Post-grinding surface integrity across rail grades: effects of stone topography

ICRI Workshop – Tokyo

Presenter: Lucas Biazon Cavalcanti 22/Sep/2025

Agenda

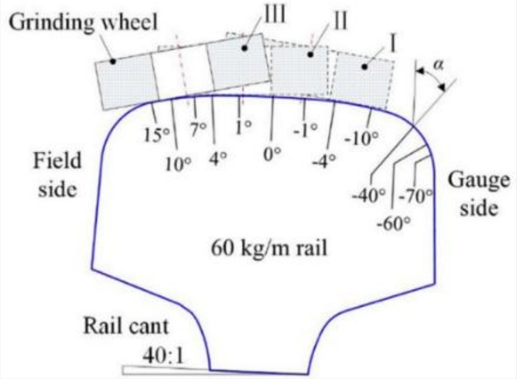
- **Rail Grinding Context**
  - Rail grinding process
  - Rail life-cycle and quality assessment
  - Grinding theory and WEL formation
  - Research motivation and objectives
- **Methodology**
  - Field and laboratory cases
  - Replicating stone topography
  - Laboratory rail grinding tests
- **Results and discussion**
  - Grinding forces and power
  - Surface and subsurface analysis
  - Evaluation of rail grade, stone topography and depth of cut
  - Discussion of rail grade in WEL formation
- **Next Steps**
  - Full railhead grinding experiments combined with full-scale tests on ground samples

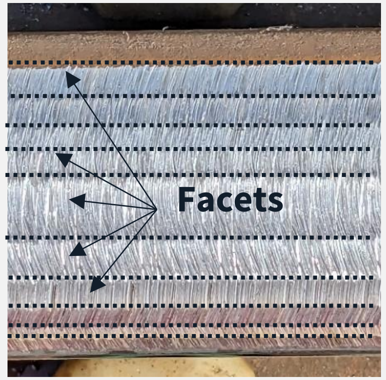
Rail Grinding Process

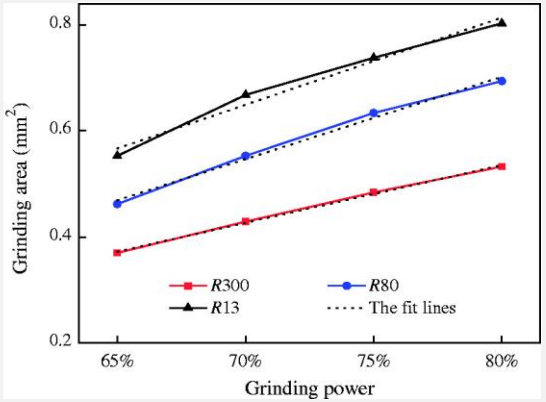
University of Sheffield

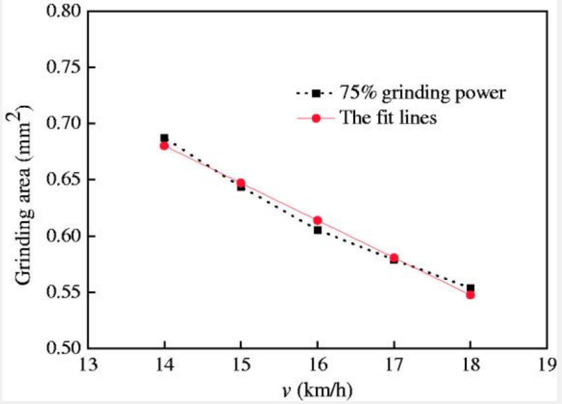
BRITISH STEEL

- **Rail grinding process**
  - A series of active rotating grinding stones embedded on a grinding train
  - Each stone is positioned in terms of angle and lateral offset across the rail head (grinding pattern)
- **Conditions:**
  - No coolant is used leading to high temperature (sparks!)
  - No dressing the stones (self sharpening)
- **Process variables:**
  - **Parameters:** spindle power, train speed, rail head position, pattern and number of passes.
  - **Rail grade:** Mechanical properties, metallurgical aspects
  - **Grinding stone composition:** Abrasive material, wheel hardness, porosity, grit size and topography









Rail life-cycle and quality assessment

- **Rail life cycle**
  - Extend the rail life: managing surface defects and reshaping the rail profile
  - Controlling the magic wear rate

Wheel-rail interface
Contact stresses
Rolling-sliding contact

Deterioration
Wear and RCF
Corrugation

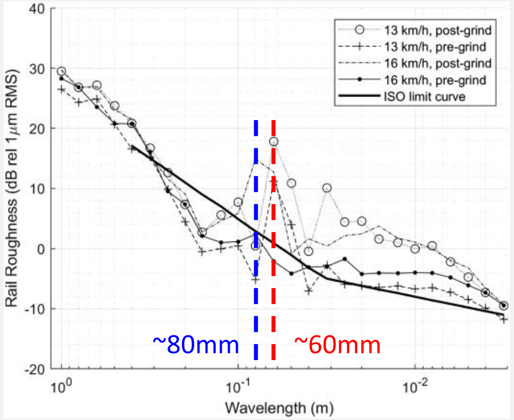
New and harder rail grades: better performance, but affecting maintenance

Rail grinding
Profile correction
Remove surface defects

New generated surface
Profiles
Surface layer properties

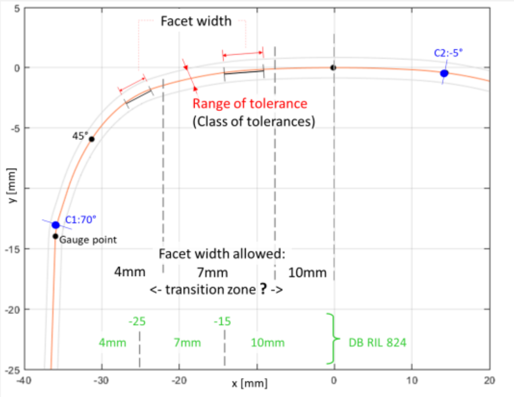
- **Post grinding outputs (EN 13231-2:2020)**
  - Transverse profile: metal removal, quality profile indices and max grinding facets width
  - Longitudinal: amplitude threshold per wavelength
  - Surface integrity: Surface quality (surface roughness), surface appearance (blueing)
  - These properties change every grinding cycle and affect the whole wheel rail contact system

Long. Profile



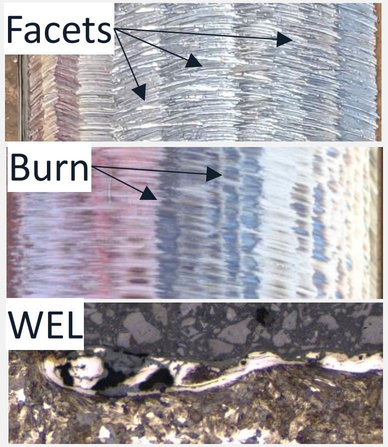
(WILKES and THOMPSON, 2025)

Transverse Profile



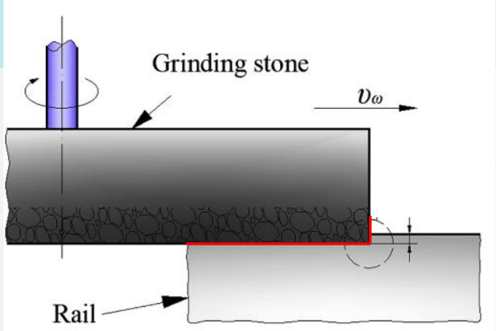
(NERLICH, 2024)

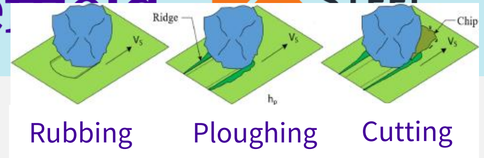
Surface Integrity

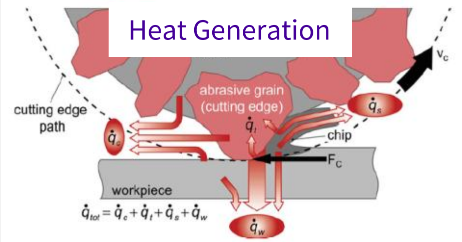


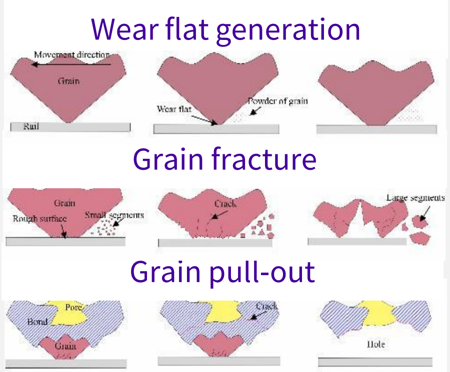
Grinding Theory and WEL Generation

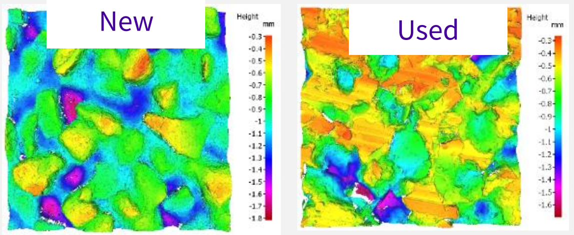
- **Material Removal Mechanism**
  - Cutting, ploughing and rubbing depending on stone height distribution, abrasive shape, etc.
  - The heat generation into the rail will depend on the ratio between these mechanisms and the heat partition
- **Grinding Stone Wear**
  - Stone wears down during the process, changing its topography
  - The ratio of these mechanisms depends on the ***grinding parameters*** and ***stone composition*** affecting material removal and heat generation
- **White Etching Layer**
  - High temperatures due to dry grinding combined with rapid cooling from bulk lead to phase transformation (martensite) that appears white when etched
  - WEL is generated from various means (not only grinding, not only thermal) and different rail grades have varying susceptibility to WEL
  - Gradient of properties like hardness and residual stresses may lead to crack nucleation a preferential propagation

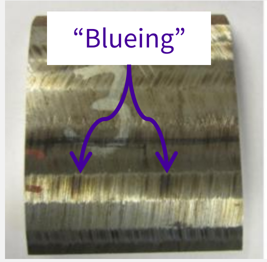


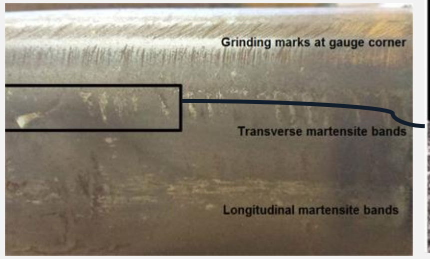


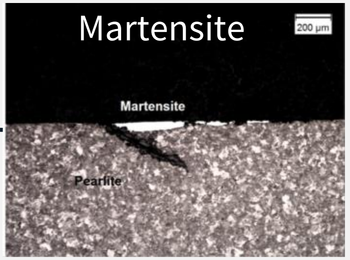




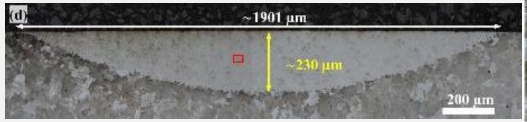




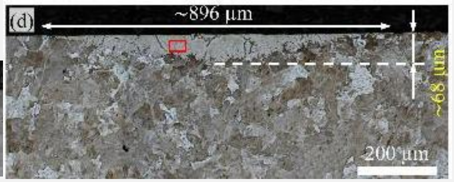




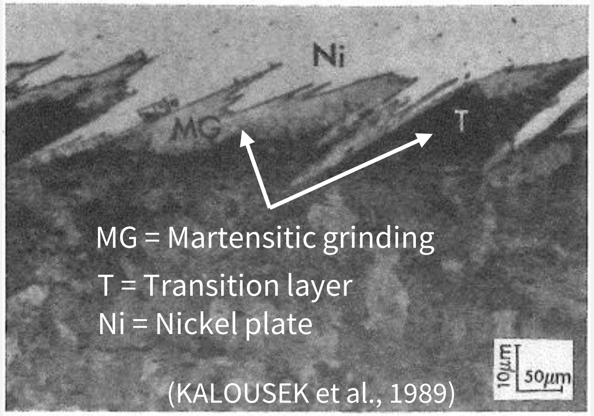
Head Hardened



Standard Carbon



- **Potential issues with premium rails:**
  - The presence of White Etching Layers (WEL) in rail grinding is not new
  - WEL and rough surfaces coupled with the premium rail's high wear resistance and geometry irregularities (transverse profile, corrugation), may result in spalling defects.
  - These defects on premium grades have been reported in different railway around Europe
    - France, Denmark, Netherlands, Switzerland, etc.



(KALOUSEK et al., 1989)

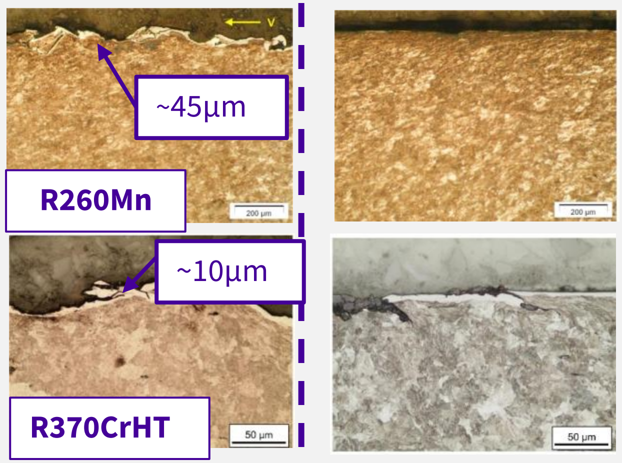
(FAU et al., 2016)

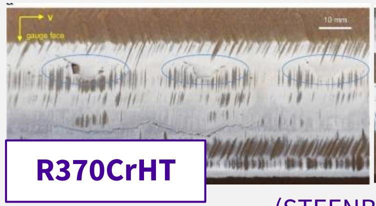
(NERLICH, 2024)

Immediately after rail grinding ⟵ ⟶ After few days of operation

Standard grade
- Run-in remove WEL

Premium grade
- WEL stays in the surface during run-in



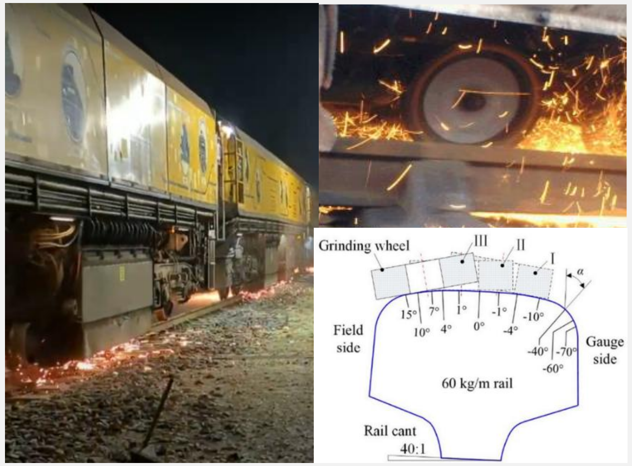


(STEENBERGEN, 2016)

Objectives

Commission a new test rig for rail grinding research and establish grinding parameters for standard and harder more durable premium rails, to ensure that material can be removed as required, but with minimal WEL generation.

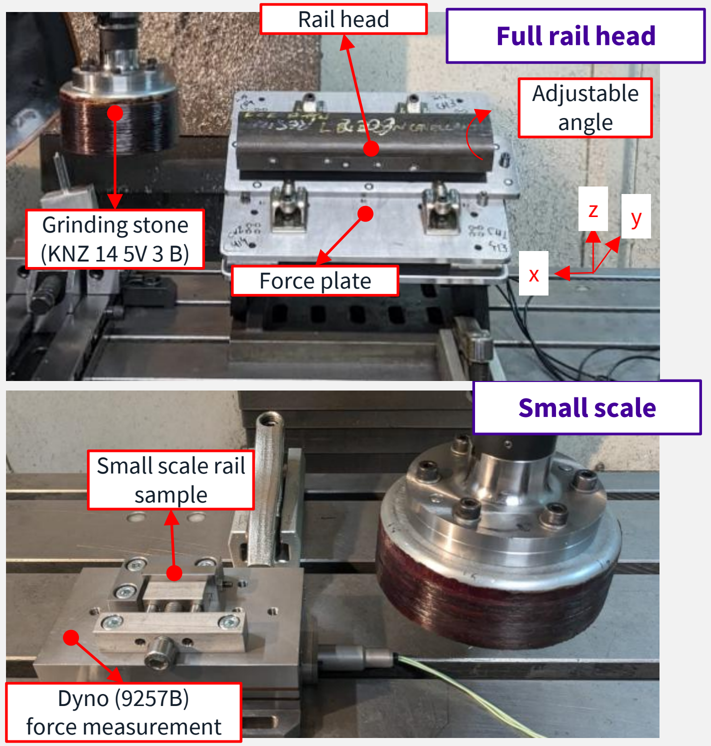
Field



- Different applications, equipment and stones:
- **Industrial site (UK):** small scale, 4 stones
  - Surface roughness and stone analysis
- **Metro (Colombia):** intermediate scale, 20 stones
  - **Surface and subsurface analysis**
- **Test track (UK):** production size, 64 stones
  - Surface roughness and **stone analysis**

- Grinding parameters
- Material removal
- **Grinding forces and power**
- **Surface and subsurface characterisation**
- **Grinding stone wear**

Laboratory



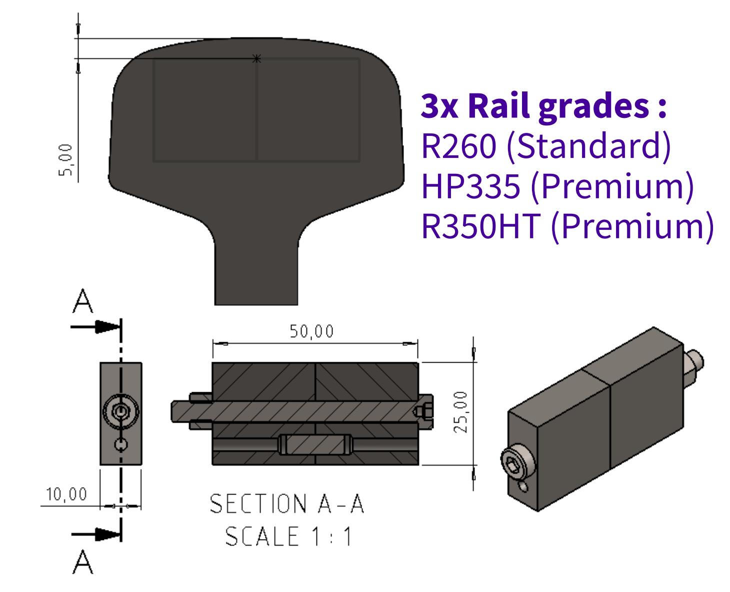
- **Dressing**
- **Small scale tests**
- Full rail head tests

Methodology: CNC Tests

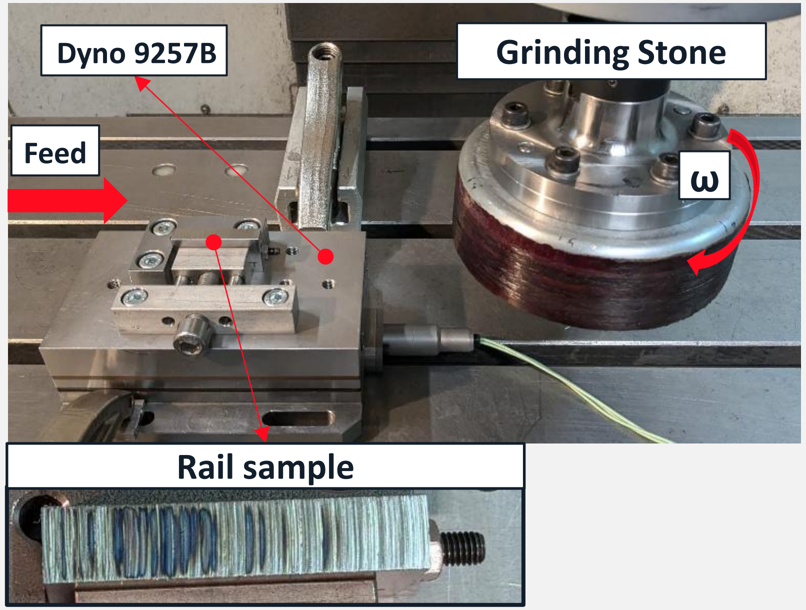
- Test setup:
  - Small sample, adaptded grinding stone and force and power monitoring
- Design of experiments: stone topography (3) x rail grades (3) x depth of cut (2)
- Post grinding characterisation:
  - **Surface roughness, subsurface, nanoindentation**

Representative test run

Sample extraction



Test set-up



Design of experiments

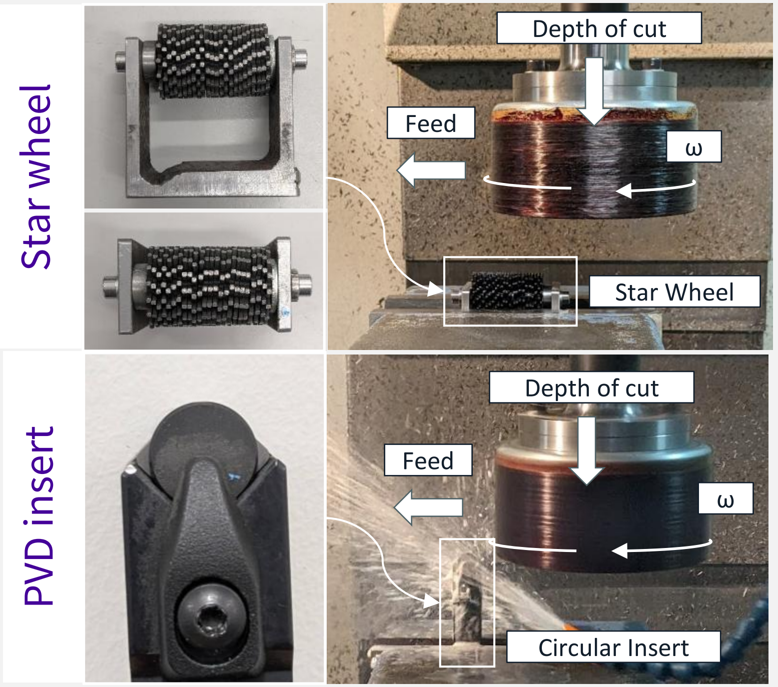
Test #	Rail Grade	Depth of cut (μm)	Stone Topography	Feed (km/h)	Rotational speed (rpm)
1	R350HT	100	Dull	2.1	3500
2	HP335				
3	R260				
4	HP335	180			
5	R260				
6	R350HT				
7	HP335	100	Worn	2.1	3500
8	R260				
9	R350HT				
10	R260	180			
11	HP335				
12	R350HT				
13	HP335	100	Sharp	2.1	3500
14	R350HT				
15	R260				
16	R350HT	180			
17	HP335				
18	R260				

Rail grades were test randomly

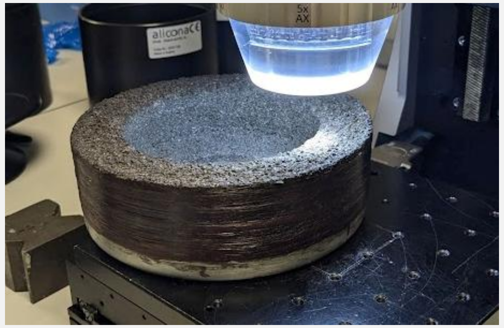
Methodology: Stone topography

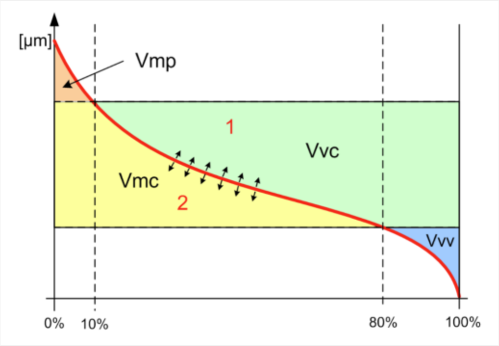
- Reproducing field stone’s topography via dressing
  - Starwheel: sharpening control;
  - PVD insert: dulling control
- Parameters for comparison
  - Peak volume (Vmp) and sum of core and valley void volume (Vvc+Vvv)
  - Wear flat ratio, largest wear flat

Dressing

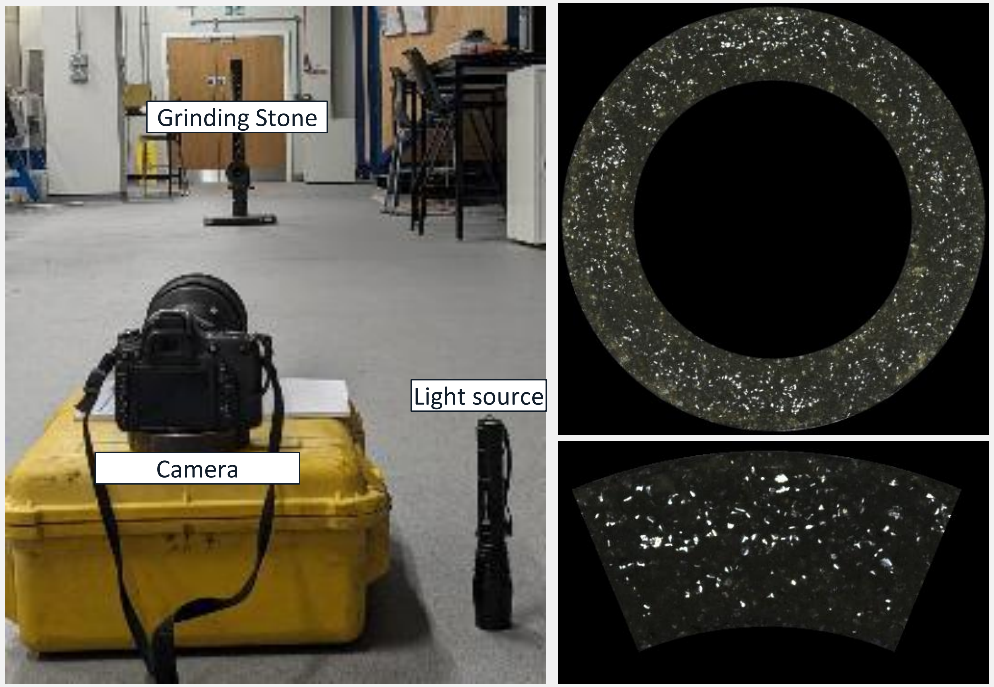


Topography analysis





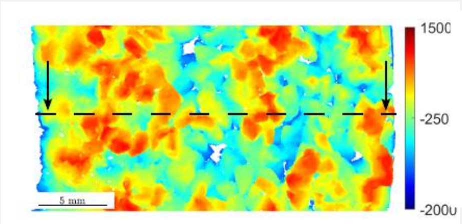
Wear flat ratio analysis



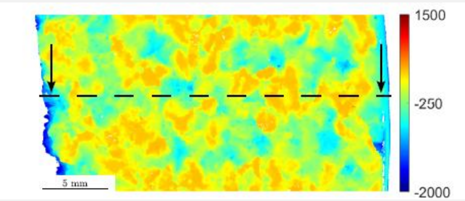
Results: Stone Topography

- Topography parameters:
  - Bearing ratio curve parameters (Vmp, Vmc, Vvc)
- Wear flat ratio

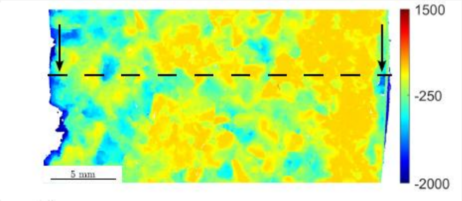
Sharp



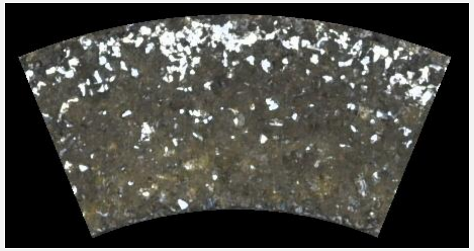
Worn



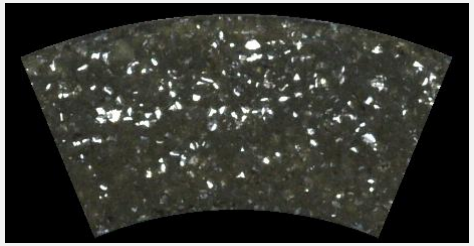
Dull



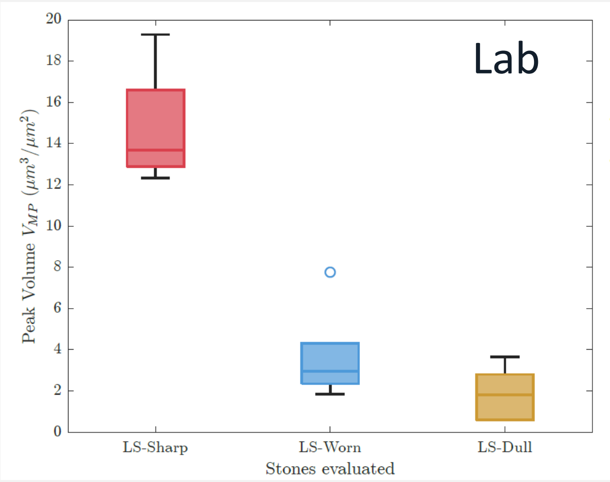
Dull

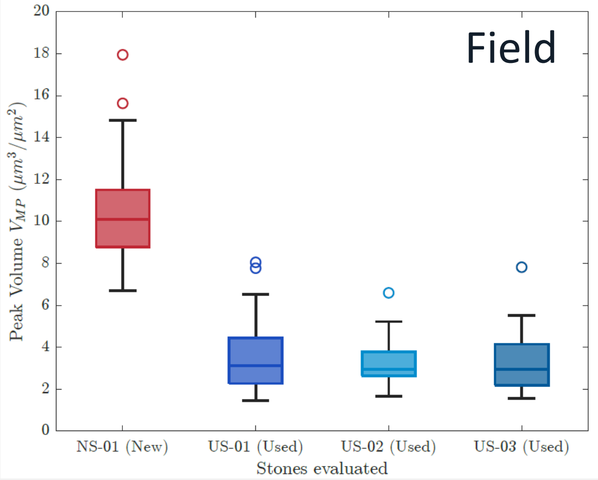


Worn

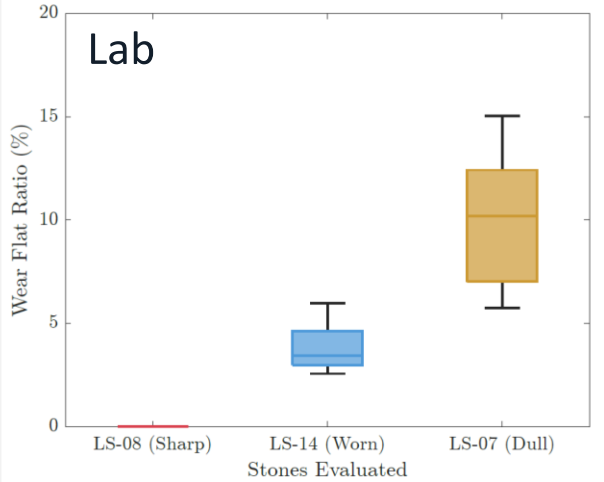


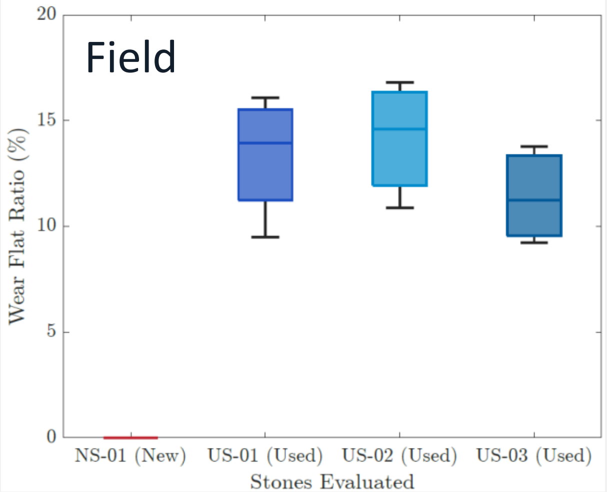
Peak volume (Vmp)





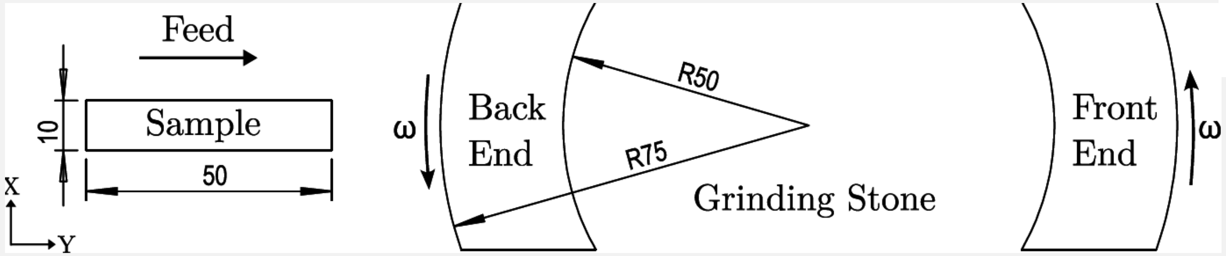
Wear flat ratio (%)



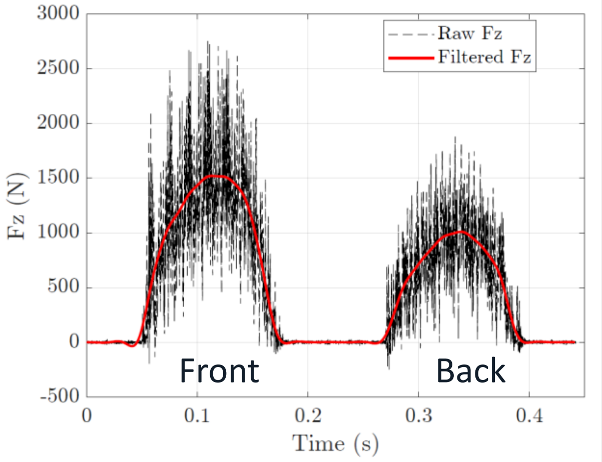


Results: Grinding Forces and Power

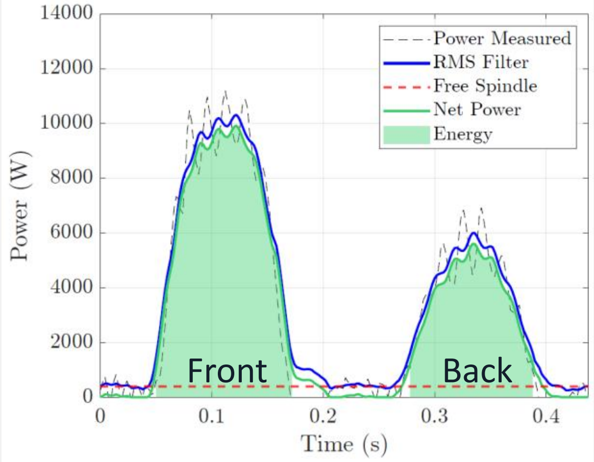
- Sample-stone engagement: “front” and “back”
- Force related metrics: Max. normal and tangential forces (N), **force ratio**, contact pressure (N/mm²), shear stress (N/mm²)
- Power related metrics: Max. power (W), heat flux (W/mm²), **energy (J)**



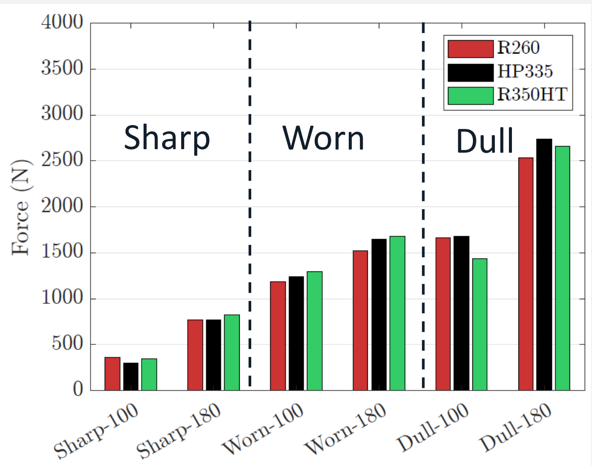
Normal Forces



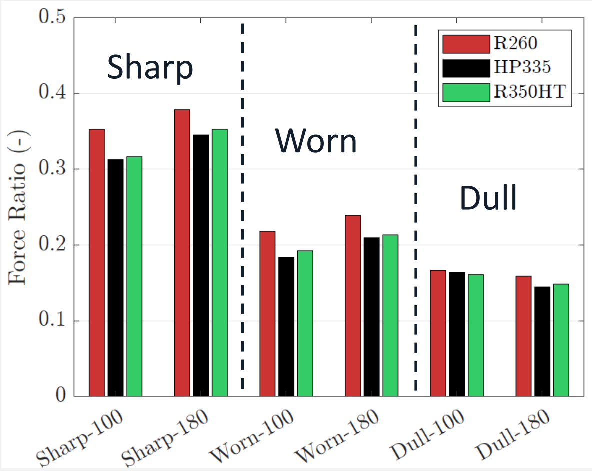
Grinding Power



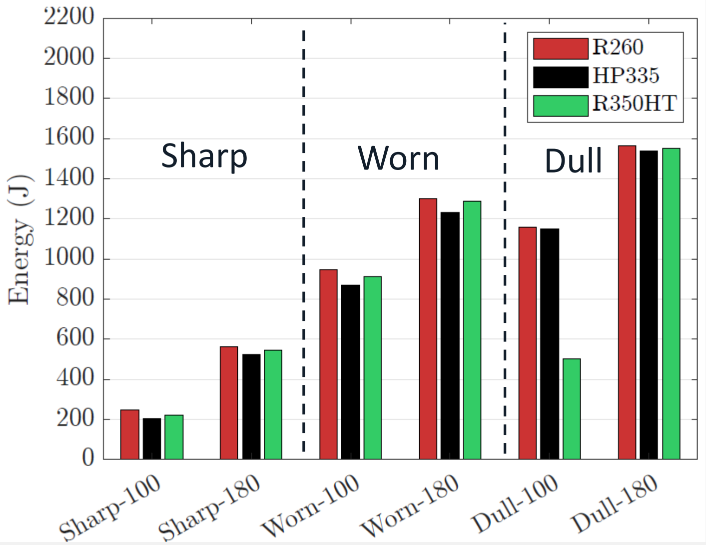
Front end: Max normal forces



Force Ratio: Fx/Fz

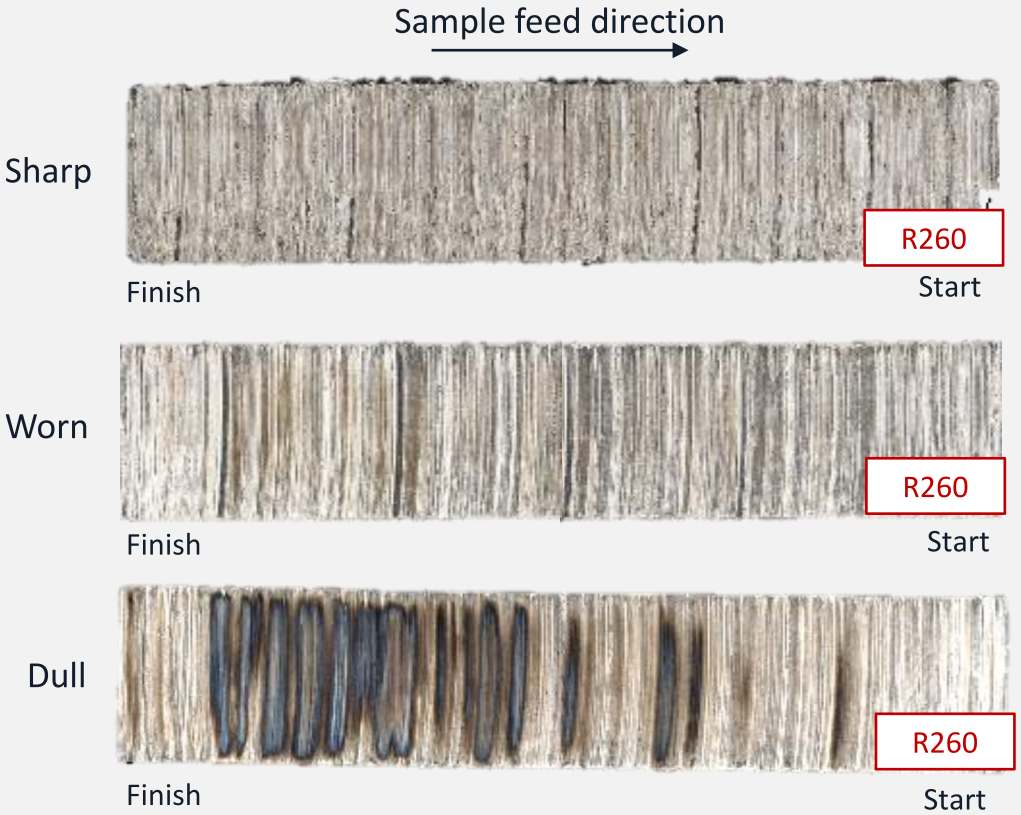


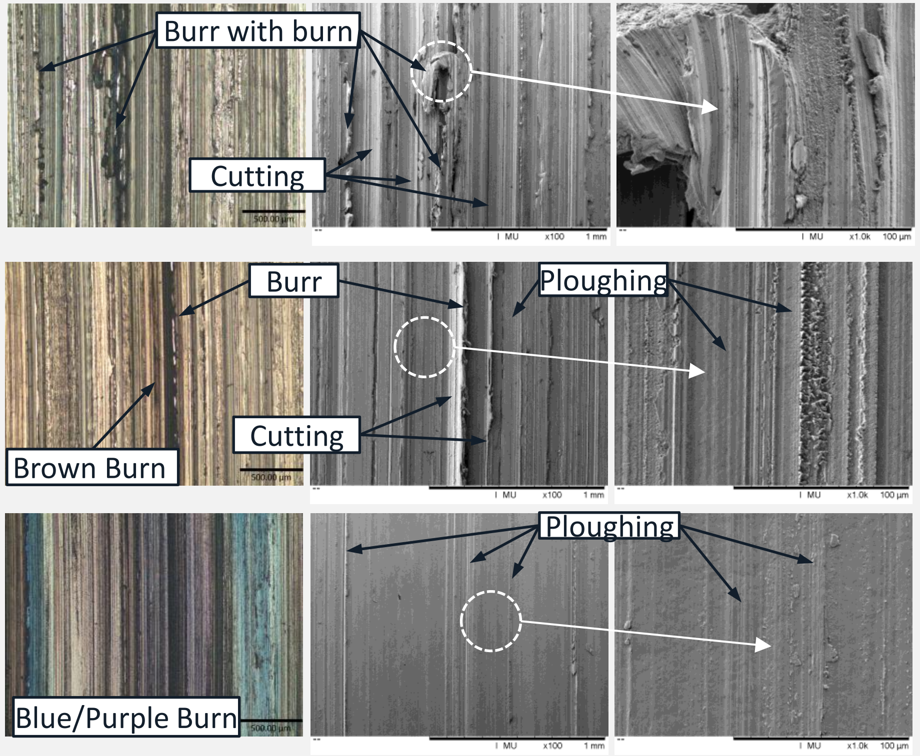
Total energy (J)



Results: Surface Aspects

- All grades and depth of cut presented similar surfaces
- Sharp stone: cutting behaviour and burr formation
- Worn stone: "brown" burn, cutting and ploughing behaviour
- Dull stone: "blue" burn, mostly ploughing with almost no cutting behaviour





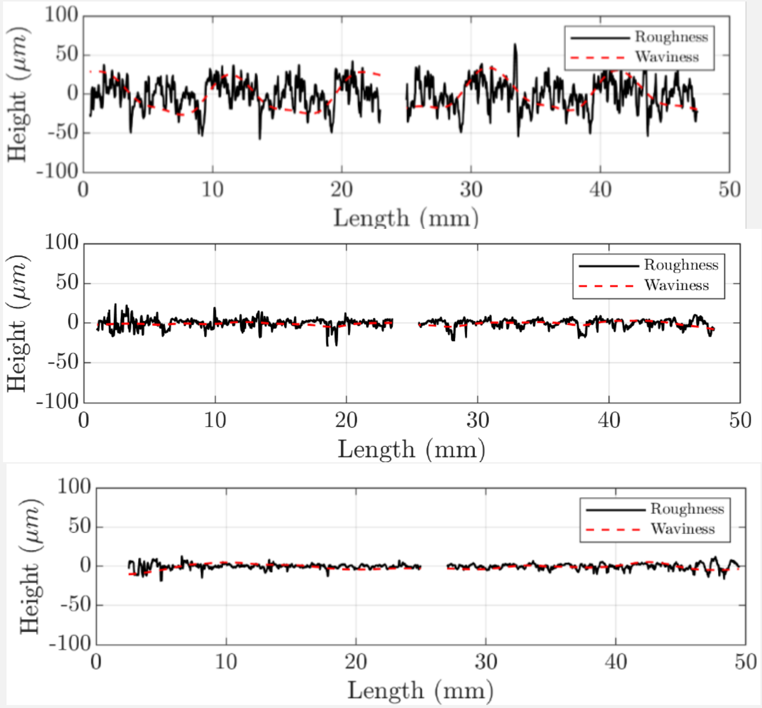
Results: Surface Roughness

- Different parameters can be extracted from surface: **Sa**, Sv, Spk, Sk, Svk
  - Cut-off used: 2.5 mm
- Correlation between stone topography and sample surface roughness
- Deep scratches are relevant as the time for the wheel rail contact reach a stready state

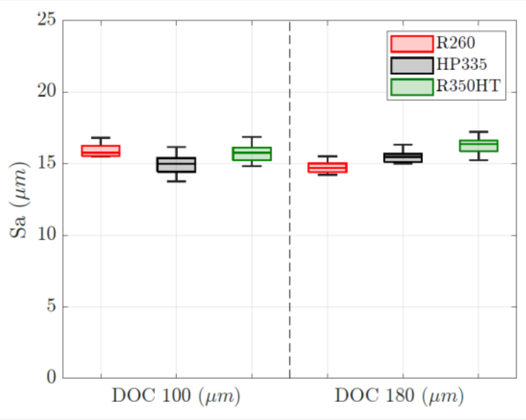
Sharp

Worn

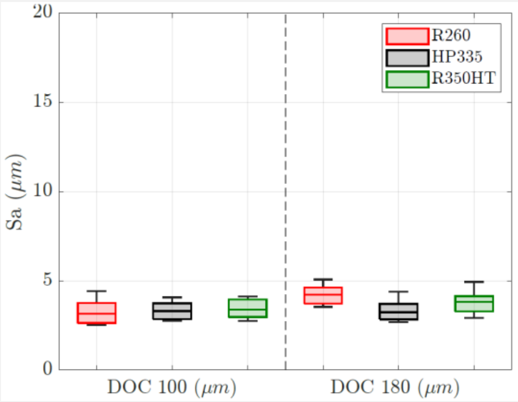
Dull



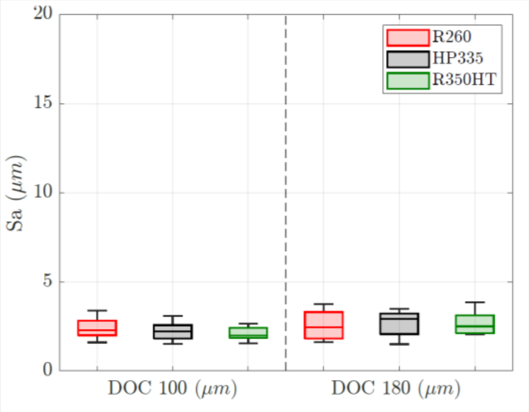
Parameter Sa: Sharp



Parameter Sa: Worn

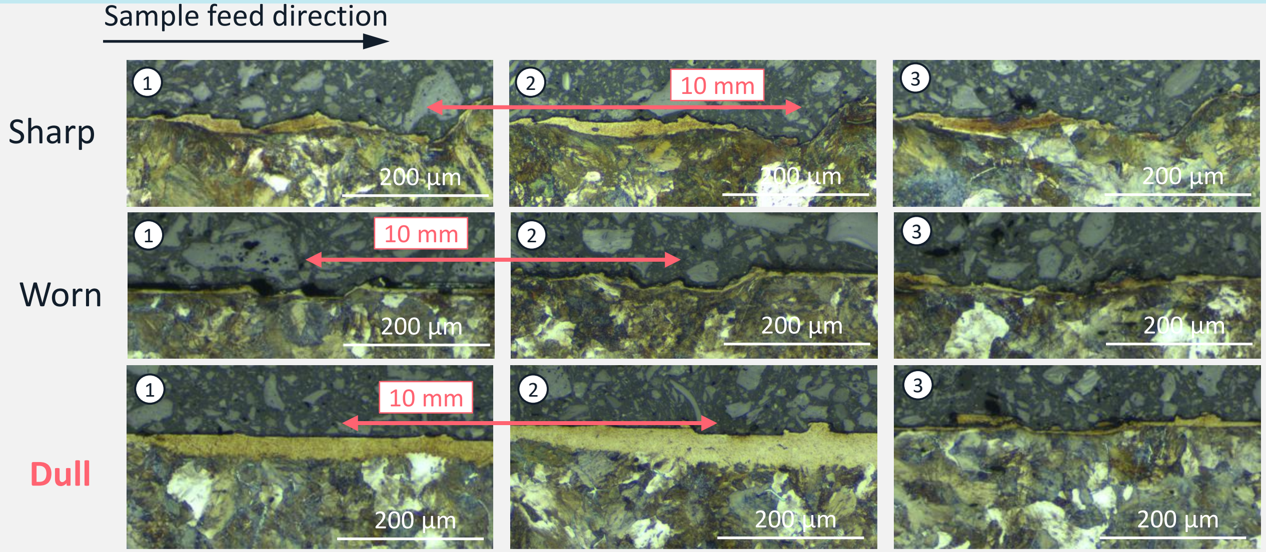


Parameter Sa: Dull

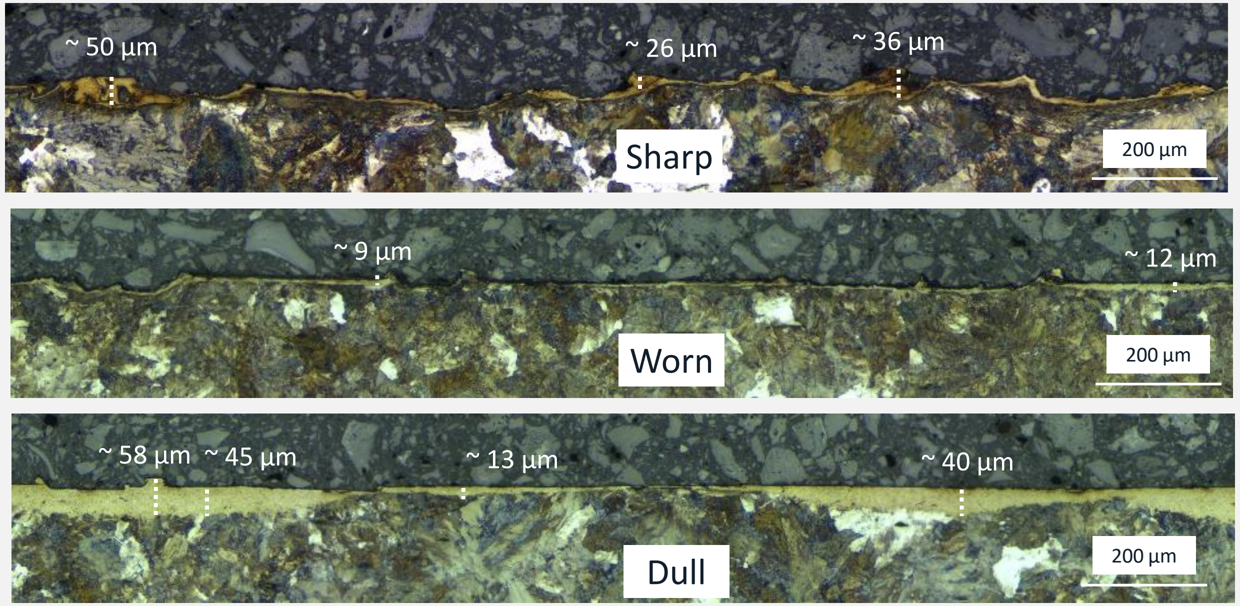


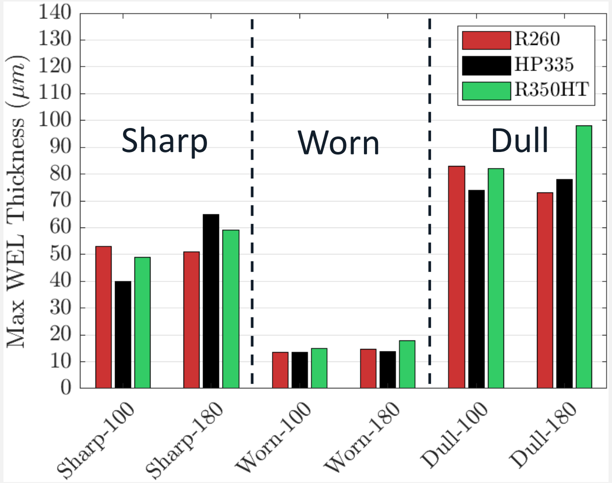
Results: Subsurface

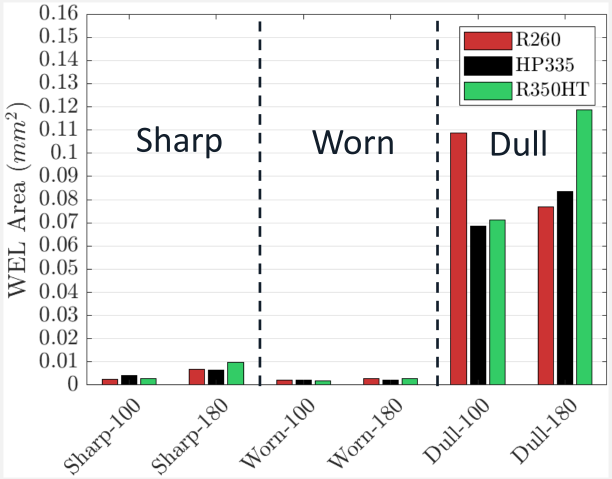
- Stone topography dictates WEL morphology
- Maximum WEL thickness and its corresponding area
  - Mixed results regarding rail grades and depth of cut
- Stone leaves a specific signature due to its topography
  - Relative position of the stone on sample also affects the signature for dull and worn stones



$$\lambda = V_{\text{feed}} / f_{\text{spindle}} = 583/58.3 = 10 \text{ mm}$$

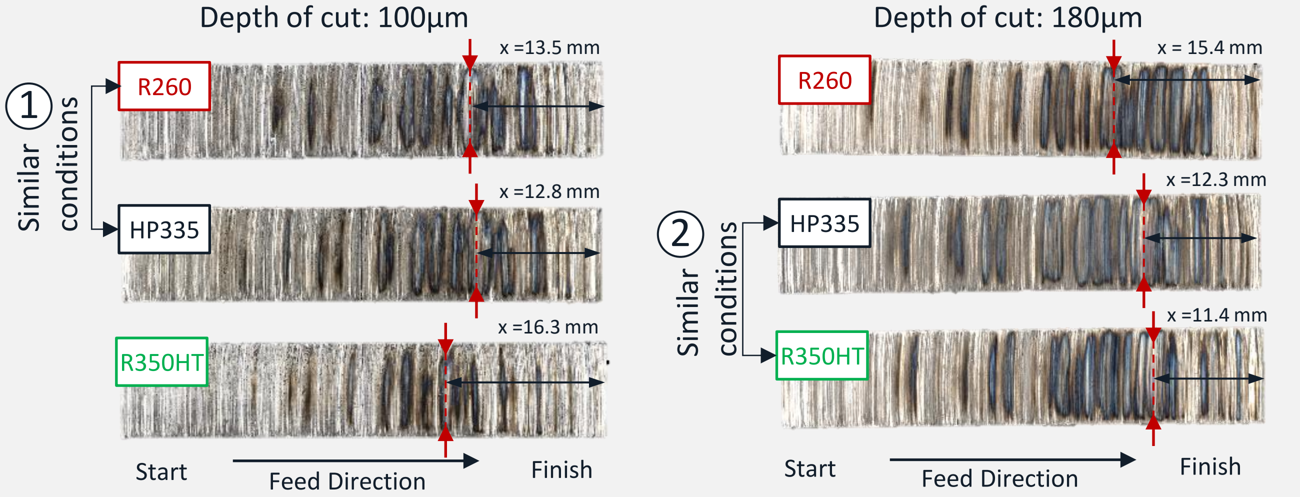




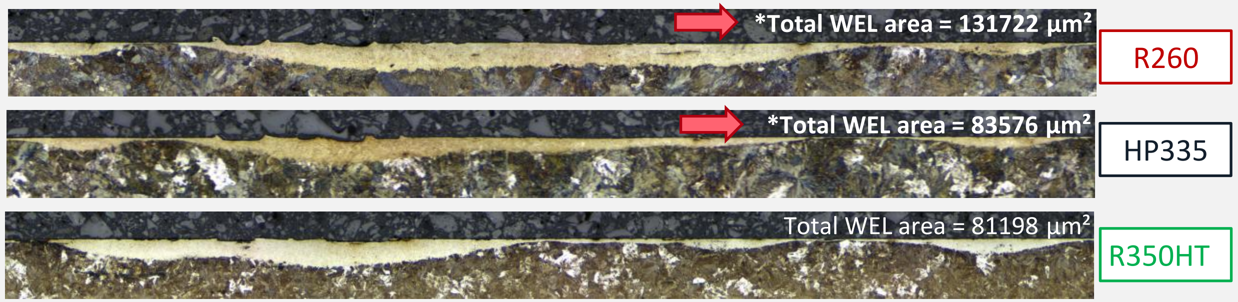


Results: Rail grade differences

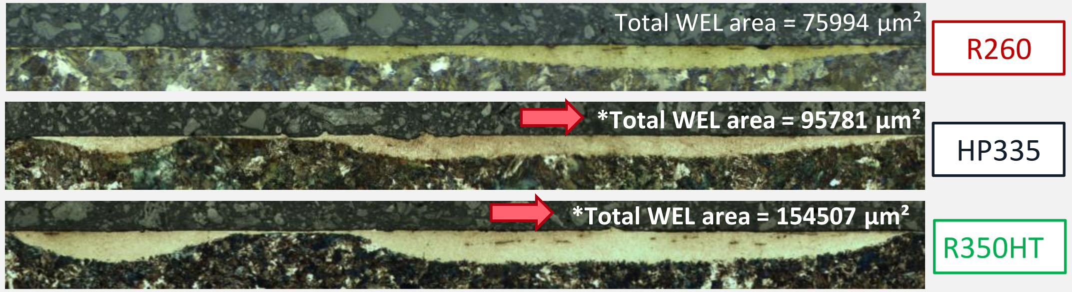
- Difference in premium rail grades further evaluated only for **dull stones** due to larger heat generation
- Analysis of all WEL patches: area and coverage (%)
  - Manually quantified: only WEL presenting thickness above 25 μm
  - Still presented mixed results
- Further analysis of individual WEL patches based on similar conditions:
  - Blueing position, forces and power
  - HP335 presenting lower WEL formation than other grades in similar conditions

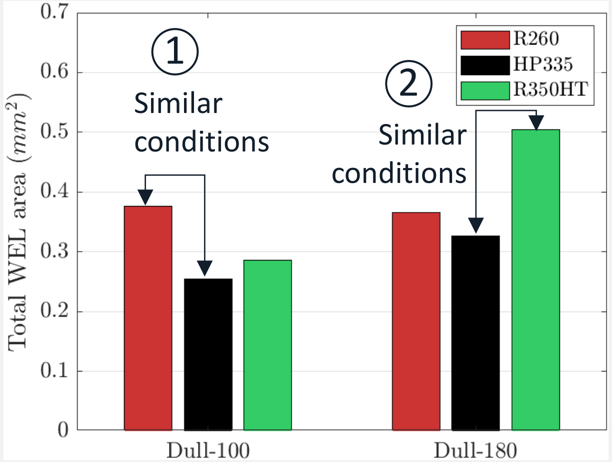


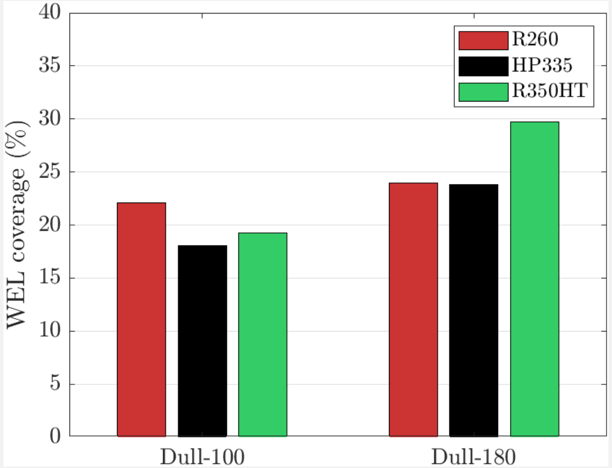
Comparison 01



Comparison 02

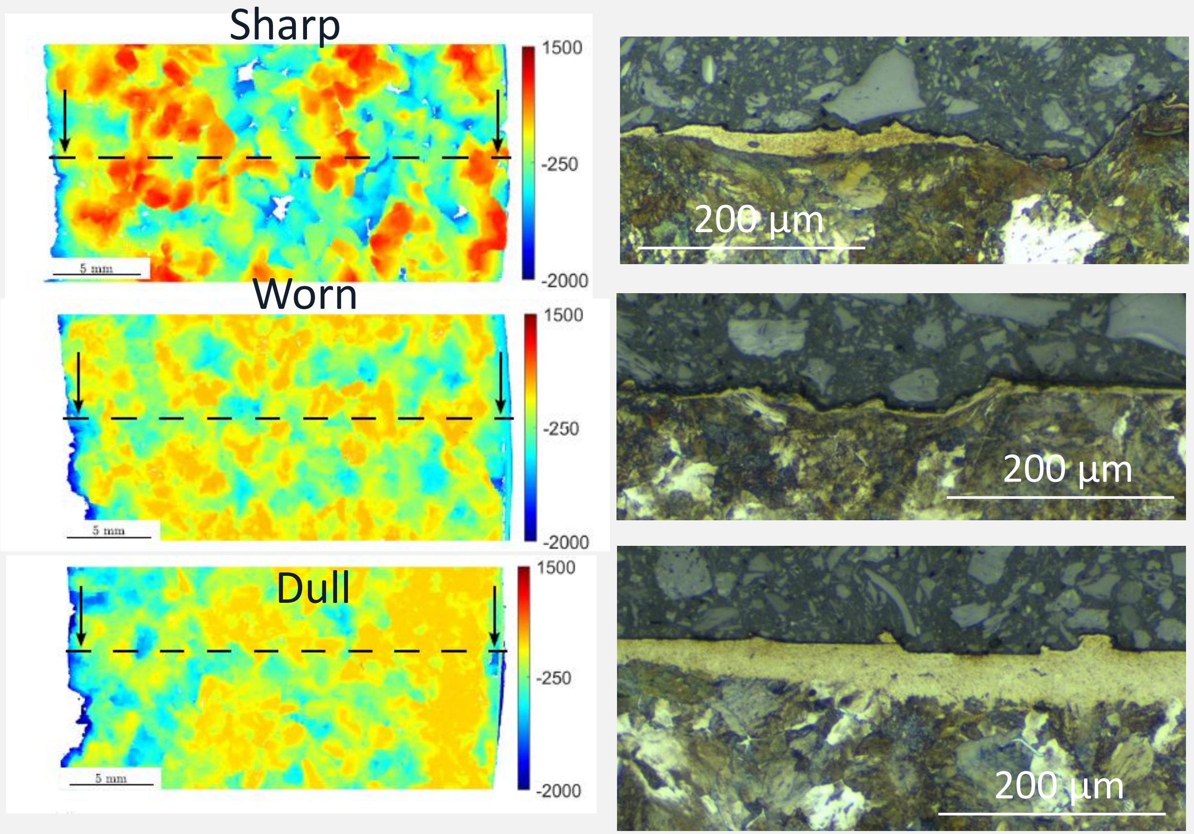






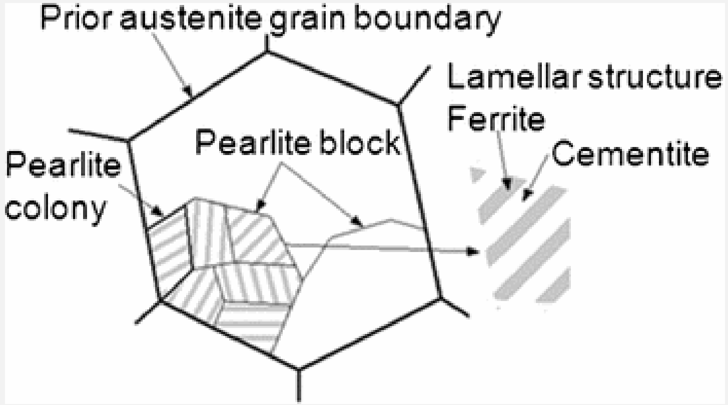
Discussion: Stone topography

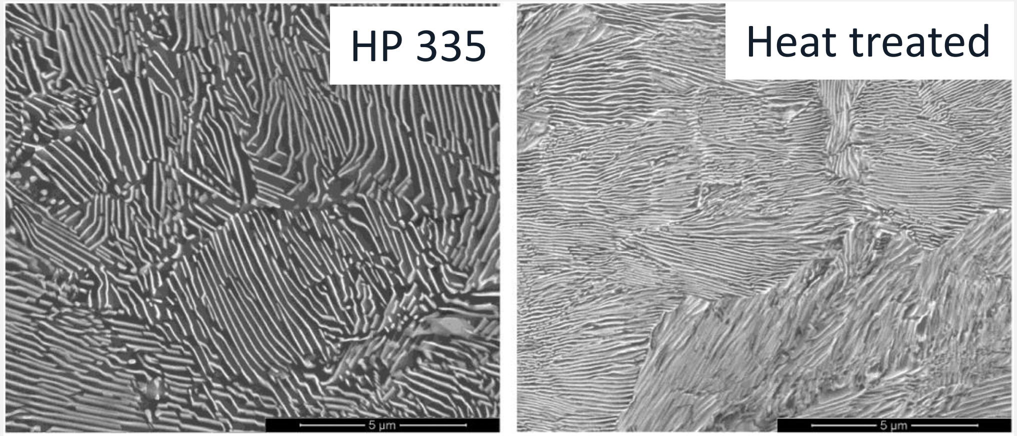
- Sharp stone:
    - Cutting dominates: higher surface roughness
    - Localised stress/temperature peaks
    - Energy mainly into chip formation
    - Irregular WEL patch, overlap between sharp grains
- Worn stone:
    - Mixed cutting and ploughing
    - Smaller and distributed wear flats
    - Energy spread more evenly
    - Thin, uniform WEL
- Dull stone:
    - Rubbing dominates (large wear flat on the outer edge)
    - Broader contact, sustained heating
    - Little chip formation, most energy into rail
    - Thick, continuous WEL, blueing



Discussion: Rail grade

- No clear difference in sharp and worn stones
- Dull stones generated larger WEL patches:
  - HP335 presented lower WEL generation than R260 and R350HT in similar conditions
  - Indicating that premium rails do not behave similarly under aproximated heat exposure
- WEL formation occurs through a two-step transformation:
  - **Austenitisation:** Cementite dissolves, carbon diffuses then austenite forms
  - Martensitic transformation: Austenite rapidly transforms to martensite during cooling (one type of WEL formation)
- Microstructure composition and morphology influence WEL formation
  - Interlamellar distance, carbon and alloying content, etc.





(PEREIRA et al., 2024)

Discussion: Field and laboratory similarities

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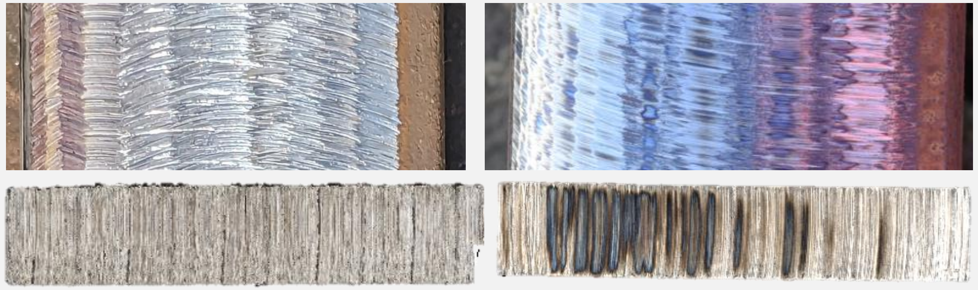
- Laboratory tests showed similarities to field:
  - Stone topography;
  - Surface feature and surface roughness
  - Subsurface: WEL morphology

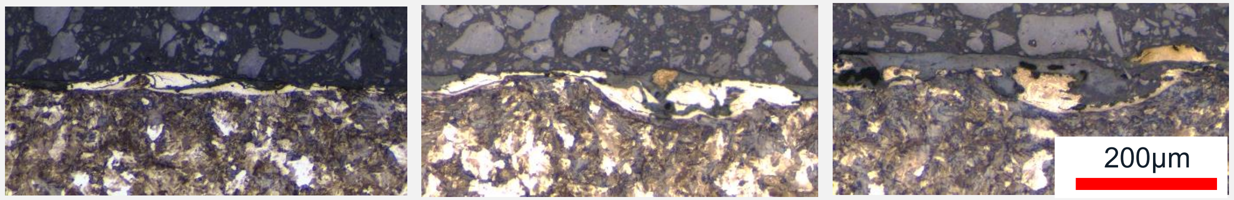
Field (Industrial Site) Field (Test Track)

Lab-sharp

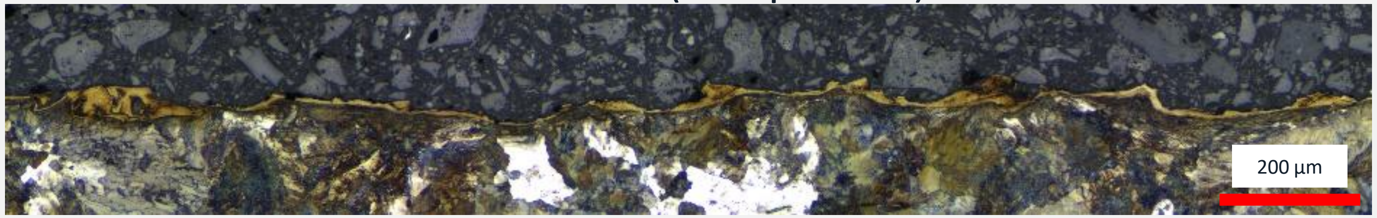


Lab-dull

Field (Metro system)

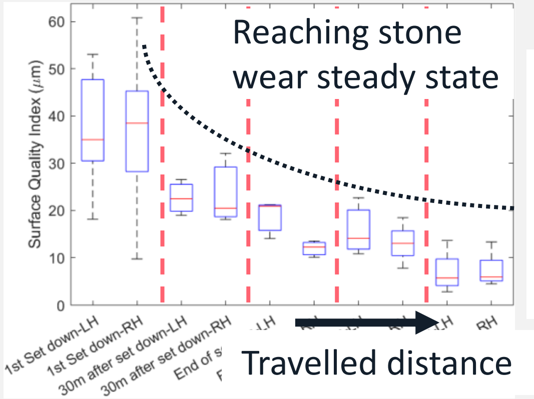


Lab (Sharp stone)

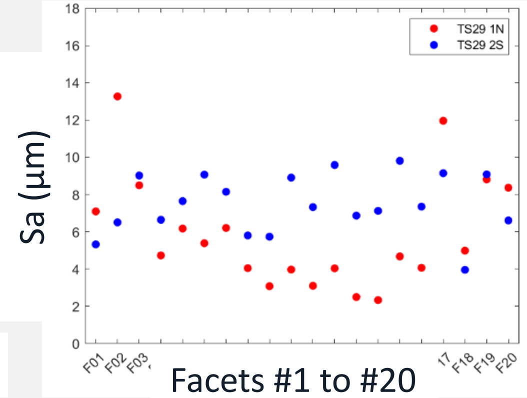


Field (New stone)

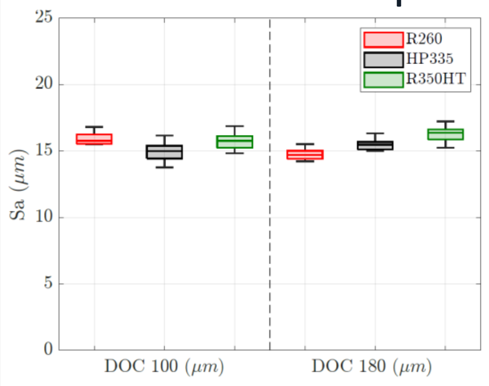
New stone



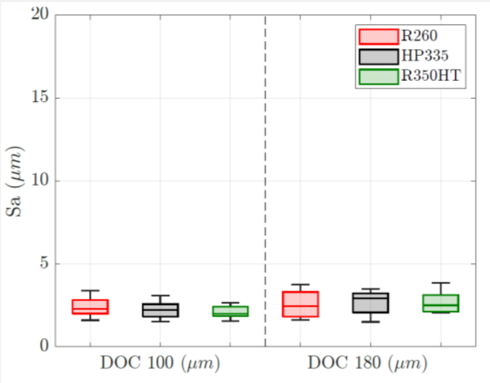
Field - Facets



Lab-Sharp



Lab-Dull



Conclusions

- Surface integrity comparison between laboratory tests and field
  - Sharp stones presented similar surface integrity than those observed from field
  - Dull stones presented similar facet blueing observed from field
- Stone toppography is the main driver of surface integrity
  - Dictates the abrasive/rail interaction resulting in variation of surface roughness and heat generation (WEL morphology)
- Rail grade differences only observable on large heat input
  - Heat treated premium rails (R350HT) presented larger WEL volume than micro-alloyed non heat treated (HP335)
- **The wear and RCF performance of these post grinding surfaces is unknown**
  - Surface integrity is only one aspect of rail grinding
  - Longitudinal and transverse profiles dictate global contact stresses

Future Directions

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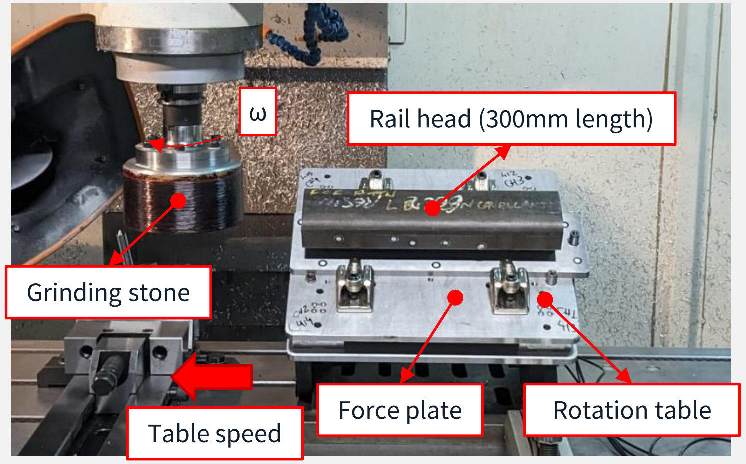
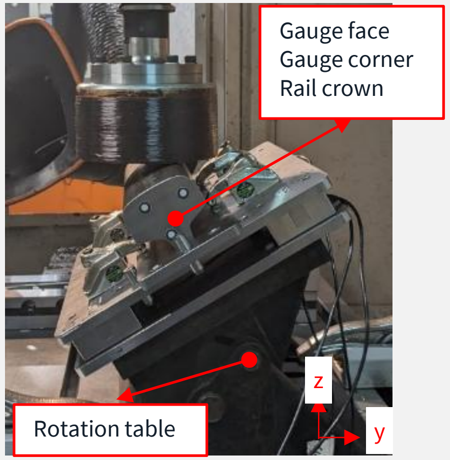
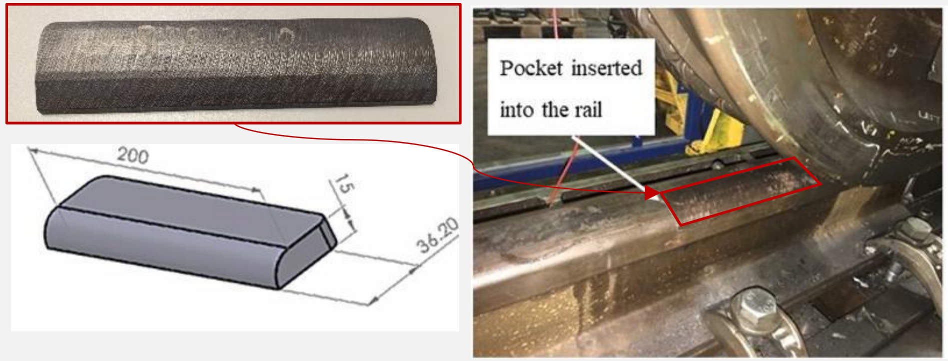
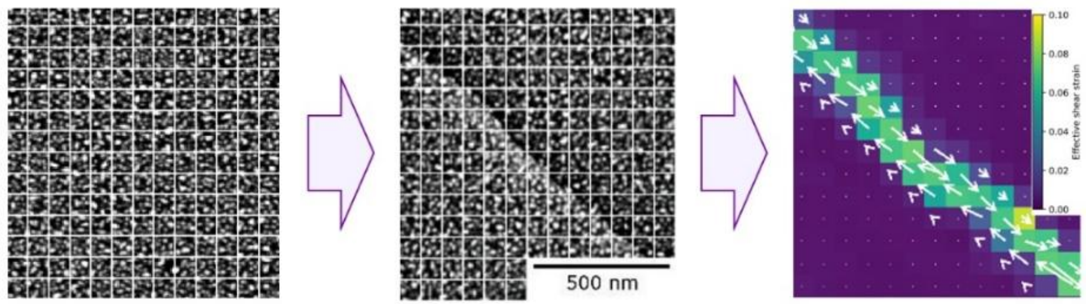
1) Full Rail Head Laboratory Tests - Full Scale Tests

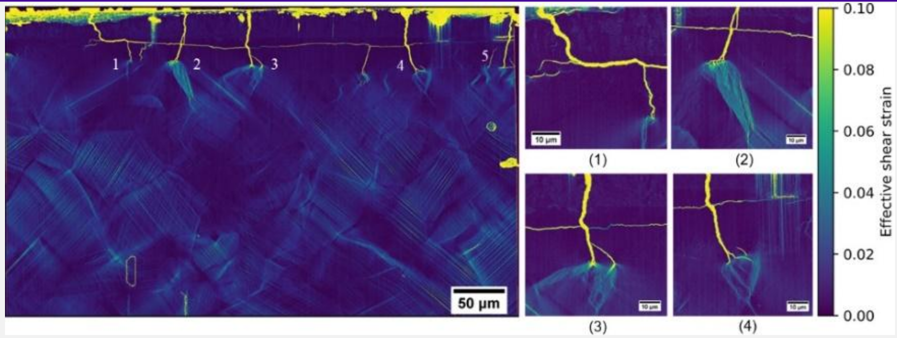


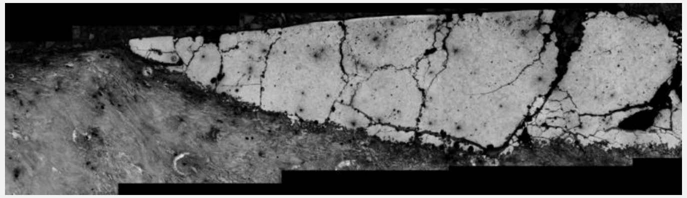




2) In-situ Bending Tests - HR-DIC







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Thank you