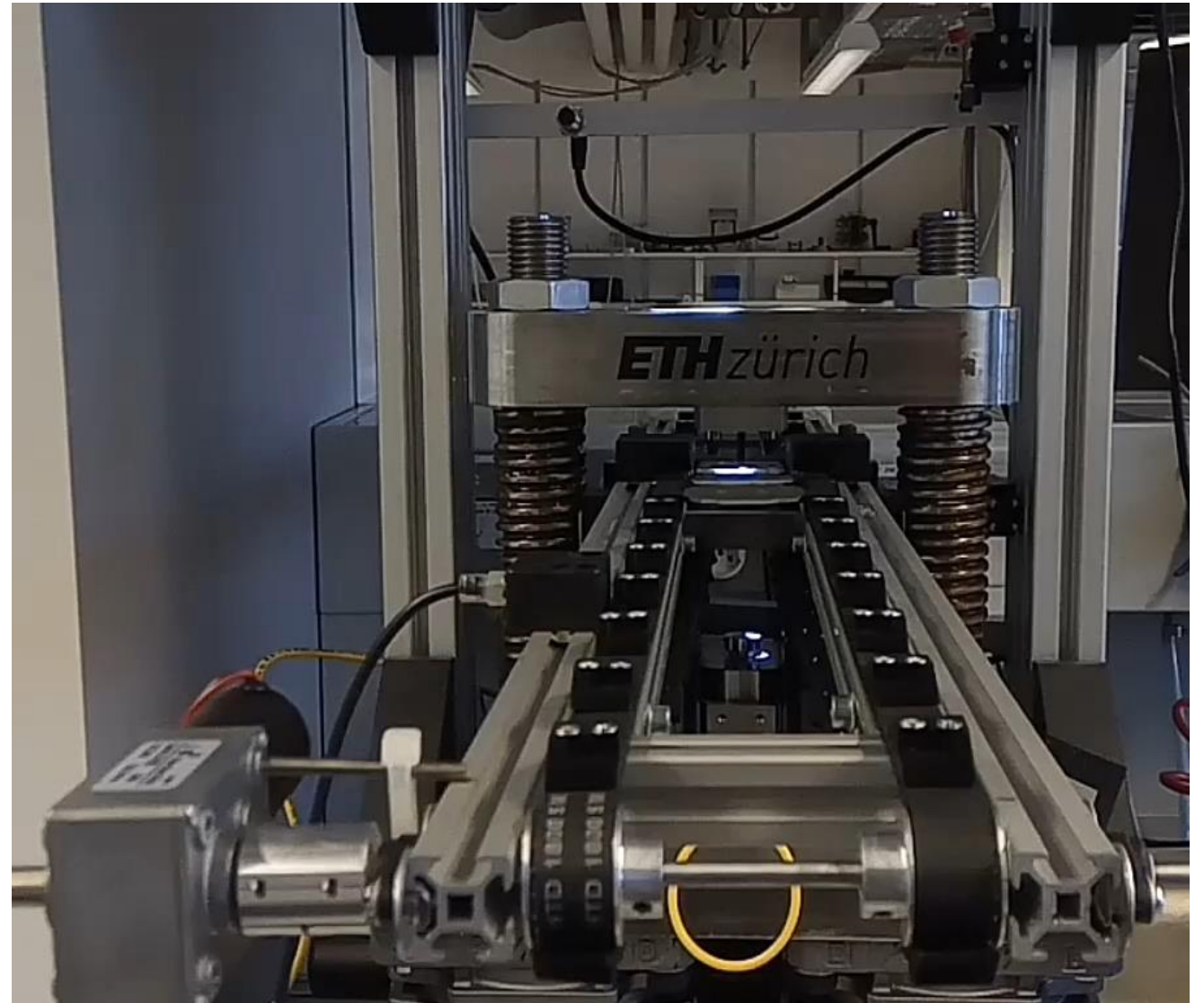
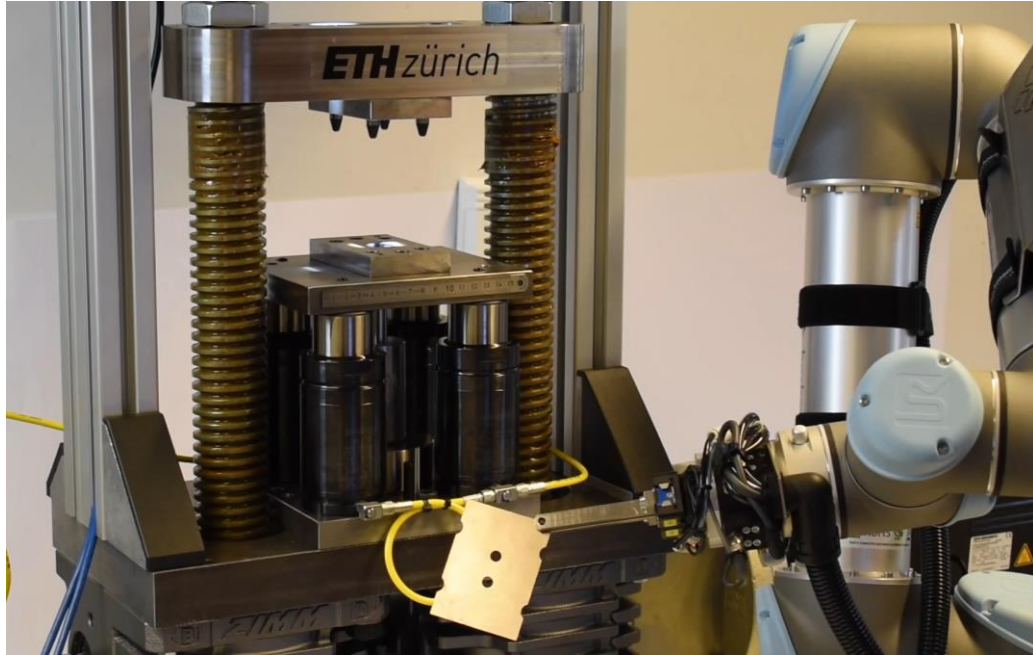


Resolution: 30 $\mu\text{m}/\text{pixel}$
Speckle size: \sim 3-5 pixels
Subset size: 29 by 29 pixels

Large field of view

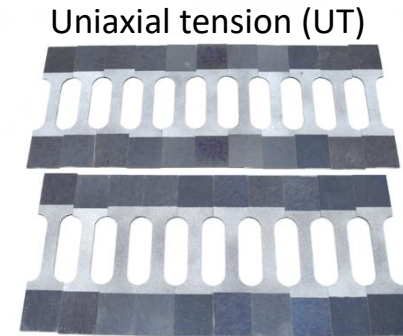


Automated Out-of-Plane Testing



Basic Plasticity & Fracture Testing Program for Steels

- Plasticity, every 15°:
 - Uniaxial Tensile: 7 orientations 0°, 15°, ... 90°
- Fracture : 0°, 45°, 90°
 - NT20, NT6, CH, SH
 - Shear: 3 geometries
 - Mini-Punch (PU)
 - Dihedral Mini-Nakazima (MN)
- 3 repeats
 - 78 experiments



Uniaxial tension (UT)



Notched tension (NT)

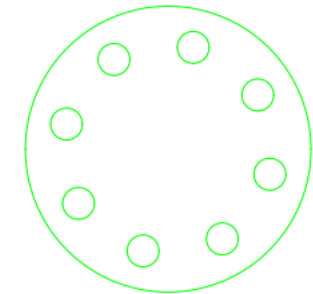
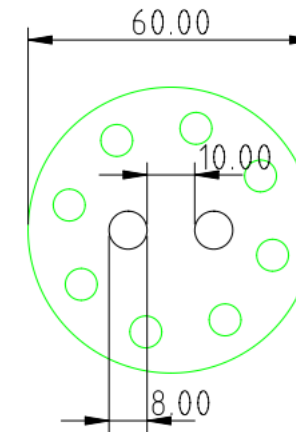
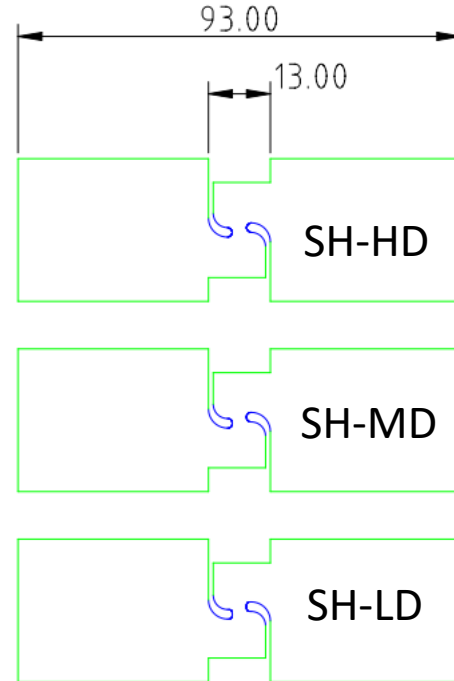
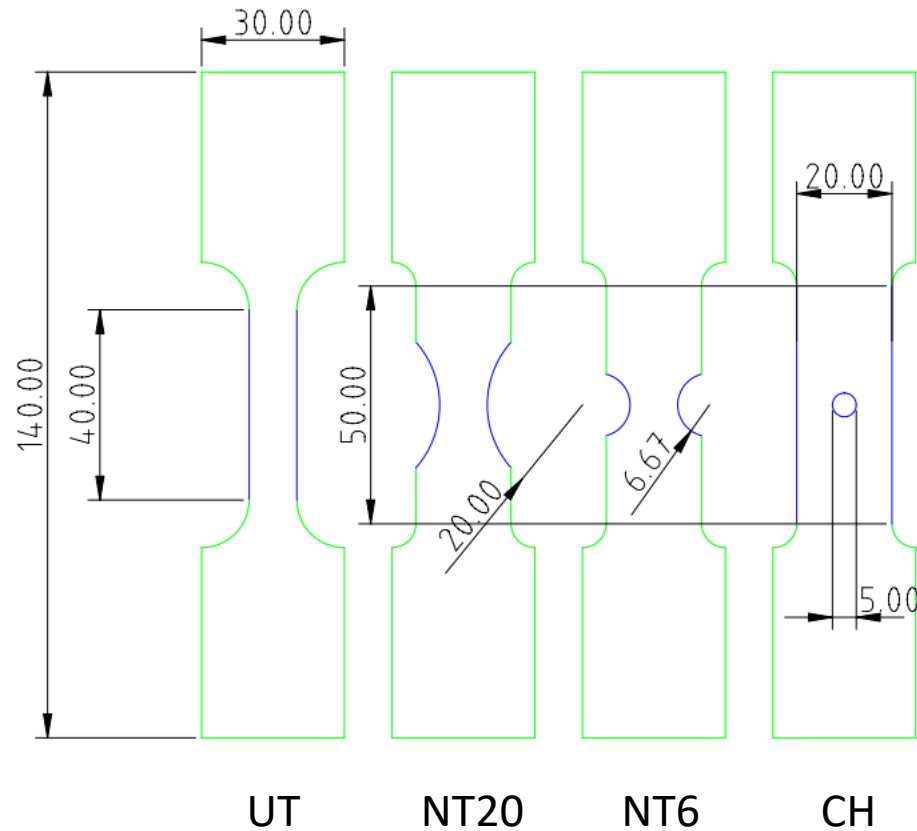
Central hole (CH) tension

In-plane shear (SH)



Mini-Nakazima (MN) & Mini-Punch (PU)

Specimen Preparation Matters



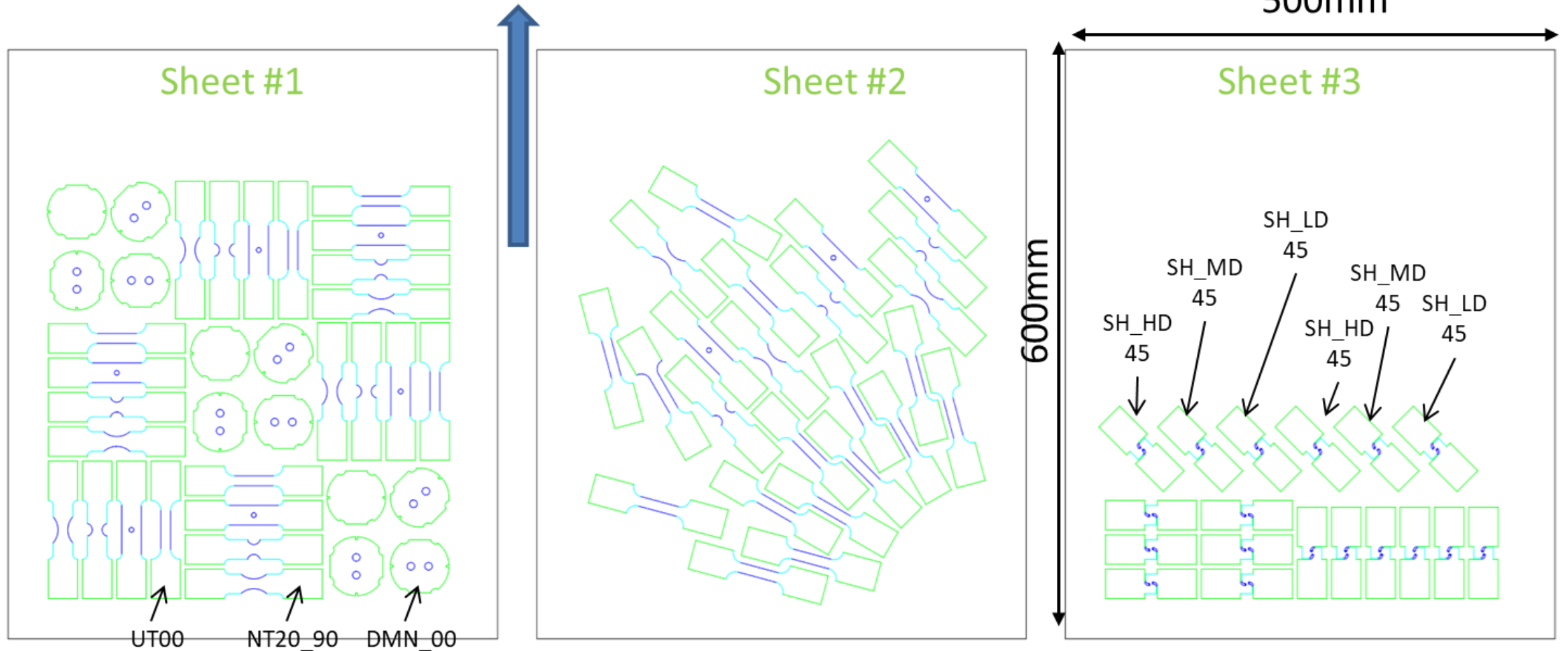
- Blue marked areas need to be of good surface quality
 - For UTs, NTs and CH outer: e.g. slow waterjet cut
 - For CH hole: milling or reaming necessary
 - For SH: EDM or micro-waterjet

- Generally waterjet cutting is ok
- Dihedral Mini Nakazima (DMN): black holes need higher quality cut, e.g reaming, CNC machining or EDM

Material Needed for Basic Testing

3 sheets of 600x500mm are required to fit all specimens

Rolling
Direction 0°



Material Card for plasticity & fracture

User Subroutine with material card

```

5  **Yield function and flow rule>HILL-NAFR-----
6  **      P12,          P33,          G12,          G22,          G33,
7     -0.711,          2, 3.045232, -0.635407, 0.947361, 2.256727, 0.0, 0.0,
8  **Har-----
9  **      e0          n          Q1          C1          s0          alpha          (3) HARD MSV
10     665.151, 0.001969,          0.2031, 196.229,          12.97,          197.38, 0.988,          3.0,
11  **H+TS>JC-----
12  **      eps0dot
13     1.0e-3,          0.000
14  **      Failure criterion -----
15  **      a
16
17  **Post
18  **      D0,
19     1.0,

```

Commercial FE code input deck

.CSV

P12	P22	P44
-0.527448	0.994022	2.86252

YLD2000		exponent m=8					
a1	a2	a3	a4	a5	a6	a7	a8
0.946104875	1.00595542	0.92682096	1.028519269	1.016296485	0.982965548	0.968143301	1.158360778

mixed Swift Voce							YSH=alpha*A*(eqps+e0)**n+(1-alpha)*(s0+Q*(1-EXP(-C*eqps)))
Swift		Swift		Voce		Voce	
A [MPa]	e0	n	Q [MPa]	C	s0 [MPa]	alpha	
665.7206125	0.014100604	0.201308862	212.0016043	10.19493478	296.6863242	0.9	

Hosford Coulomb Fracture Initiation model				
Orientation [°]	a	b	c	n
0	1.4900	1.1100	0.0650	0.1
90	1.4600	1.1100	0.0660	0.1

Future extensions

Basic Plasticity & Fracture Testing Program

Name	Orien-tation [°]	# repeats	use
UT	0	3	P
UT	15	3	P
UT	30	3	P
UT	45	3	P
UT	60	3	P
UT	75	3	P
UT	90	3	P

Name	Orien-tation [°]	# repeats	use	
NT	20	0	3	P&F
NT	20	45	3	P&F
NT	20	90	3	P&F
NT	6	0	3	P&F
NT	6	45	3	P&F
NT	6	90	3	P&F
CH	5	0	3	F
CH	5	45	3	F
CH	5	90	3	F

Name	Orien-tation [°]	# repeats	use	
SH	LD	0	2	F
SH	LD	45	2	F
SH	LD	90	2	F
SH	MD	0	2	F
SH	MD	45	2	F
SH	MD	90	2	F
SH	HD	0	2	F
SH	HD	45	2	F
SH	HD	90	2	F

Name	Orien-tation [°]	# repeats	use
PU		3	F
DHPST	0	3	F
DHPST	45	3	F
DHPST	90	3	F

Add-on “Basic FLC”

Name	Orien-tation [°]	# repeats	
W	20	0 or 90	3
W	50	0 or 90	3
W	80	0 or 90	3
W	90	0 or 90	3
W	100	0 or 90	3
W	120	0 or 90	3
W	200	0 or 90	3

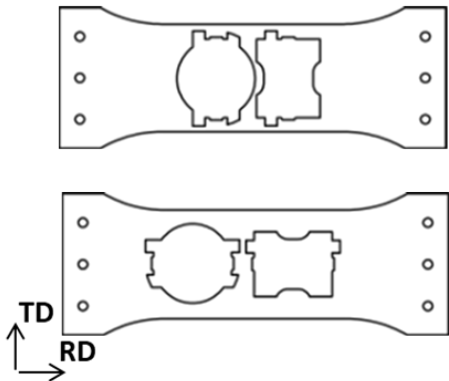
Add-on “Pre-strain FLC”

XXL-UT pre-straining		type of FLC
strain level	Orientalion [°]	
0	n.a.	FLC-0
0	n.a.	FLC-90
ε1	0	FLC-0
ε1	0	FLC-90
ε1	90	FLC-0
ε1	90	FLC-90
ε2	0	FLC-0
ε2	0	FLC-90
ε2	90	FLC-0
ε2	90	FLC-90

Add-on “Strain rate”

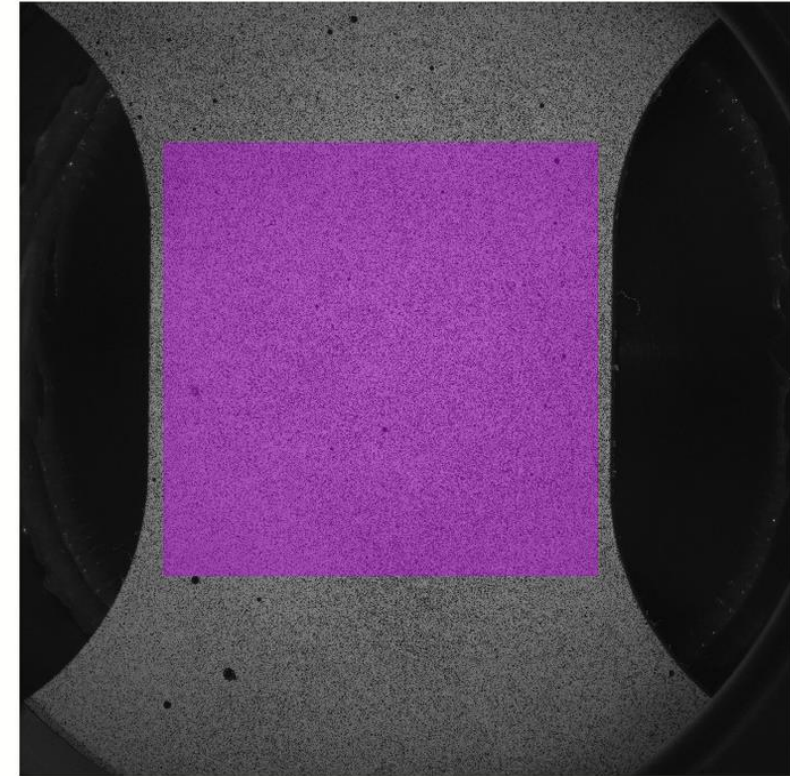
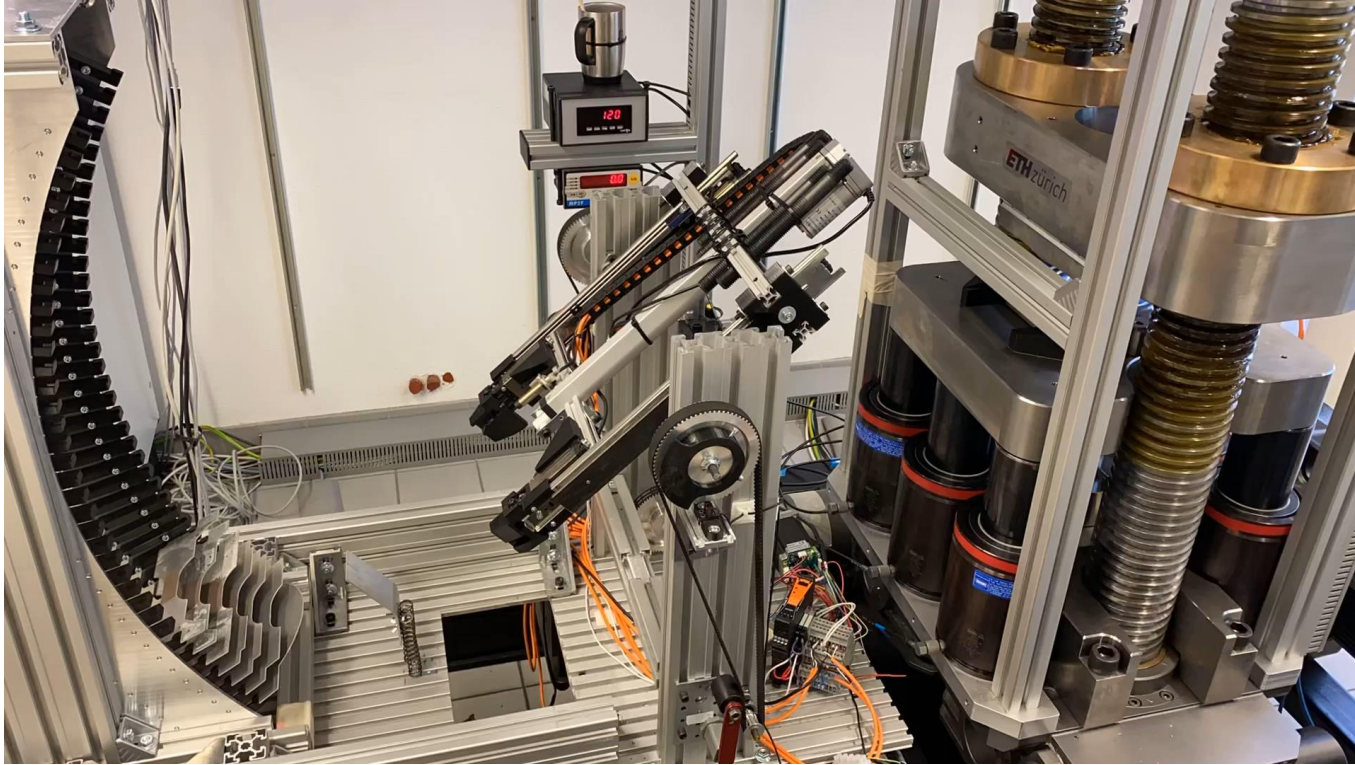
Name	speed	Orien-tation [°]	# repeats	
UT	1/s	0 or 90	3	
NT	20	1/s	0 or 90	3
NT	6	1/s	0 or 90	3
CH	5	1/s	0 or 90	3
SH	MD	1/s	0 or 90	3
SH	LD	1/s	0 or 90	3
SH	HD	1/s	0 or 90	3

Name	speed	Orien-tation [°]	# repeats	
UT	1000/s	0 or 90	3	
NT	20	1000/s	0 or 90	3
NT	6	1000/s	0 or 90	3
CH	5	1000/s	0 or 90	3
SH	MD	1000/s	0 or 90	3

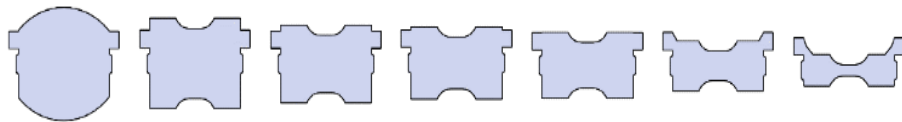


Automated Nakazima / Marciniak testing

DC01 RM 00°RD W05



@ 1 mm / s and 25°C



Insertion of up to 35 specimens

Positioning

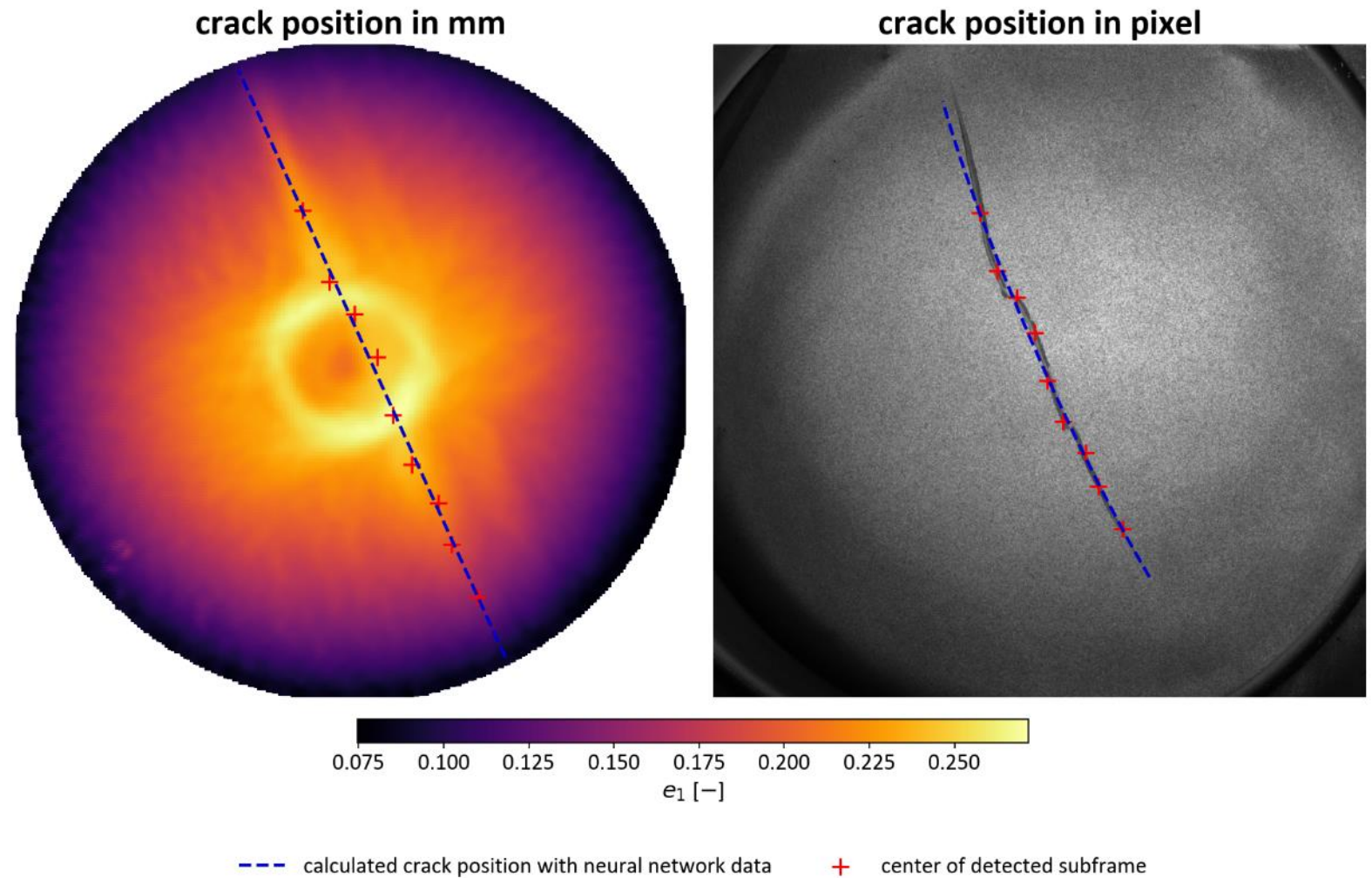
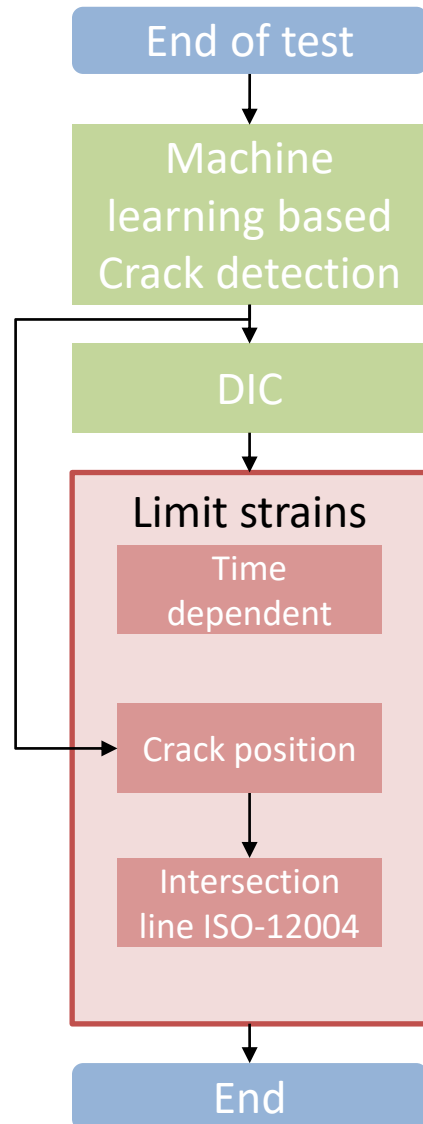
Clamping

Testing

Unloading

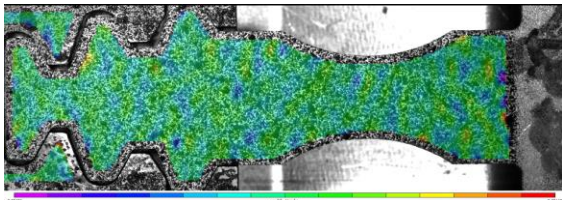
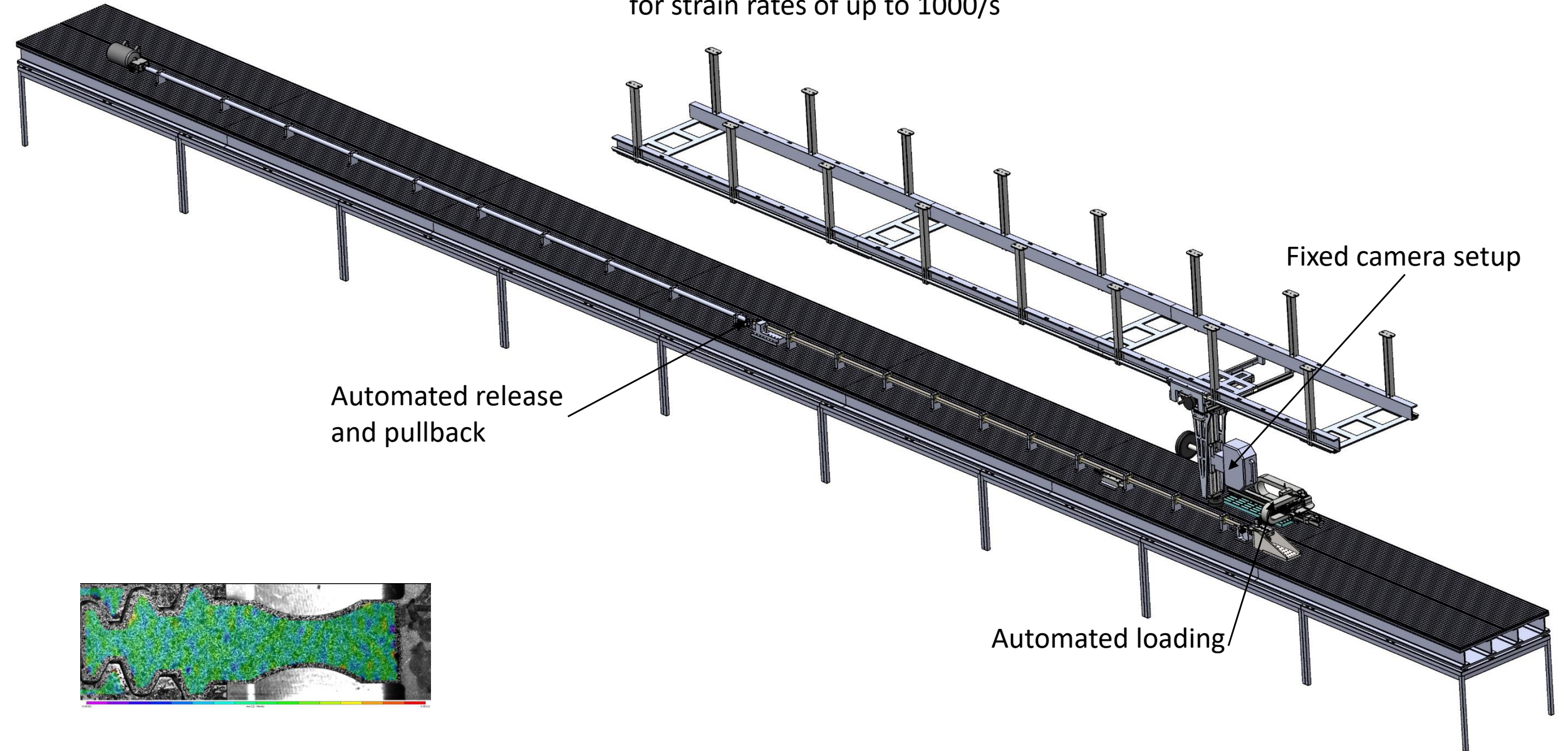
Real duration
up to 4 min/specimen

Automated Crack Detection

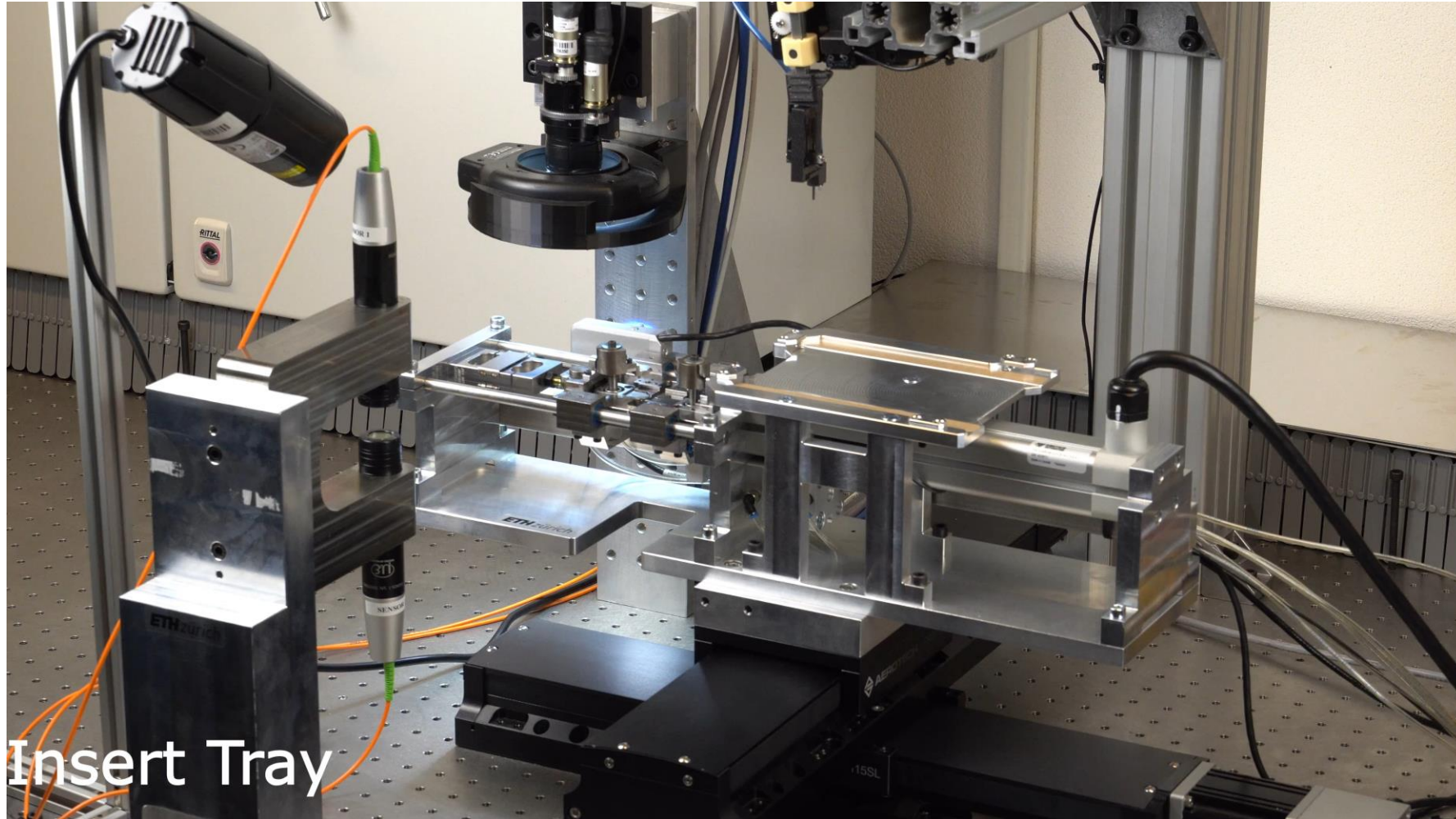


Automated Split Hopkinson Bar System

for strain rates of up to 1000/s



Automated MicroTesting



Insert Tray

Conclusion: Our Vision has become Reality

