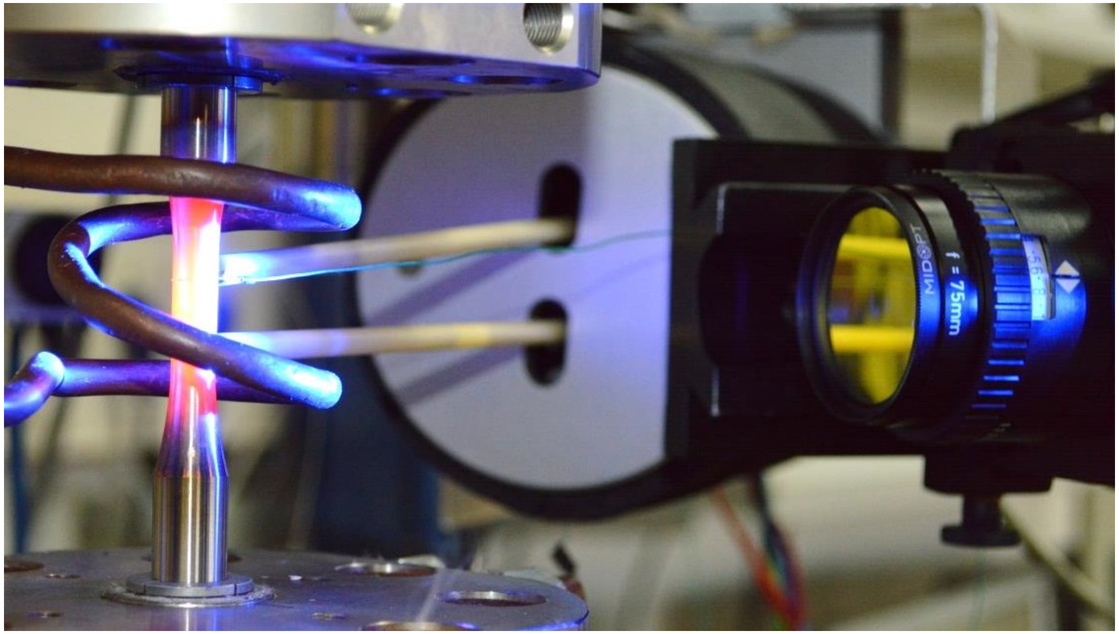
Marker-free GPU-based Digital Image Correlation System for High-Temperature Strain-Controlled Fatigue Measurements

A. Blug[1*], D.J. Regina[1], S. Eckmann[2], M. Senn[2], C. Eberl[2], A. Bertz[1], D. Carl[1]



[1]: Fraunhofer Institute for Physical Measurement Techniques IPM, Freiburg, Germany
[2]: Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany
[*]: Andreas.blug@ipm.fraunhofer.de; +49 761 8857-328

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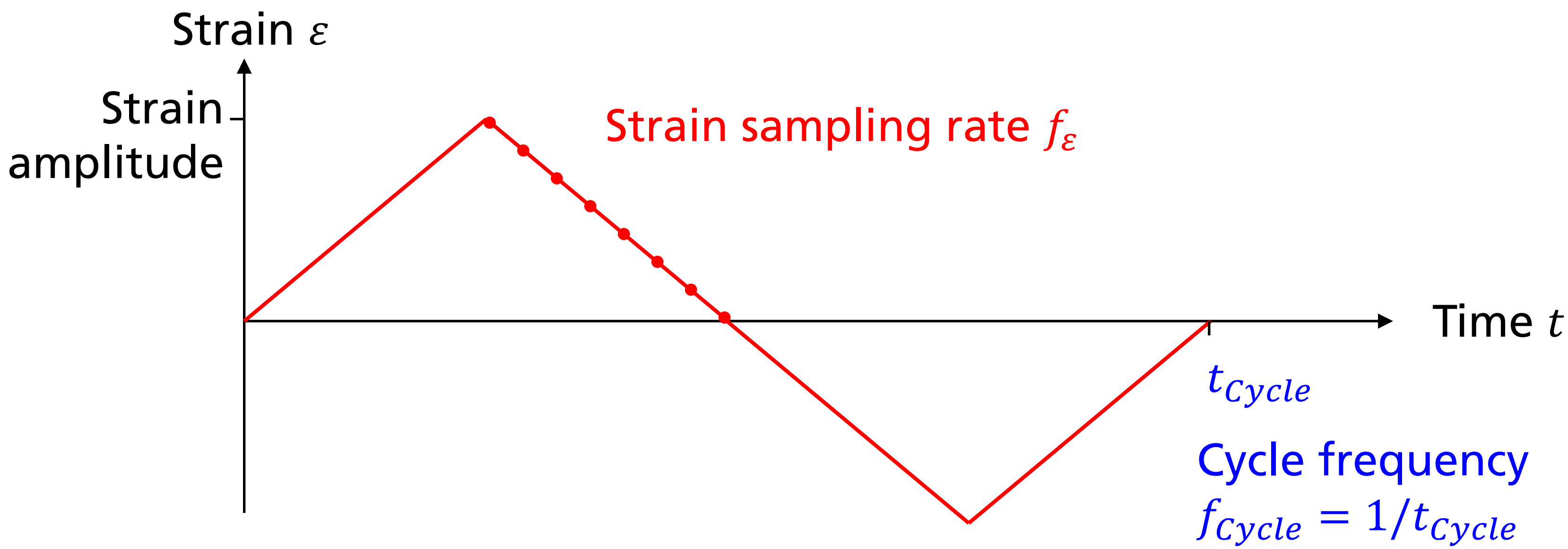
Standard Strain-controlled Testing (ASTM E 606)



- Strain amplitude resolution of 1 % ⇔ 400 strain measurements per cycle
- Cycle frequency limited by sampling rate: $f_{Cycle} < f_\varepsilon/400$
- Typical low cycle fatigue (LCF) lifetime: 10.000 cycles

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State-of-the-Art 2D DIC Systems

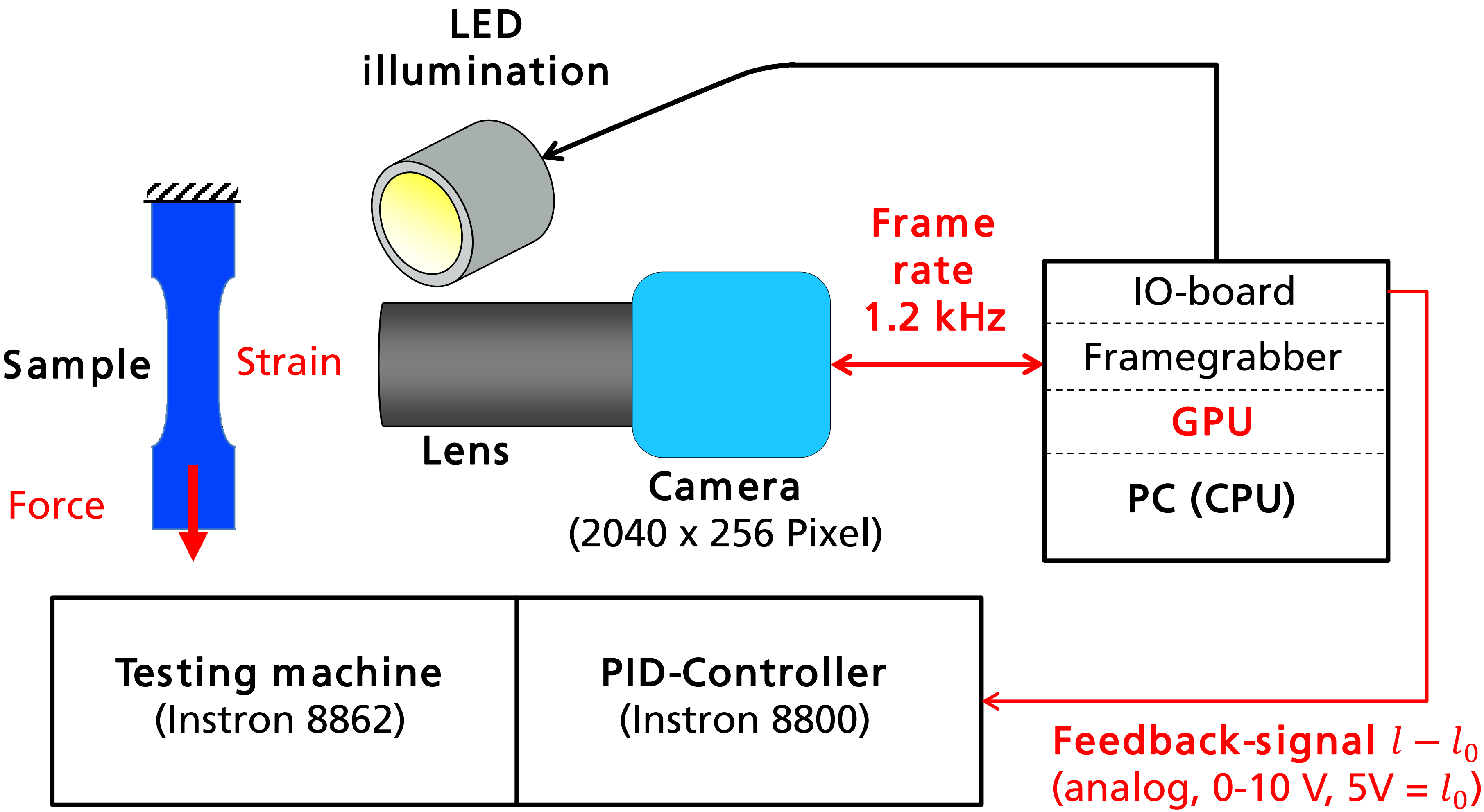
Marker

Zwick Roell videoXtens HP

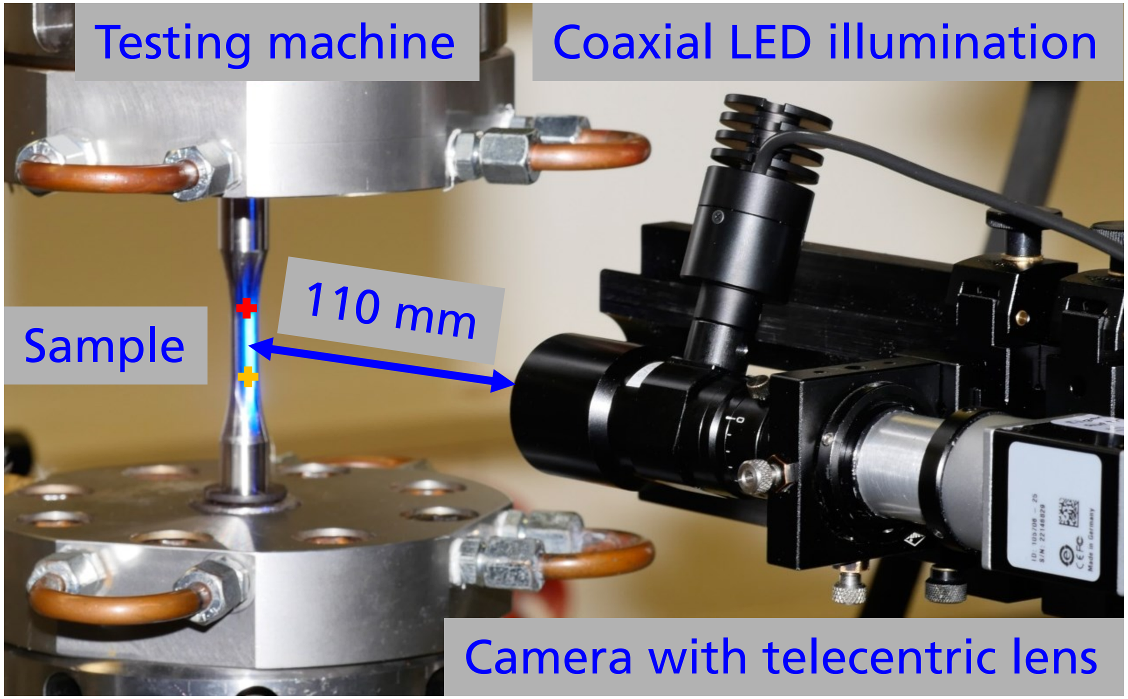
- **Optical extensometers (DIC):** $f_{\varepsilon} \sim 160\ Hz \Leftrightarrow f_{Cycle} < 0.4\ Hz$
  ➔ measurement time of 15 h for 10.000 cycles
- **Mechanical extensometers:** $f_{\varepsilon} \sim 5000\ Hz \Leftrightarrow f_{Cycle} \sim 1\,..\,10\ Hz$
  ➔ measurement time of 0.3 to 3 h for 10.000 cycles

Reference:
Zwick Roell Produktinformation videoXtens 2-120 HP,
https://www.zwick.de/extensometer/videoxtens-hp

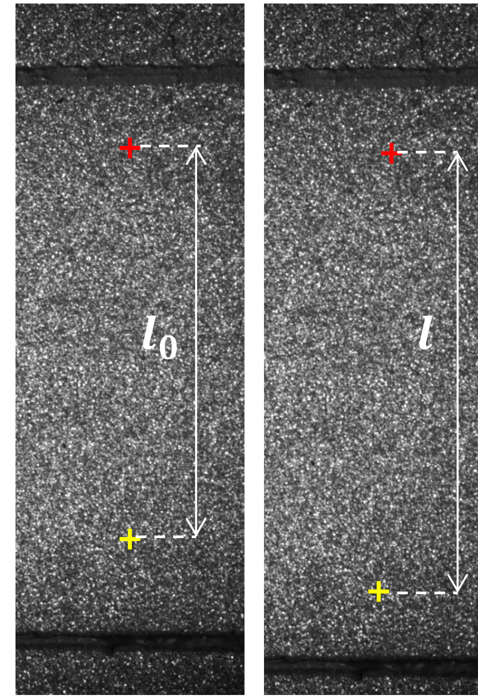
Setup for Strain-controlled Closed-Loop System



Marker-free DIC Measurement



Sample surface



Ref. Meas.

- Camera resolution: 2040 x 256 pixel
- Field-of-view: 11.2 x 1.4 mm^2 (5.5 µm/Pixel)

Strain: $\varepsilon = \frac{l - l_0}{l_0}$

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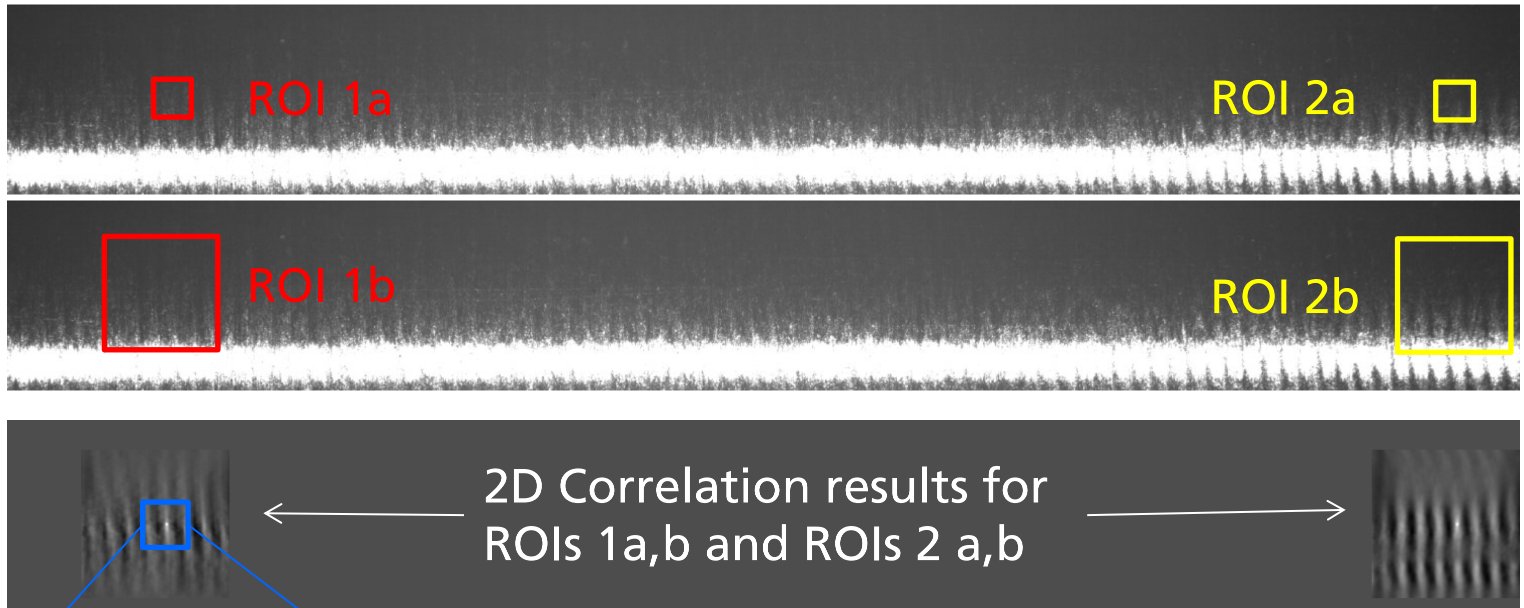
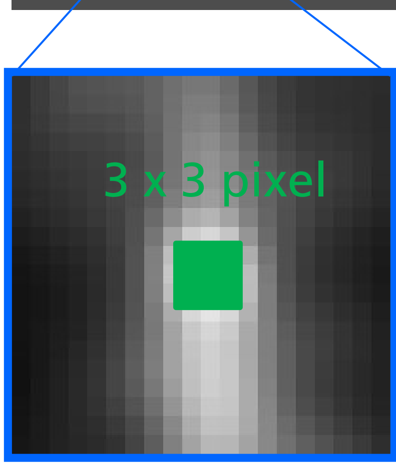
Subpixel Displacement Measurement

Ref:

Meas.:





Fit of 2D-Polynomial to 3x3 neighborhood of correlation maximum:

$$P_{Fit}(\Delta x, \Delta y) = a + b\,\Delta x + c\,\Delta y + d\,\Delta x\,\Delta y + e\,\Delta x^2 + f\,\Delta y^2$$

Displacement: Maximum $(\Delta x, \Delta y)$ of P_{Fit}

2D Image Correlation of Graphics Boards (GPU)

Calculation on CPU in space domain:

$$c_{ROI}(i,j) = \frac{1}{\sigma_a \sigma_b} \sum_{k=i-r}^{i+r} \sum_{l=j-r}^{j+r} ROI_a(k,l) ROI_b(k+i, l+j) \qquad O(N^2)$$

Calculation on CPU in Fourier domain:

$$c_{ROI}(i,j) = FFT^{-1}\left(A^*\left(\omega_i, \omega_j\right) B\left(\omega_i, \omega_j\right)\right) \qquad O(N \, log_2 N)$$

with

$$A\left(\omega_i, \omega_j\right) = FFT(ROI_a(i,j))$$

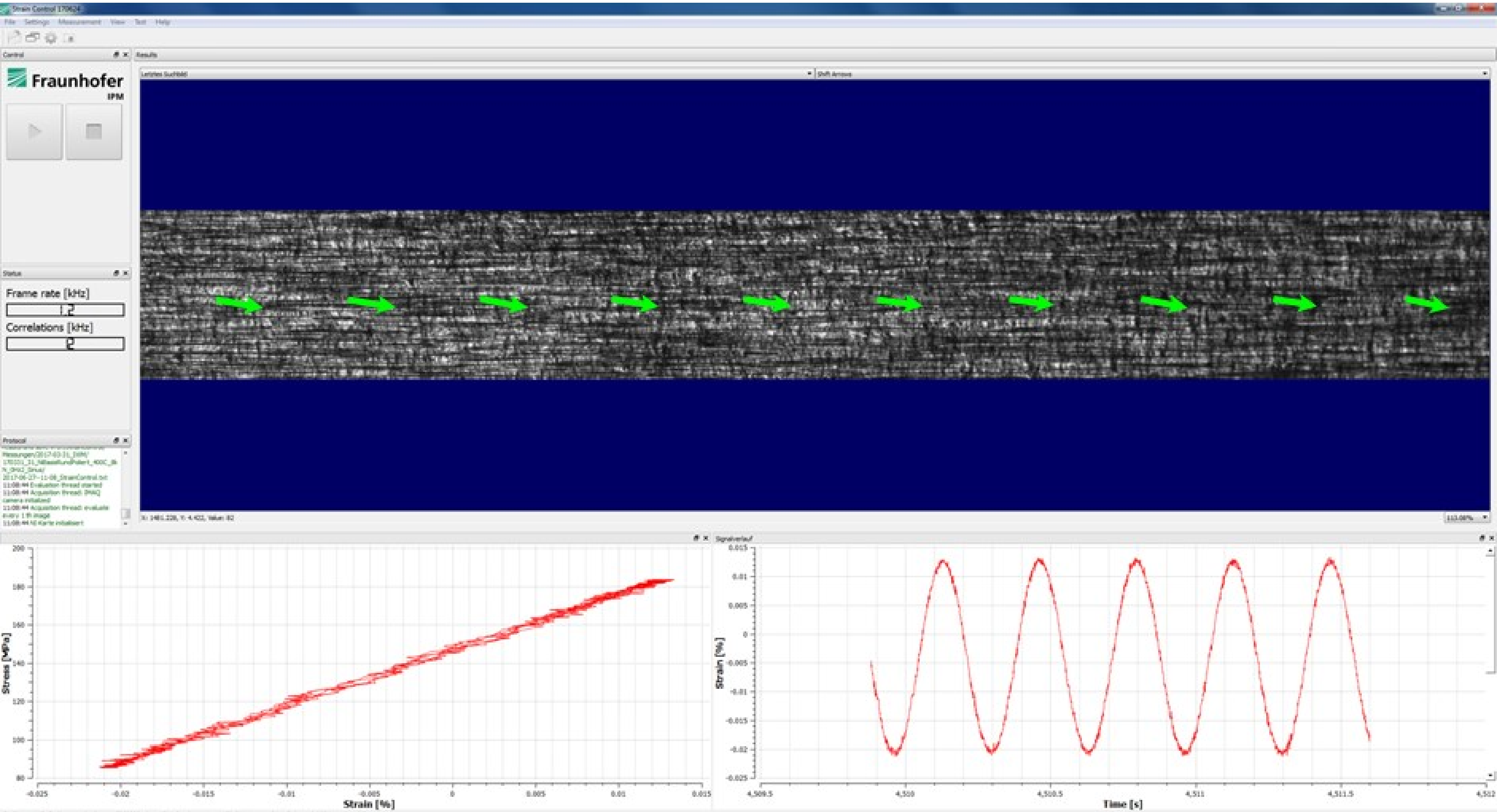
$$B\left(\omega_i, \omega_j\right) = FFT(ROI_b(i,j))$$

Measured correlation rate on Core i7, 256 x 256 Pixel: 600 Hz

Calculation on GPU in Fourier domain: $O(log_2 N)$

Measured correlation rate on Nvidia GTX 1080, 256 x 256 Pixel:
12.000 to 25.000 Hz

Strain Measurement with $f_\varepsilon = 1.2\ kHz$ and 10 ROIs



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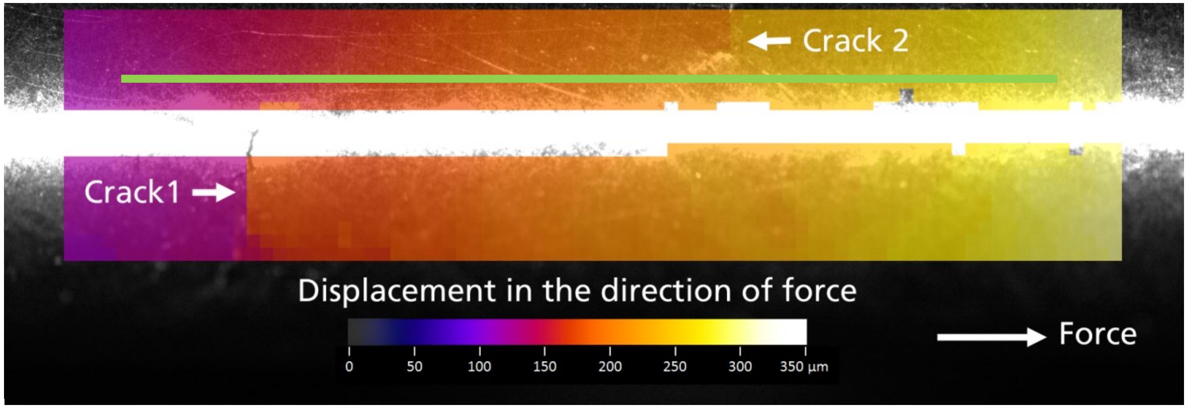
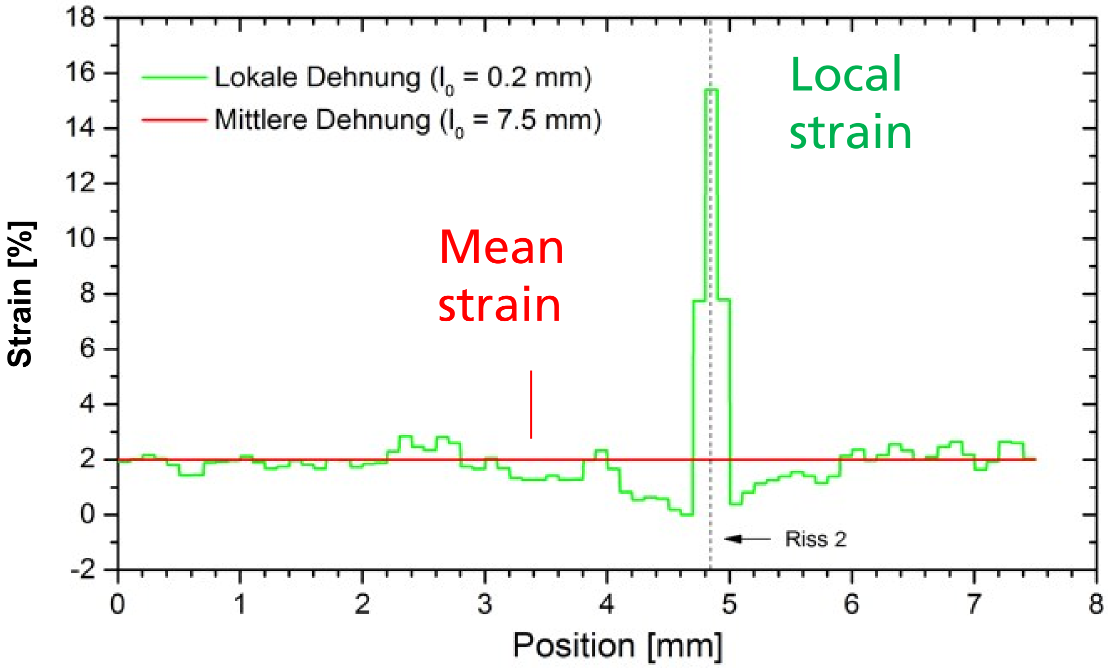
Real-Time Full-field Analysis at 10 Hz with 2500 ROIs





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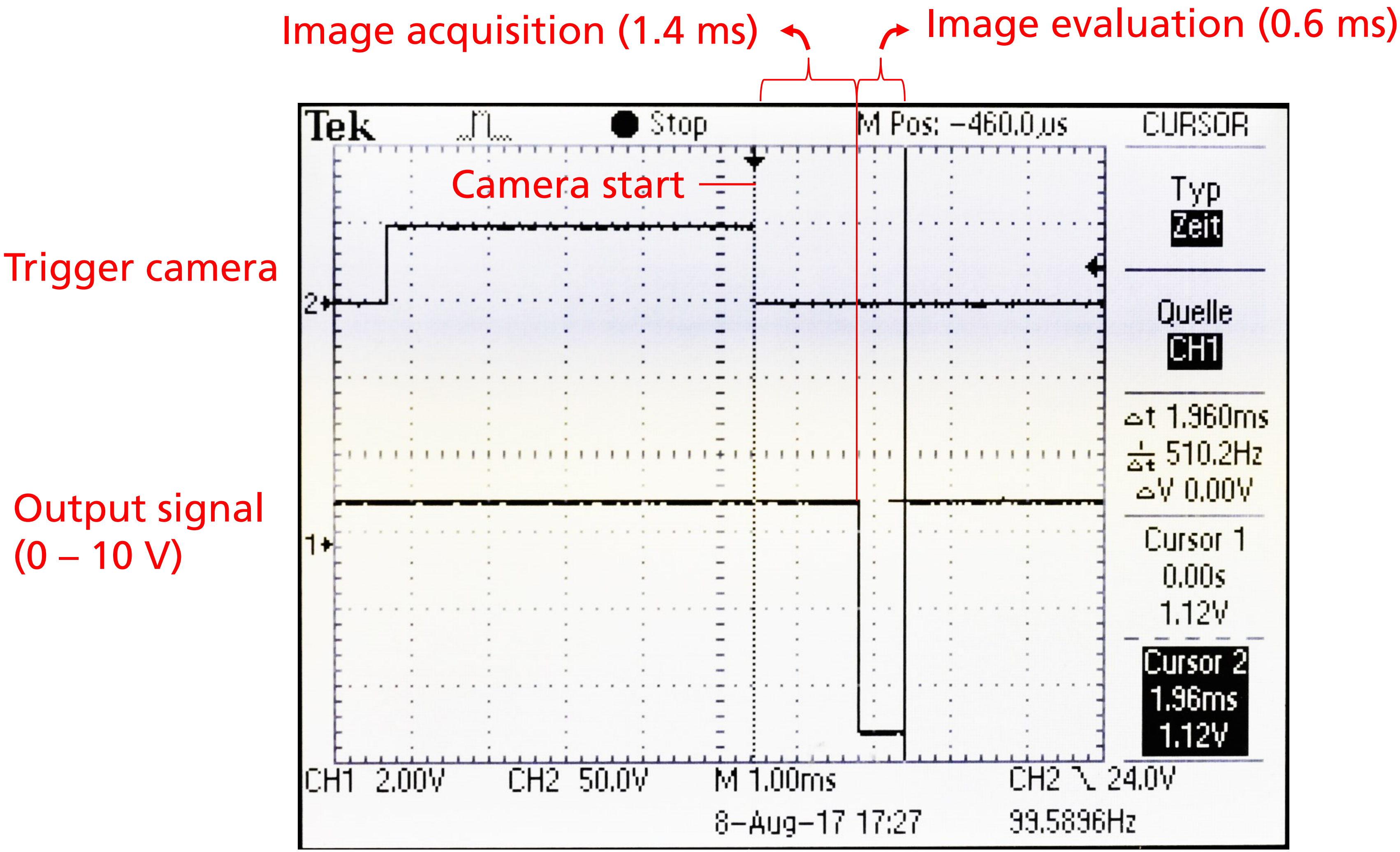
Closed-loop System: Mean Dead Time < 2 ms



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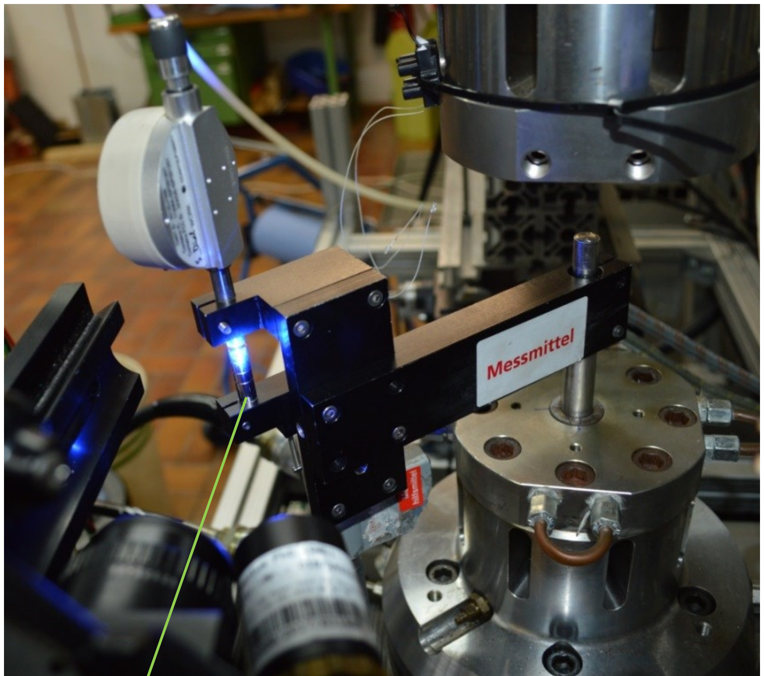
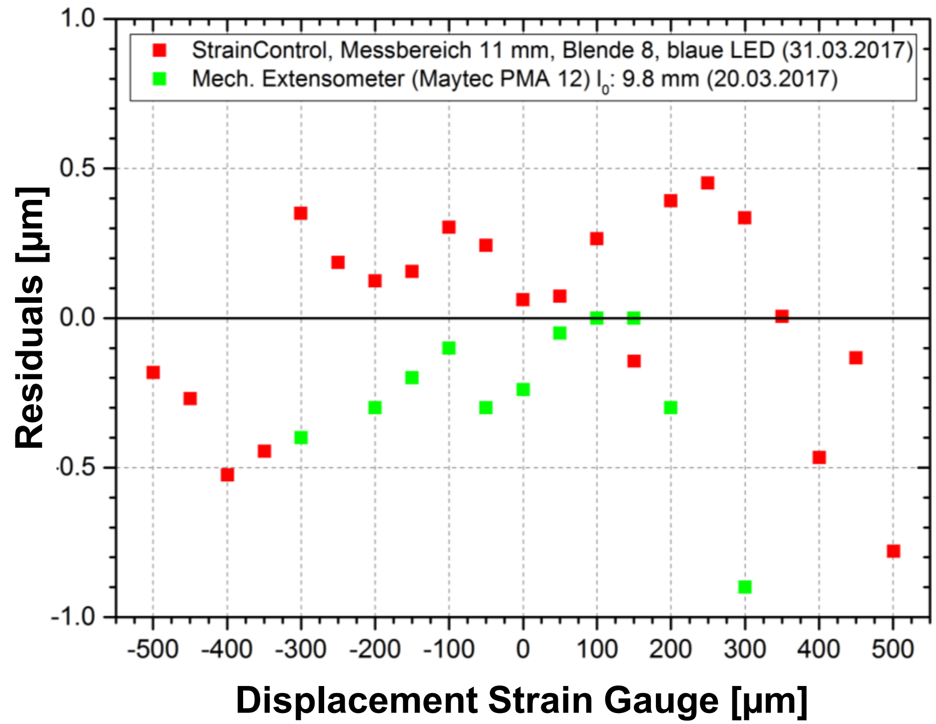
Calibration with Strain Gauge





Calibrated strain gauge
(Sylvac S_Dial Work Nano Bluetooth 2.5 mm)

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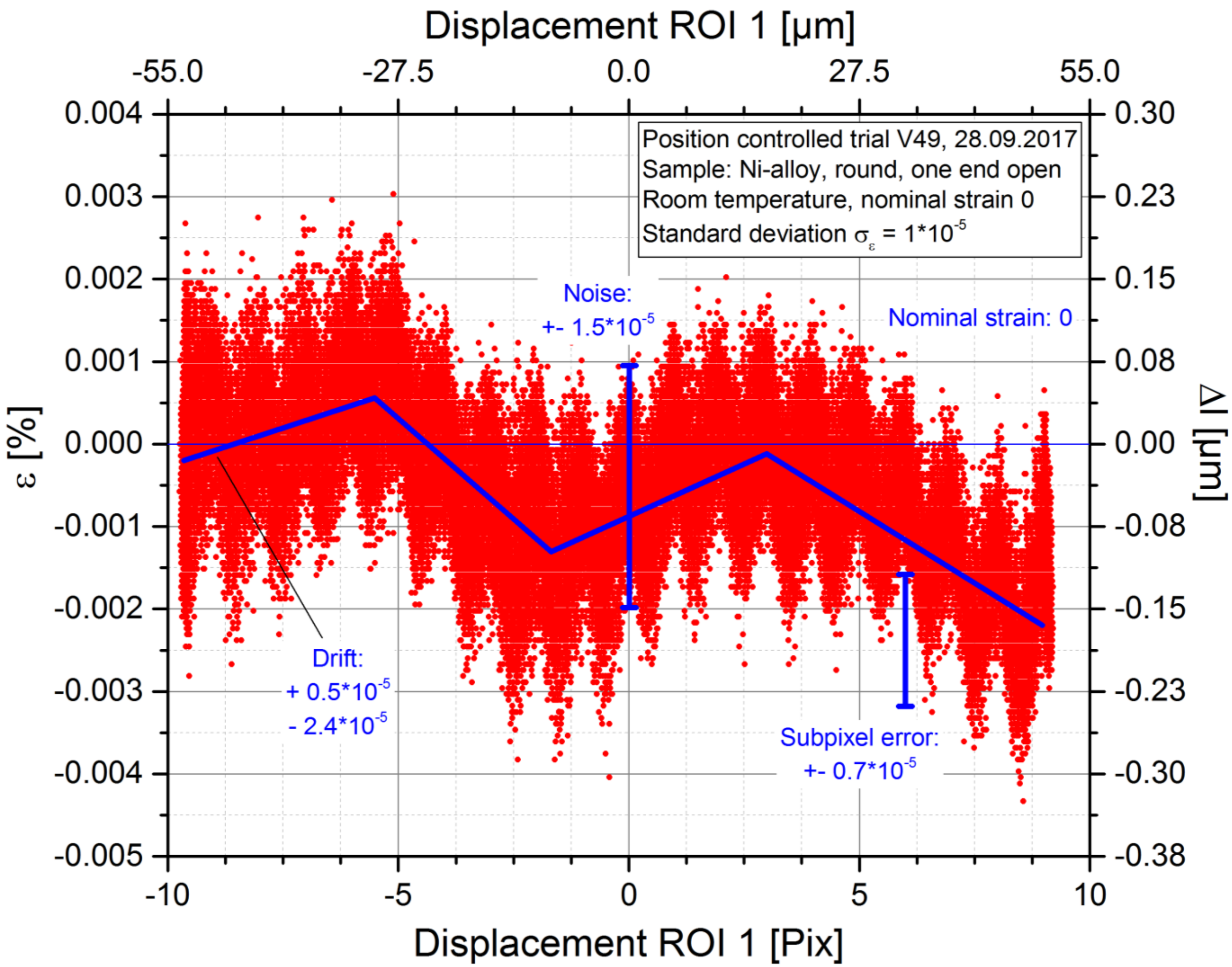
Zero-strain Test Result



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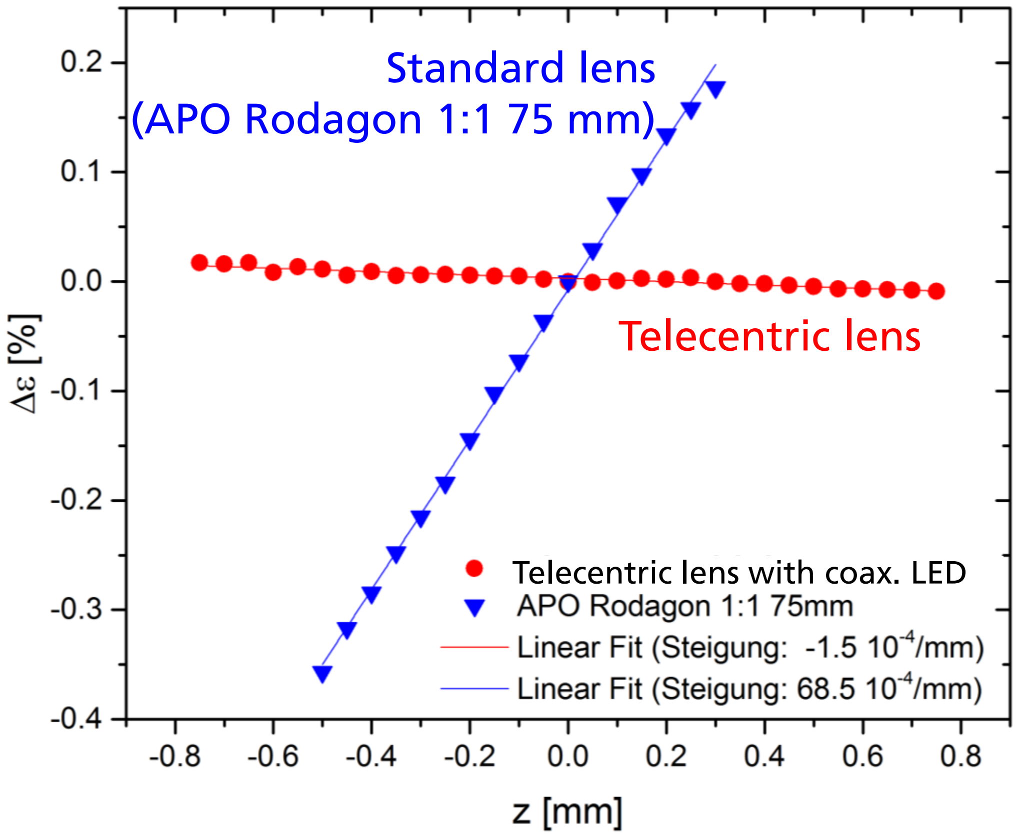
Out-of-plane Error



- Uncertainty $\Delta z < 0.1\ mm$ in axial direction (sample thinning, machine tolerance …)
- Telecentric lens: $|\Delta\varepsilon| < \quad 1.5\ 10^{-4}\ mm^{-1} \cdot 0.1\ mm = \quad 1.5\ 10^{-5}$
- Standard lens: $|\Delta\varepsilon| < 68.5\ 10^{-4}\ mm^{-1} \cdot 0.1\ mm = 68.5\ 10^{-5}$

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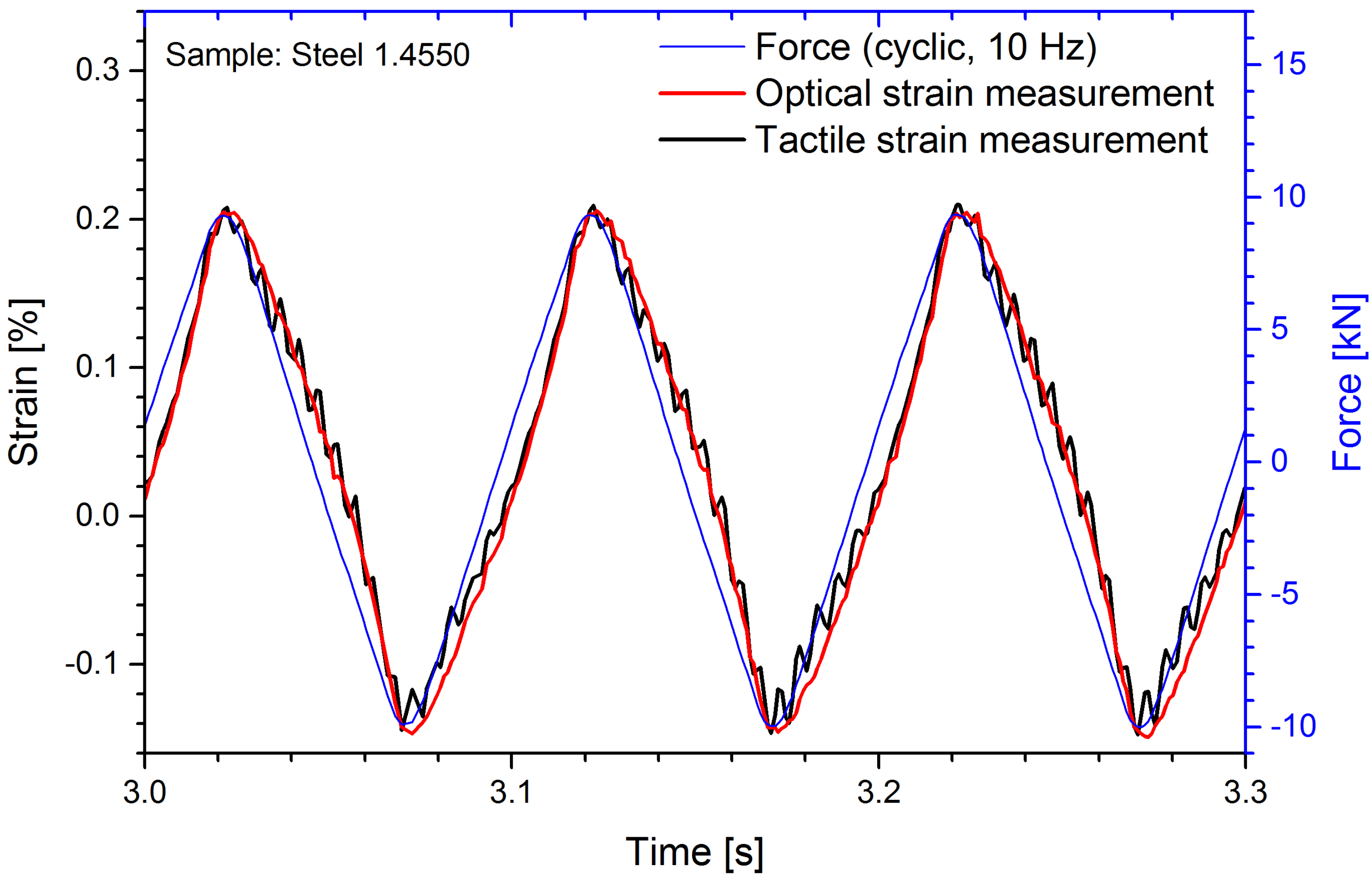
Tactile and Optical Strain Measurements



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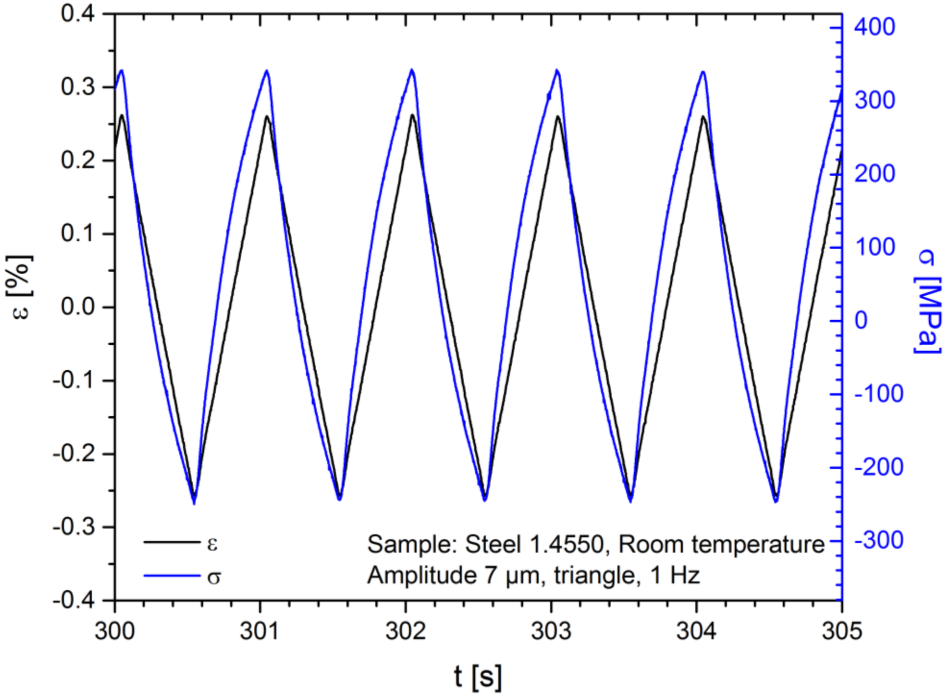
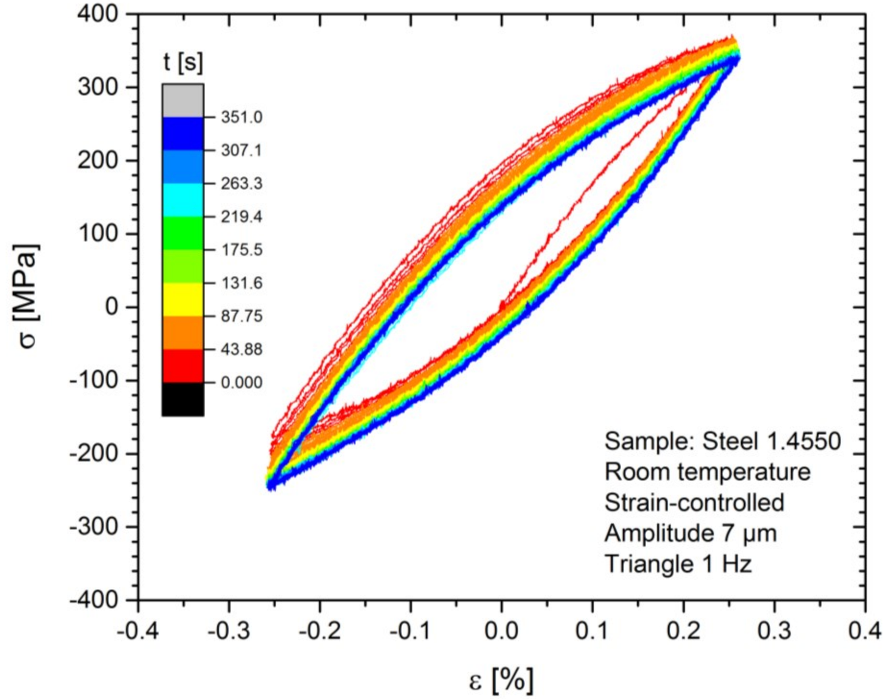
Strain-controlled Measurement at 1 Hz Cycle Frequency





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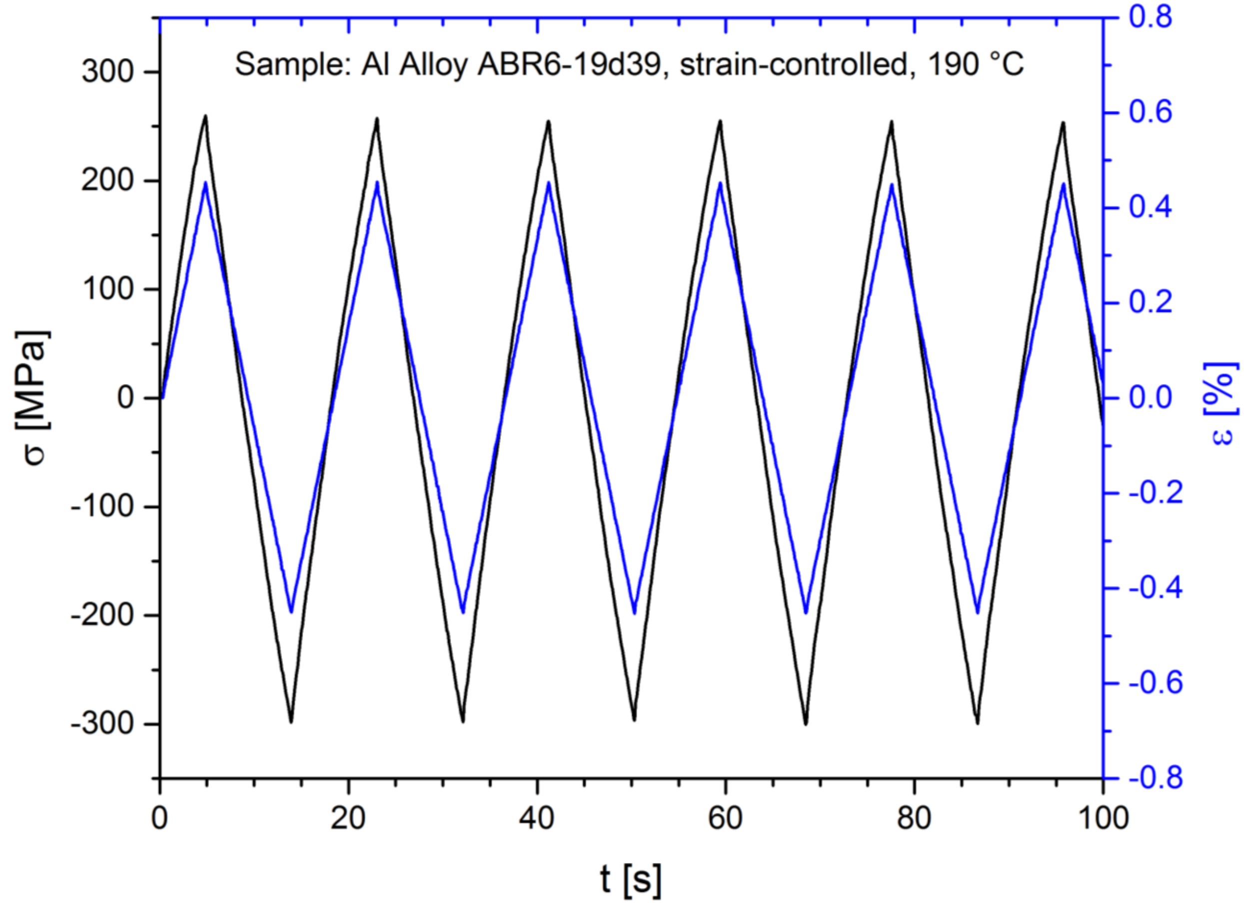
Strain-controlled LCF-Measurement on Al: Start



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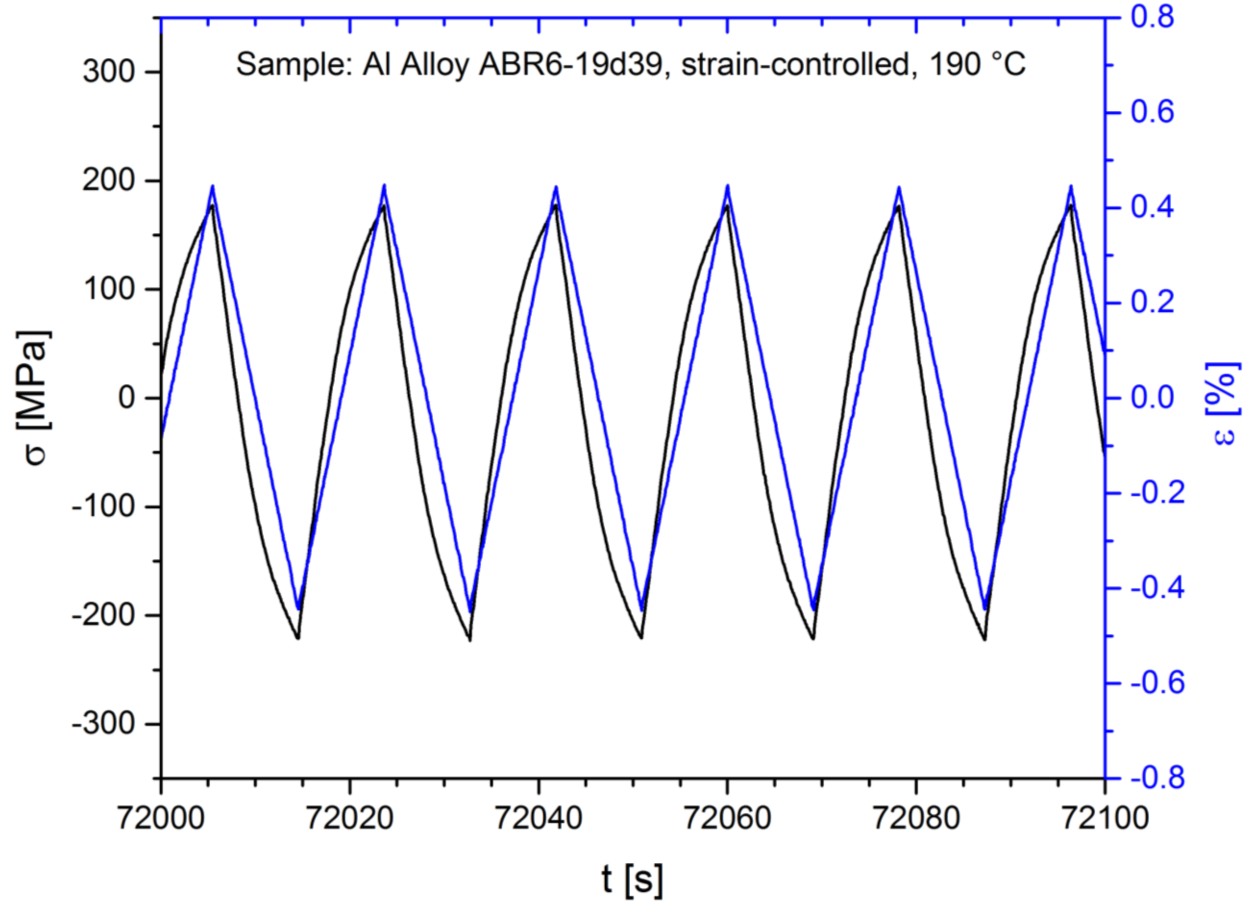
Strain-Controlled LCF-Measurement on Al: After 20 h



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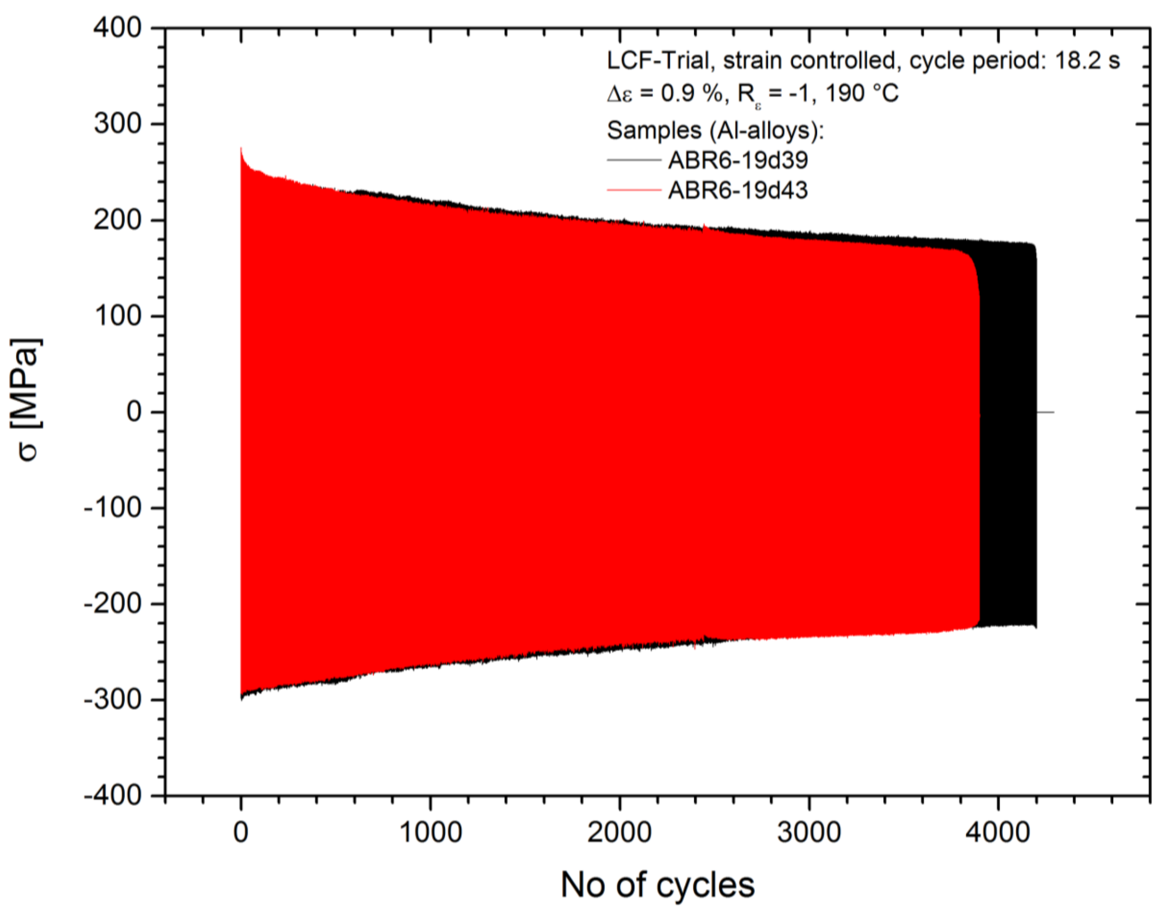
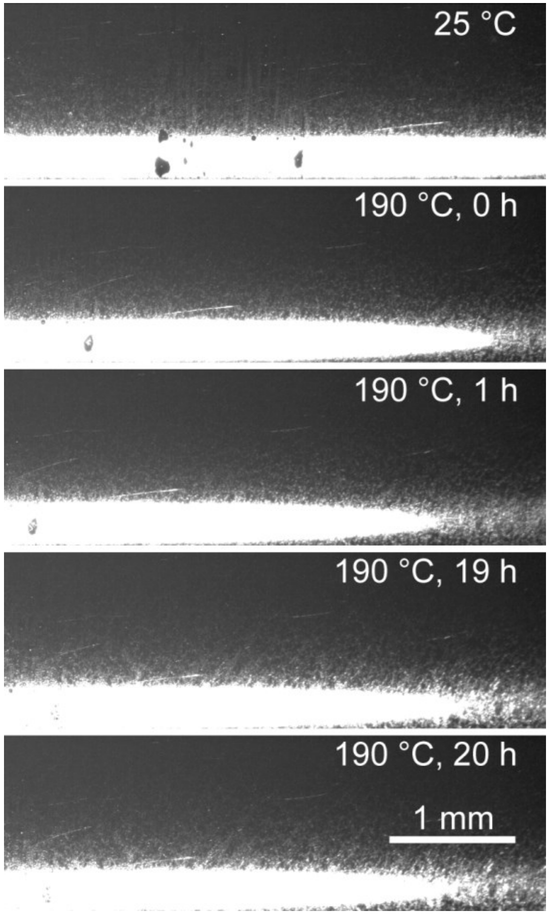
Strain-Controlled LCF-Measurement: Stress Amplitude





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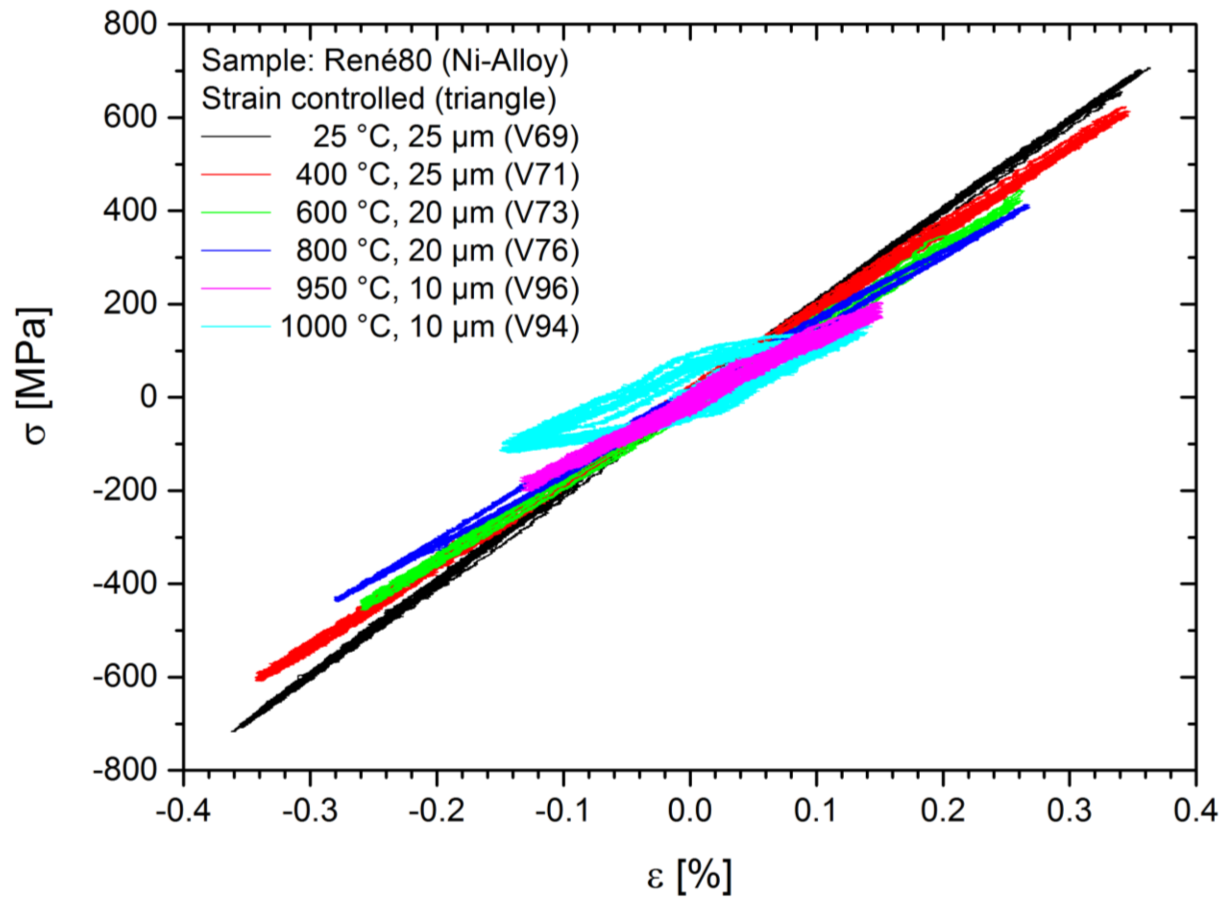
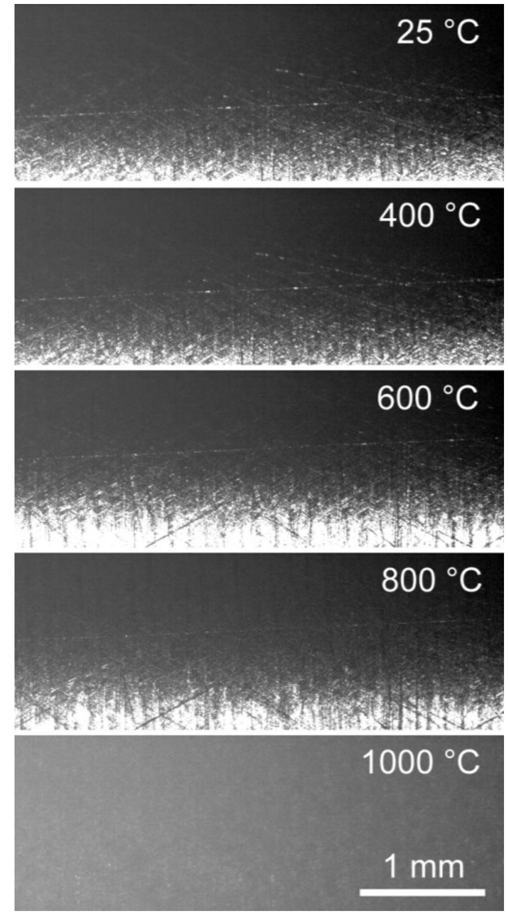
Marker-free Strain-controlled Measurements at 1000 °C





Rene-80: Coating required above 800 °C

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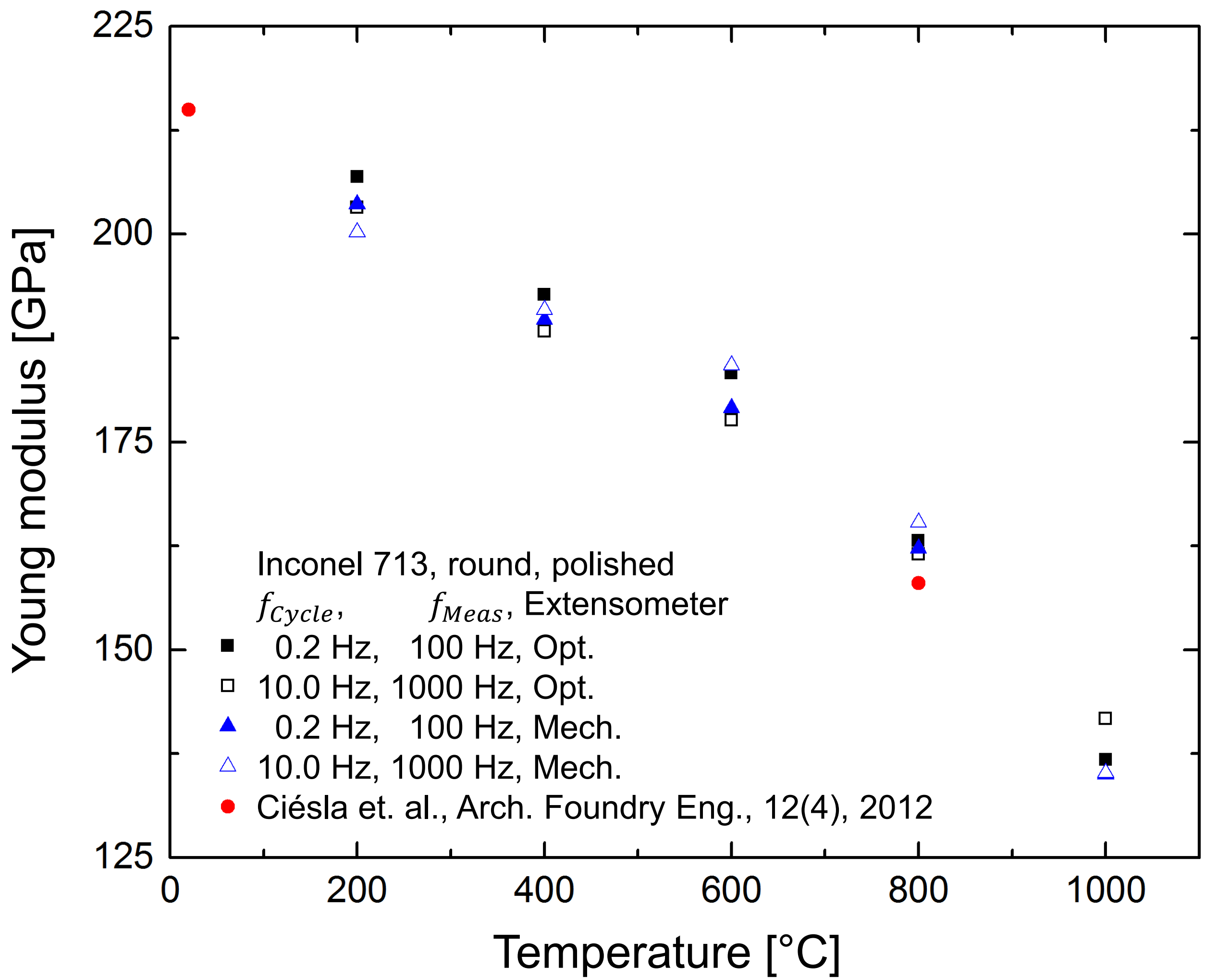
Variation of Cycle Frequency



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Conclusion

	Mechanical Extensometer	2D DIC on CPU (state-of-the-art)	2D DIC on GPU
Displacement uncer-tainty (FOV 10 mm)	0,5 µm	0,5 µm	0,5 µm
Contacting	yes	no	no
Strain sampling rate f_ε	5 kHz	160 Hz	1,2 kHz (dead time: 2 ms)
Cycle frequency f_{Cycle}	1 .. 10 Hz	0,4 Hz	3 Hz
LCF measurement time (10.000 cycles)	0.3 - 3 h	7.5 h	1 h
Full-field analysis	no	yes (offline)	yes (real-time, 10 Hz)
	Errors due to normal pressure and slippage	Contactless, marker required	Contactless, marker-free,

Combines advantages of both, optical and mechanical extensometers

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