SAND2020-9051 TR (slides)
SAND2020-9046 TR (videos)

CHAPTER 2:
DESIGN OF DIC MEASUREMENTS

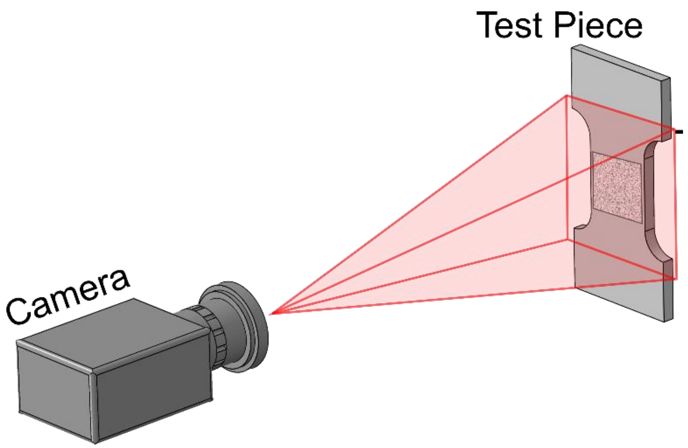
SEC. 2.1:
MEASUREMENT REQUIREMENTS

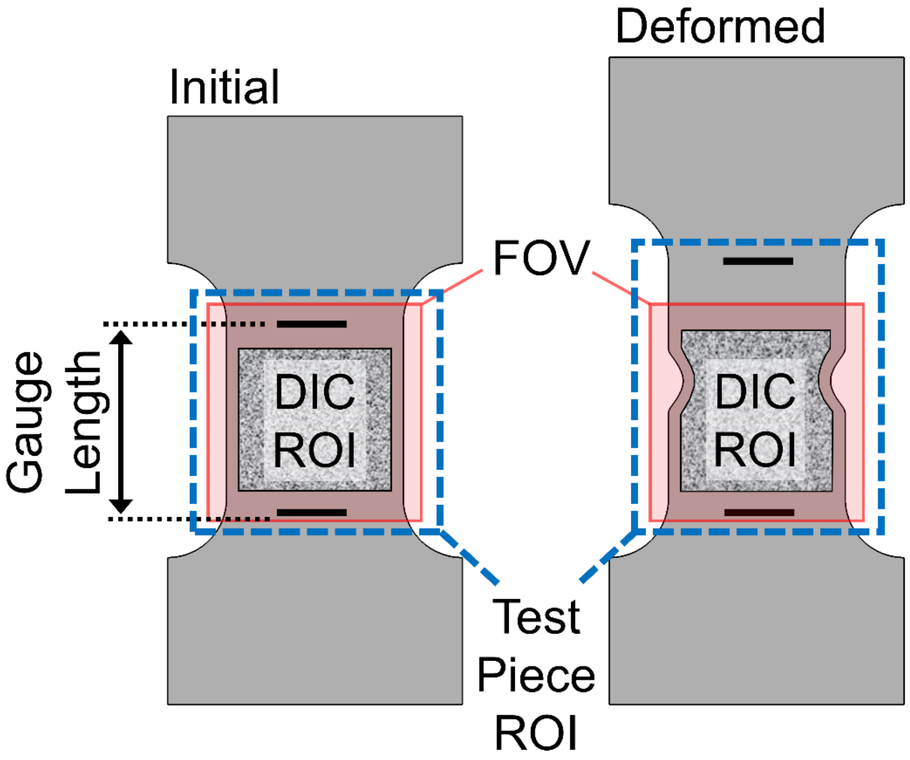
Quantity-of-Interest (QOI), Region-of-Interest (ROI), and Field-of-View (FOV) Sec. 2.1.1 – Sec. 2.1.3

1. Determine the QOIs
   - Examples include: shape, displacement, velocity, acceleration, strain, strain-rate, etc.
   - Application specific:
     - Strain field near hole or necking region?
     - Displacements at grips?

2. Select the ROI of the test piece

3. Determine the required FOV, based on the ROI
   - Recommendation 2.1: ROI should fill FOV, accounting for anticipated motion





iDICs

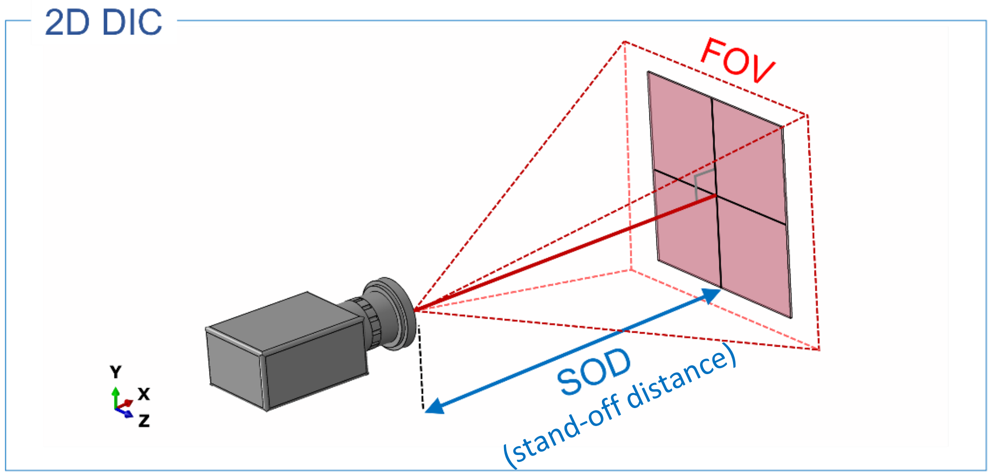
2D-DIC vs Stereo-DIC
Sec. 2.1.5

2D-DIC:

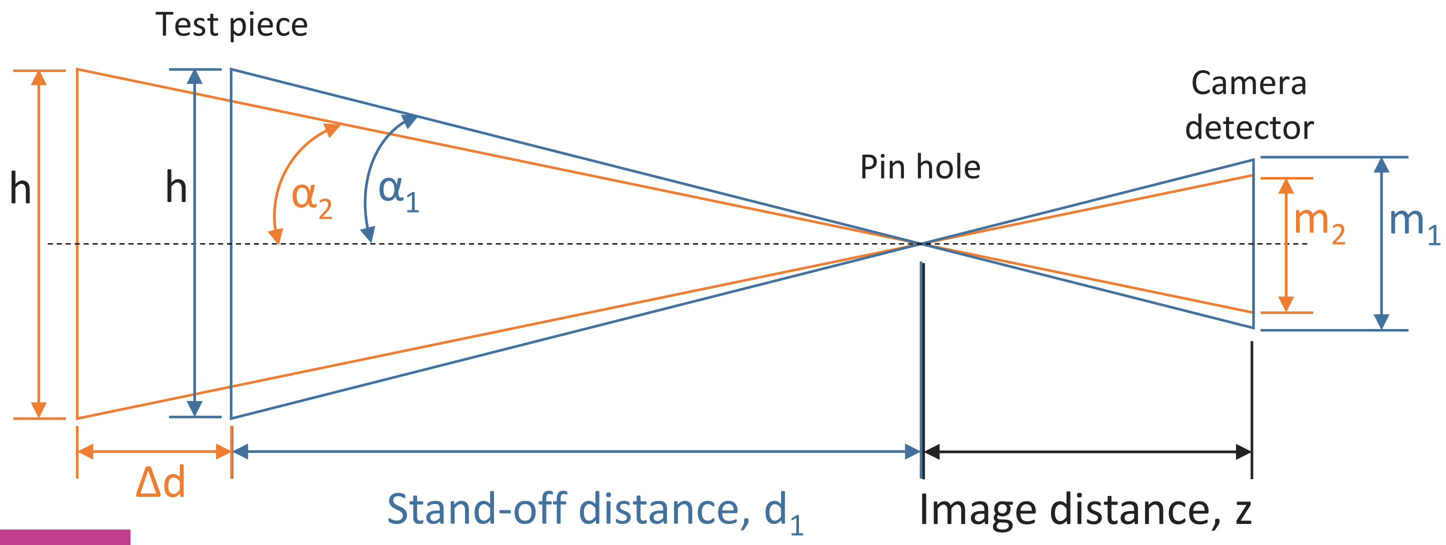
- One camera, perpendicular to a planar test piece
- Gives in-plane displacements and strains

- Caution 2.1: Test piece should be planar and perpendicular to camera, and remain so during the test

- Recommendation 2.3: Estimate errors due to out-of-plane motion



Schematic top view of experimental setup



$$① \tan(\alpha_1) = \frac{h}{d_1} = \frac{m_1}{z} \qquad ② \tan(\alpha_2) = \frac{h}{d_1 + \Delta d} = \frac{m_2}{z}$$

$$\text{False Strain} \approx \frac{m_2 - m_1}{m_1} = \frac{d_1}{d_1 + \Delta d} - 1$$

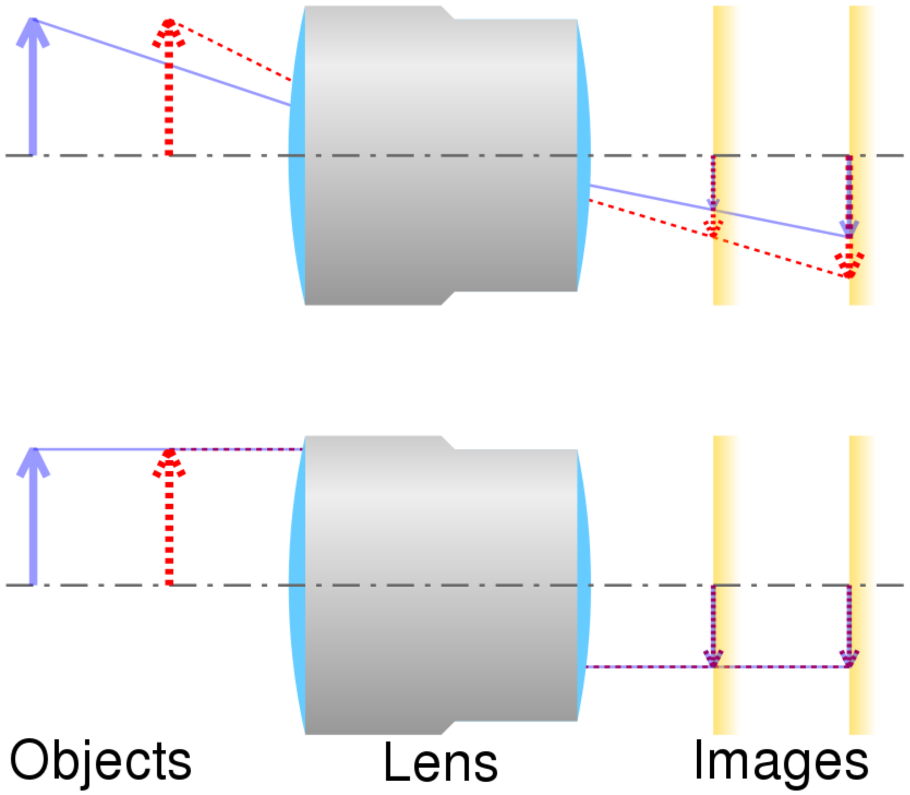
d_1	Δd	False Strain
250 mm	1 mm	0.4 %
500 mm	1 mm	0.2 %
1000 mm	1 mm	0.1 %

2D-DIC: Telecentric lenses
Sec. 2.2.1

- Recommendation 2.6:
  - For 2D-DIC, bi-lateral telecentric lenses are recommended
  - If a telecentric lens isn't available, use a longer focal length lens

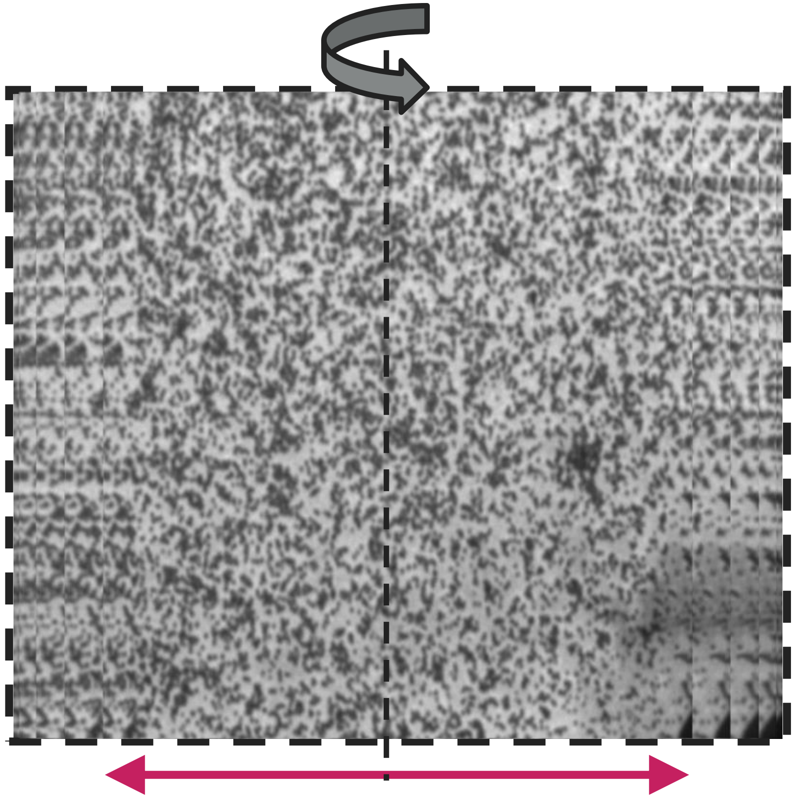
Standard lens:
Image size *depends* on stand-off distance and image distance

Bi-telecentric lens:
Image size *independent* of stand-off distance and image distance



- Caution 2.5
  - Do not use telecentric lenses for stereo-DIC!

- Caution! (not in Guide)
  - False strains may still occur from out-of-plane *rotations*, even with a telecentric lens.

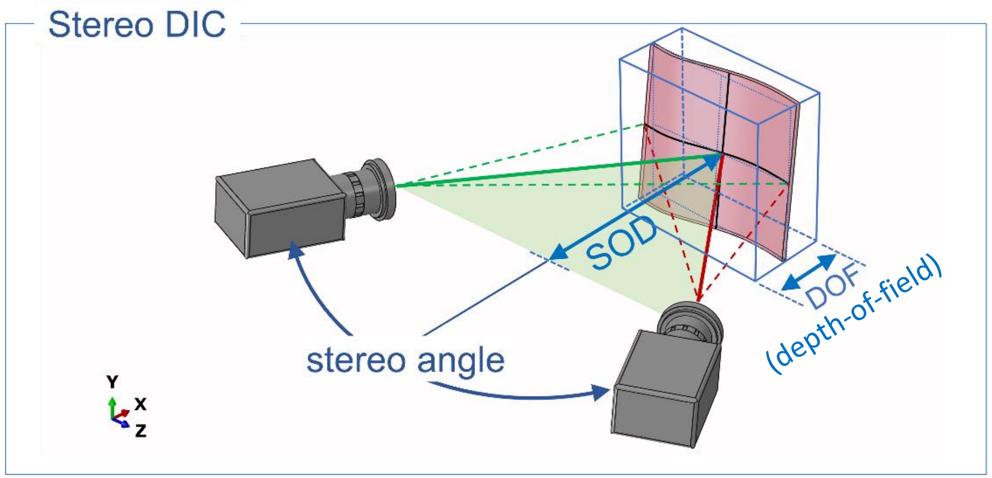


2D-DIC vs Stereo-DIC
Sec. 2.1.5 – 2.1.7

Stereo-DIC:

- Two cameras oriented at a stereo angle (typically 15-35 degrees)
- Gives 3D coordinates, displacements, strains on the surface of the test piece

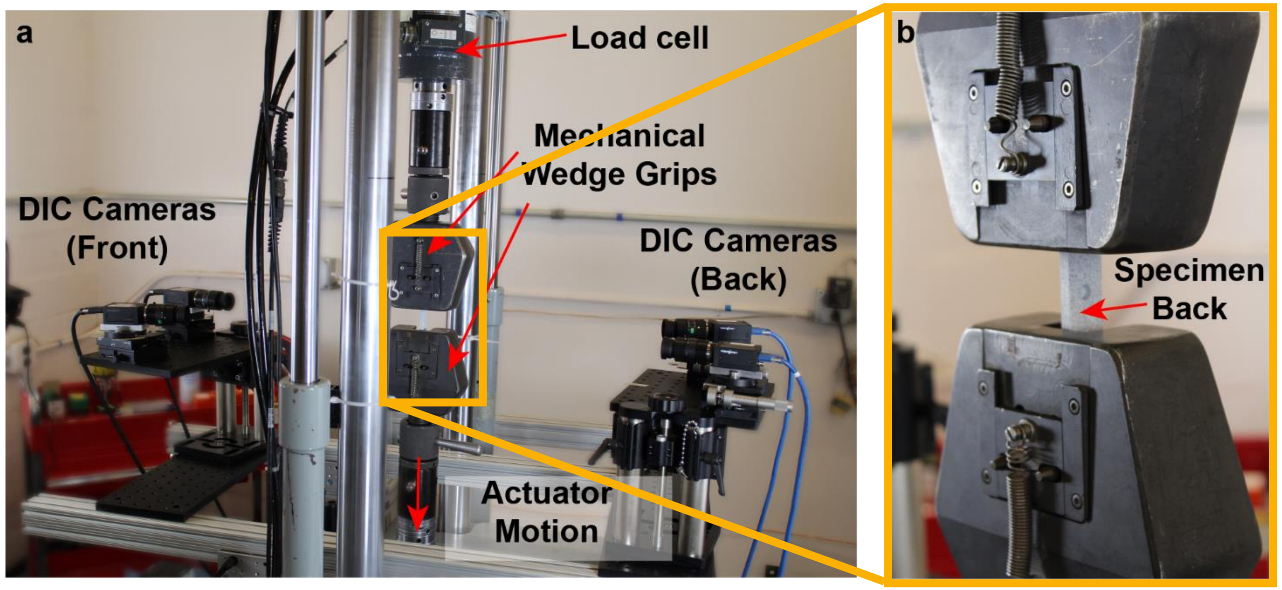
- Tip 2.2
  - Smaller stereo angles
    - better in-plane accuracy
    - ROI in focus for both cameras for larger range of out-of-plane motion
  - Larger stereo angles
    - better out-of-plane accuracy



DEMO 01

Position Envelop for Hardware
Sec. 2.1.4

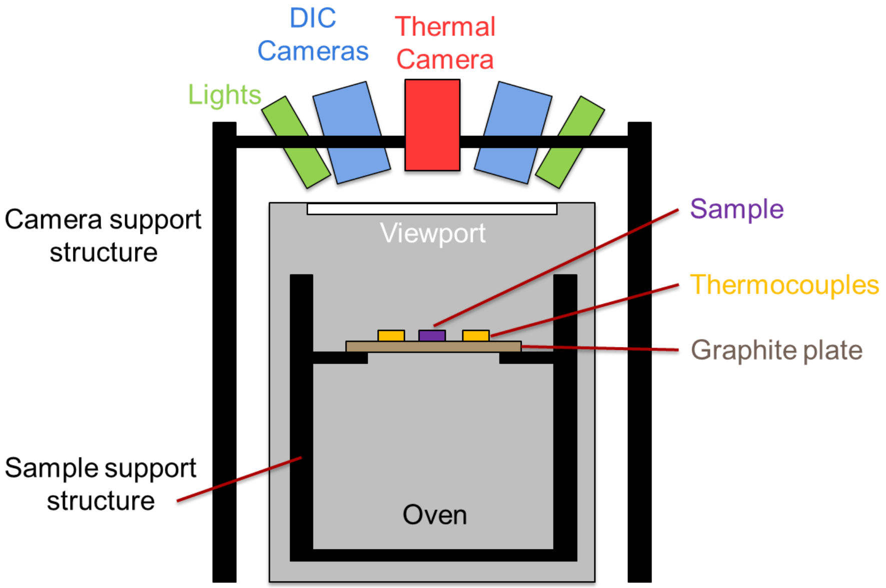
- Considerations include:
  - How big is your load frame?
  - Does any equipment restrict the field of view or causes shadows?
  - How big are your cameras?
  - How will you mount lights? Do you need different lights for the test versus calibration? Can you switch between them without bumping your cameras? (Tip. 2.19)
  - Vibration isolation: physically separate any vibrating equipment (load frame, fans, lights) from cameras
  - Mounting equipment? Need to purchase or fabricate?



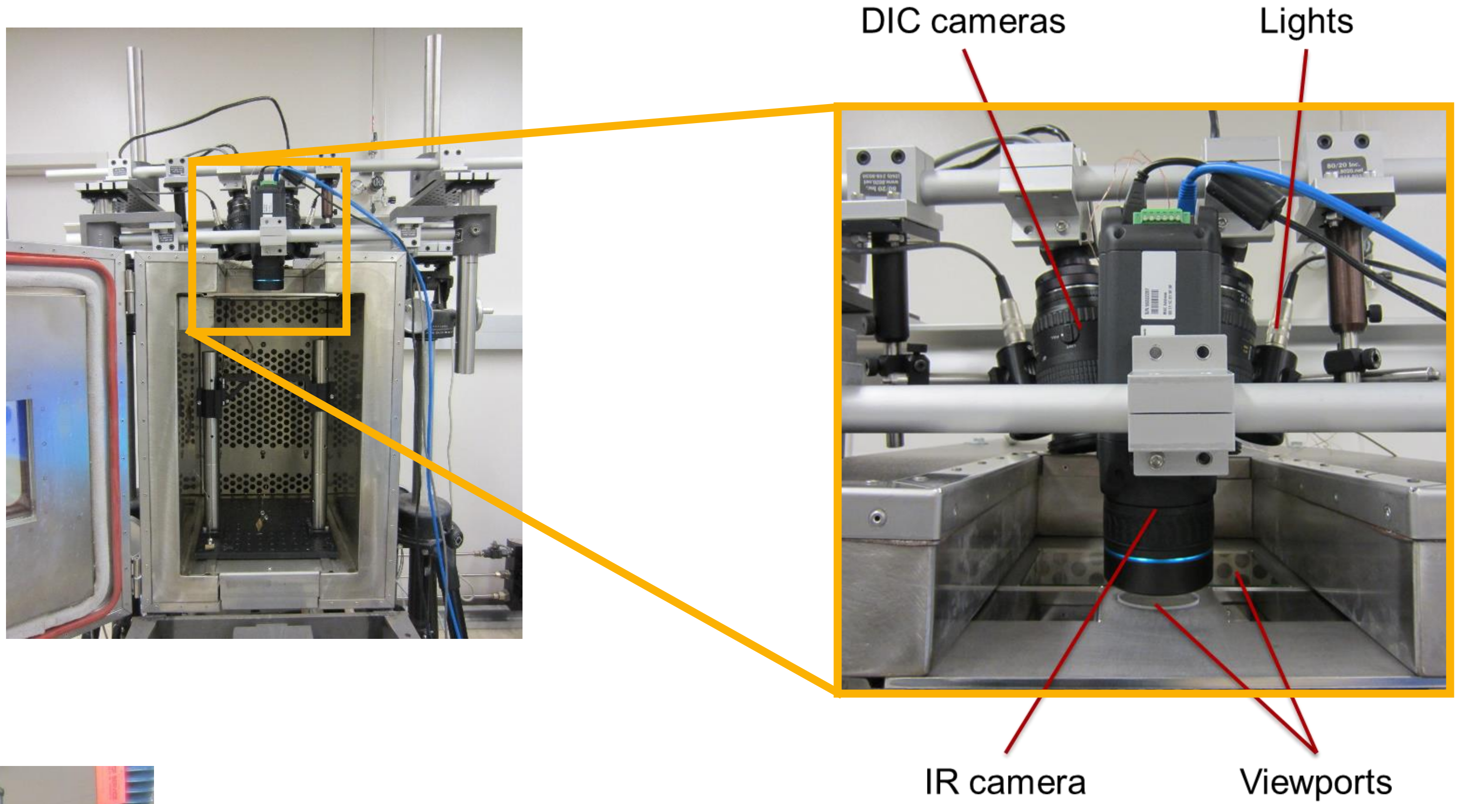
Example 1

- Relatively straightforward setup of a tensile test on a load frame
- Flexibility for hardware position with few major restrictions
- Lights must be placed carefully to avoid shadows from the large grips

Position Envelop for Hardware
Sec. 2.1.4



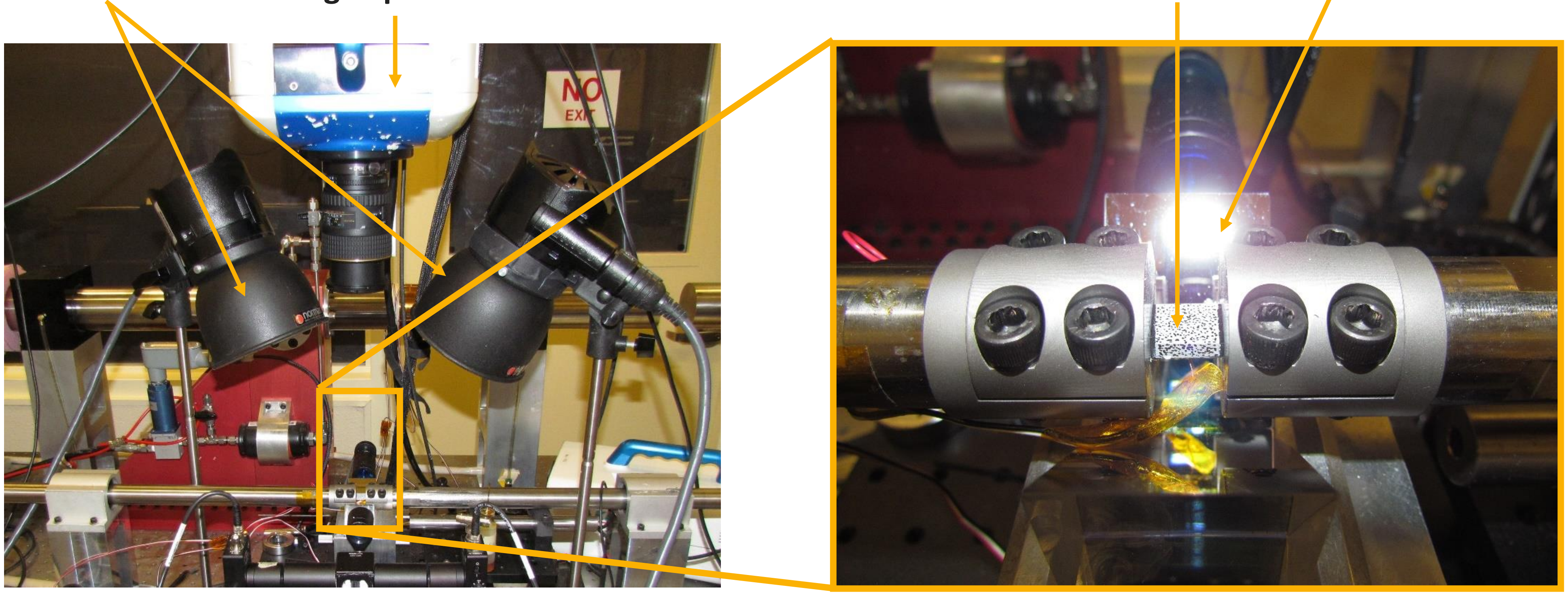
Front View



Example 2

- Test piece was heated in an oven
- Test piece had to be horizontal, forcing cameras to be above the oven
- Limited flexibility and major restrictions on position envelop

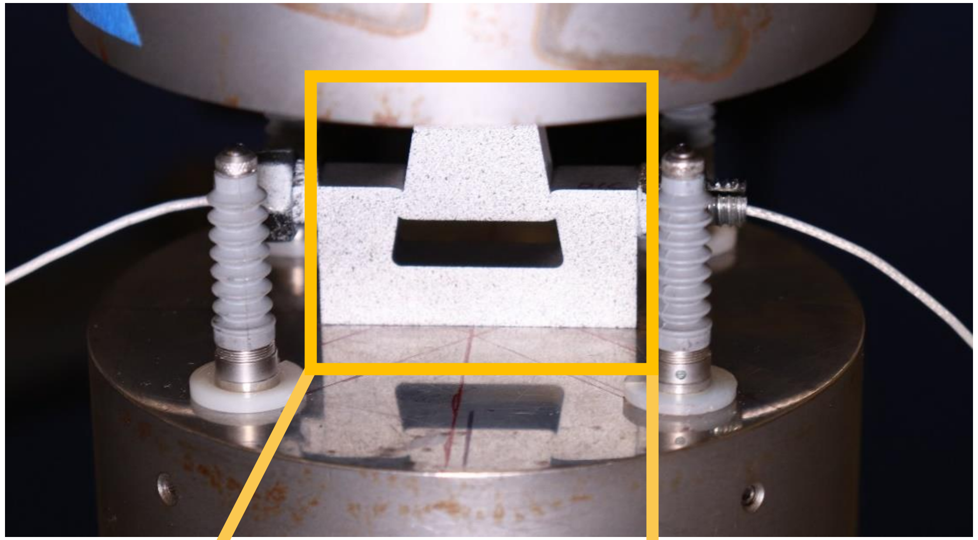
Position Envelop for Hardware
Sec. 2.1.4



Example 3

- Hopkinson bar mechanical test
- Ultra-high-speed cameras usually have a large body
- Hopkinson bar test pieces are usually small
- Mirrors used to view three sides of the test piece with one camera

Position Envelop for Hardware
Sec. 2.1.4

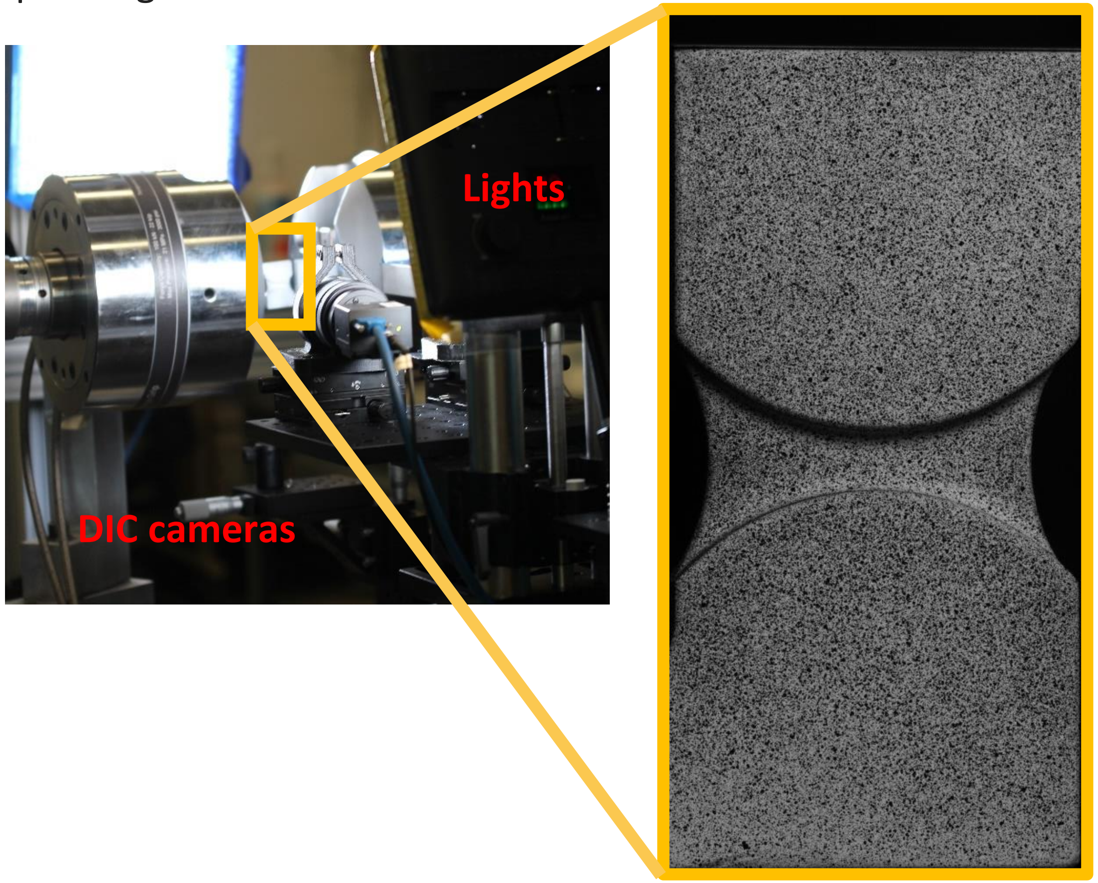


Example 4

- Compression test setup
- Shadow difficult to avoid due to size of compression platens
- Shadow may worsen with increased compression
- Displacement transducers block edges of test piece and optical path if stereo angle is too wide

Example 5

- Tension test of an atypical test piece geometry
- Test piece geometry may cast shadows or block the optical path depending on camera orientation

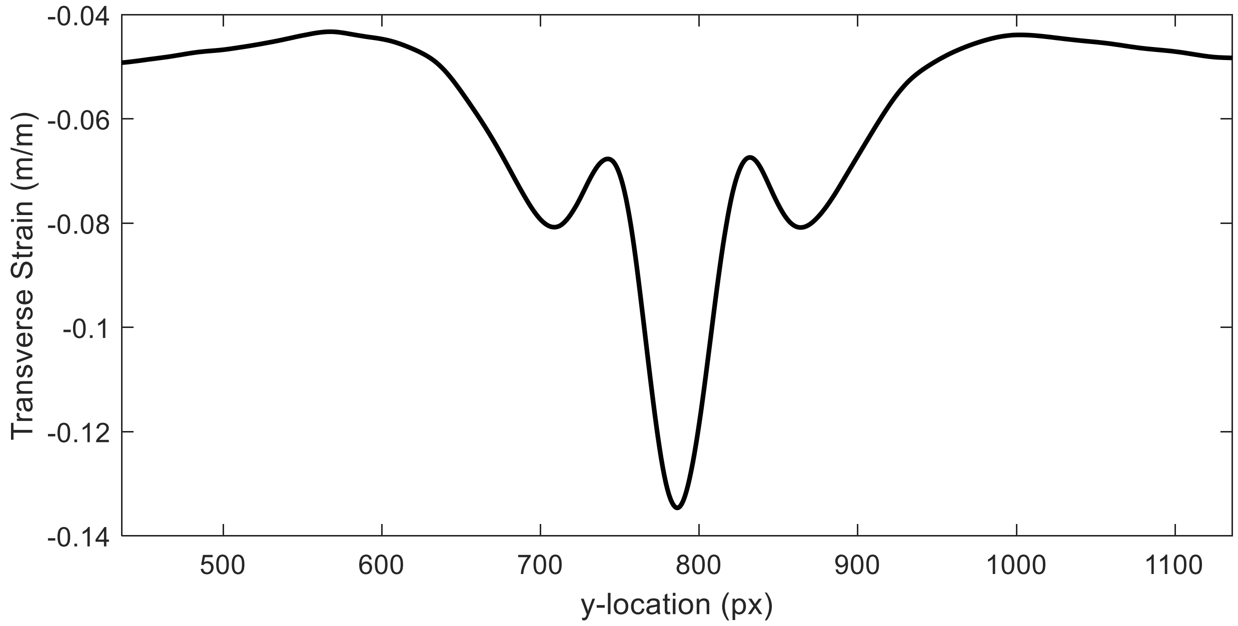


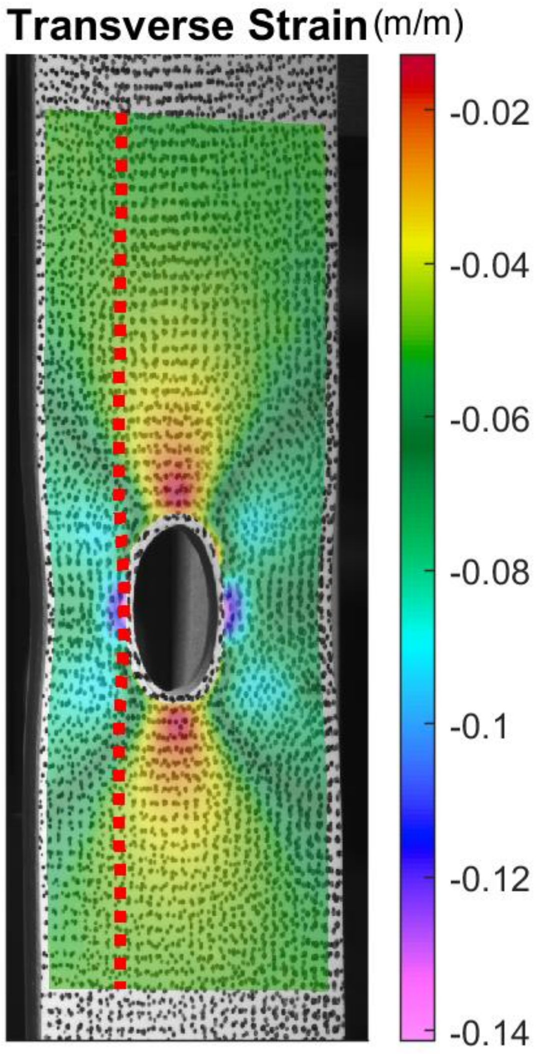
Spatial Gradients
Sec. 2.1.8

- Estimate expected spatial gradients of QOIs
- This determines required spatial resolution
- Estimation typically requires *a priori* information about expected deformation field

- Tip 2.4: If you have high gradients, consider higher magnification

1. Use a camera with a higher resolution and use a pattern with smaller features
2. Reduce the ROI of the test piece and zoom-in on a smaller region





Noise Floor
Sec. 2.1.9

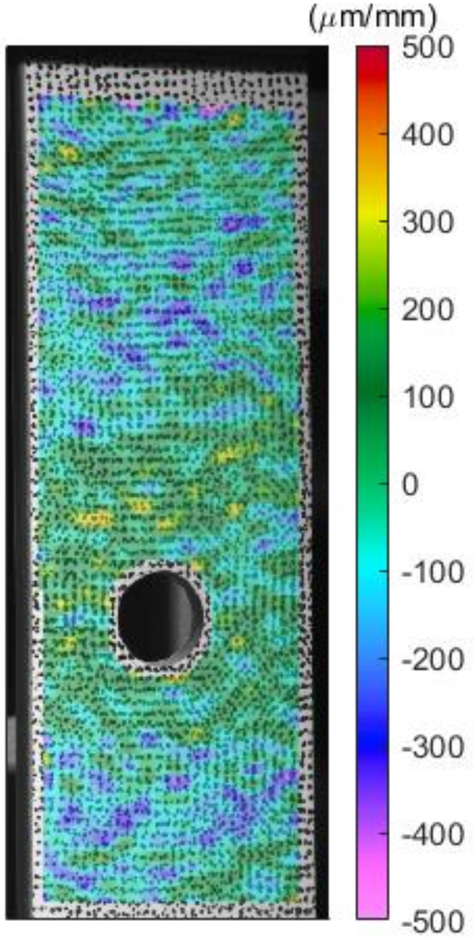
- Smallest resolvable QOI
- Any measurement smaller than your noise floor cannot be distinguished from noise
- Any measurement larger than your noise floor is significant/meaningful

- Typical Values
  - 0.01 px in-plane
  - 3X larger for out-of-plane

- Tip 2.5: Acceptable noise-floor is often determined by subject matter expert

- More information on evaluating the noise-floor in Chapter 5.

Noise of Transverse Strain Field (from correlation of a static image)

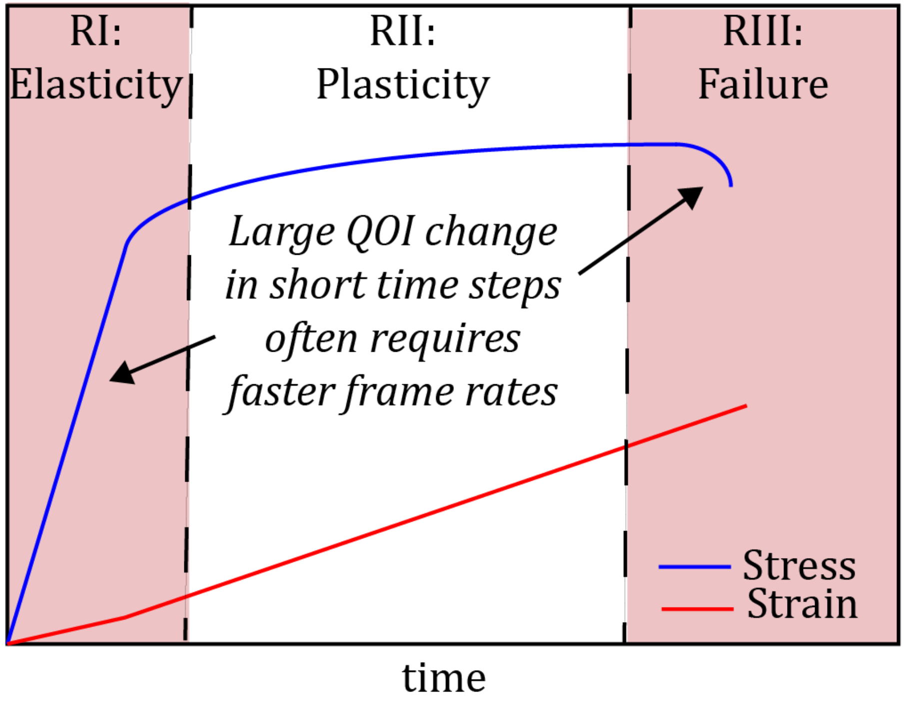


Frame Rate
Sec. 2.1.10

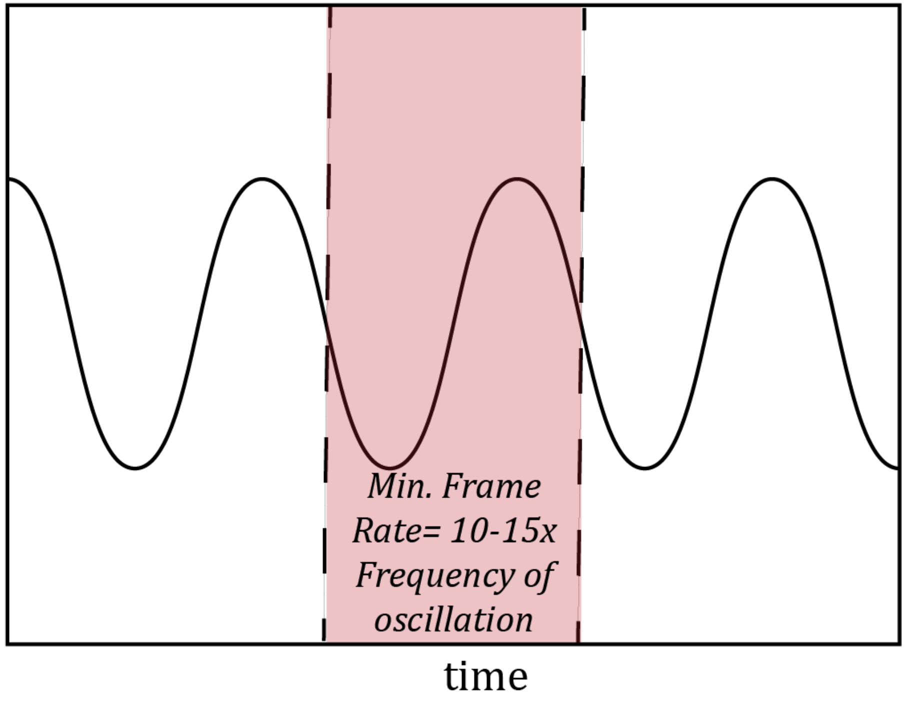
- Optimal frame rate is application specific
- Tip 2.6: Several factors to consider:

1. **Desired temporal resolution**
2. Amount of displacement between frames
3. Amount of data collected during a mechanical test

Example 1: Metal plasticity



Example 2: Cyclic loading



Exposure time, Synchronization and Triggering
Sec. 2.1.11 – 2.1.12

Exposure Time

- Key point: prevent motion blur
- Tip 2.7: Maximum allowable test piece motion over the course of the exposure time is ~0.01 px (conservative) or up to 0.3 px (less conservative)
- $\text{Displacement per exposure (px)} = \left(\text{Velocity}\left(\frac{mm}{s}\right)\right) * \left(\text{Image Scale}\left(\frac{px}{mm}\right)\right) * (\text{Exposure Time}\ (s))$
- Tip 2.8: Exposure time is independent of frame rate, but cannot be larger than 1/frame rate

Synchronization and Triggering

- How will DIC images be synchronized to other measurements of interest, such as applied force or displacement, strain gauges, thermocouples, etc.?
- How will all data acquisitions be triggered at the start of the test?
  - 3-2-1-GO?
  - TTL pulse?

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CHAPTER 2: DESIGN OF DIC MEASUREMENTS

SEC. 2.2: EQUIPMENT AND HARDWARE

Lens selection
Sec. 2.2.1

- Field-of-view, stand-off distance, and lens focal length are all intertwined.

Focal Length	Stand-Off Distance	Field-of-View
↑	Constant	↓
↑	↑	Constant
Constant	↑	↑

Constant stand-off distance

28 mm lens

50 mm lens

70 mm lens

210 mm lens

Lens selection
Sec. 2.2.1

- Tip 2.12: Two main types of lenses
  - Fixed focal length lenses: FOV changed only by changing SOD
    - Also called “prime lens”
  - Zoom lenses: FOV changed by either changing SOD or focal length
    - Pro: Adds flexibility to experimental setup
    - Con: More complicated optics can lead to larger lens distortions

DEMO 02

- Recommendation 2.7
  - Lenses with ability to lock moving components (e.g. focus, aperture) are preferred

Fixed focal length or Prime lens

Zoom lens

Camera selection
Sec. 2.2.1

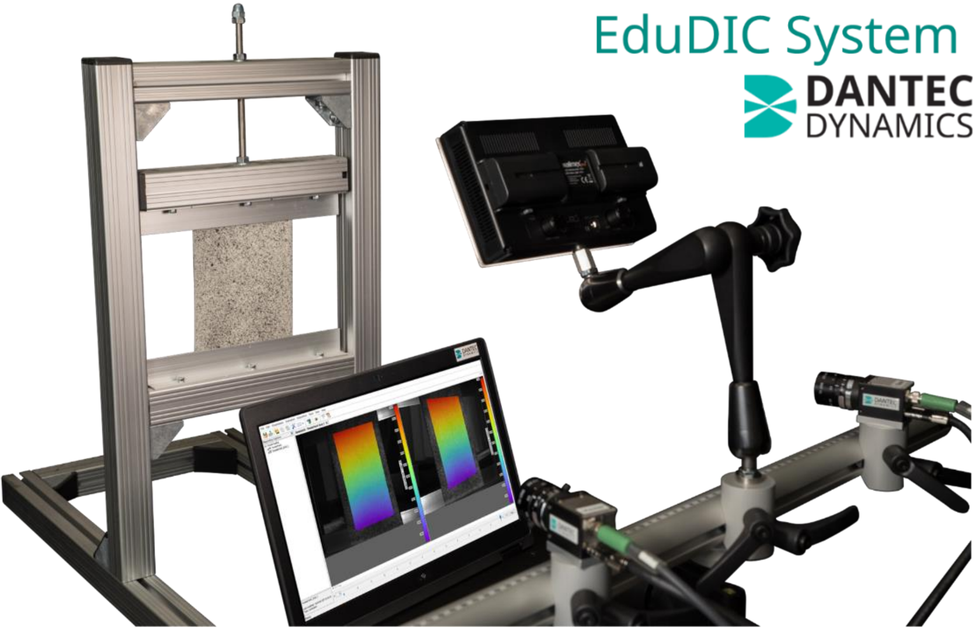
- Tip 2.10: Experience is necessary to determine if a camera or lens is of sufficient quality; vendors evaluate equipment for you.
- Recommendation 2.5: Machine-vision, monochromatic cameras with square pixels and global shutters are recommended
- Caution 2.3: Avoid auto-focus of the lens or apertures that automatically open/close
- Tip 2.11: Know if your camera has any built-in low-pass (anti-aliasing) filters in front of the detector

General characteristics of mounting system
Sec. 2.2.2.1

- **Caution 2.7: Any relative motion between cameras will induce errors!**
- Include sufficient degrees of freedom for precise adjustment of the cameras/lenses
- Have a plan for making room for the calibration target
- Mount camera/lens near its combined center of mass
- Stabilize and strain relieve cables
- Ensure camera support structure is stable (can add sandbags)
- Minimize vibrations being transferred to cameras

Types of Mounting Systems
Sec. 2.2.2.2

Examples of vendor-supplied rigs



EduDIC System
DANTEC DYNAMICS

MatchID
Metrology beyond colors

LAVISION
FOCUS ON IMAGING

correlated SOLUTIONS

gom
a ZEISS company

Types of Mounting Systems
Sec. 2.2.2.2

Build your own mounting system

- This is not an exhaustive list
- iDICs, SEM, SNL, and NIST do not endorse these companies

Edmund optics | worldwide

THORLABS

Newport
Experience | Solutions

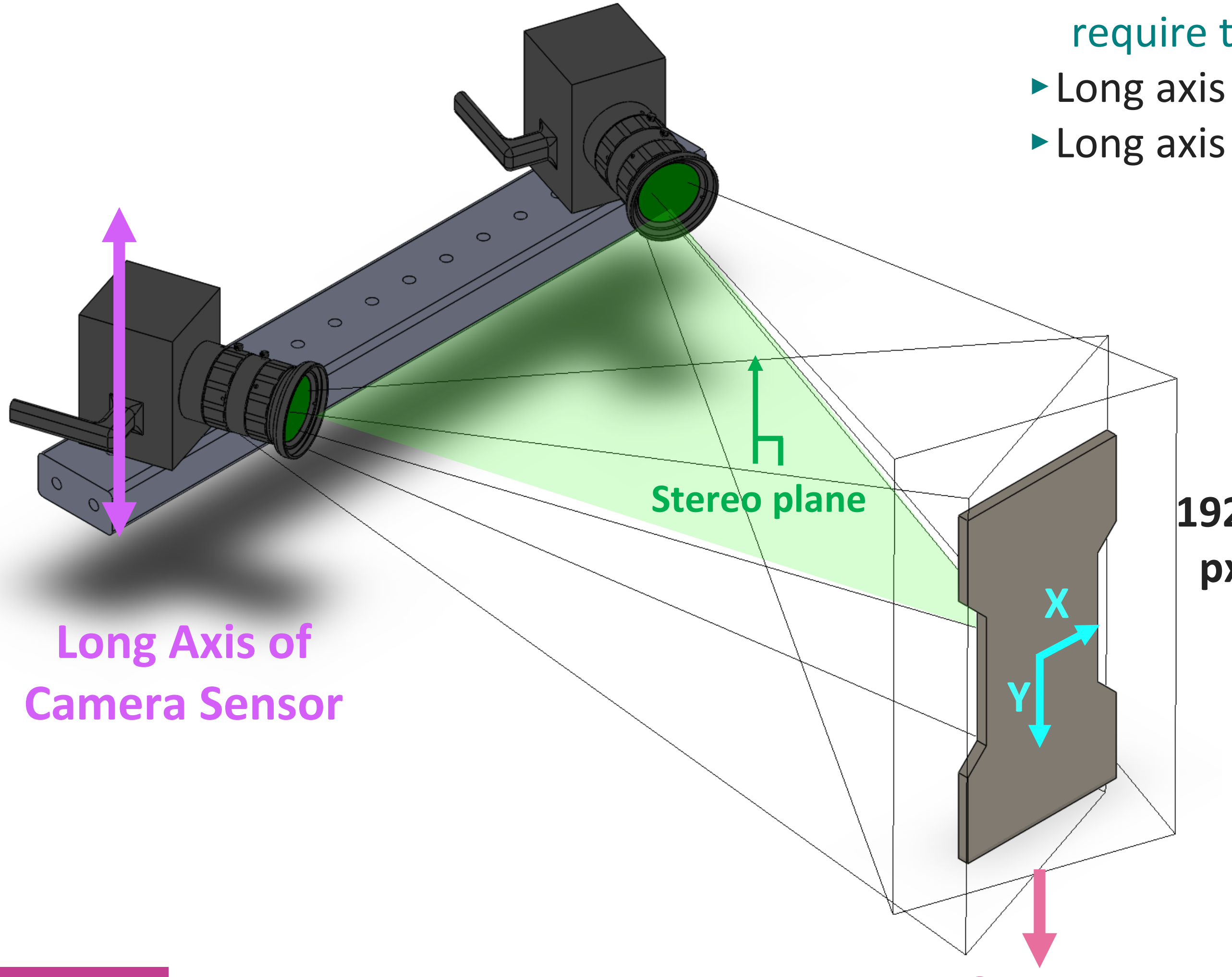
80/20 Inc.
The Industrial Erector Set

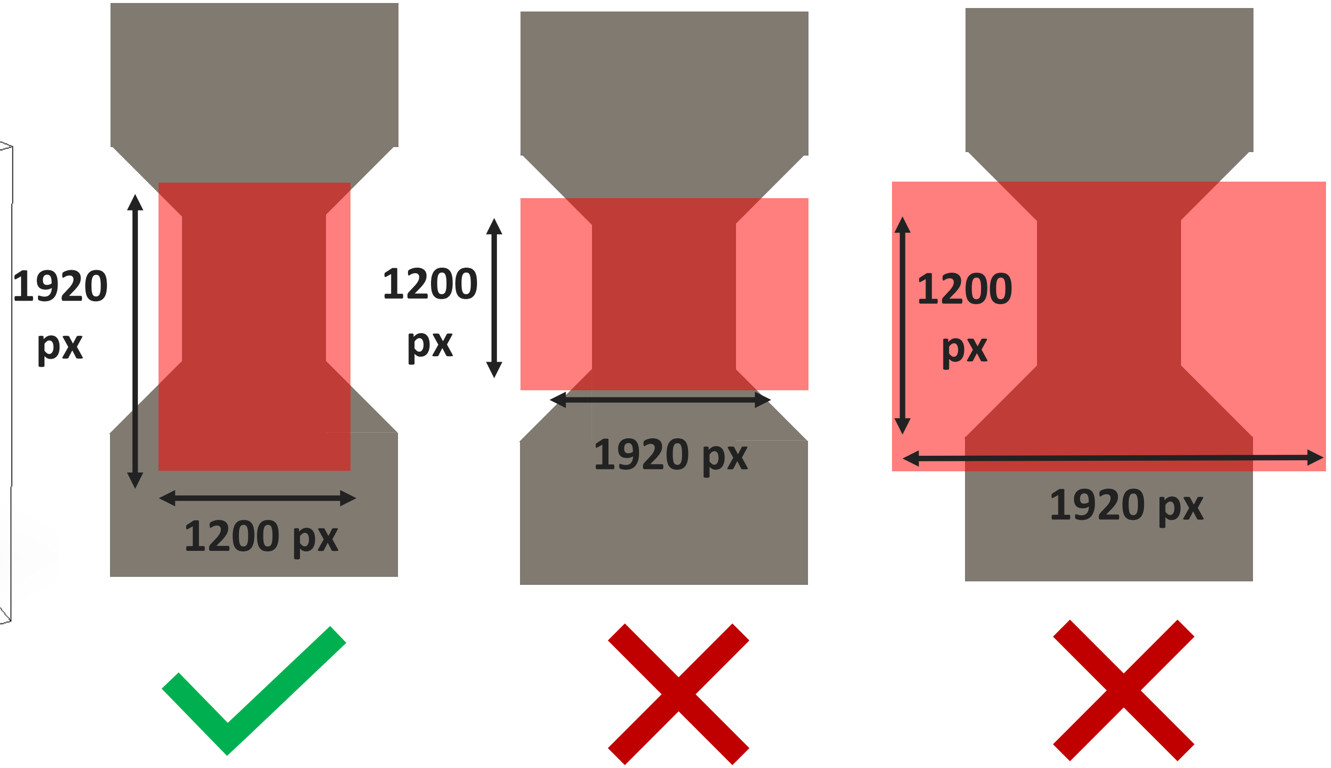
OptoSigma

Recommended Camera Orientations

Recommendation 2.8, Figure 2.1

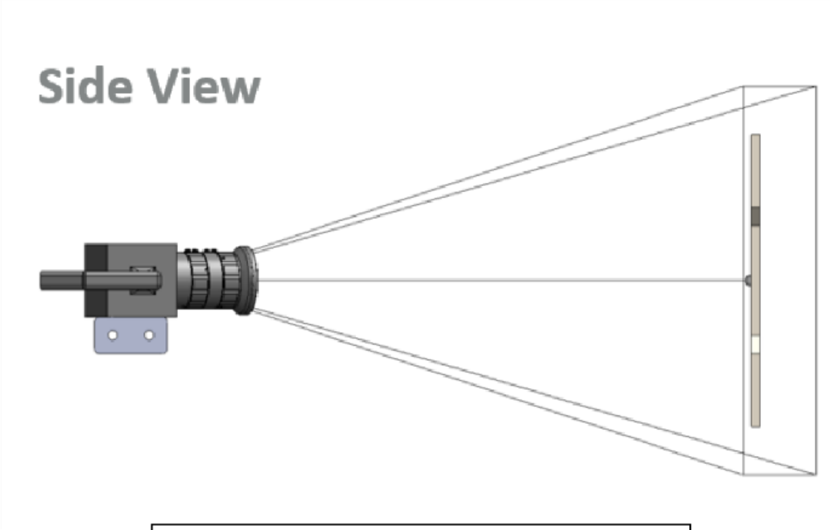
1. Align the **long axis of your camera sensor** with the direction you require the **highest spatial resolution;** typically this equates to:
   - Long axis of camera sensor aligned with long axis of the test piece
   - Long axis of camera sensor aligned with direction of deformation

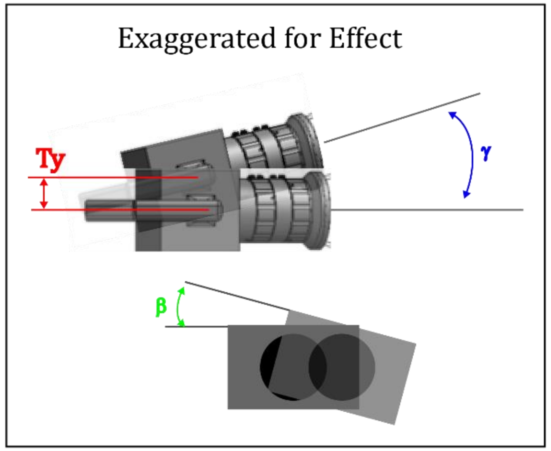


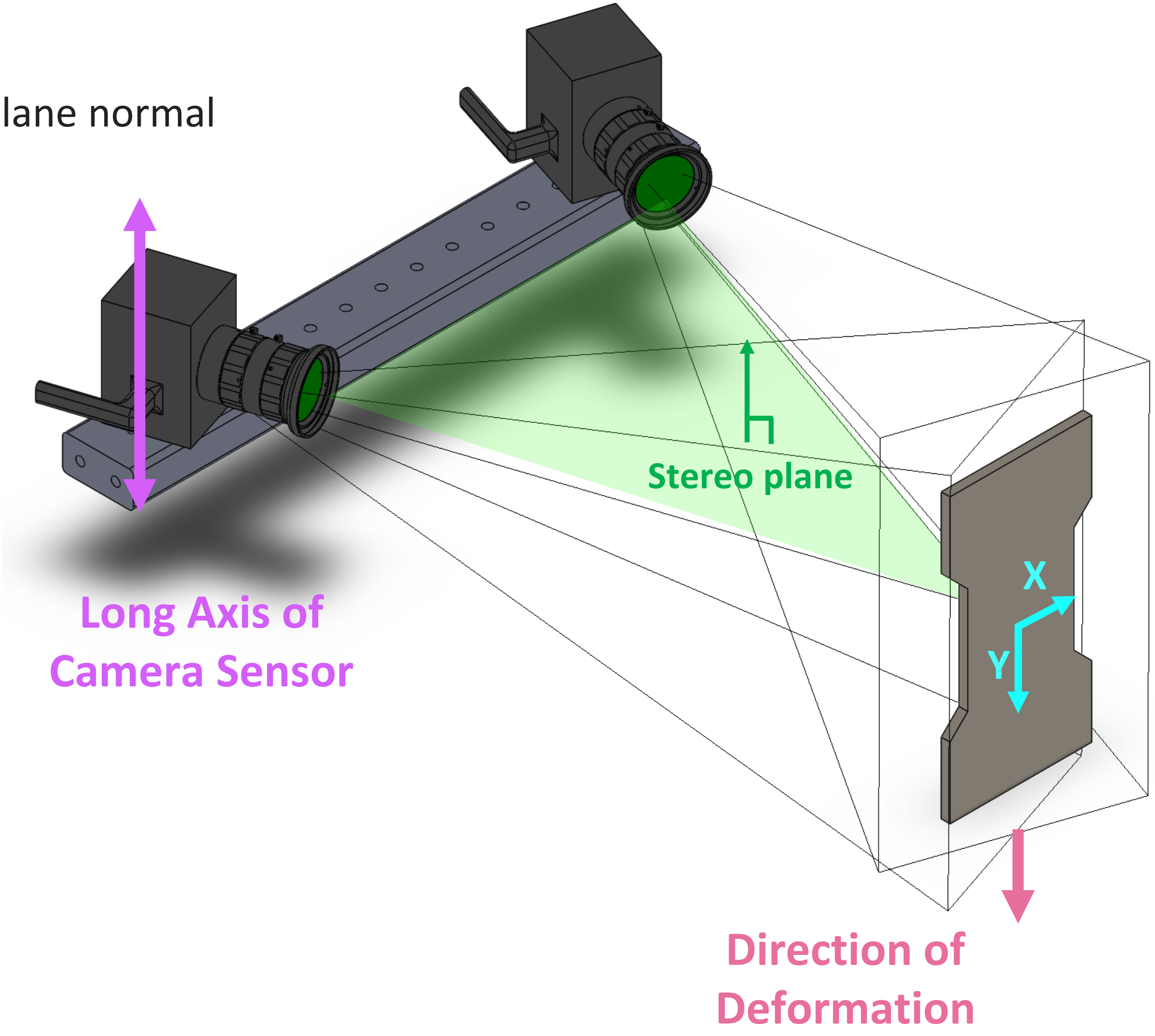


Recommended Camera Orientations
Recommendation 2.8, Figure 2.1

2. Orient your **stereo rig** to minimize **perspective errors**
   - Avoid compound angles
   - Long axis of test piece should be aligned with the stereo-plane normal







Recommended Camera Orientations

Recommendation 2.8, Figure 2.1

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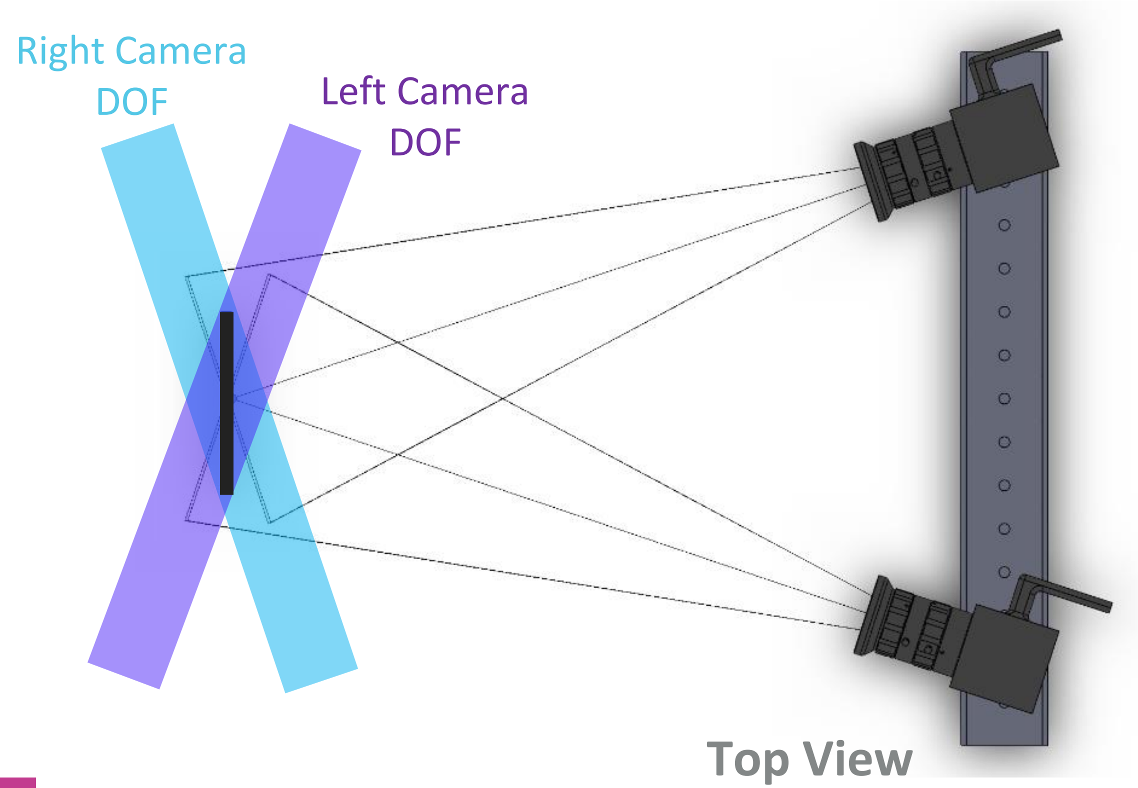
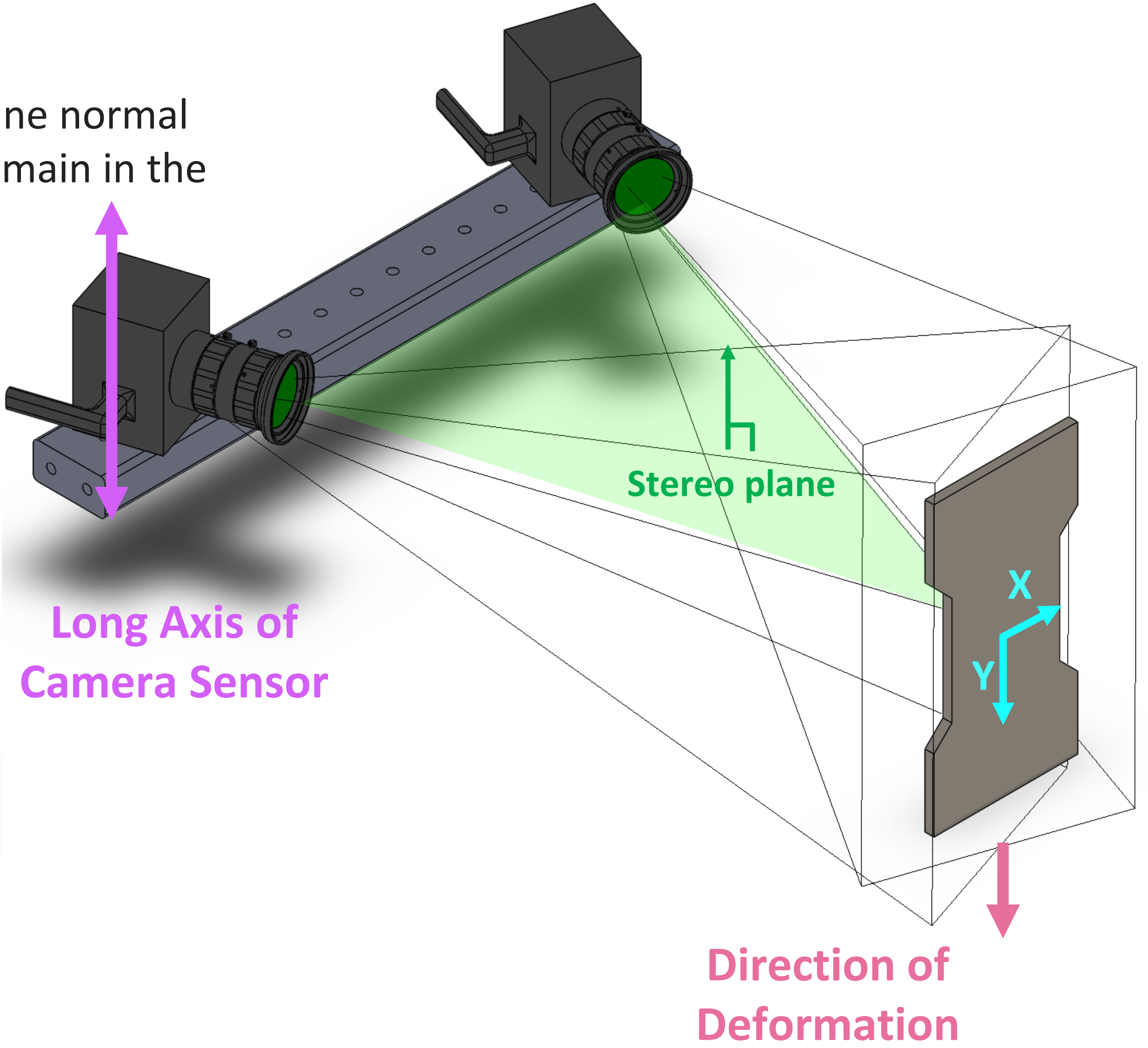
   - Test piece geometry and direction of deformation should remain in the center of the DOF for both cameras





Recommended Camera Orientations
Recommendation 2.8, Figure 2.1

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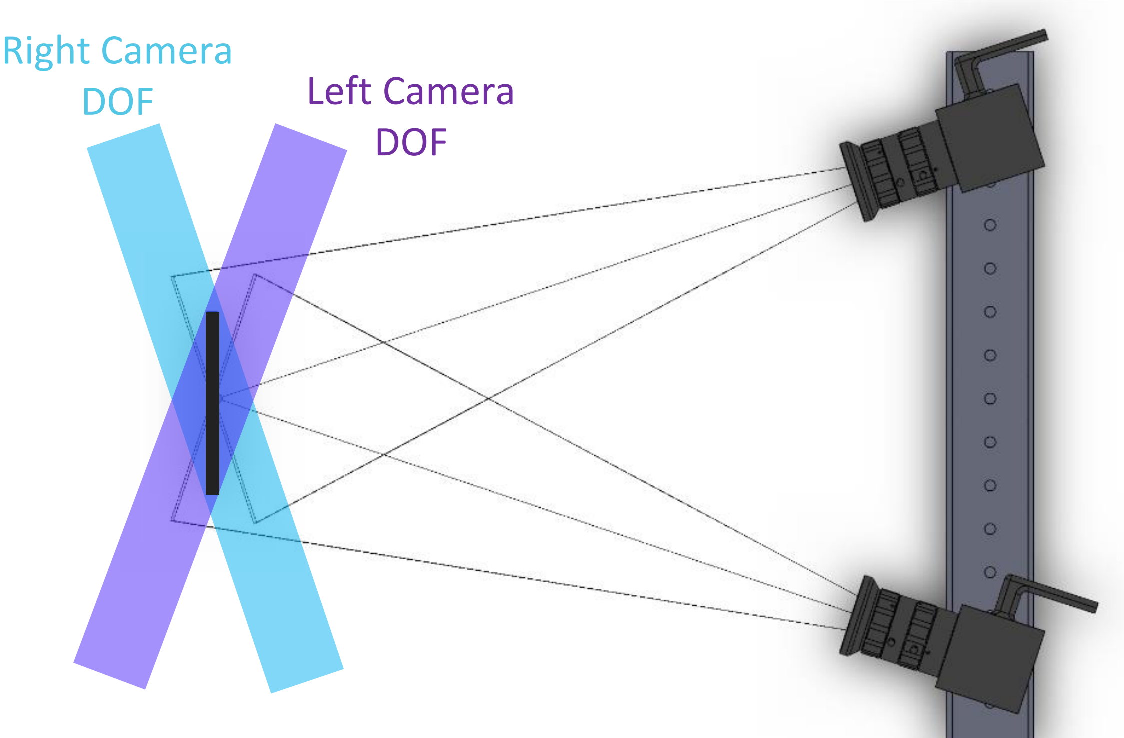

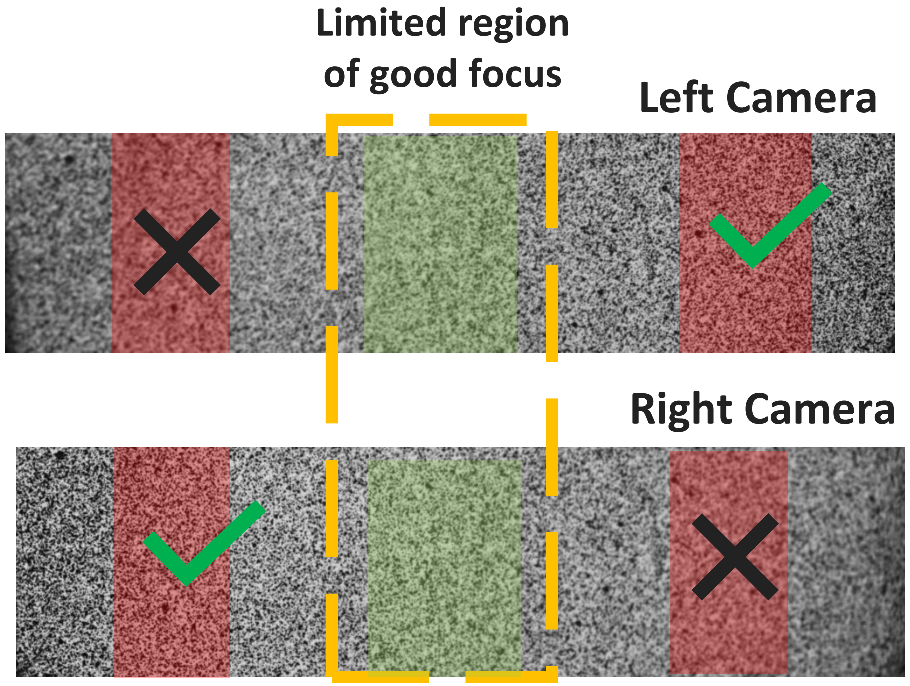

Recommended Camera Orientations
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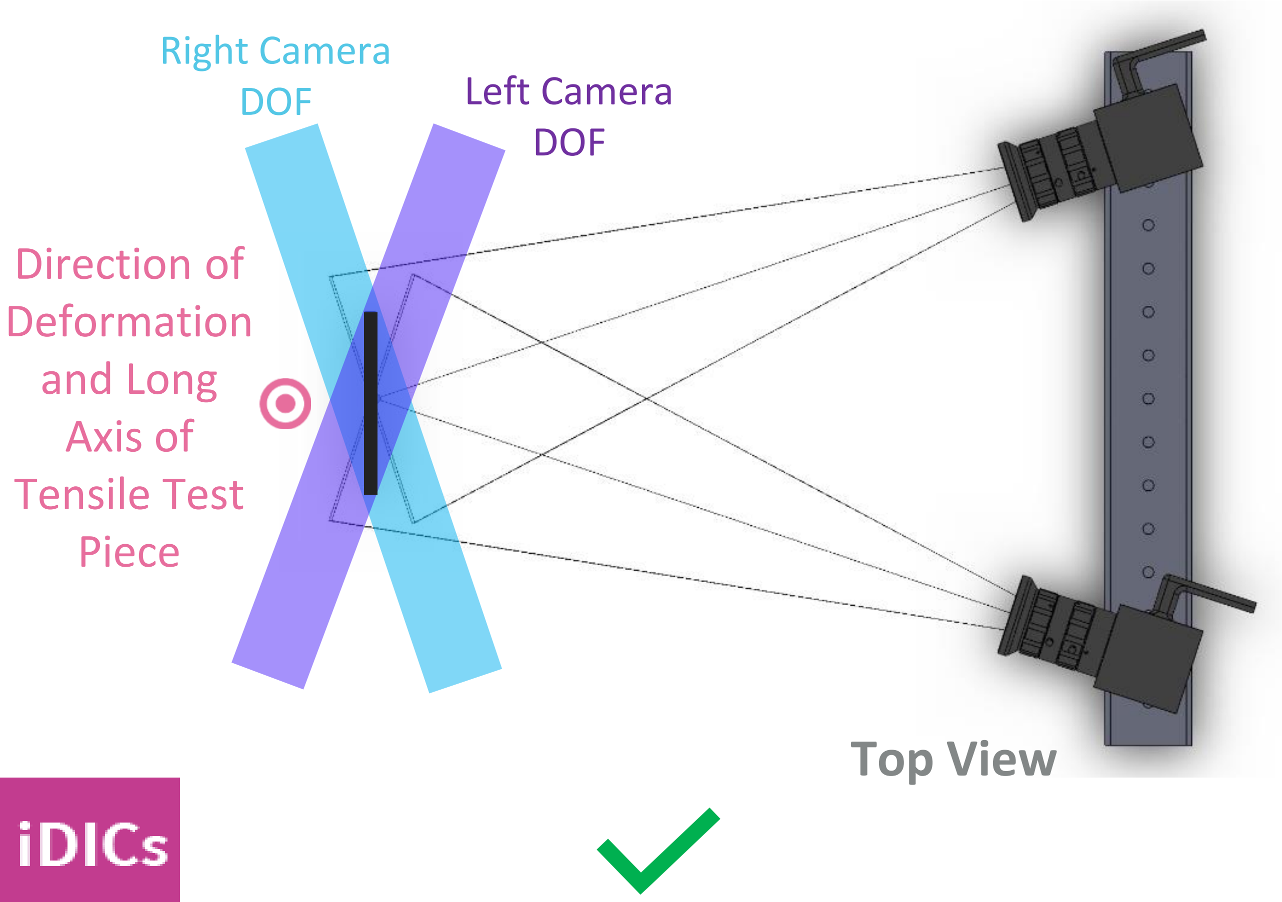
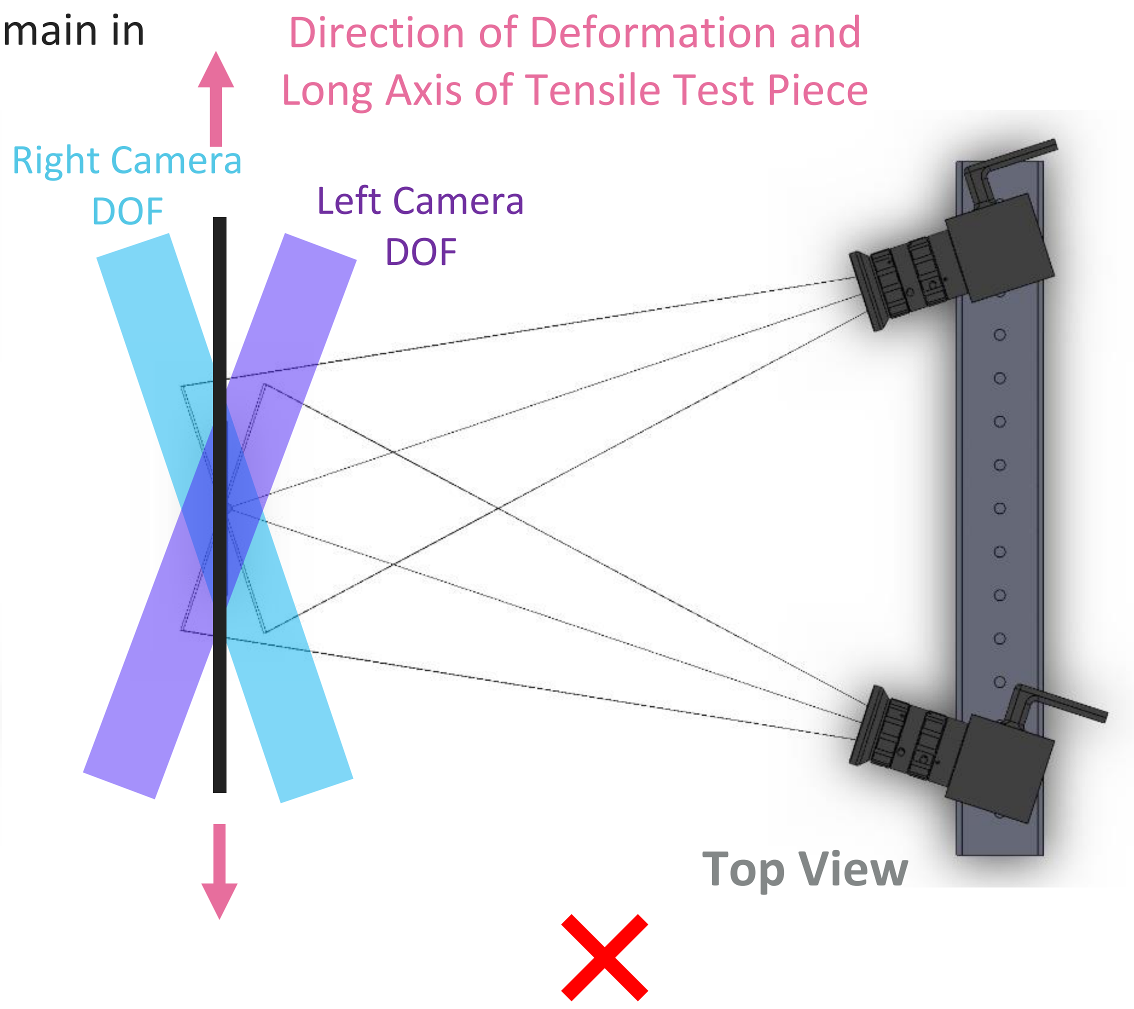
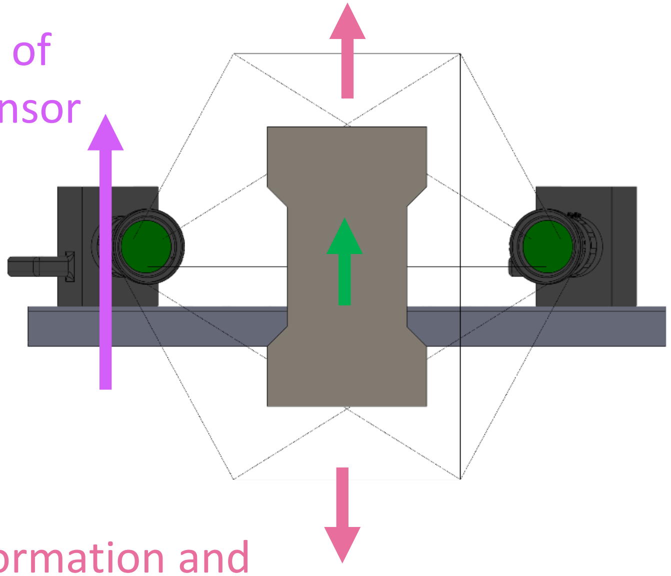


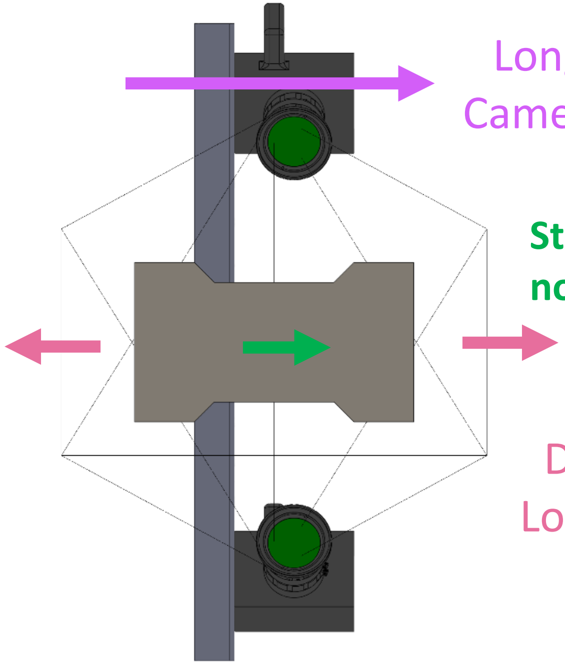


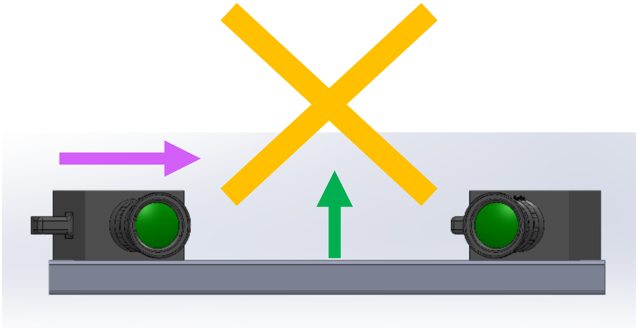
Recommended Camera Orientations
Recommendation 2.8

Recommended Vertical Tensile Test Piece Orientation of Rig and Cameras



Recommended Horizontal Tensile Test Piece Orientation of Rig and Cameras





DEMO 03

Note: Some adaptors may be required to optimize the camera mounting scheme for your test design

Aperture
Sec. 2.2.3

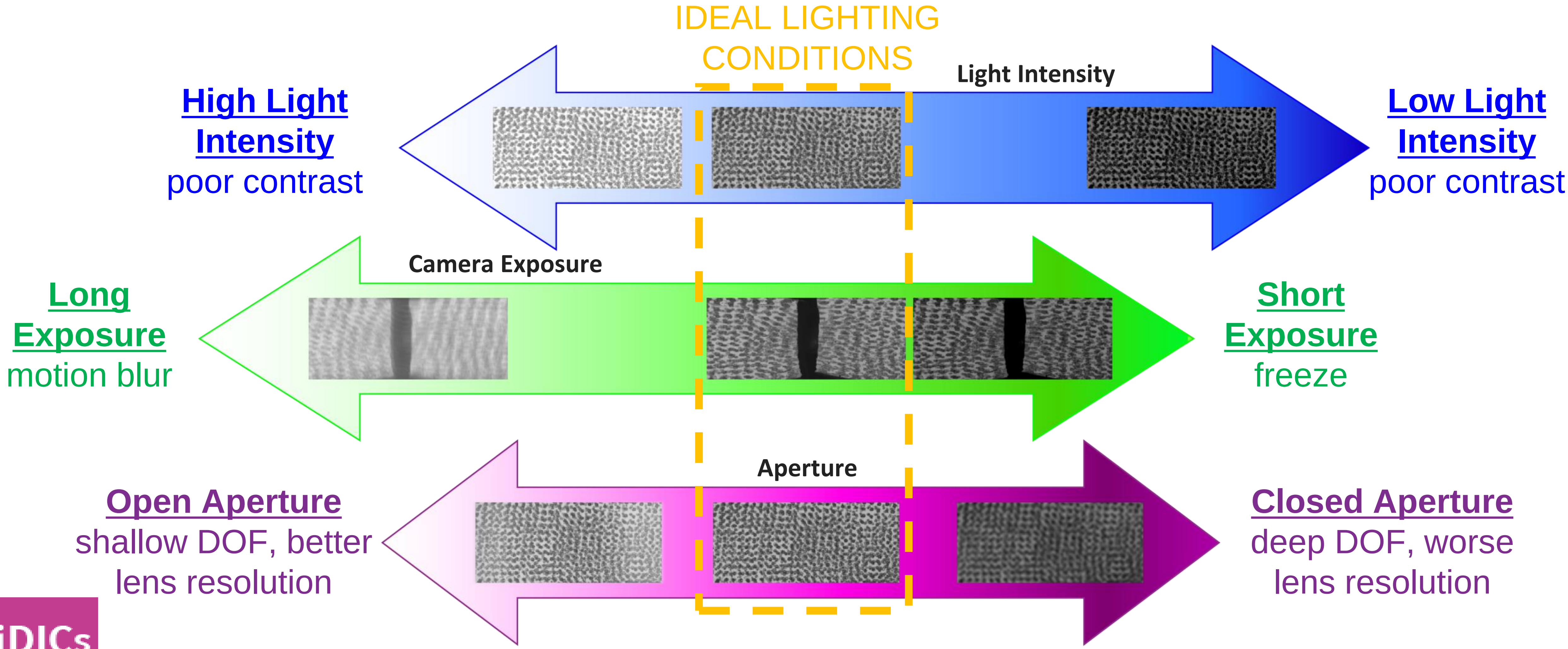
- Often measured by the f-number: ratio of focal length to aperture diameter

- Tip 2.16 / Tip 2.17:
  - Larger aperture = more light and smaller DOF
  - For DIC, aperture should be used only to control DOF
  - Control image brightness with exposure and lighting

- Caution 2.11:
  - Small apertures may cause diffraction errors
  - Large apertures may accentuate optical aberrations
  - Recommend moderate apertures in the range of f/5.6-f/11

Aperture, Lighting, Exposure, Gain and Contrast
Sec. 2.2.3 – Sec. 2.2.4

- **Recommendation 2.13: The better the image contrast is, the less noisy the DIC results are.**
  - For 8-bit cameras, minimum contrast is 50 grey-level counts or 20%.



Aperture, Lighting, Exposure, Gain and Contrast
Sec. 2.2.3 – Sec. 2.2.4

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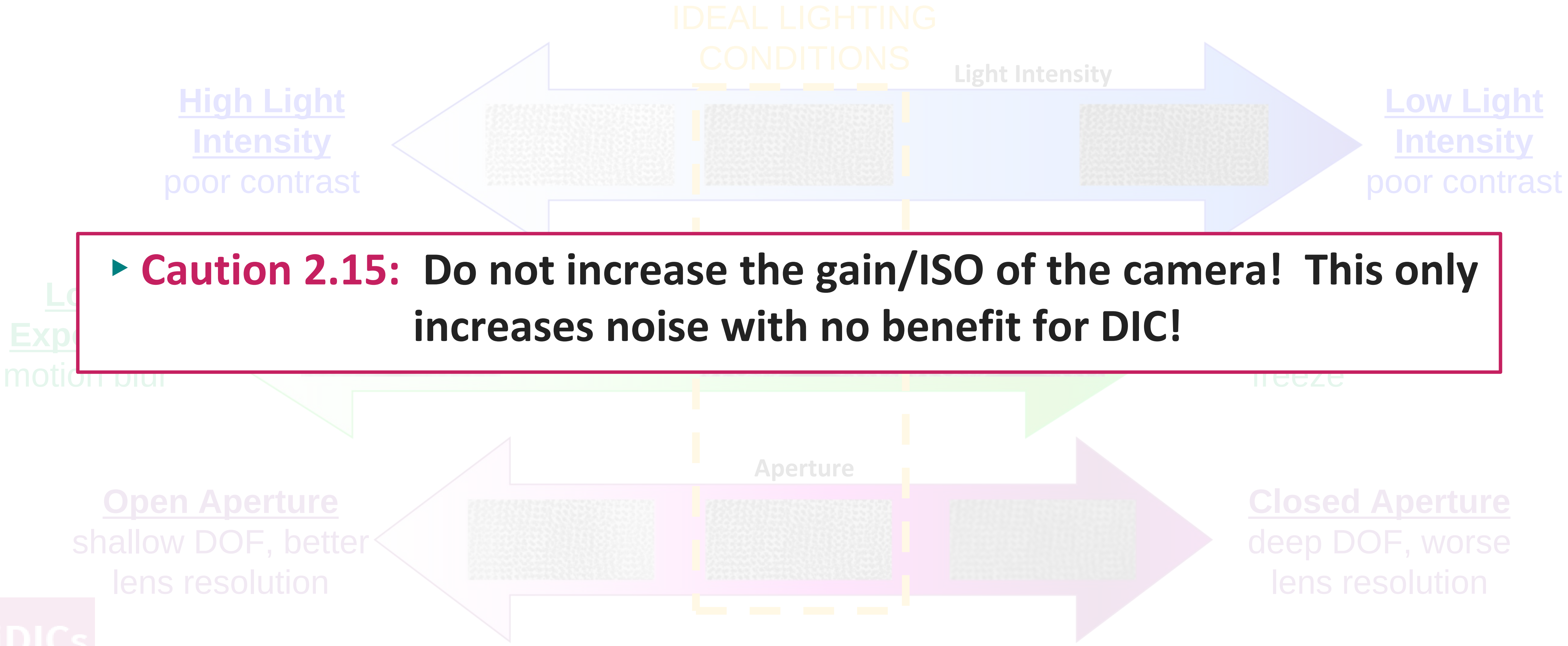
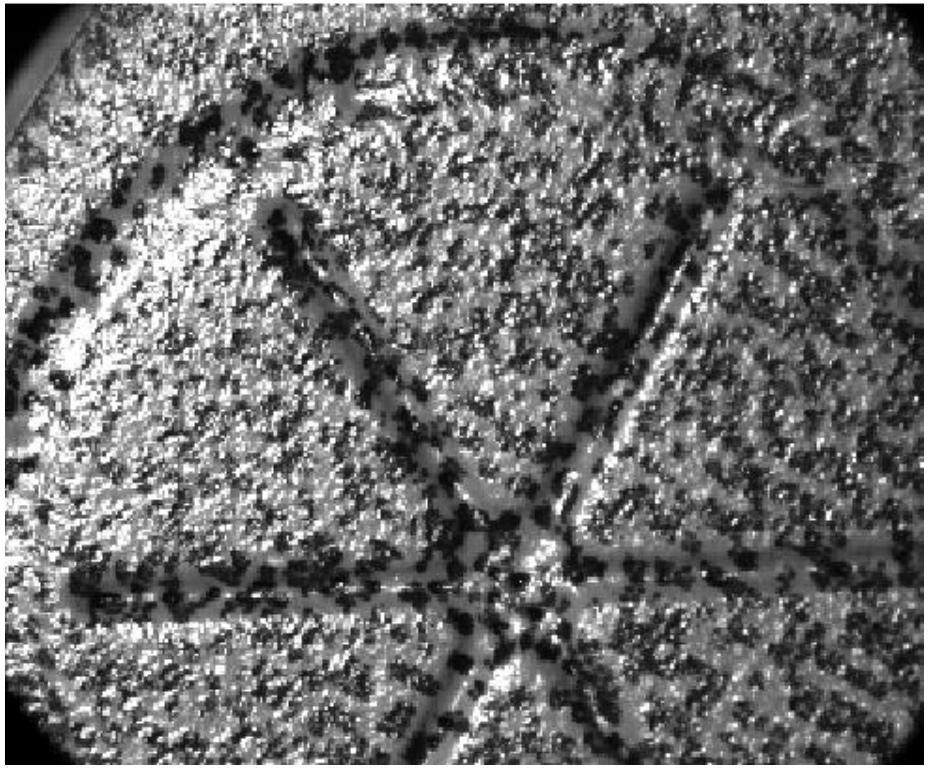


- **Caution 2.15: Do not increase the gain/ISO of the camera! This only increases noise with no benefit for DIC!**

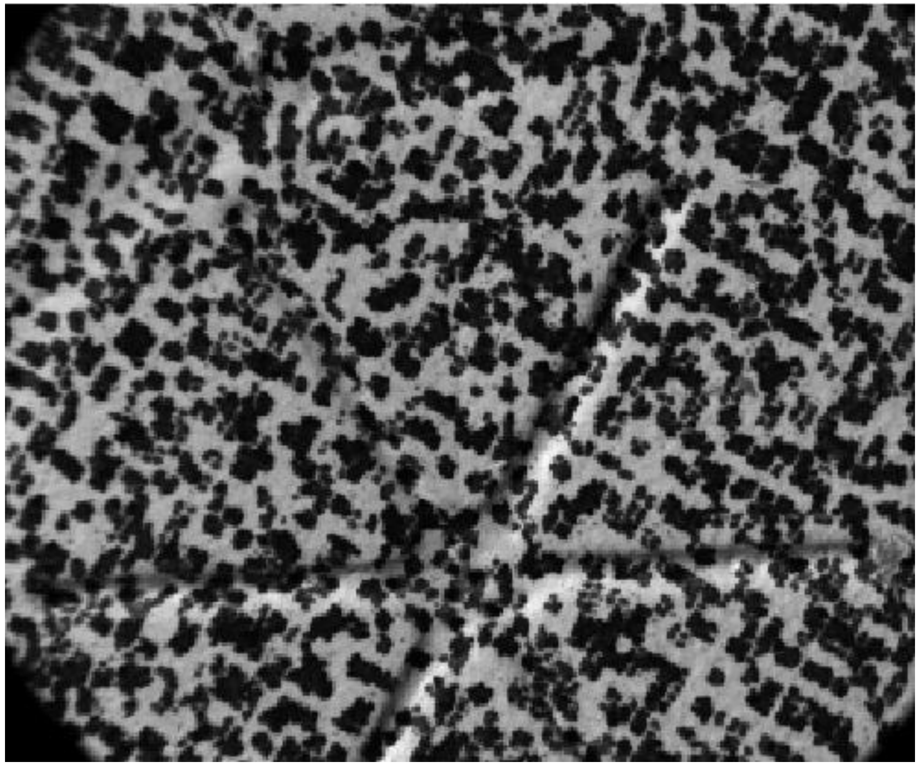
Cross-Polarized and Diffuse Light
Sec. 2.2.4.1

- Image brightness needs to be uniform across the ROI.
- Caution 2.14: Ensure no ROIs are overexposed or underexposed, and that there is no glare.
- Recommendation 2.11: Cross-polarized light or diffuse light reduce or eliminate glare caused by specular reflections.

Randomly polarized light = strong glare



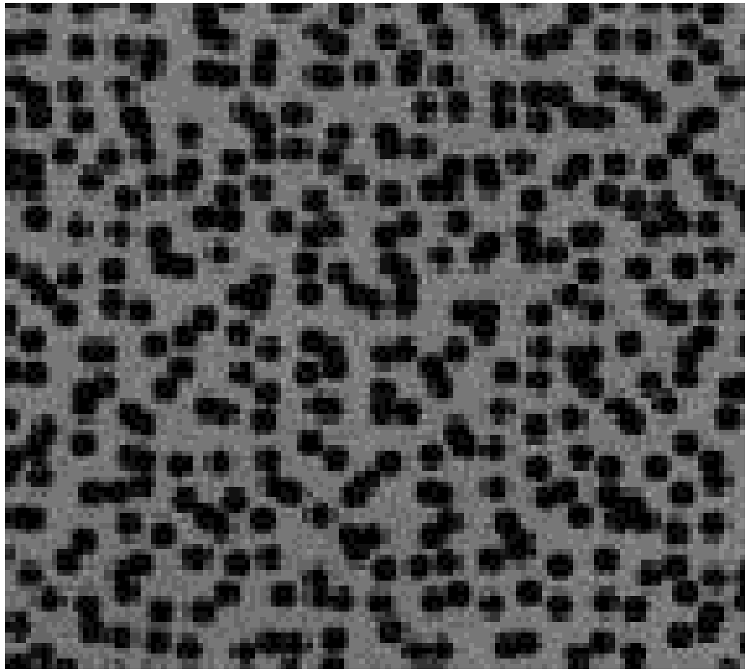
Cross-polarized light eliminates glare

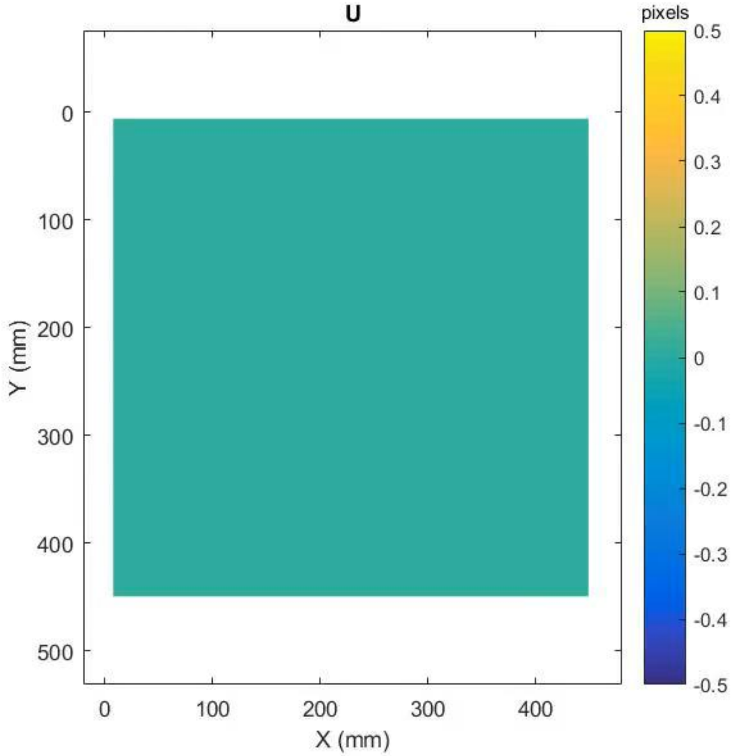


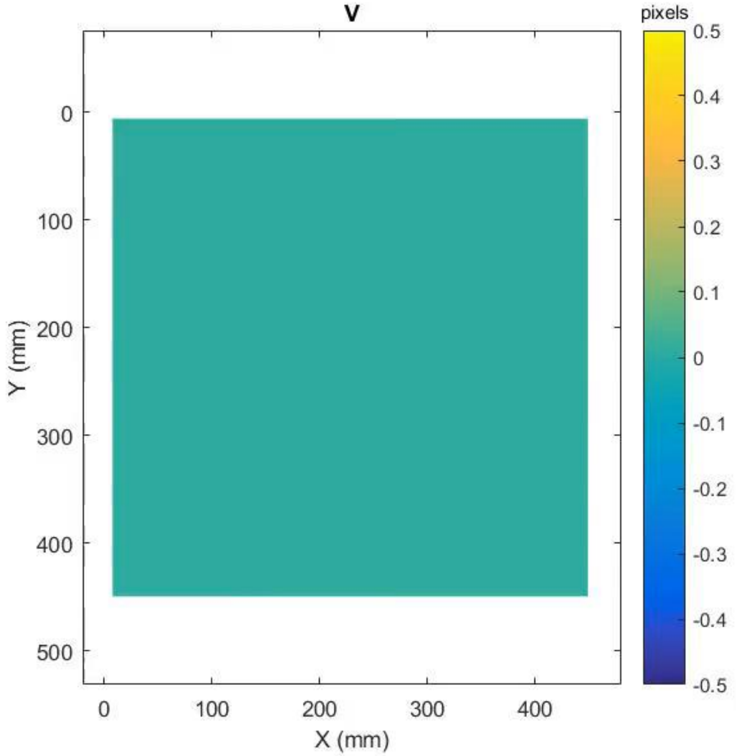
Hardware Heating
Sec. 2.2.5

DEMO 04

- **Caution 2.16: Almost all cameras and lights become hotter than room temperature.**
  - Changes size and positions of camera detector and lenses
  - Heats mounting structure, which can result in relative motion between two cameras
  - Induces convective air currents – “heat wave”, “heat haze”, “mirage effect”
- Tip 2.21, Recommendation 2.15: Avoid introducing hot equipment between cameras and the test piece. Mount lights *above* and *behind* cameras.







EMC Jones (2018) *Exp. Mech.* 58:1133-1156

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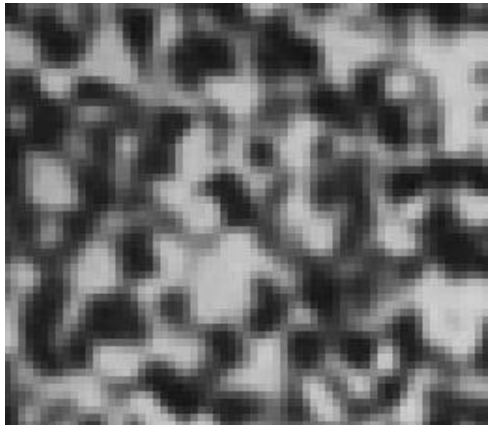
CHAPTER 2: DESIGN OF DIC MEASUREMENTS

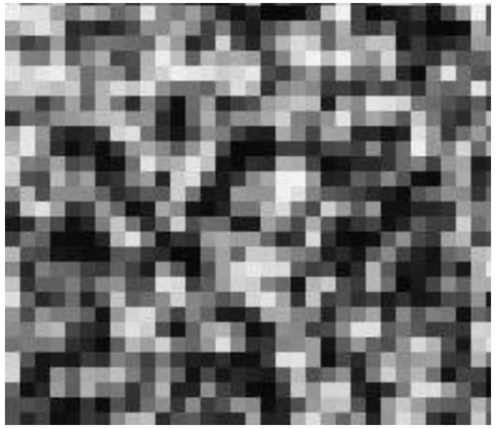
SEC. 2.3: DIC PATTERN

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

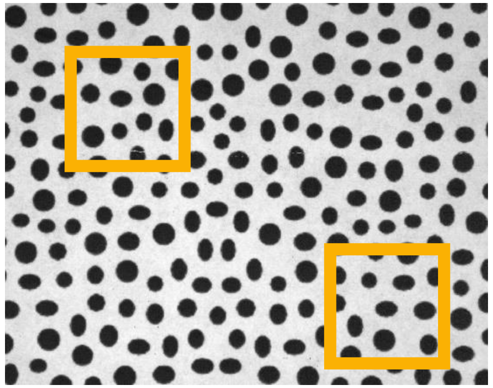
- **One fundamental assumption of DIC is that motion and deformation of the pattern that is imaged exactly replicates the underlying test piece motion and deformation.**
- *Natural patterns:* If the sample surface is heterogeneous, you may be able to image the test piece directly
- *Applied patterns:* Much more common
- *Size (Sec. 2.3.2.1):* 3-5 pixels
  - Applies to both white and black features!
  - Caution 2.19:
    - Aliased features add error to DIC results
    - Large features reduce spatial resolution
- *Variation (Sec. 2.3.2.2)*: Sufficient variation that subsets can be identified uniquely.



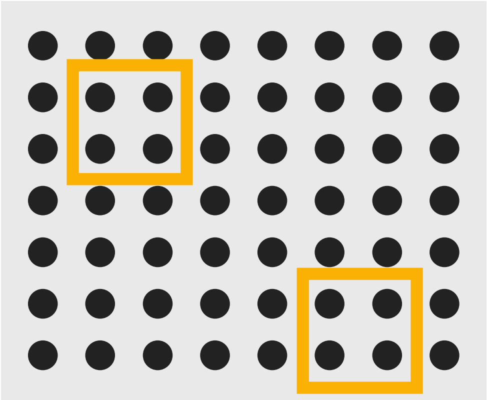
Appropriate size



Too small – aliased



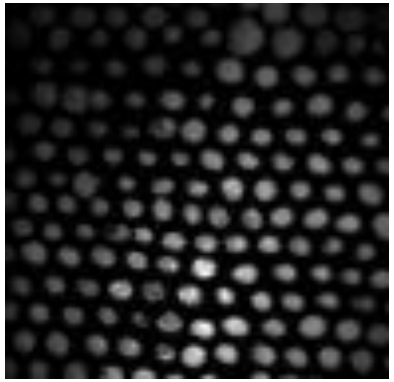
Random



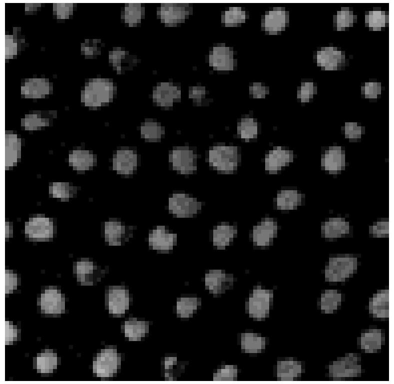
Oriented, regular

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

- *Density (Sec. 2.3.2.3)*: ~ 50% black and white
  - With round speckles, density may be closer to 25-40% in order to maintain at least 3 pixels between speckles

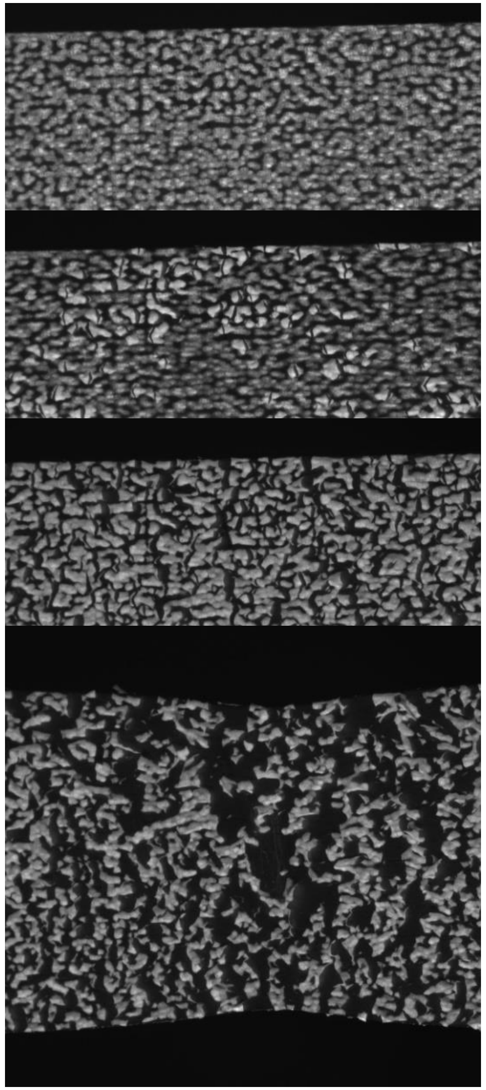


Appropriate density

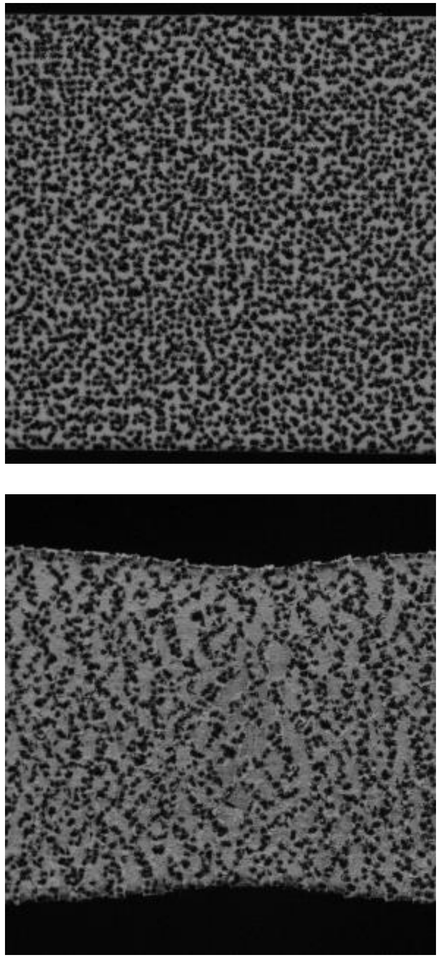


Sparse pattern

- *Quality (Sec. 2.3.2.4)*: Pattern should not degrade during testing
  - Tip 2.26: Types of degradation include:
    - Morphological changes, slip bands (natural patterns)
    - Fading, cracking, debonding (applied patterns)
  - Tip 2.27: Pretest samples to verify suitability of pattern throughout test



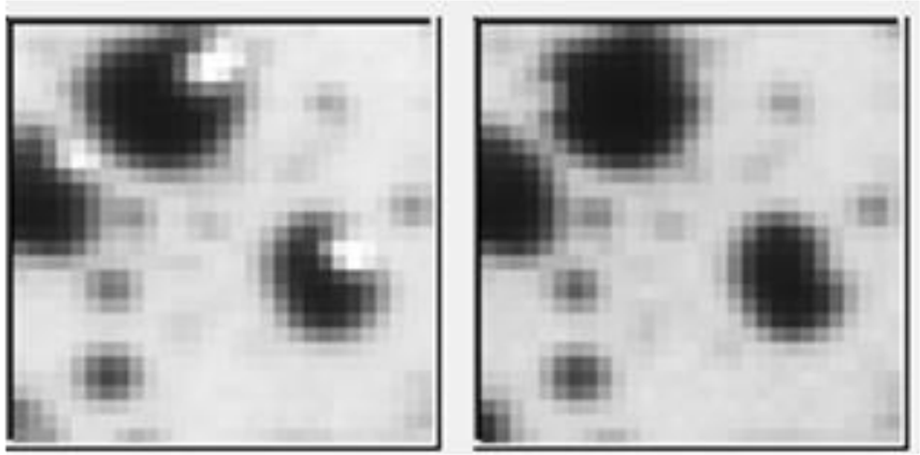
Speckle cracking and debonding



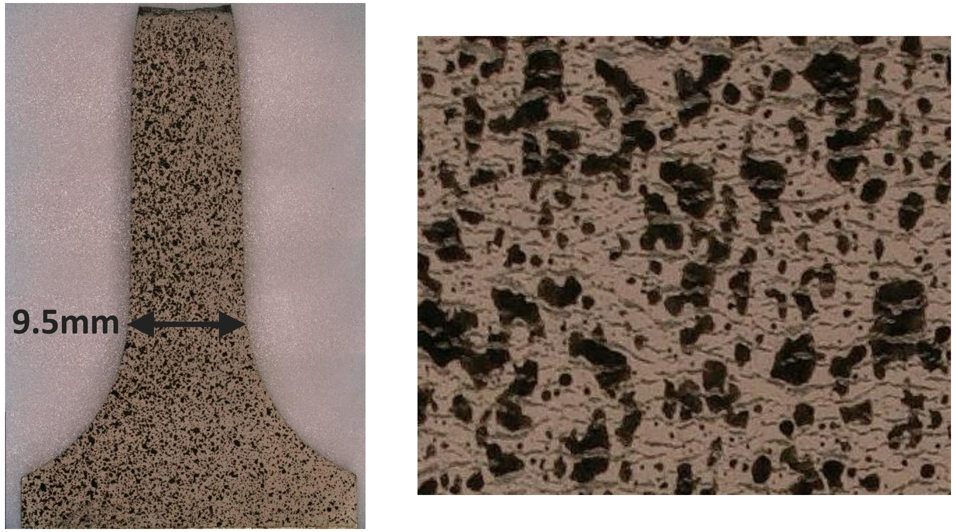
Paint debonding and speckle banding

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

- *Reflections (Sec. 2.3.2.5):* Pattern should be matte, not glossy
- *Compliance (Sec. 2.3.3.1):* Applied patterns should be thin and compliant relative to the test piece
  - Caution 2.22: Thick/stiff patterns could affect deformation of thin/compliant test pieces.
- *Bonding (Sec. 2.3.3.2):* Applied patterns should be well-bonded to the test piece



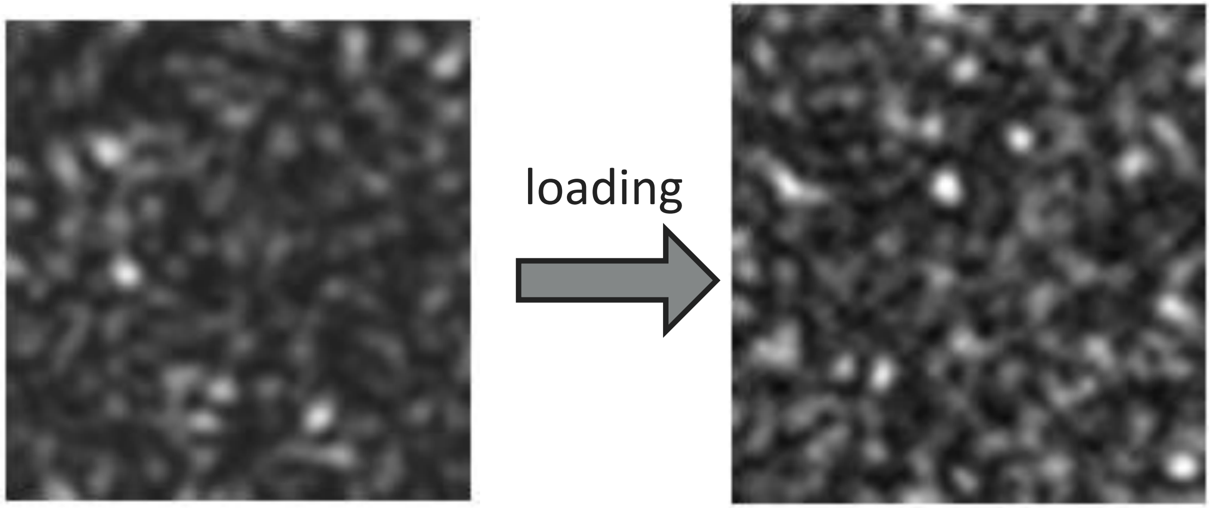
Specular reflection on each speckle **Matte pattern**



Paint cracking and debonding at a small scale

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

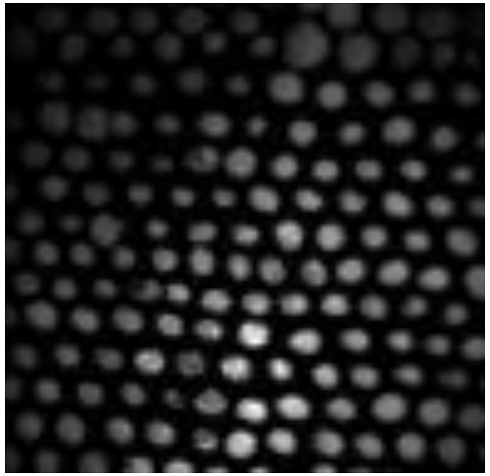
- *Fidelity (Sec. 2.3.3.3):* Applied pattern should deform conformally with the test piece.
  - Tip 2.29:
    - Large deformation → ductile pattern
      - Test immediately after painting, while the paint is still wet/ductile
    - Brittle fracture → brittle pattern
      - Fully cure the paint (consider baking) so paint cracks at same time as the test piece
  - Caution 2.24:
    - Laser speckle patterns are not appropriate for DIC!
- *Thickness (Sec. 2.24):* Applied patterns should be uniform thickness.



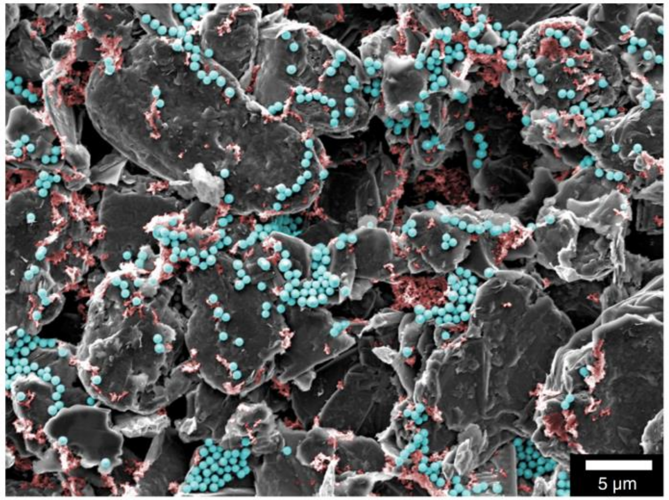
Laser speckle pattern before/after loading

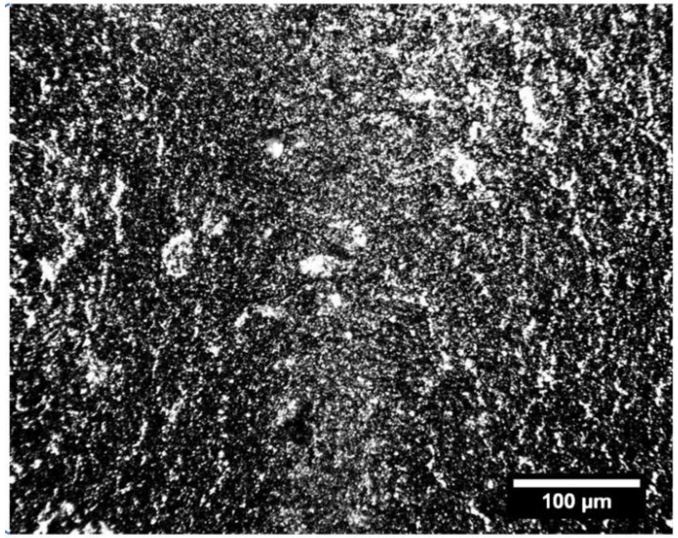
Note: Issues with patterns may appear in results as:
- Higher correlation residual / uncertainty
- Missing data points (holes) / failure to correlate
- Higher epipolar error
- Non-physical data
- **Or no obvious effect! → Carefully examine patterns**

Patterning Techniques: Limited only by the imagination
Sec. 2.3.4

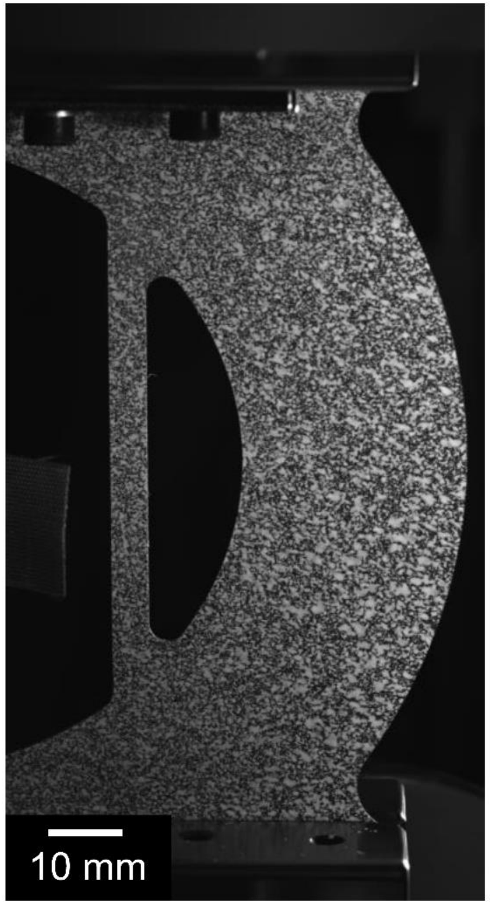


Thermographic phosphor

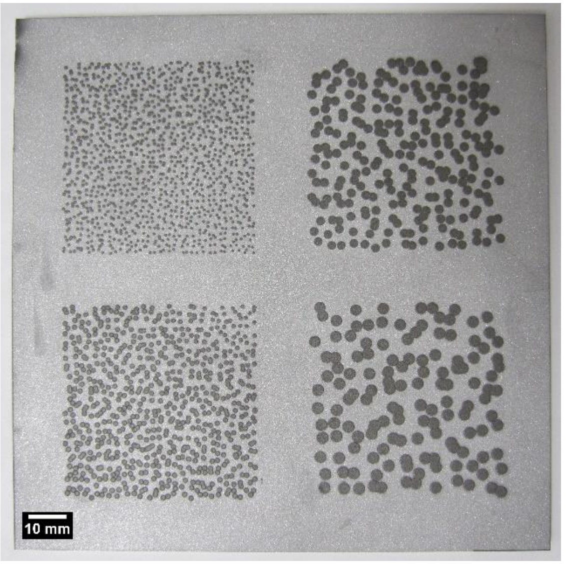


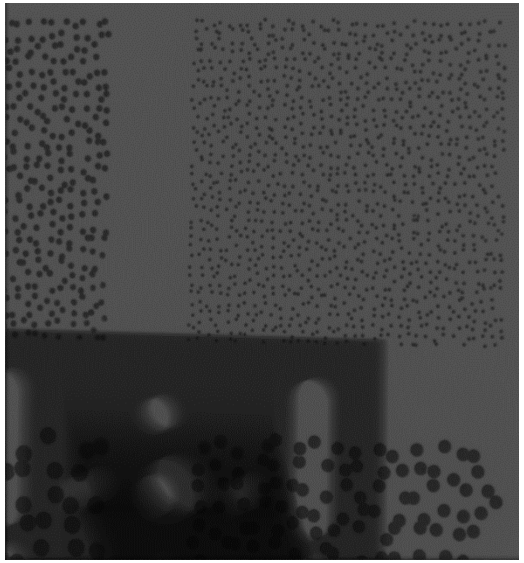


Fluorescent silica nano-particles on a composite battery electrode

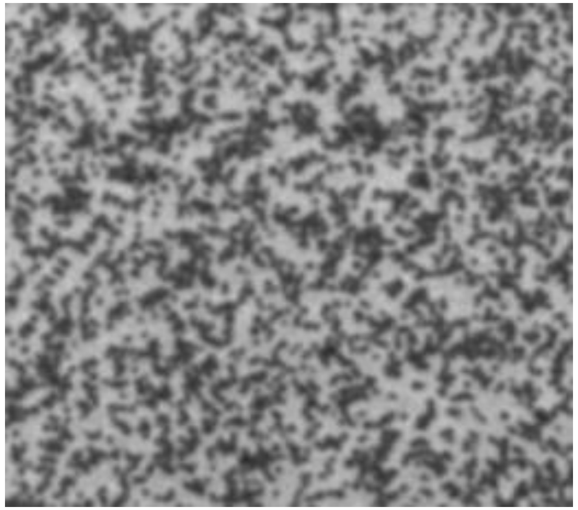


White paint on bare metal





Ta on Al – X-ray DIC



Carbon powder on white paint