Understanding the role of glaze layer with aligned images from multiple surface characterization techniques

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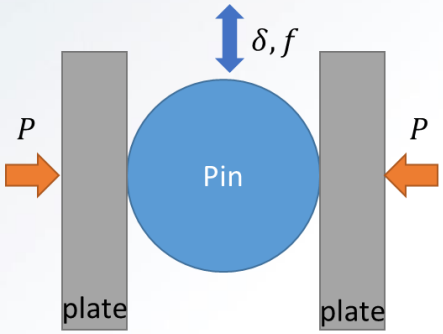
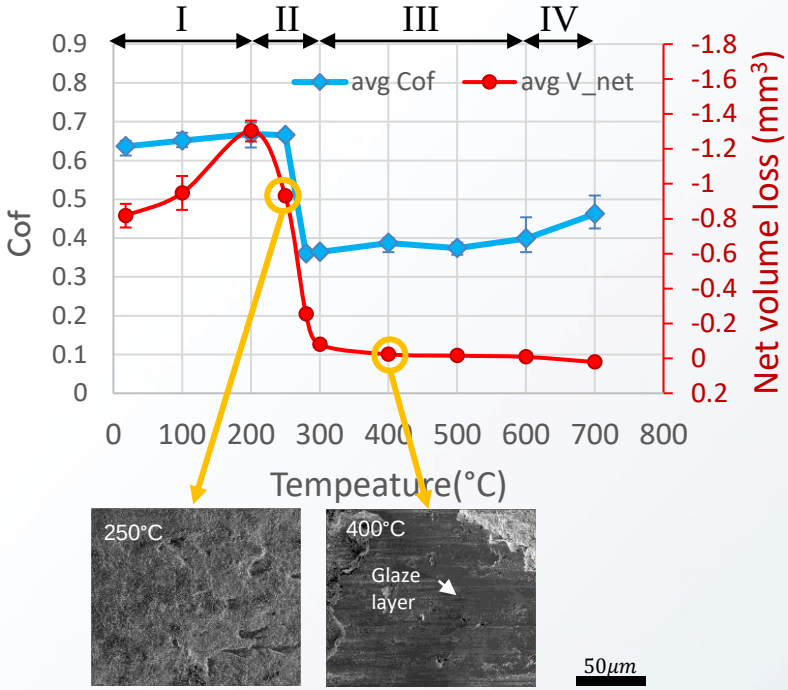
Introductions about “glaze layer”

- **“Glaze layer”** : shiny, smooth, highly oxidized, compacted, superficial layer formed spontaneously at the contact interfaces and largely reduces friction and wear.
- Example: severe-to-mild wear transition of 310s-310s [WP1.40]
- Possible mechanisms:
  - Prevent metal-metal contact
  - Superior mechanical properties



- 310s: austenitic, Cr & Ni rich
- Like-on-like, cylinder on flat, P=150N, δ=±200μm, f=10Hz
- Characterizations used in this work



- Distribution of glaze layer matters!

Study distribution of glaze layer is challenging

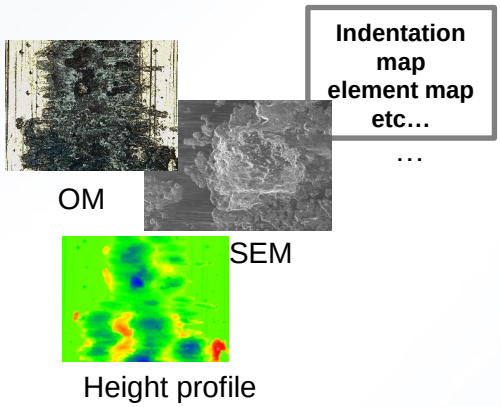
- Height profile itself does NOT incorporate the chemical/mechanical properties information.
- Challenges of bringing in other type of characterization (spectrum):
  - 1. high quality **alignment**
    - Hard to find one tool that “do-it-all”
  - 2. precise **boundary detection** of glaze layer
    - Accurate quantitative description of glaze layer is missing.

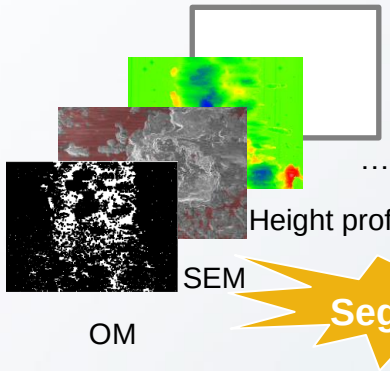
Our solution:

- Height profile itself does NOT incorporate the chemical/mechanical properties information.

- Challenges of bringing in other type of characterization (spectrum):
  - 1. high quality **alignment** : **image alignment workflow**
    - **Post align** images with subpixel error, Pixel res up to 0.73 μm
  - 2. precise **boundary detection** of glaze layer: **glaze layer identification workflow**
    - New Quantitively criterion: H-V criterion

- **Software approach (domain knowledge + computer vision algorithm)**

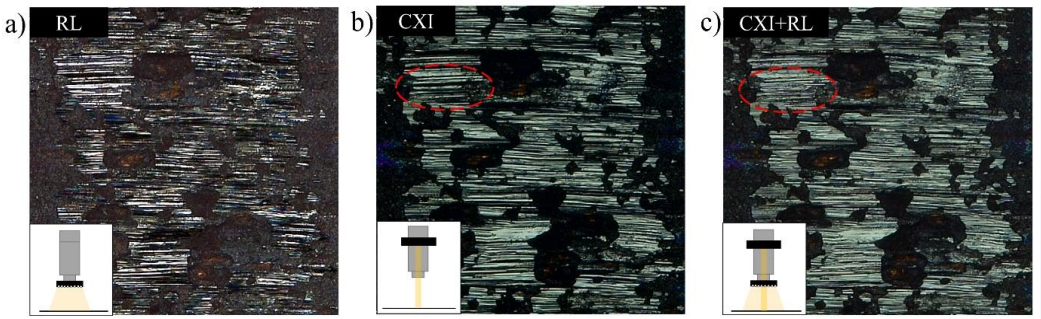




Characterization tool used in this work

- **Optical Microscope(OM)**

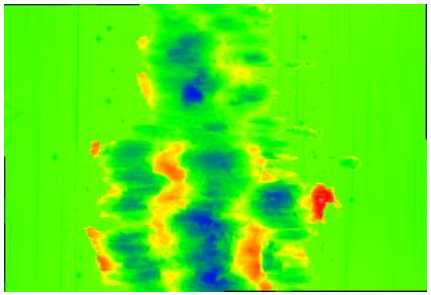
  - Glaze layer is highly reflective under CXI
  - wear trace is lightened with additional RL
  - green-blue color hints possible criteria

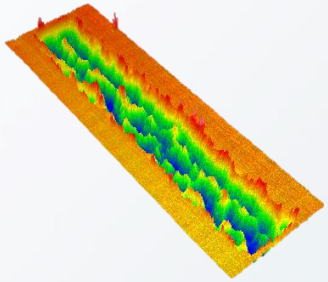


60% RL 20% CXI 20% CXI 10%RL

- **Zygo profilometer**

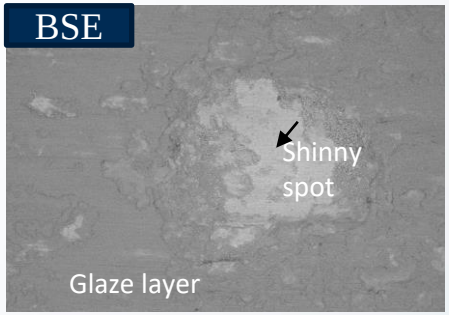
  - height profile (xyz point cloud, color coded in 2D)
  - Tilt corrected with associated software
  - Height info for glaze layer to be studied





- **SEM**

  - Chemical composition (BSE) and Topography(SE)
  - Glaze layer appears dark for both SE and BSE
  - Assisted glaze layer identification criterion evaluation



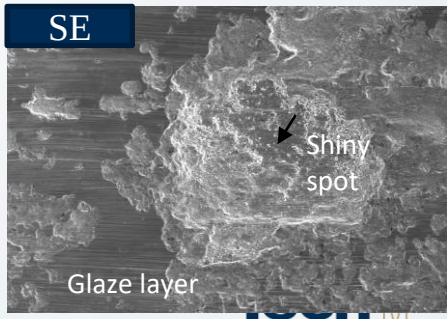
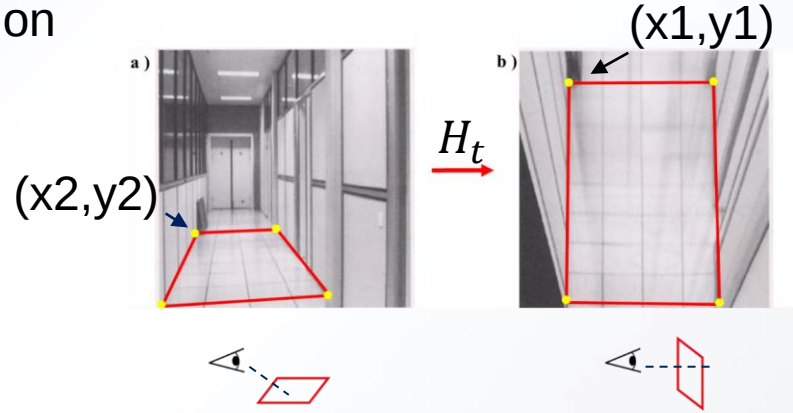


Image alignment workflow

- Computer vision tool --- Homography transformation
  - Describes relation between two individual 2D images of same planar object.

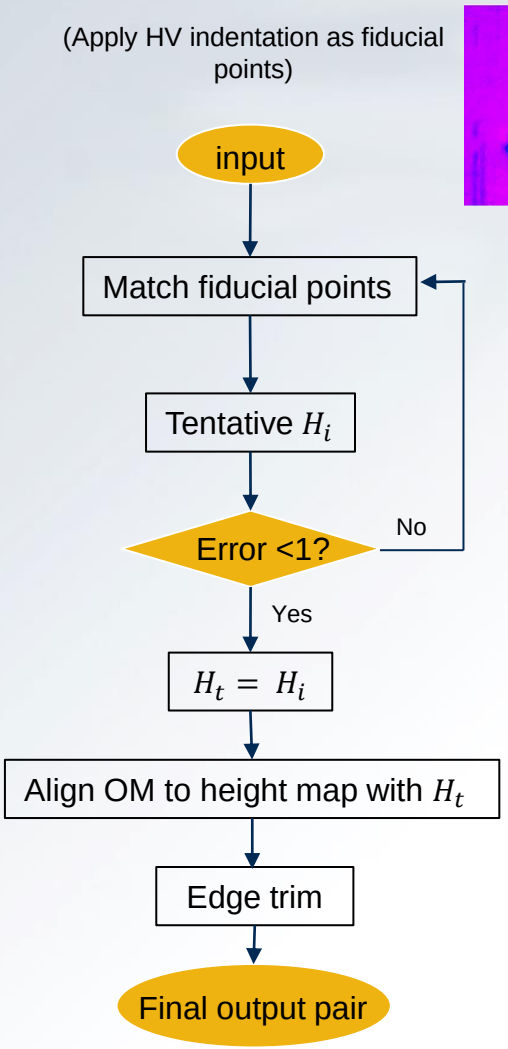
$$H_t \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} = \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

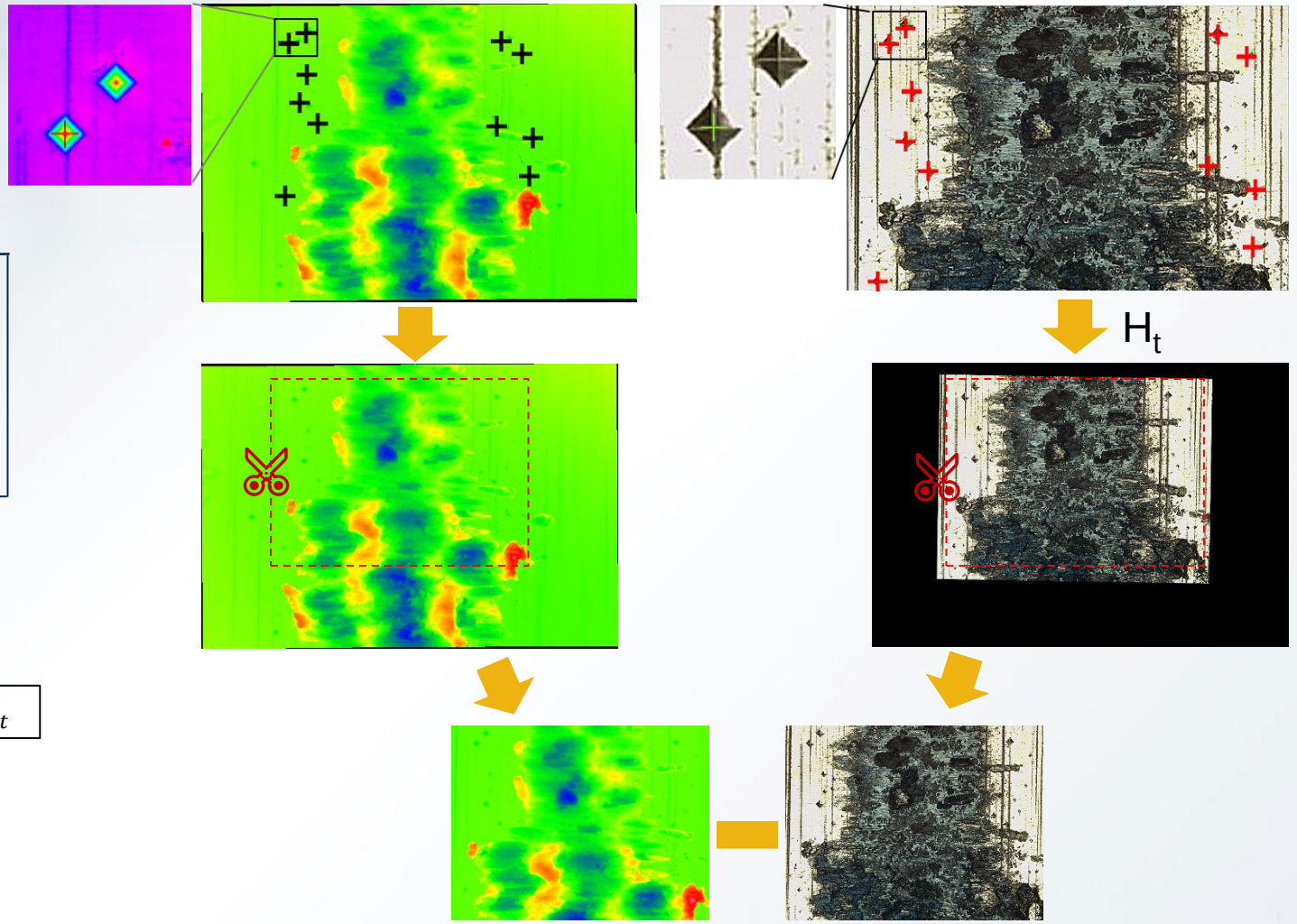
    - 3X3 matrix
    - 8 DOF (minimum 4 fiducial-point pairs)
  - Correlate all corresponding points from one image to another (pixel-to-pixel match).
  - Transfer image to align with the reference image with **same magnification, perspective, and pixel resolution.**



[Hartley and Zisserman, 2003]

Image alignment workflow





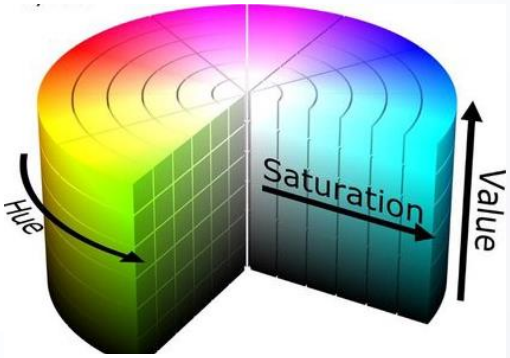
- Pixel-to-pixel match between OM and Height map with sub pixel error

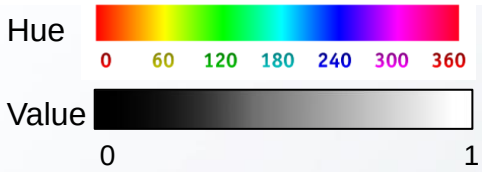
Glaze layer identification workflow

- Computer vision tool --- HSV separation

Original

[Szeliski, 2010]



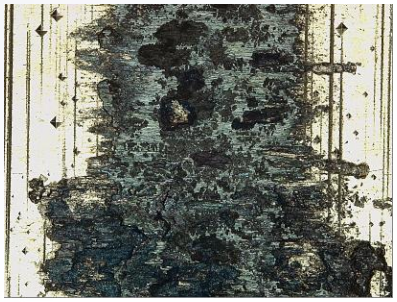


https://medium.com/neurosapiens/segmentation-and-classification-with-hsv-8f2406c62b39

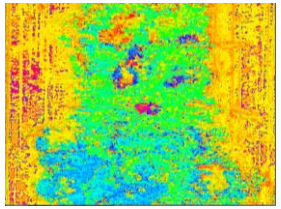
- *H-requirement*: its color should fall in a hue range from H_{min} to H_{max};
- *V-requirement*: its brightness should be no smaller than a minimum V value, V_{min}

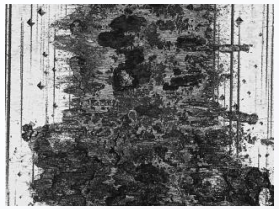
A pixel i with (H_i, V_i) hue and value is labeled as glaze layer only if **BOTH** H and V requirements are met,

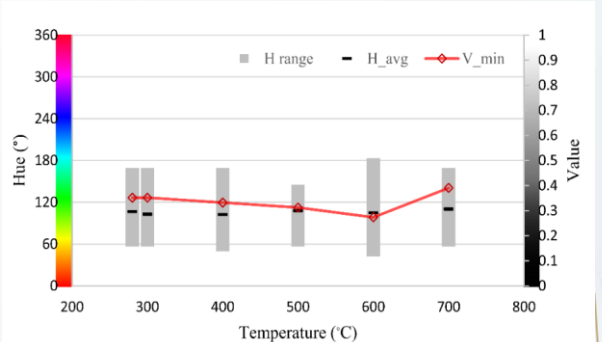
$$\begin{cases} \boldsymbol{H_{max} \geq H_i \geq H_{min}} \\ \boldsymbol{V_i \geq V_{min}} \end{cases}$$



OM



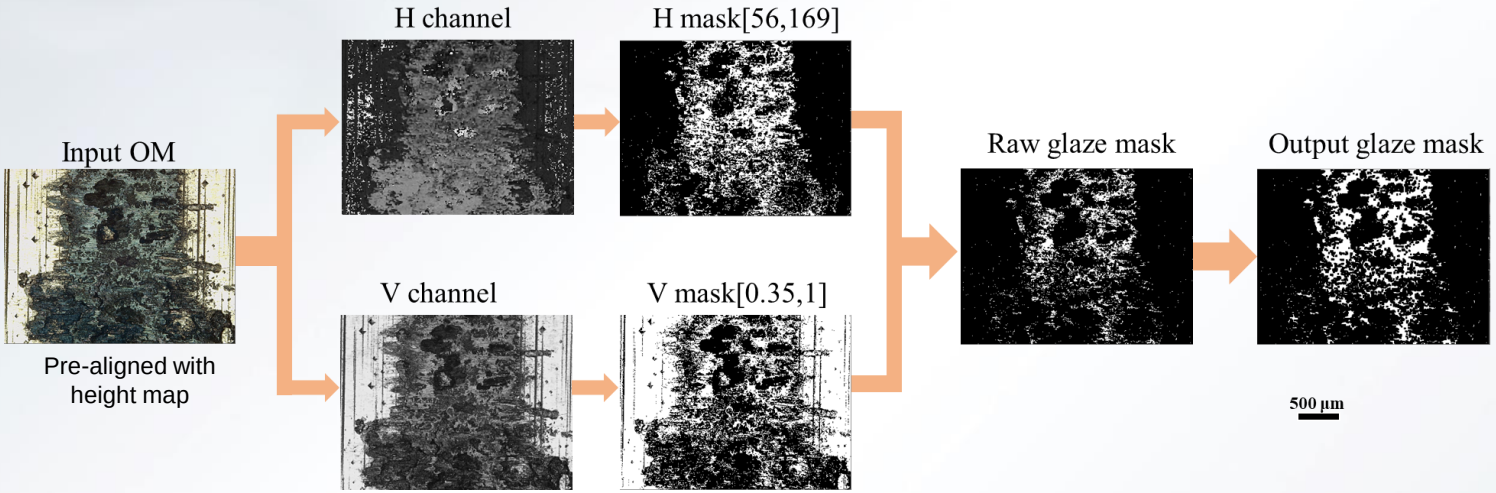




Relatively stable H_{max}, H_{min} and V_{min} that hint composition and/or thickness

Glaze layer identification workflow

- **H-V criterion** $\begin{cases} H_{max} \geq H_i \geq H_{min} \\ V_i \geq V_{min} \end{cases}$

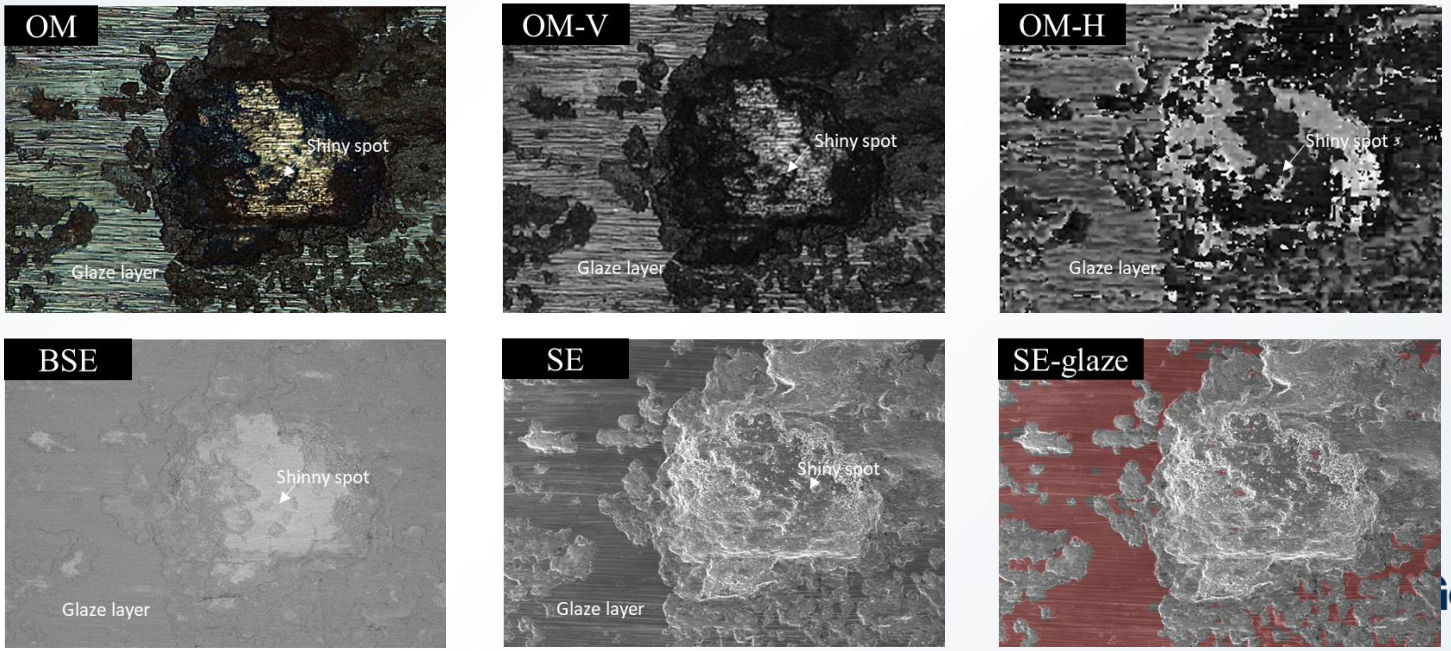


- Perfect alignment from input to output
- Retained alignment with height map
- Fused information

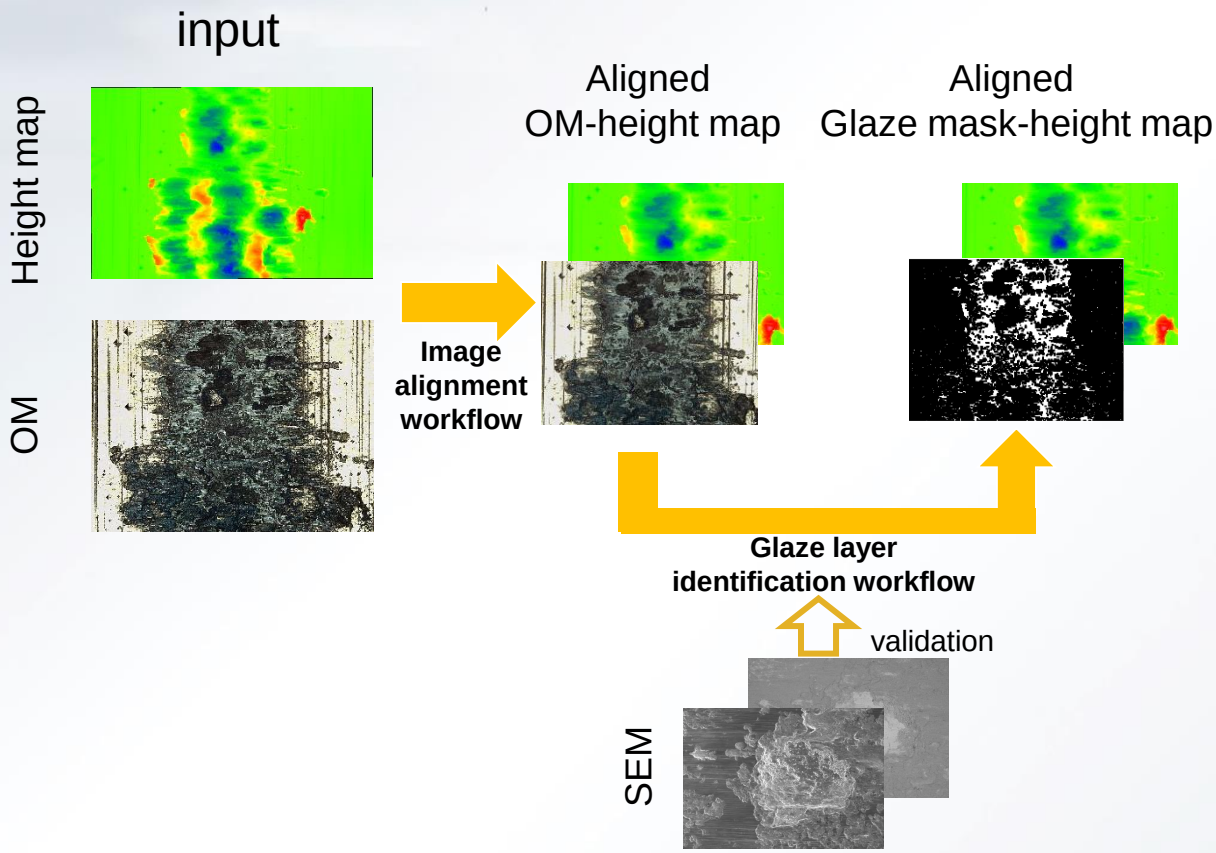
Evaluation of H-V criterion

- Type I error (false negative):
  - mis-identify glaze layer as non-glaze layer –reduced by RL
- Type II error (false positive):
  - mis-identify non-glaze as glaze layer
  - One Type II source: **shiny spot**
- H-V criterion is **NOT** redundant

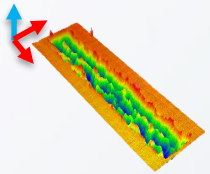
	Glaze layer	Shinny spot	Reference
O	22.2 ± 3.0	1.4 ± 0.3	2.0 ± 1.0
Cr	20.4 ± 1.0	26.7 ± 0.2	25.5 ± 0.2
Fe	41.4 ± 1.7	52.1 ± 0.3	50.0 ± 2.1
Ni	14.6 ± 0.3	18.7 ± 0.3	18.2 ± 0.7



Overview of the assembled workflows



- Application 1: Height distribution
- Application 2: Glaze coverage



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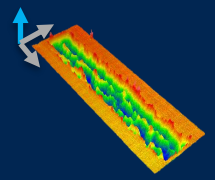
Application1: Height distribution

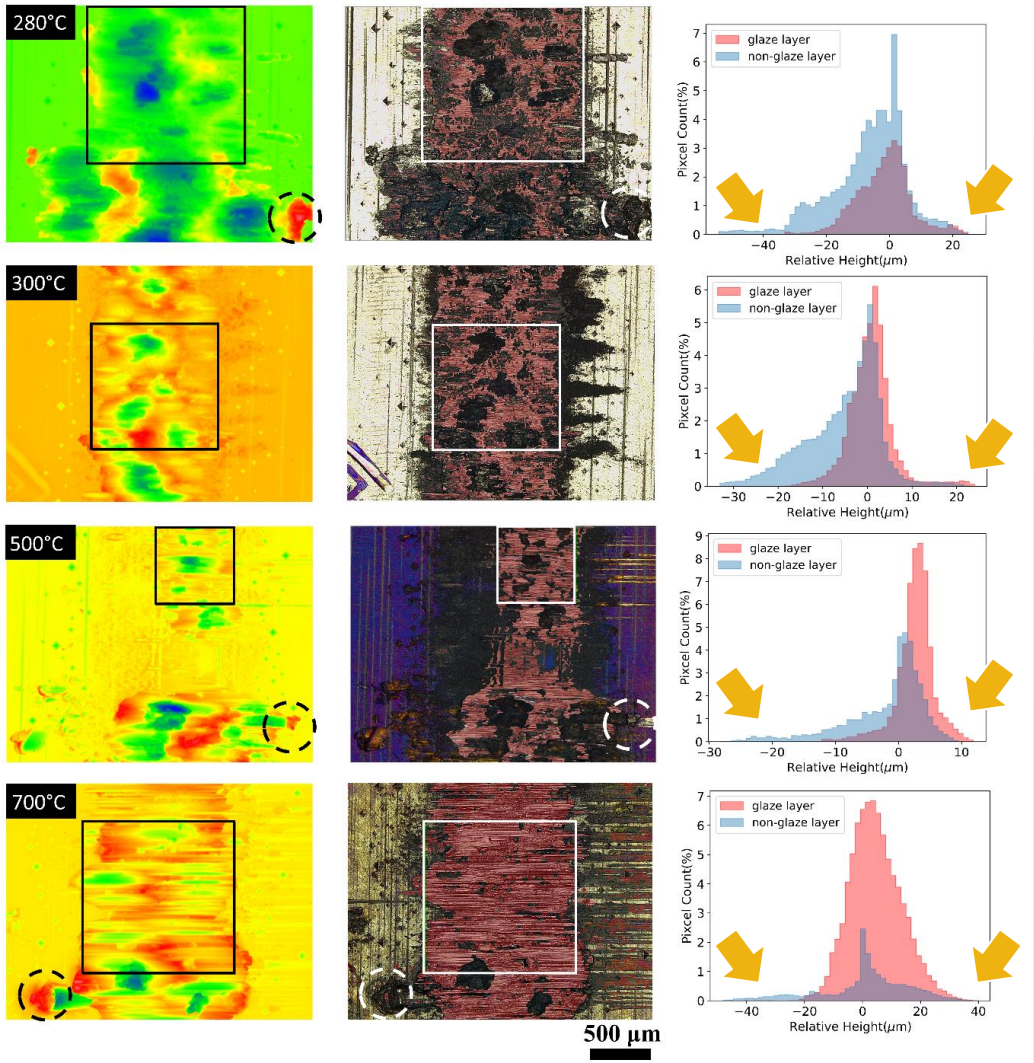


- Glaze layer prefers relatively **high** locations in wear scar
  - Avg height
  - Statistically significant

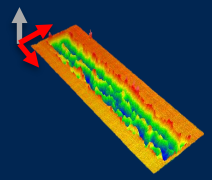
Sample	μ_{glaze} (μm)	μ_{non_glaze} (μm)	t value	p value
280C_pl	-1.722	-6.530	-95.3395	<0.001
300C_pl	0.797	-5.203	-140.693	<0.001
400C_pl	4.749	-3.583	-188.358	<0.001
500C_pl	3.015	-1.698	-109.091	<0.001
600C_pl	-1.753	-2.252	-6.48722	<0.001
700C_pl	4.483	3.400	-13.3717	<0.001

- Support Sintering theory of glaze layer formation

- Glaze layer reduces friction and wear by eliminating metal-metal contact and reducing real contact area

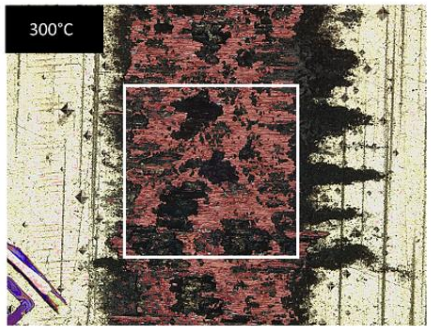


Application2: glaze layer coverage



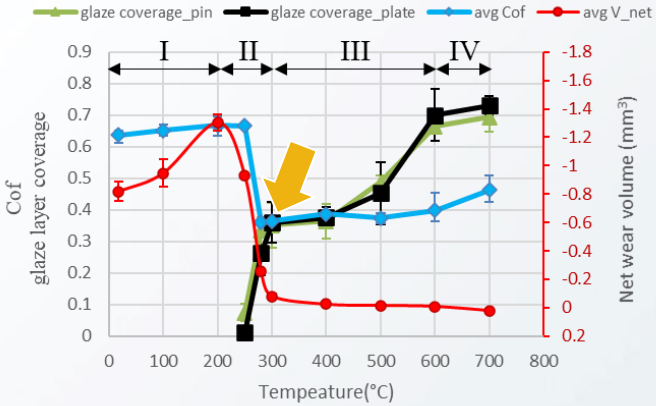
- Same pixel resolution
  → convert glaze layer coverage to **pixel count**

$$C_p = \frac{\text{Area covered by glaze layer}}{\text{Total projected area of wear scar}} \Rightarrow C_p = \frac{n_{glaze}}{n_{tot}} = \frac{n_{glaze}}{n_{glaze} + n_{non-glaze}}$$



- 36% projective coverage upon finishing severe-to-mild wear transition

- Glaze coverage increases with temperature
  - 3 stages
  - Glaze layer → severe-to-mild wear transition



Significance and Conclusions

- **Open-source** workflow using **computer vison** algorithms that enable multi-spectrum analysis without upgrading existing hardware
  - **Image alignment** : easily **transferable** to all other applications in academia and industry.
  - **Glaze identification: Quantitative** criterion that enables fast, accurate, and automatic glaze layer identification

- Two workflows revealed new knowledge:
  - Glaze layer occupies **high locations** within wear scar
  - Glaze layer has relatively **stable H-V parameters** regardless of testing temperature
  - **36%** projected coverage of glaze layer towards finishing severe-to-mild wear transition of the studied 310S fretting system.

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THANKS!

Zhang, Chuchu, and Richard W. Neu. "Understanding the role of glaze layer with aligned images from multiple surface characterization techniques." *Wear* (2021): 203837.

Related work:

[WP1.40] Chuchu Zhang, and Richard W. Neu. “Wear rate and mechanism map for austenitic stainless steel at high temperature”

zhcc09@gatech.edu
https://github.com/mch360/glaze_layer_analysis

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