SUPSI

University of Applied Sciences and Arts of Southern Switzerland

Exploring Ultrafast Laser Ablation as a scalable solution for surface modification of Ti6Al4V orthopaedic implants

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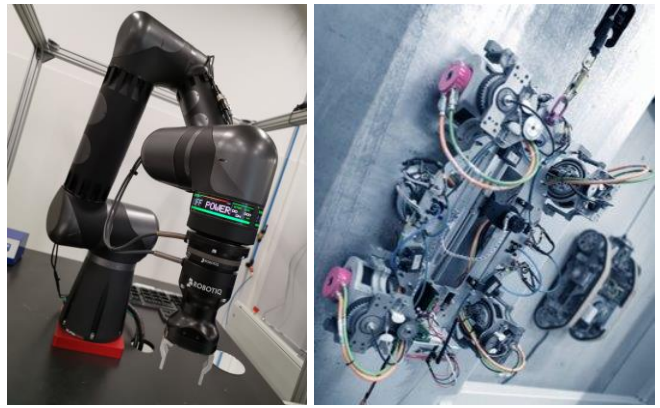
SWISS PHOTONICS

Outline

- ARM Lab Overview
- Research Challenge
  - Bone remodelling cycle
  - Bacterial Adhesion
- Anterior Lumbar Interbody Fusion (ALIF)
- Ultrafast Laser Ablation
- Equipment
- Methodology
  - Characterization
  - Groove
  - Chemical Treatment
  - Simulated Body Fluid (SBF)
  - X-ray Photoelectron Spectroscopy (XPS)
- Interdisciplinary Activities
  - Antibiotic Coating
  - In-vitro tests
- Future Directions
- Conclusions

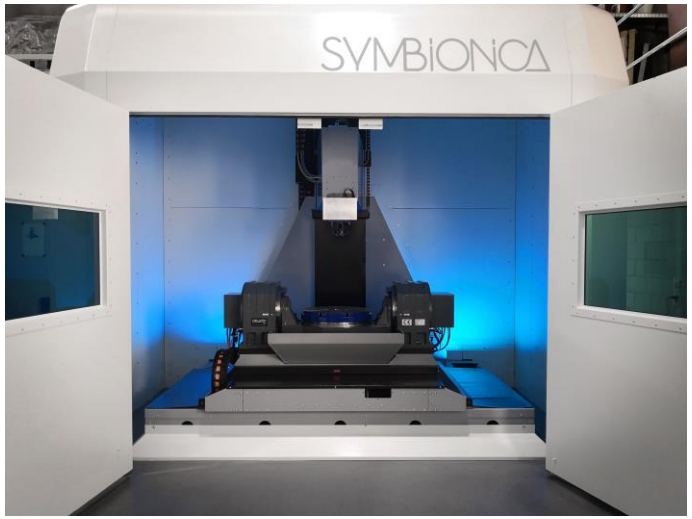
Automation, Robotics,
and Machines Laboratory
(ARM lab)

Robotic platforms

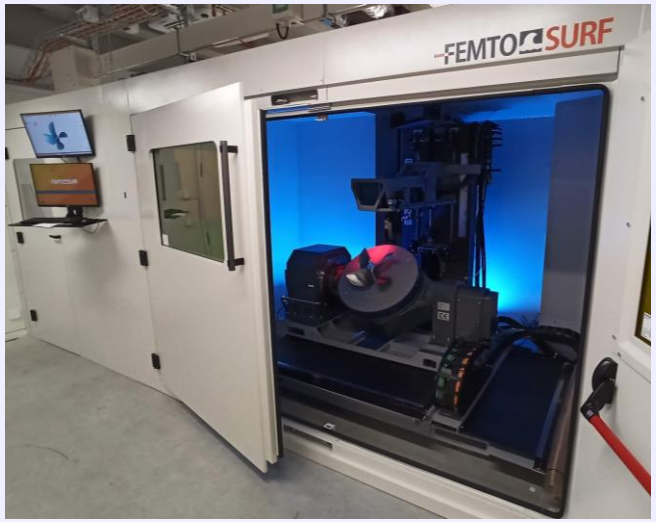


Laser Machines for industrial applications

Additive manufacturing



Femtosecond laser processing



Research Challenge

Orthopedic Devices

- Orthopaedic Implants
  - Aseptic Loosening
    - Bone resorption
  - Infection
    - Bio film formation
- Biological Characterization of textured surface

Swiss National Joint Registry Data for THA and TKA

Table 3.3b

Reason for revision* of total hip arthroplasty

Multiple responses possible (percentages do not sum to 100). 2016 – 2021

	N	%
Loosening femoral	3,244	21.2
Infection	3,200	20.9
Loosening acetabular	2,583	16.9
Periprosthetic fracture	2,647	17.3
Dislocation	1,850	12.1
Wear	1,053	6.9
Metallosis	774	5.1
Acetabular osteolysis	622	4.1
Position/Orientation of cup	715	4.7
Femoral osteolysis	574	3.8
Trochanter pathology	242	1.6
Status after spacer	331	2.2
Implant breakage	316	2.1
Blood ion level	239	1.6
Position/Orientation of stem	384	2.5
Impingement	210	1.4
Acetabular protrusion	173	1.1
Squeaking	90	0.6
Other	1,649	10.8
Total	**20,896**	

Table 4.3b

Reason for revision* of primary total knee arthroplasty

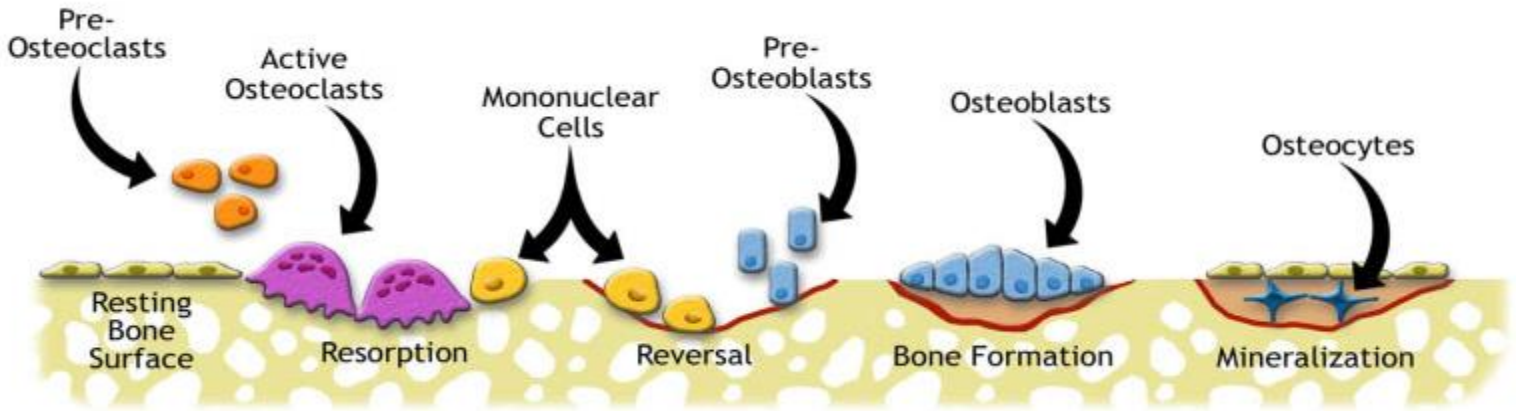
Multiple responses possible (percentages do not sum to 100). The reasons for revisions categories as listed below are only available from 2015 onwards

	N	%
Patella problems	3,319	27.0
Loosening tibia	2,234	18.1
Infection	2,529	20.5
Femorotibial instability	2,222	18.1
Pain (of unclear origin)**	1,249	10.1
Loosening femur	1,408	11.4
Wear of inlay	676	5.5
Joint stiffness/arthrofibrosis	735	6.0
Component malposition femur	547	4.4
Component malposition tibia	484	3.9
Loosening patella	266	2.2
Patellar instability	300	2.4
Periprosthetic fracture femur	256	2.1
Sizing femoral component	177	1.4
Periprosthetic fracture tibia	94	0.8
Sizing tibial component	61	0.5
Periprosthetic fracture patella	52	0.4
Other	1,333	10.8
Total 2016–2021	**17,942**	

Background - Bone Remodelling cycle

Dynamic process

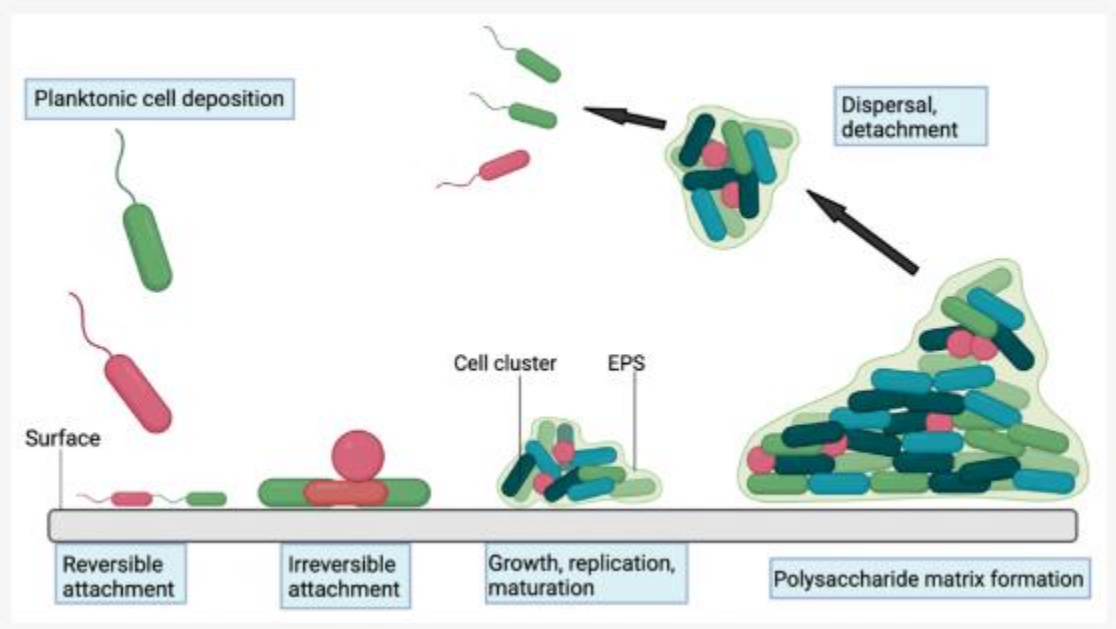
- Osteoblasts
  - Responsible for bone growth → *cuboid shape ca. 10 µm*
  - Sensitive to surface characteristics → *cell contact guidance mechanism*
- Osteoclasts
  - Responsible for bone resorption



Background - Bacterial Adhesion

Attachment steps

- Adherence
  - Van der Waals forces
  - Electrostatic
  - Hydrodynamic
- Accumulation
  - Bio-film formation
- Maturation
- Detachment

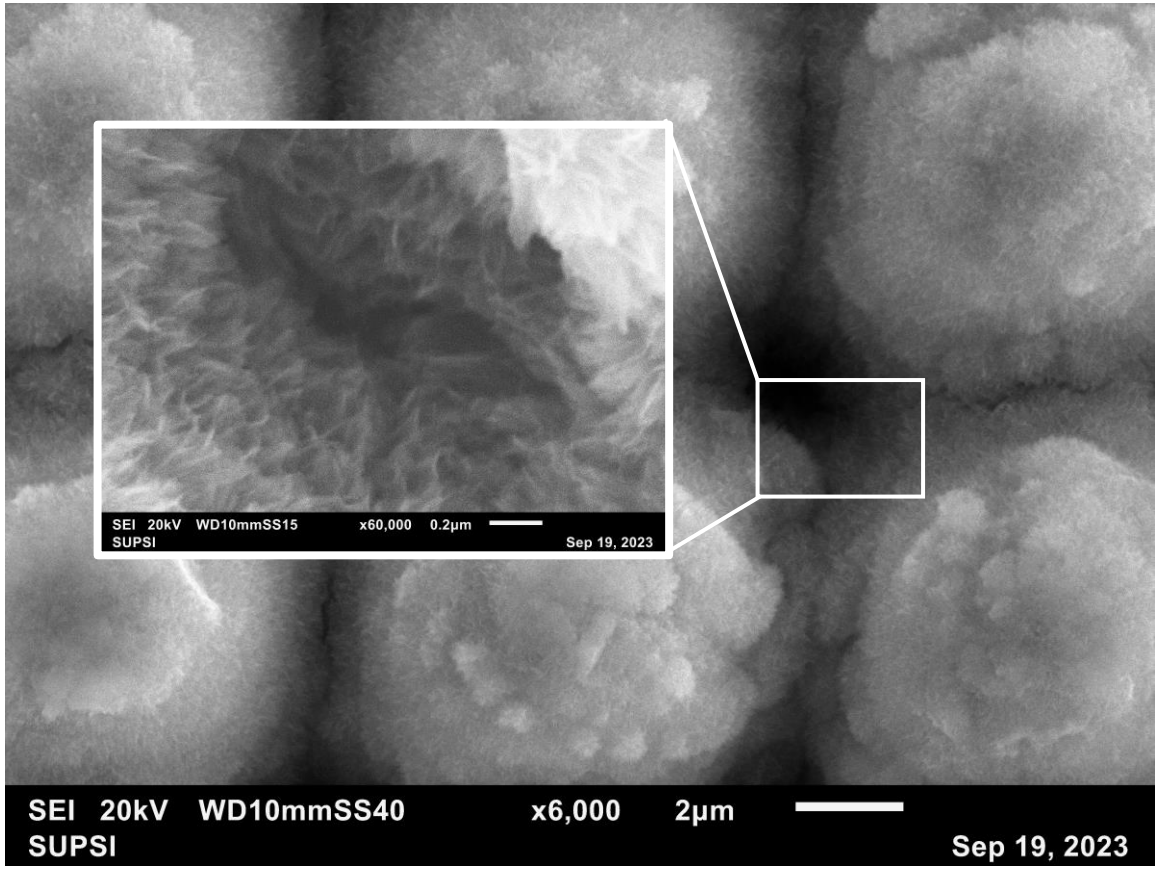


Anterior Lumbar Interbody Fusion (ALIF)

- Goals
  - Osteointegration
    - Slow bone generation
  - Enhanced anti-bacterial activity
    - Frequent infections in the screw housing
  - No cell growth
    - Surrounding tissue adhesion to the device

Ultrafast Laser Ablation

- Minimal Heat Affected Zone (HAZ)
- High reproducibility and resolution
  - Meso-scale structures
    - Structure [µm]
    - Laser Induced Periodic Surface Structures LIPSS [nm]

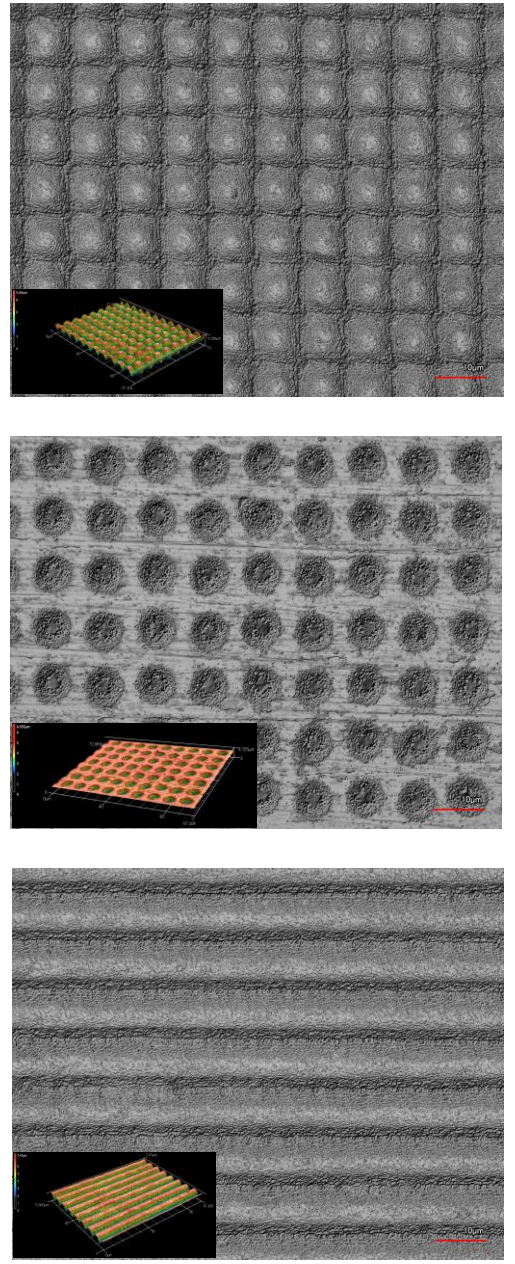


Equipment

- Mesomorph Machine
  - Wavelength: 515-1030 nm
  - Pulse Duration: 225 fs-10 ps
  - Rep. Rate: 60-1000 kHz
  - Max. Power: 20 W
  - Max. Fabrication Speed: 200 mm/s
- 3 Stations
  - Femtosecond laser station
  - Interferometric measurements
  - Direct atomic layer processing DALP

Methodology

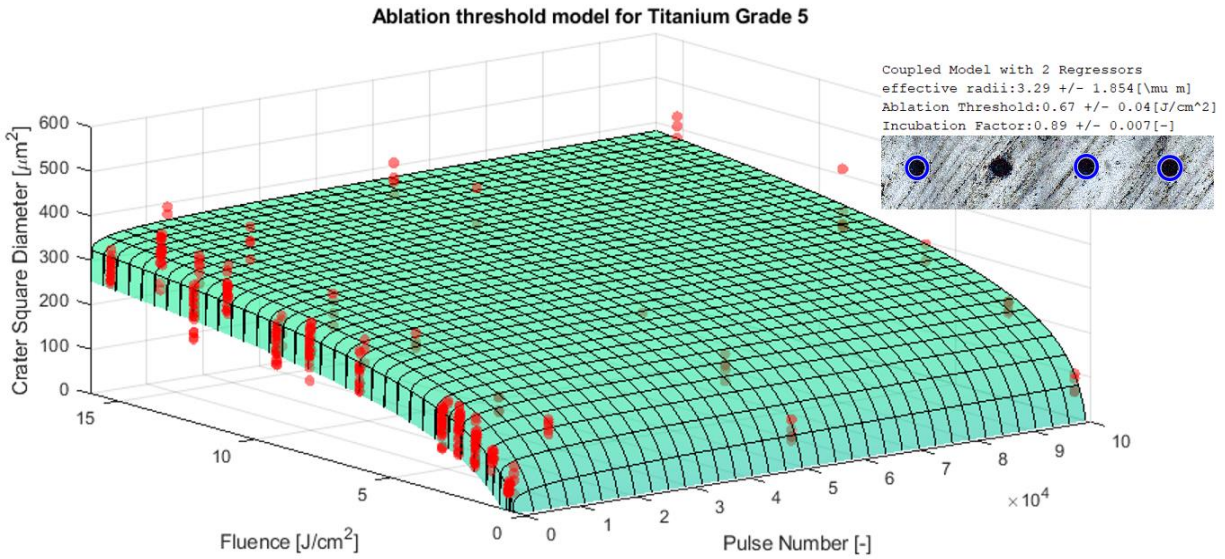
- Ti6Al4V Samples
  - Ablation threshold definition
  - Surface structuring optimization
- Machined pattern
  - Grooves 10 µm
  - Data Collection
- Chemical Treatment
  - None or Alkali Treatment (NaOH)
- Simulated Body Fluid
  - Apatite coating
- XPS Measurements
- In-vitro tests
- Antibiotic Coating



Structured surfaces - (Red line, 10 µm length)

Ti6Al4V Samples

- D-squared Measurements
  - Ablation Threshold
  - Incubation Factor
- Crater Measurement
  - Feature Detection
  - Automatic measurement of diameter



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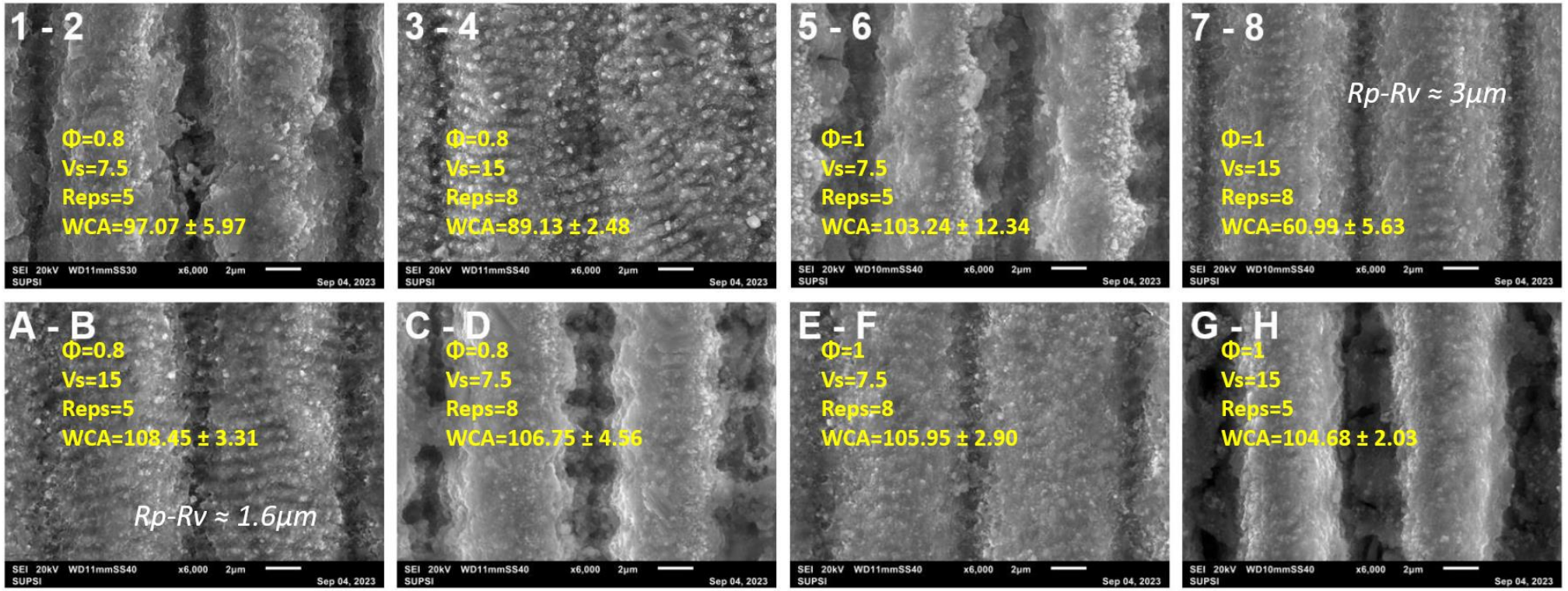
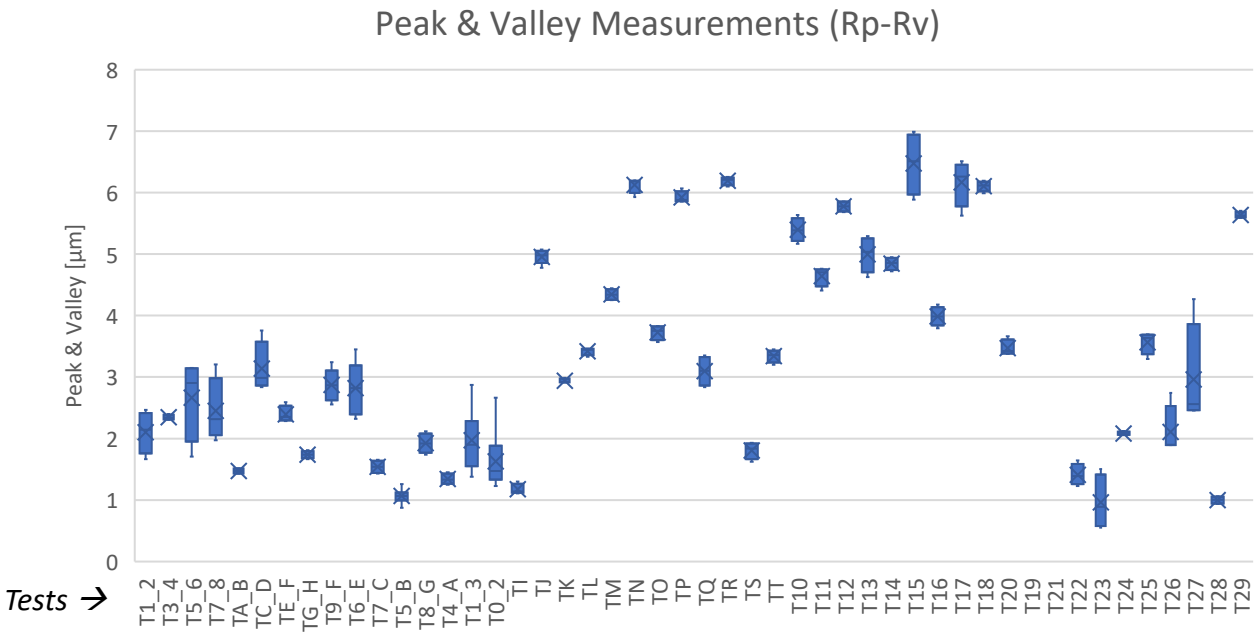
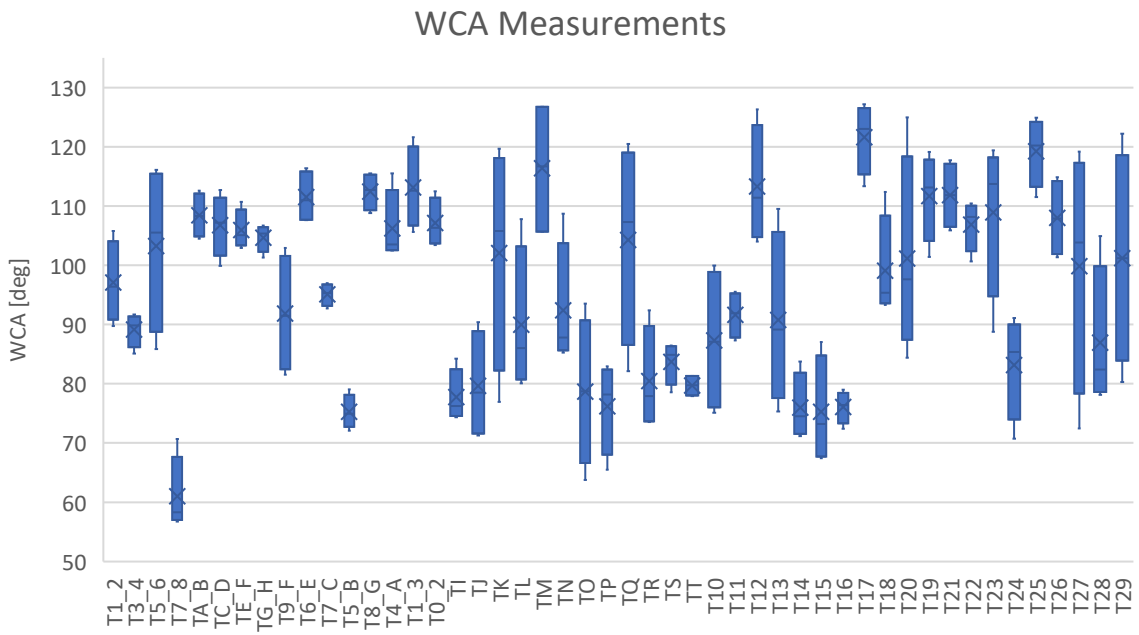
Machined Pattern

- Fixed Parameters
  - Pulse duration → 900 fs
  - Rep. Rate → 1000 kHz
  - Wavelength → 1030 nm
- Experimental Variables
  - Power → min 123 – max 337 mW
  - Pulse Overlap → min 0.5 - max 1 µm
  - Nr Repetitions → min 5 – max 20





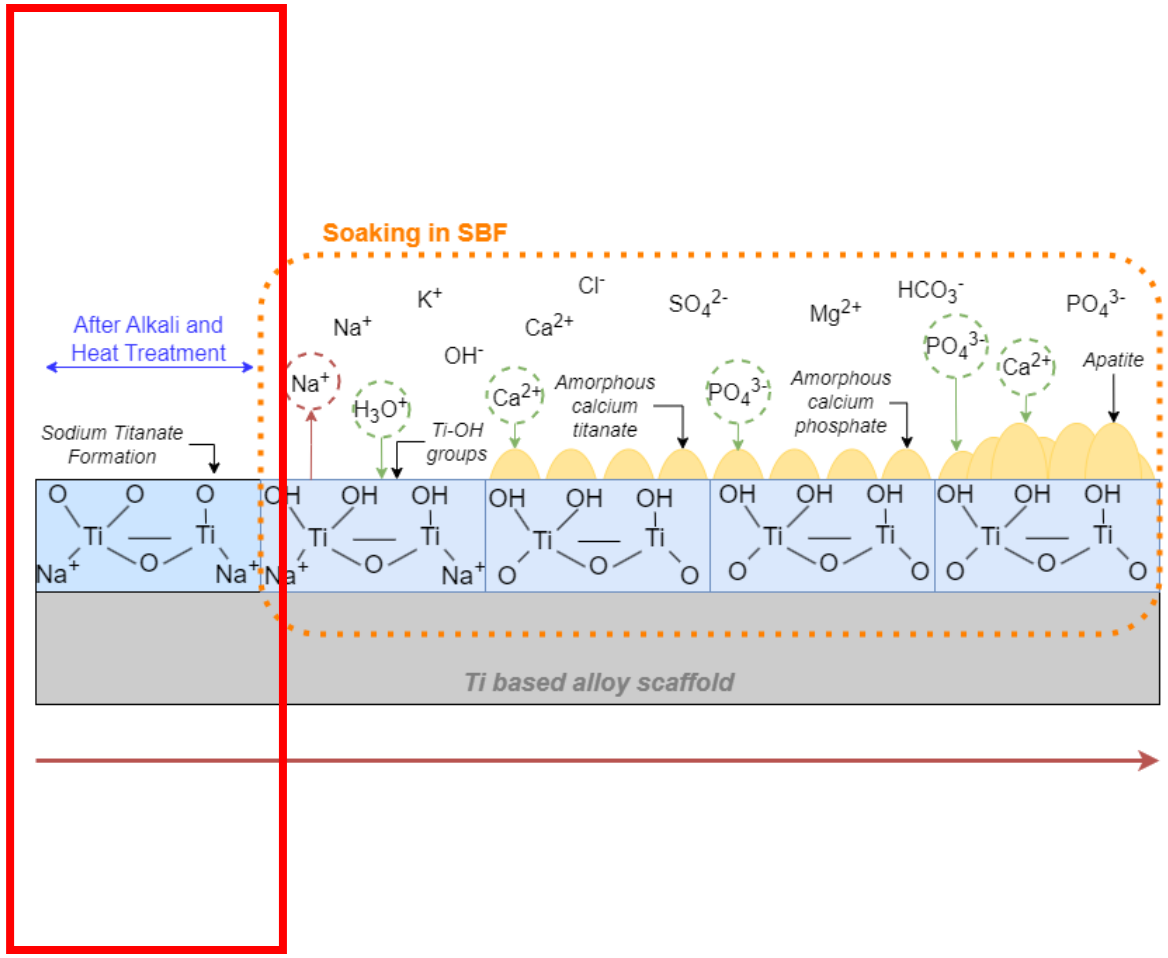


Groove Measurements

- Analysis
  - Low Rp-Rv Variability
  - Water contact angle (WCA) stable measurements for some tests (± 3.5 °)

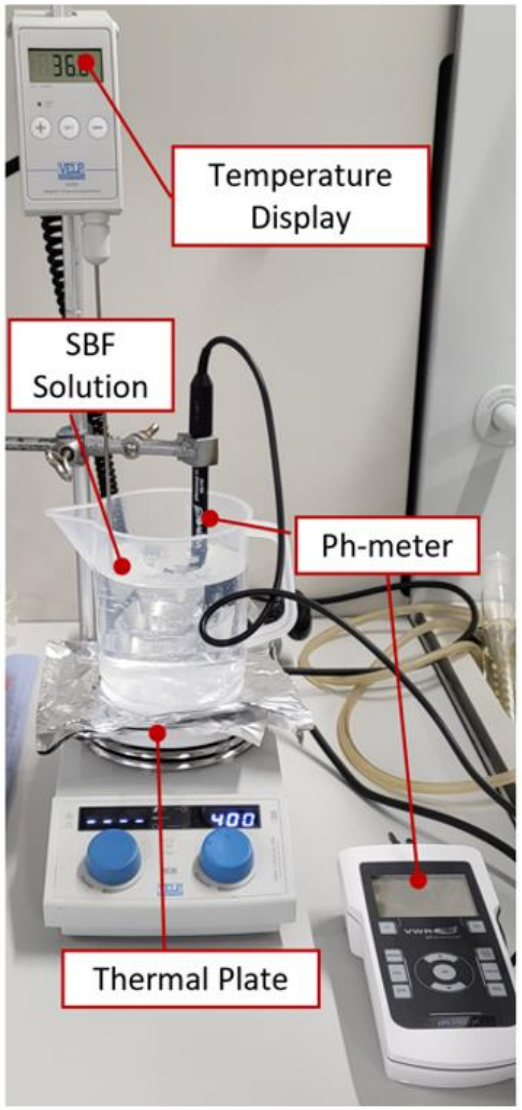
Chemical Treatment

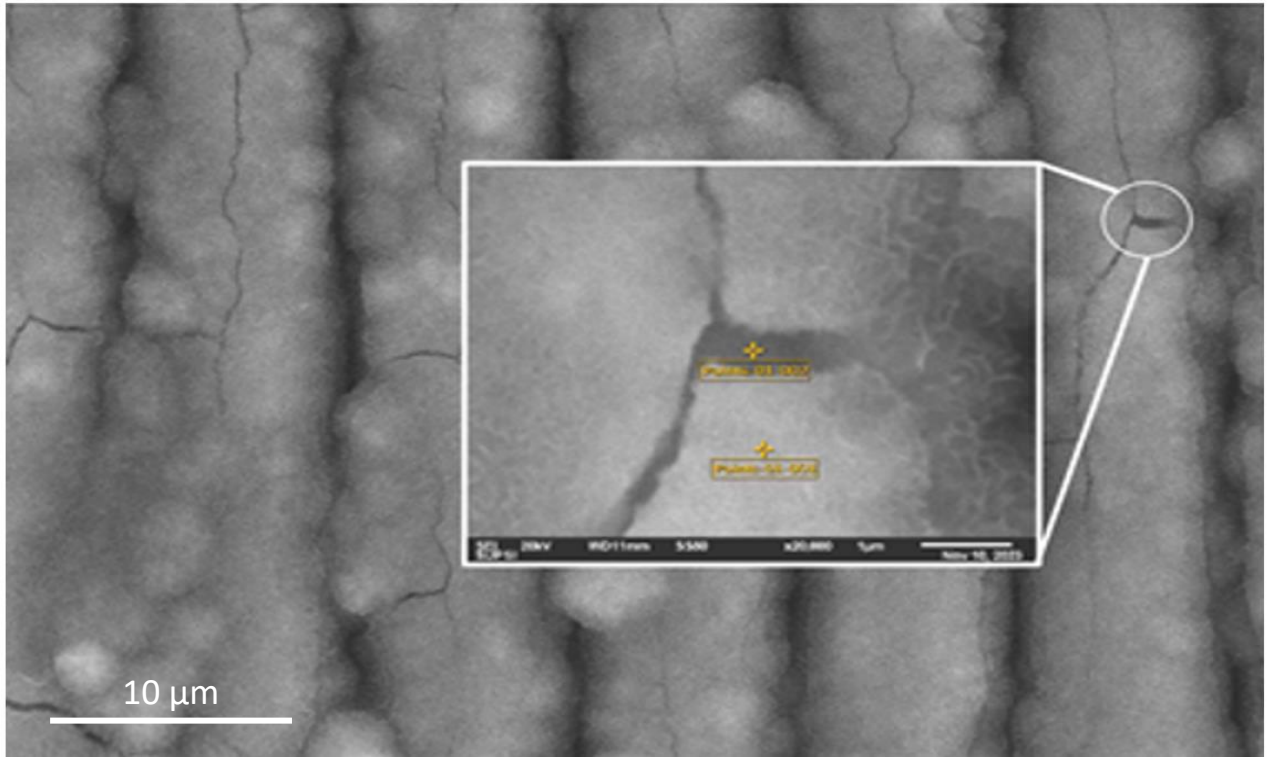
- Procedure
  - 5M solution of NaOH
  - 24 hrs at 60°C
  - Washing steps in distilled water for 1 hr at 80°C
  - 24 hrs drying at room temperature
  - 24 hrs at 250°C
- Formation of Sodium Titanate onto the surface
  - Improves osteointegration process

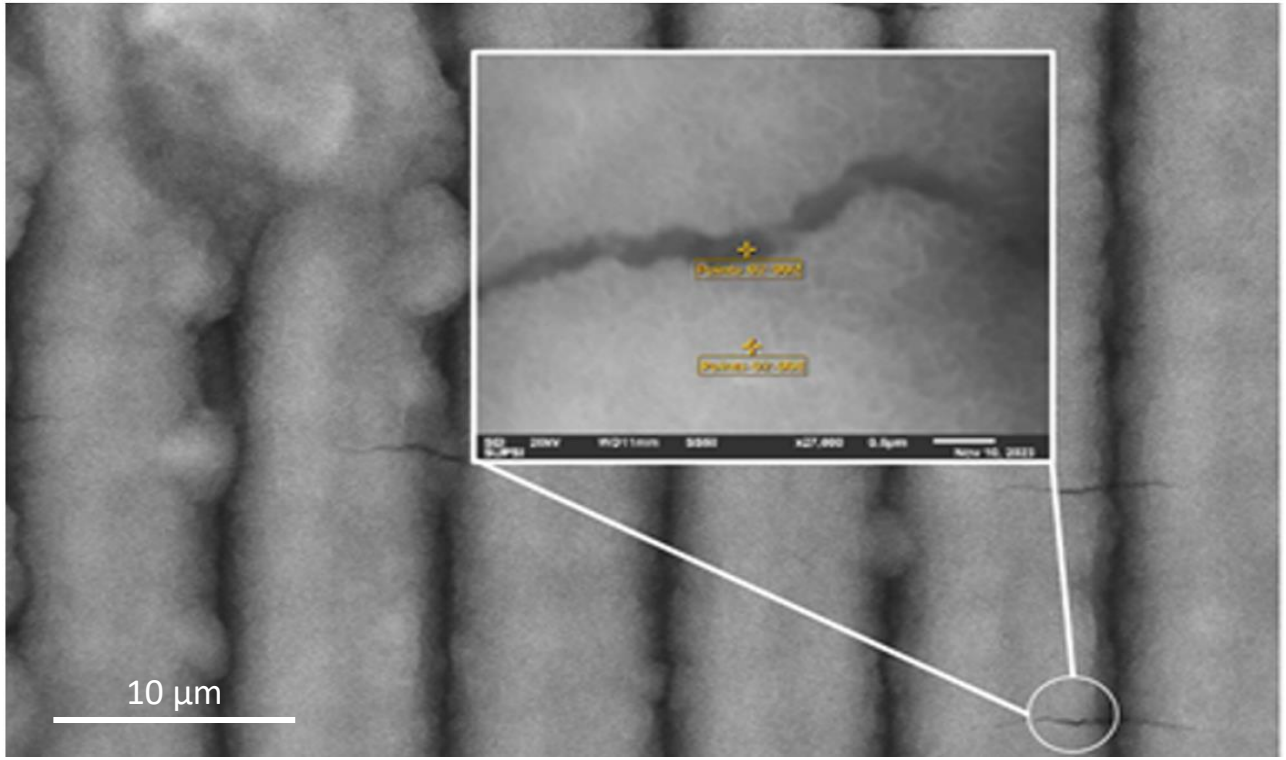


Simulated Body Fluid (SBF)

- Preparation
  - ISO 23317 Formulation
- Testing
  - 7 days at 37 ± 0.5 °C
- Goal
  - Assessment of Mineralization of the surface
    → Apatite formation





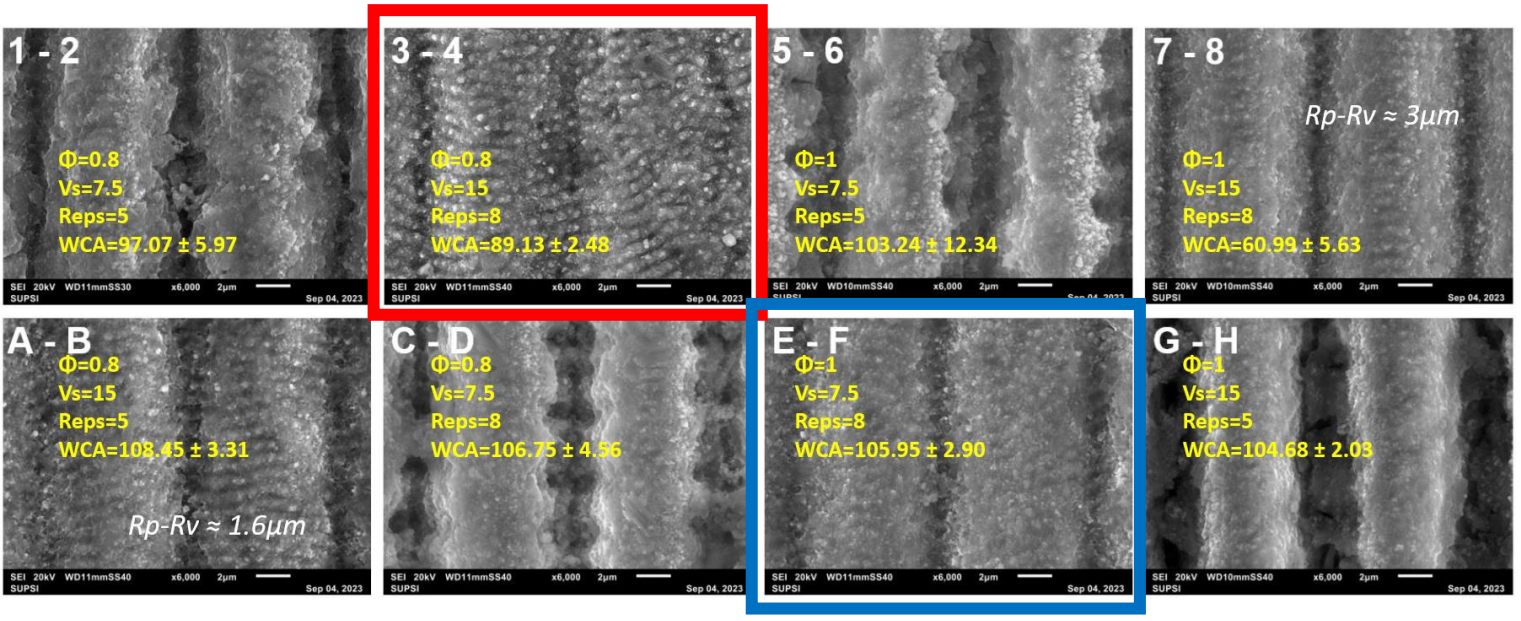


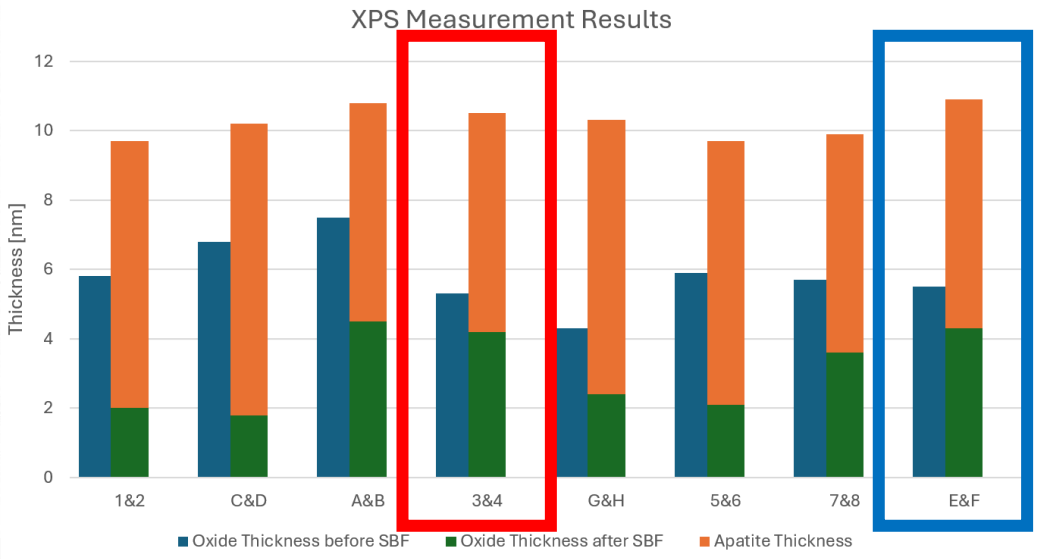
Simulated Body Fluid (SBF) testing

- Samples Alkali-treated
  - Higher apatite deposition (≈ +10%)
  - Additional step critical for impurities
- Samples with no additional chemical treatment
  - Lower apatite deposition
  - Homogeneous layer, smaller orthogonal cracks

XPS Measurements

- X-ray photoelectron Spectroscopy (XPS) Measurements
  - Oxide Layer integrity
  - LIPSS enhanced patterns show more resistance to corrosive environments
    - Oxide layer reduced by ≈ 15%

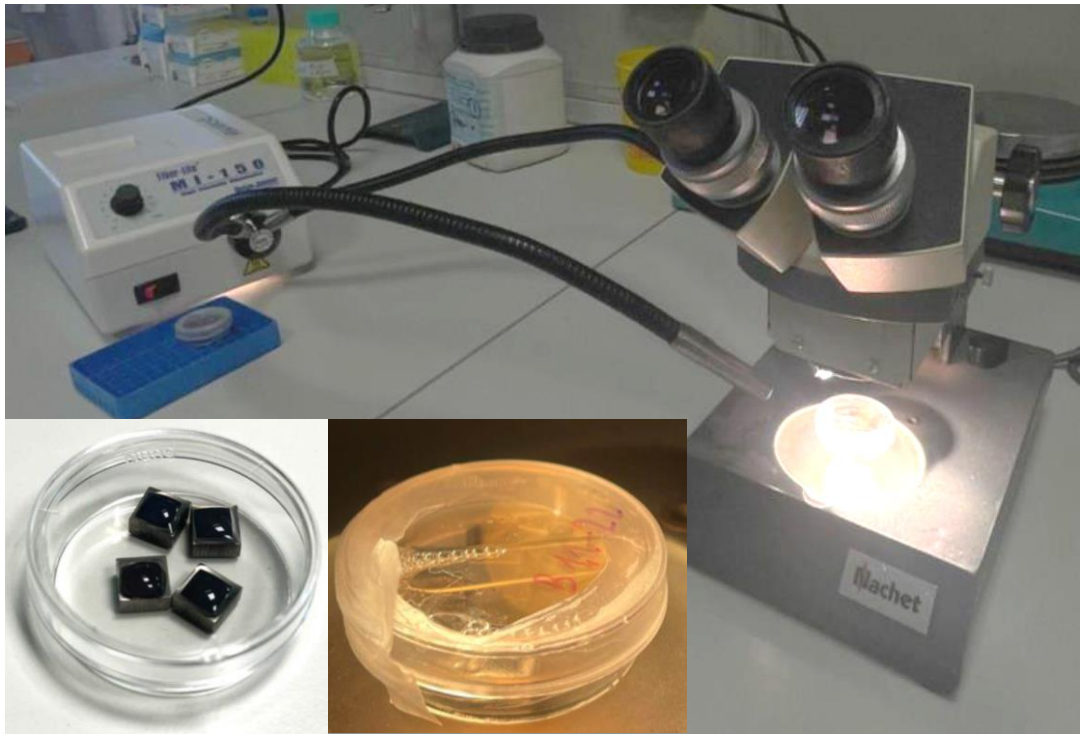




In-vitro tests

In collaboration with USI – Biomedical Sciences NRLab, Prof. Perale

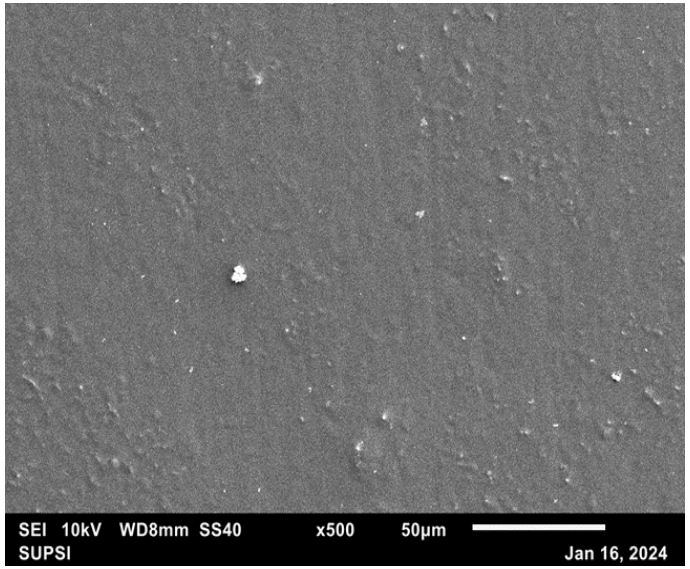
- Media Loading
  - Human Mesenchymal cells Isolated from Adipose Tissue
  - Droplets onto surface ca. 2500 cells/cm2
- Analysis
  - Variability of cells in input → droplet
  - Lack of nutrient flow
  - Discrete measurements



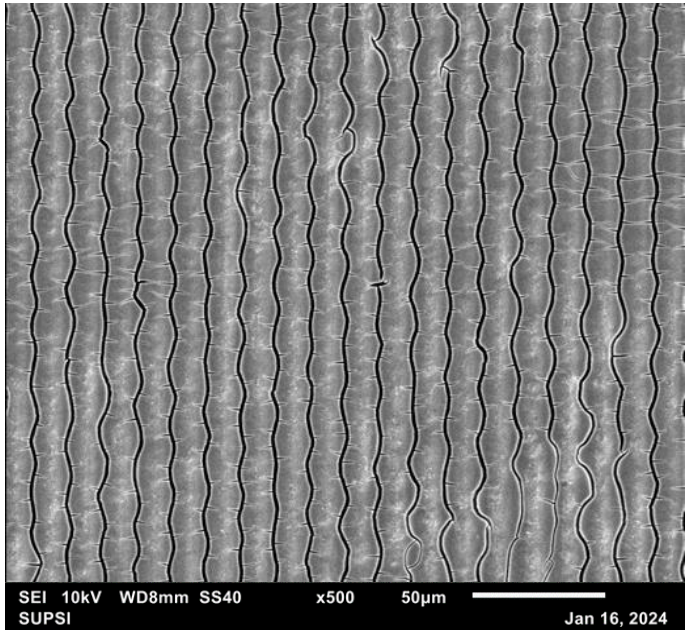
Antibiotic Coating

In collaboration with Memti Lab – Sr. Researcher De Corso

- Layer-by-layer coating technology for antibiotic placement
  - Non-treated surface vs fs-treated surface
  - After 48 hrs Non-treated surface released all the drug → coating is absent



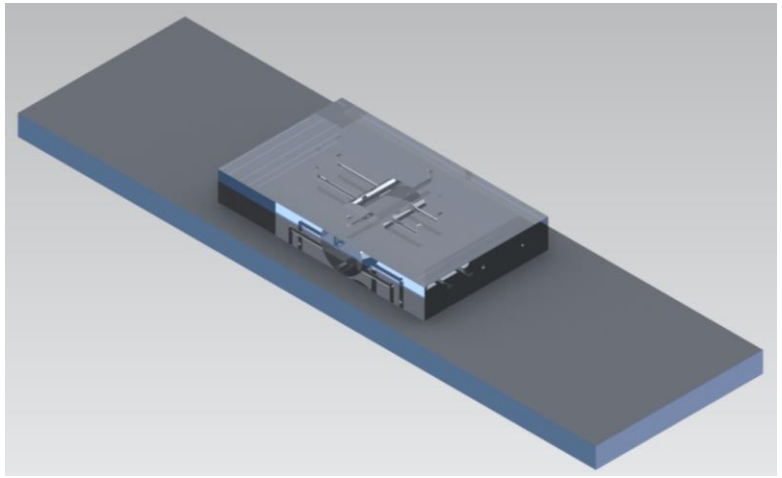
Non-Treated Surface
→ coating is absent

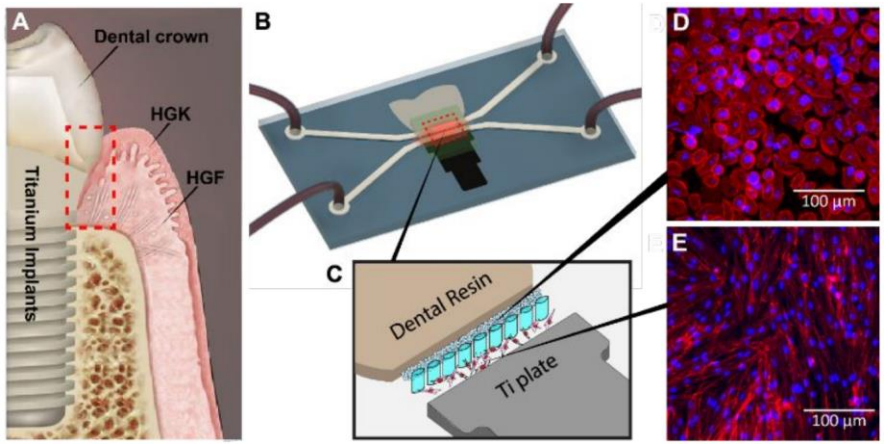


Treated Surface

Future Directions

- Advanced In-vitro testing
  - Precise spatiotemporal control & manipulation *i.e. loading conditions, cell flow*
  - Single cell behaviour
  - Cell-cell interaction
- AI and Machine Learning
  - Algorithms for topological process recipes designed for medical devices





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Conclusions

- Grooves
  - Non-alkali treated samples allow for a homogeneous apatite layer
  - LIPSS allow the surface for higher resistance in corrosive environment
- Ongoing activities
  - In-vitro tests are correlated with fs process recipes
  - Maximize drug release tests
- Machining time (7x7 mm) → Up to **400 CHF** saving in production costs!
  - Commercial machine → 3.5 hrs
  - Mesomorph machine → 9 mins

Thank you!