Microstructural characterization and enhancement of the wear behavior of 316L+WC Metal Matrix Composite processed by Directed Energy Deposition

Tommaso MAURIZI ENRICI, Olivier DEDRY, Neda HASHEMI, Daniele MARIO, Anne MERTENS, Jérôme Tchoufang TCHUINDJANG

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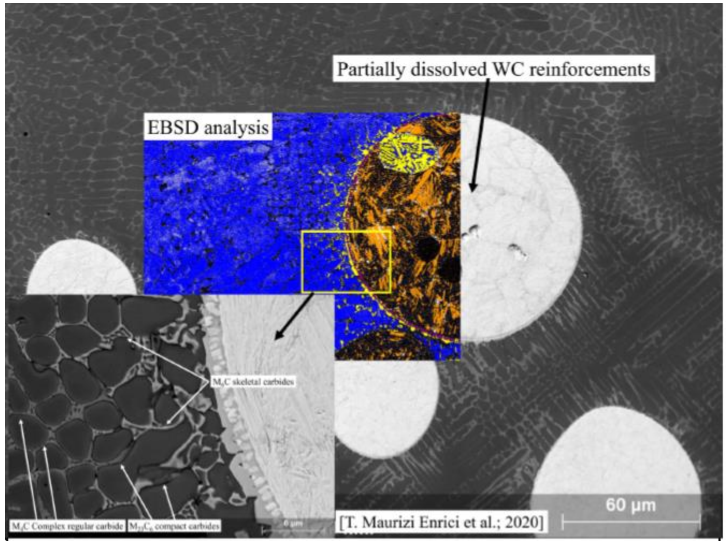
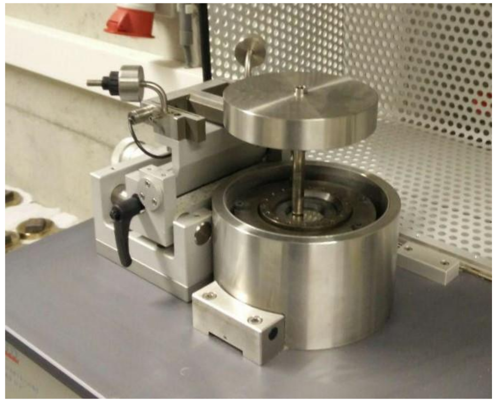
Outline

- Introduction
- Background
- Materials
- Experimental Methods
- Results
- Discussion
- Conclusions

Introduction

- Development, metallurgical and tribological characterization of complex alloys and metal matrix composites obtained from manufacturing processes under non-equilibrium conditions [PhD Thesis, T. Maurizi Enrici, 2022]
- Designing new materials from Additive Manufacturing Processes prior to checking for defined properties
- Issue about hierarchical structures achieved that exhibit cyclical regime under dry sliding conditions





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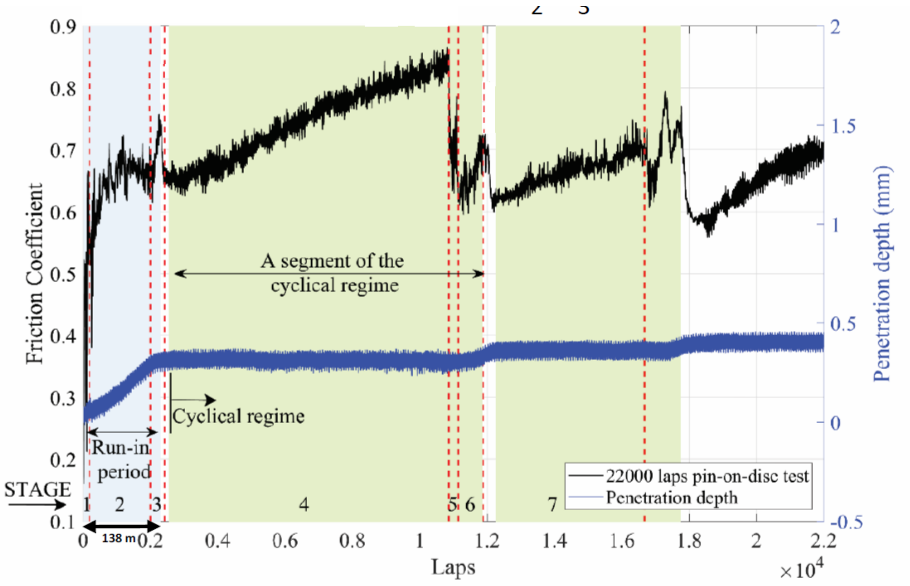
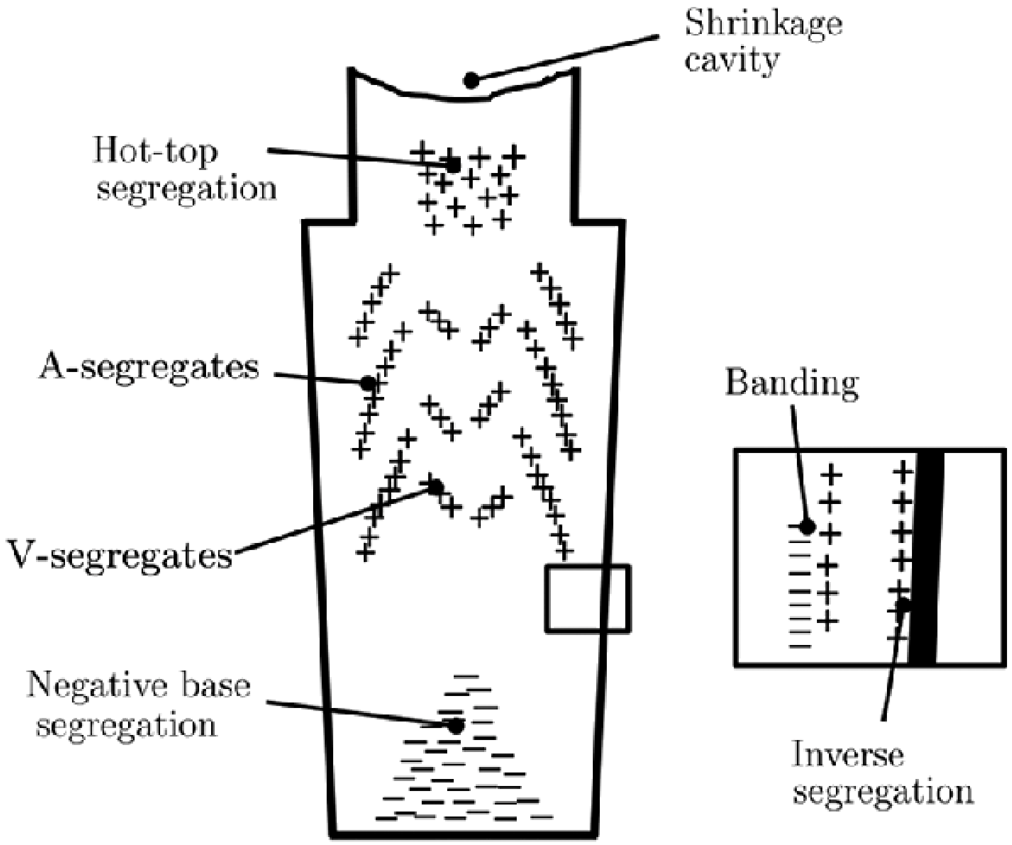
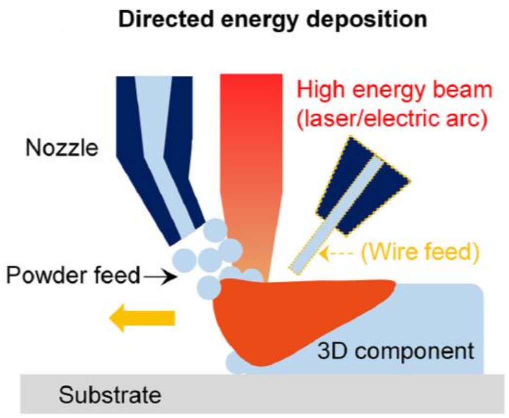


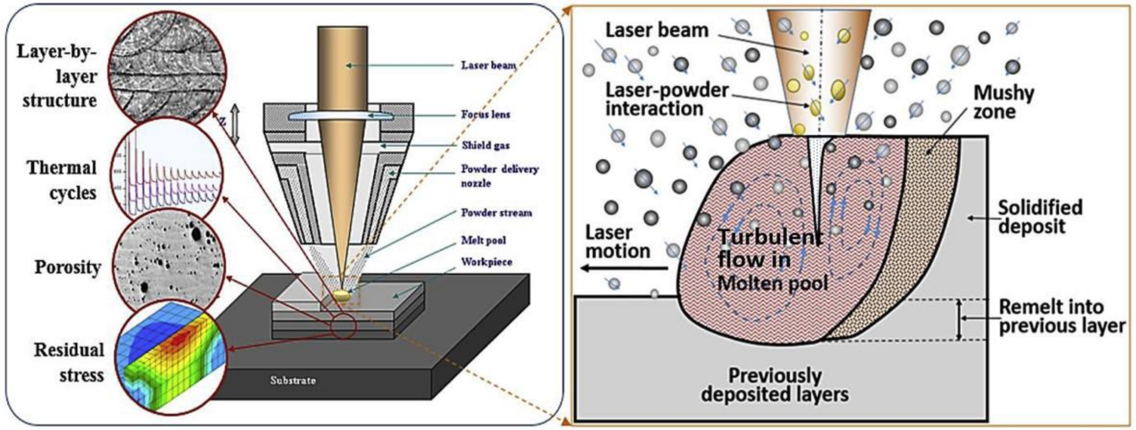
Background
Conventional casting VS Additive Manufacturing processes (DED)



Macrosegregations in a large ingot [Pickering, 2013]
Length scales ~ cm to m



Directed Energy Deposition (DED) process [Liu, 2022]

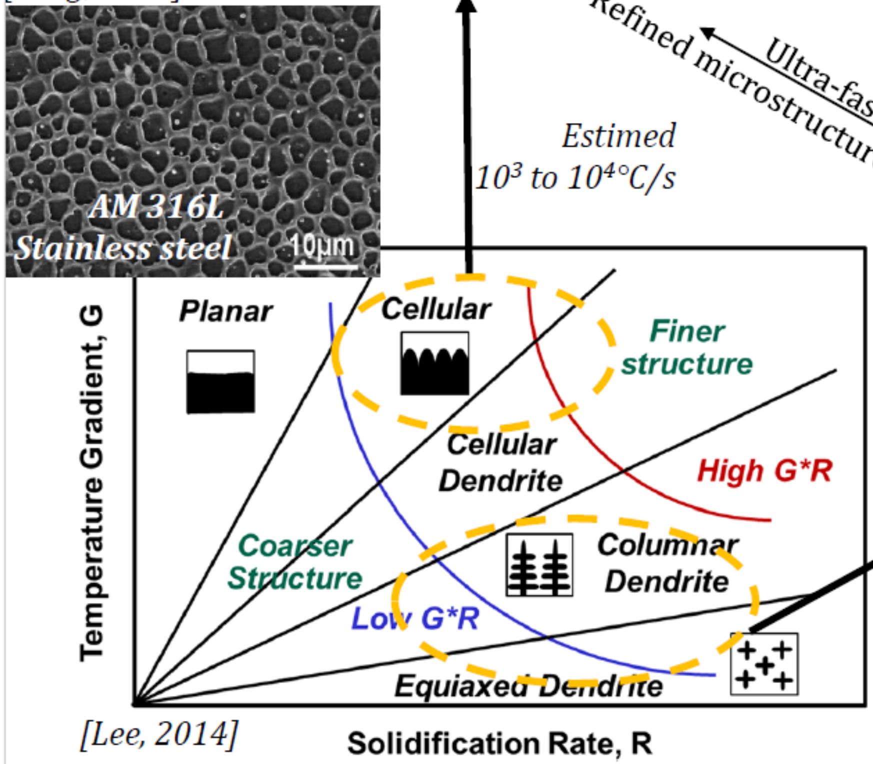


Various issues related to DED process and interactions between powder, laser beam and **melt pool** (MP) [Zheng, 2019]
Length scale for MP ~ microns

Background
Solidification modes and supersaturation

Metals in Additive Manufacturing (AM)

[Song, 2016]



[Lee, 2014]

Estimed
10^3 to 10^4°C/s

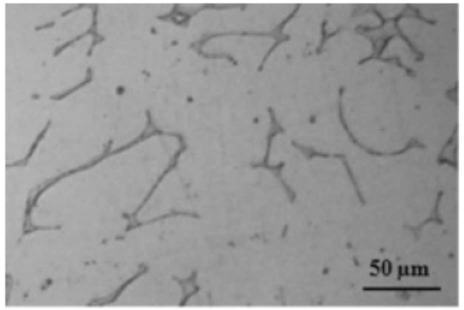
Ultra-fast cooling rates

Refined microstructures and improved properties

Estimed
10 to 300°C/s

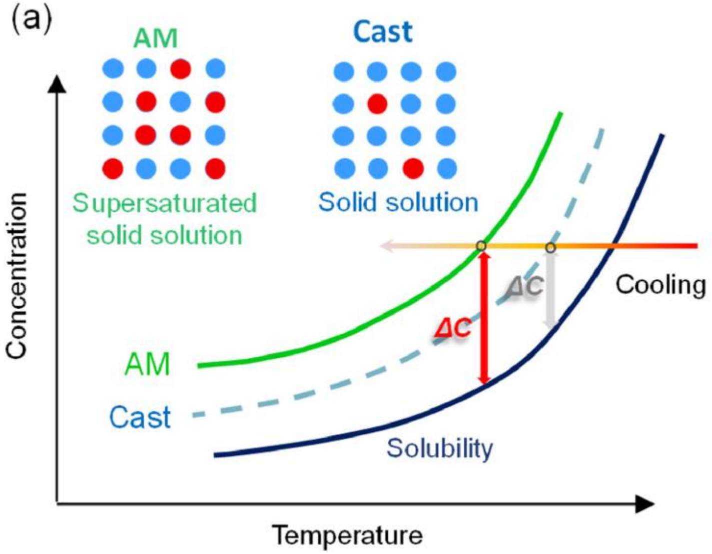
Classical 316L Stainless steel

[El-Hadad, 2014]



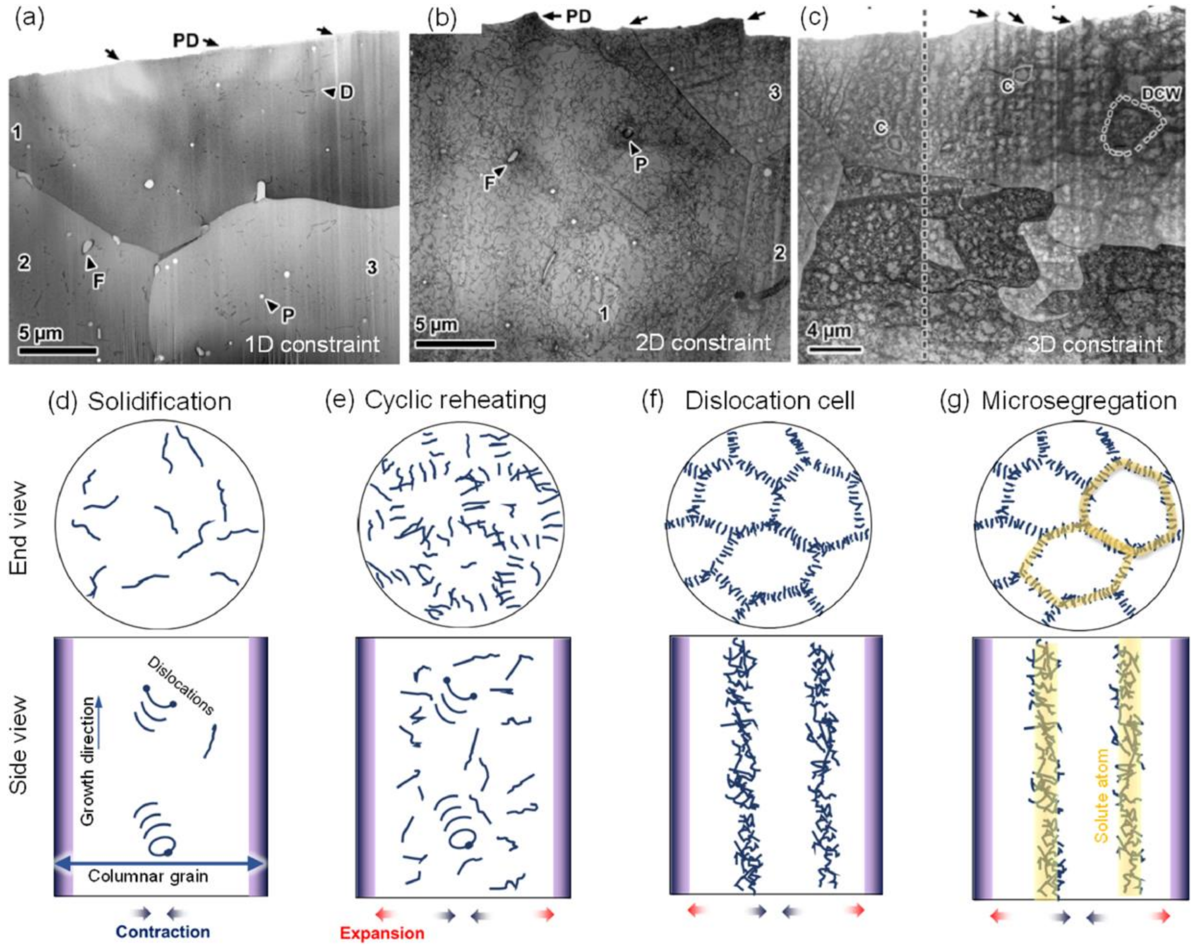
Classical manufacturing process

Powder Metallurgy
Metal Injection Molding
Sintering

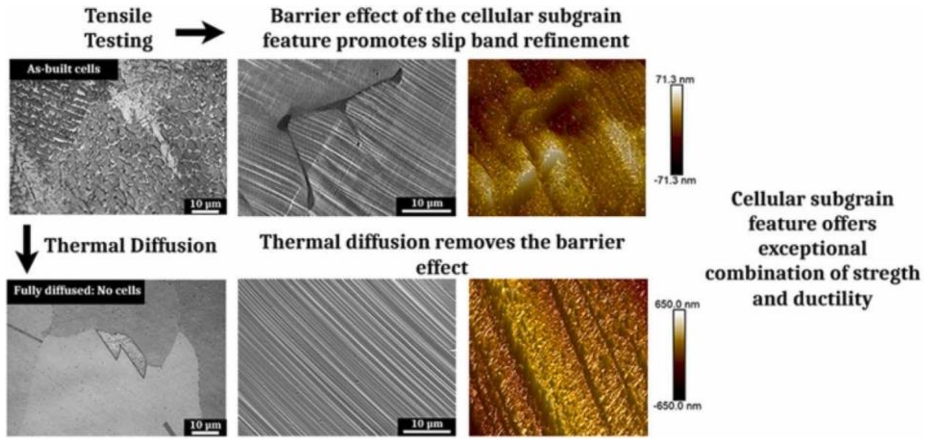


Supersaturation with enhanced solubility in AM processes [Liu, 2022]

Background
Subgrains (cell boundaries) as key features for mechanical properties

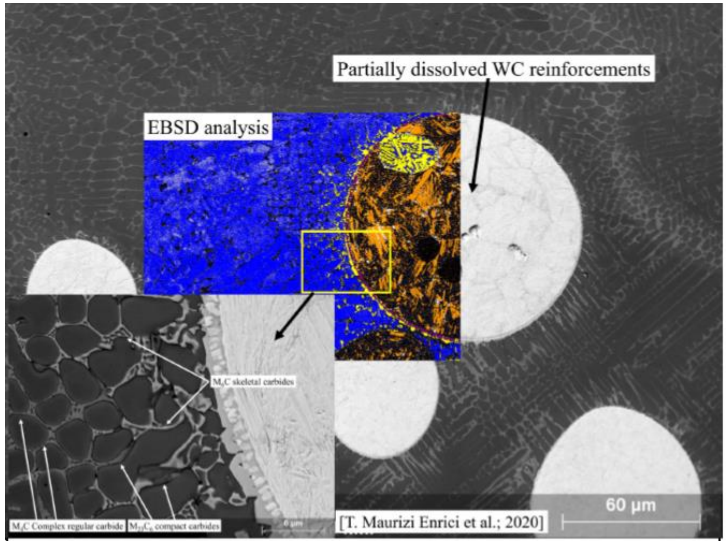


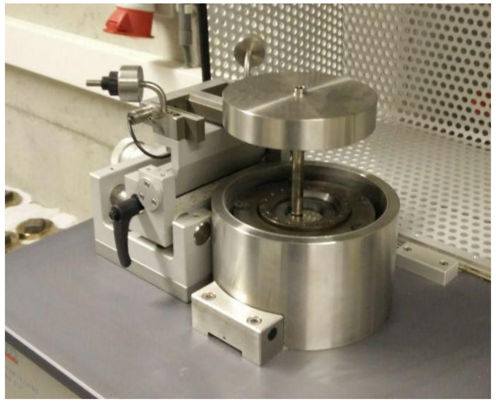
Schematic of dislocation cell formation process during AM [Liu, 2022]

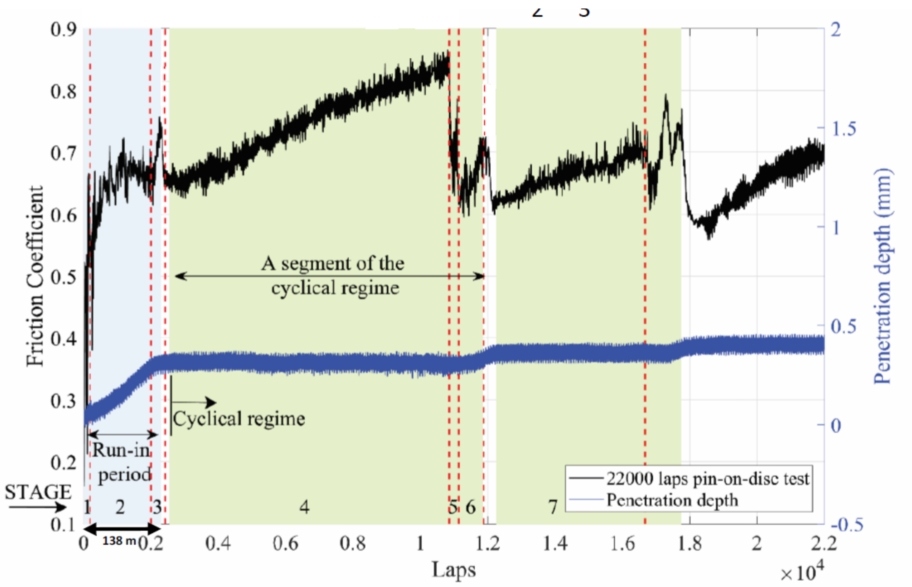


Cellular subgrain features offers exceptional combination of strength and ductility [Wanni, 2022]

Background
Subgrains (cell boundaries) as key features for mechanical properties

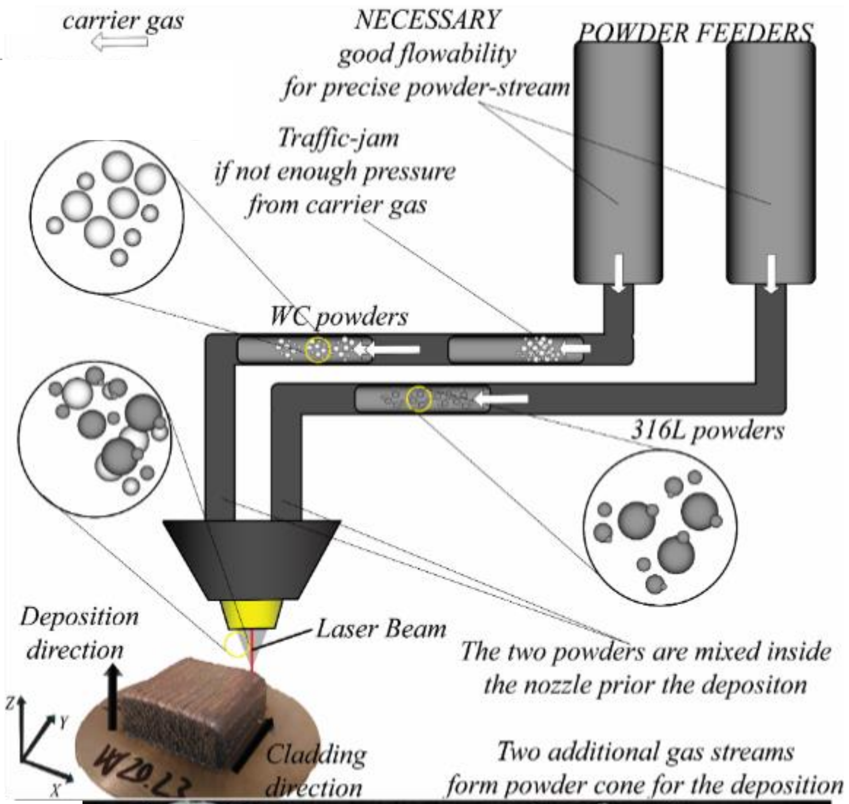


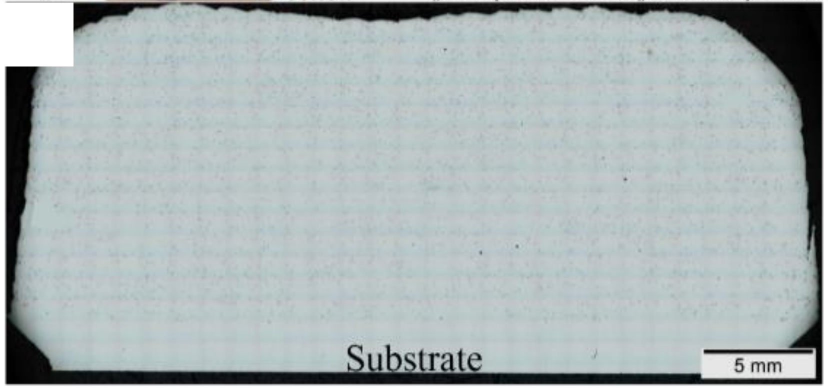


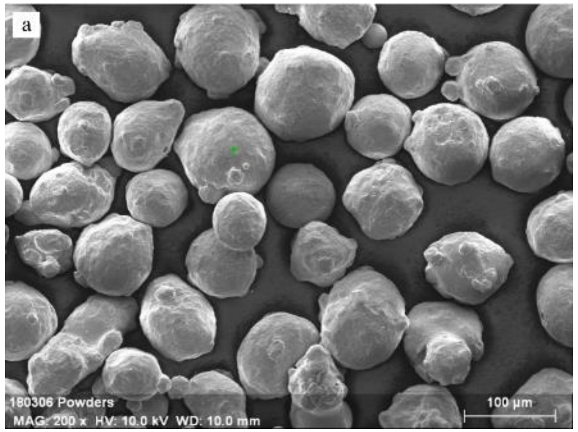


Enhancement of wear mechanisms (instead of conventional wear features (CoF, Wear Rate, etc.) to better understand wear behavior of MMC 316L+20%WC...

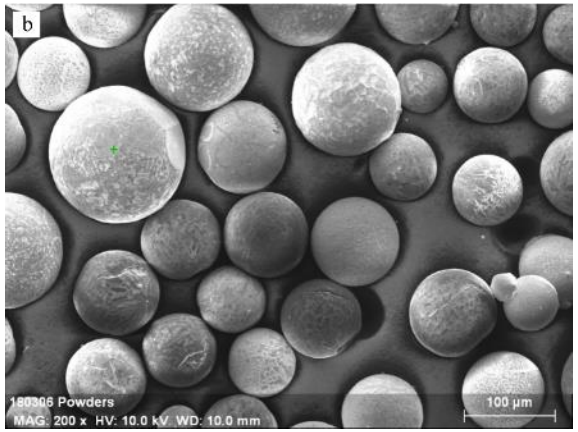
Materials





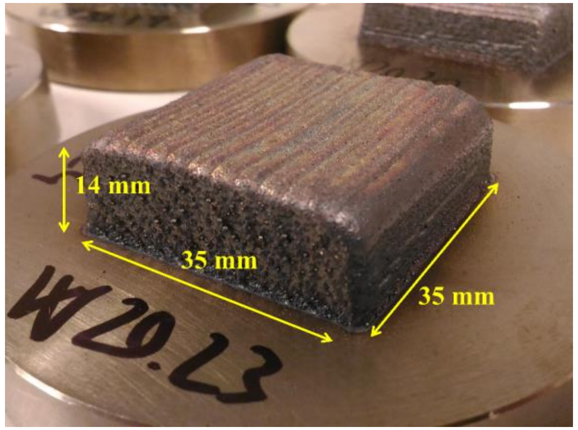


316L powder as reference + for MMC



WC powder

Laser Power	570 W
Scanning speed	290 mm/min
Powder feed rate	23,4 gr/min
Laser diameter	1,5 mm
Layer thickness	600 µm

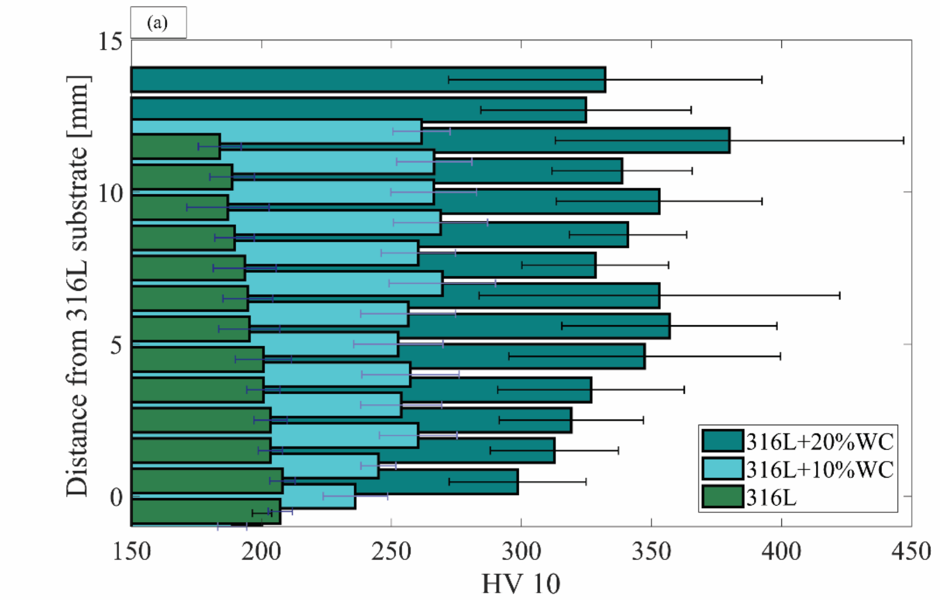


As-built deposit

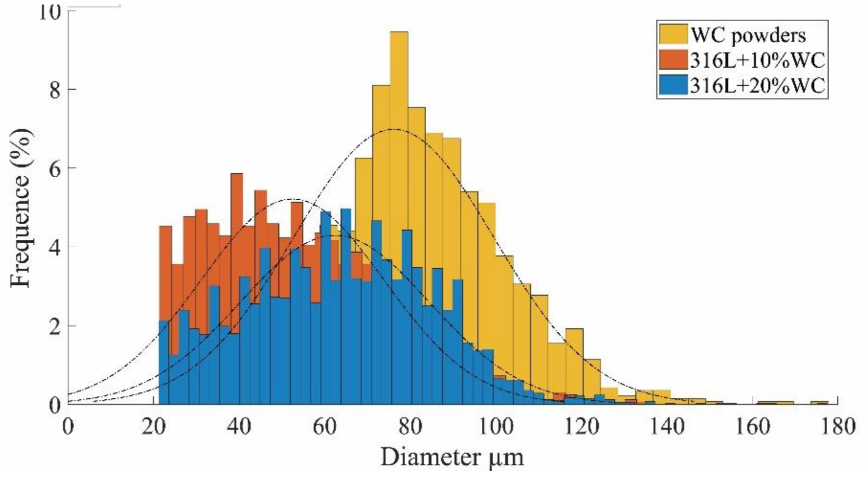
Experimental methods

- EDM + final machining (Ra < 0,2 µm)
- Macroscale : HV10 (ten points/layer), OM (quantitative metallography)
- Microscale : SEM/EDX - EBSD (local chemical compositions and phase nature)
- Nano-indentation (grid; depth control of 2 µm)
- Pin-o-disc tests (Al2O3 (Ø6 mm), 10N, 10cm/sec, 1105 m (22000 laps)
- Interrupted wear tests: @750 laps, 9300 laps, 11700 laps, 15000 laps)

Results : Macro scale… (Macro Hardness and WC reinforcements size)

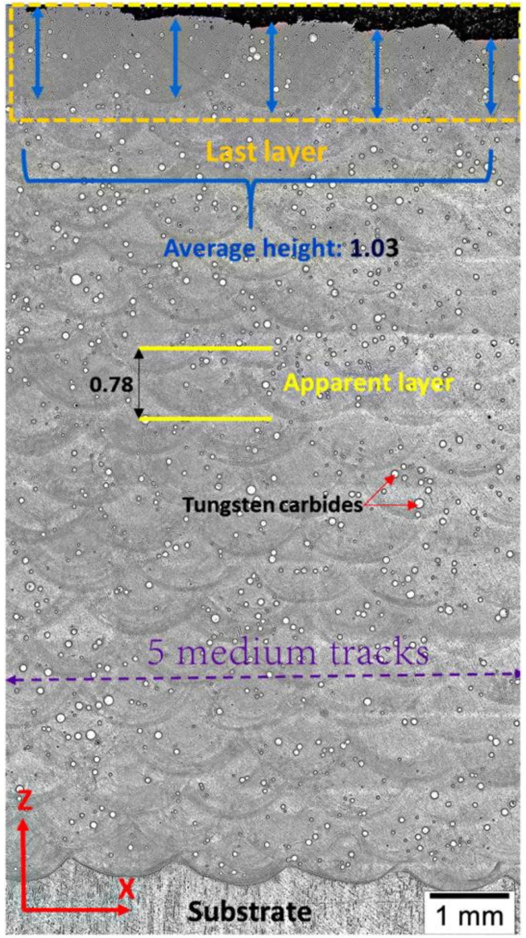


Average Vickers hardness per layer within cladded deposits (316L vs MMCs)

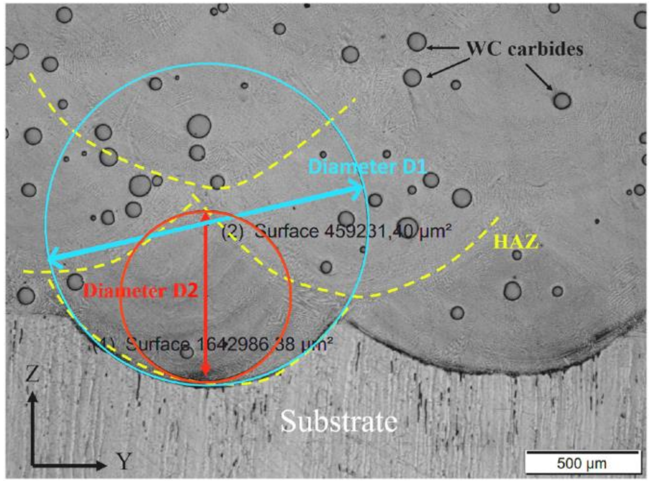


Size particle distribution (virgin WC) and average diameter of reinforcements dissolved in MMC clads

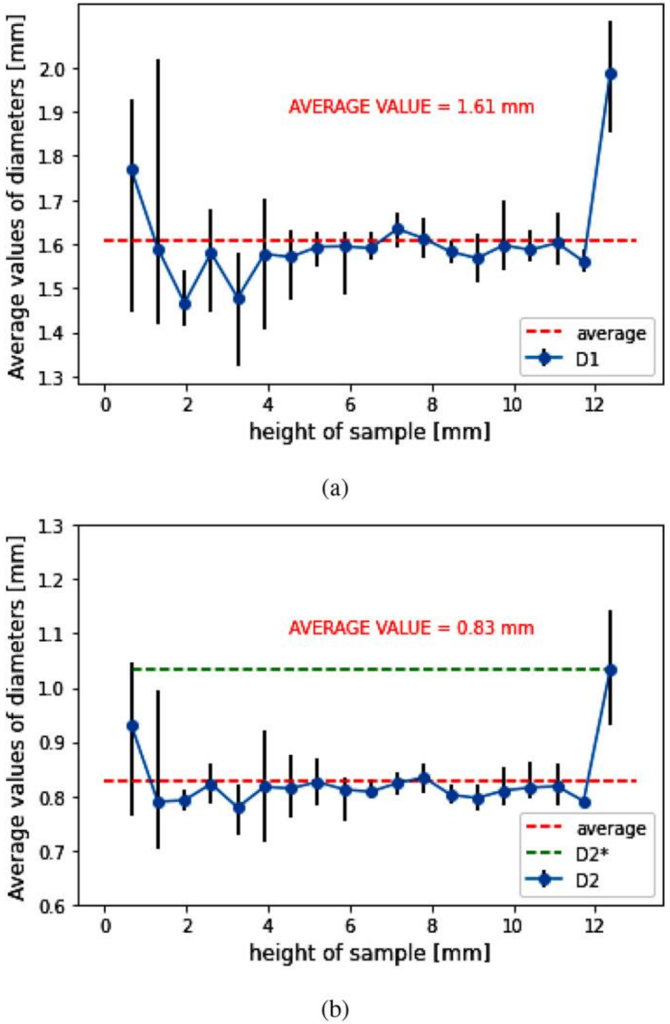
Results : Macro scale... (Layer thickness and melt pool sizes)



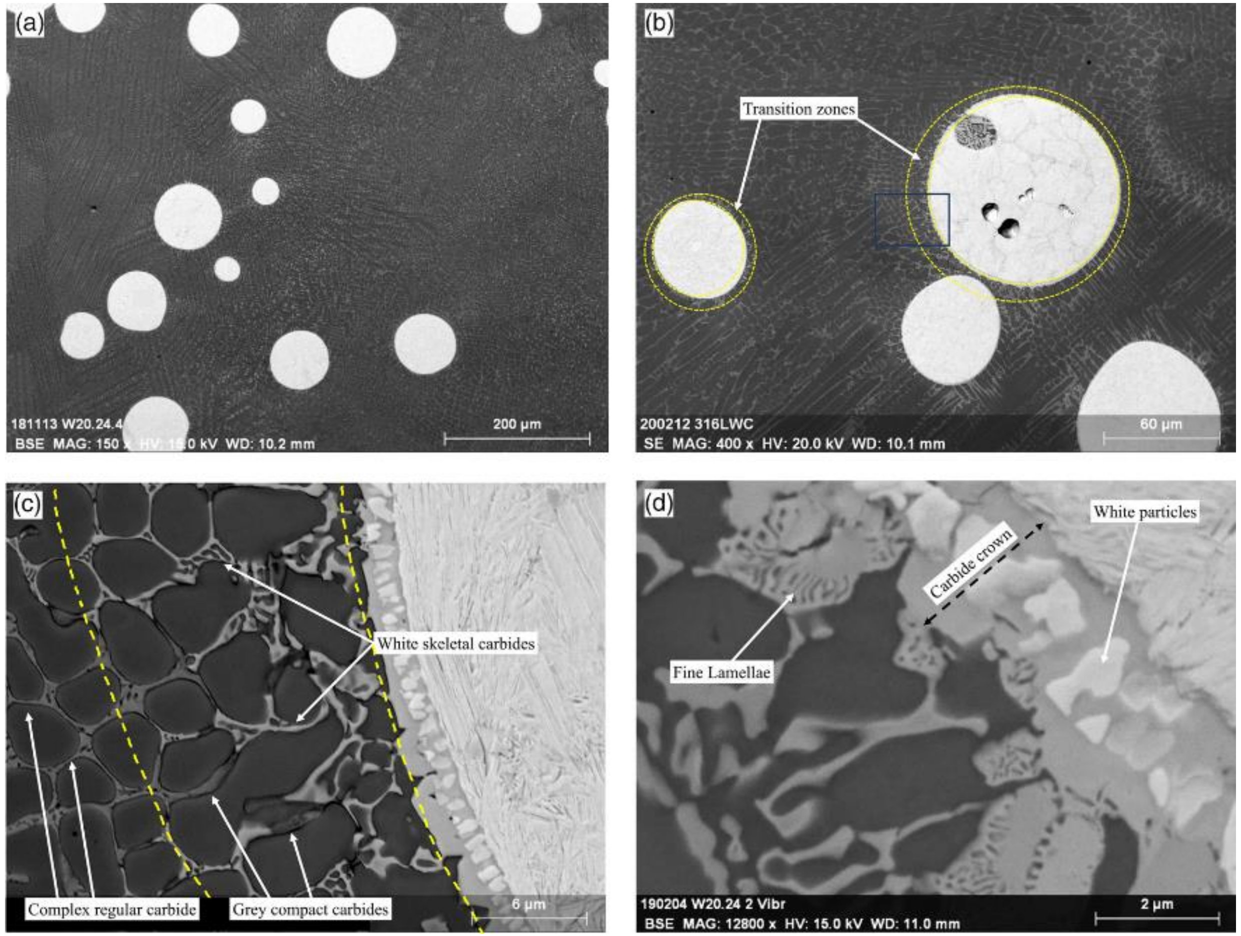
Average layer thickness assessment

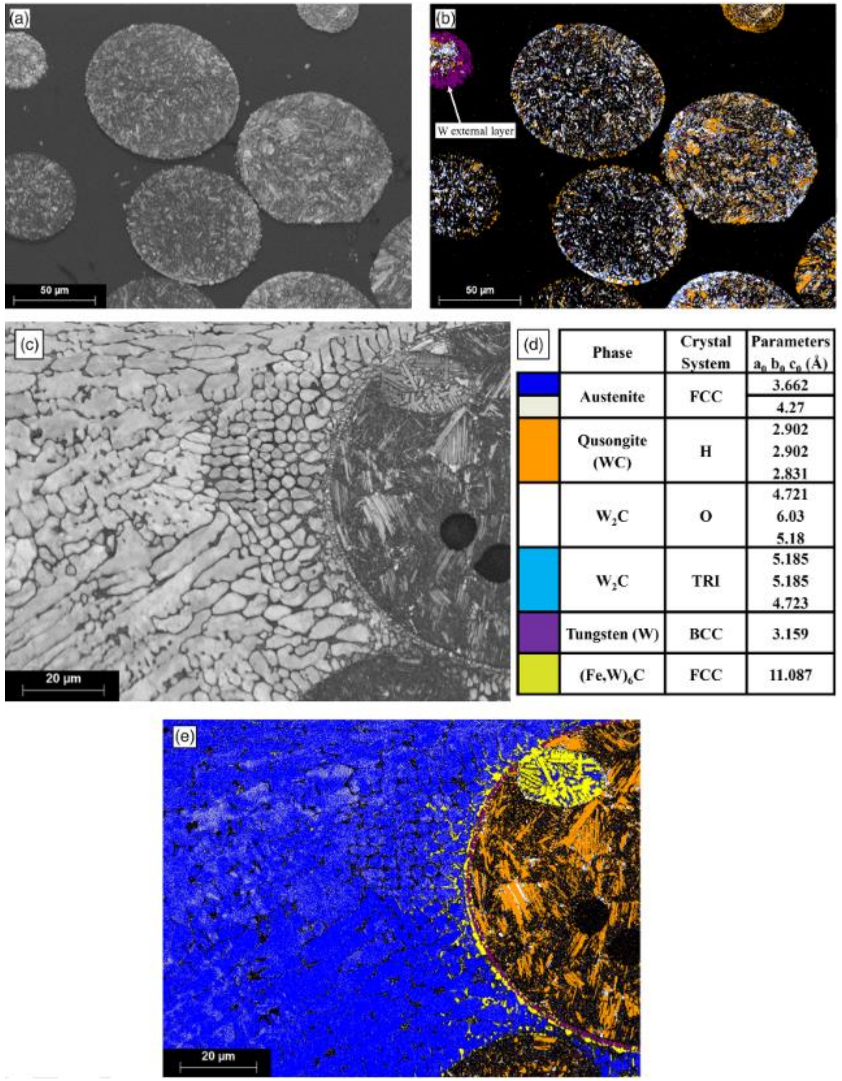


Melt pool size assessment (effective D1; apparent D2)



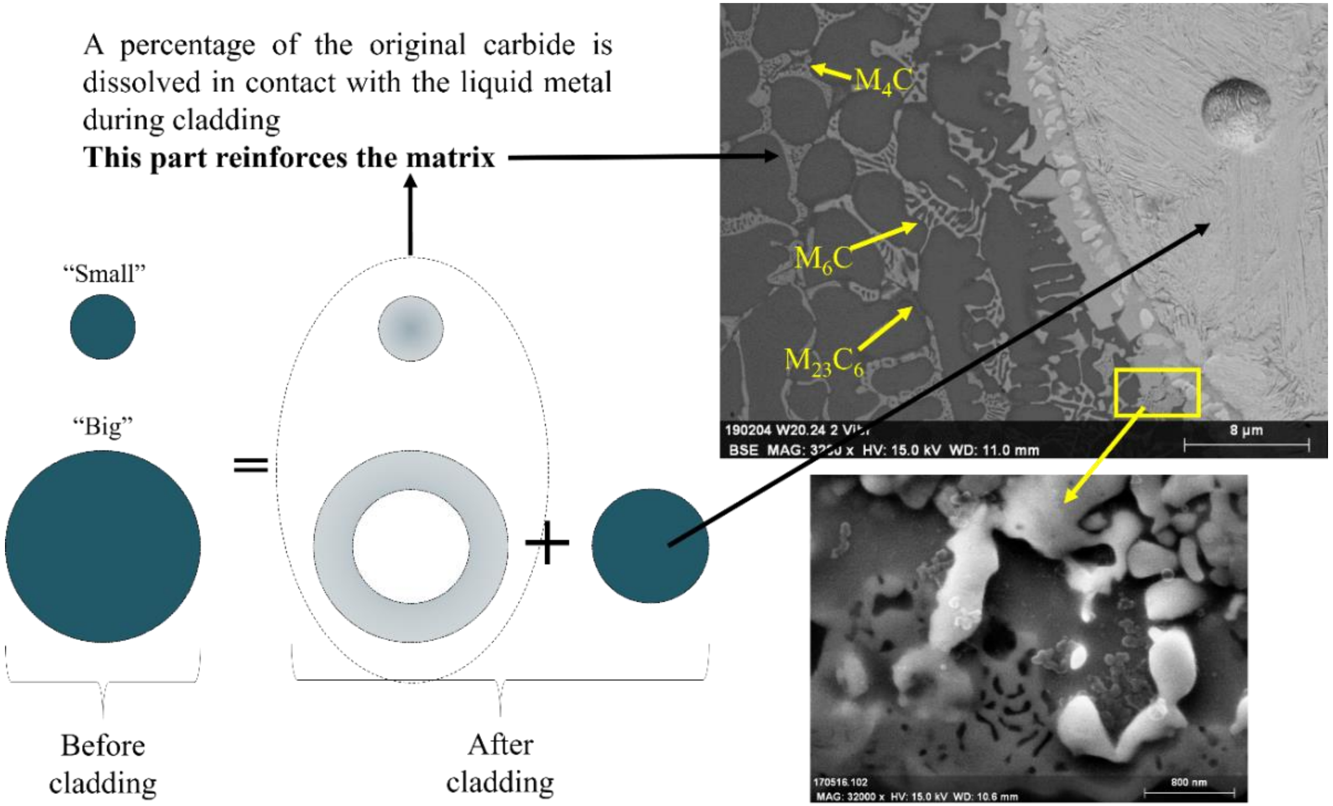
Results : Micro scale… (phase identification and WC dissolution)





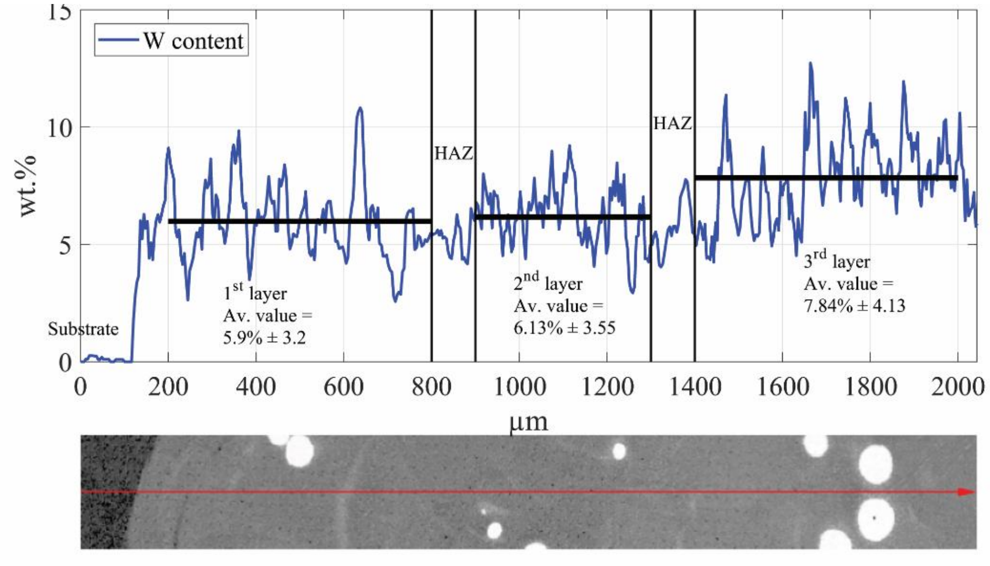
Fully/partial dissolution of WC with **crown** on the surface; in-situ eutectic carbides network within the matrix

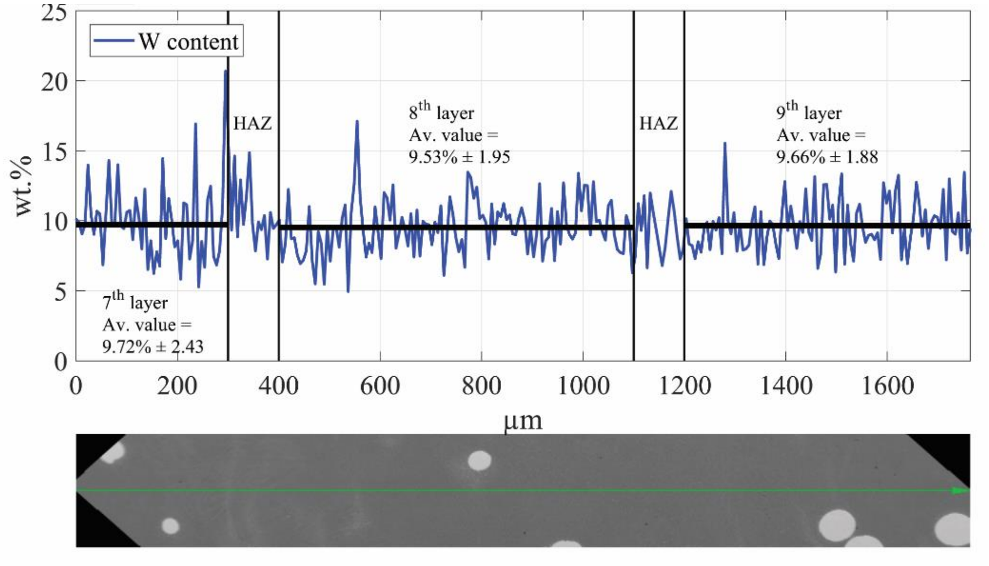
Results : Macro scale… (dissolution of the WC reinforcements within the matrix)



Fully/partial dissolution depending on the initial WC powder diameter.
Complete dissolution possible for smaller WC particles.
In-situ eutectic carbides network inside de matrix

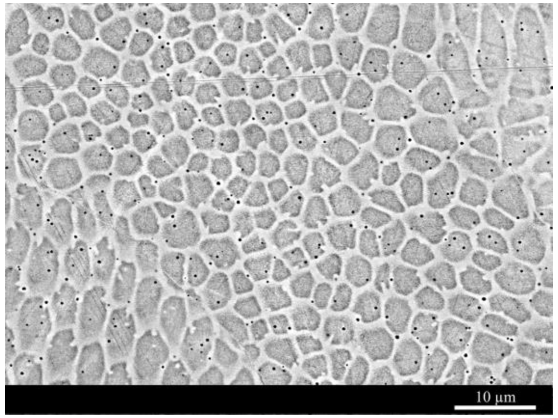
Results : Micro scale… (dissolution of the WC reinforcements within the matrix)



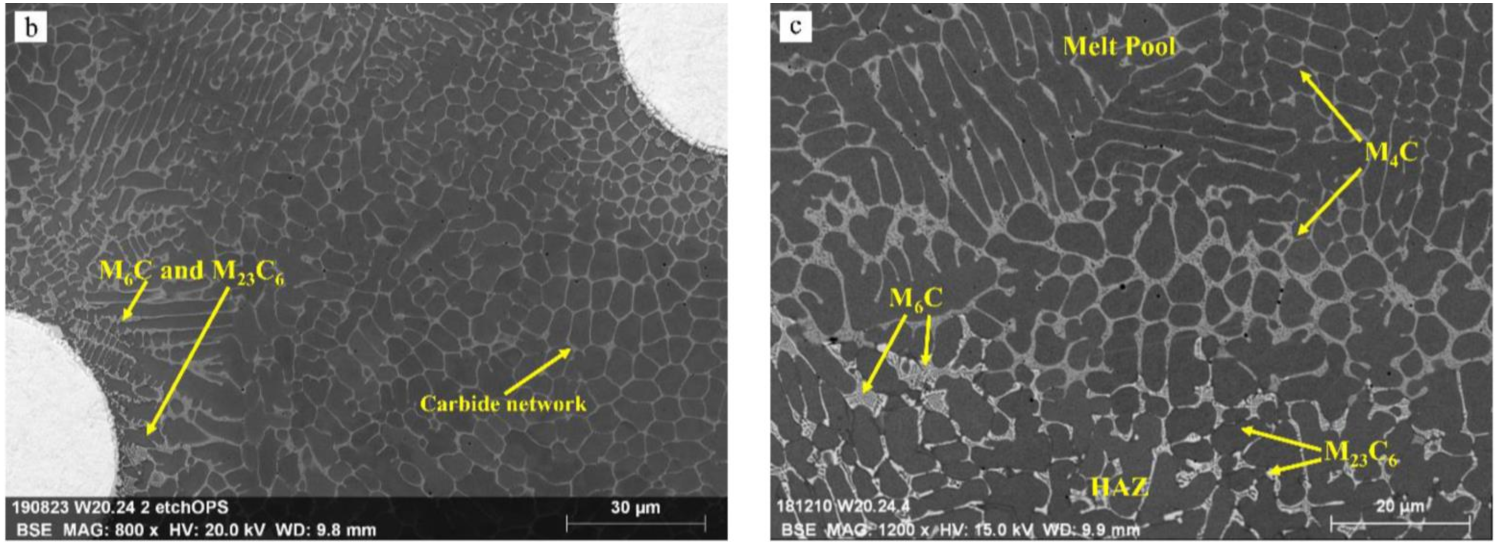


W distribution inside the MMC matrix clad (20%WC) away from undissolved WC for the first layers (increasing amount) and in the middle of the deposit (maximum and stable amount)

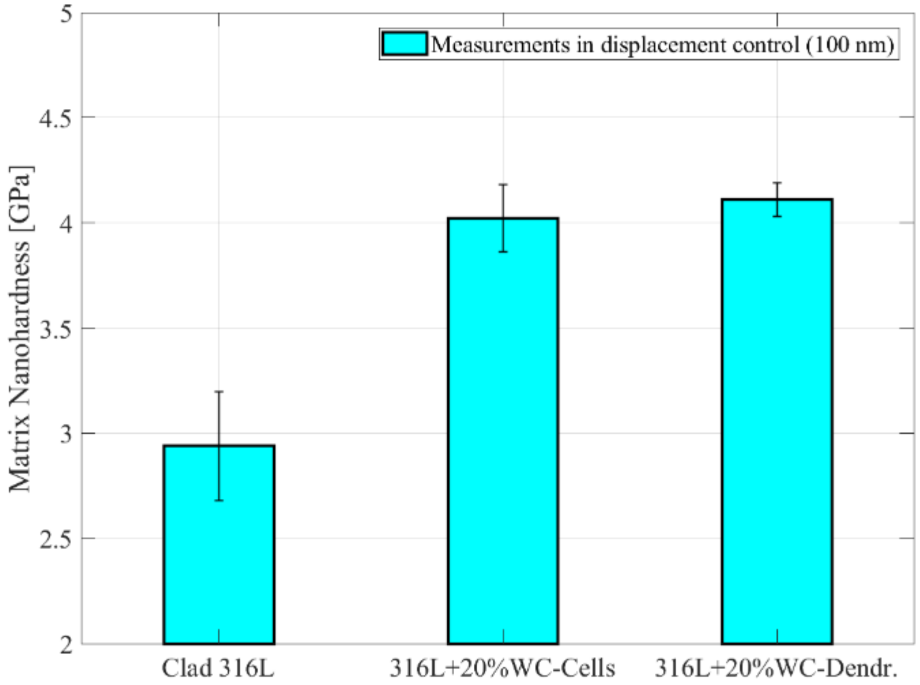
Results : Micro scale (cellular microstructures)



316L DED

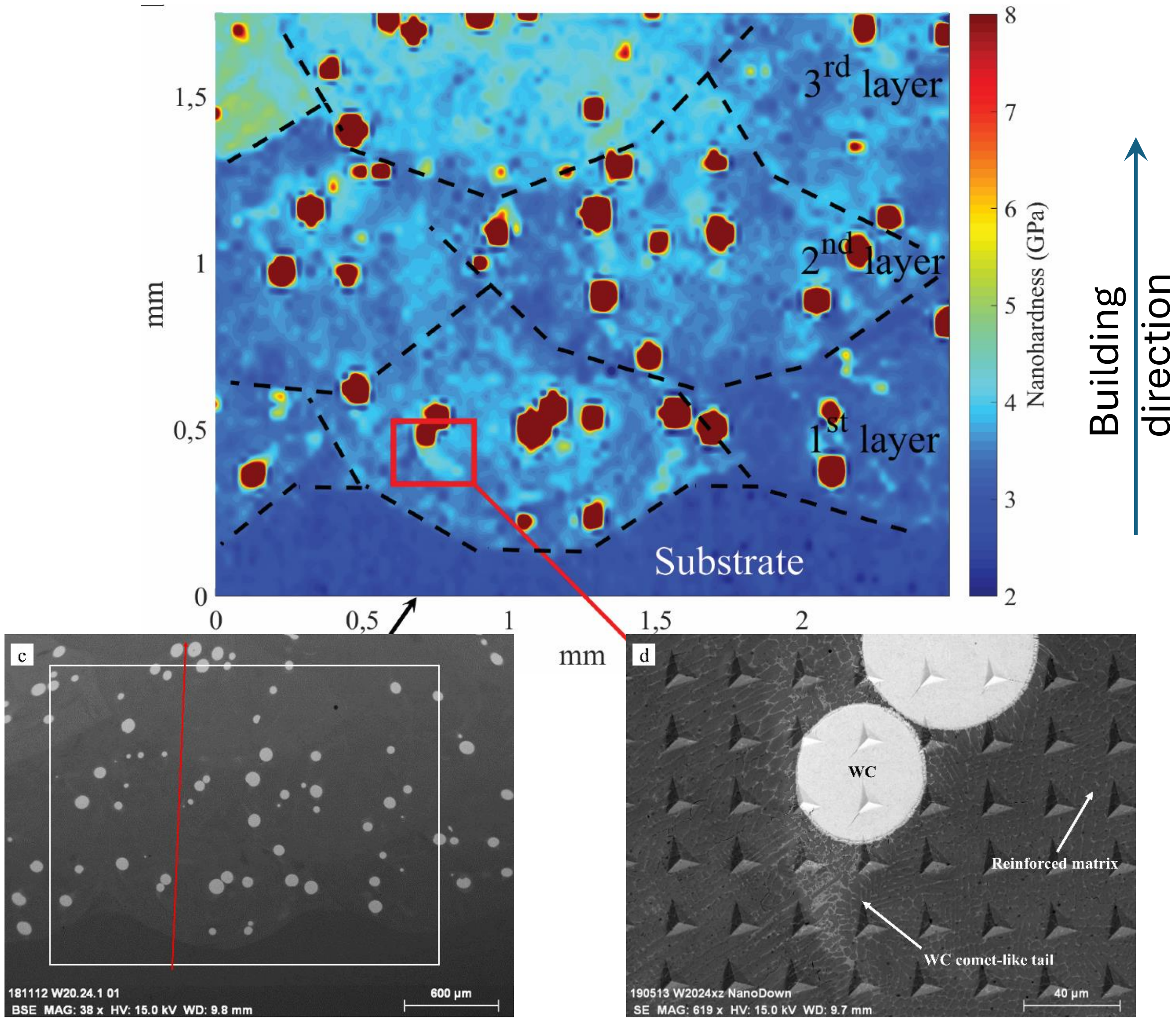


MMC DED and various carbide networks



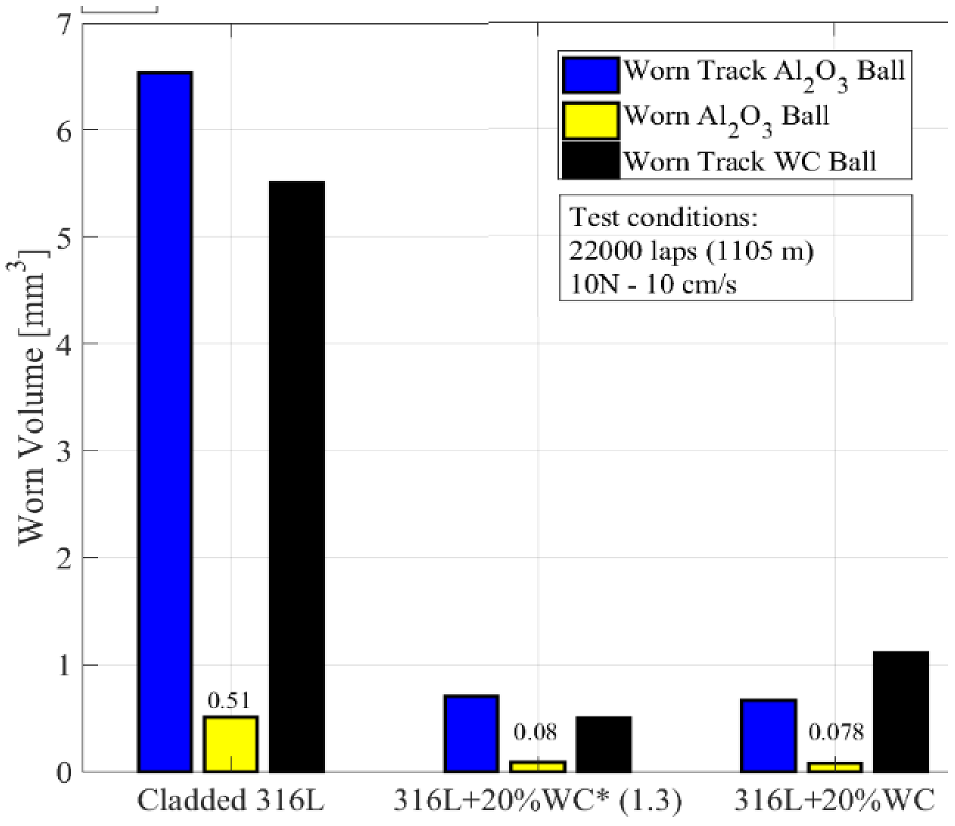
Cellular-like structure within MMC DED with phases enhancement (MP vs HAZ)

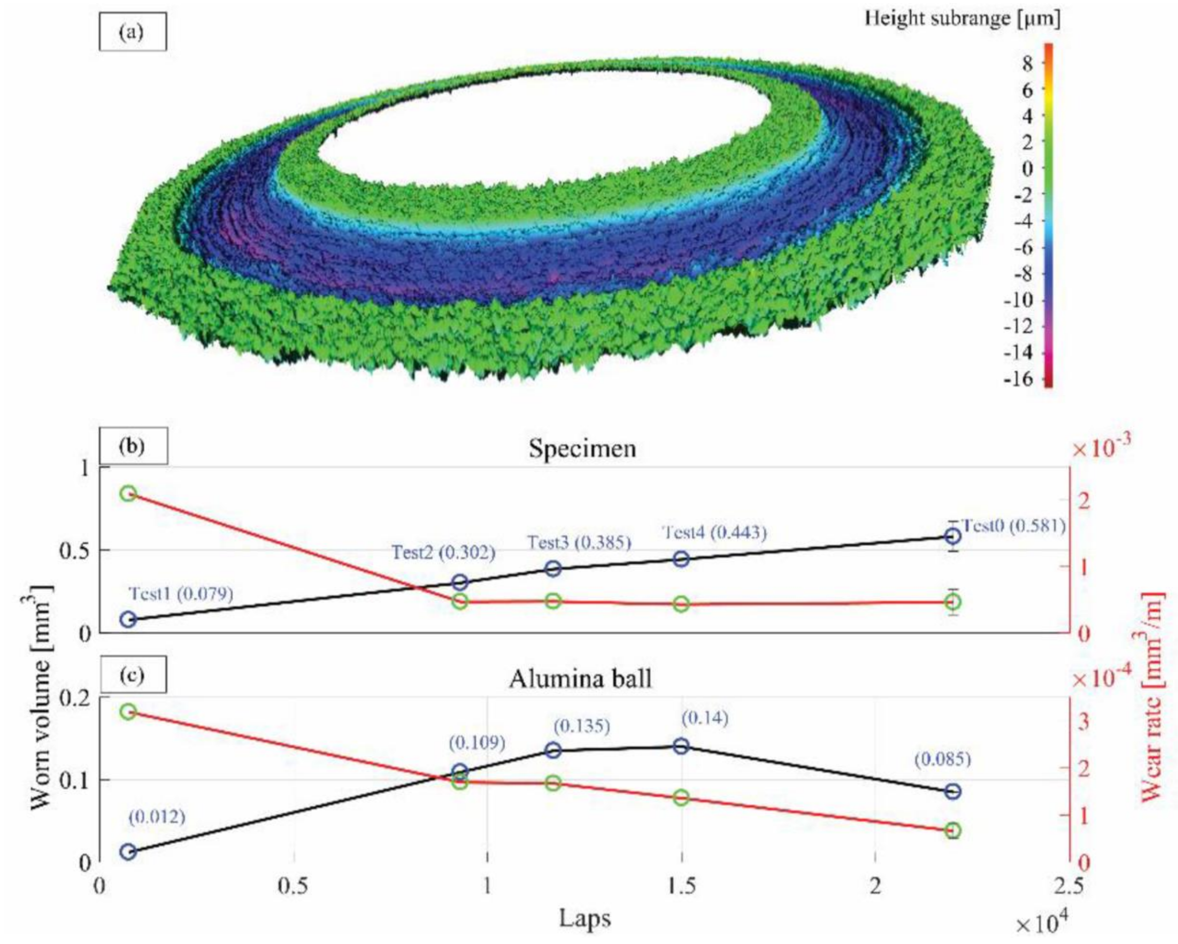
Results : Nanoscale (Solid solution strengthening)



Nanoindentation map and close-up view
(W diffusion)
Solution hardening increasing with deposition
(heat accumulation effect)

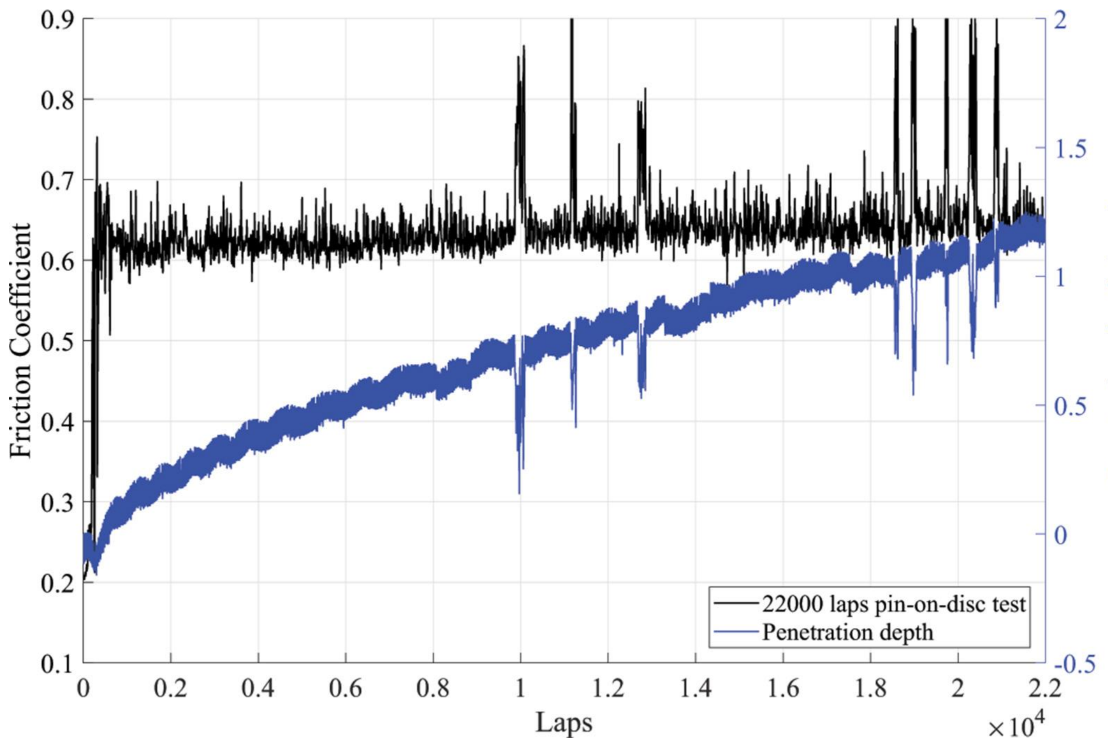
Results : Wear behavior (Worn volumes and wear rates)



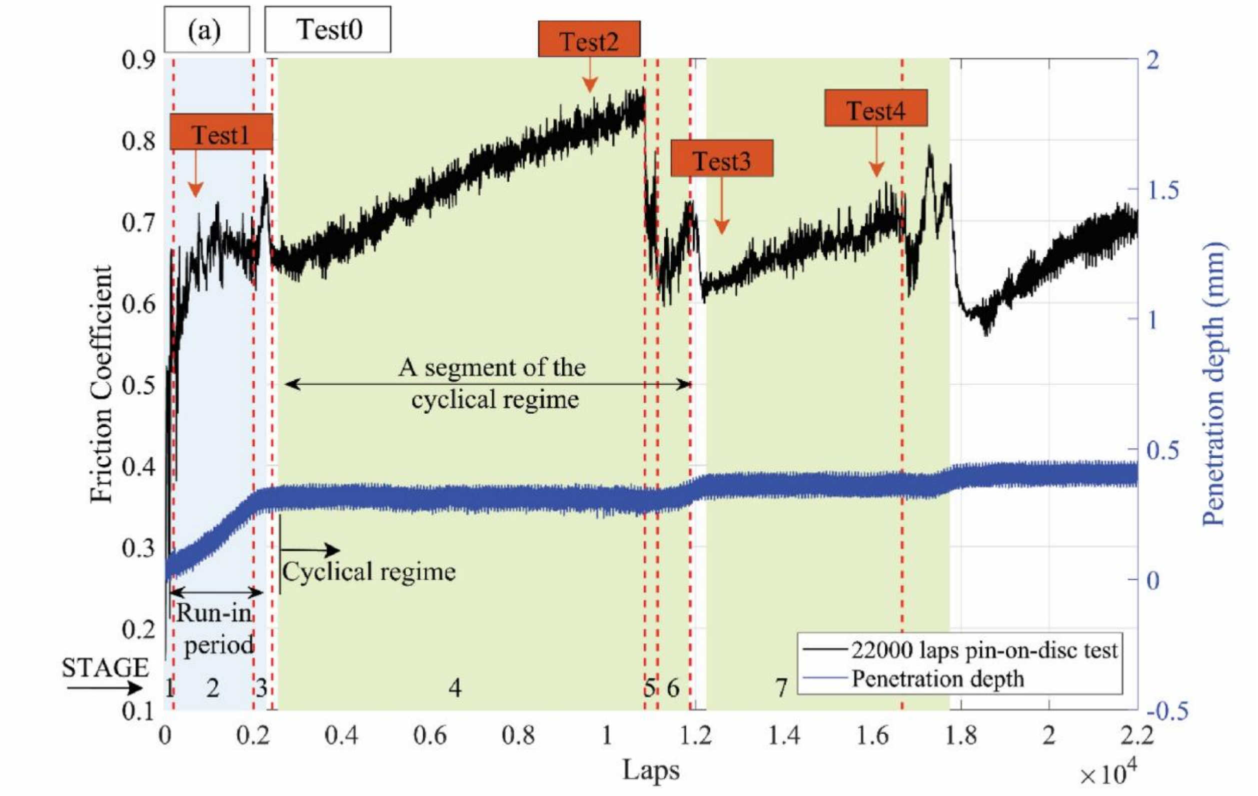


Topography of the wear surface after 220000 laps Measured worn volumes on both wear track and counterbody

Results : Wear behavior (MMC DEDed VS 316L DEDed; CoF and PDe evolution)

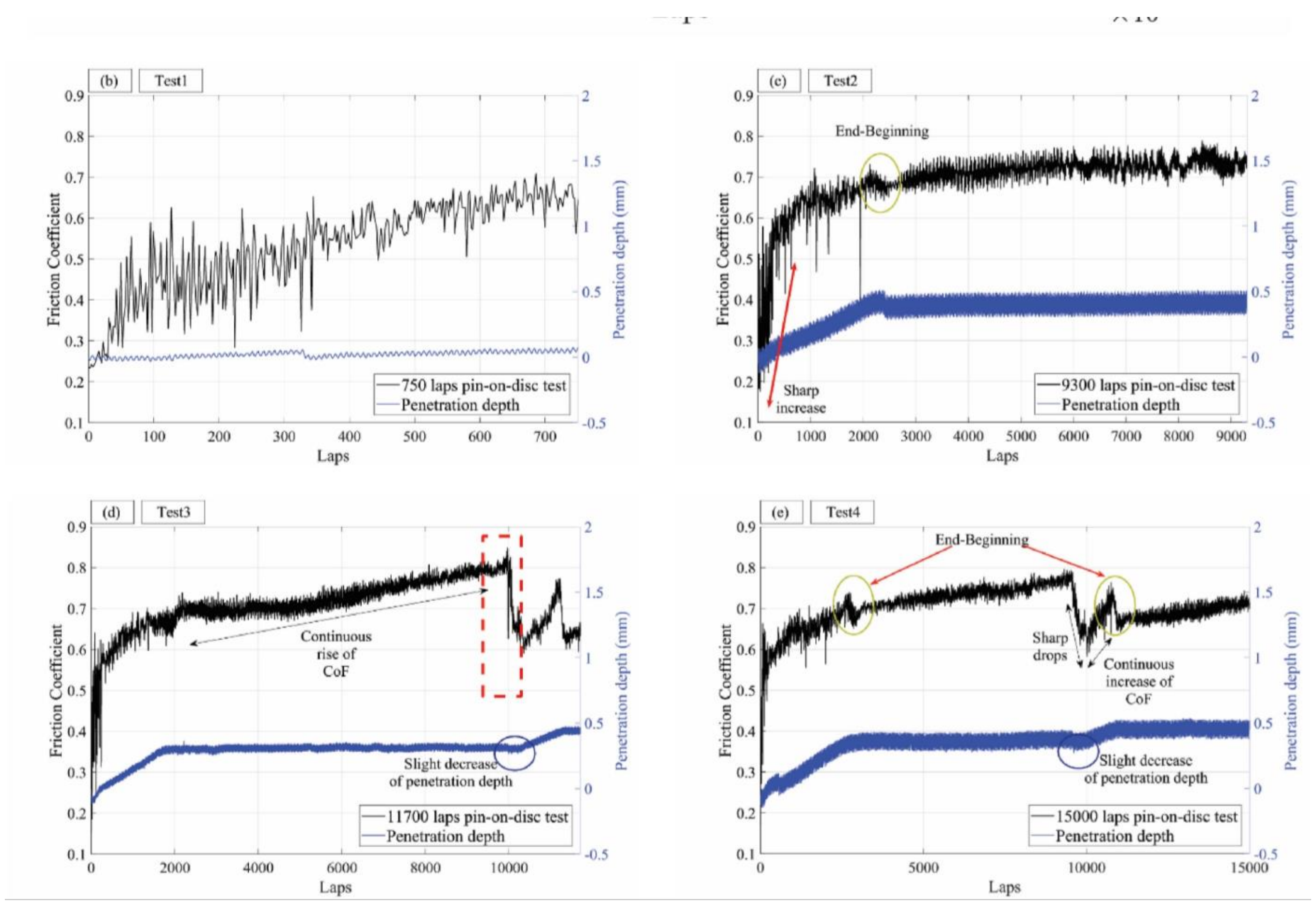


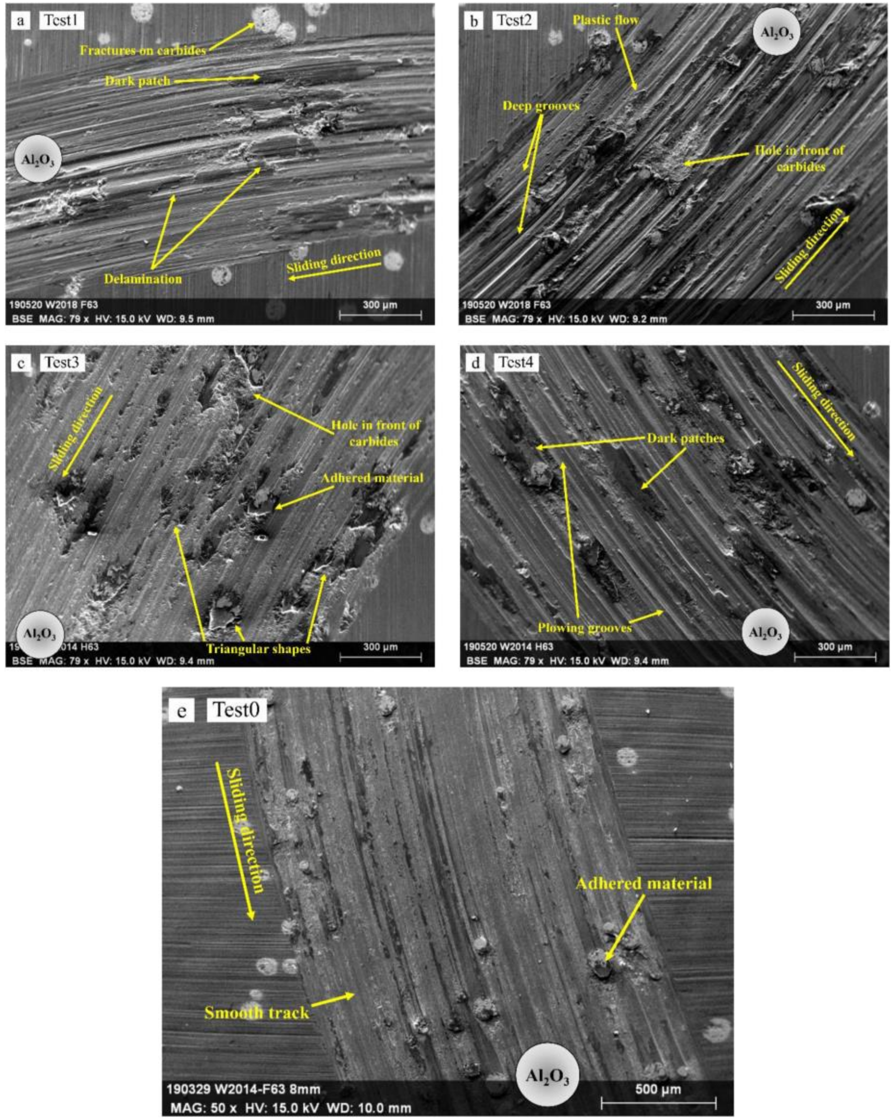
316L (Constant CoF with increasing PDe)



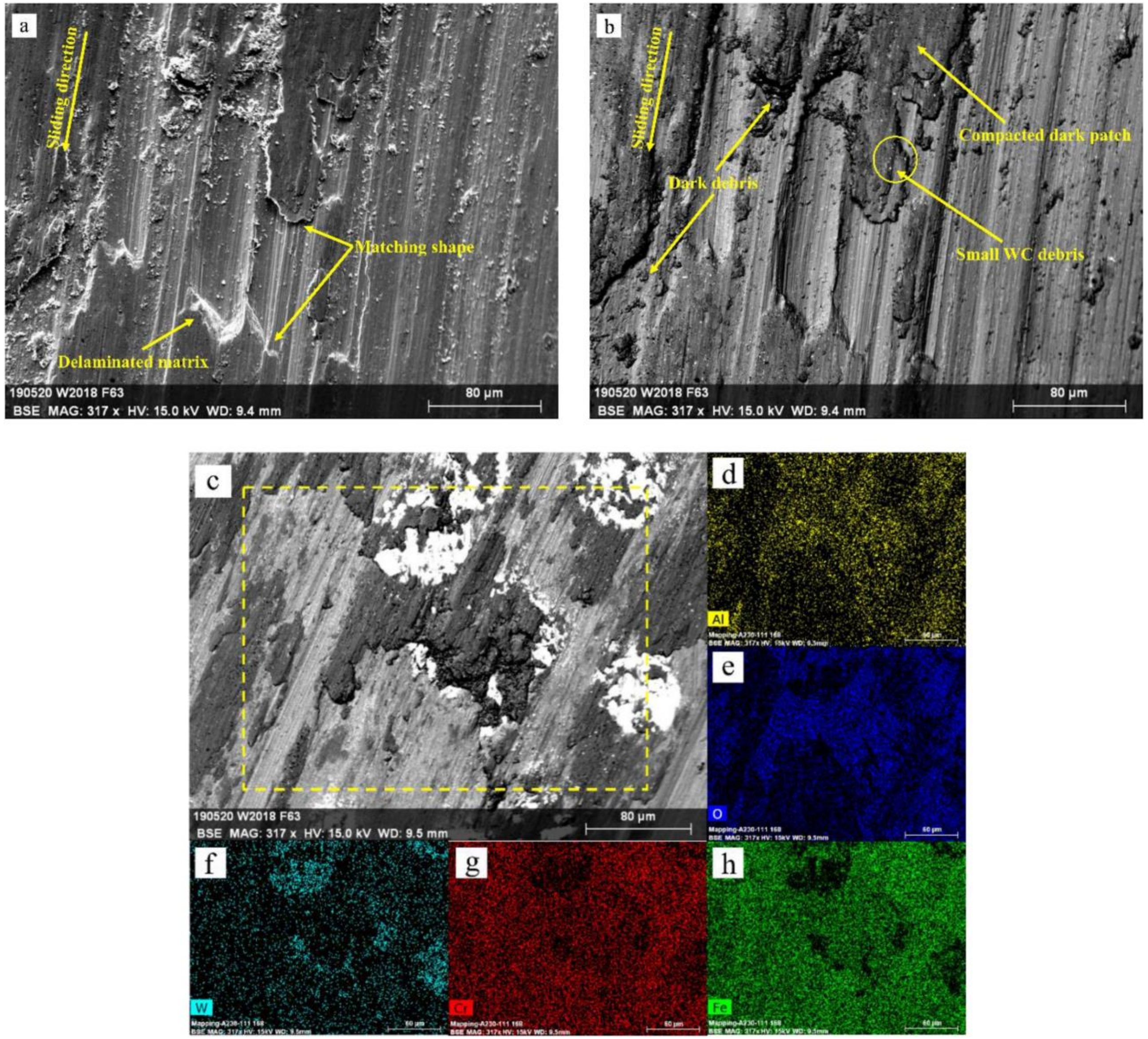
MMC (Cyclical regime)

Results : Wear behavior (Interrupted tests)



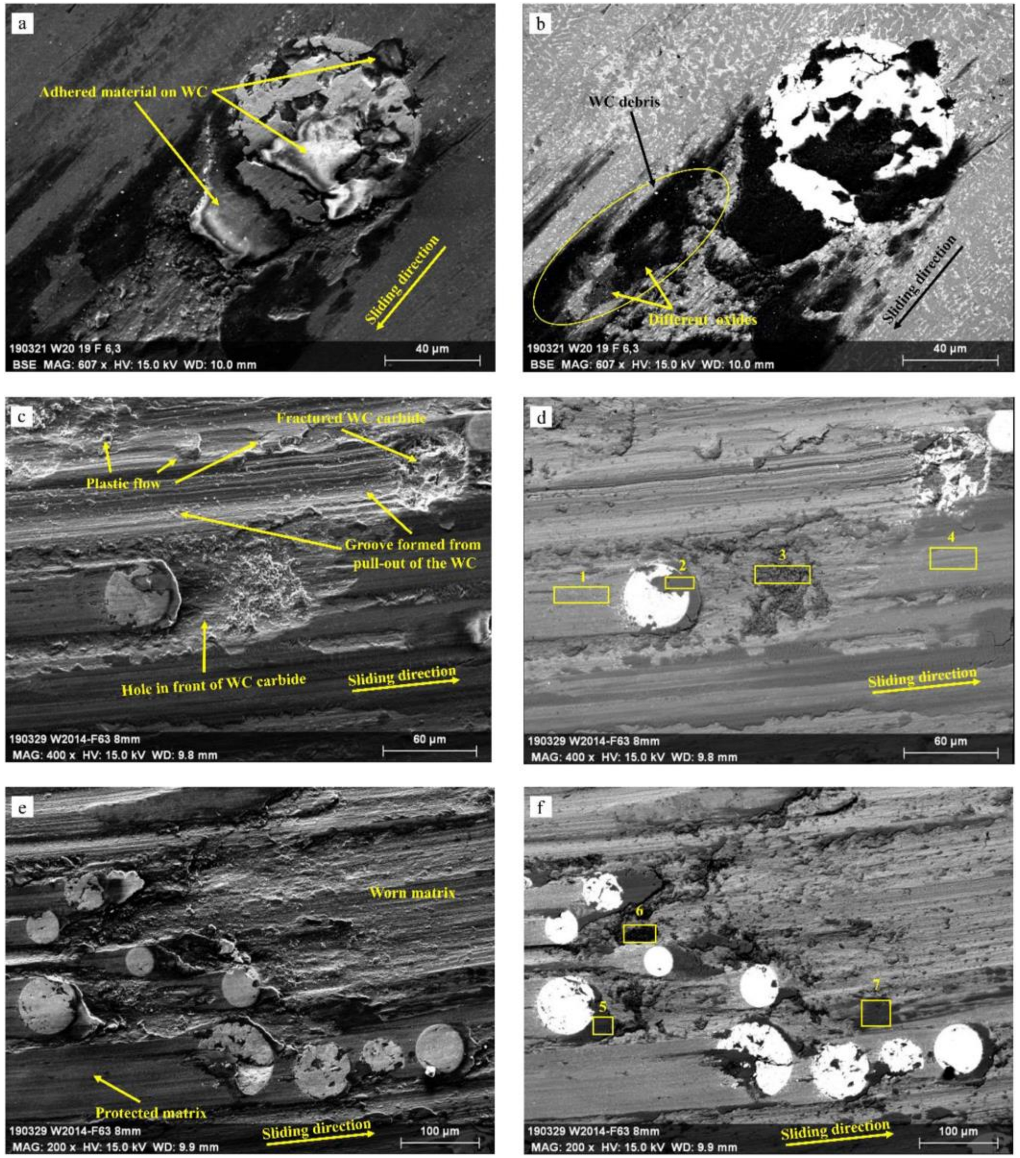


Results : Wear behavior (After 750 laps)



- Brittle failure after material delamination
  - Complex Al-rich oxide « coating » upon and ahead of WC reinforcements

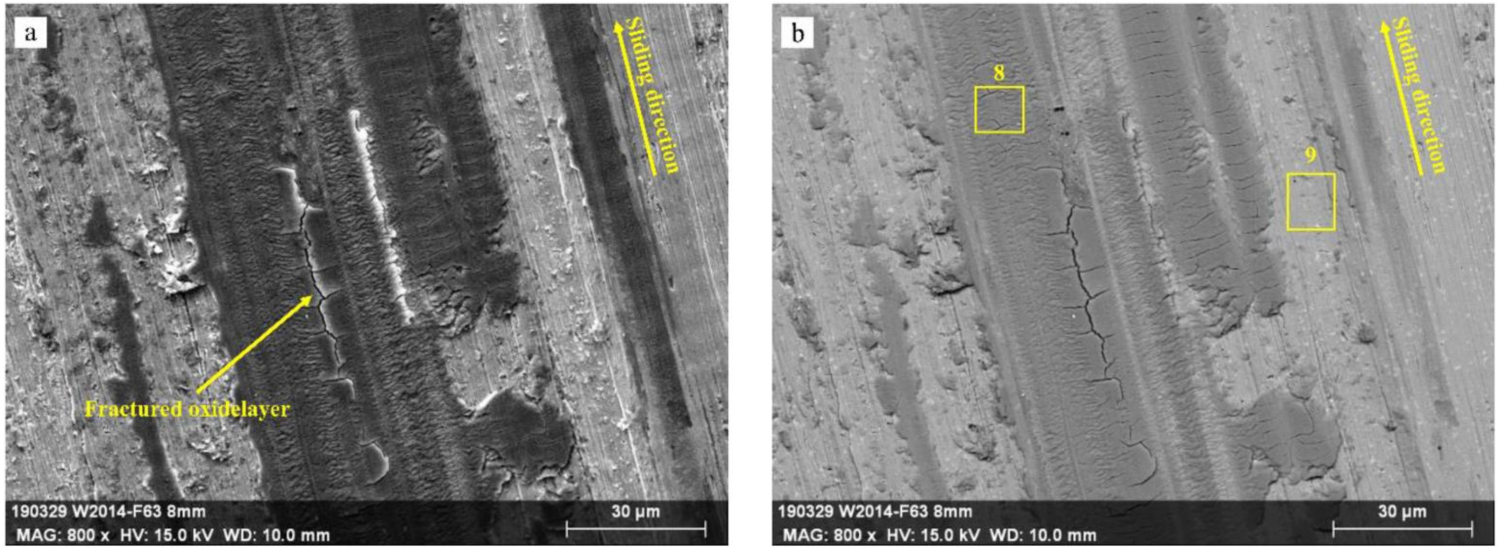
Results : Wear behavior (After 750 laps)



% At.	C	O	Cr	Fe	Al	W	Ni	Mo
Point	Features in the vicinity of WC							
1	5.7	21.6	12.9	46.6	1.2	2.6	8.2	0.9
2	7.2	65.5	2.8	9.4	4.4	8.9	1.7	0.1
3	7.1	46.1	8.2	28.0	3.4	1.7	4.7	0.5
4	6.9	31.8	10.3	38.9	1.5	2.6	7.1	0.6
5	6.3	68.1	3.6	13.2	3.1	3.1	2.4	0.2
6	8.0	60.3	3.6	13.9	9.6	2.1	2.3	0.2
7	6.3	53.3	6.5	23.8	2.9	2.6	4.3	0.4

- Brittle failure after material delamination
- Complex Al-rich oxide « coating » upon and ahead of WC reinforcements
- Beginning of tribolayer formation

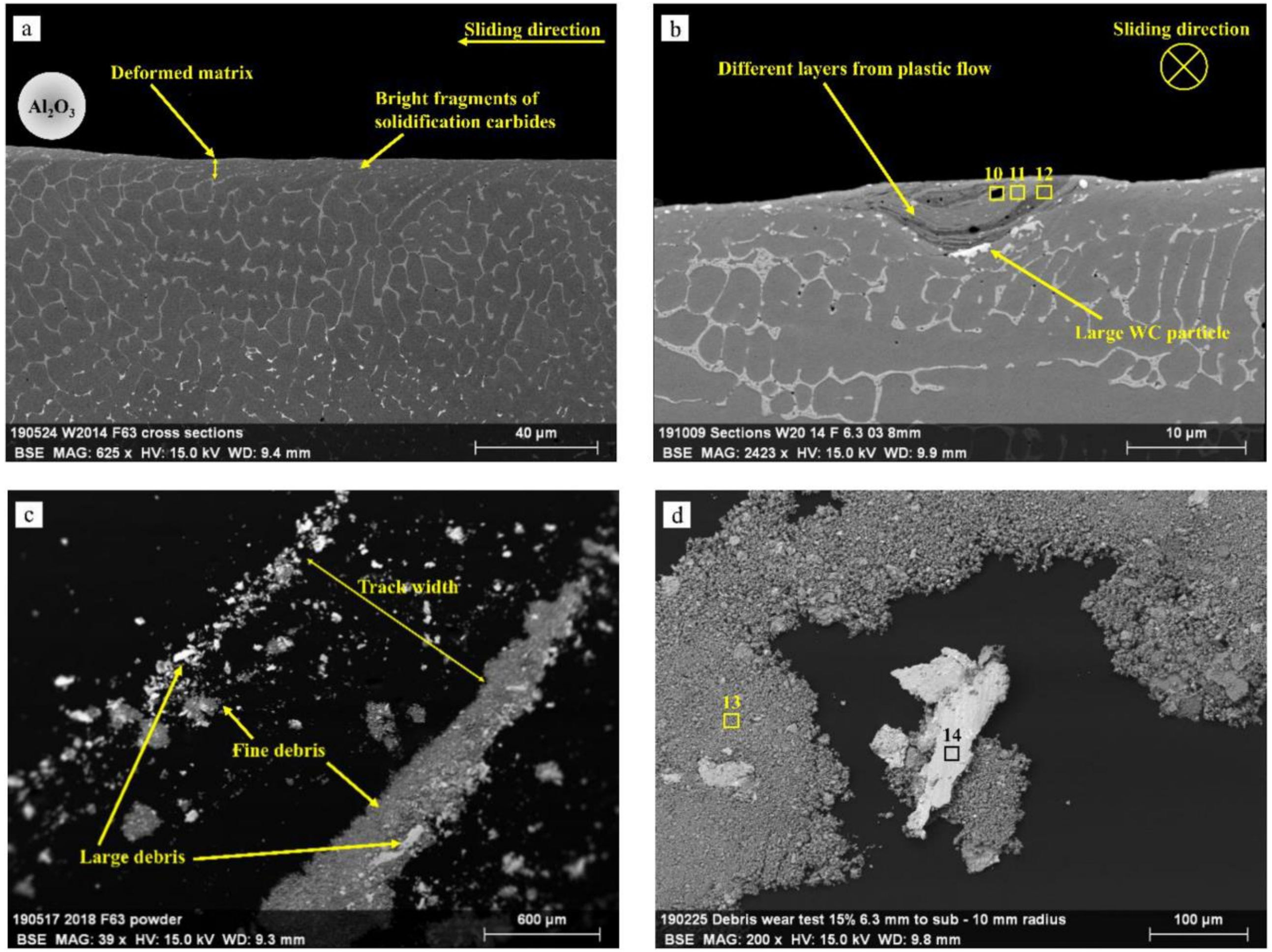
Results : Wear behavior (After 9300 laps)



% At.	C	O	Cr	Fe	Al	W	Ni	Mo
Point				Features of the matrix				
8	2.2	27.0	8.6	31.8	3.4	16.8	5.4	0.9
9	1.8	2.5	14.3	54.8	0.3	7.5	10.2	2.0

Crack within the oxide layer (compacted tribolayer) that covers almost all the wear track

Results : Wear behavior (After 22000 laps)

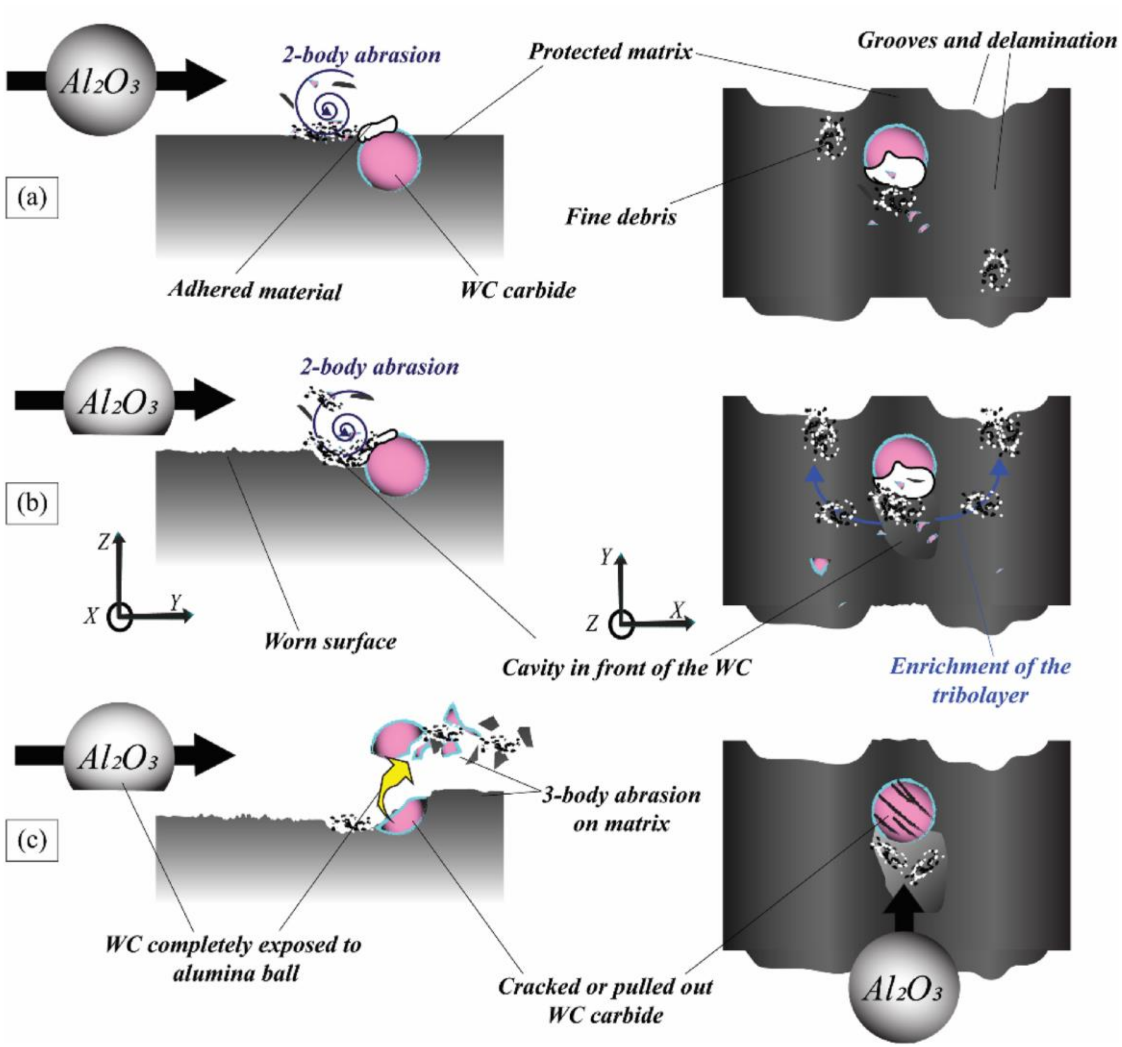


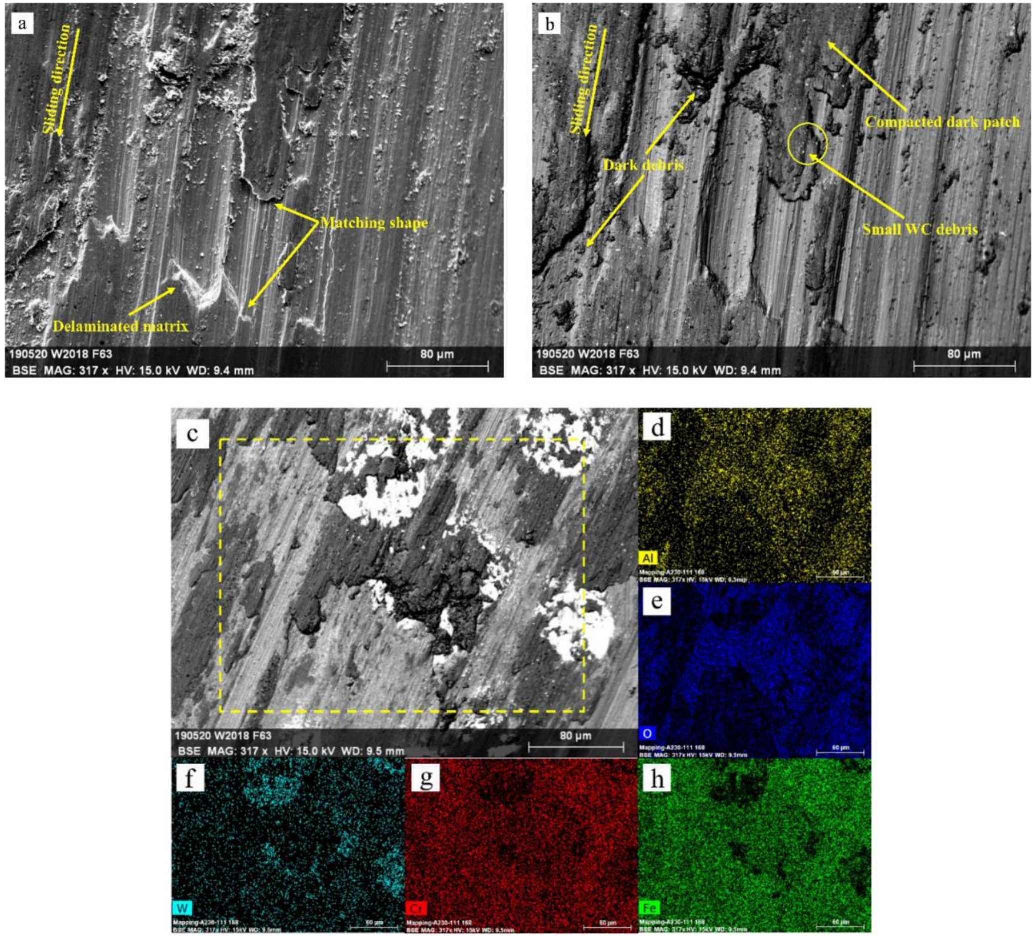
% At.	C	O	Cr	Fe	Al	W	Ni	Mo
Point	Perpendicular cross-section							
10	5.9	49.4	3.1	9.5	29.9	0.5	1.2	0.3
11	12.2	7.0	13.4	52.7	0.1	2.4	9.3	0.9
12	9.4	40.3	8.0	31.1	1.9	2.0	5.5	0.6
		Debris						
13	6.2	14.2	11.3	45.2	4.6	11.1	7.5	/
14	25.0	8.5	10.5	44.6	0.4	1.4	9.4	0.9

Thin mechanical mixed layer (MML) within the wear track, with debris on the borders made of cracked WC and oxidized matrix

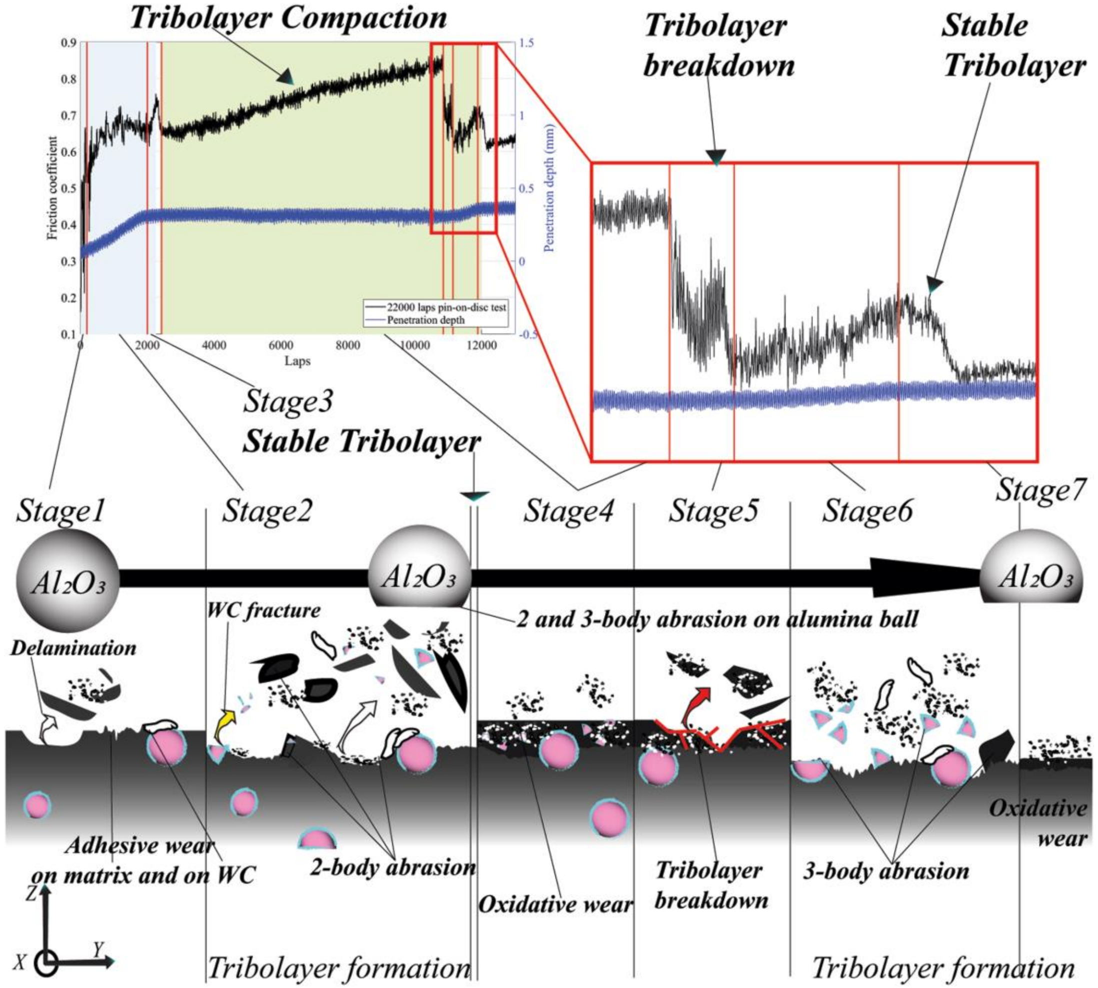
- Cross sections with the plastically deformed layer on the surface (= crack-free MML) ~10 µm
- Debris on the edges of the wear track

Discussion : Wear mechanisms highlighted





Discussion : Wear mechanisms highlighted



Delamination → Tribolayer formation → Stable Tribolayer → Oxidative Wear → Tribolayer breakdown → Tribolayer formation → Oxidative wear

Conclusions

- Complex hierarchical structure of cellular-type with reinforcements for MMC 316L+20%WC processed by DED.
- Dissolved WC leading to both in-situ M_2C eutectic carbides and solid solution strengthening.
- Cyclical wear regime achieved under dry sliding conditions.
- Important insights into the complex wear sequence of the MMC thanks to interrupted tests approach.
- Higher wear rate achieved during run-in period (MMC + Counterbody) involving delamination, adhesive and abrasive wear mechanisms.
- Formation, compaction and stabilization of a tribolayer within run-in period.
- Mild wear after run-in regime associated with oxidative wear and tribolayer breakdown

Thanks for your attention