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Study on Microstructure Characteristics of Steel in Two-Body Abrasive Wear

31 October 2023 | Technical Topic Webinar

Dr. Balaji Trichy Narayanaswamy

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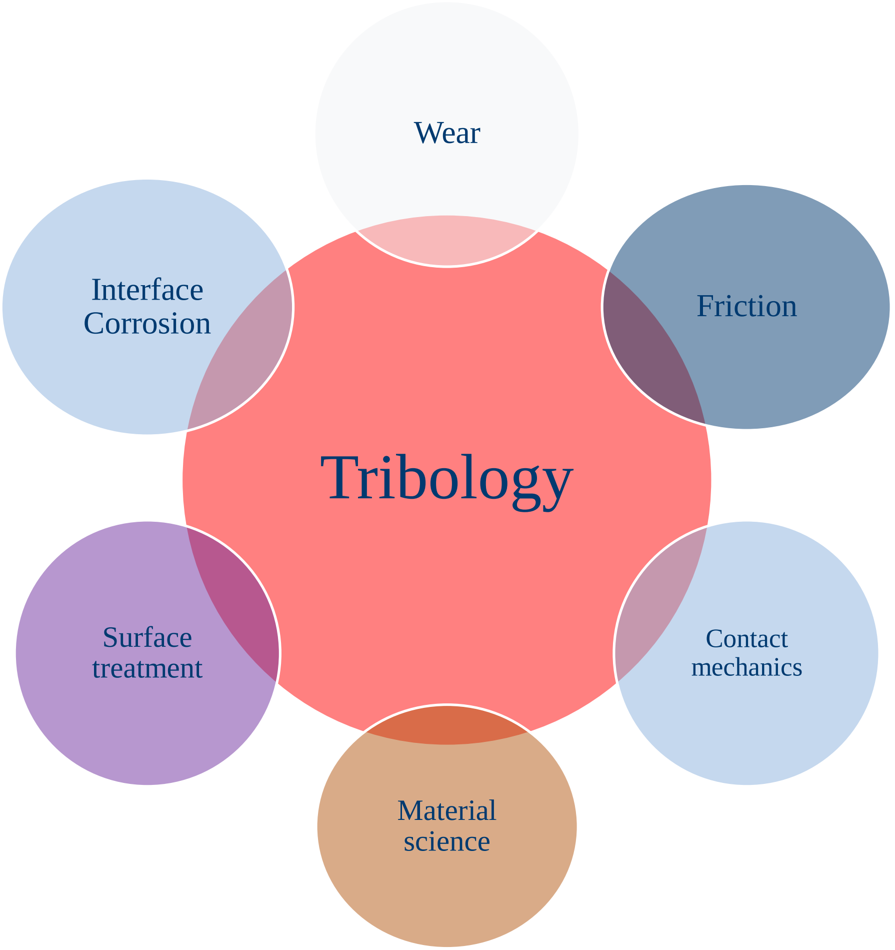
Introduction - Presenter

Dr. Balaji Trichy Narayanaswamy

- Balaji is an Interdisciplinary Lecturer at the University of Sydney.
- Specializes in industry and community project units with a real-world problem focus.
- Holds a background in Mechanical and Materials.
- Completed a PhD at Deakin University in 2017 under Deakin University Postgraduate Research Scholarship.
- Career highlights include winning the 'Victoria International Student of the Year 2016-Regional' award and being a finalist in the 'Fame Lab 2015' science talk competition for presenting 'Sandwich steel structures for tackling abrasive wear.'

Tribology-Introduction



[1] *B B. Introduction to Tribology. 2 ed Hoboken. 2013*

Different modes of wear

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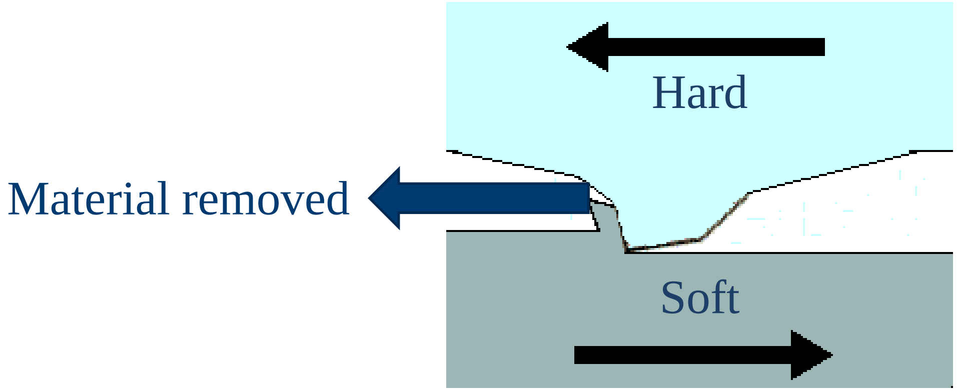
- Adhesive wear
- Abrasive wear
- Fatigue wear
- Tribochemical or corrosive wear
- Fretting wear

Process of material removal when a hard surface slides (or abrades) against a relatively soft surface



Abrasive wear contributes towards 50% of wear in most industrial applications, especially in mining and mineral processing industries[2].

[2] *Archard J. Friction between metal surfaces. Wear. 1986;113:3-16*

Industrial scenario-Bucket wheel excavator that undergoes abrasin phenomenon

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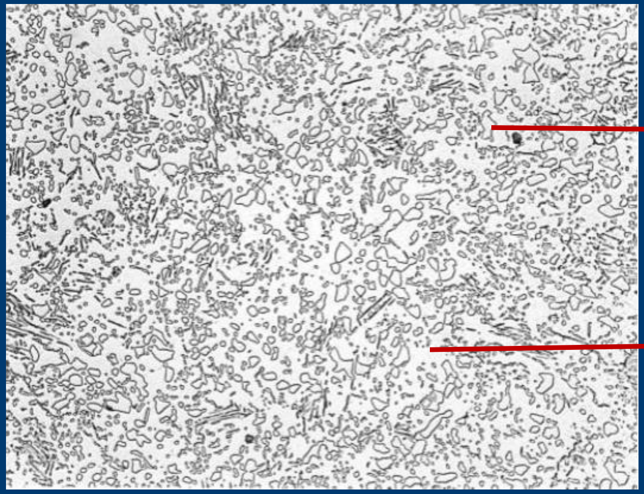
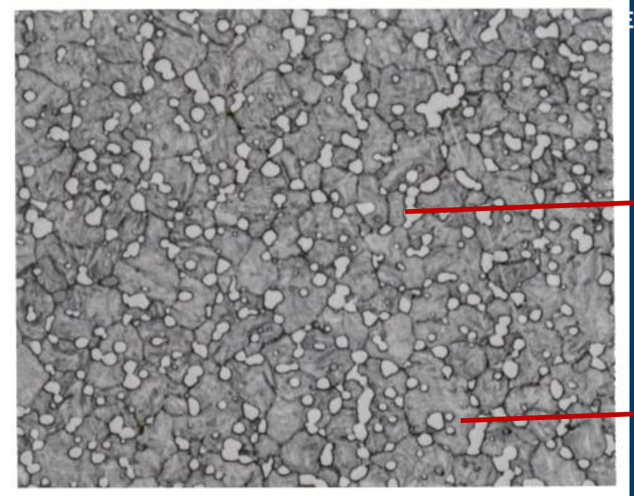
- US spends $500 billion dollars due to inadequate control of friction and wear ^
- 1/3 of world's energy resources are utilized in overcoming friction and wear

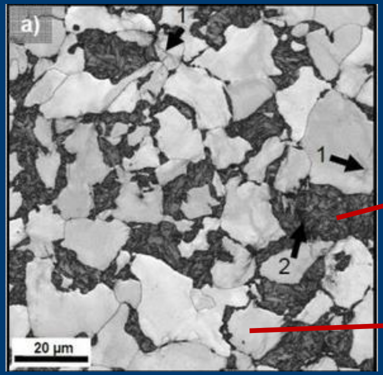
Background: Commonly used microstructures to resist abrasion



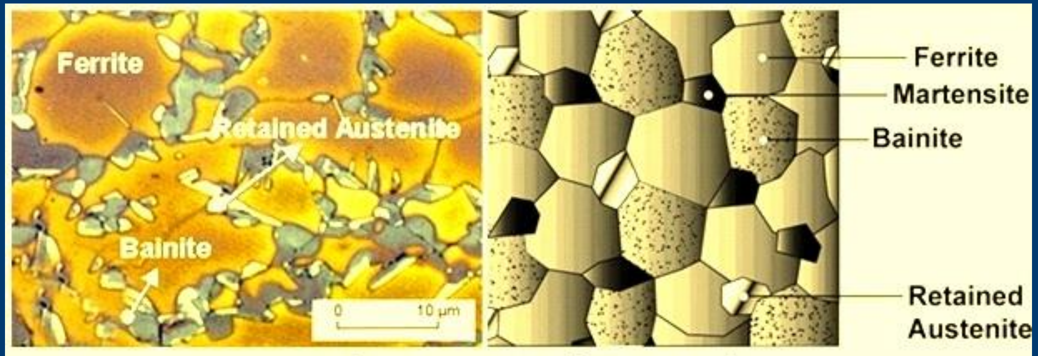
Quenched and spheroidised steels



Quenched and tempered steels



Dual phase steels



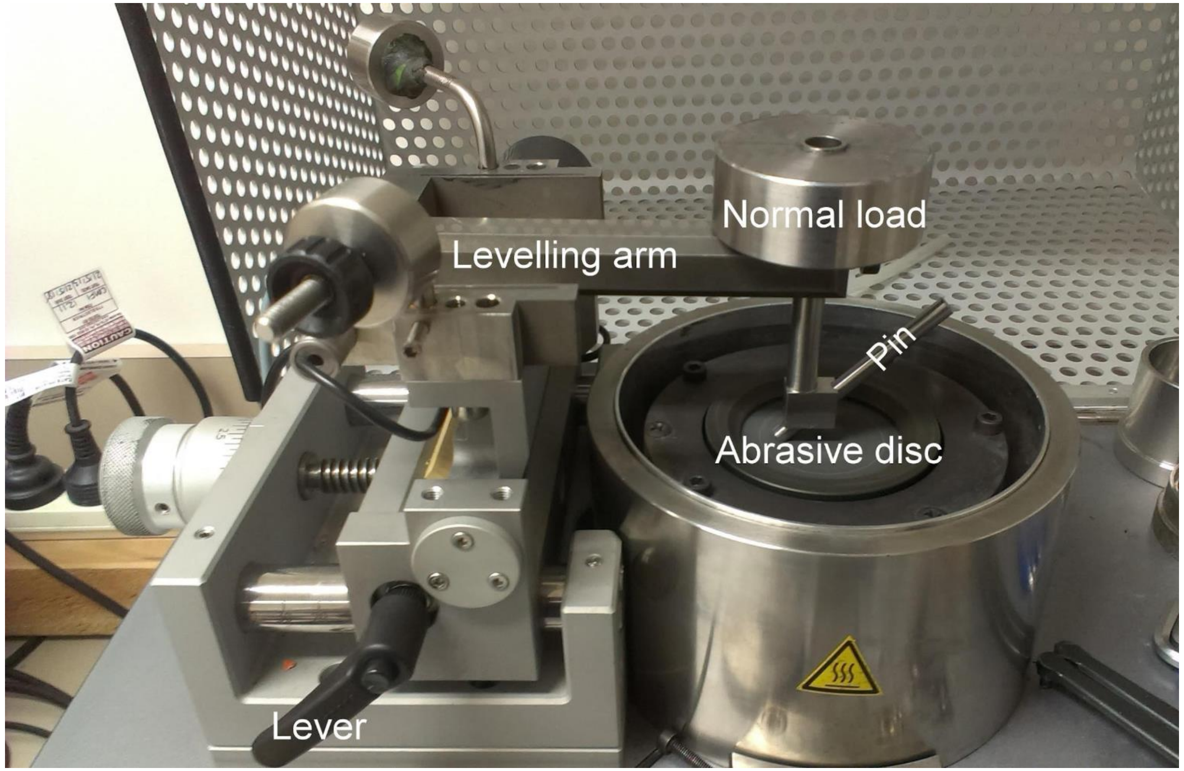
Microstructure of TRIP steel

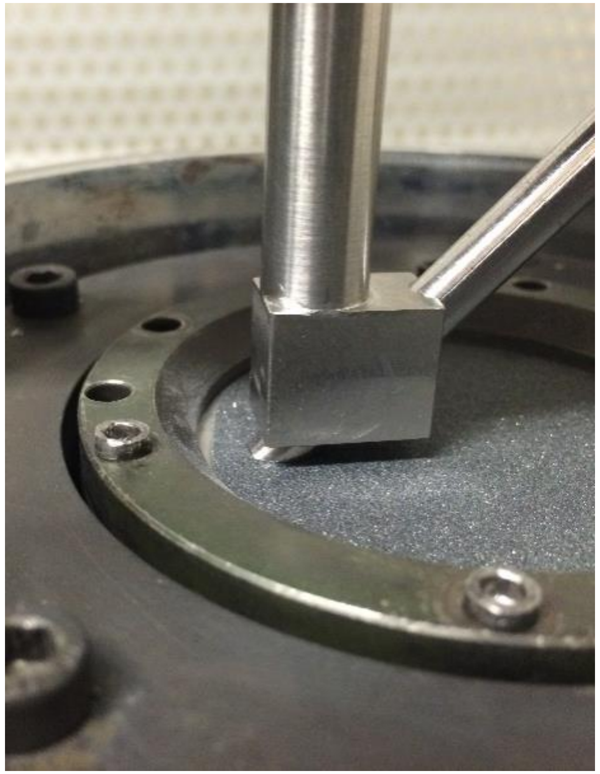
In multi-phase microstructures, the role of individual phases in abrasion is quite complex.

Objectives

A. To evaluate the effect of ferrous microstructures with similar bulk hardness on abrasive wear.
B. To understand the impact of microstructures with similar constituents (e.g., carbides or retained austenite) on abrasive wear
C. To conduct an in-depth investigation on the two-body abrasive wear behaviour of ferrous microstructures (similar hardness) using controlled environment.

Laboratory experimental set-up: High temperature pin on disc tribometer



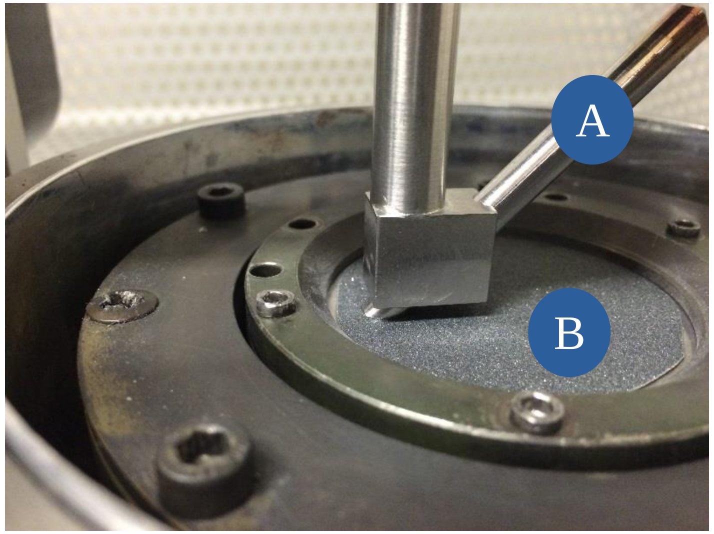


Variables affecting abrasive wear

Material-metallurgical factors, e.g., microstructure and hardness (A)

Abrasive particles- morphology, hardness and fracture toughness (B)

Environment (C)



Influence of microstructure with similar hardness on abrasive wear

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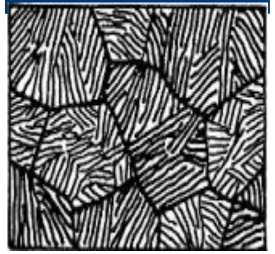
Chemical composition of different steels

Alloys	C	Si	Mn	Cr	Mo	Ni	Al	Co
Steel A	0.261	1.61	3.51	1.05	0.275	1.69	0.78	0.49
Steel B	0.046	0.26	1.84	0.0078	0.251	0.0087	0.0702	0.0066
Steel C	0.844	0.27	0.67	0.02	0.006	0.04	0.002	0.004

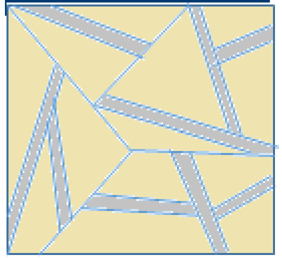
Alloys	Heat treatment	Final microstructure
Steel A	Austenization:1000°C-30 min + austempering: 300°C-5h	Bainite
Steel A	Austenization:1000°C-30 min + rapid water quenching + tempering: 500°C-3h	Tempered martensite
Steel B	Austenization:900°C-5 min + rapid water quenching	Martensite
Steel C	As received	Pearlite

Similar hardness (350-360 $HV_{0.01N}$)

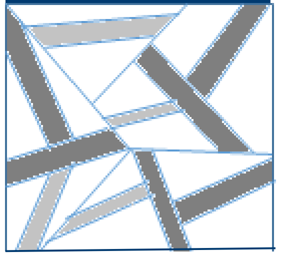
Steel C-Pearlite



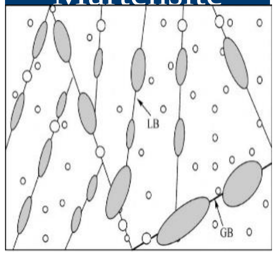
Steel A-Bainite



Steel B-Martensite



Steel A-Tempered Martensite



Microstructural behaviour towards abrasion:

- Specific wear rate and frictional study.
- Topographic analysis
- Wear track analysis
- Sub-surface characteristics
- Work-hardening

Microstructures with similar hardness level (350-$360\ HV_{20kgf}$)

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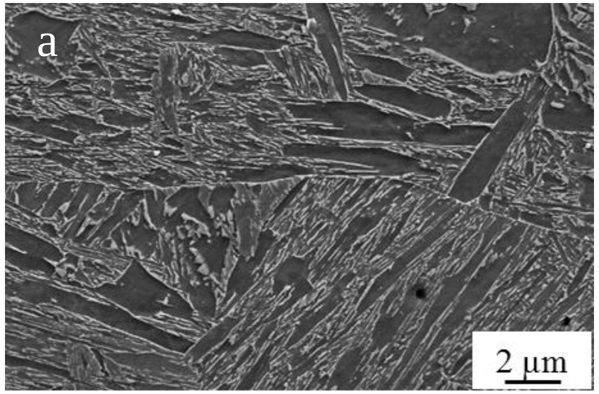
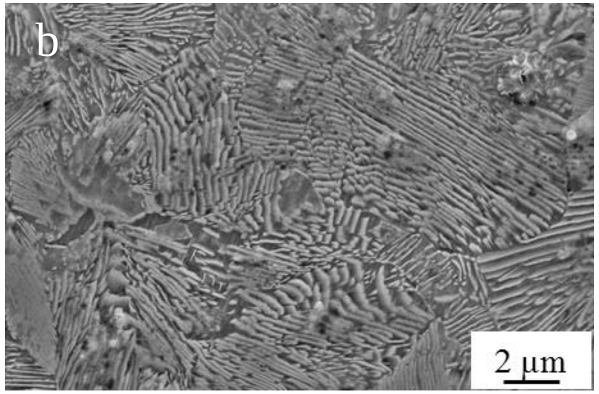
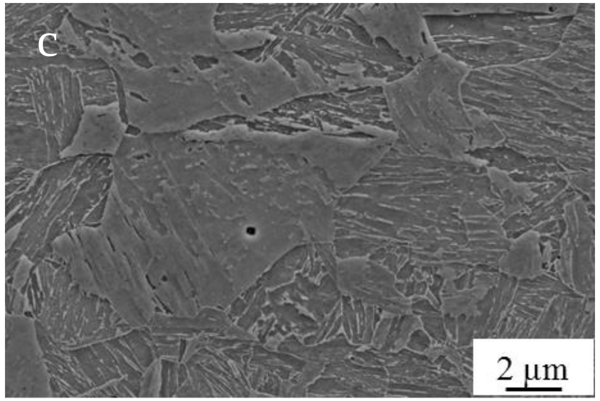


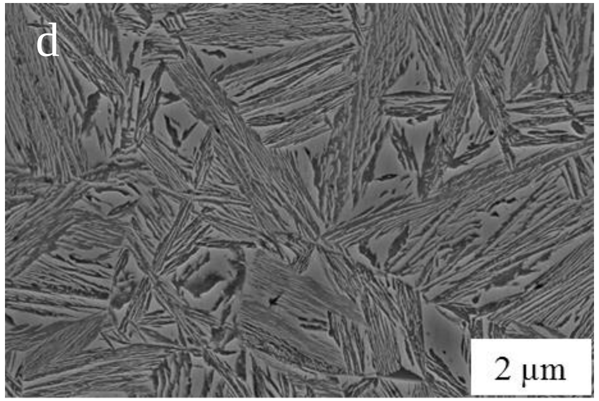
Bainite: $HV_{0.01N}$=358±2



Pearlite: $HV_{0.01N}$=326±2

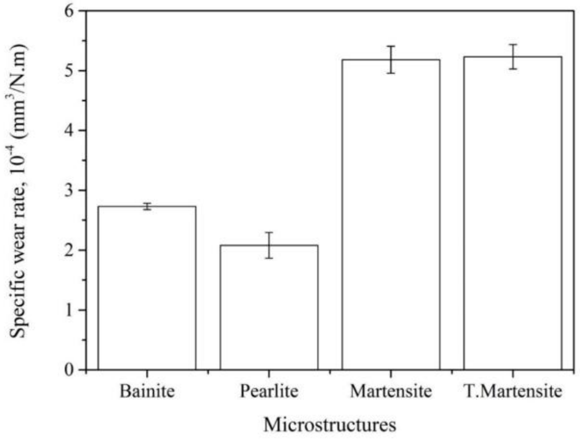


Martensite: $HV_{0.01N}$=355±3

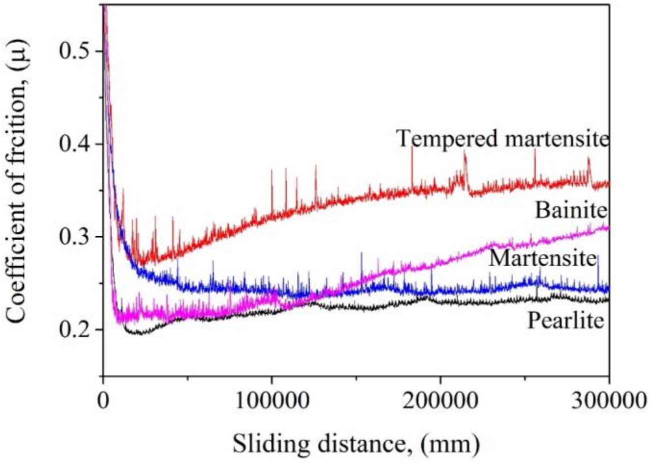


Tempered martensite: $HV_{0.01N}$=357±3

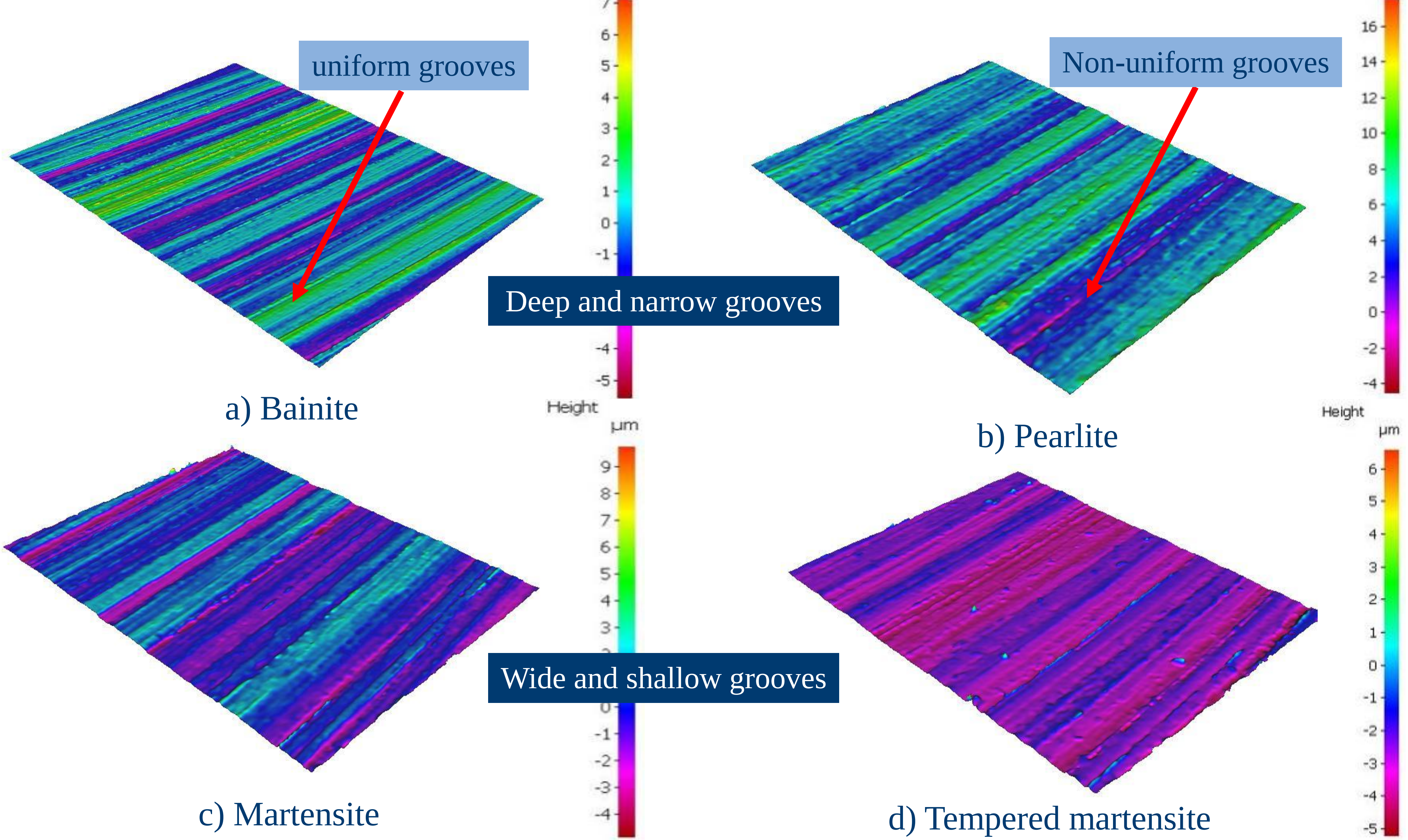
Specific wear rate of microstructures



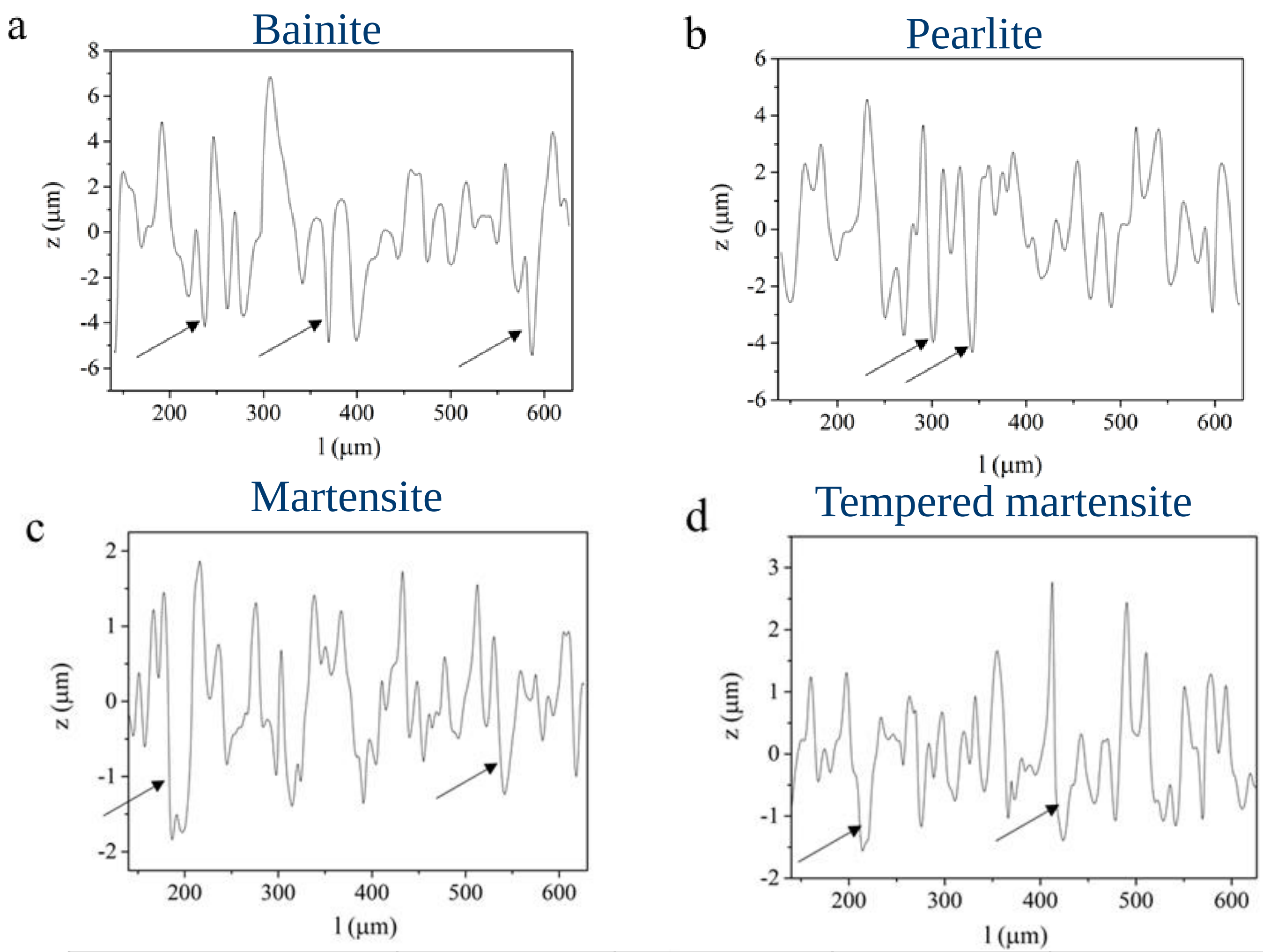
Frictional curve of microstructures



Topographic analysis of abraded surfaces



Surface profile analysis of abraded surfaces



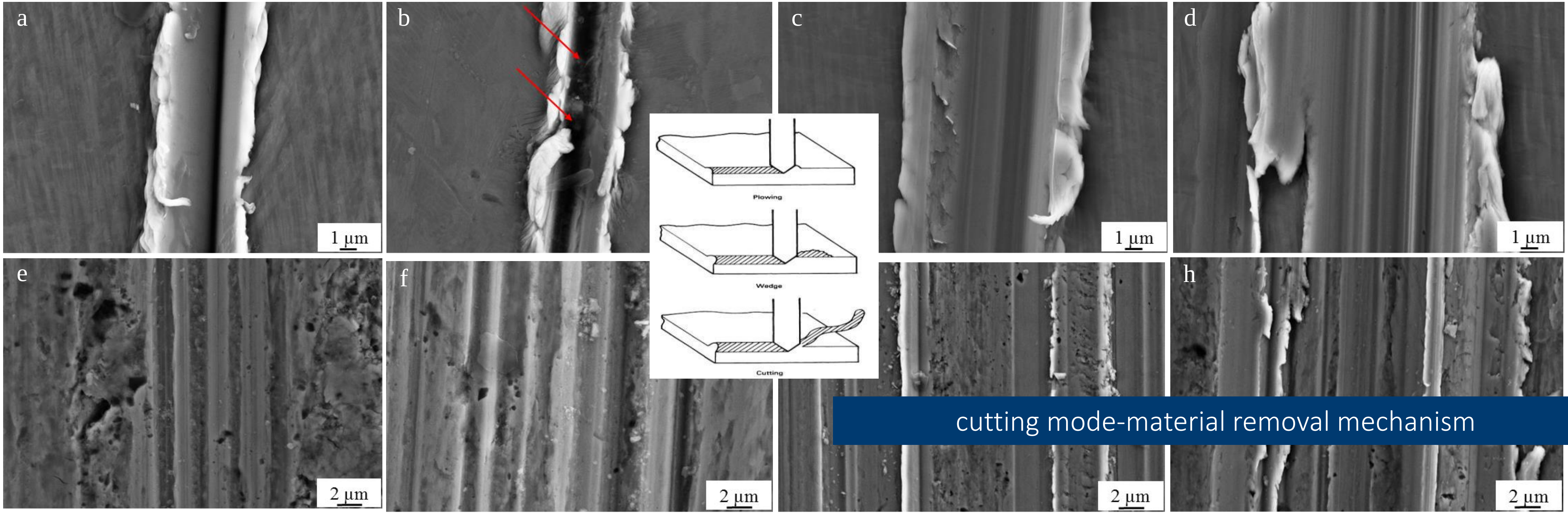
Deep and narrow grooves

Wide grooves – high material loss

Microstructure	R_a (nm)	R_q (nm)	R_z (μm)	R_t (μm)
Bainite	565	722	2.88	4.42
Pearlite	424	519	2.07	3.16
Martensite	529	659	2.46	3.25
Tempered martensite	693	968	4.12	6.62

Single and multi-wear track characteristics of microstructures

Bainite | Pearlite | Martensite | Tempered Martensite

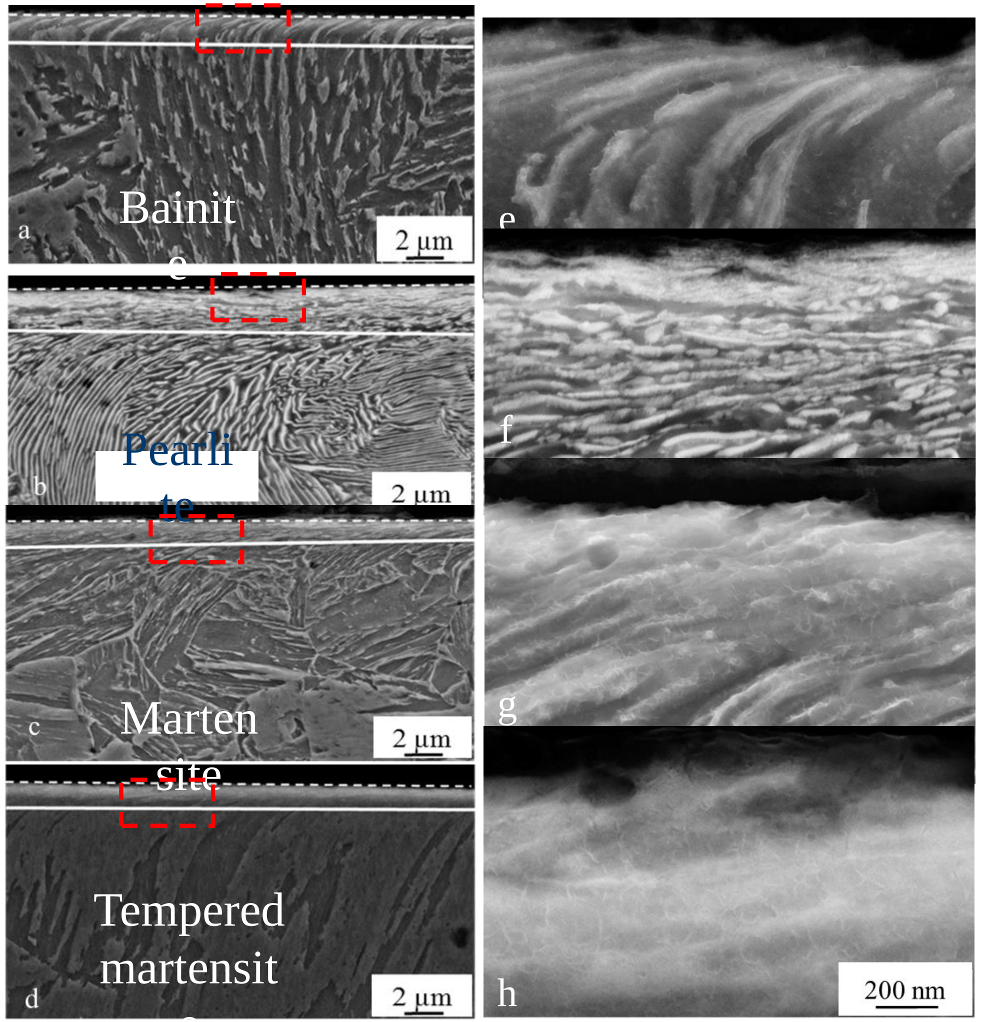


cutting mode-material removal mechanism

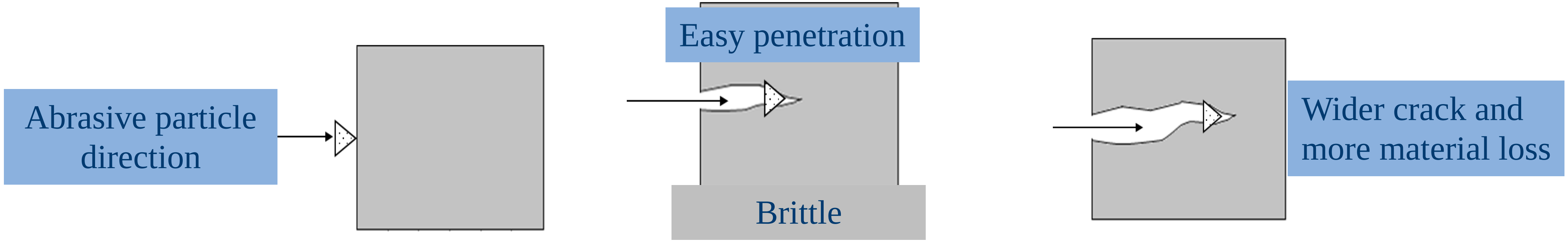
ploughing and wedge formation-material removal mechanism

Sub-surface characteristics of microstructures

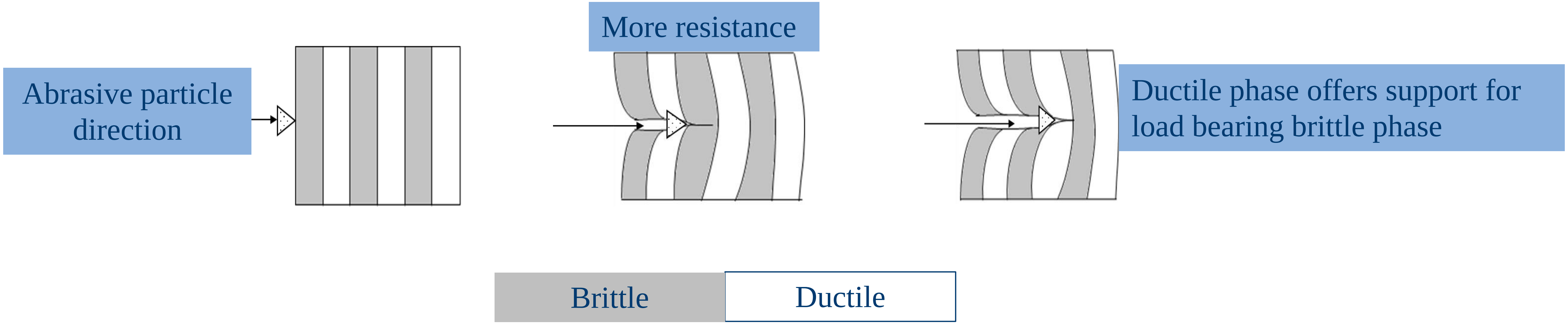
Differential abrasive response of microstructures:
a) realignment of microstructural constituents and
b) formation of white layer



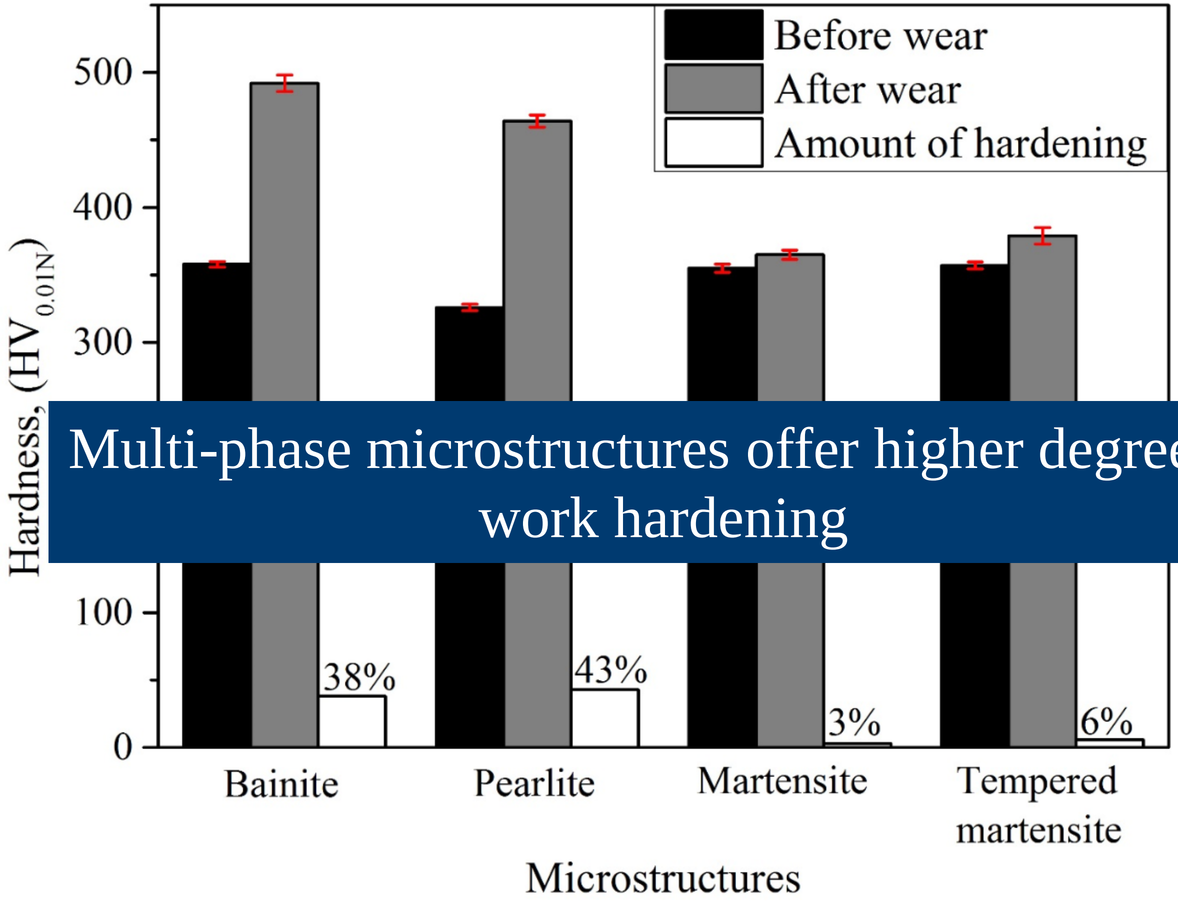
Single-phase (brittle or ductile) microstructures



Multi-phase (brittle and ductile) microstructures



Effect of work hardening on the abraded microstructures



Multi-phase microstructures offer higher degree of work hardening

Summary - A

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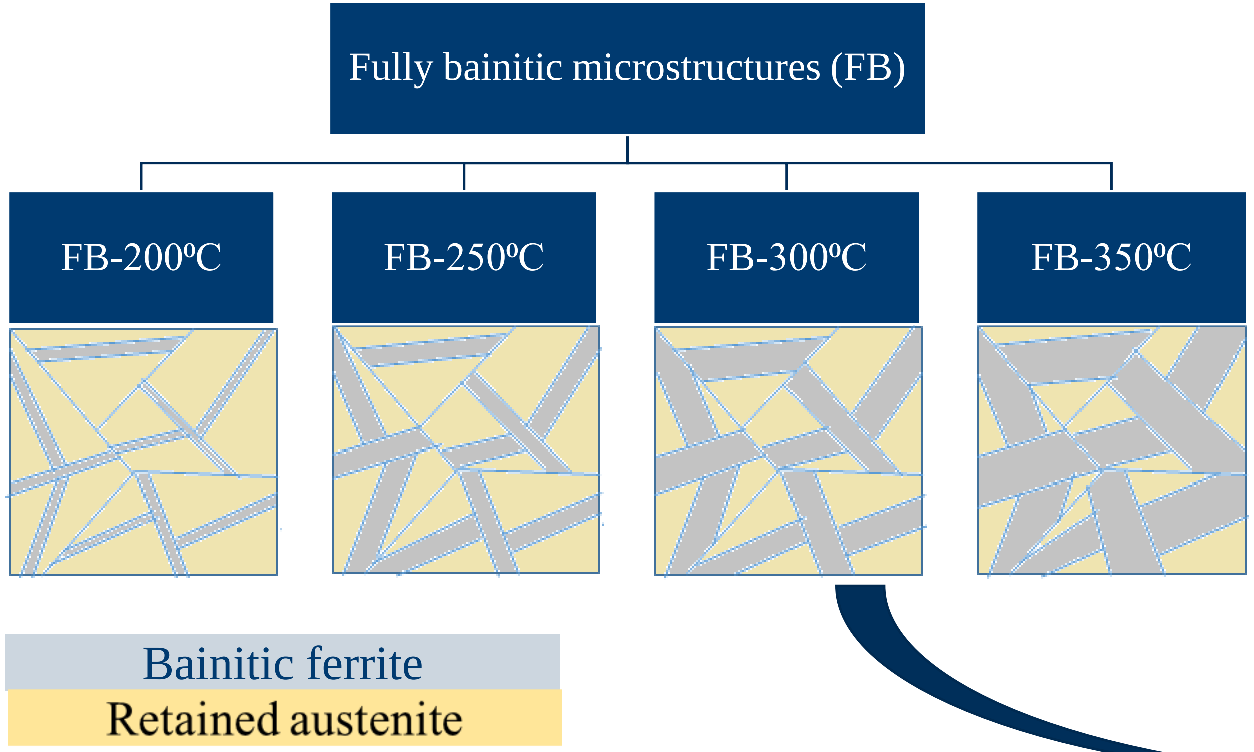
- **Multi-phase microstructures** (i.e., bainite and pearlite) exhibited **superior abrasion resistance** than single-phase microstructures (i.e., martensite and tempered martensite).
- The sub-surface analyses were crucial in determining their abrasive response, **i.e., realignment of microstructural constituents** (pearlite and bainite) and/or **formation of white layer** (martensite and tempered martensite).
- The **distinct material removal processes** of the microstructures were attributed towards their microstructure matrix. **Multi-phase microstructures** - **ploughing and wedge formation** mechanisms - narrow and deep wear tracks. **Single-phase microstructures**, the **cutting mode** - wide and shallow wear tracks.

To understand the impact of microstructures with similar constituents (i.e., bainitic ferrite and retained austenite) on abrasive wear

Alloys	C	Si	Mn	Cr	Mo	Al	Co
Steel X	0.79	1.5	1.98	0.98	0.24	1.06	1.58

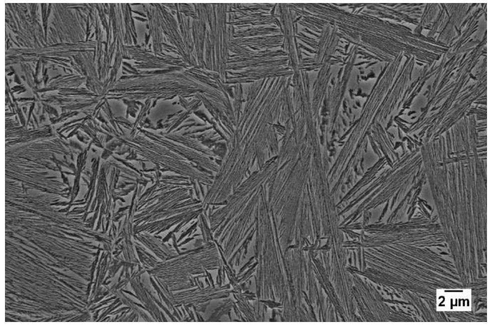


Alloys	Heat treatment	Final microstructure
Steel X	Austenization: 900°C-30 min + austempering: 350°C-1 day	Fully bainite 350°C
Steel X	Austenization: 900°C-30 min + austempering: 300°C-2 days	Fully bainite 300°C
Steel X	Austenization: 900°C-30 min + austempering: 250°C-5 days	Fully bainite 250°C
Steel X	Austenization: 900°C-30 min + austempering: 200°C-10 days	Fully bainite 200°C

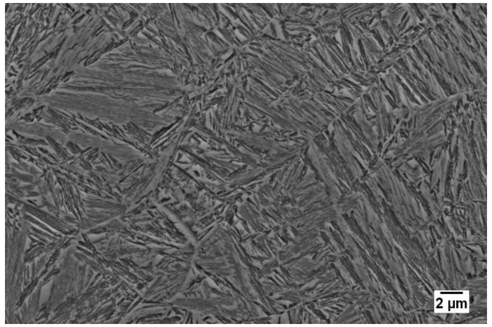
Microstructural behaviour towards abrasion:

- Specific wear rate and frictional study.
- Topographic analysis
- Wear track analysis
- Sub-surface characteristics
- Work-hardening

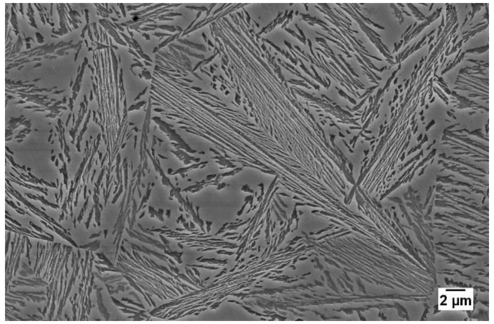
Characterization of the fully bainitic microstructures



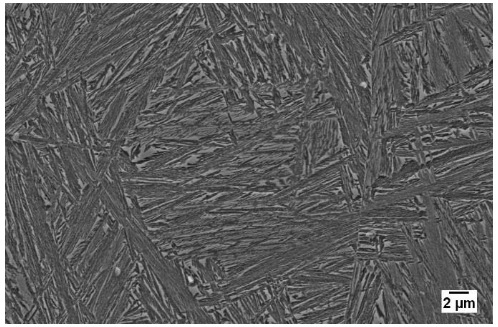
FB-350ºC - 413±5 $HV_{0.01N}$



FB-250ºC - 584±4 $HV_{0.01N}$



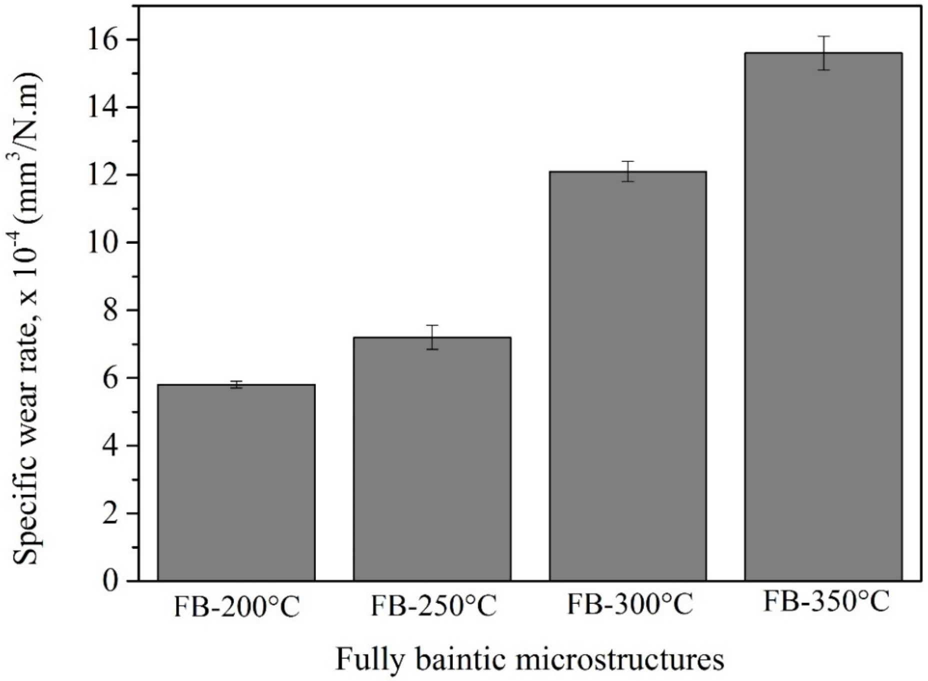
FB-300ºC - 500±5 $HV_{0.01N}$



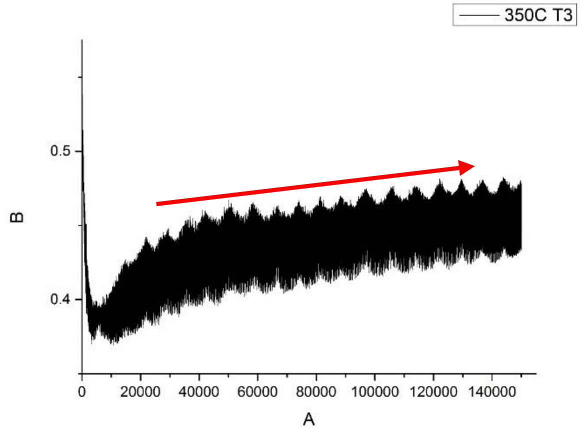
FB-200ºC - 632±5 $HV_{0.01N}$

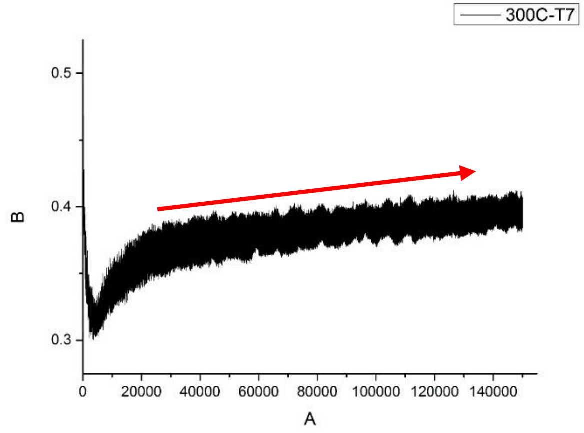
Microstructures	Bainitic ferrite thickness (nm)	Bainitic ferrite dislocation density (m^{-2})	Vol. fraction of retained austenite (%)	Retained austenite thickness (nm)	Morphology of retained austenite
FB-350ºC	300±100	$2x10^{15}$	54	70±30	Films and block
FB-300ºC	118±40	$2.9x10^{15}$	51	60±20	Films and block
FB-250ºC	80±20	$3.65x10^{15}$	17	30±10	Mostly films
FB-200ºC	60±10	$4.7x10^{15}$	16	30±5	Mostly films

Specific wear rate of microstructures

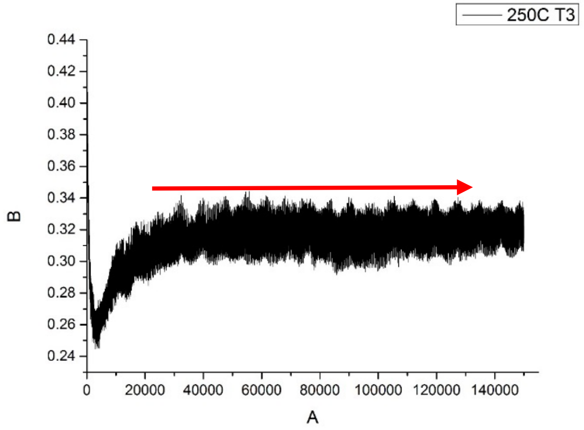


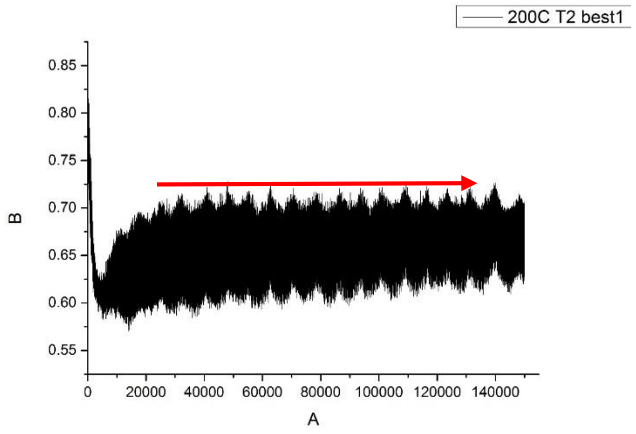
Frictional curve of microstructures





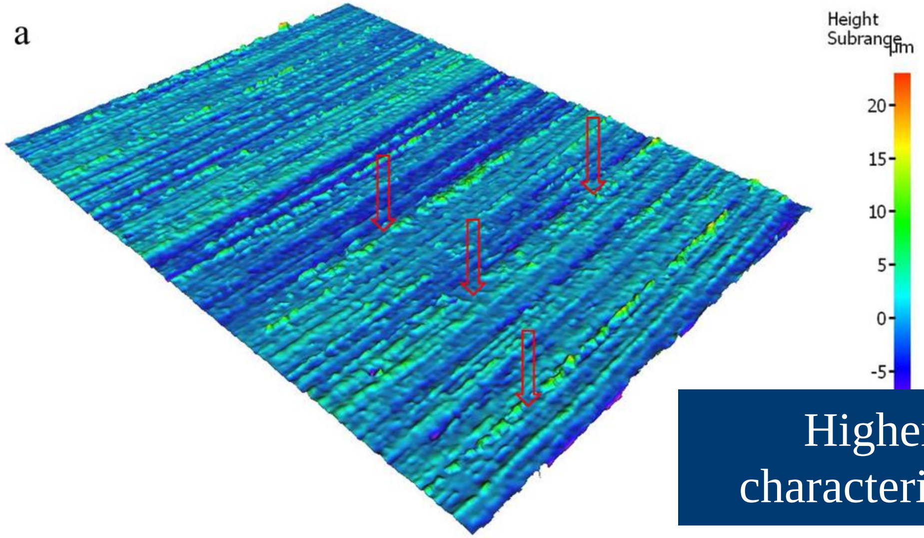
Continual increase in ‘μ’ due to the material loss



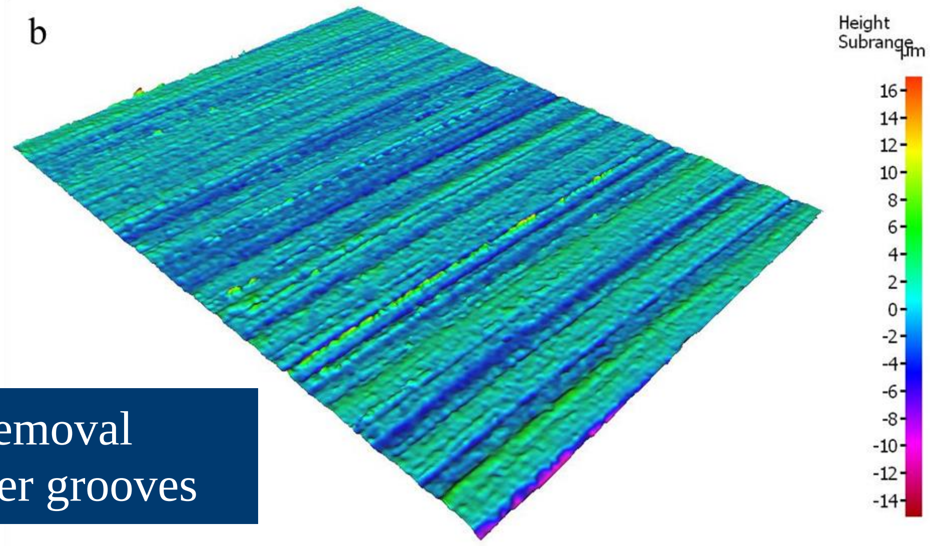


Relatively stable ‘μ’

Topographic analysis on abraded surfaces

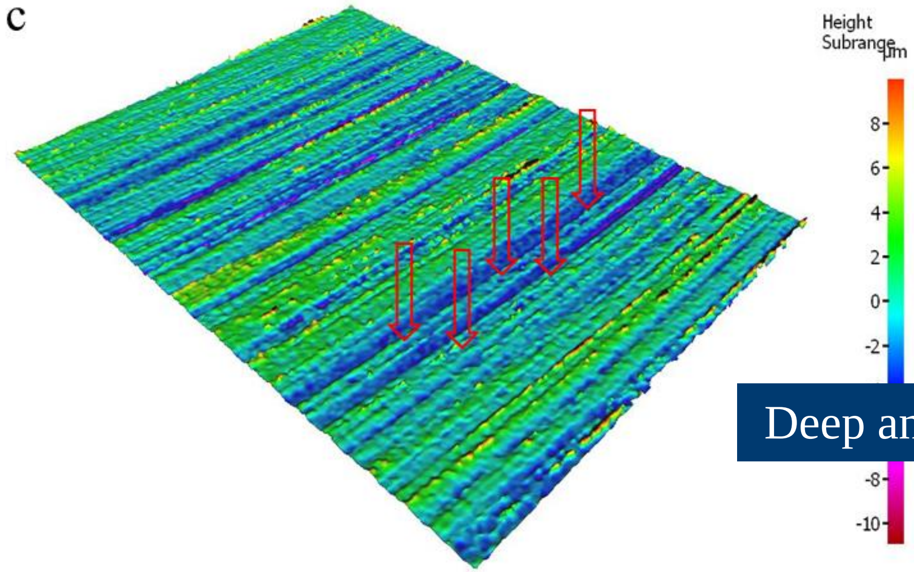


FB-350ºC - 413±5 $HV_{0.01N}$

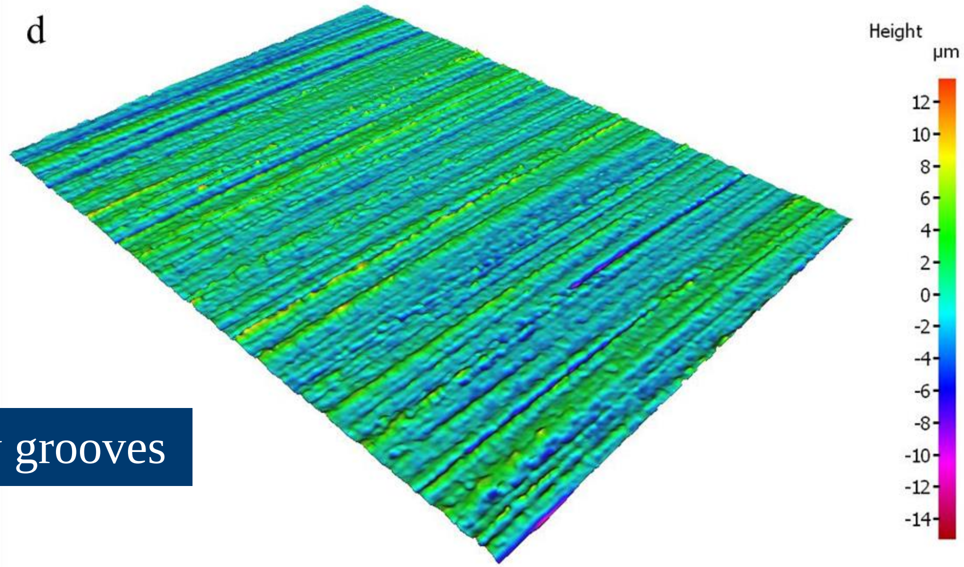


FB-300ºC - 500±5 $HV_{0.01N}$

Higher material removal characterized by wider grooves



FB-250ºC - 584±4 $HV_{0.01N}$

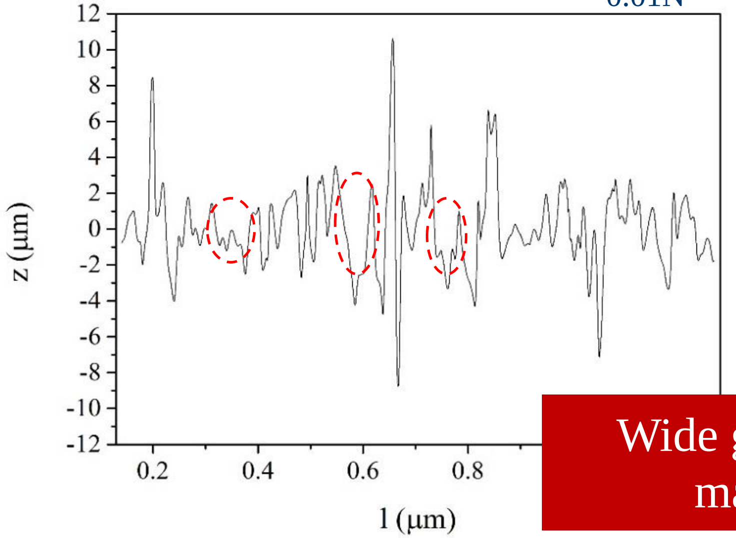


FB-200ºC - 632±5 $HV_{0.01N}$

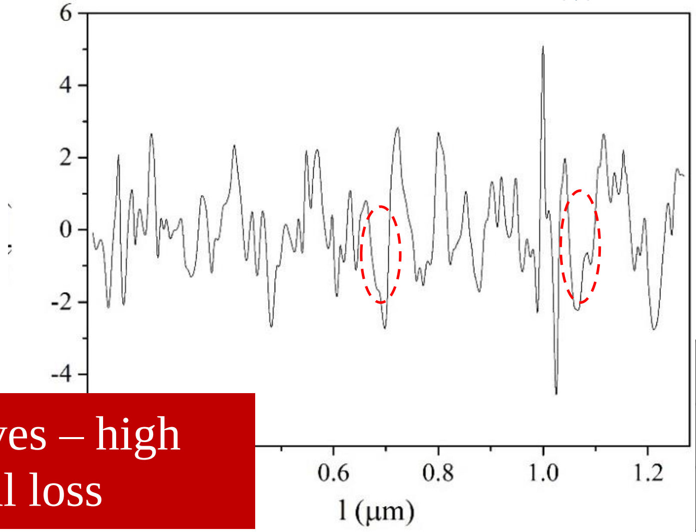
Deep and narrow grooves

Surface profile analysis of abraded surfaces

FB-350ºC - 413±5 $HV_{0.01N}$

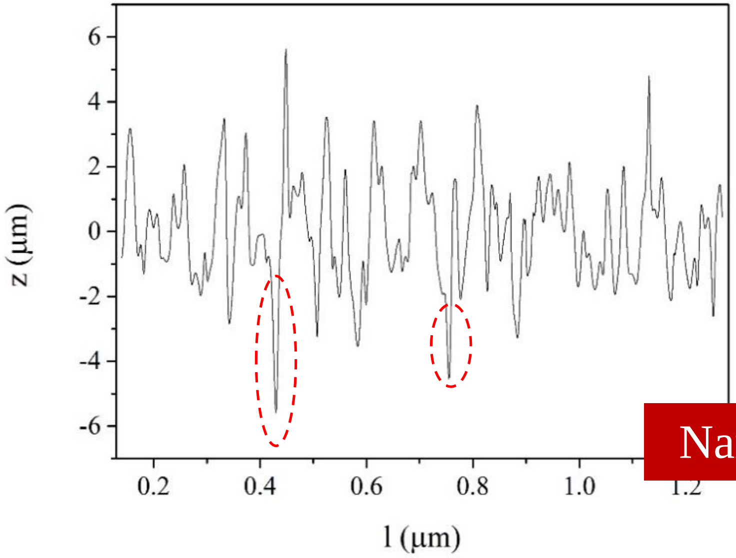


FB-300ºC - 500±5 $HV_{0.01N}$

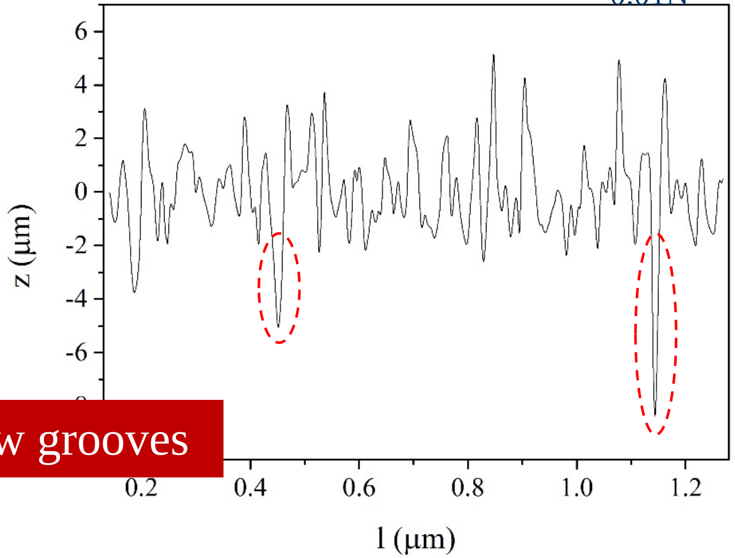


Wide grooves – high material loss

FB-250ºC - 584±4 $HV_{0.01N}$



FB-200ºC - 632±5 $HV_{0.01N}$

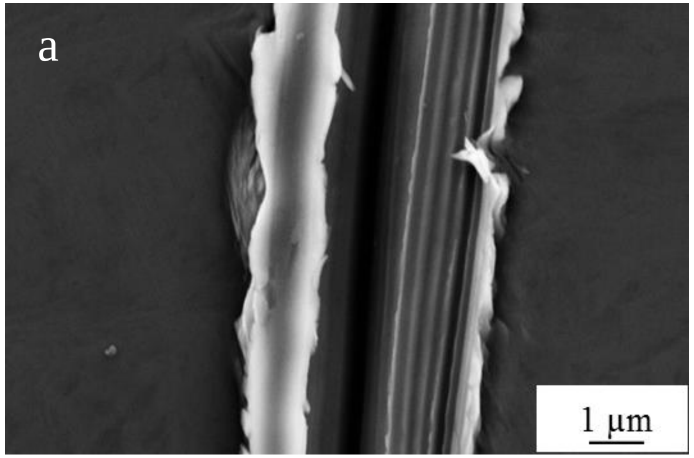


Narrow grooves

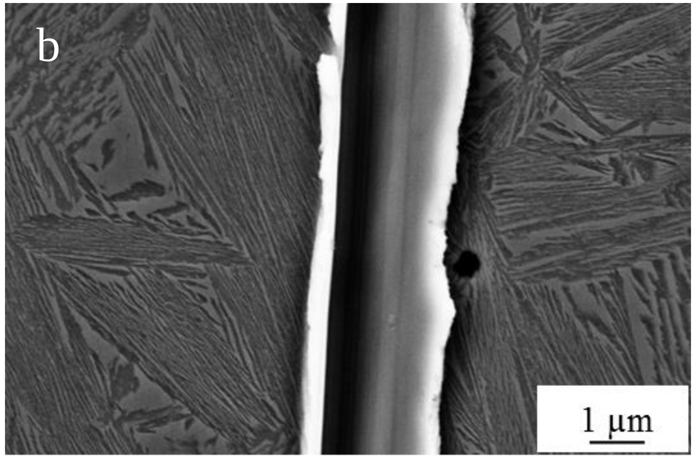
Microstructure	R_a (µm)	R_q (µm)	R_z (µm)	R_t (µm)
FB-350ºC	1.16	1.5	6.5	10.16
FB-300ºC	1	1.28	6.1	9.65
FB-250ºC	1.29	1.6	7.8	11.22
FB-200ºC	1.42	1.95	9	15.48

Single wear track characteristics

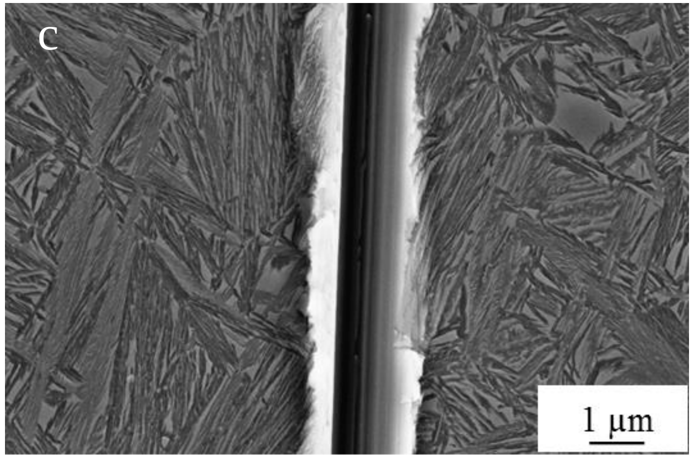
FB-350ºC - 413±5 $HV_{0.01N}$



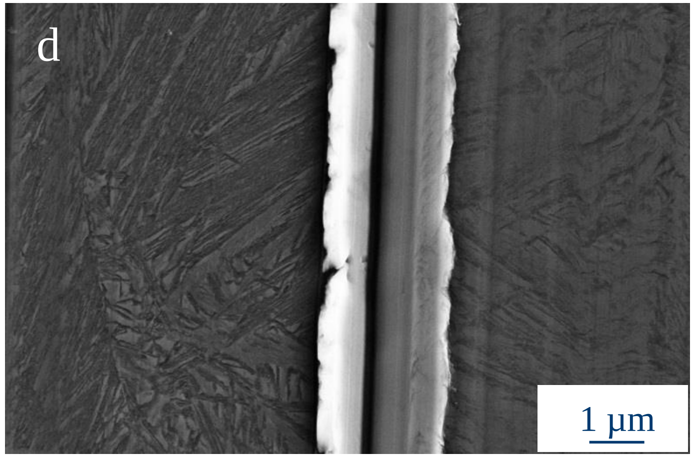
FB-300ºC - 500±5 $HV_{0.01N}$



FB-250ºC - 584±4 $HV_{0.01N}$



FB-200ºC - 632±5 $HV_{0.01N}$



ploughing and wedge formation-material removal mechanism

Schematic representation of single-wear track and material displacement for different fully bainitic conditions

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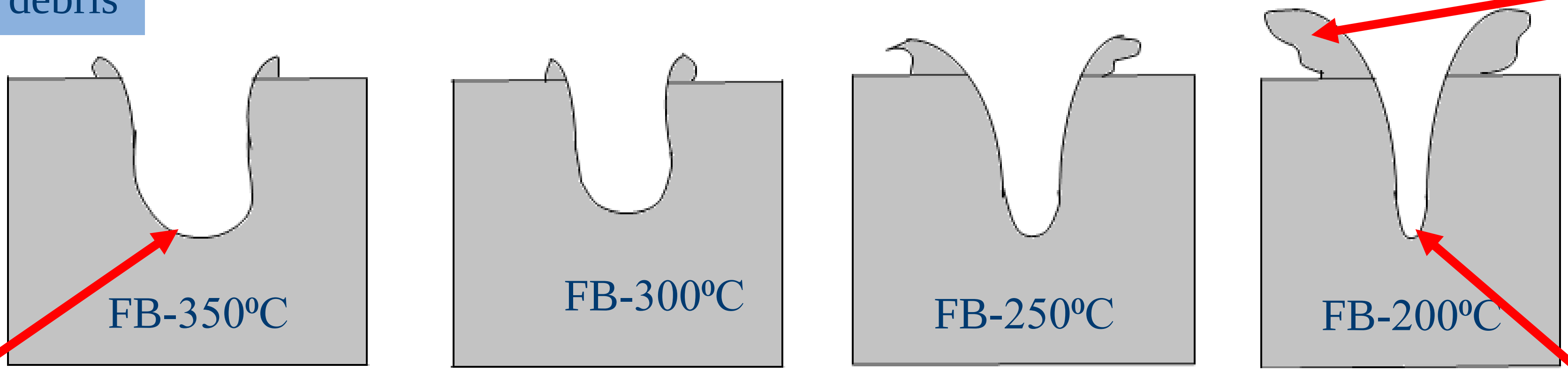
Most of the abraded material is lost as debris

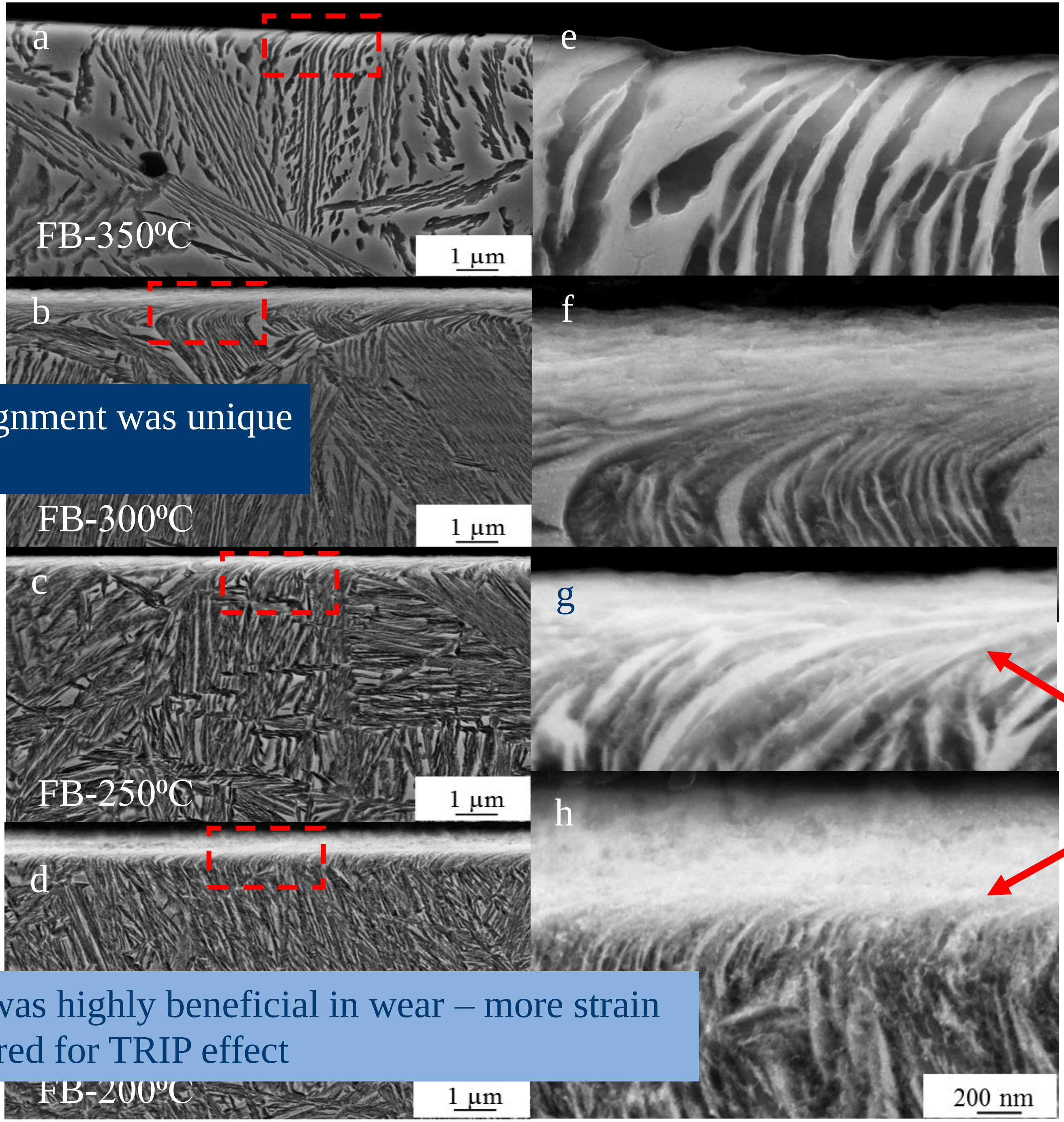
Abraded material is displaced to the sides.



At higher transformation temperatures, wear tracks are shallow and wide

At lower transformation temperatures, wear tracks are deep and narrow

Sub-surface characteristics of microstructures

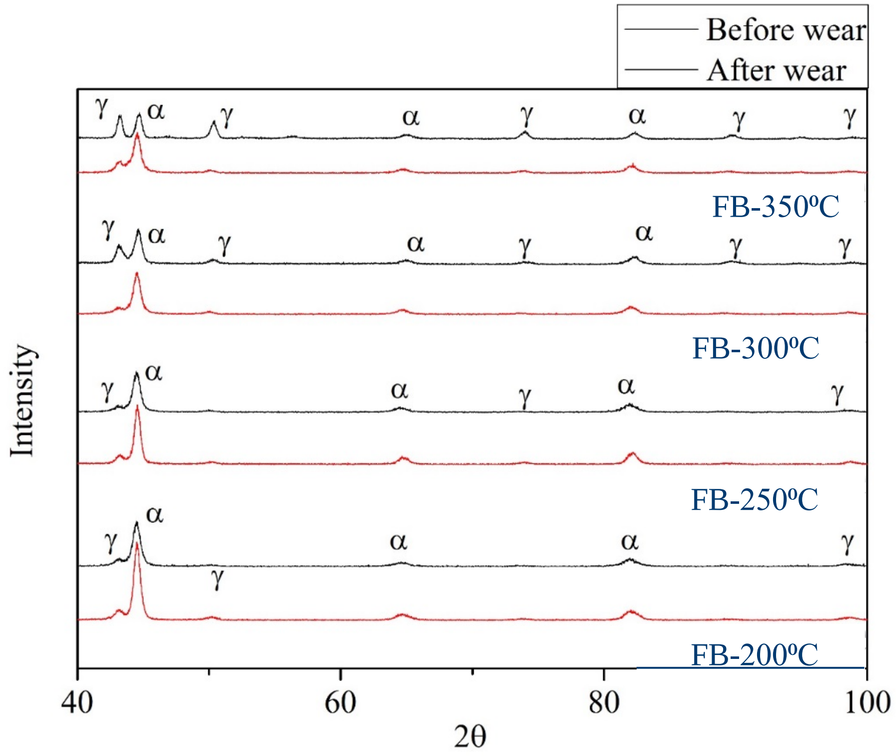


Extent of microstructural realignment was unique for different microstructures

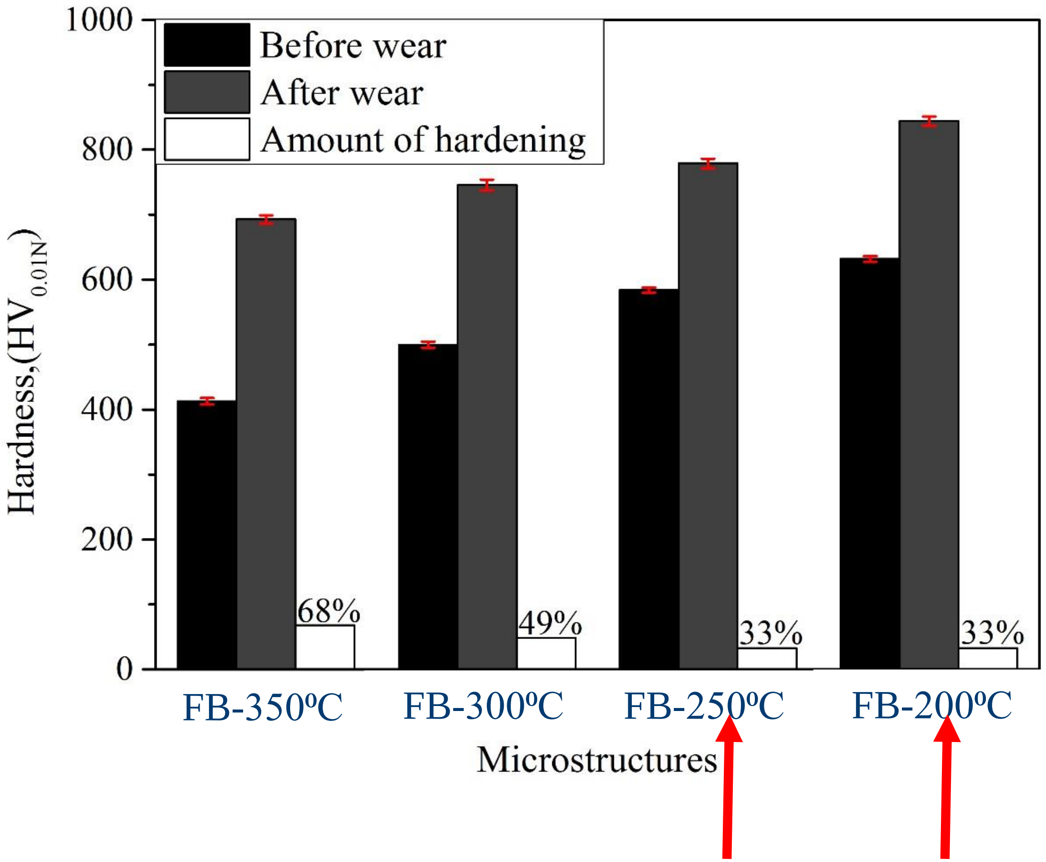
Highly deformed white layer

Stable film morphology RA was highly beneficial in wear – more strain required for TRIP effect

Effect of retained austenite (TRIP effect) during abrasive wear



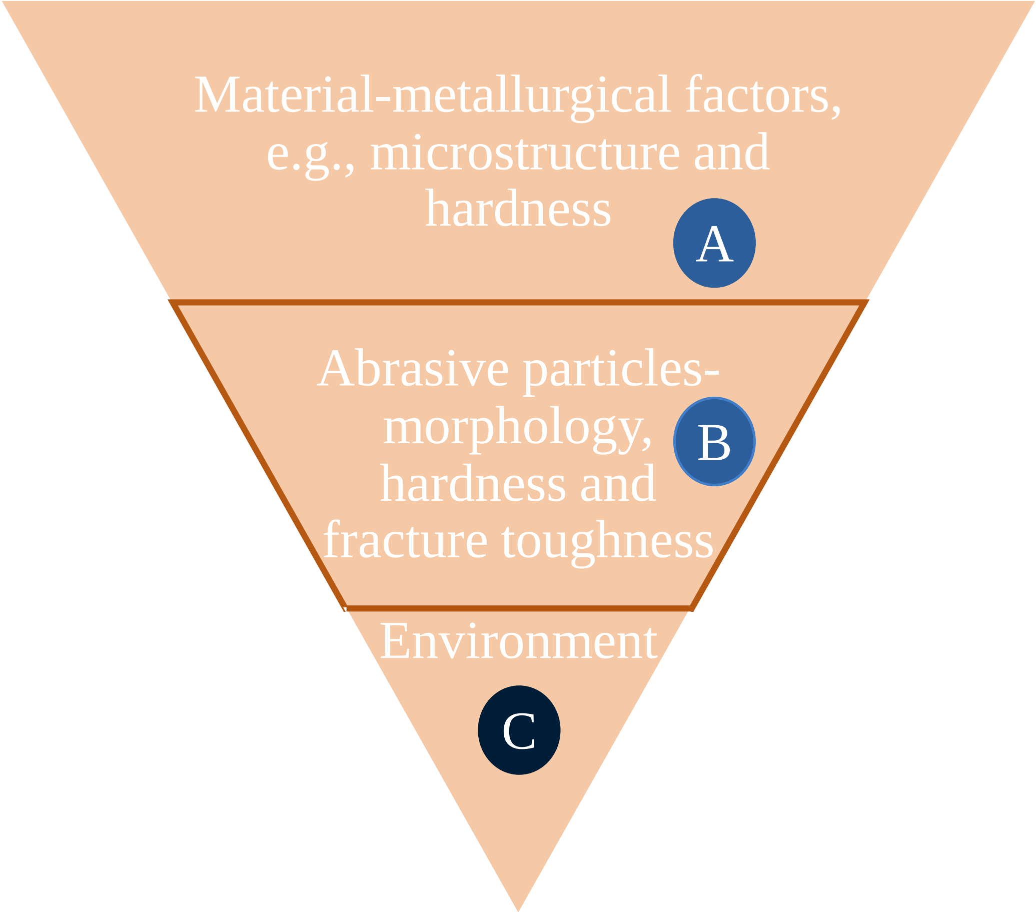
Microstructures	Before wear test	After wear test
FB-350ºC	54%	24%
FB-300ºC	51%	19%
FB-250ºC	17%	15%
FB-200ºC	16%	14%

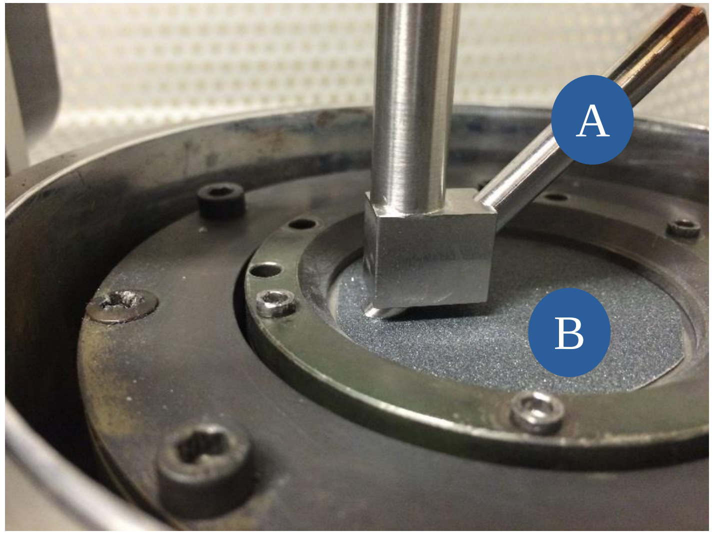


Summary-B

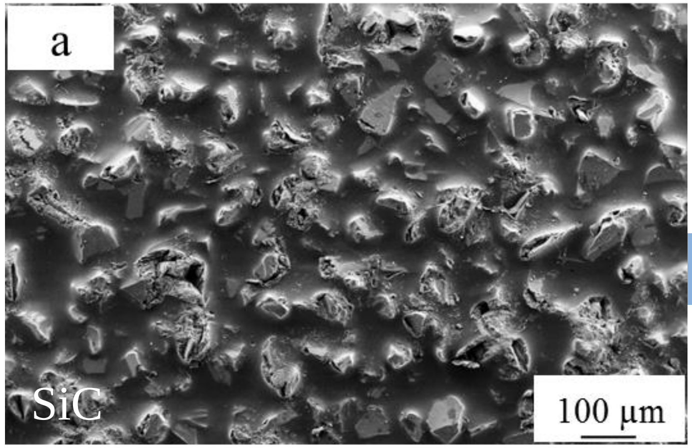
- The **characteristics of the microstructural constituents** (i.e., morphology, size, vol. fraction and dislocation density) determined the **abrasion behaviour** of the fully bainitic microstructures.
- Microstructures with finer microstructural constituents (i.e., <100 nm-FB-200^{o}C & FB-250^{o}C) had better abrasion resistance than the bainitic microstructures with relatively coarse microstructural constituents (i.e. >100 nm-FB-300^{o}C & FB-350^{o}C).
- The **groove characteristics** and the **surface profile** of the abraded microstructures determined the **amount and mechanism of material removal** in the microstructures .
- The **morphology of retained austenite** was crucial in sliding abrasion, as it determined the beneficial aspects of TRIP effect.

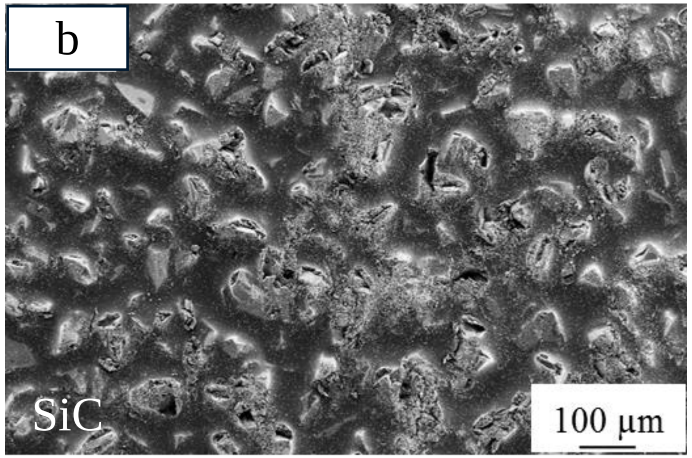
Variables affecting abrasive wear

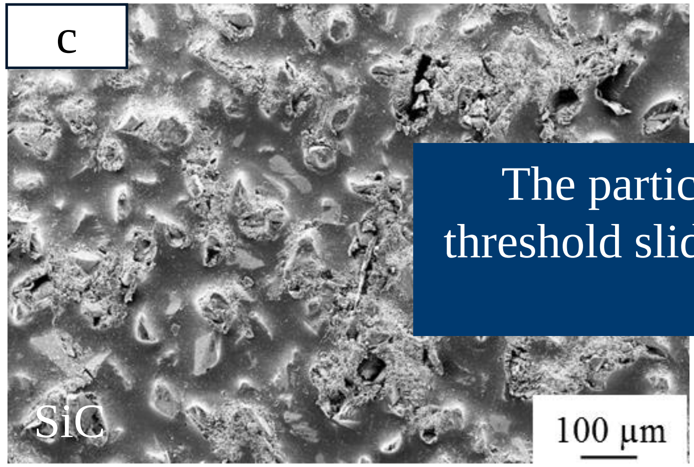


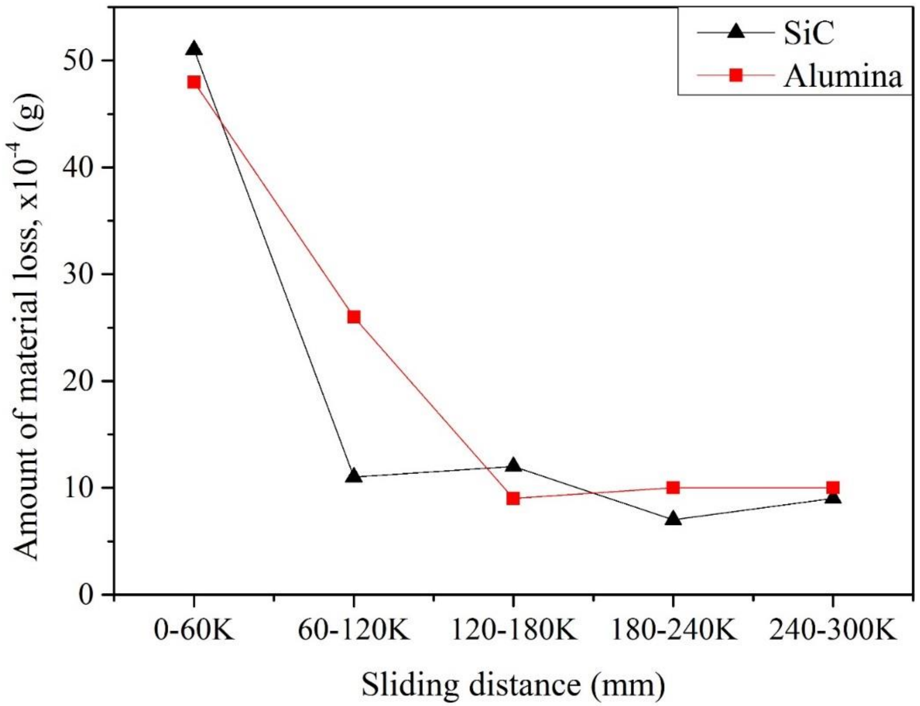


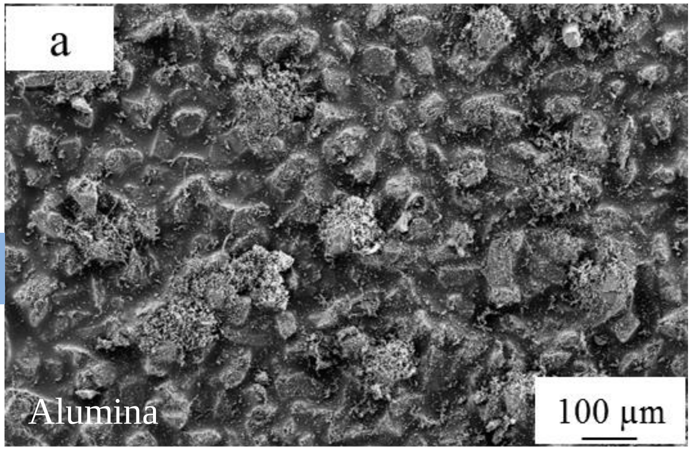
Interrupted abrasive tests- efficiency of abrasive particles

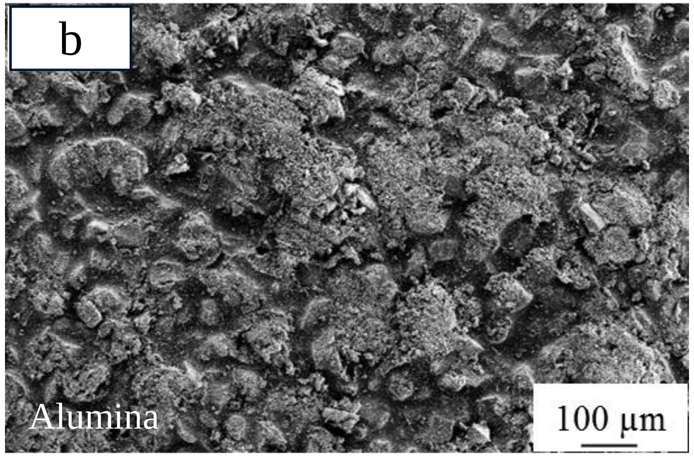


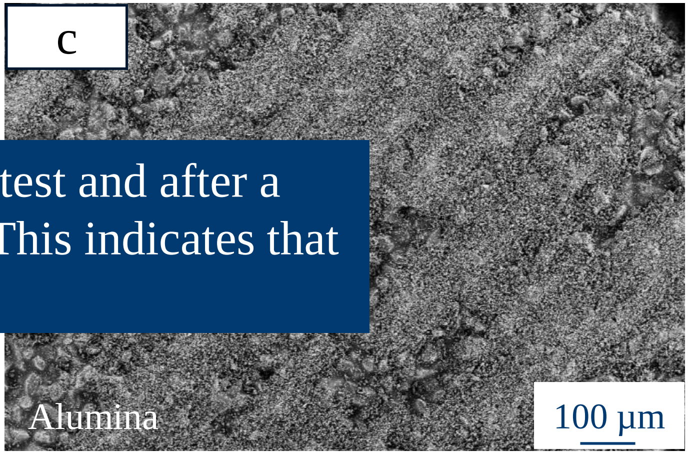








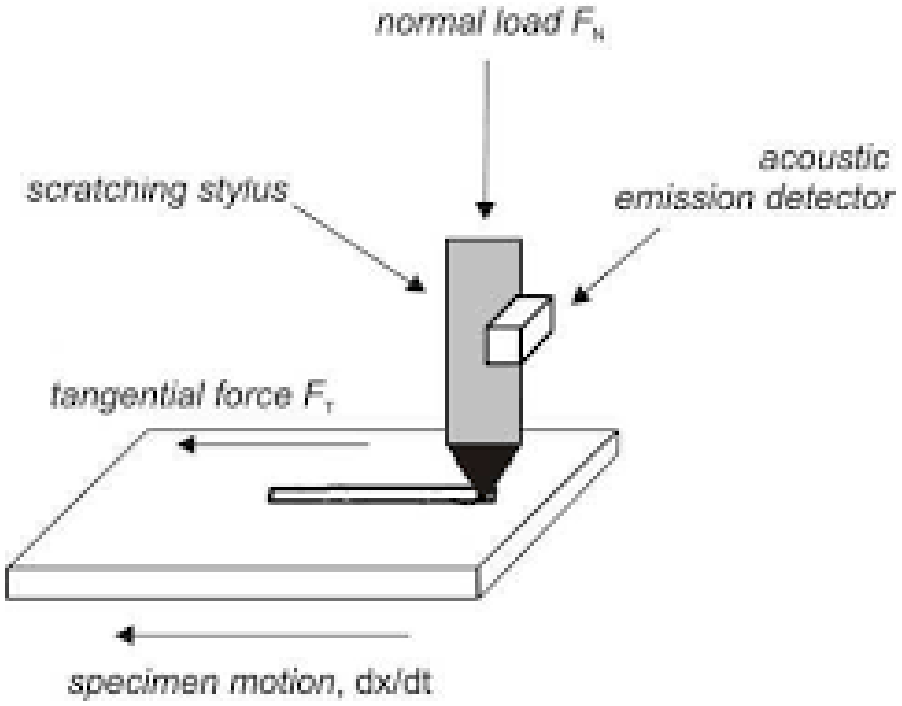


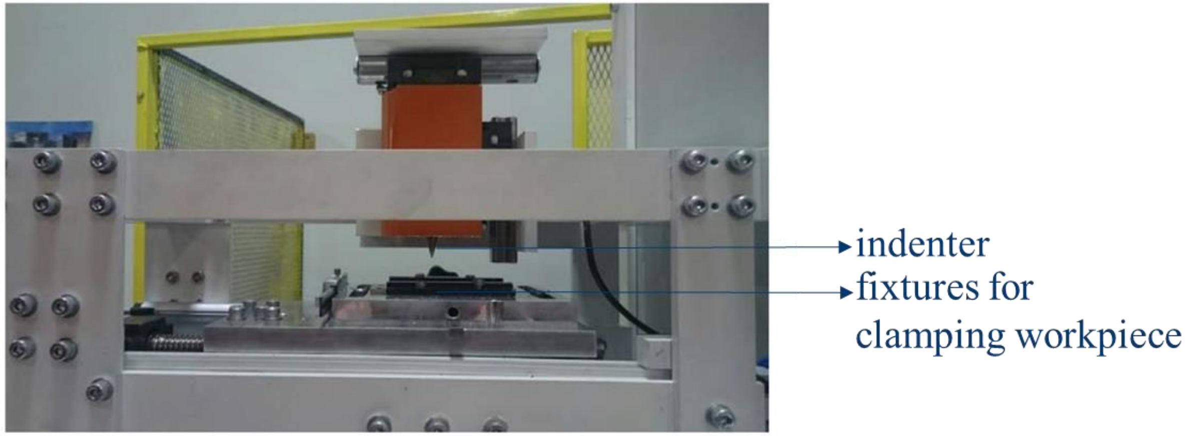


The particle efficiency is pronounced during the initial period of test and after a threshold sliding distance, there is a reduction in material removal. This indicates that the abrasive environment is **dynamic**.

To conduct an in-depth investigation on the two-body abrasive wear behaviour of ferrous microstructures (similar hardness) using <u>controlled abrasive environment</u>.

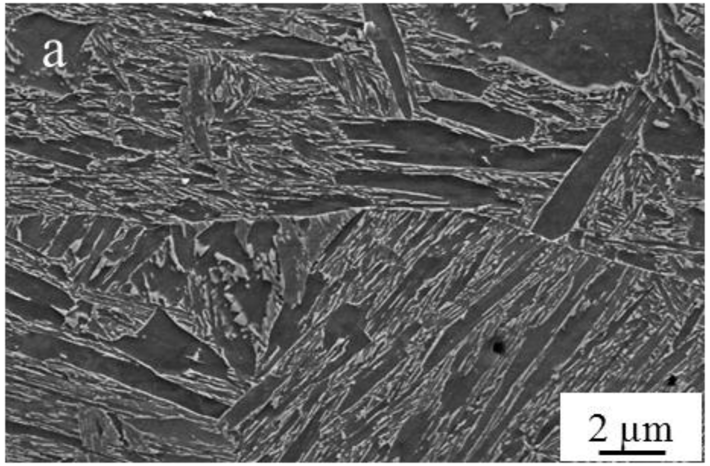
- The two-body abrasive wear behaviour of four distinct microstructures (used in previous study) was carried out using a **<u>high-stress scratch test method</u>**.
- The scratch test employs a robust indenter (hard metal) which abrades the microstructure surface, thereby offering more control over the abrasive environment characteristics.



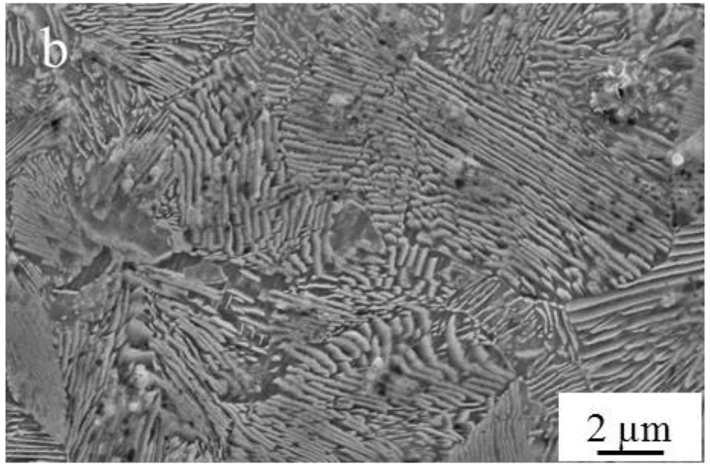


Test parameters	Units	Values
Normal load	N	200, 500, 1000, 1500 & 2000
Sliding speed	mm/s	1
Sliding distance	mm	30
Indenter tip size	µm	~820

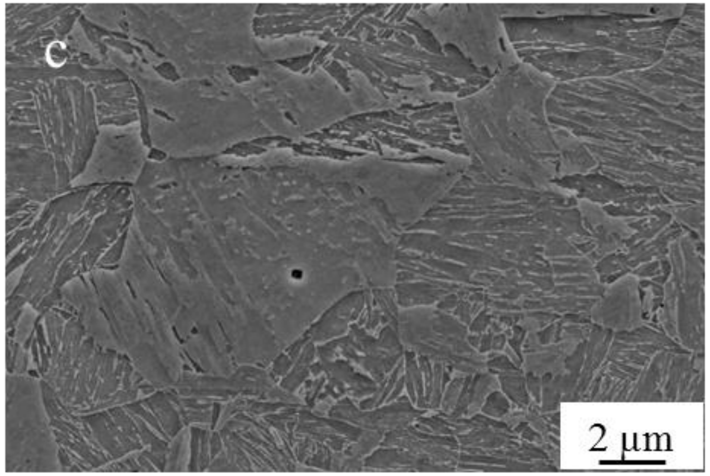
Microstructures with similar hardness level (330-30 HV0.01N):a) Steel B – martensite, b) Steel A – tempered martensite c) Steel A – bainite and d) Steel C – pearlite.



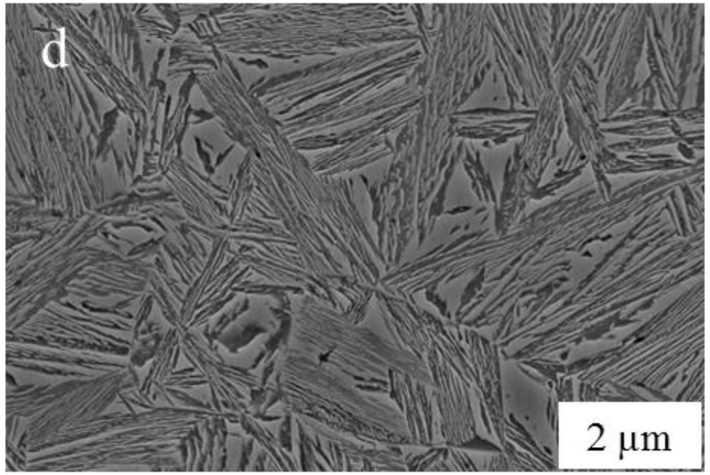
Bainite: $HV_{0.01N}$=358±2



Pearlite: $HV_{0.01N}$=326±2



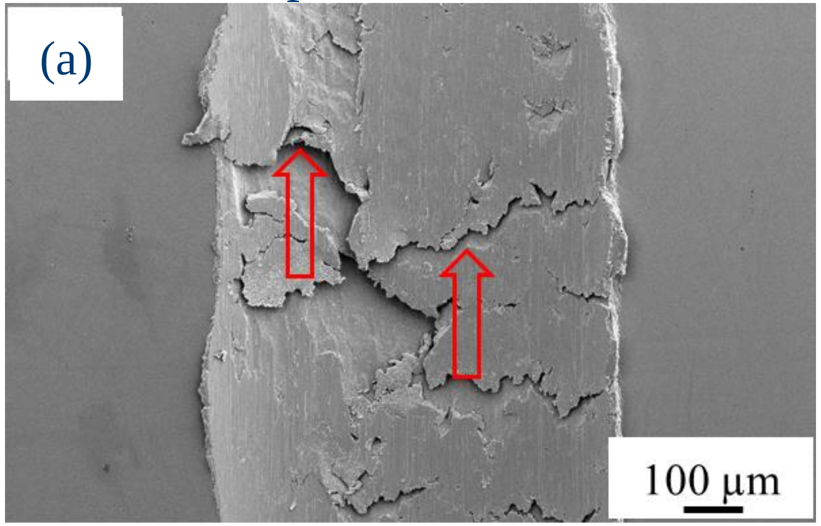
Martensite: $HV_{0.01N}$=355±3



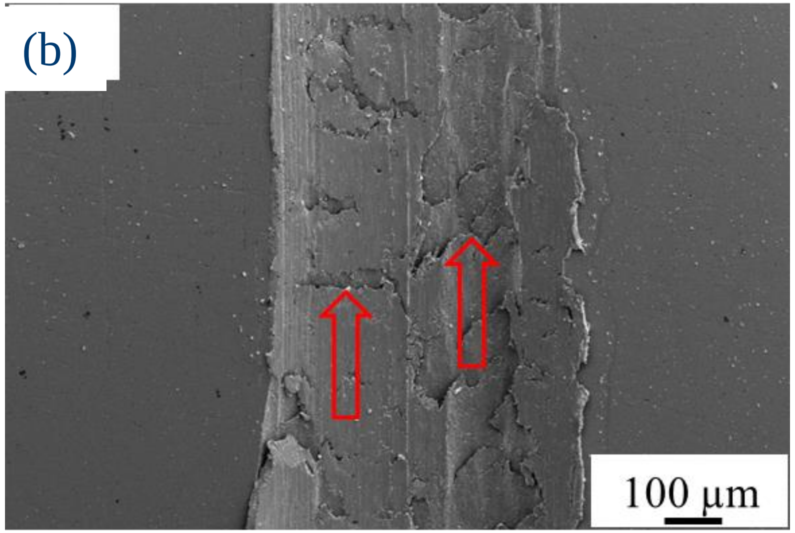
Tempered martensite: $HV_{0.01N}$=357±3

SEM analysis on the grooves of microstructures at 100N normal load

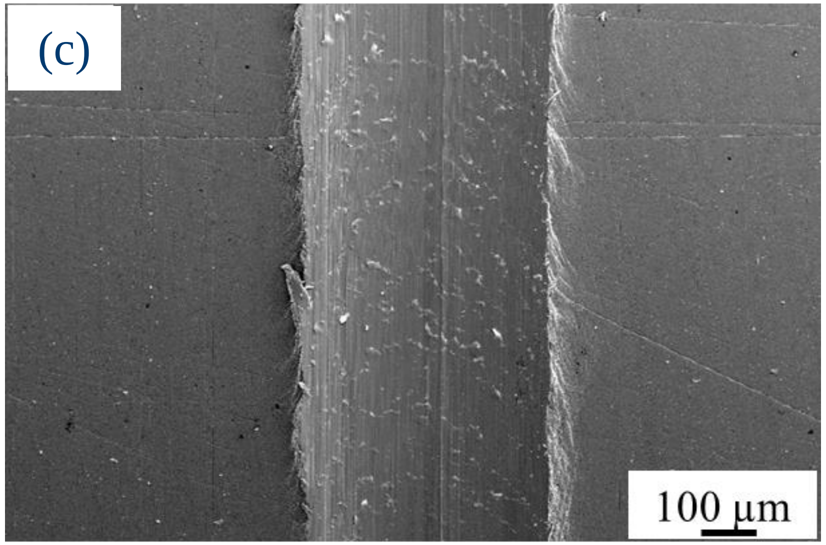
Tempered martensite



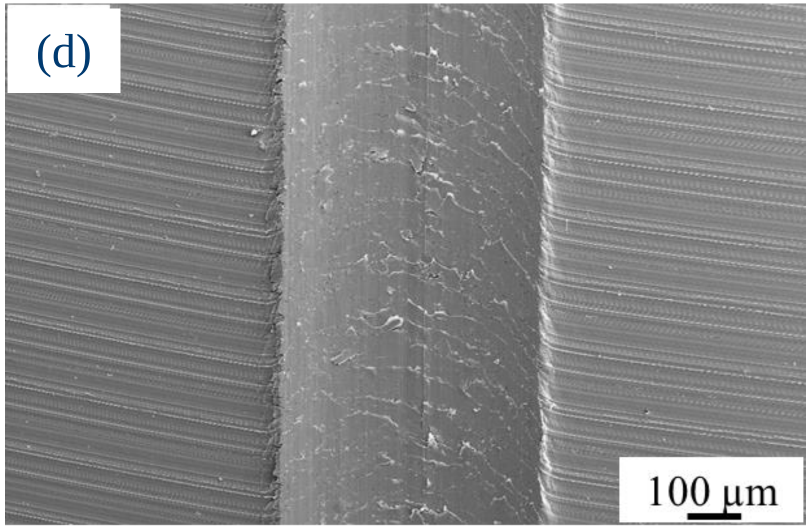
Martensite



Bainite

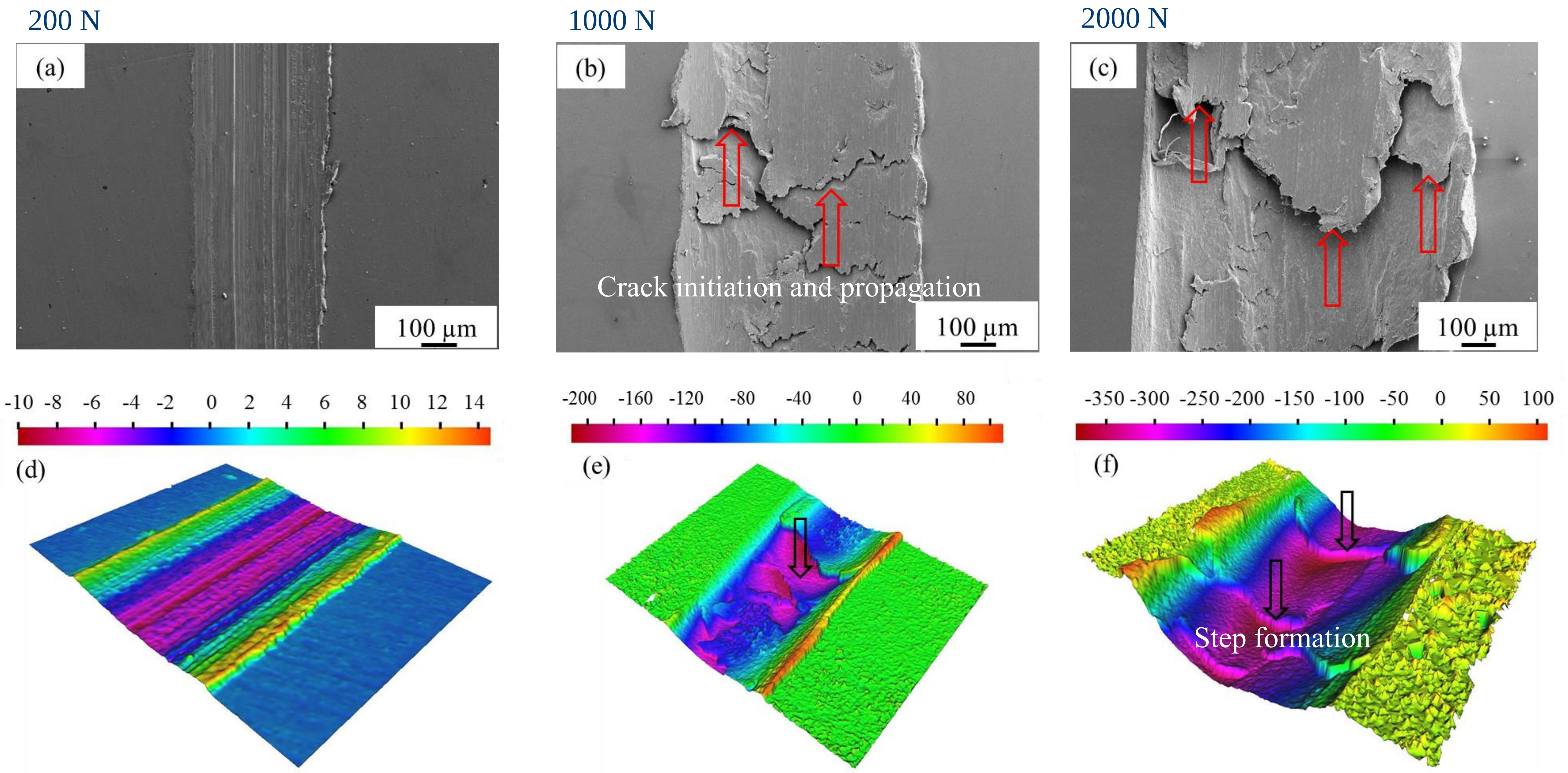


Pearlite

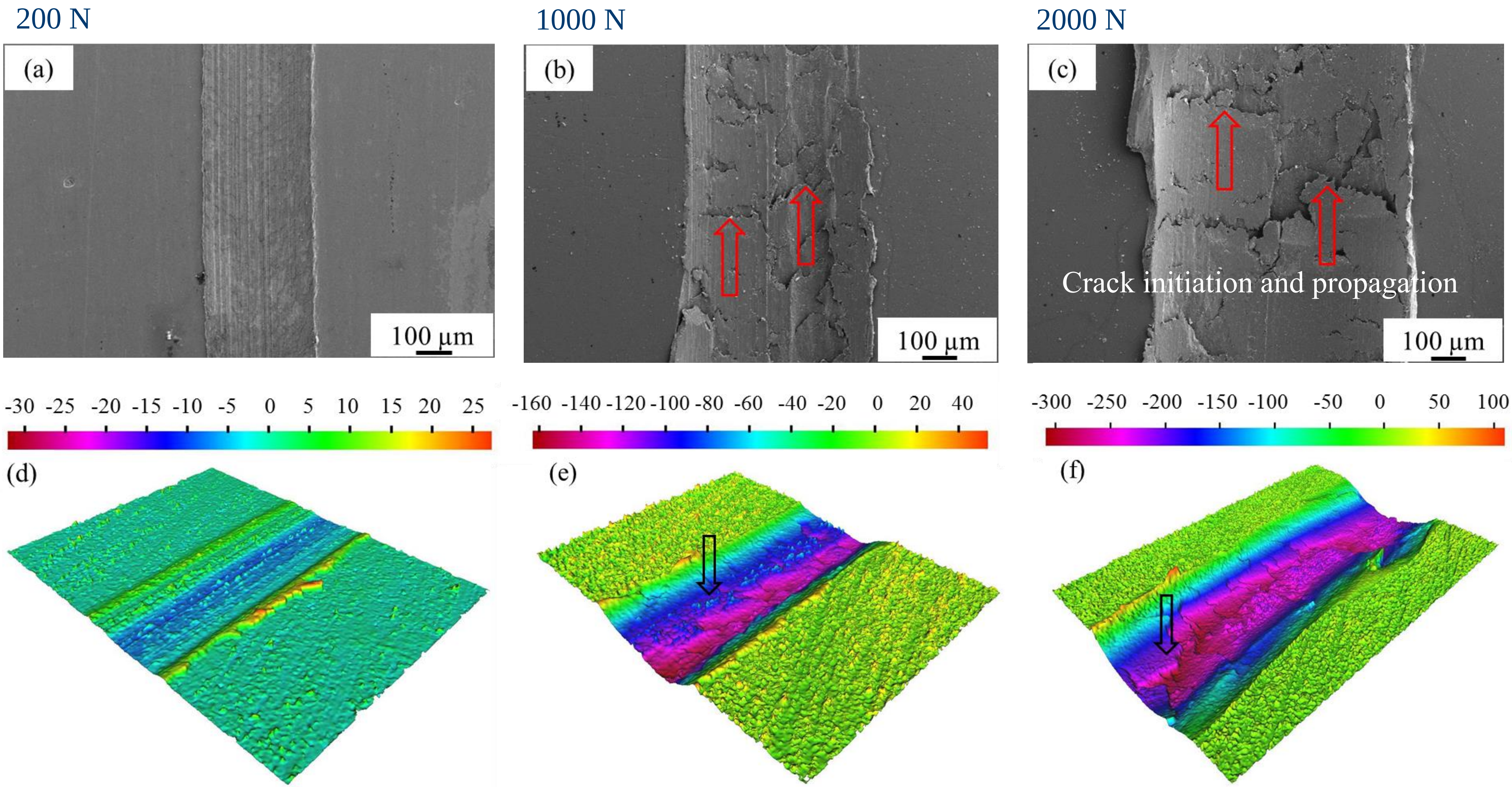


Narayanaswamy, B., Ghaderi, A., Hodgson, P., Cizek, P., Chao, Q., Safi, M., & Beladi, H. (2019). Abrasive wear resistance of ferrous microstructures with similar bulk hardness levels evaluated by a scratch-tester method. *Metallurgical and Materials Transactions A*, *50*(10), 4839-4850.

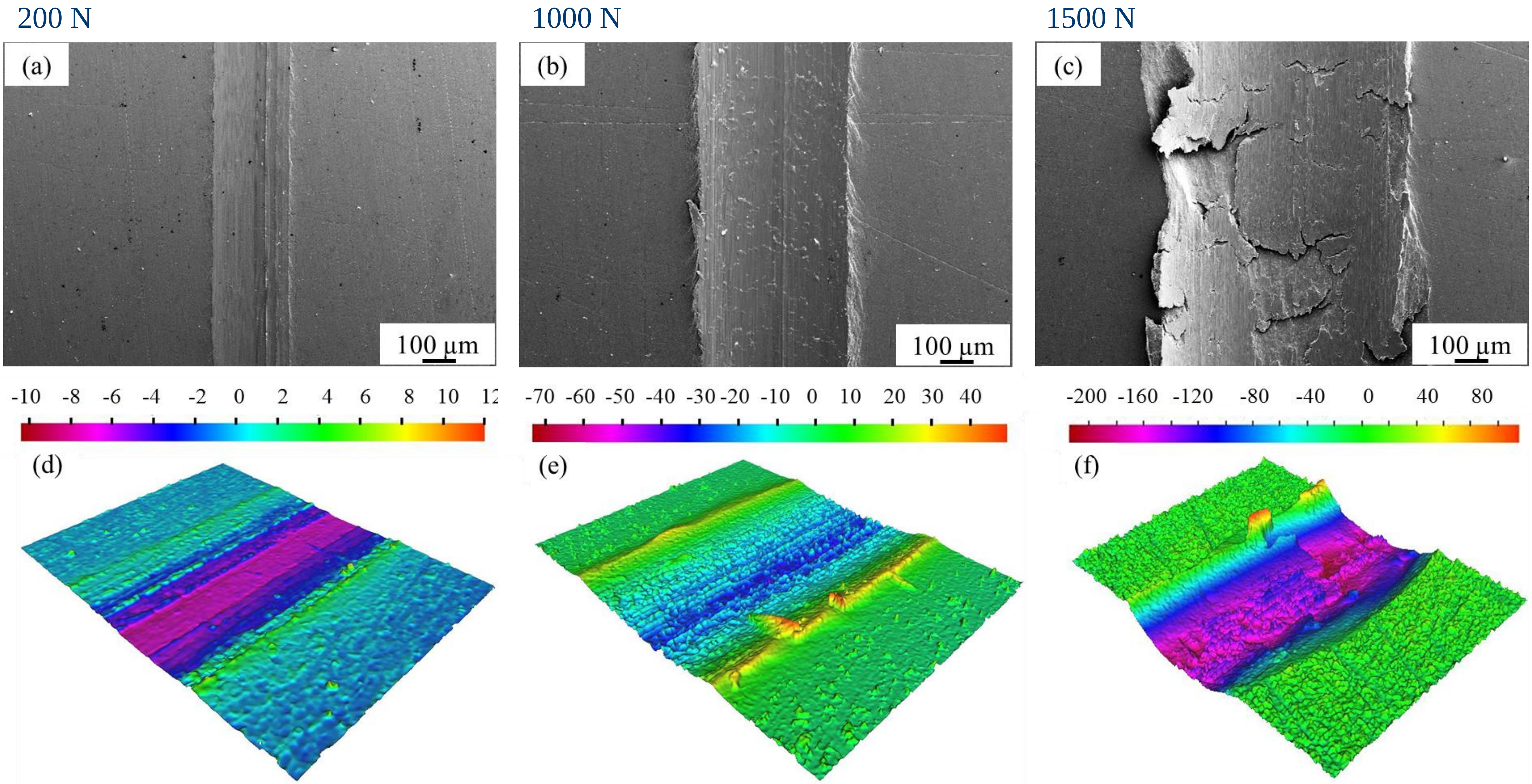
SEM (a-c) and topographical analysis (d-f) of the grooves in martensite microstructure at different load conditions



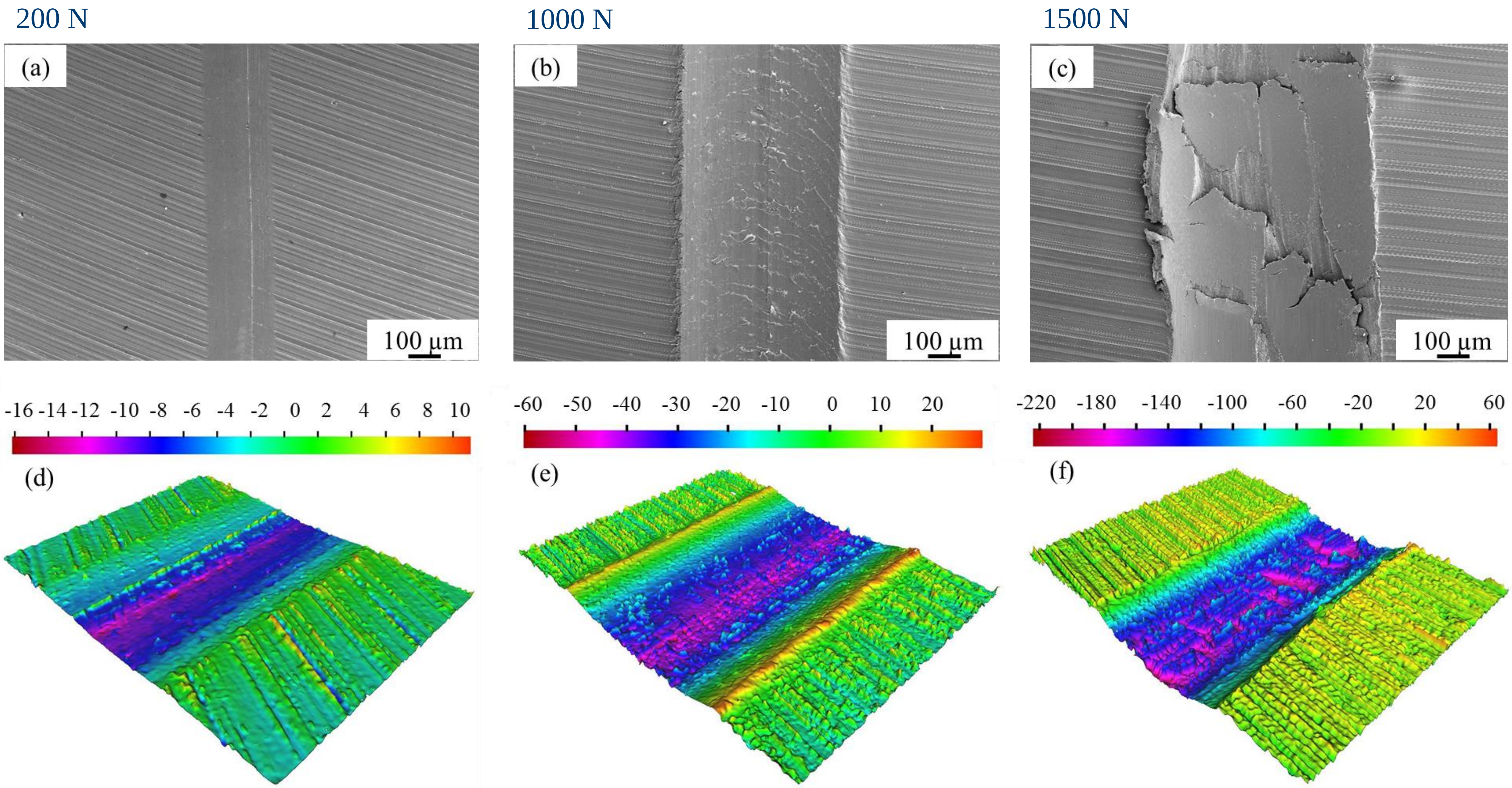
SEM (a-c) and topographical analysis (d-f) of the grooves in tempered martensite at different load conditions



SEM (a-c) and topographical analysis (d-f) of the grooves in bainite microstructure at different load conditions



SEM (a-c) and topographical analysis (d-f) of the grooves in pearlite microstructure at different load conditions



Cross section of a groove with material displaced to the sides as built-up edges in schematics

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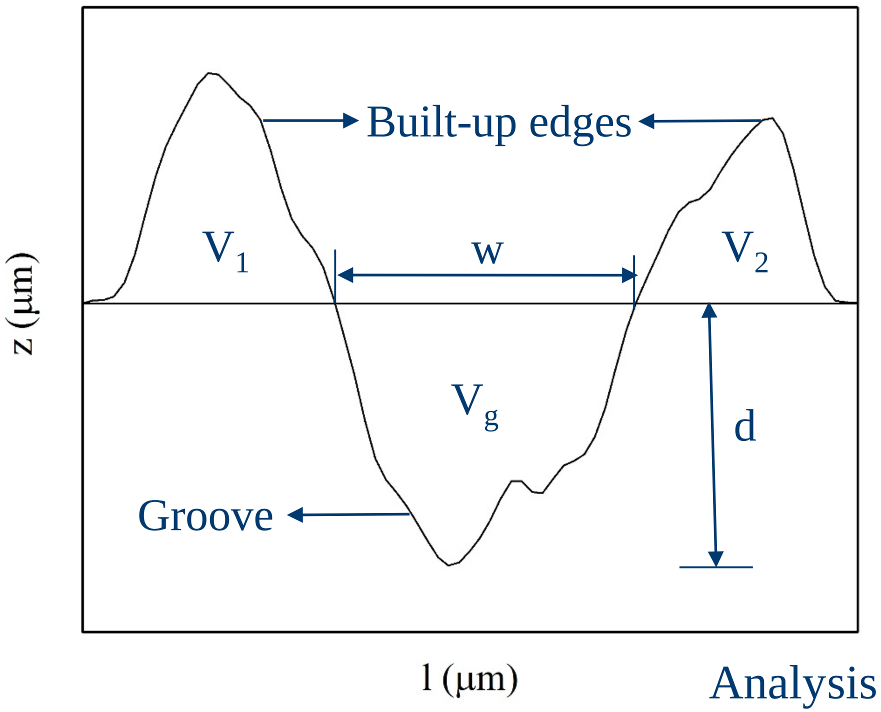
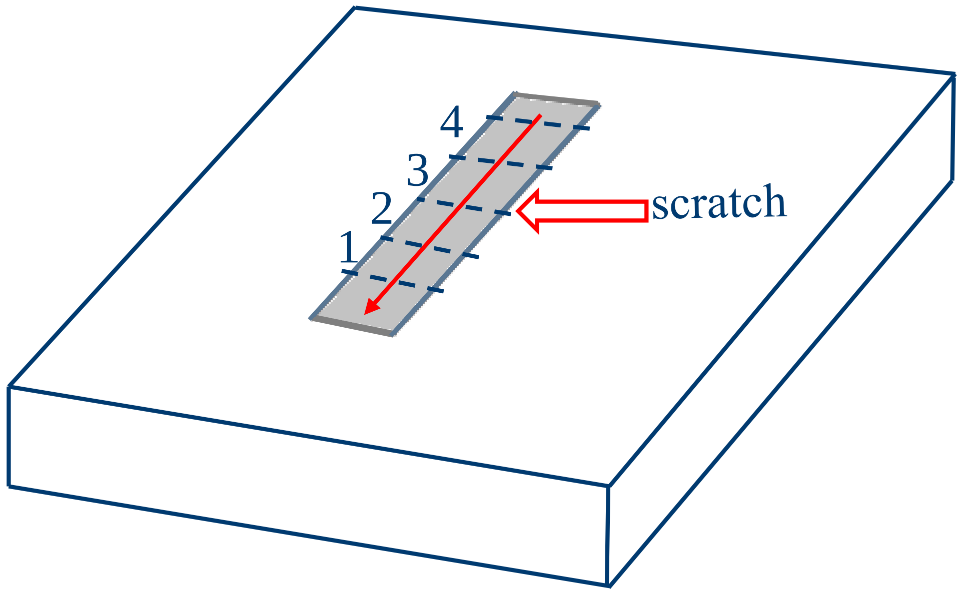




Analysis:

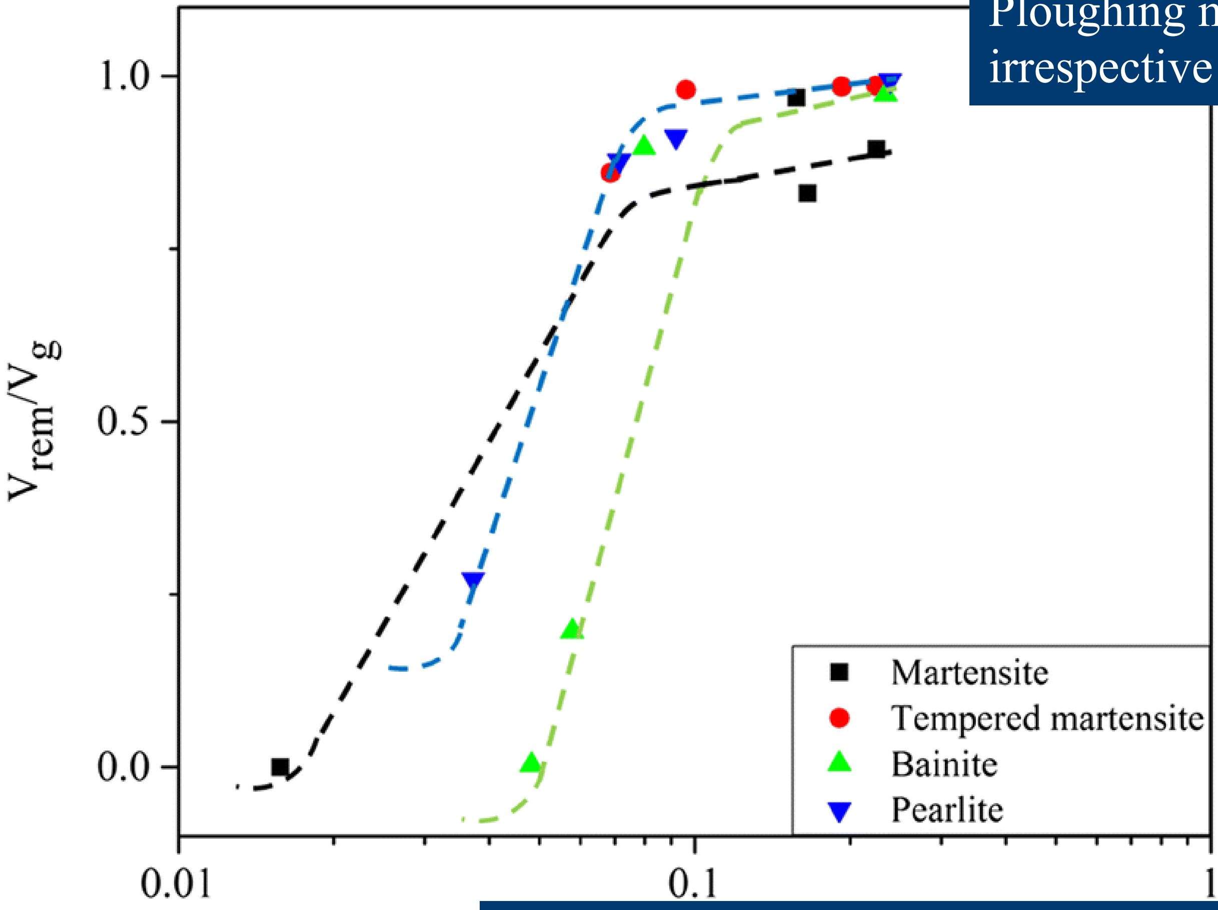
V_1 & V_2 are the volume of the built-up edges (mm^3);

V_g is the volume of the groove (mm^3);

Volume of material removal, $V_{rem} = [V_g – (V_1 + V_2)]$ (mm^3);

Degree of penetration, $D_p = 2d/w$.

Material removal mechanism in microstructures

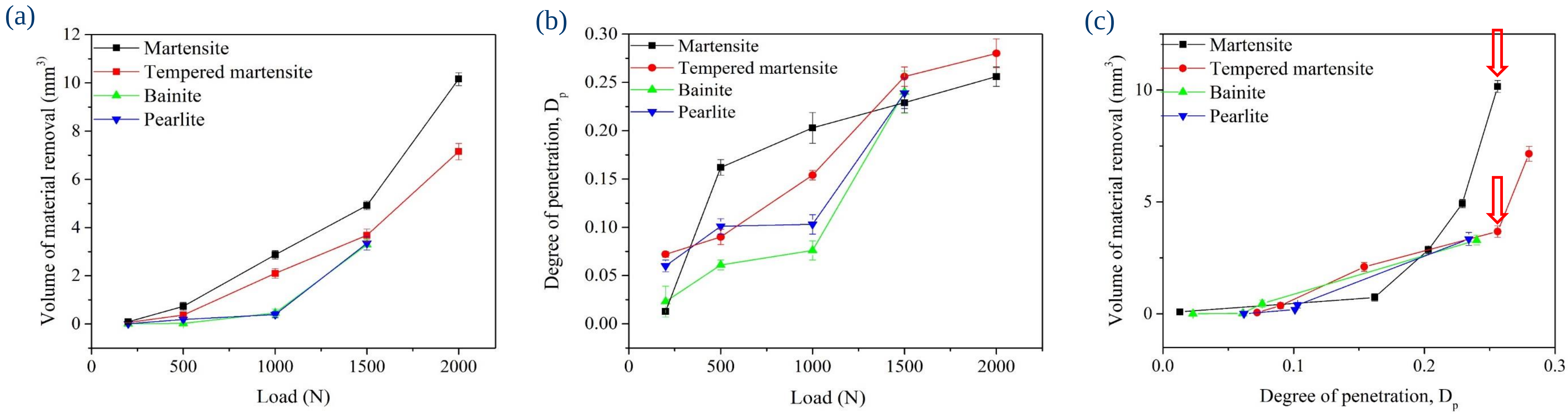


Ploughing mechanism was observed at low loads (200–500 N), irrespective of the microstructure type.

Fraction of material removal (*i.e.*, $V_{rem}/V_g = f$), was plotted against D_p for all microstructures. The process of material removal was identified based on the value of *f*, *i.e.*, ploughing, $f \sim 0$ and cutting, $f \sim 1$).

Cutting mechanism was dominant at loads above 1000 N.

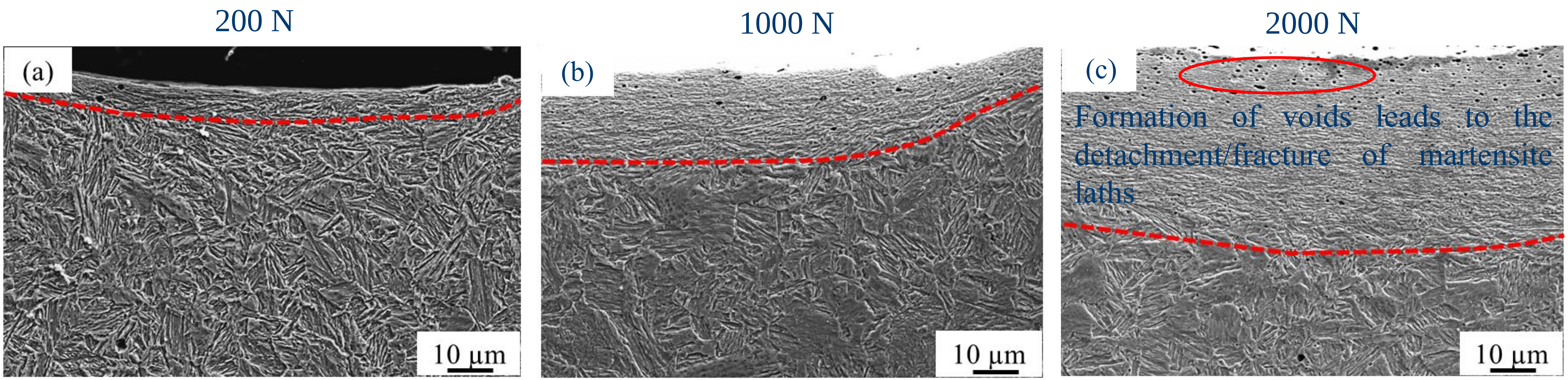
Groove profile analysis



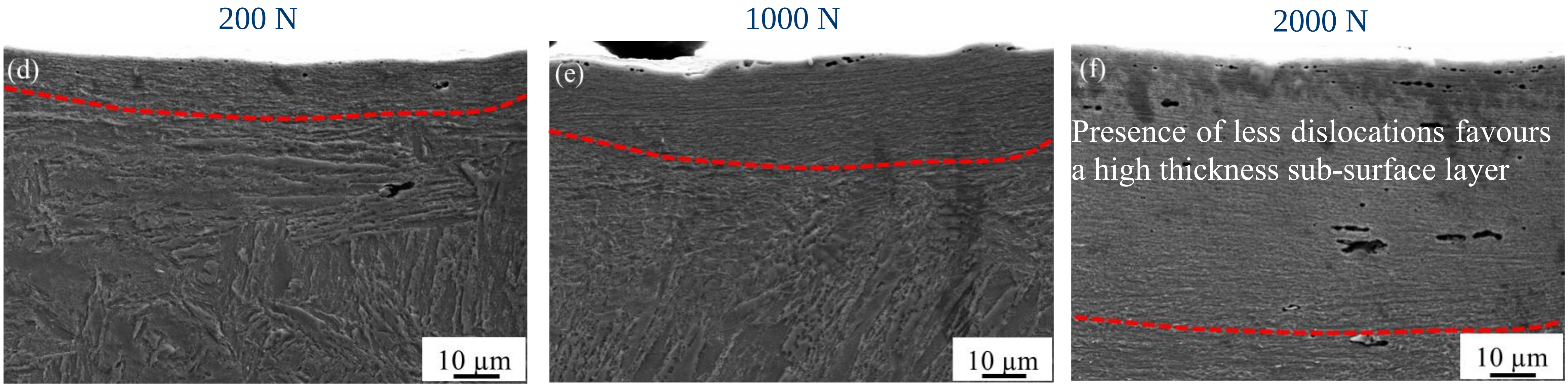
Observations:

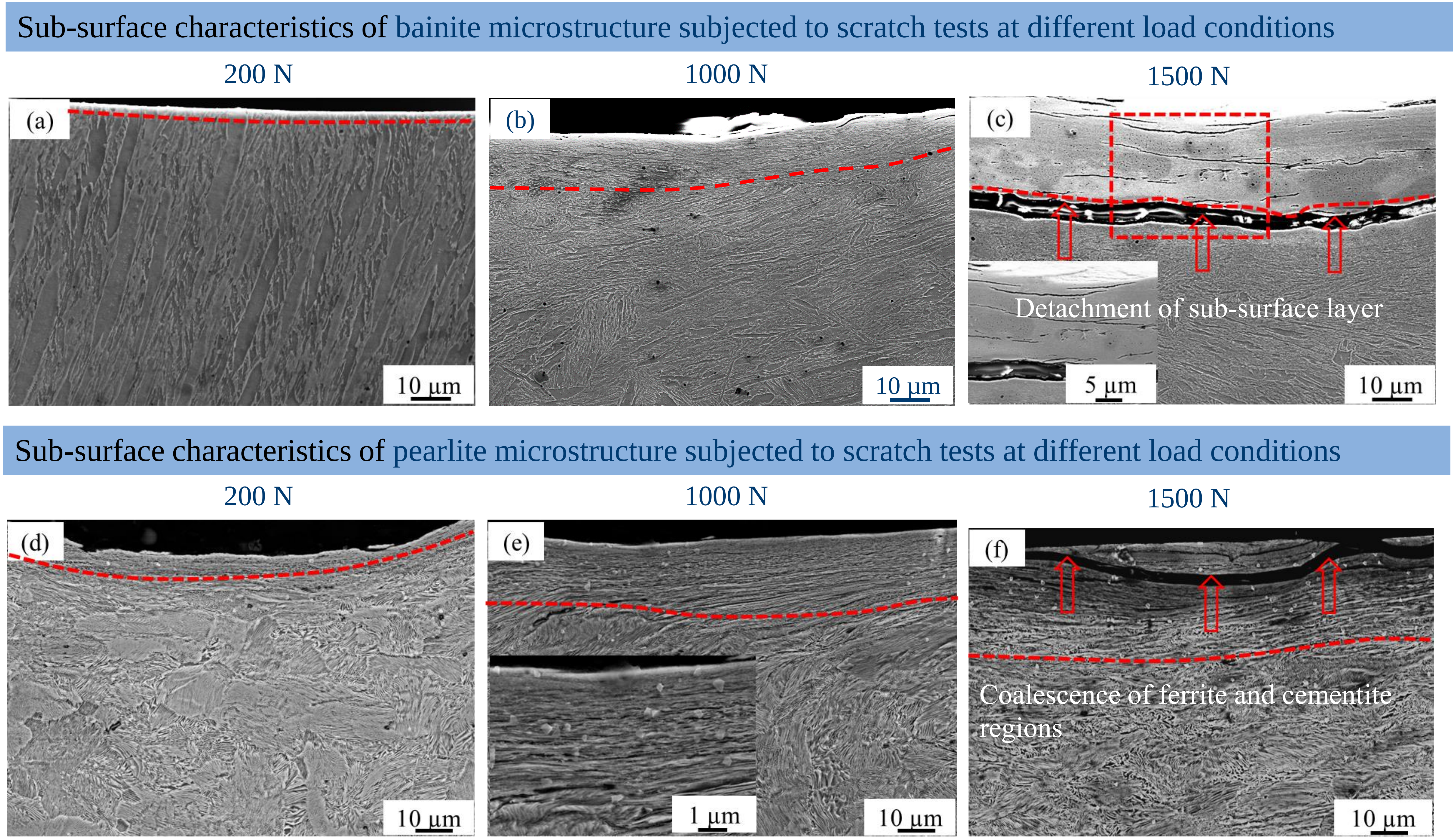
- The volume of material removal and degree of penetration was directly proportional to the normal load subjected during the test.
- Little correlation between the degree of penetration and the volume of material removed.
- At lower loads (200-1000N), bainite and pearlite displayed better abrasion resistance than other microstructures.

Sub-surface characteristics of martensite microstructure subjected to scratch tests at different load conditions



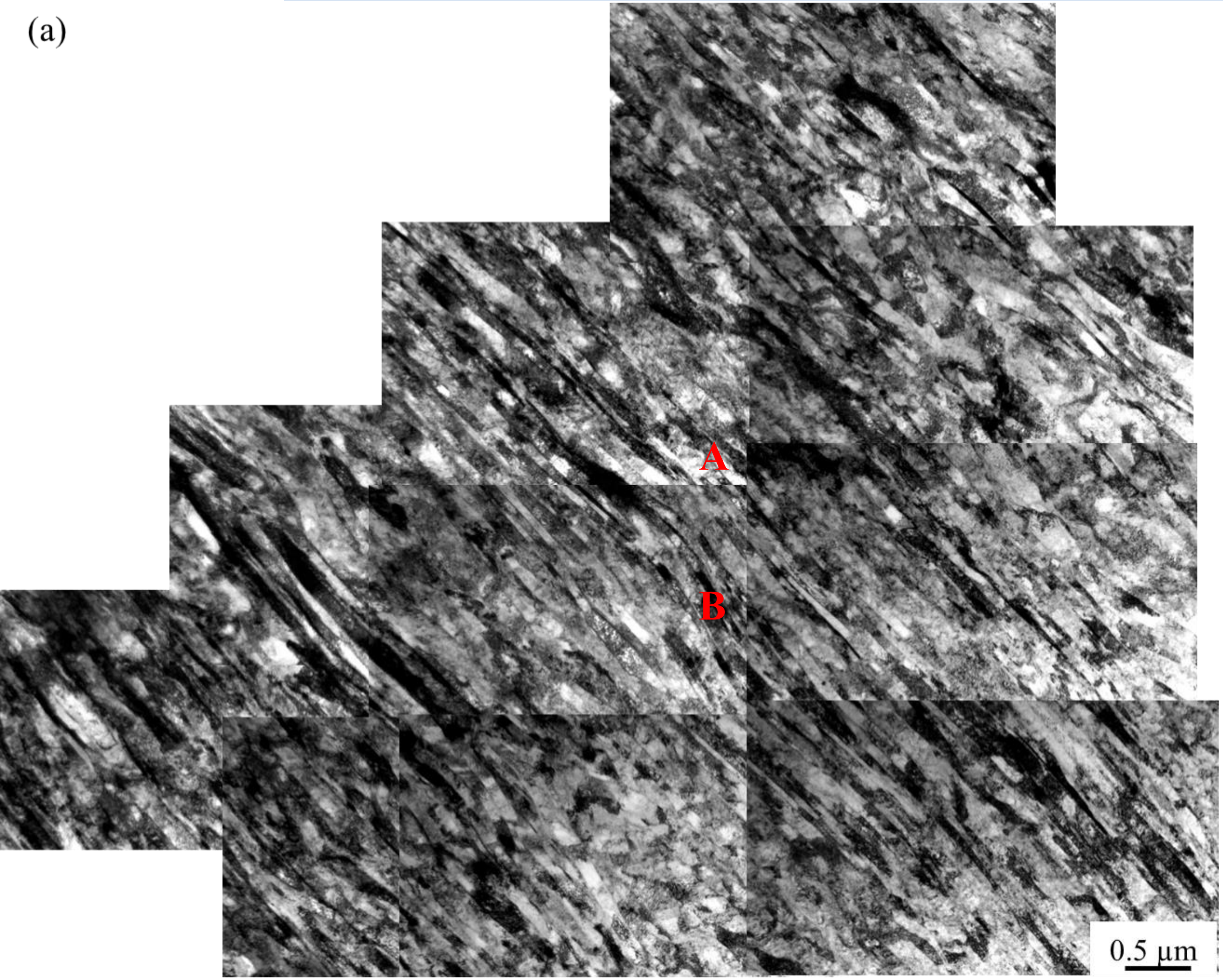
Sub-surface characteristics of martensite microstructure subjected to scratch tests at different load conditions



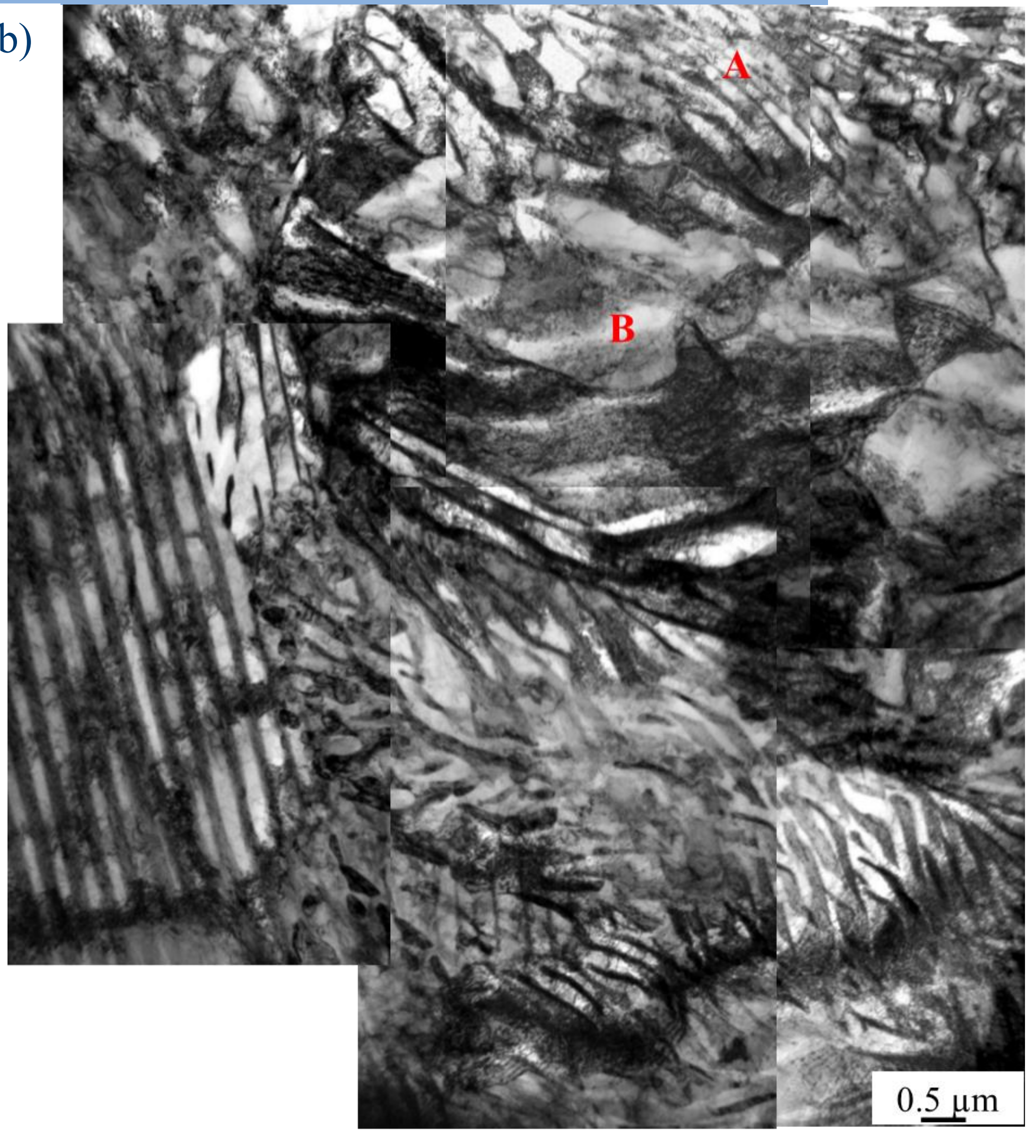

Sub-surface characteristics of bainite microstructure subjected to scratch tests at different load conditions
200 N
1000 N
1500 N
(a)
10 µm
(b)
10 µm
(c)
Detachment of sub-surface layer
5 µm
10 µm
Sub-surface characteristics of pearlite microstructure subjected to scratch tests at different load conditions
200 N
1000 N
1500 N
(d)
10 µm
(e)
1 µm
10 µm
(f)
Coalescence of ferrite and cementite regions
10 µm

TEM characterization of the martensite and pearlite sub-surface layer subjected to a scratch test.

(a)



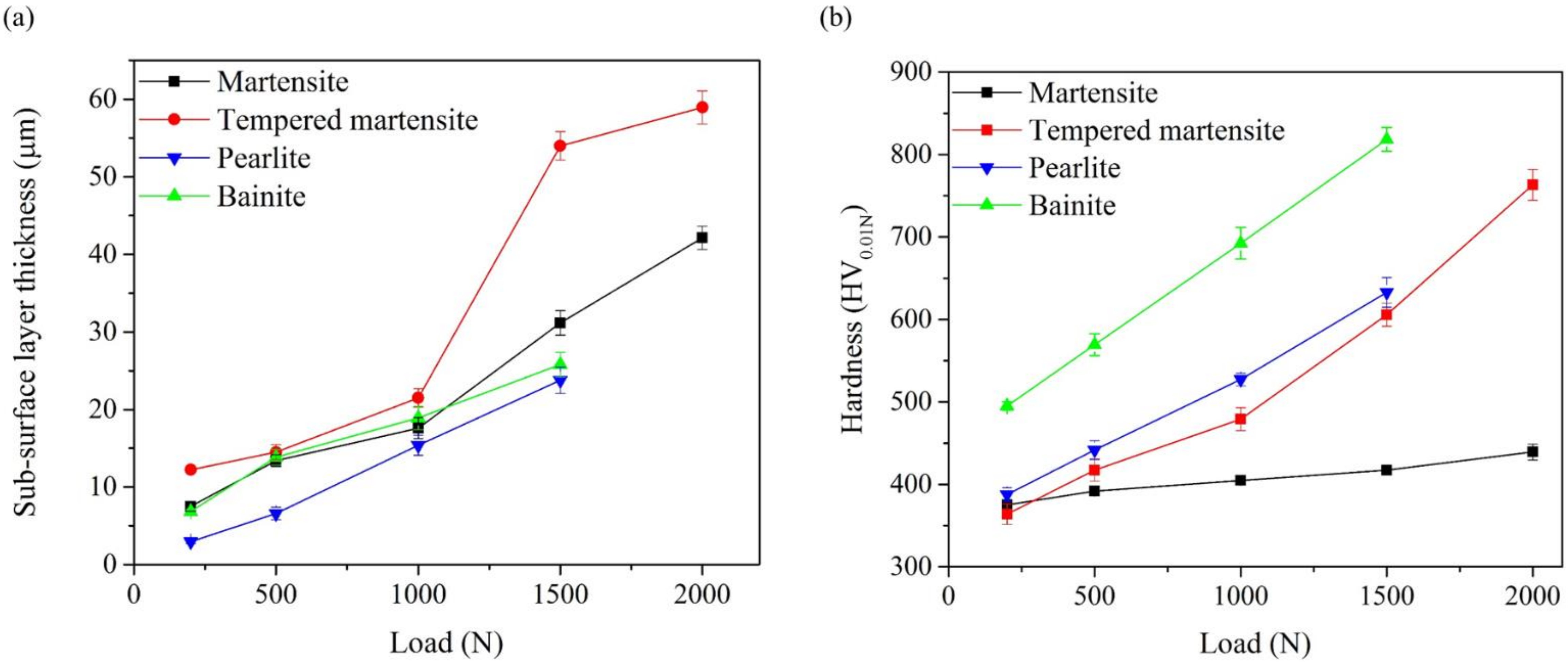
(b)



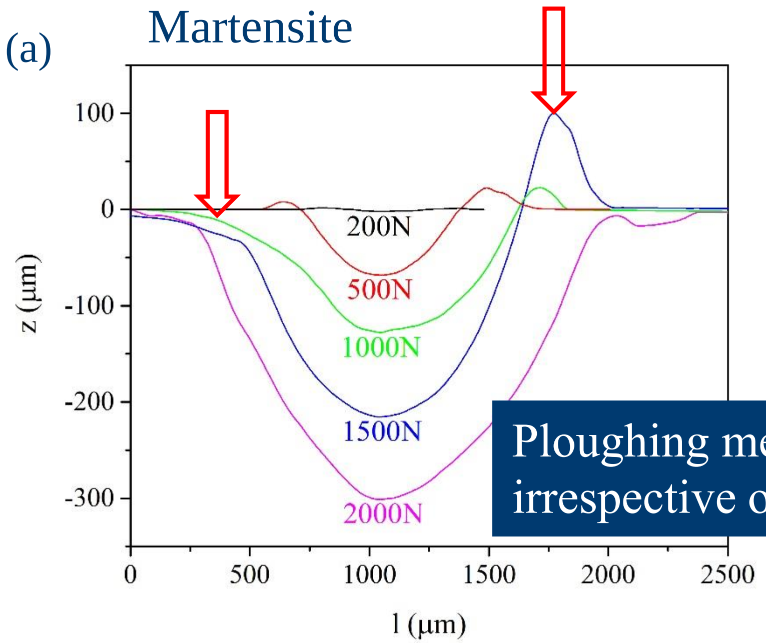
A-Fragmentation of the martensite laths
B-Formation of equiaxed/fine grains along with rows of elongated grains

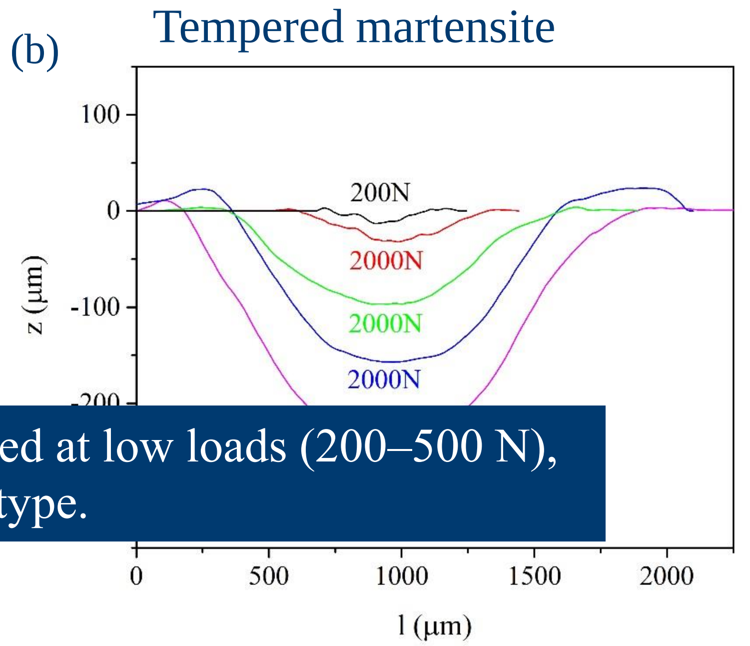
A- Cementite fragmentation
B- cementite dissolution in a highly dislocated ferrite

Characterization of sub-surface layers in different microstructures.

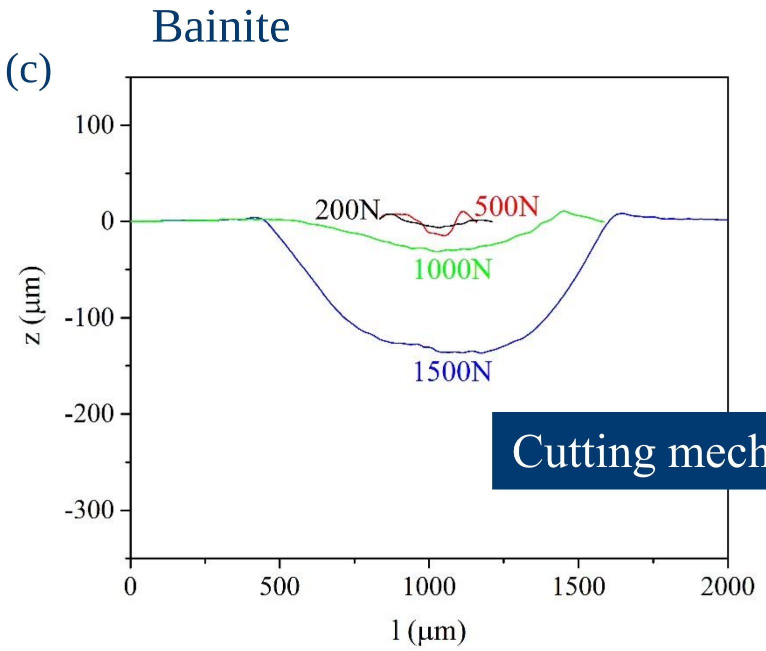


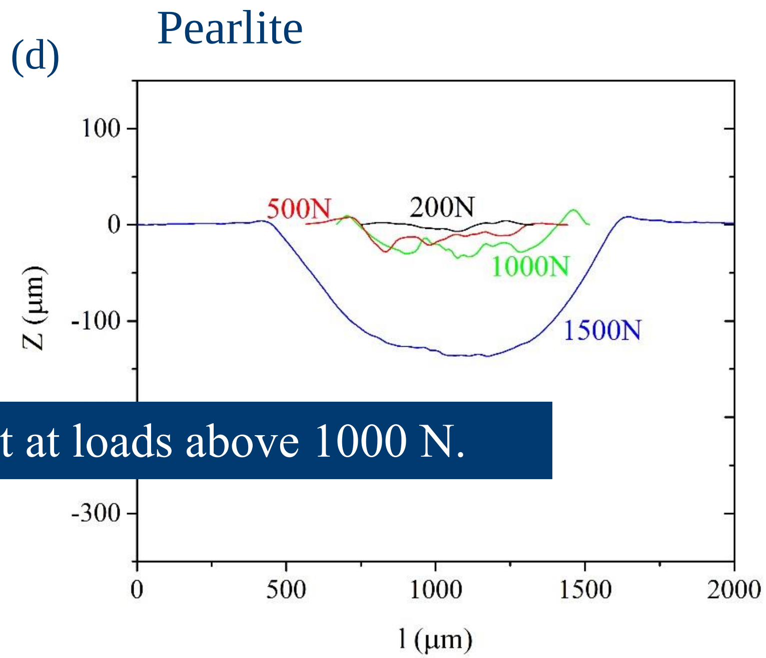
Comparative groove profile of different microstructures as a function of normal load.





Ploughing mechanism was observed at low loads (200–500 N), irrespective of the microstructure type.





Cutting mechanism was dominant at loads above 1000 N.

Summary - C

- In general, **multi-phase microstructures** displayed relatively **low volume of material removal in comparison with single-phase microstructures** martensite and tempered martensite.
- The **groove characteristics** (i.e., width, w and depth, d) of the microstructures were significantly influenced by the properties of the **microstructure constituents and the normal load**.
- A **transition in the material removal me**chanism (i.e., ploughing to cutting mechanism) was observed with respect to the **normal load** subjected during the scratch testing.
- The distinct sub-surface characteristics of the microstructures were a clear indication of their response to the abrasive scratch test.
- The amount of **work-hardening** (i.e., increase in sub-surface hardness) had a **direct and positive correlation with respect to the abrasive behaviour** of the microstructures.

Publications:

- B. Narayanaswamy, A.Ghaderi, P.Hodgson, P.Cizek, Q.Chao, M.Safi, H.Beladi, Abrasive wear resistance of ferrous microstructures with similar bulk hardness levels evaluated by a scratch- tester method, Metallurgical and Materials Transactions A, 50 (2019) 4839-4850.
- B. Narayanaswamy, P. Hodgson, H. Beladi, Comparisons of the two-body abrasive wear behavior of four different microstructures with similar hardness levels, Wear, 350-351 (2016) 155-165.
- B. Narayanaswamy, P. Hodgson, H. Beladi, Effect of particle characteristics on the two-body abrasive wear behaviour of a pearlitic steel, Wear, Volumes 354–355, (2016) 41-52.
- B. Narayanaswamy, P. Hodgson, Ilana Timokhina and H. Beladi, The impact of retained austenite characteristics on the two-body abrasive wear behaviour of ultra-high strength bainitic steels, Metallurgical and Materials Transactions A, 47 (2016) 4883-4895.

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