European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Microstructural characterization of mechanical and corrosion wear mechanisms of bio-tribological coatings, carried out by TEM technique

www.imim.pl

Łukasz Major

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

Suggestions for topics

1). Thin Films Deposition- …….

2). Nucleation and Growth of Thin Films- …….

3). Materials Design Inspired by Nature- …….

4). Sample Preparation Techniques for Transmission Electron Microscopy-…….

5). The Transmission Electron Microscope (instrument, contrast mechanism, scaning transmission electron microscopy)

6). Structure Defects- …….

7). Standard Micromechanical and Tribological Testing- ……..

8). In-situ Electron Microscopy- …….

9). Wear- …….

10). Corrosion- ……..

11). Cell-Material Interaction and Biocomatibility- …….

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

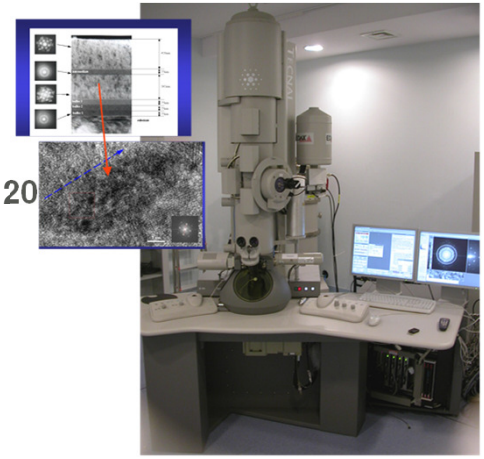
European Union
European Social Fund

Accredited Testing Laboratories

at the Institute of Metallurgy and Materials Science of the Polish Academy of Sciences
25, Reymonta Str., 30-056 Kraków,
phone: (0048)(12) 295 28 00; e-mail: zlb@imim-pan.krakow.pl

ilac-MRA
PCA Polskie Centrum Akredytacji
BADANIA
AB 120

LABORATORY OF ANALITICAL ELECTRON MICROSCOPY (L-2)



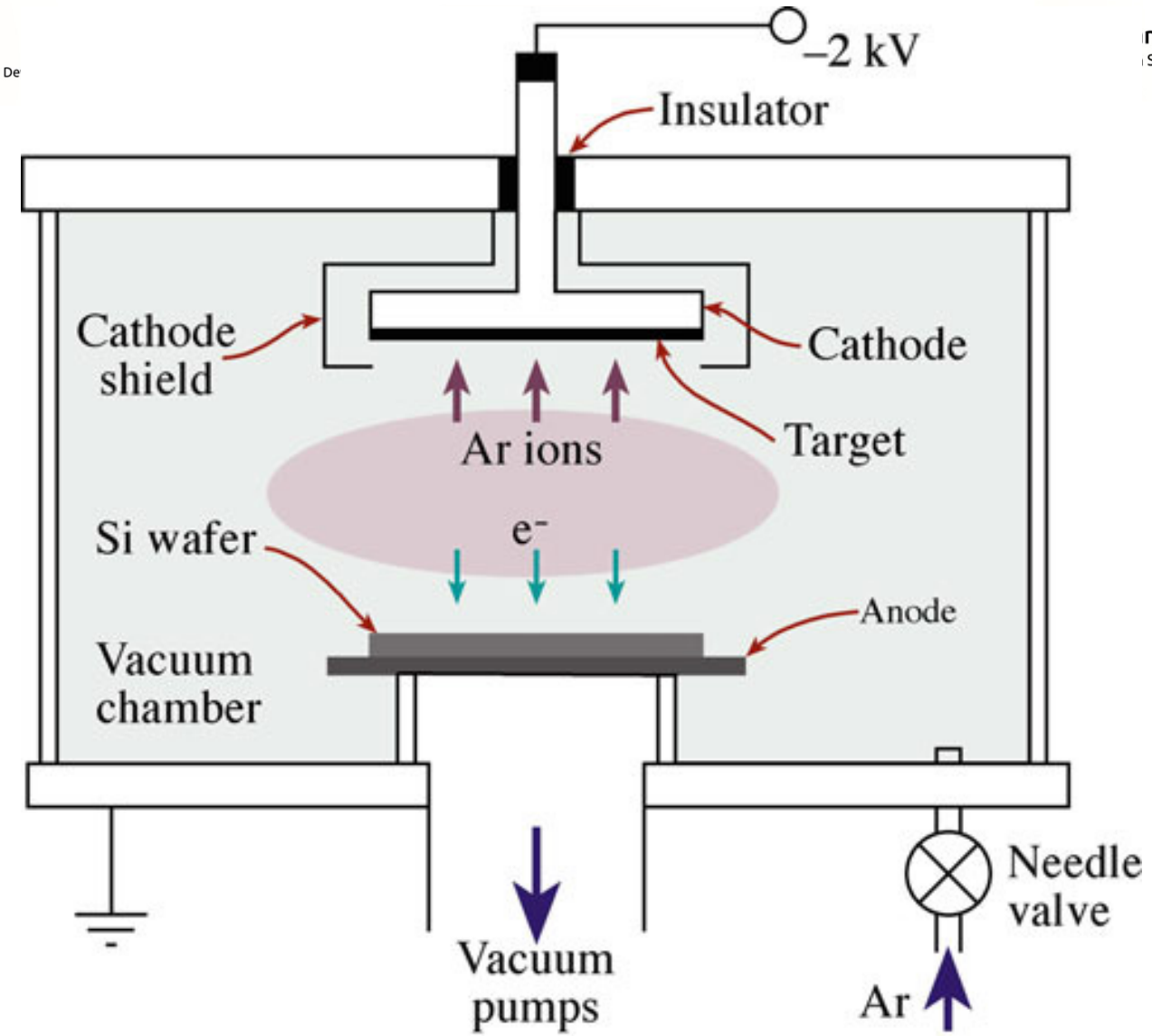
Authorisation:

Accredited activity is defined in the Scope of Accreditation No. AB 120

Quantitative and qualitative analysis of elements in alloys and ceramic materials,
identification of phases, analysis of chemical composition and shape of precipitates,
examination of structure of grain boundaries,
High resolution analysis (atomic scale)
determination of surface morphology, shape and size of inclusions.

Institute of Metallurgy and Materials Science Polish Academy of Sciences

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds



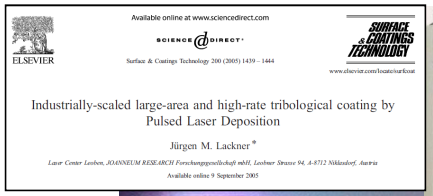
European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

JOANNEUM RESEARCH MATERIALS

High-vacuum deposition processes

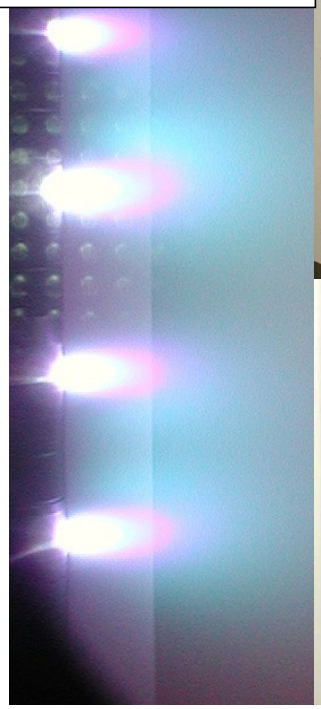

Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Surface & Coatings Technology 200 (2005) 1439 – 1444
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat

Industrially-scaled large-area and high-rate tribological coating by Pulsed Laser Deposition

Jürgen M. Lackner *

Laser Center Leoben, JOANNEUM RESEARCH Forschungsgesellschaft mbH, Leobner Strasse 94, A-8712 Niklasdorf, Austria

Available online 9 September 2005

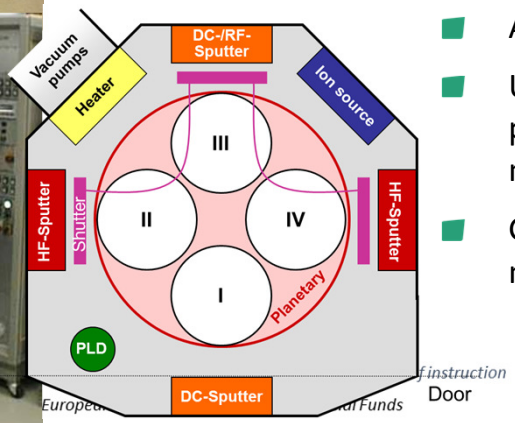


Pulsed Laser Deposition (PLD)

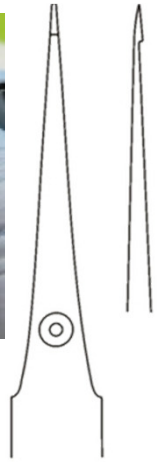
Magnetron sputtering (MS)

Anode Layer Ion Source treatment and assisted deposition (ALS)

- PLD: KrF & Nd:YAG multi-beam evaporator
- MS: DC, DC-pulsed, RF on 1-4 sputter magnetrons
- ALS: Veeco ALS 340
- Usable chamber volume: planetary diameter 560 mm, 450 mm
- Gas pressure: 10^{-4} to 10^{-2} mbar



Surgical tools/

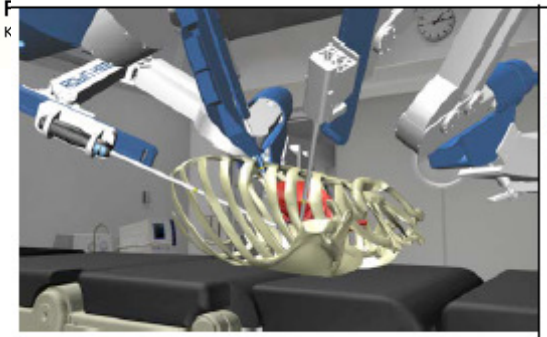
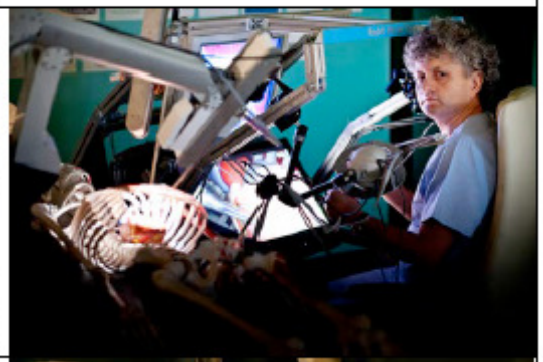
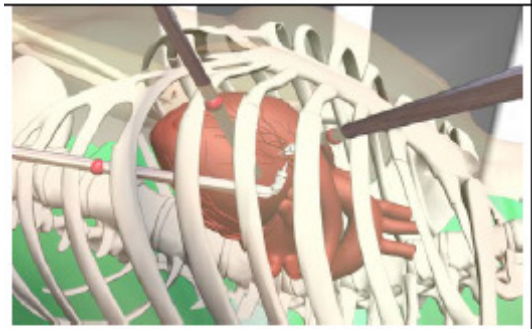
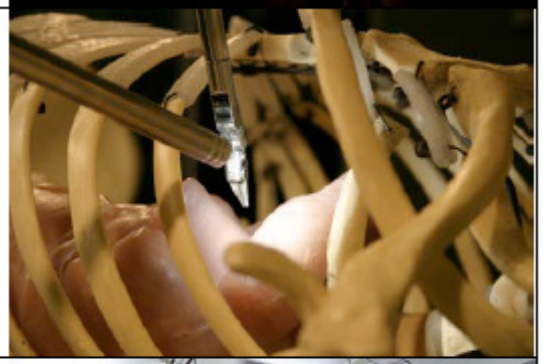
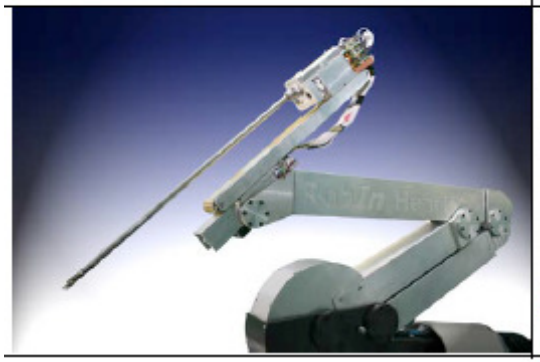


Industrial partner

CHIRMED®
POLSKI PRODUCENT NARZĘDZI MEDYCZNYCH
MANUFACTURER OF SURGICAL AND MEDICAL INSTRUMENTS

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

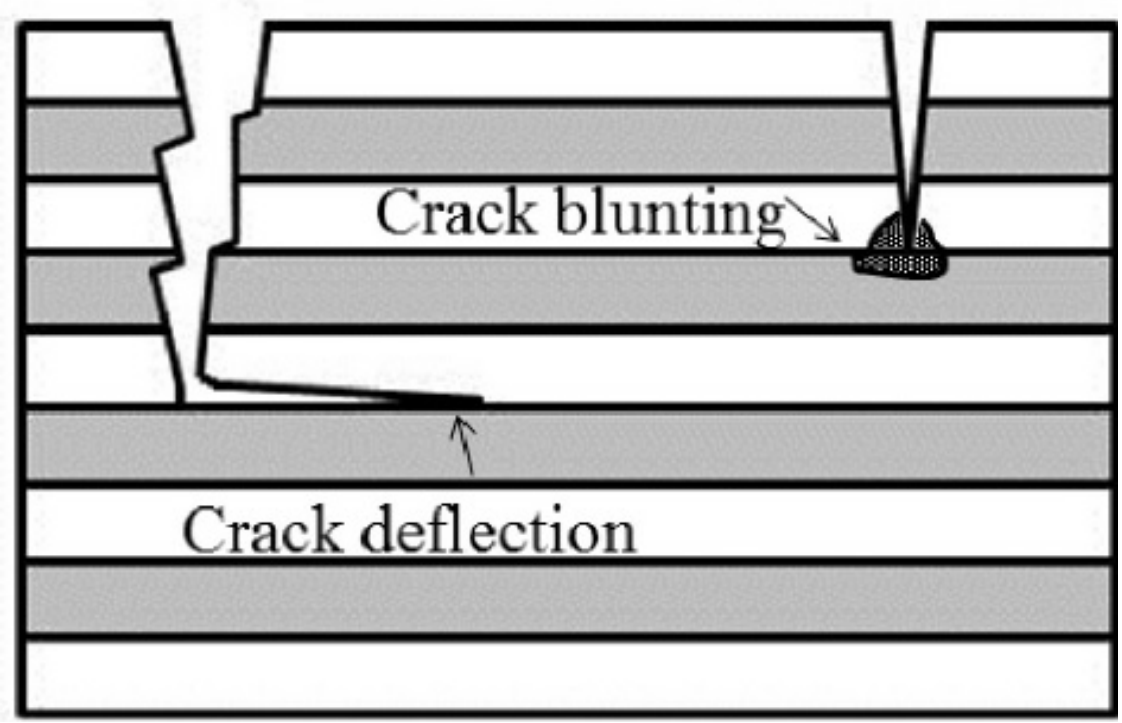
ROBIN HEART


nstruction

Project co-financed by the European Union within the European Social Funds

The role of the multilayer coating



Biomimetics

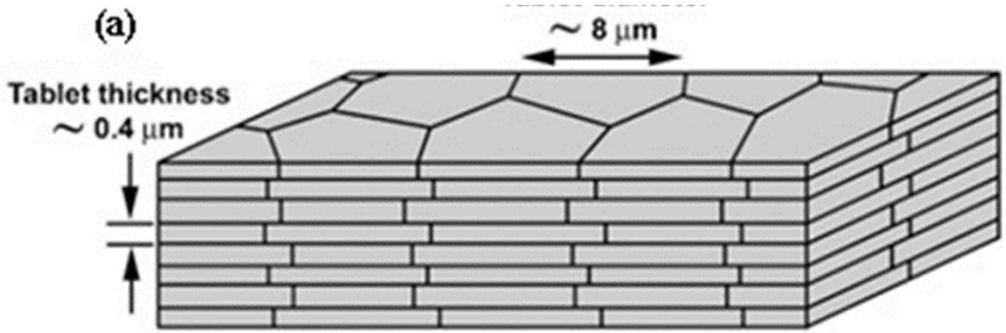
Biomimetics

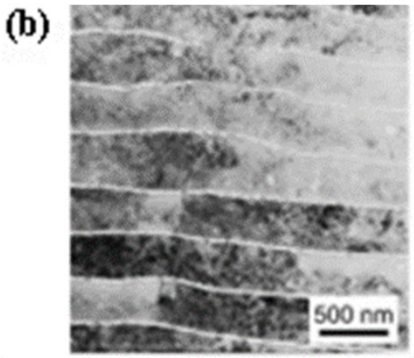
=

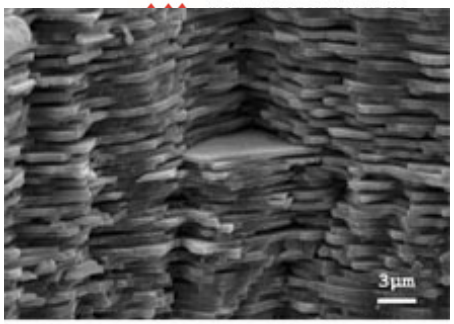
Study and simulation of biological systems with desired properties

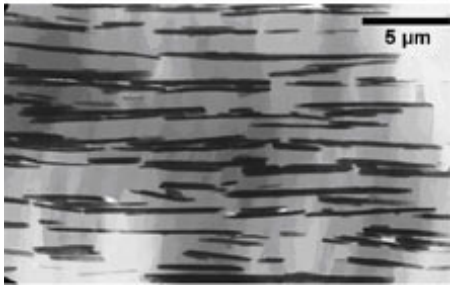
+

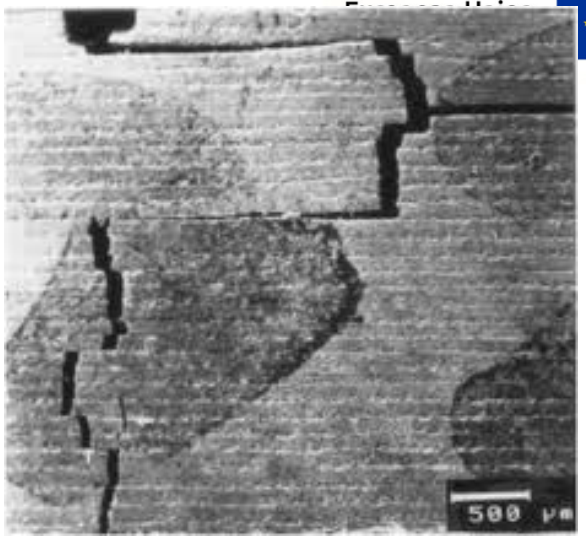
Transformation of the underlying principles **into man-made technology**

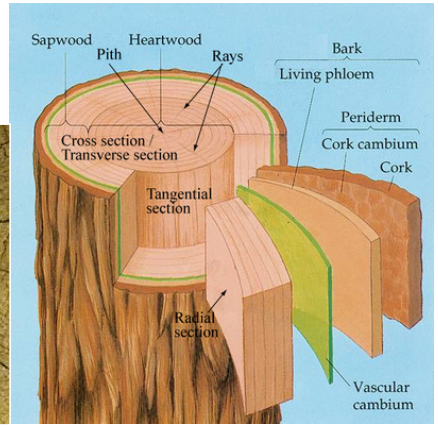












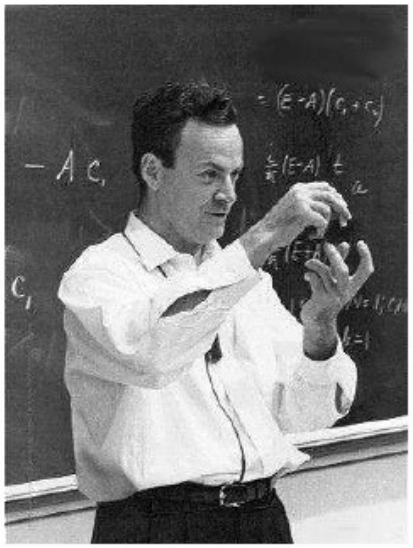
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

In 1959.
Richard Feynman gives his famed talk "There is Plenty of Room at the Bottom"



Richard Feynman © 1965

"What I want to talk about is the problem of manipulating and controlling things on a small scale."

In this talk, Feynman said that we have progressed to the point where we can and should manipulate matter at what today we call the nano-scale.

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

Resolution

Ability to distinguish between 2 closely spaced points.

Resolution of human eye:
100 µm
(100 µm = 0.0039 inches)

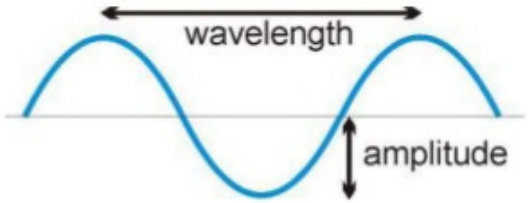
If > 100 µm

Will see 2 objects

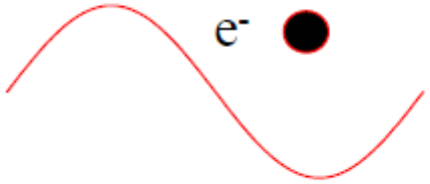
If < 100 µm

Will see only 1 object

In order to see the element in the size of „d" it is a need to have $\lambda < d$. For example the length of visible light is $\rightarrow 0.5\ \mu m$

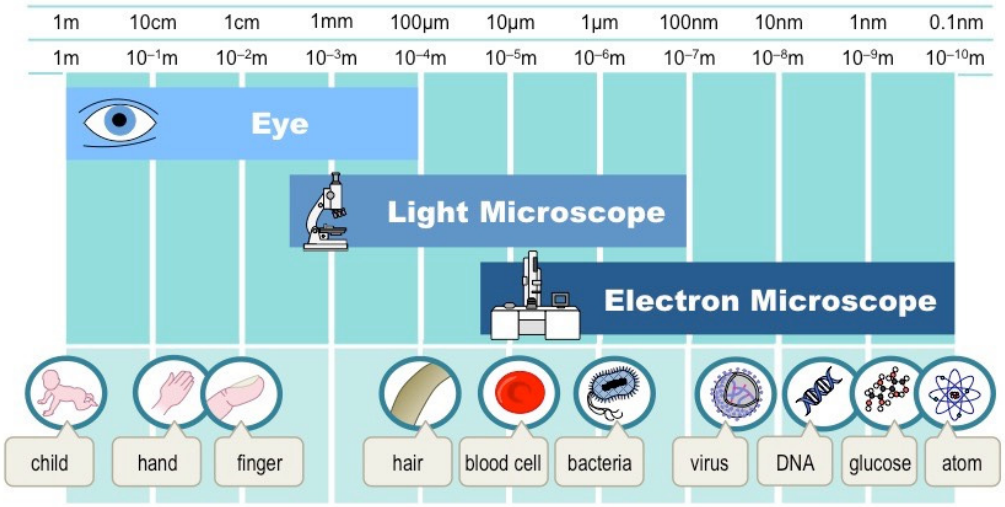


In general, to receive information about atomic structure it is necessary to apply $\lambda < 0.1$ nm

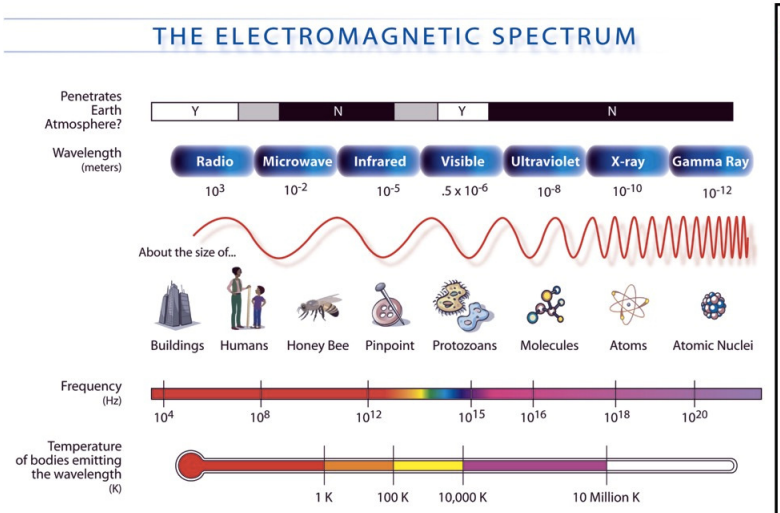


$\lambda = \sqrt{150/V}$, where
λ- wavelength in Angstroms,
V- accelerating voltage in volts

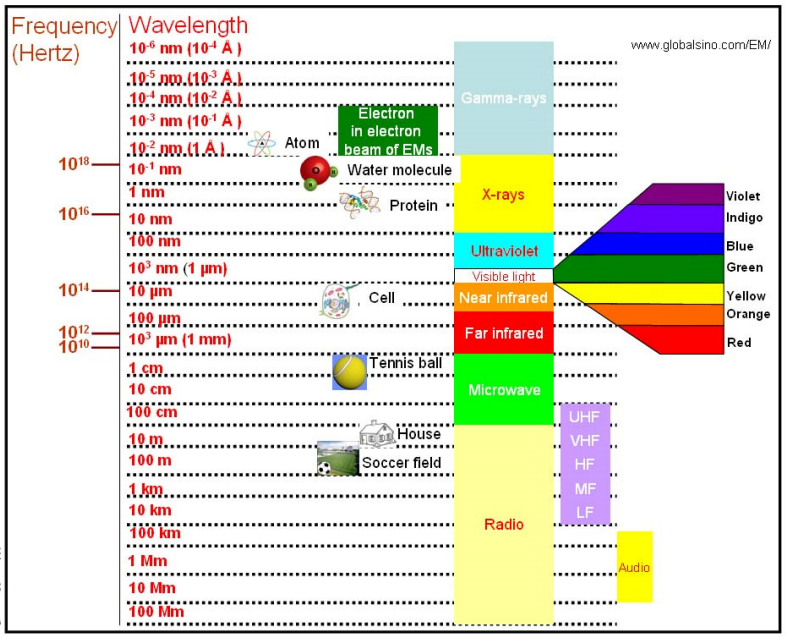
European Funds
Knowledge Education Development

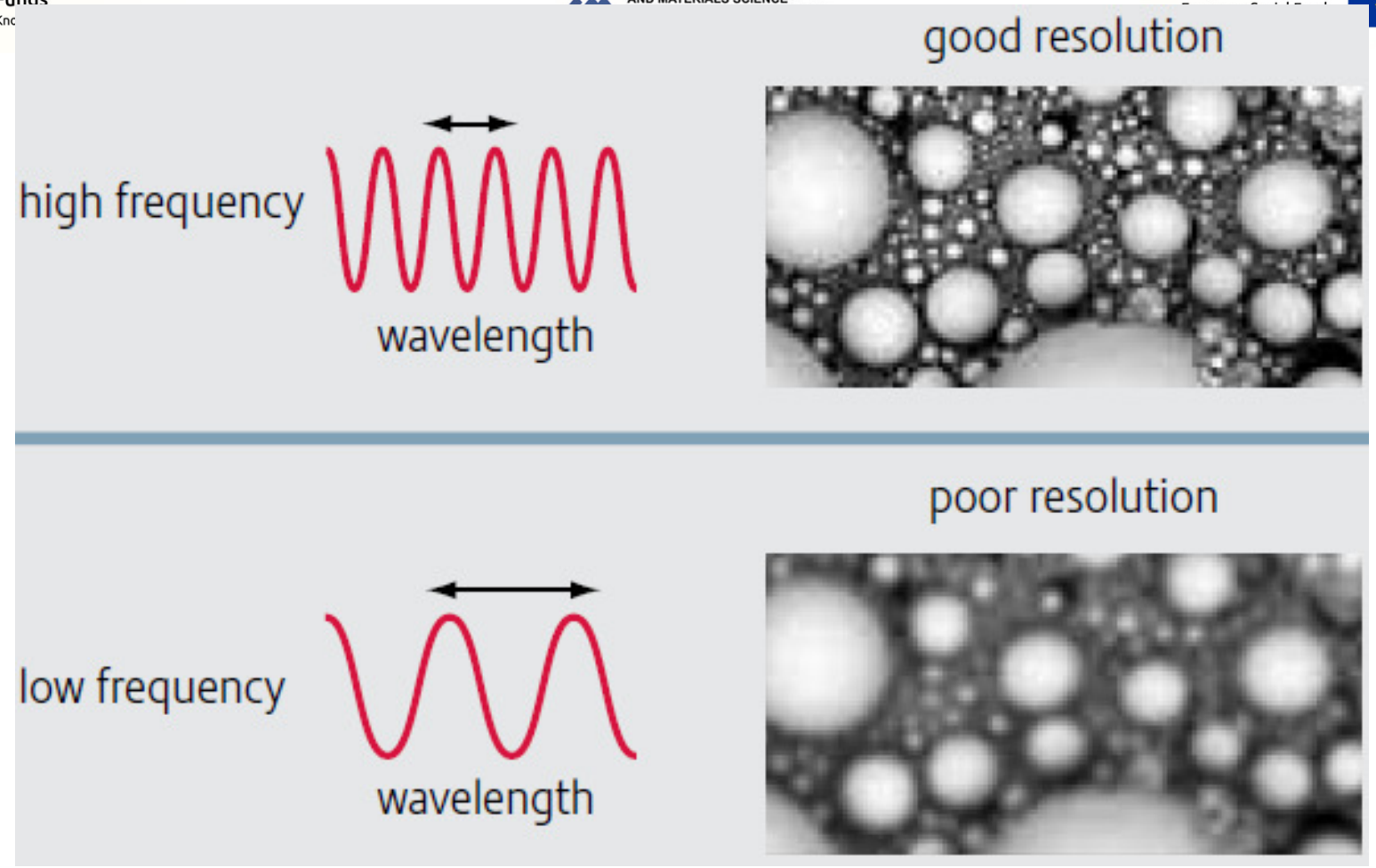


European Union
European Social Fund



Project WND-POWR.0
International interdisciplinary PhD Studies in Materials
Project co-financed by the European Un



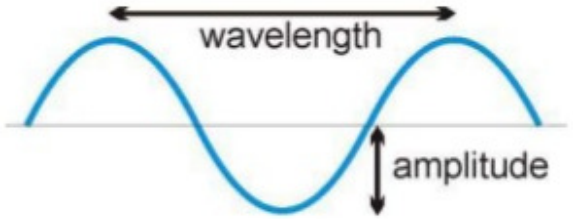


Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Electron Microscopy

- An electron microscope is a microscope that uses **accelerated electrons as a source of illumination.**
- Electron microscopes were developed due to the limitations of Light Microscopes which are limited by the physics of light.
- In the early 1930's there was a scientific desire to see the fine details of the interior structures of organic cells (nucleus, mitochondria...etc.).
- This required **>10000x** magnifications which could not be achieved by simple light/optical microscopy.
- Because the **wavelength of an electron can be up to 100,000 times shorter** than that of visible light photons, the electron microscope has a higher resolving power than a light microscope and can reveal the structure of smaller objects.

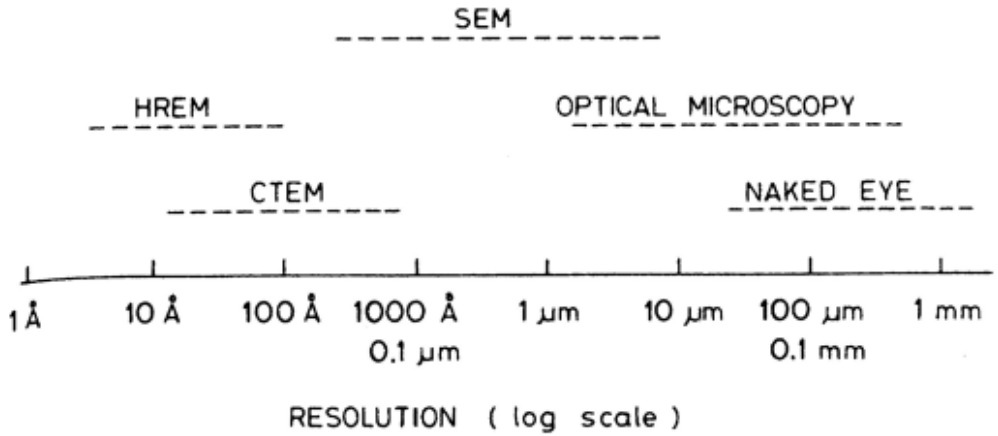
$\lambda = \sqrt{150/V}$, where
λ- wavelength in Angstroms,
V- accelerating voltage in volts



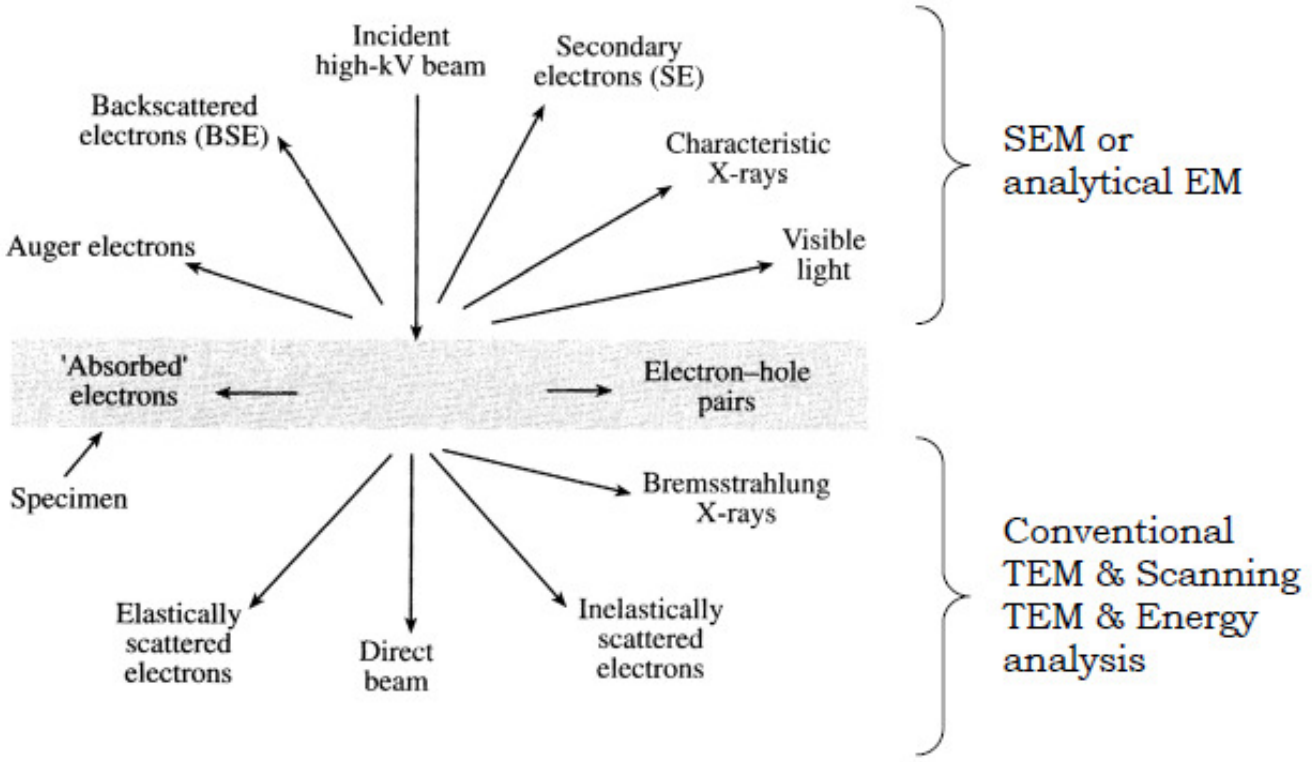
Fundamentals of Electron Microscopy

Scanning electron microscopy (SEM): For studying the texture, topography and surface feature, resolution ~ 10 nm

Transmission electron microscopy (TEM): Lattice imaging, resolution < 0.2 nm



Interaction of Electron with Samples



Project WND-POWR.03.02.00-00-I043/16

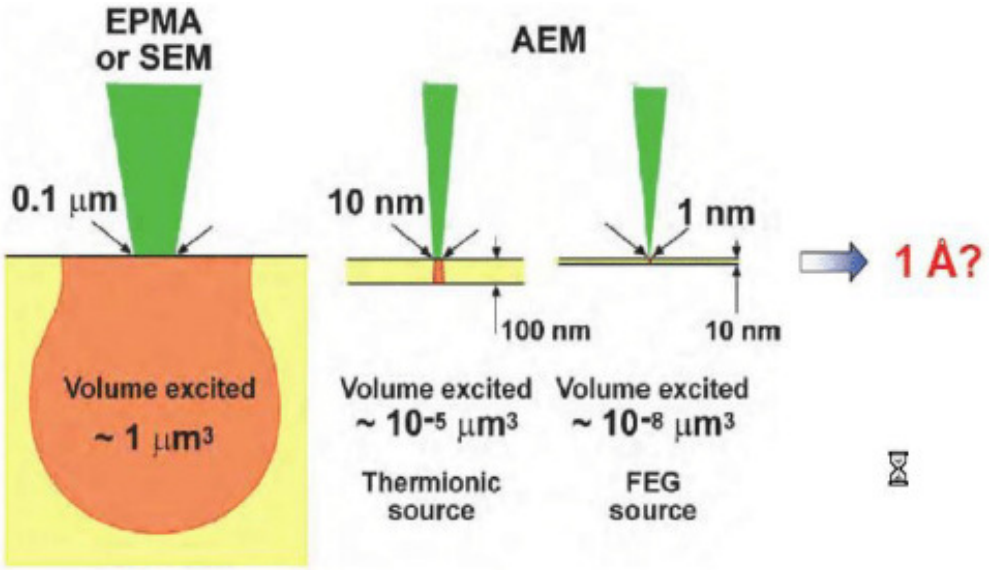
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

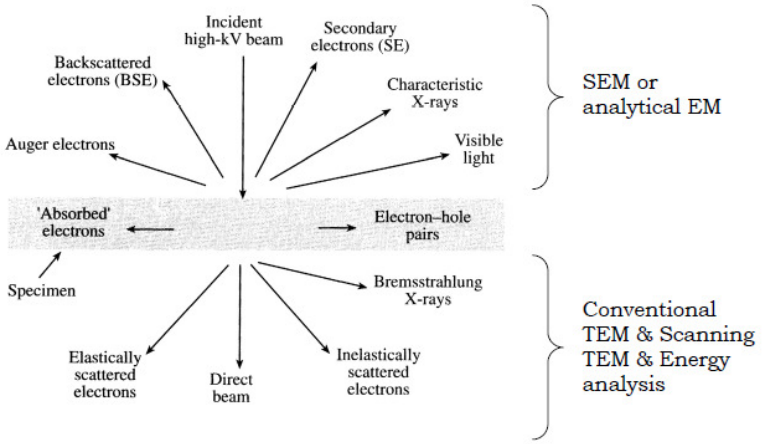
Comparing SEM and TEM

	TEM	SEM
Electron Beam	Broad, static beams	Beam focused to fine point; sample is scanned line by line
Voltages Needed	TEM voltage ranges from 60-300,000 volts	Accelerating voltage much lower; not necessary to penetrate the specimen
Interaction of the beam electrons	Specimen must be very thin	Wide range of specimens allowed; simplifies sample preparation
Imaging	Electrons must pass through and be transmitted by the specimen	Information needed is collected near the surface of the specimen
Image Rendering	Transmitted electrons are collectively focused by the objective lens and magnified to create a real image	Beam is scanned along the surface of the sample to build up the image

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

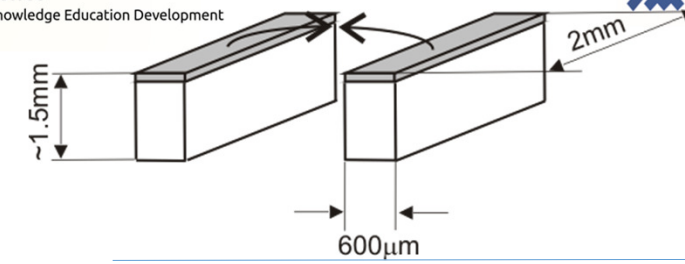


Spatial resolution ↑ → **Analytical sensitivity** ↓

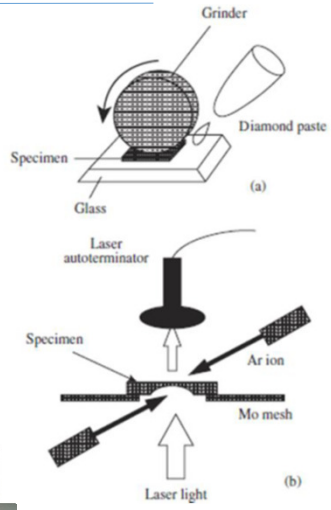


International int

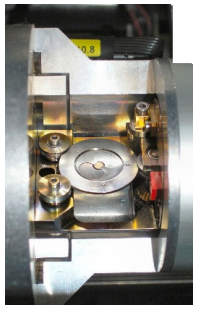
P



Parameters



- Bench top system
- Two opposite arranged ion guns
- Ion energy: 1 keV to 10 keV
- Gun tilt: ± 45° (each gun)
- Sample tilt: 0° to 180°
- Milling angle: 0° to 90°



Project WND-POWR.03.02.00-00-I043/16

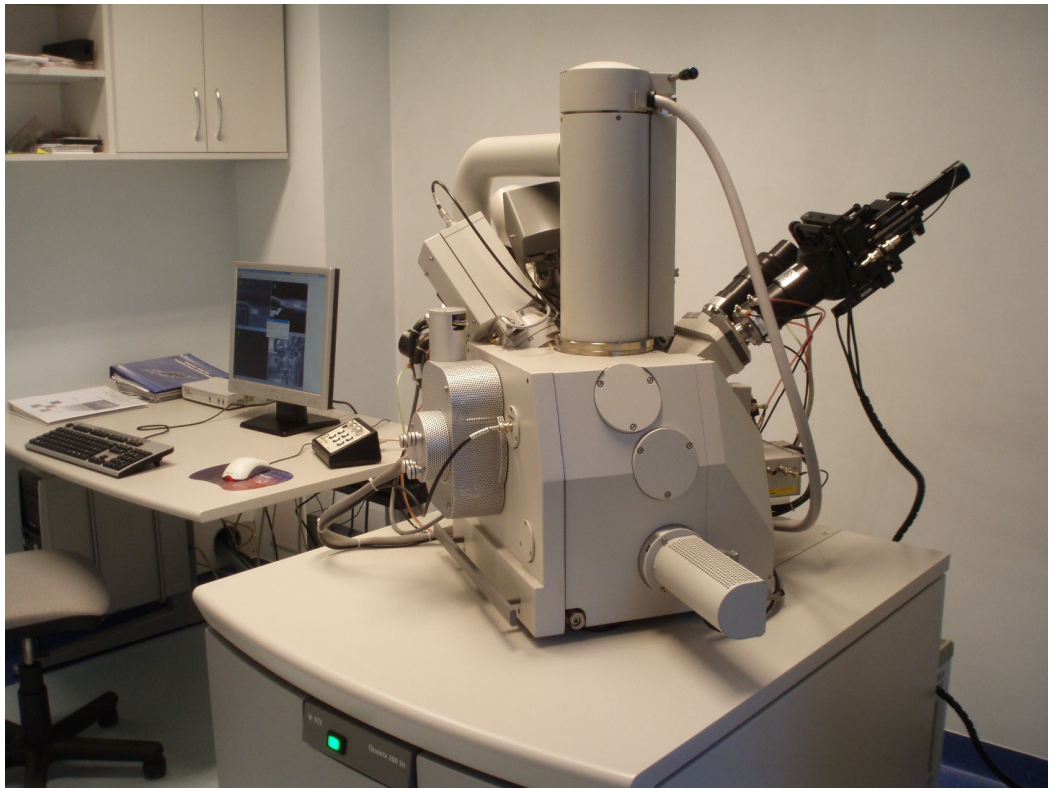
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

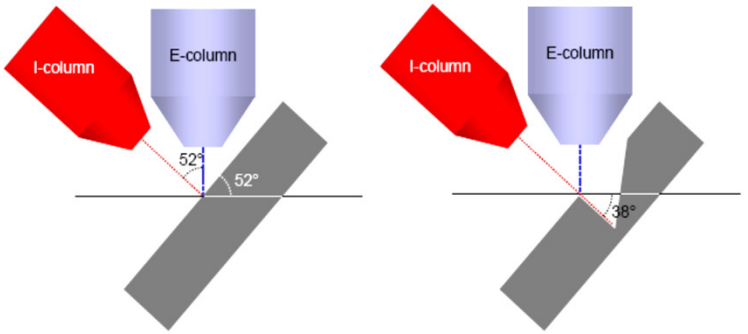
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

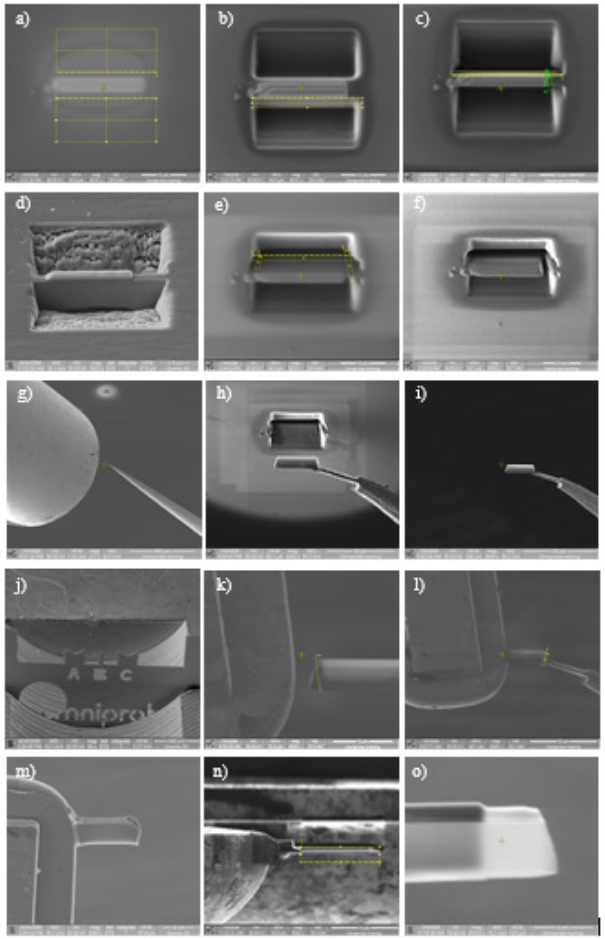




Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

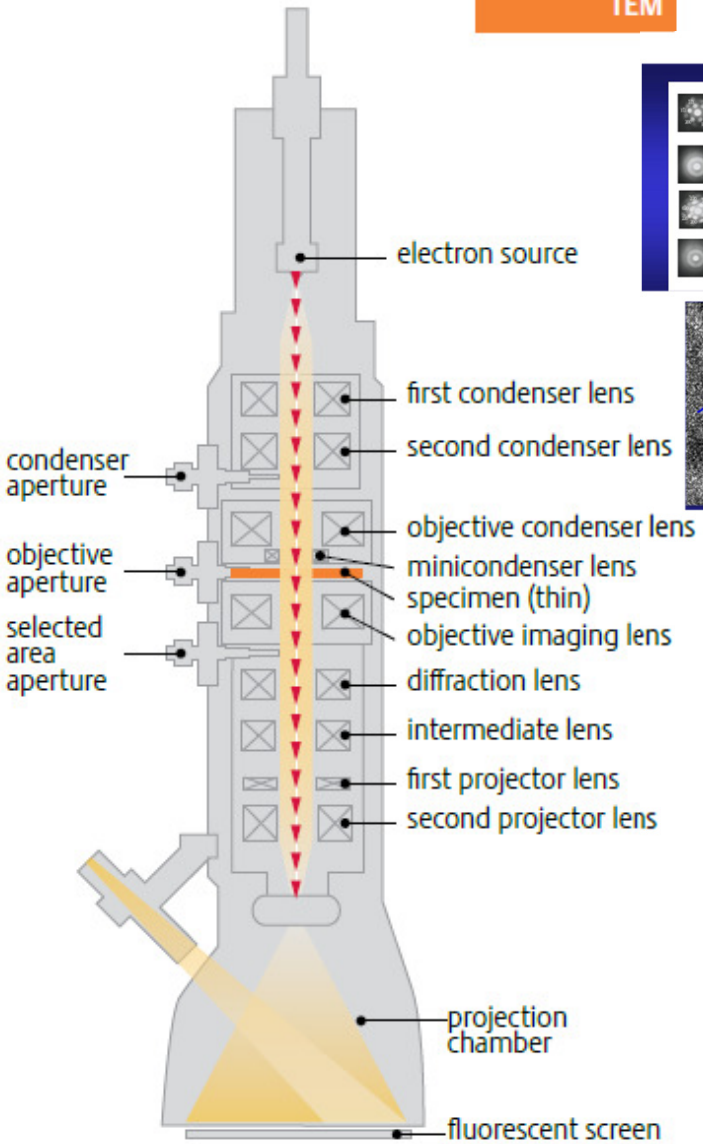
Project co-financed by the European Union within the European Social Funds

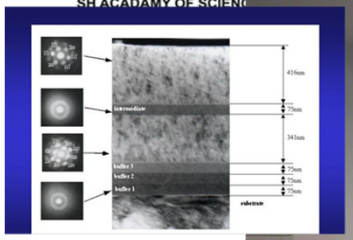


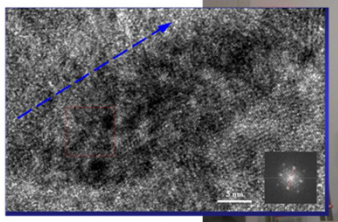
Project WND-POWR.03.02.00-00-I043/16

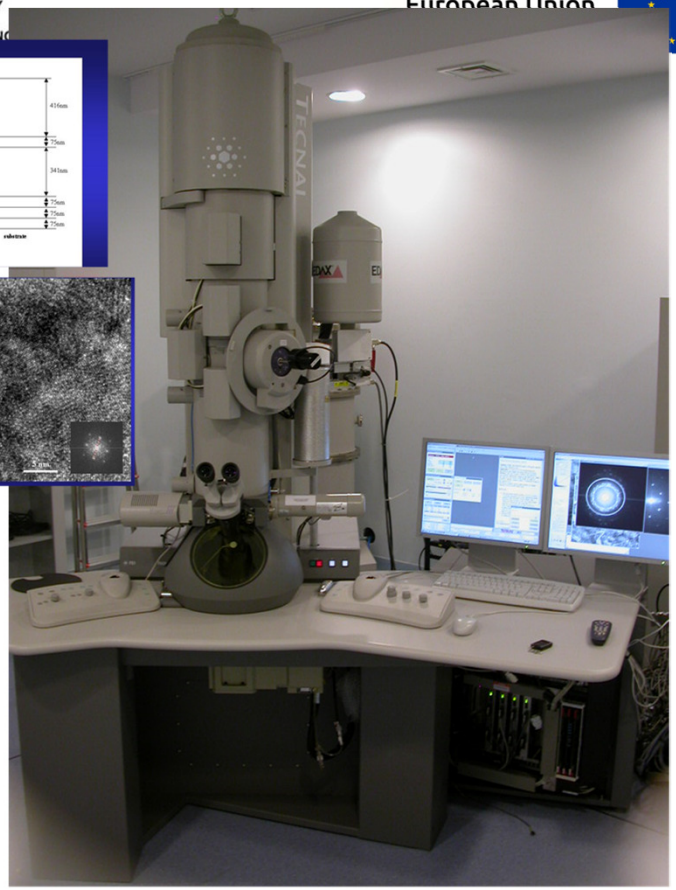
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds





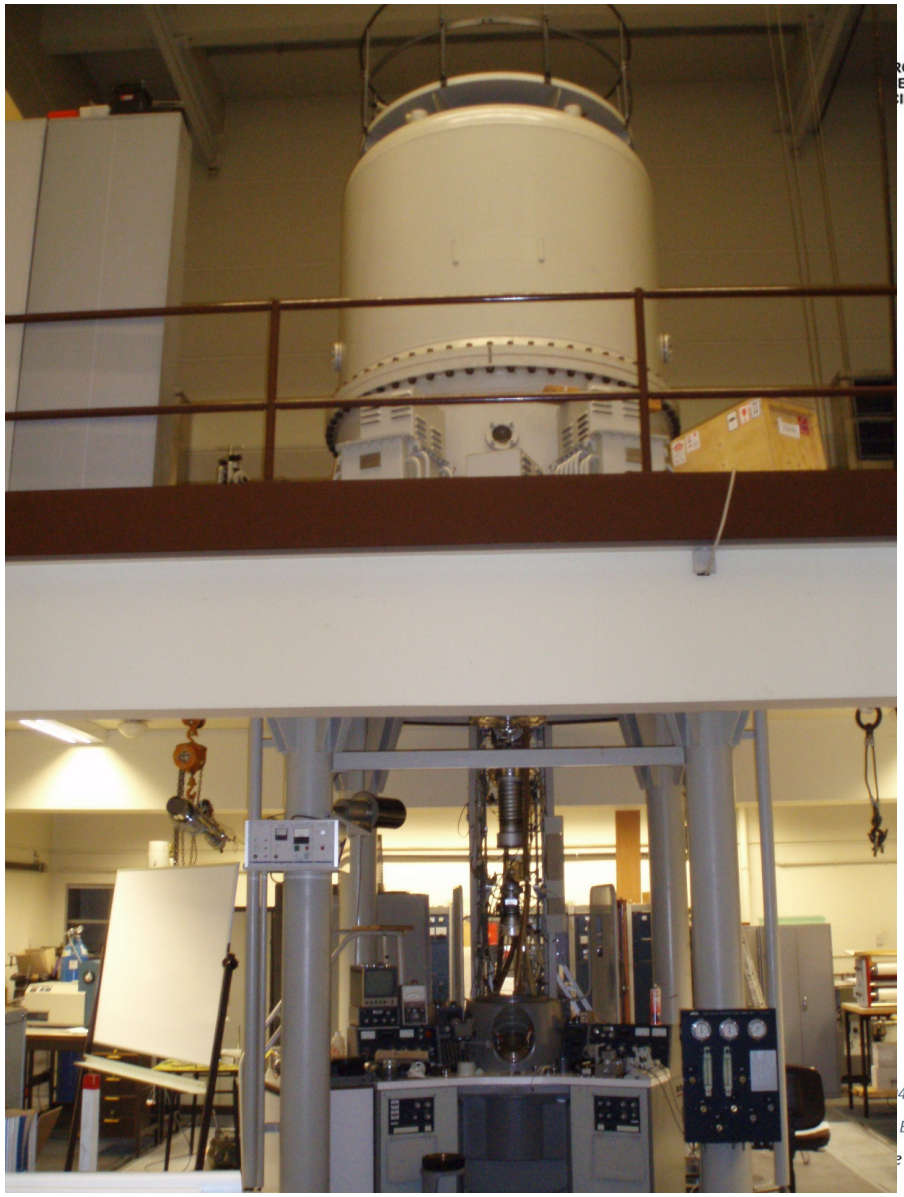




WR.03.02.00-00-I043/16

terials Science with English as the language of instruction

an Union within the European Social Funds

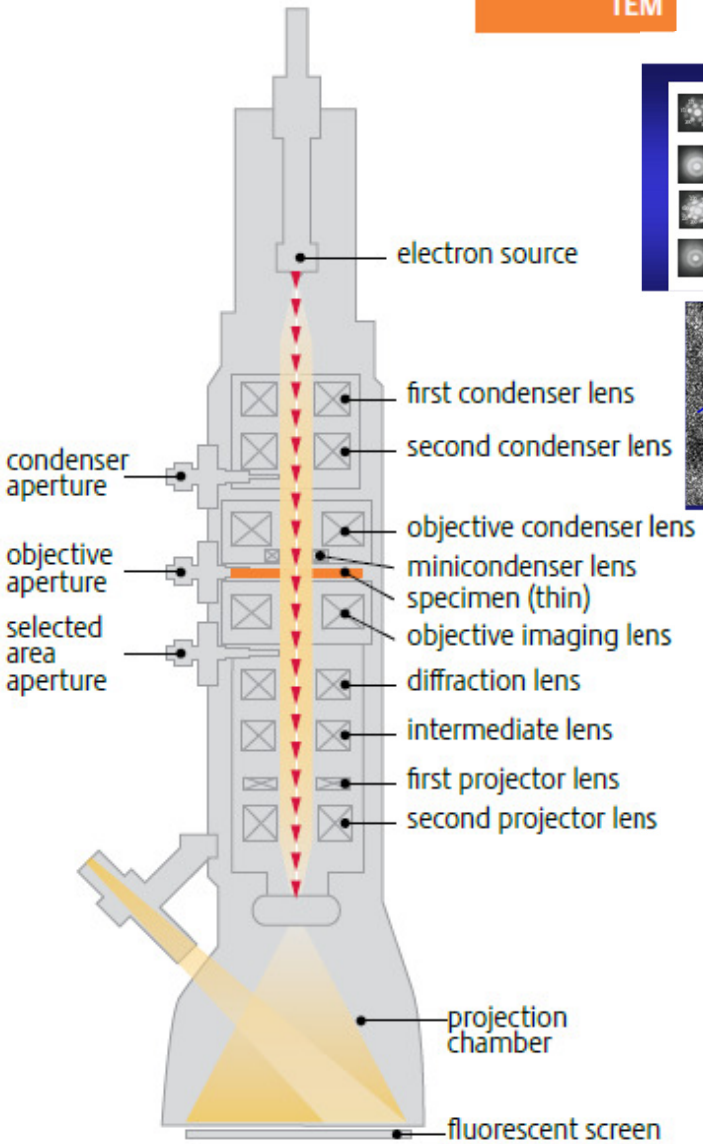


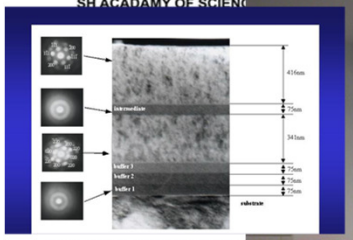
RGY
E
CIENCES

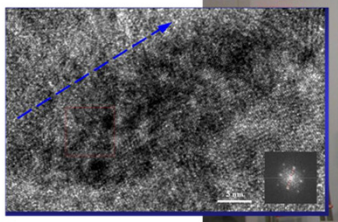
43/16

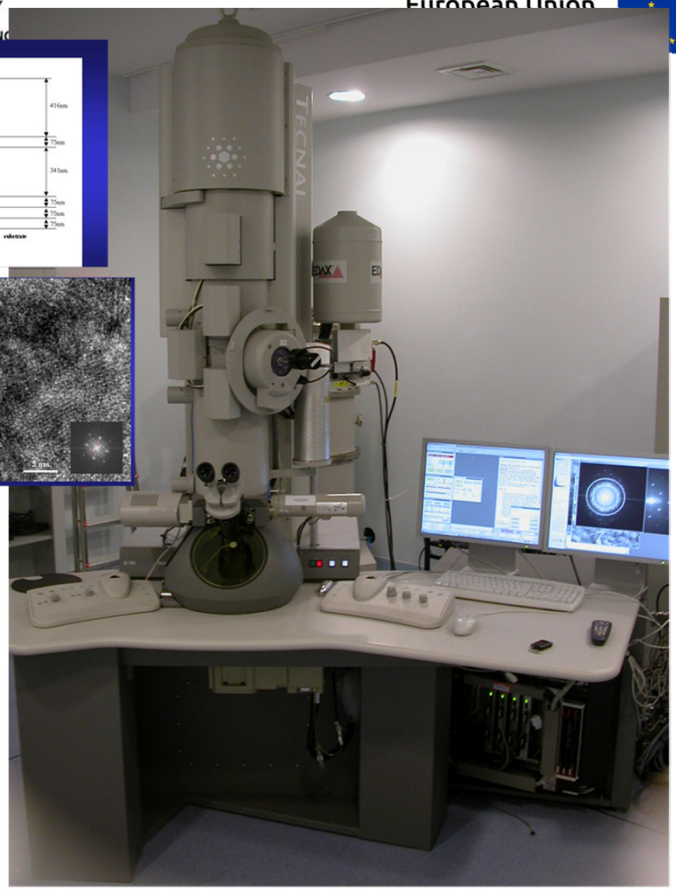
English as the

e European Soc







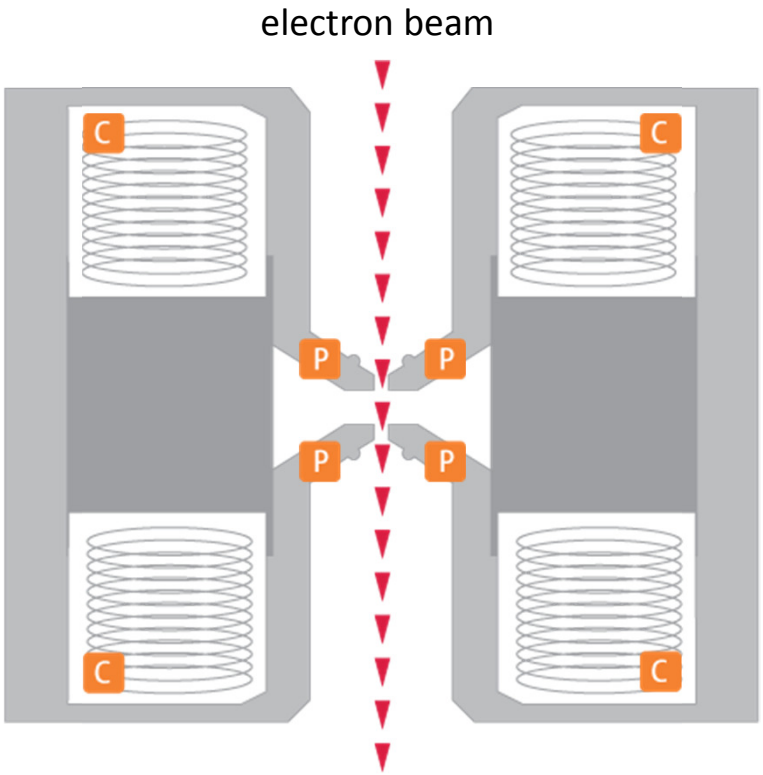


WR.03.02.00-00-I043/16

terials Science with English as the language of instruction

an Union within the European Social Funds

CORE TECHNOLOGY: Electromagnetic Lenses



C electrical coil

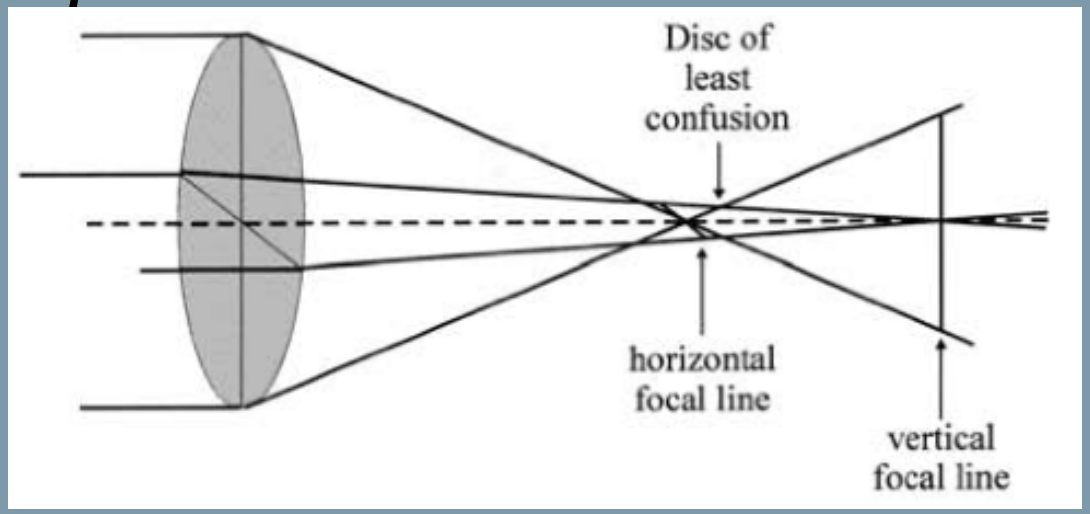
P soft iron pole piece

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

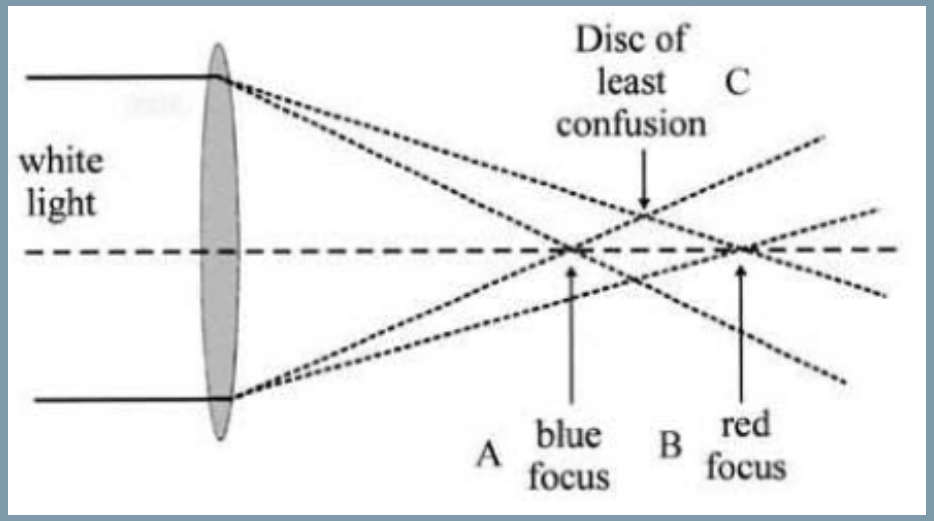
Project co-financed by the European Union within the European Social Funds

spherical aberration



- arises because a simple lens is more powerful at the edge than at the centre
- is not a problem with glass lenses (can be ground to shape)
- disc of *minimum confusion* results instead of point focus:
- is *not correctable* for electromagnetic lenses

chromatic aberration



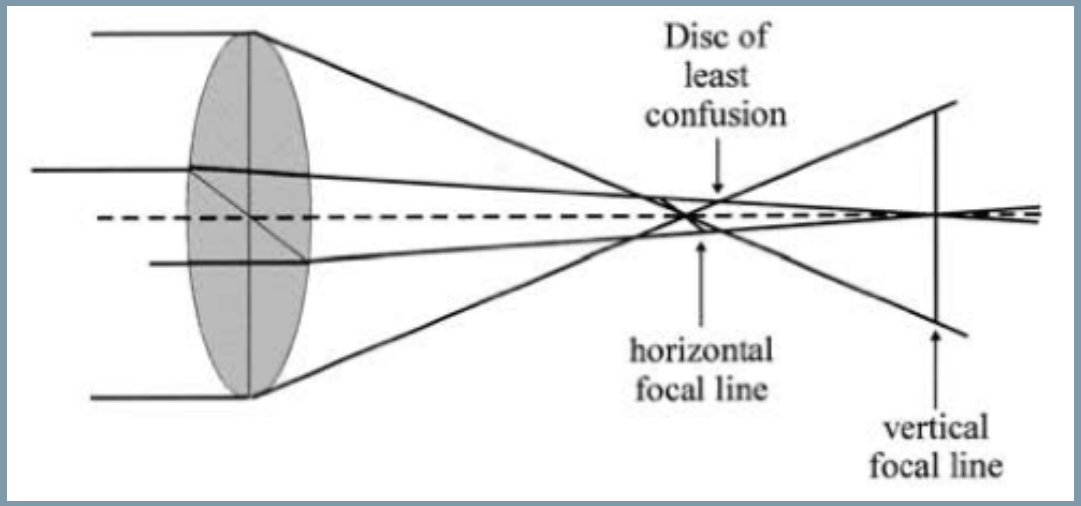
- light of different λ brought to different focal positions
- λ for electrons can be controlled by fixed KV and lens currents
- but λ of electrons can *change* by interaction with specimen !
- rule of thumb: **resolution >= (specimen thickness)/10**

Project WND-POWR.03.02.00-00-I043/16

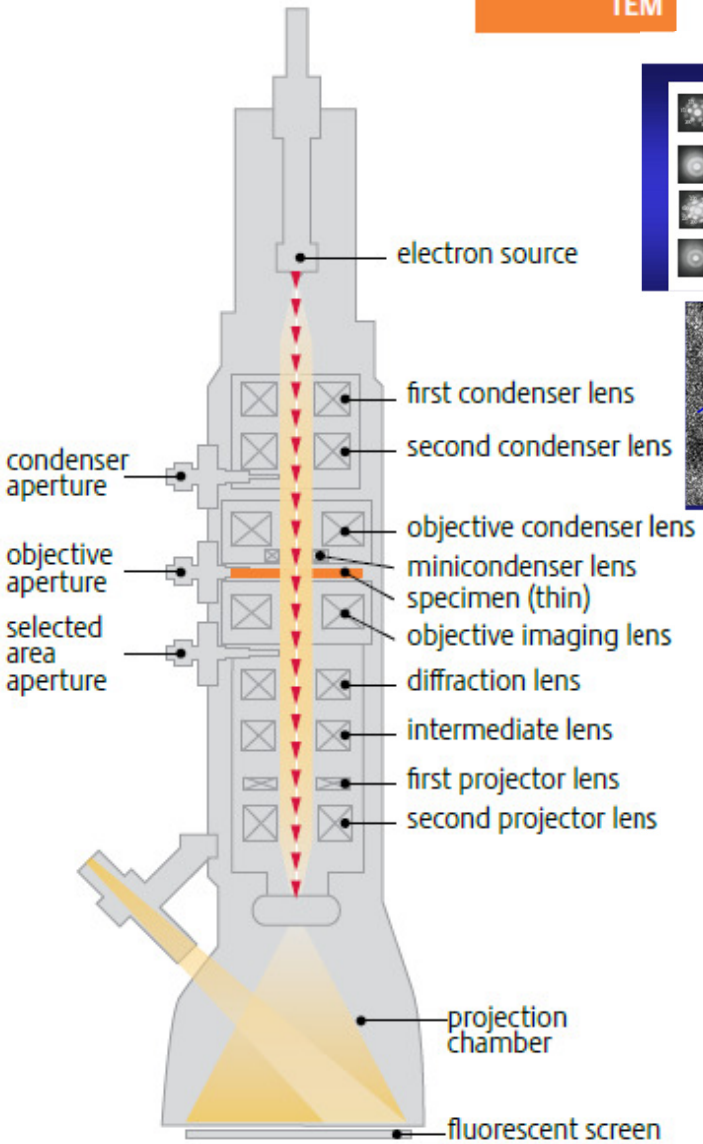
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

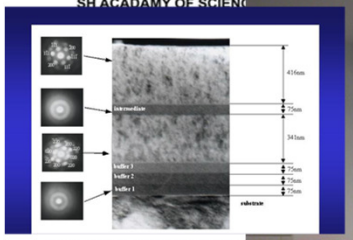
Project co-financed by the European Union within the European Social Funds

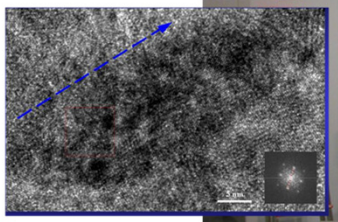
astigmatism

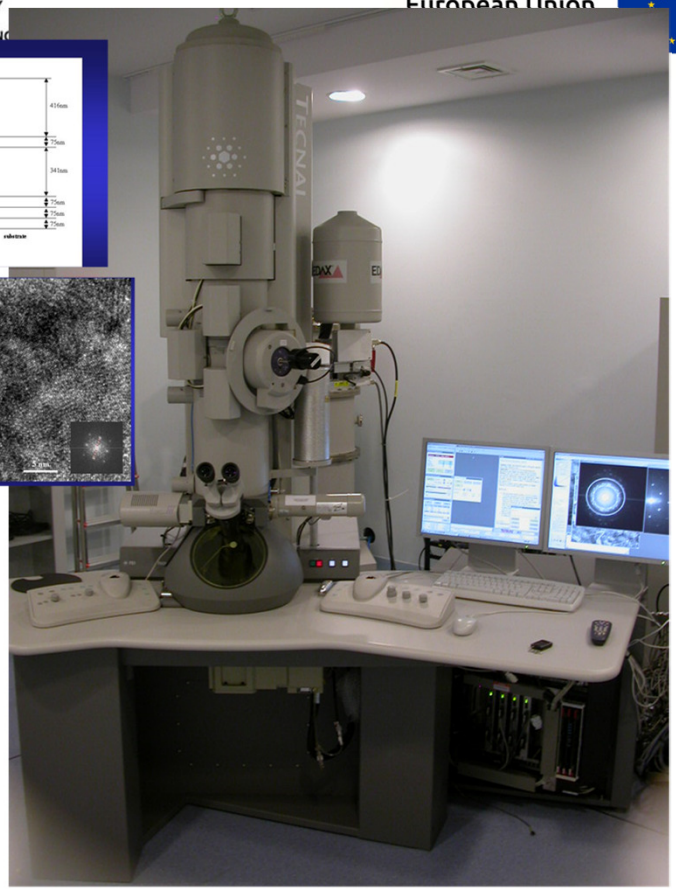


- arises when the lens is more powerful in one plane than in the plane normal to it
- causes points to be imaged as short lines, which ‘flip’ through 90 degrees on passing through ‘focus’ (minimal confusion)





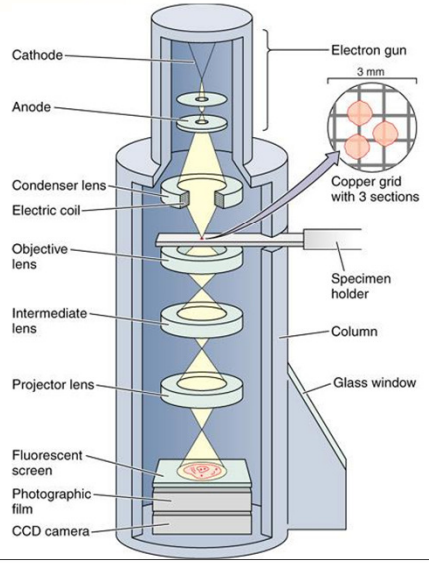


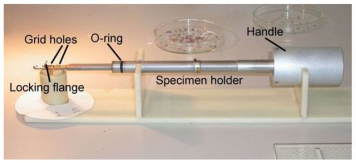


WR.03.02.00-00-I043/16

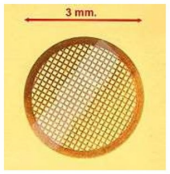
terials Science with English as the language of instruction

an Union within the European Social Funds

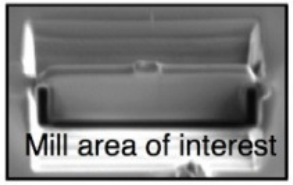


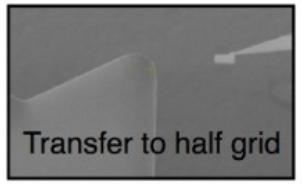


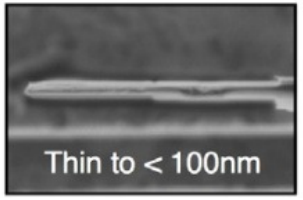
TEM specimen holder

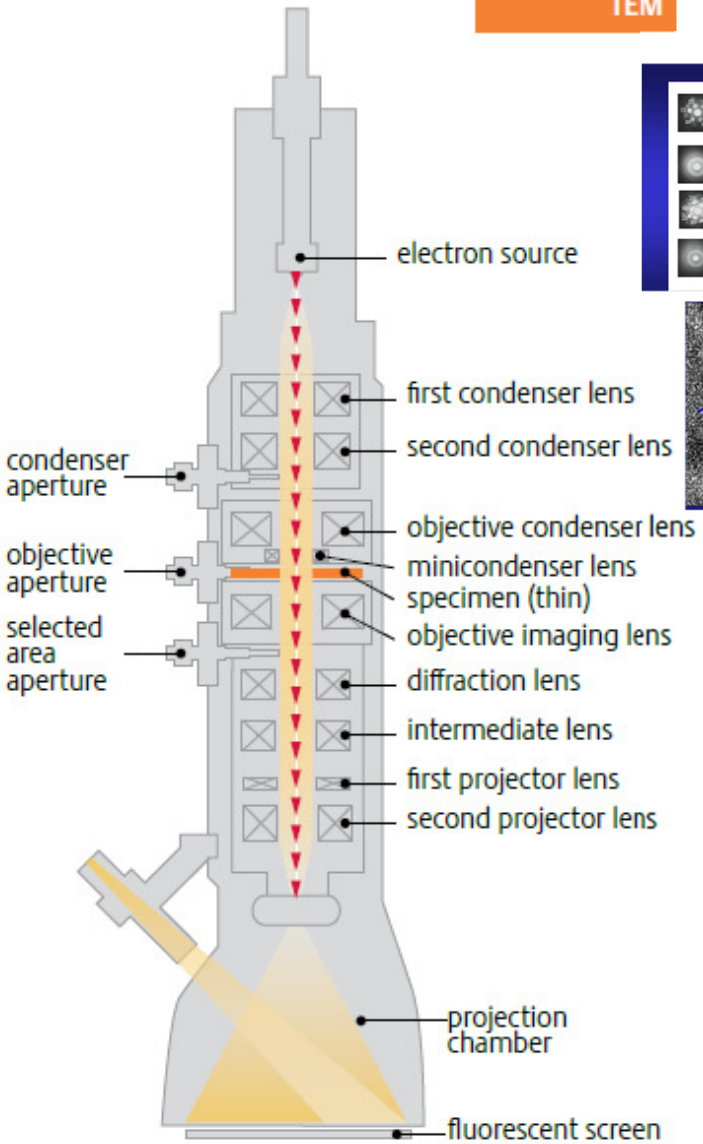


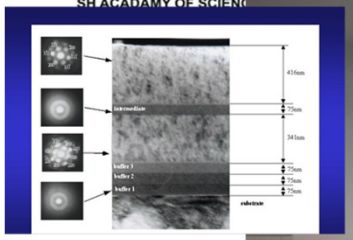
Supporting grid for TEM specimens

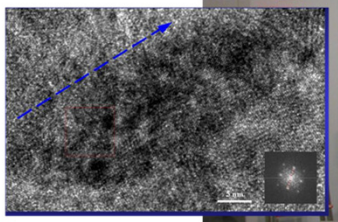


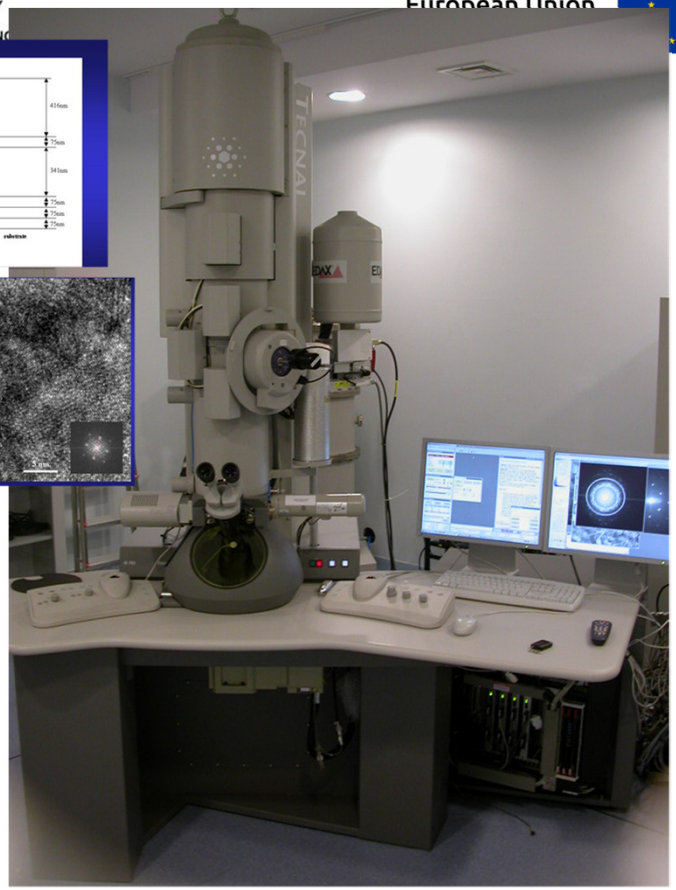












WR.03.02.00-00-I043/16

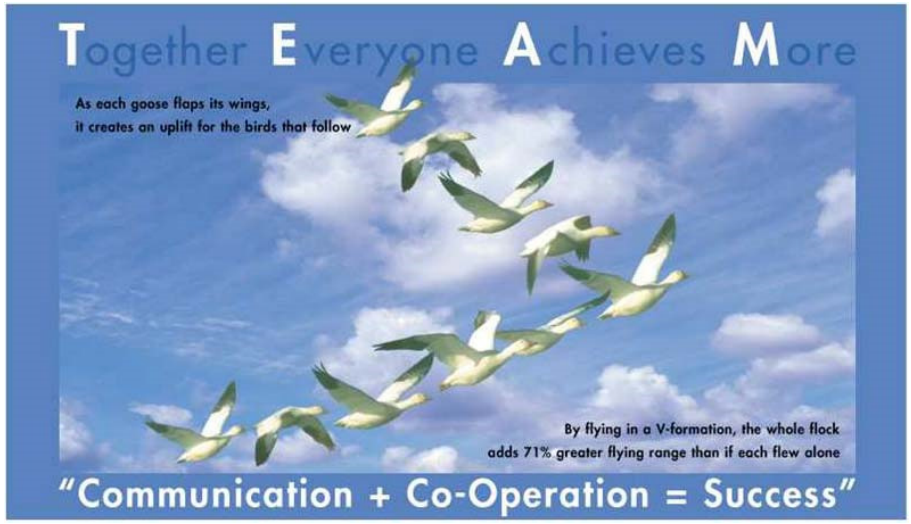
terials Science with English as the language of instruction

an Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

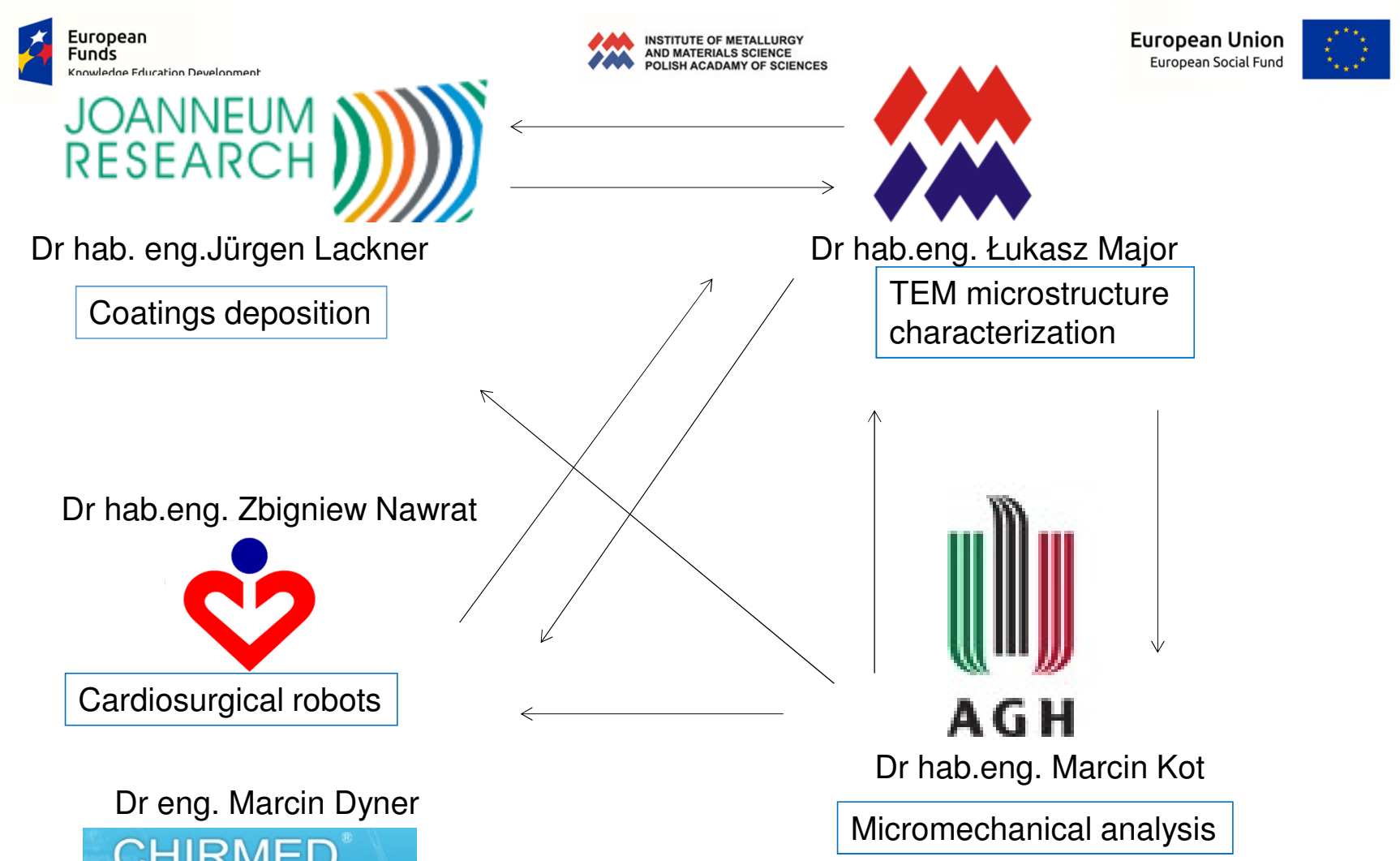
European Union
European Social Fund



Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

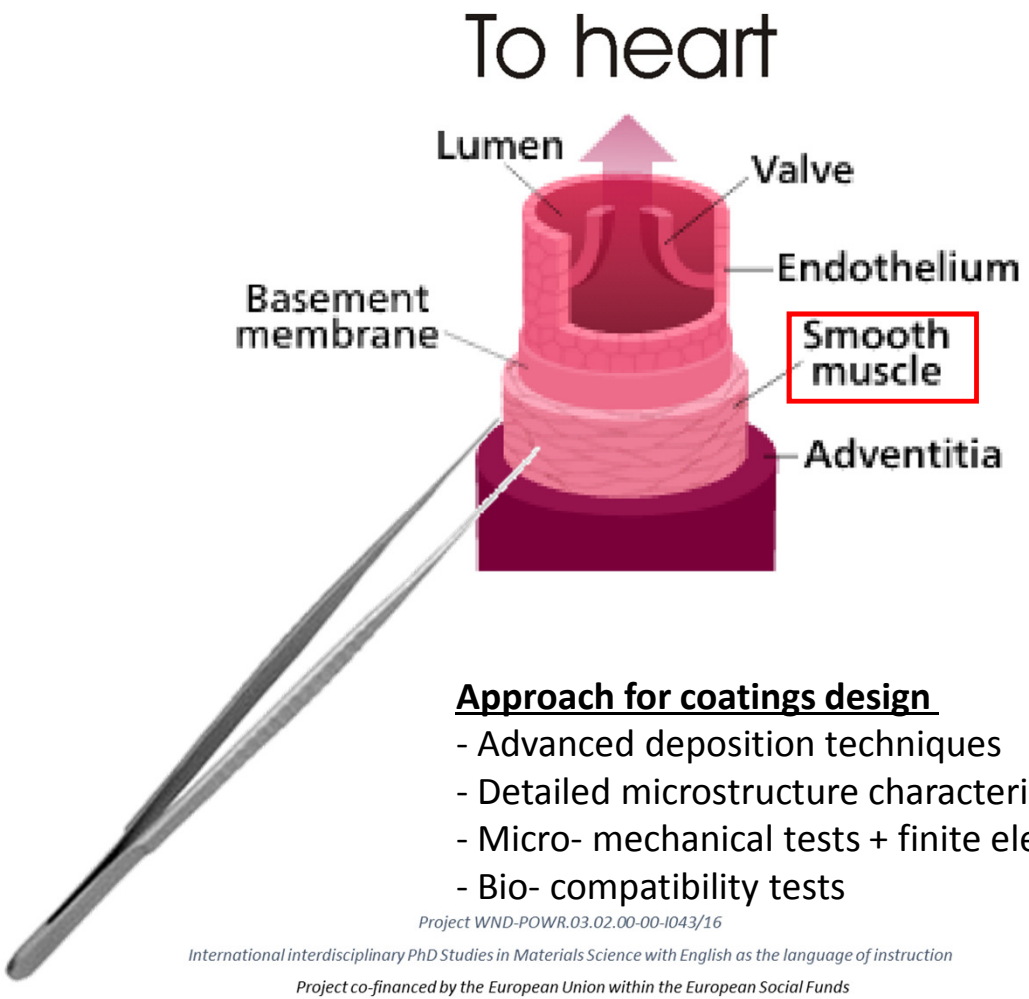
Project co-financed by the European Union within the European Social Funds



Project WND-POWR.03.02.00-00-I043/16

national interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds



Approach for coatings design

- Advanced deposition techniques
- Detailed microstructure characterization
- Micro- mechanical tests + finite elements modeling
- Bio- compatibility tests

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

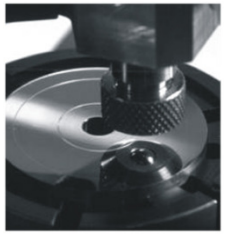
European Union
European Social Fund

Coatings were selected by:

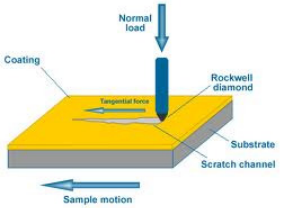
Coatings were characterized by:

Mechanical test

-Ball- on- disc wear test

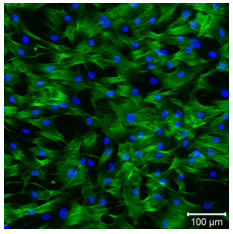


- Scratch adhesion test



Bio- compatibility test

-Test by smooth muscle cells



- Confocal microscopy

Transmission Electron Microscopy

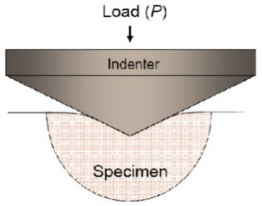
Bio- tribological tests

Microstructure characterization

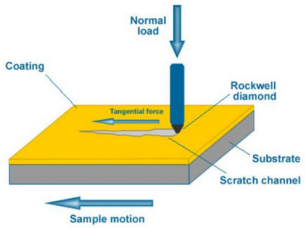
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

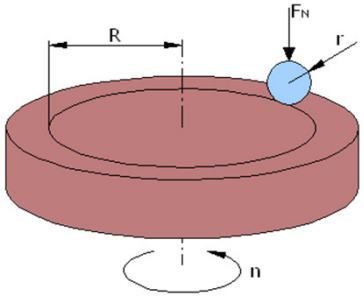
Standard, ex- situ tests

Indentation test (Hardness test)



Scratch test set-up

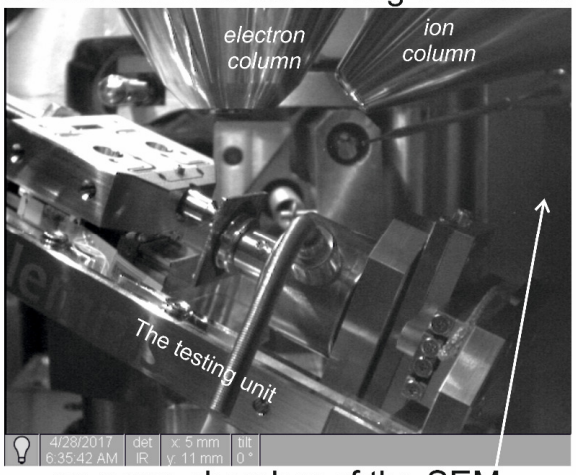


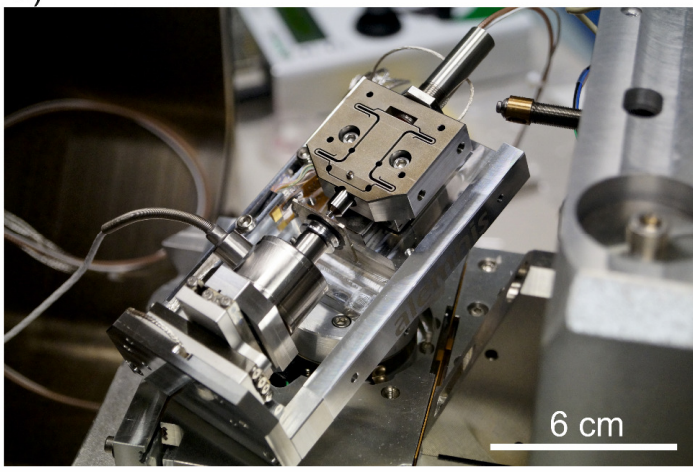


- **Hardness – resistance to penetration of a hard indenter**

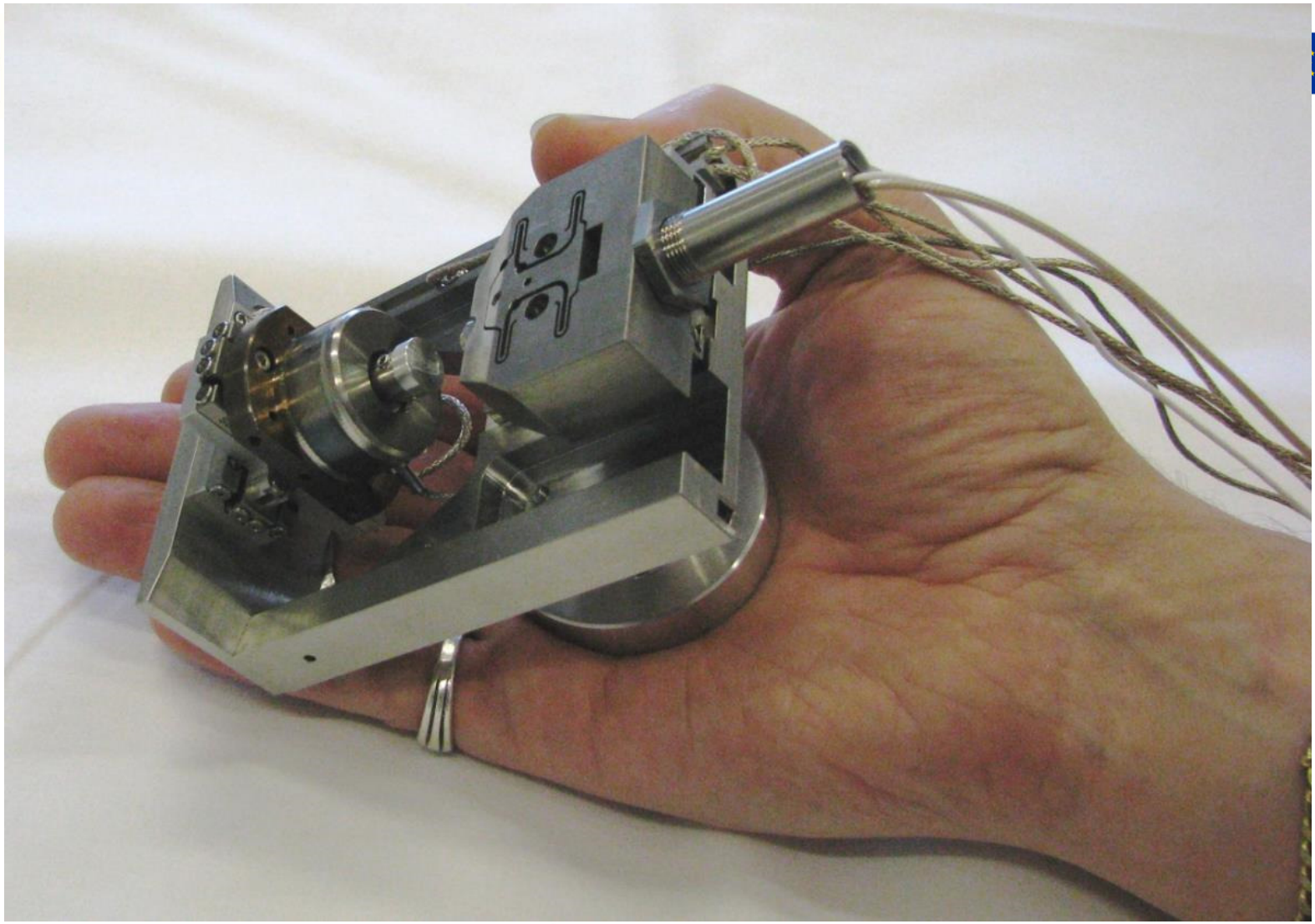
In- situ tests

a) SEM chamber with the testing unit inside b)



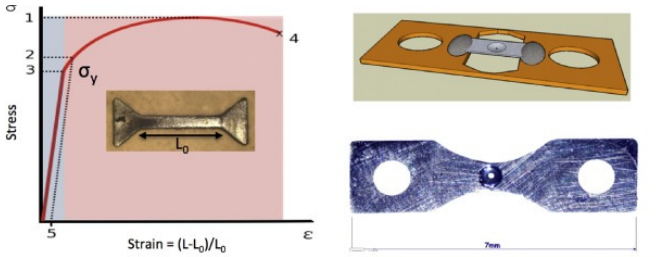


vacuum chamber of the SEM



International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

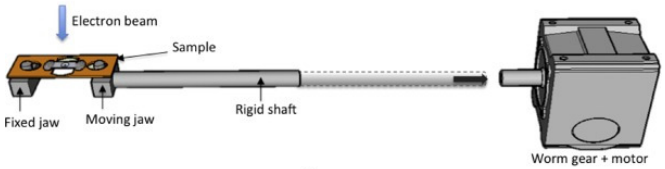
Project co-financed by the European Union within the European Social Funds


σ
1
2
3
4
5
σy
Stress
L0
Strain = (L-L0)/L0
ε

a)

7mm

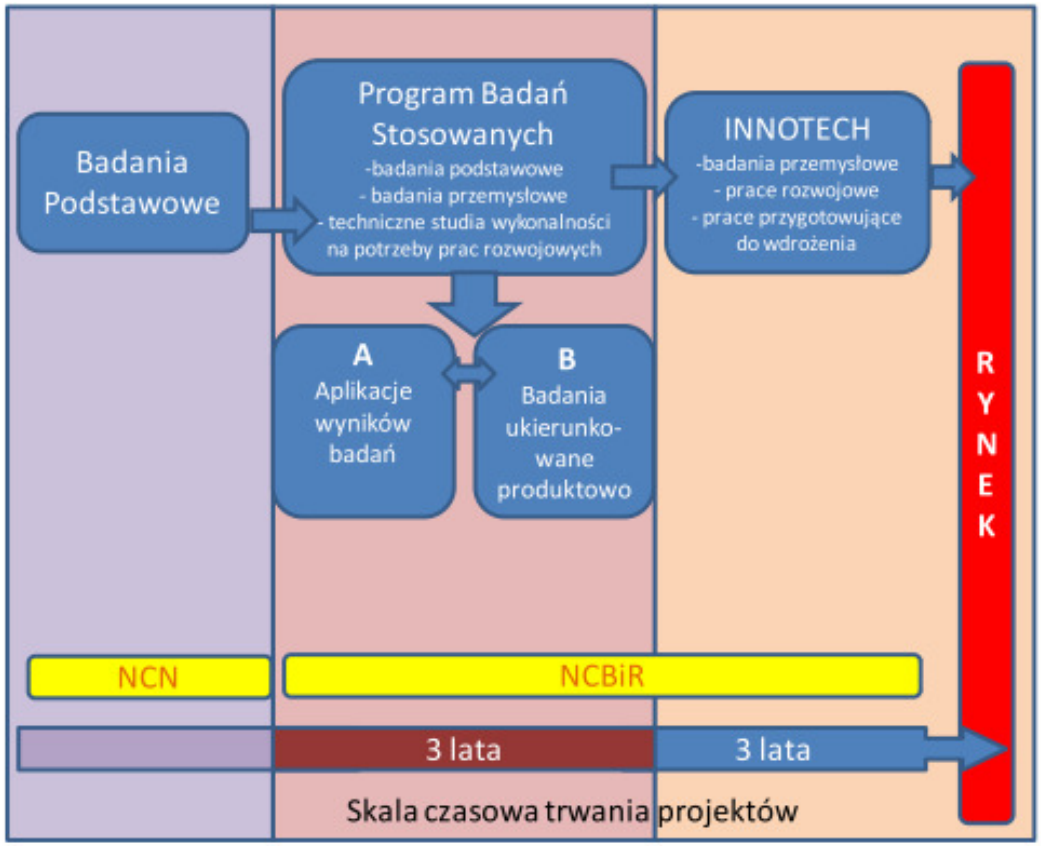
b)

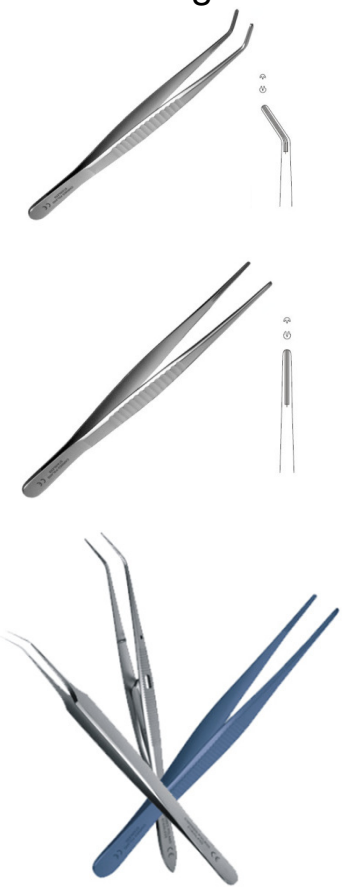

Electron beam
Sample
Fixed jaw
Moving jaw
Rigid shaft
Worm gear + motor

c)

d)

General goal





- Project NCN nr: 3066/B/T02/2011/40- *FINISHED*
- Project NCN nr: 2012/06/M/ST8/00408- *HARMONIA- FINISHED*
- Project NCN nr: 2012/07/B/ST8/03396- *OPUS- FINISHED*
- Project NCN nr: 2014/15/B/ST8/00103- *OPUS- FINISHED*
- Project NCN nr: 2015/19/B/ST8/00942- *OPUS- in progress*
- Project NCBR, number: DZP/M-ERA.NET-2015/285/2016- *in progress*

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Title: Development and diagnostics of multifunctional ceramic/ hydrogenated amorphous carbon coatings for elements of pumps of ventricle assist pumps

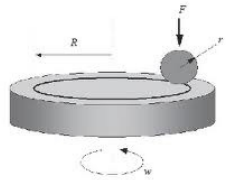
Project WND-POWR.03.02.00-00-I043/16

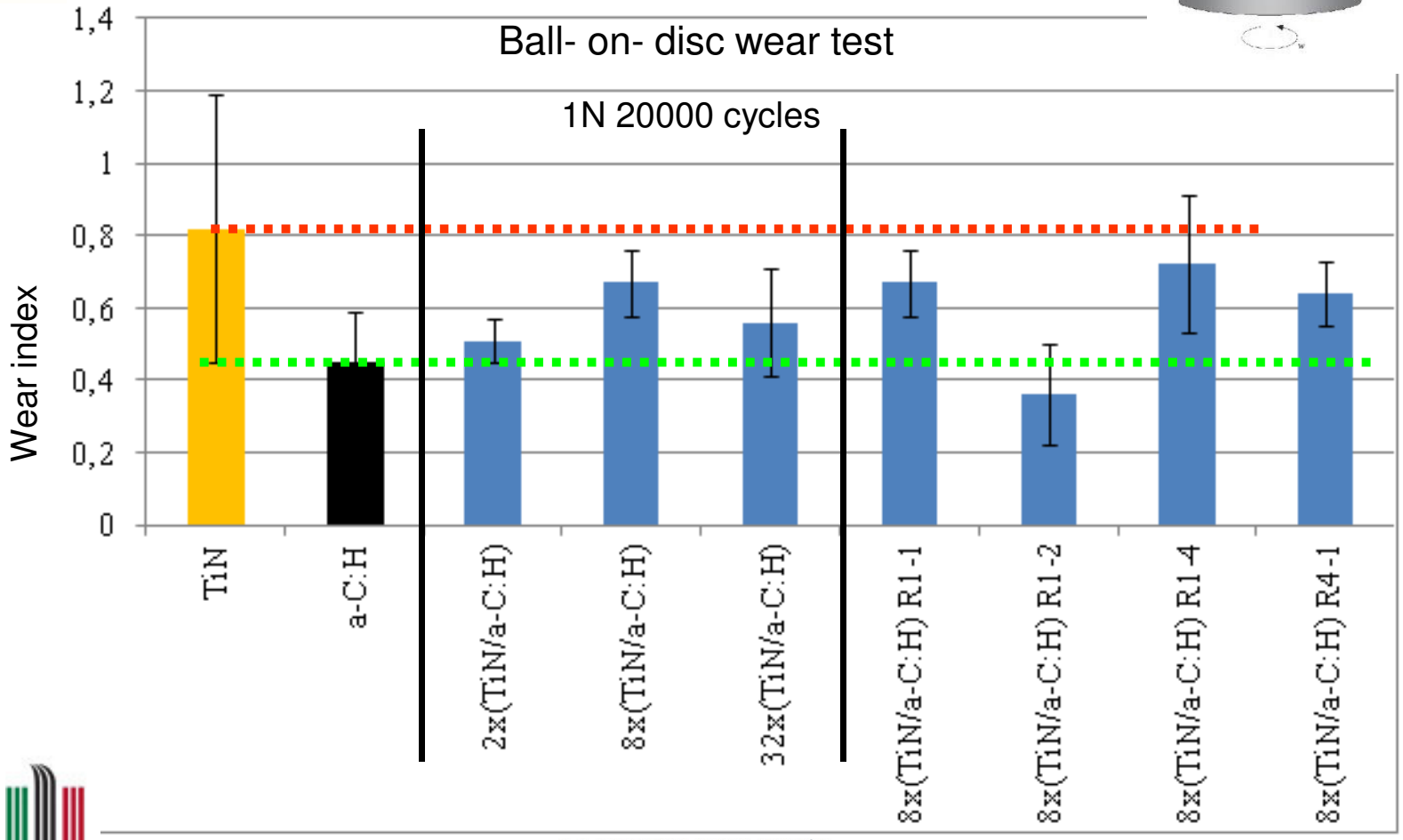
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES



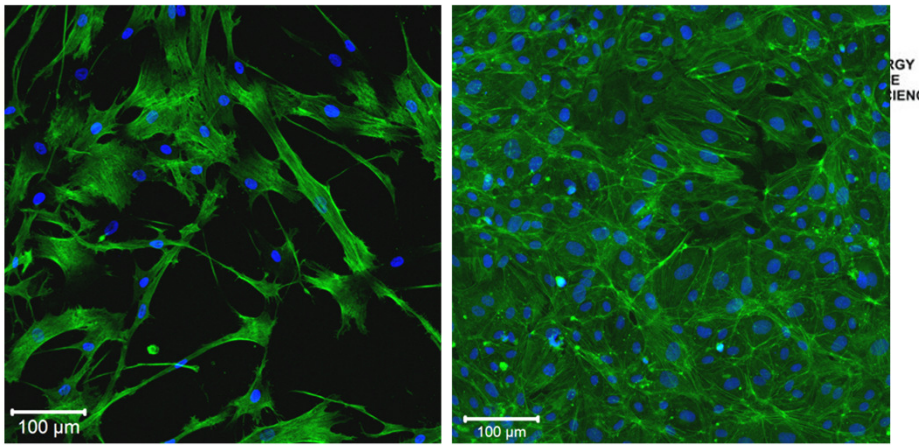


AGH

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

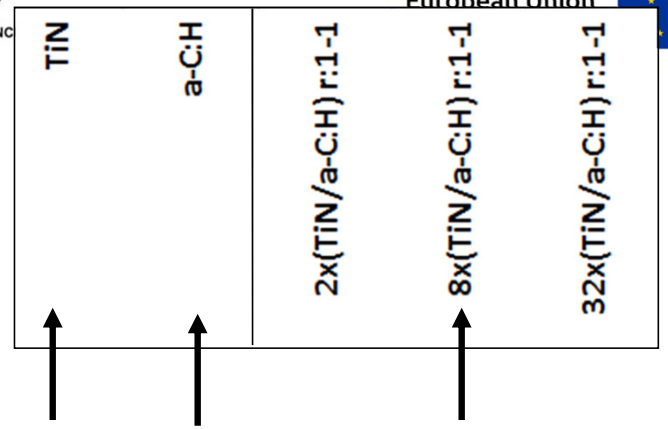
Project co-financed by the European Union within the European Social Funds

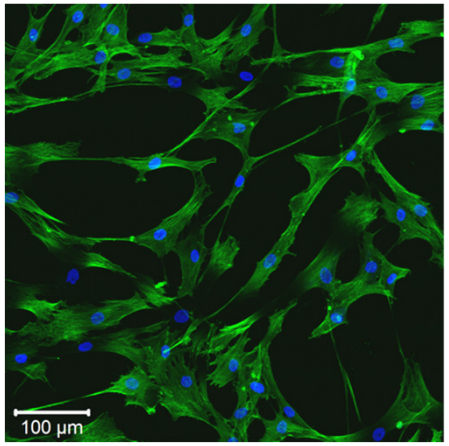


TiN a-C:H

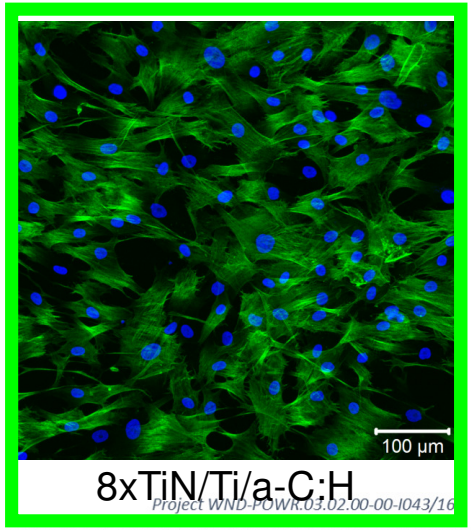
Reference coatings

Bio- compatibility test

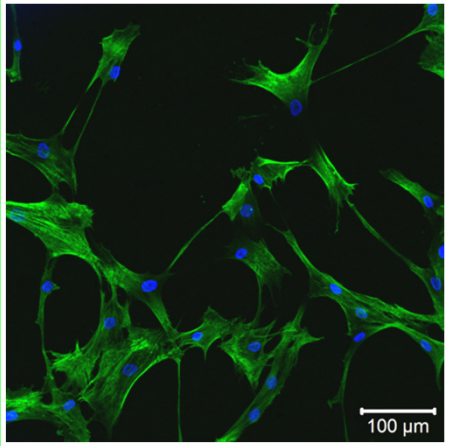




2xTiN/Ti/a-C:H



8xTiN/Ti/a-C:H



32xTiN/Ti/a-C:H

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Single layer a-C:H coating

As deposited coating (Before mechnaical tests)

Microstructure characterization

Project WND-POWR.03.02.00-00-I043/16

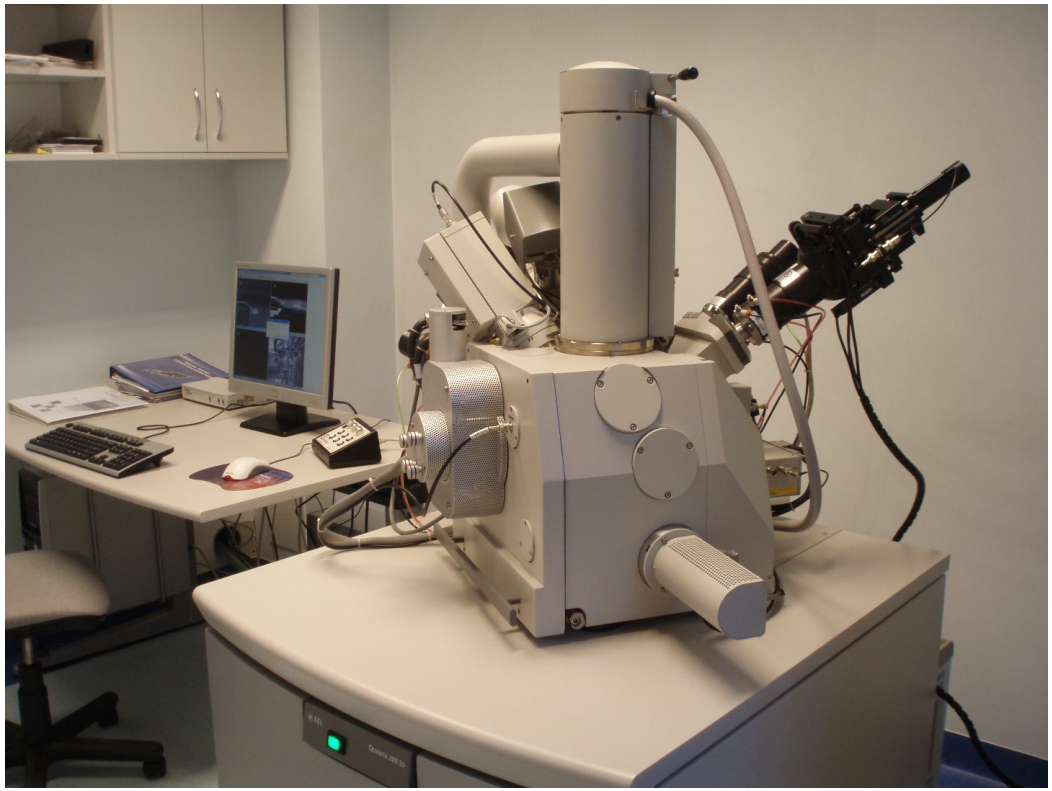
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

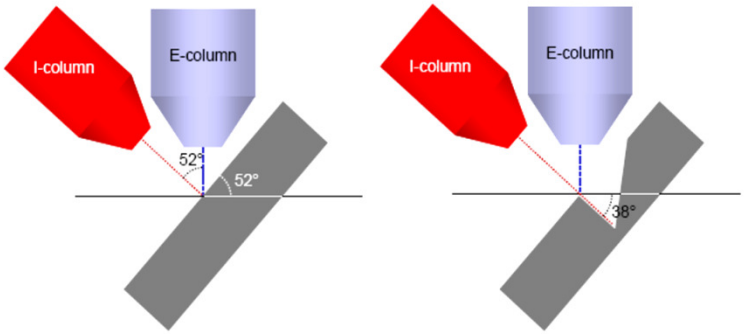
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

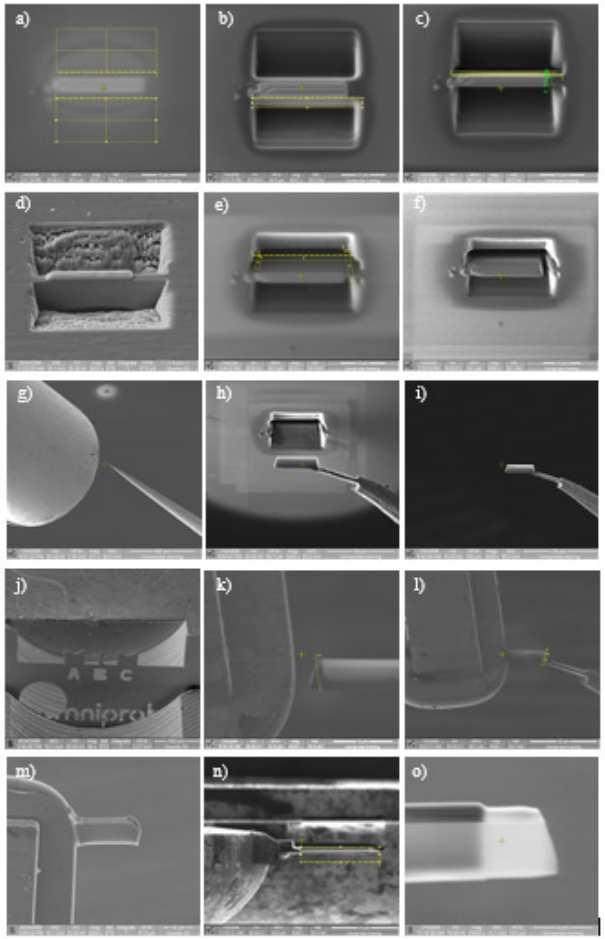




Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

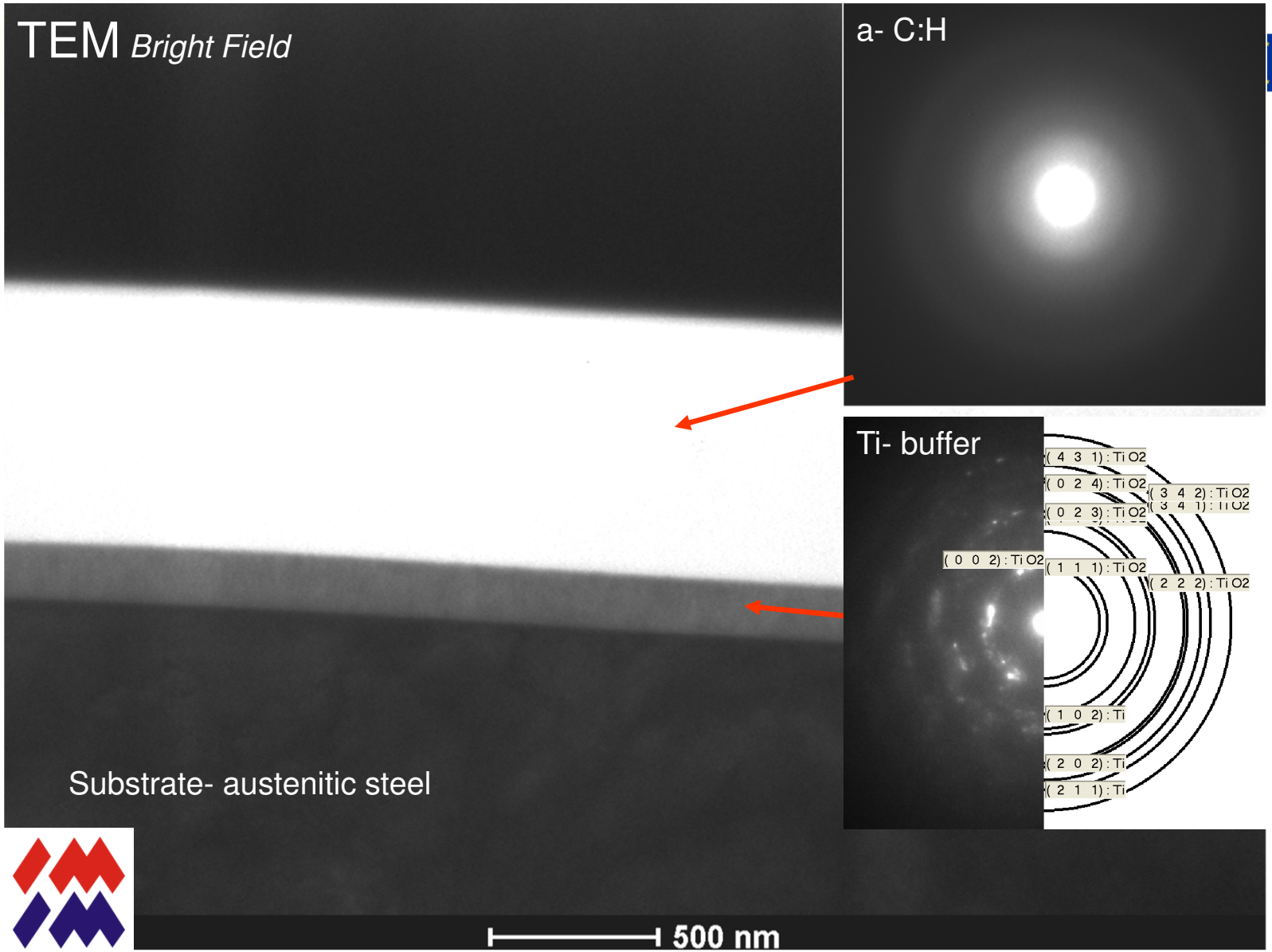
Project co-financed by the European Union within the European Social Funds

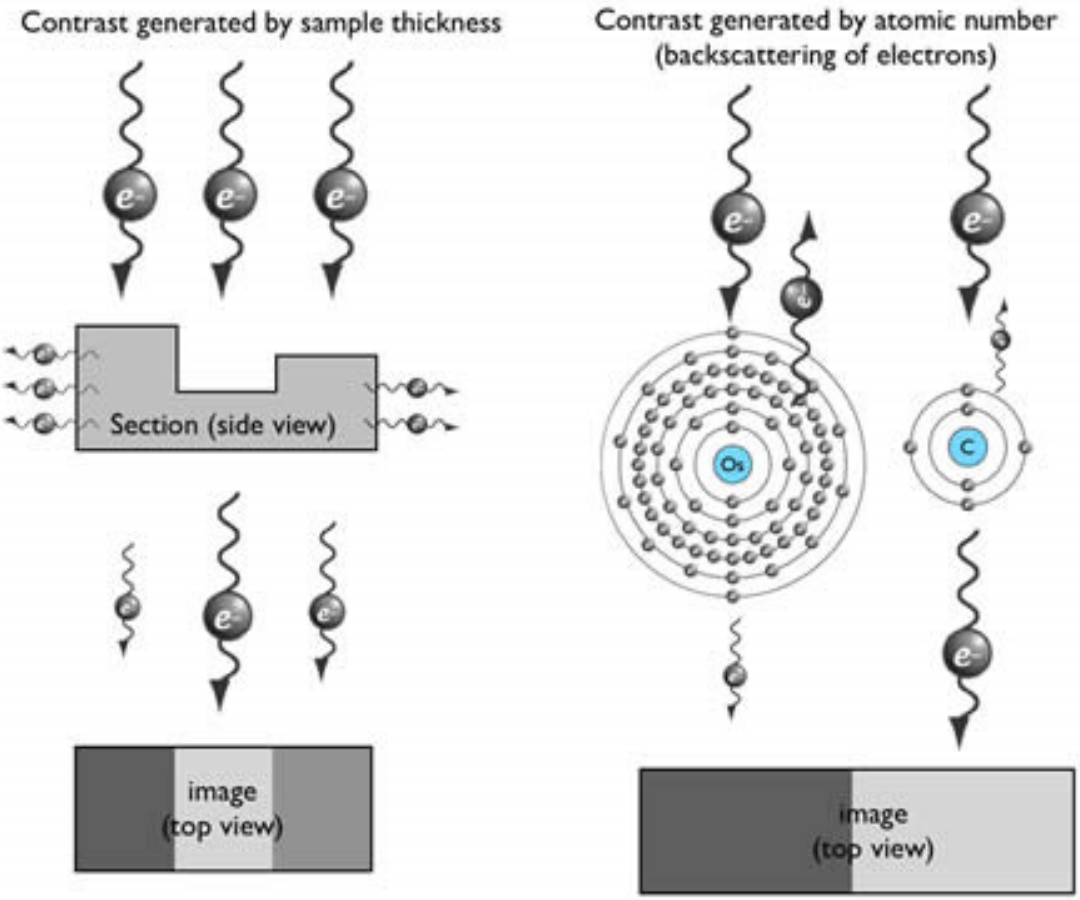


Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

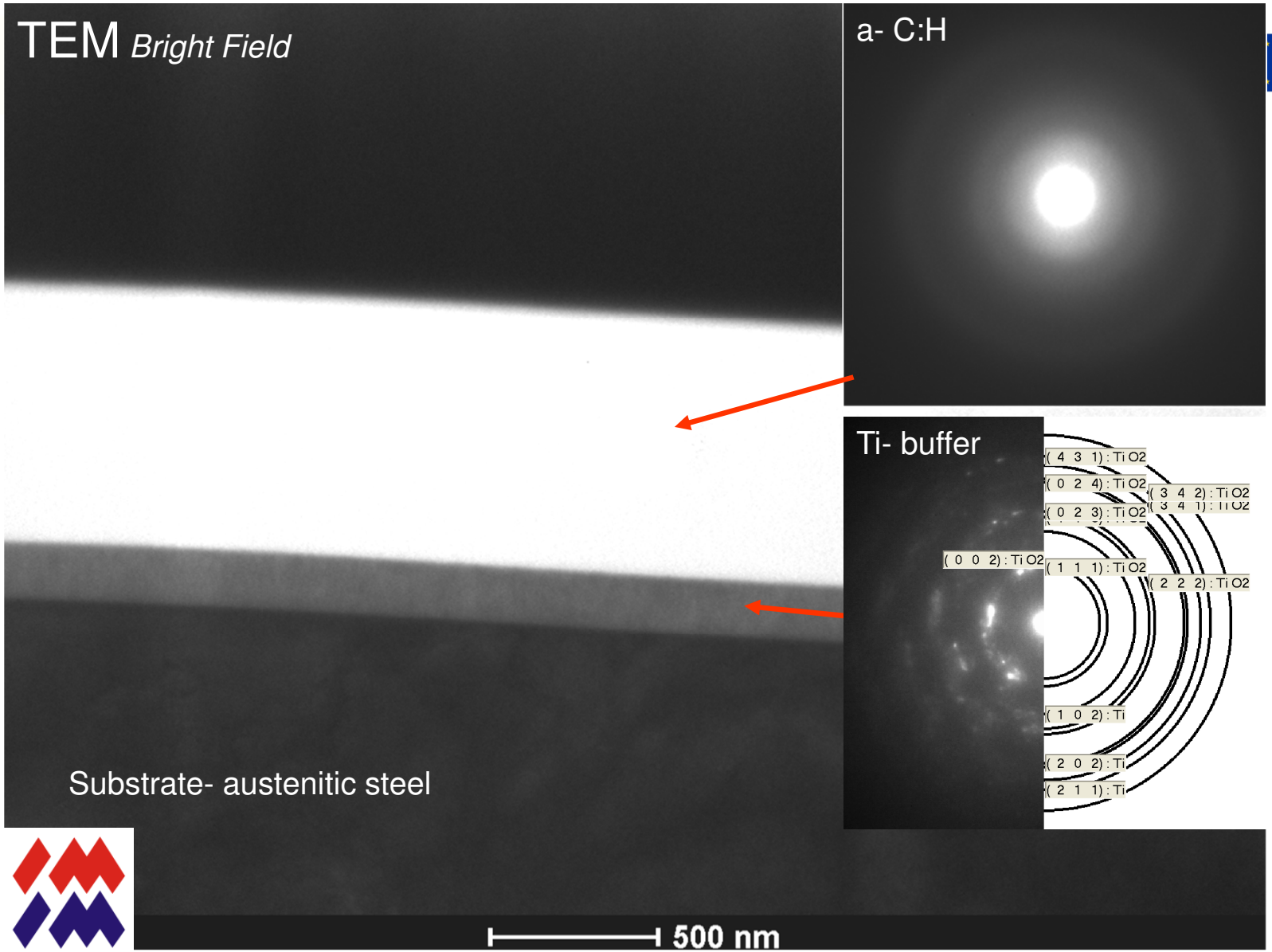

TEM Bright Field
a- C:H
Ti- buffer
(4 3 1) : Ti O2
(0 2 4) : Ti O2
(3 4 2) : Ti O2
(0 2 3) : Ti O2
(0 0 2) : Ti O2
(1 1 1) : Ti O2
(2 2 2) : Ti O2
(1 0 2) : Ti
(2 0 2) : Ti
(2 1 1) : Ti
Substrate- austenitic steel
500 nm



Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds


TEM Bright Field
a- C:H
Ti- buffer
(4 3 1) : Ti O2
(0 2 4) : Ti O2
(3 4 2) : Ti O2
(0 2 3) : Ti O2
(0 0 2) : Ti O2
(1 1 1) : Ti O2
(2 2 2) : Ti O2
(1 0 2) : Ti
(2 0 2) : Ti
(2 1 1) : Ti
Substrate- austenitic steel
500 nm

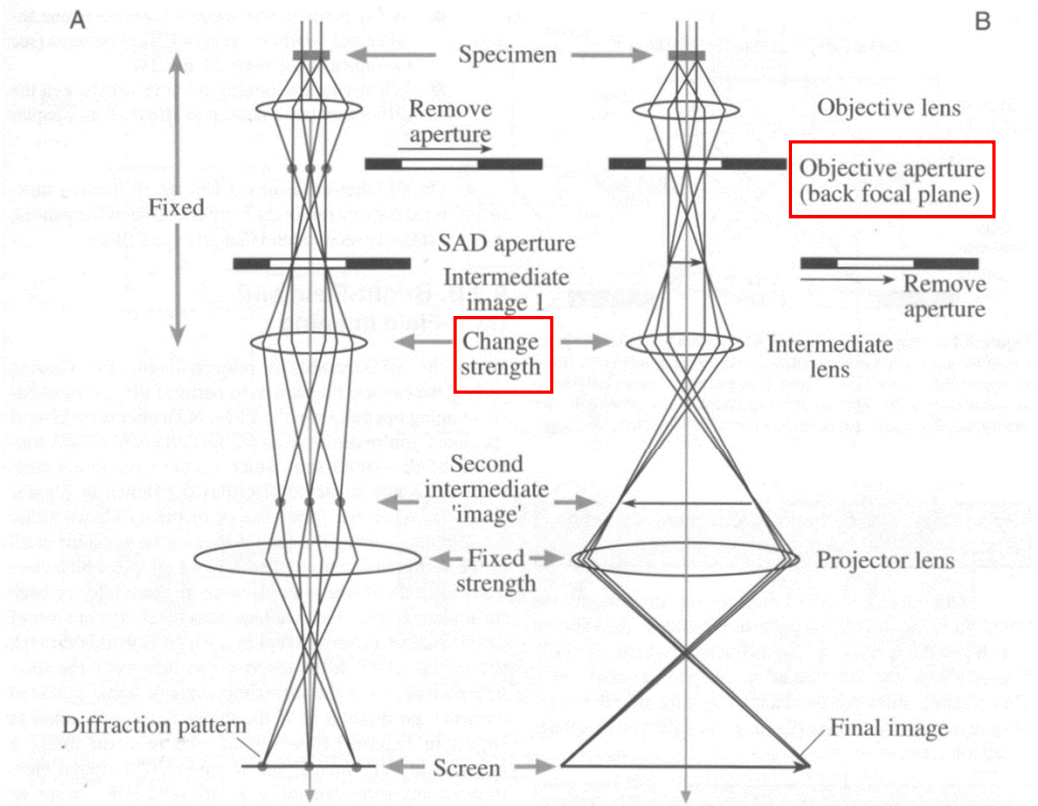
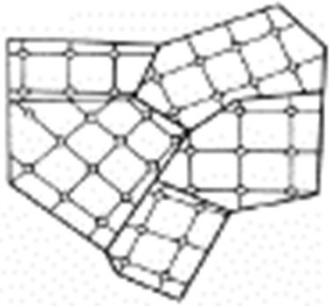


Figure 9.12. The two basic operations of the TEM imaging system involve (A) projecting the diffraction pattern on the viewing screen and (B) projecting the image onto the screen. In each case the intermediate lens selects either the back focal plane or the image plane of the objective lens as its object.

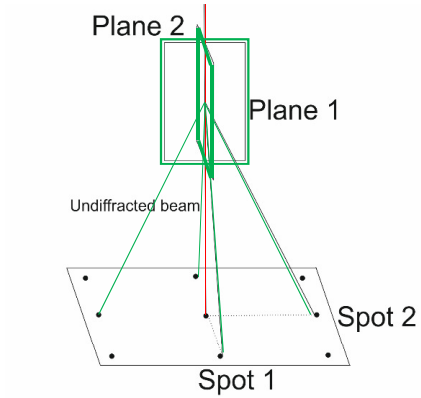
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

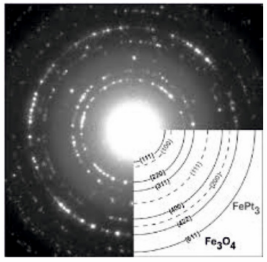
European Union
European Social Fund

Single crystal

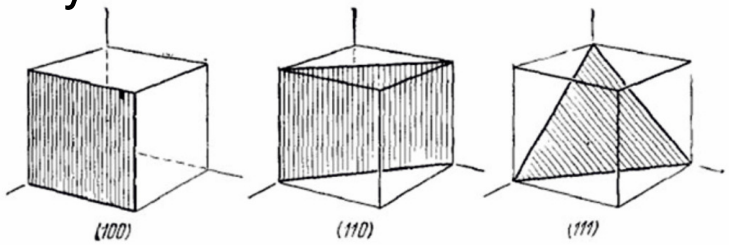


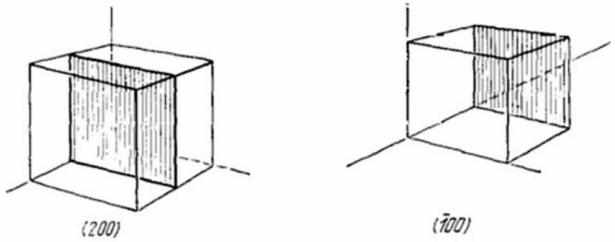
Poly crystal





Miller indices of major cystal planes of the regular system





European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

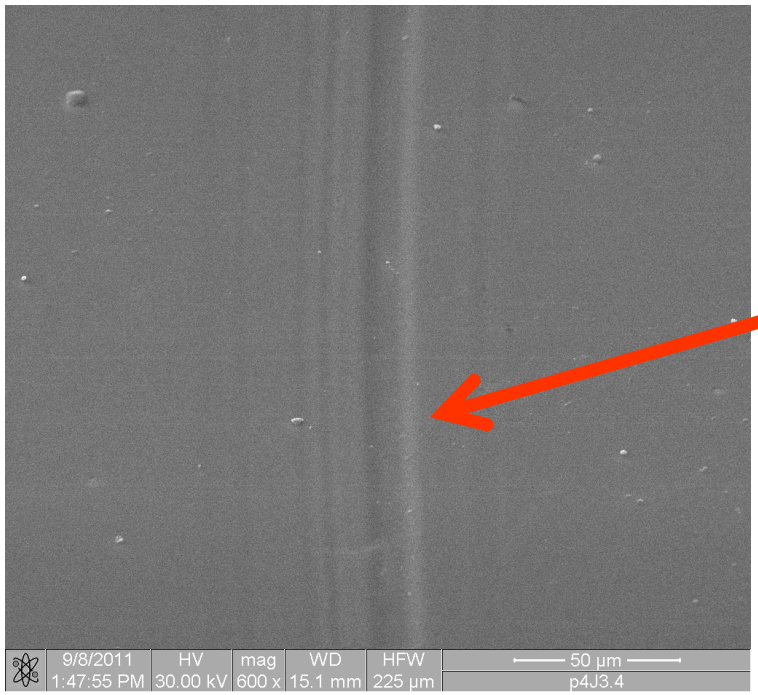
European Union
European Social Fund

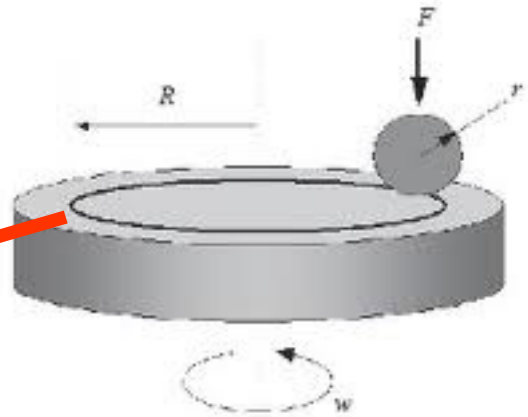
Single layer a-C:H coating

Coating after mechanical tests (Ball-on-disc 1N; 2000 cycles)
Microstructure characterization

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

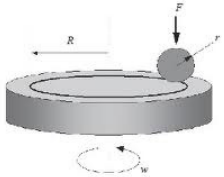
SEM

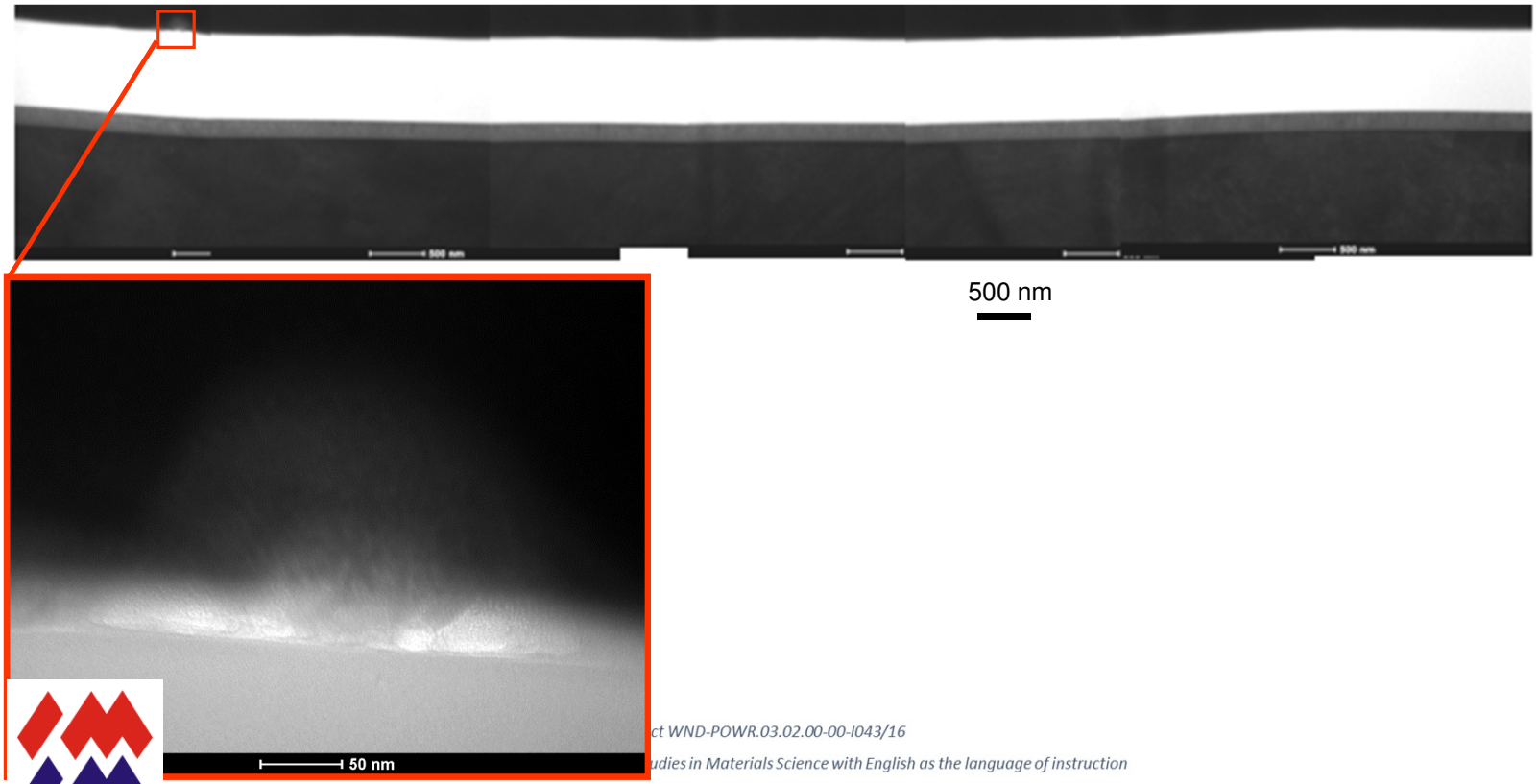

9/8/2011
1:47:55 PM
HV
30.00 kV
mag
600 x
WD
15.1 mm
HFW
225 µm
50 µm
p4J3.4


F
R
w

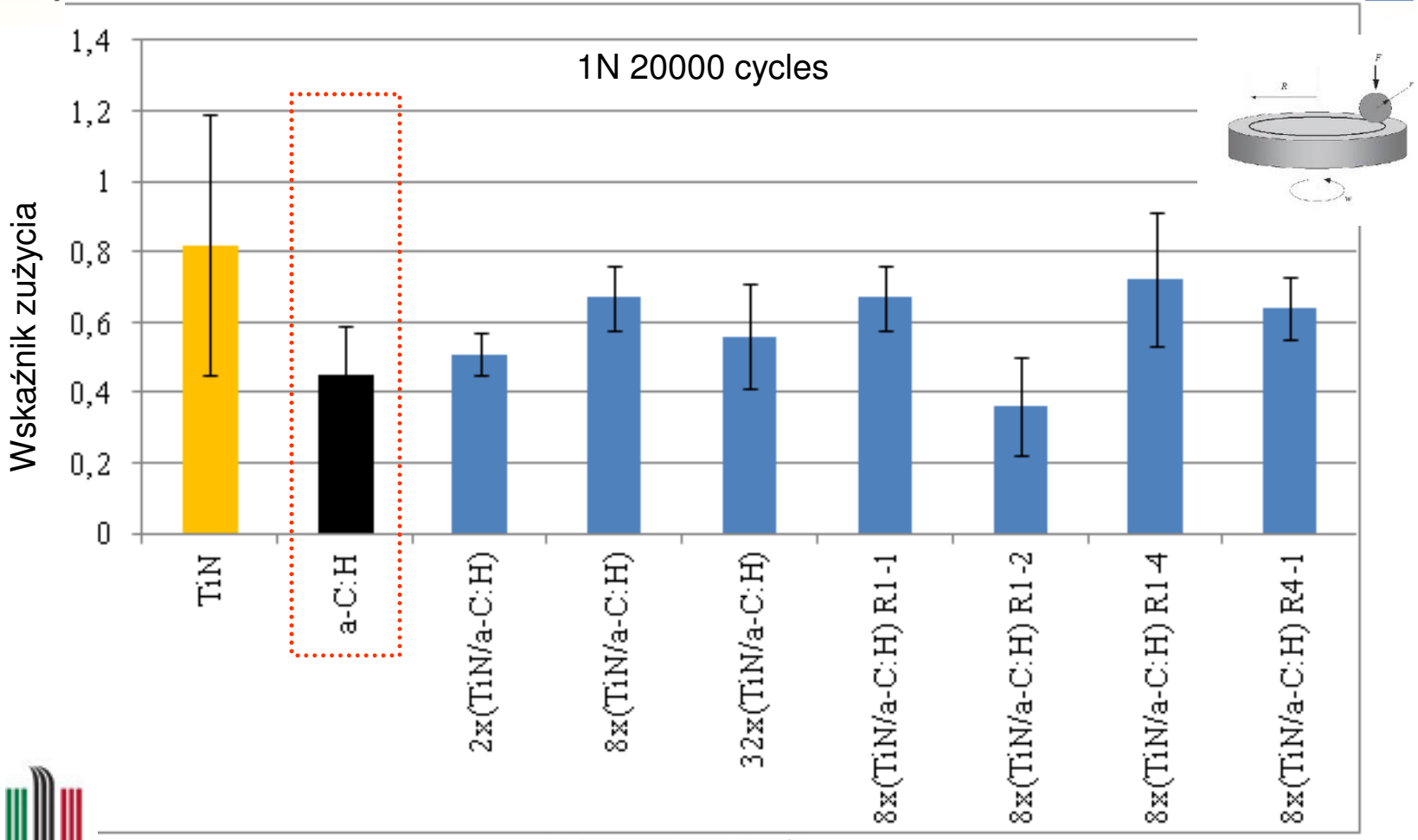
TEM *Bright Field;*

Coating after mechanical test





ct WND-POWR.03.02.00-00-I043/16
udies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds


1N 20000 cycles
Wskaźnik zużycia
1,4
1,2
1
0,8
0,6
0,4
0,2
0
TiN
a-C:H
2x(TiN/a-C:H)
8x(TiN/a-C:H)
32x(TiN/a-C:H)
8x(TiN/a-C:H) R1-1
8x(TiN/a-C:H) R1-2
8x(TiN/a-C:H) R1-4
8x(TiN/a-C:H) R4-1

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Single layer TiN coating

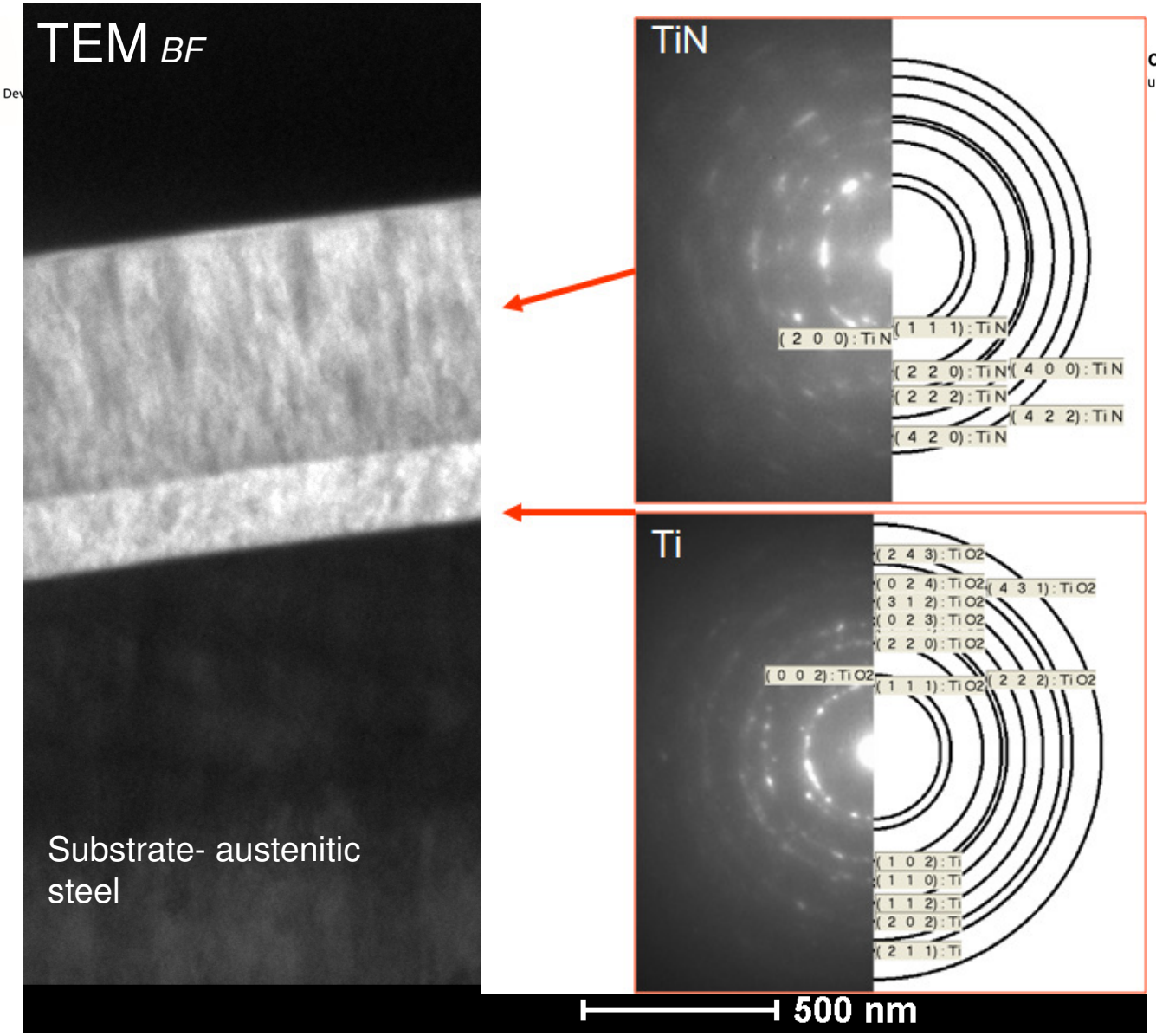
As deposited coating (Before mechnaical tests)

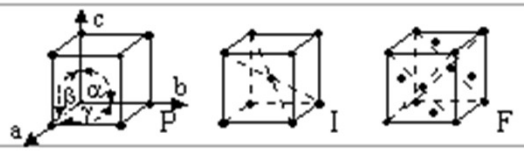
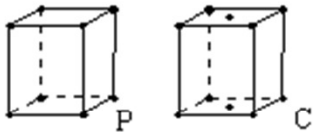
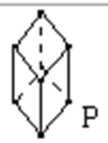
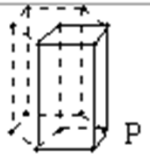
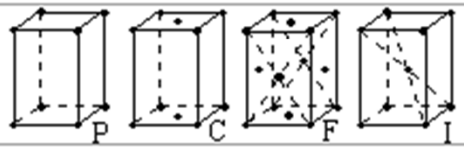
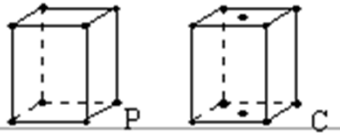
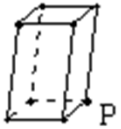
Microstructure characterization

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

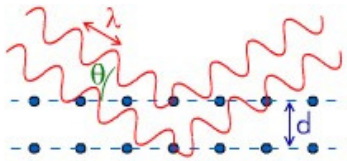

TEM BF
Substrate- austenitic steel
TiN
(2 0 0) : Ti N
(1 1 1) : Ti N
(2 2 0) : Ti N
(4 0 0) : Ti N
(2 2 2) : Ti N
(4 2 2) : Ti N
(4 2 0) : Ti N
Ti
(2 4 3) : Ti O2
(0 2 4) : Ti O2
(4 3 1) : Ti O2
(3 1 2) : Ti O2
(0 2 3) : Ti O2
(2 2 0) : Ti O2
(0 0 2) : Ti O2
(1 1 1) : Ti O2
(2 2 2) : Ti O2
(1 0 2) : Ti
(1 1 0) : Ti
(1 1 2) : Ti
(2 0 2) : Ti
(2 1 1) : Ti
500 nm

Regularny $\alpha = \beta = \gamma = 90^0$ $a = b = c$	23, m3, $\bar{4}$3m, 432, m3m	
Tetragonalny $\alpha = \beta = \gamma = 90^0$ $a = b \neq c$	4, $\bar{4}$, 4/m,422, $\bar{4}$2m, 4mm, 4/mmm	
Trygonalny $\alpha = \beta = \gamma \neq 90^0$ $a = b = c$	3,$\bar{3}$, 3m, 32, $\bar{3}$m	
Heksagonalny $\alpha = \beta = 90^0$ $\gamma = 120^0$ $a = b \neq c$	6, $\bar{6}$, 622, 6/m, $\bar{6}$m2, 6mm, 6/mmm	
Rombowy $\alpha = \beta = \gamma = 90^0$ $a \neq b \neq c$	222, mm, mmm	
Jednoskośny $\alpha = \gamma = 90^0$ $\beta \neq 90^0$ $a \neq b \neq c$	2, m, 2/m	
Trójskośny $\alpha \neq \beta \neq \gamma \neq 90^0$ $a \neq b \neq c$	1, $\bar{1}$	

Miller indices of major cystal planes of the regular system

Bragg's Law:

$$n\lambda = 2d\sin(\theta)$$



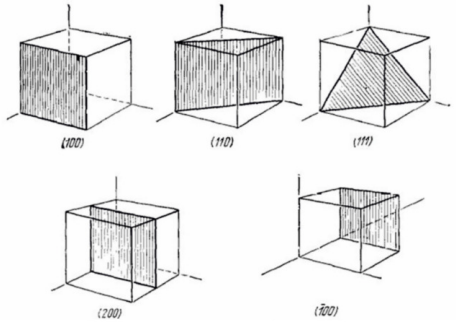
where

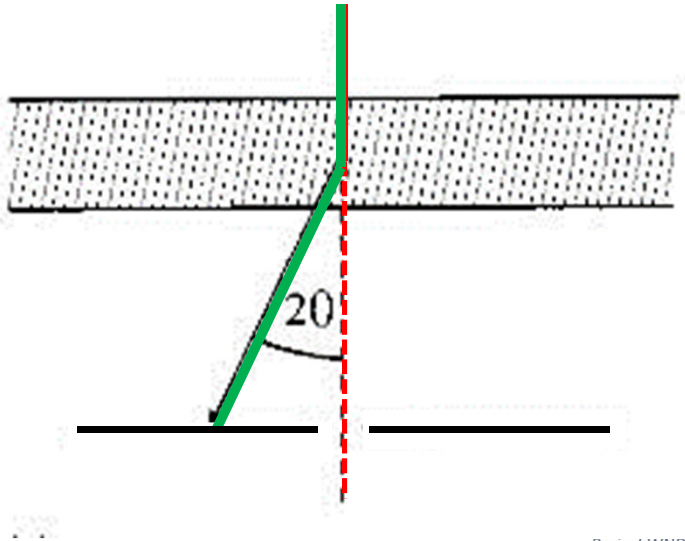
λ is the wavelength of the rays

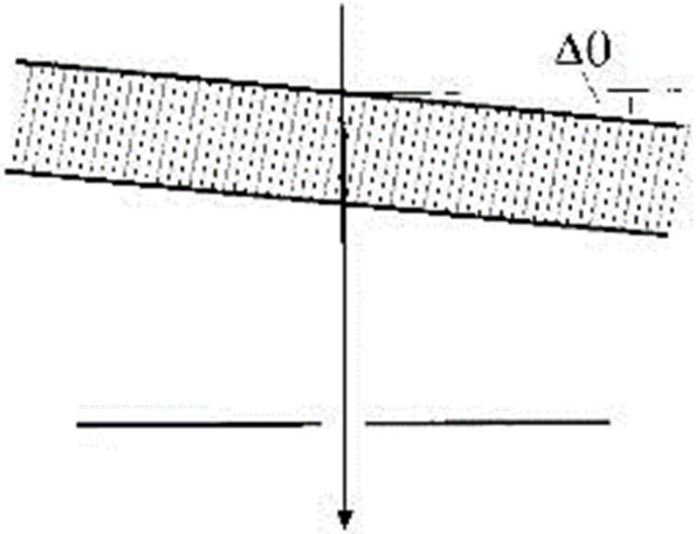
θ is the angle between the incident rays and the surface of the crystal

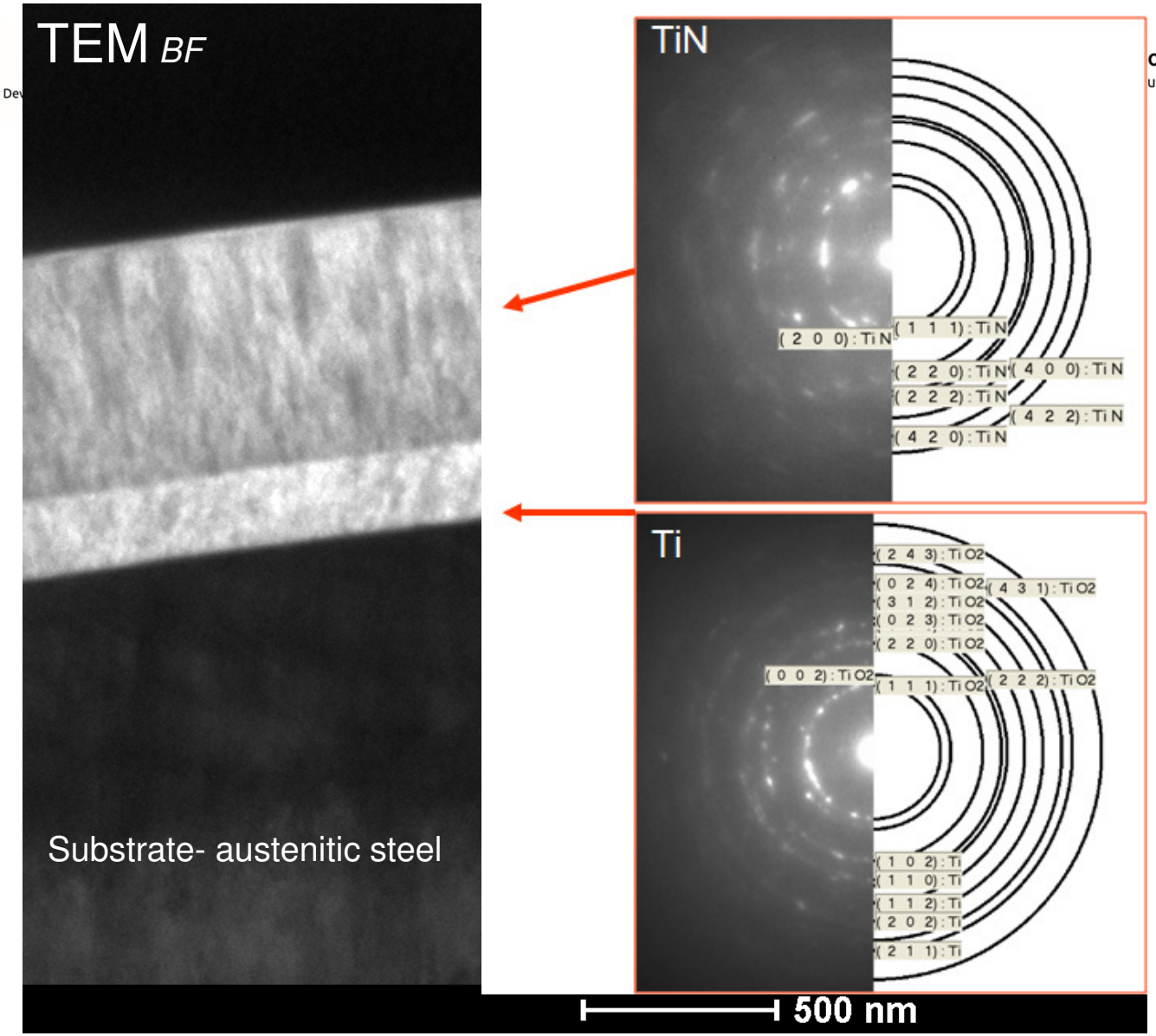
d is the spacing between layers of atoms

and constructive interference occurs when n is an integer (whole number)








TEM BF
Substrate- austenitic steel
TiN
(2 0 0) : Ti N
(1 1 1) : Ti N
(2 2 0) : Ti N
(4 0 0) : Ti N
(2 2 2) : Ti N
(4 2 2) : Ti N
(4 2 0) : Ti N
Ti
(2 4 3) : Ti O2
(0 2 4) : Ti O2
(4 3 1) : Ti O2
(3 1 2) : Ti O2
(0 2 3) : Ti O2
(2 2 0) : Ti O2
(0 0 2) : Ti O2
(1 1 1) : Ti O2
(2 2 2) : Ti O2
(1 0 2) : Ti
(1 1 0) : Ti
(1 1 2) : Ti
(2 0 2) : Ti
(2 1 1) : Ti
500 nm

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

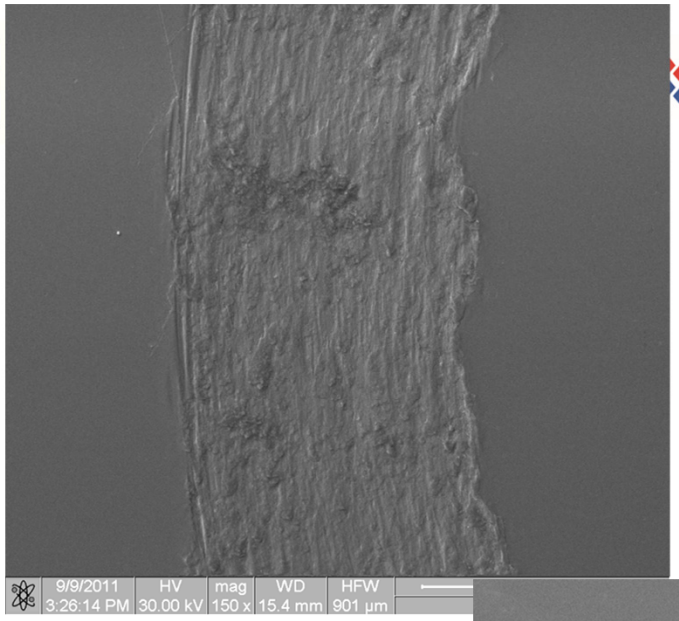
Single layer TiN coating

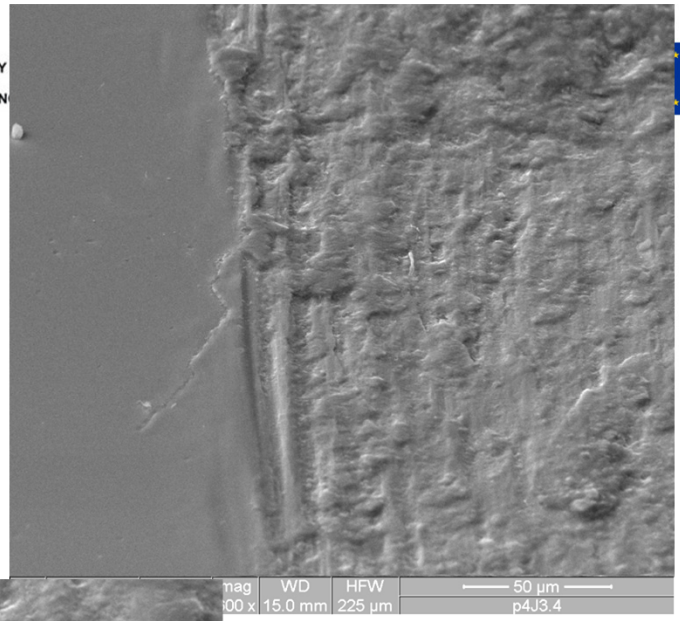
Coating after mechanical tests (Ball-on-disc 1N; 2000 cycles)
Microstructure characterization

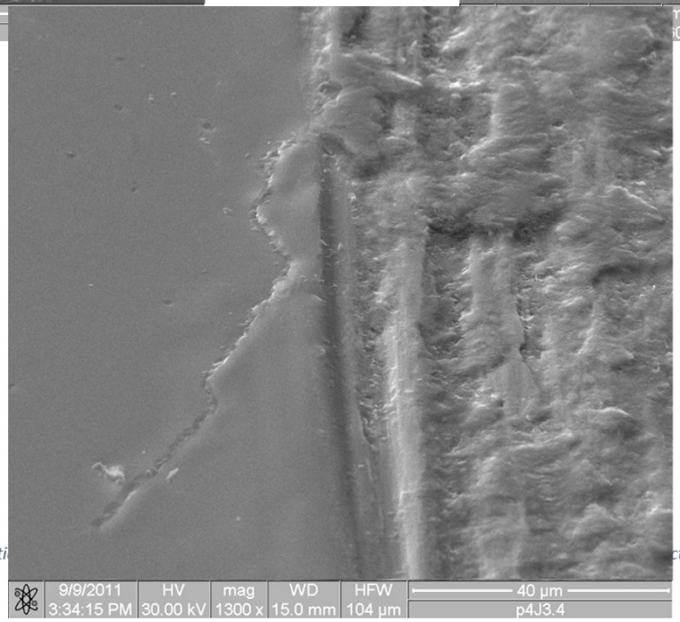
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

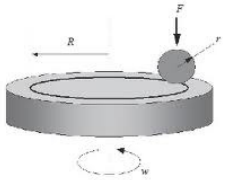
SEM

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIEN





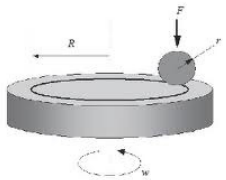


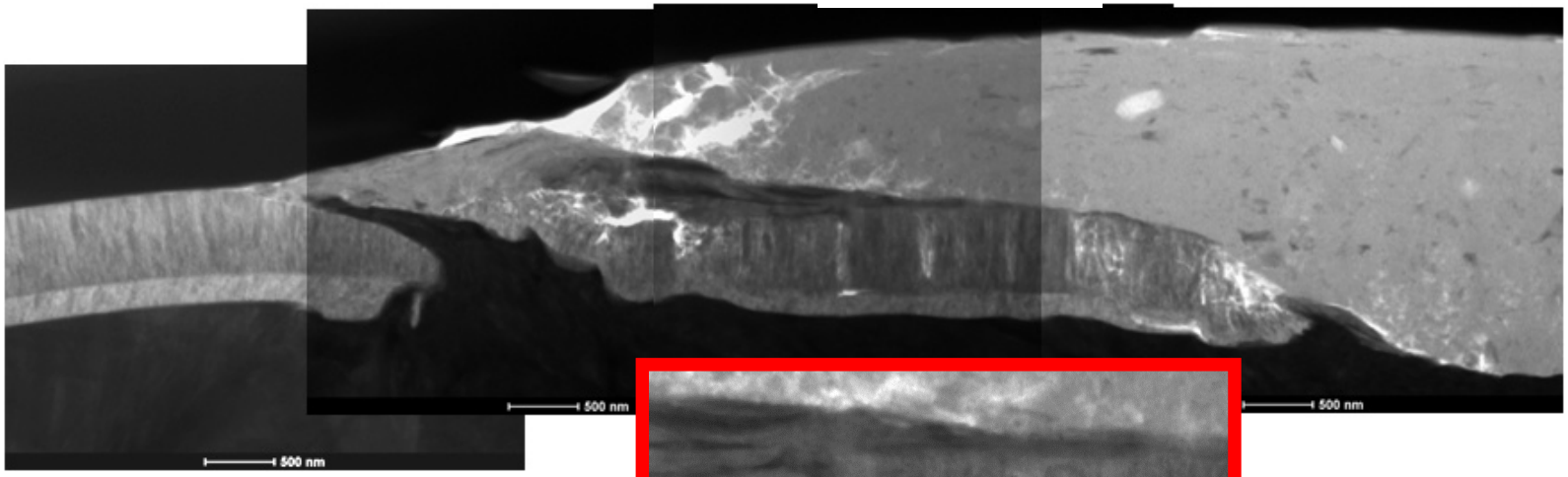


Internati ction

TEM *BF;*

Coating after mechanical tests

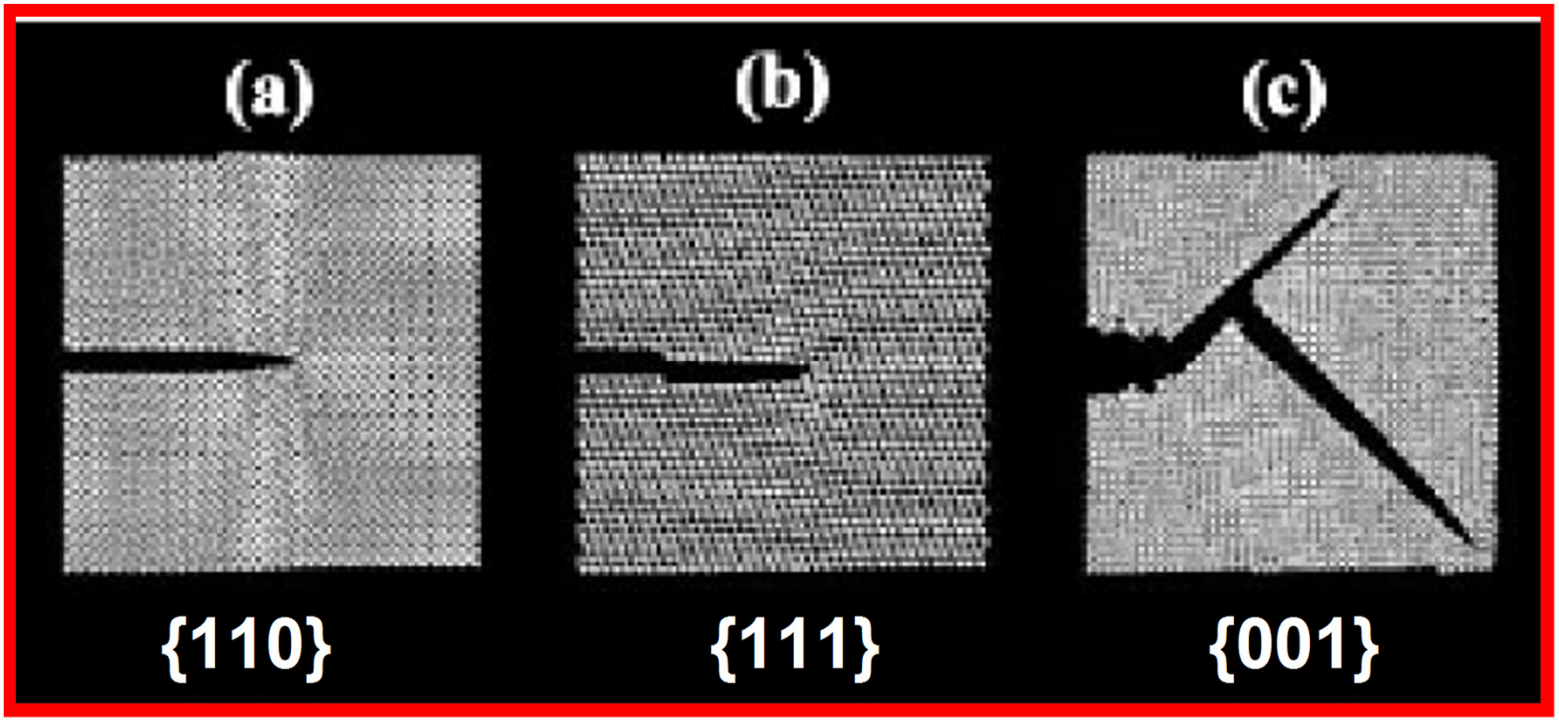




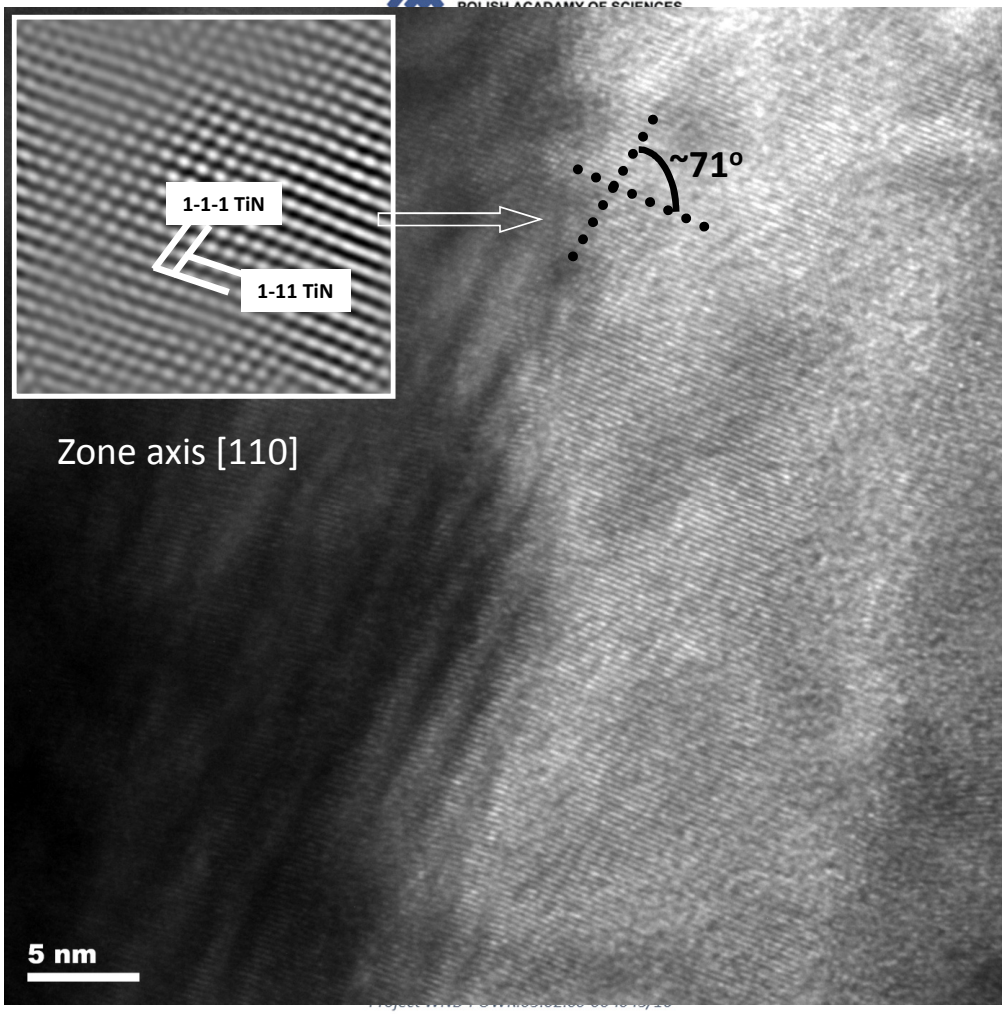
International interdisciplinary Ph

Project co-finance

Atomic structures images of brittle cracking along particular crystallographic planes:



TiN



(1 1 1)

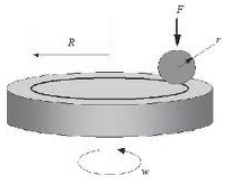
(-1 1 1)

(1-1 1)

(-1-1 1)

European Funds
Knowledge Education Development

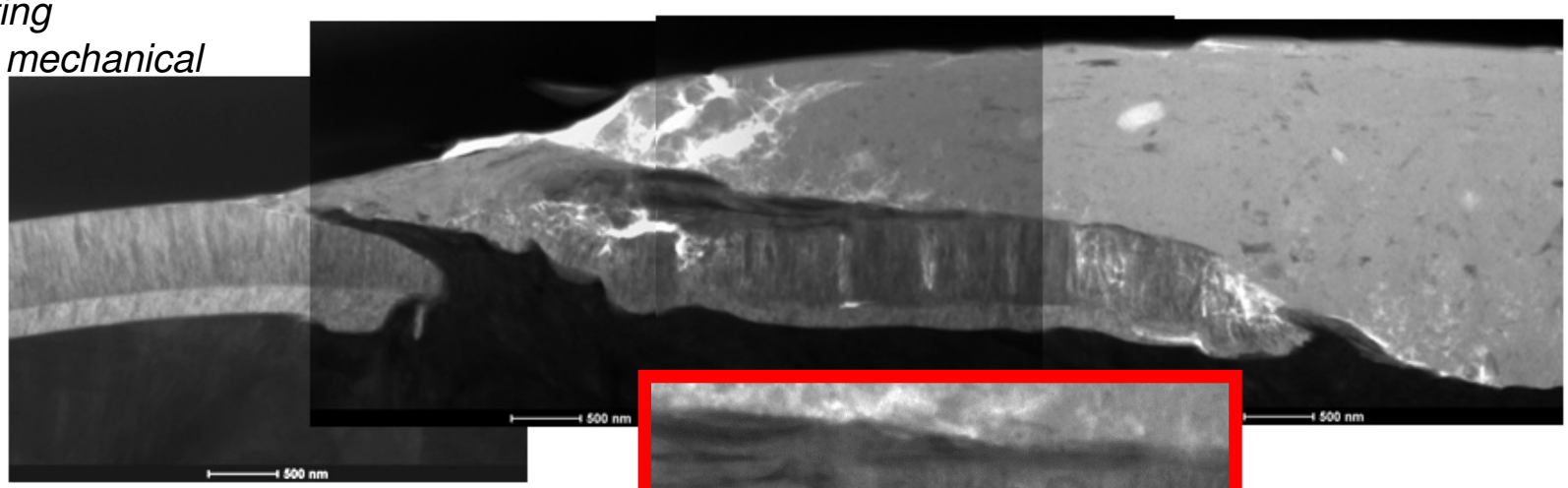
INSTITUTE AND MATE POLISH AC

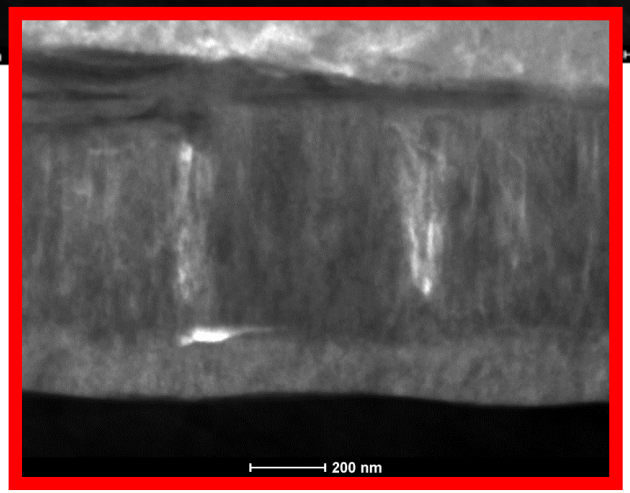


European Union
European Social Fund

TEM *BF;*

Coating after mechanical tests





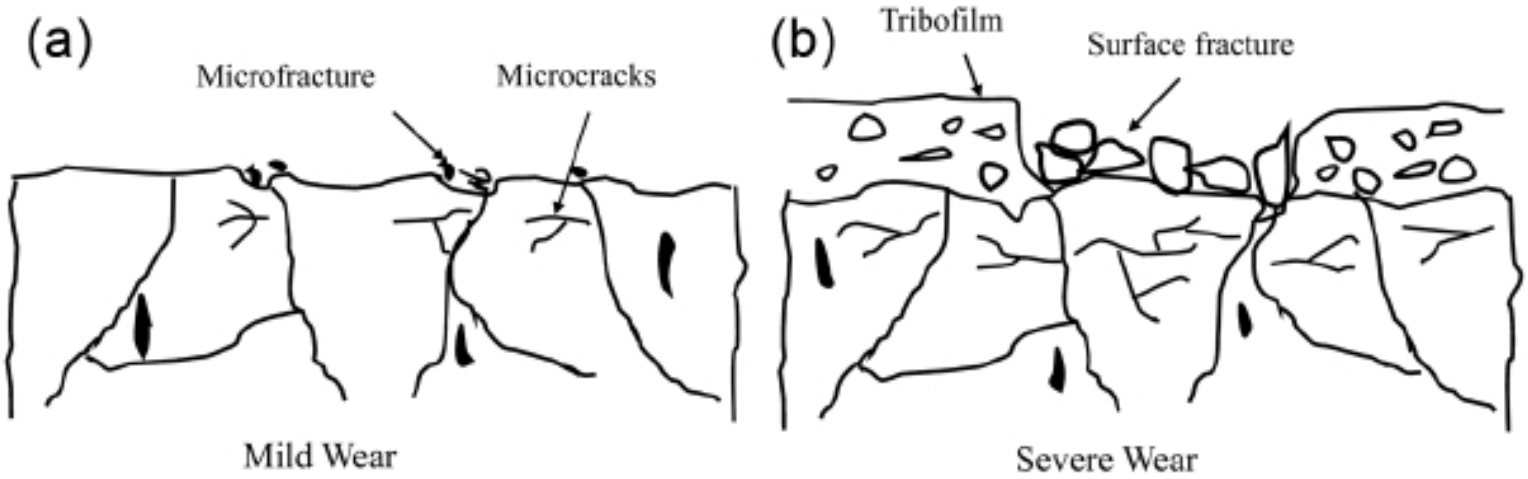
Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

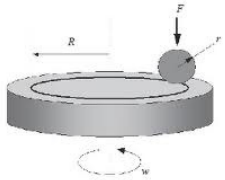
Microstructural characterization of the coatings by TEM after the wear test

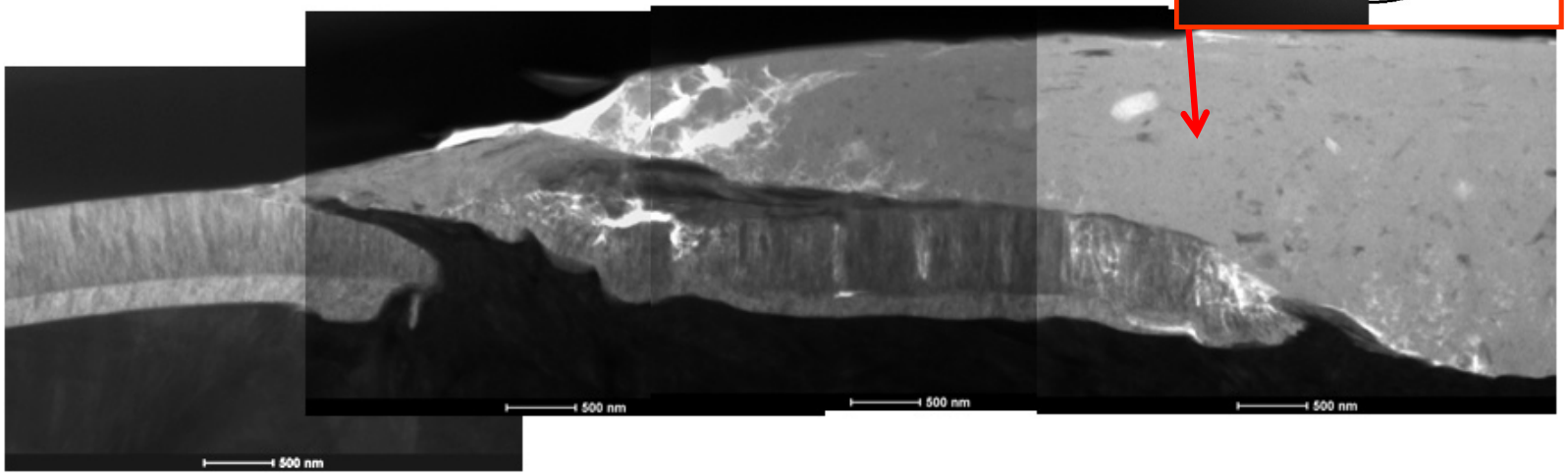
Soft Ti phase
+
Hard Ti_2N phase



TEM *BF;*

Coating after mechanical tests

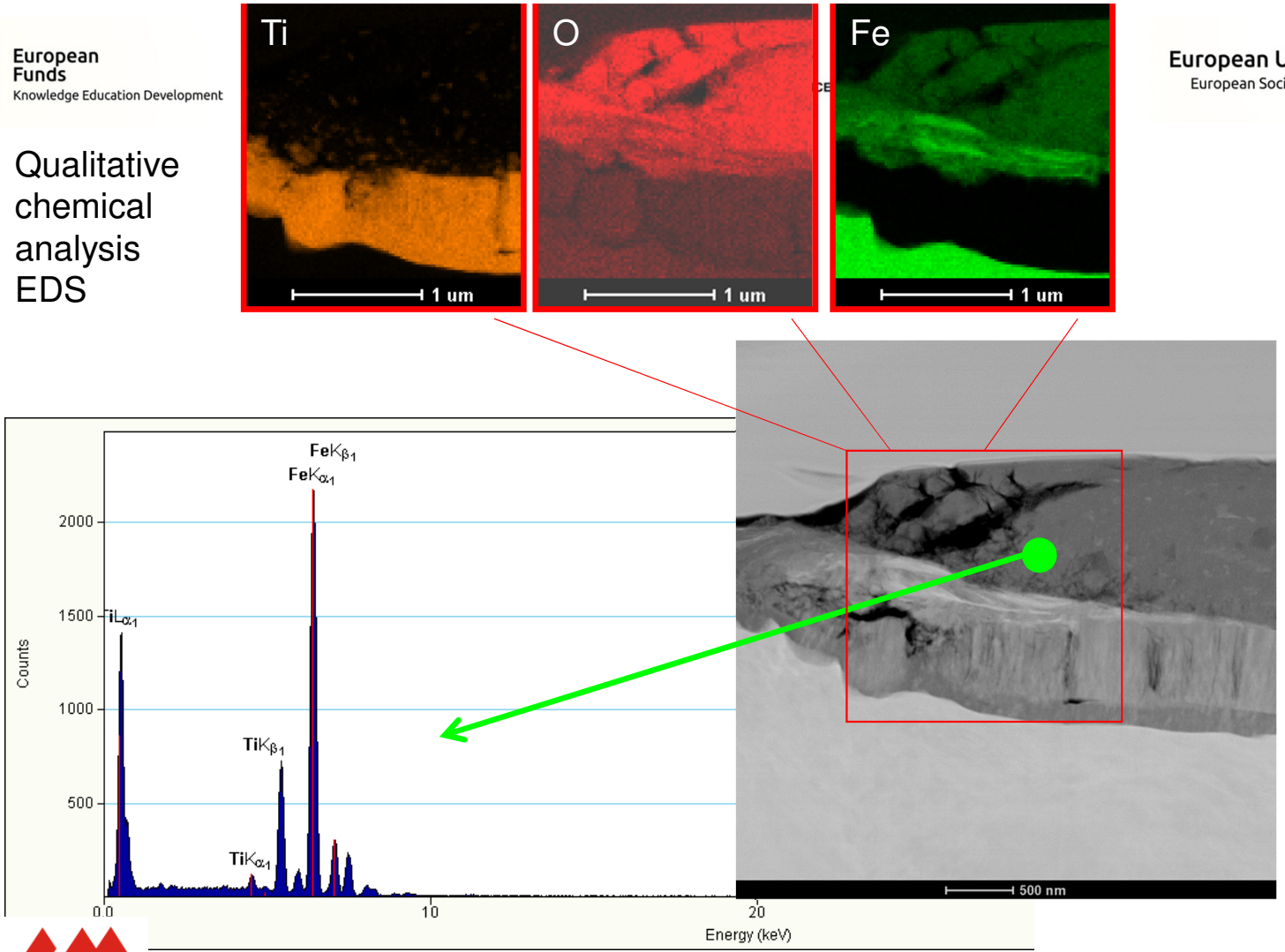




European Funds
Knowledge Education Development

European Union
European Social Fund

Qualitative chemical analysis EDS

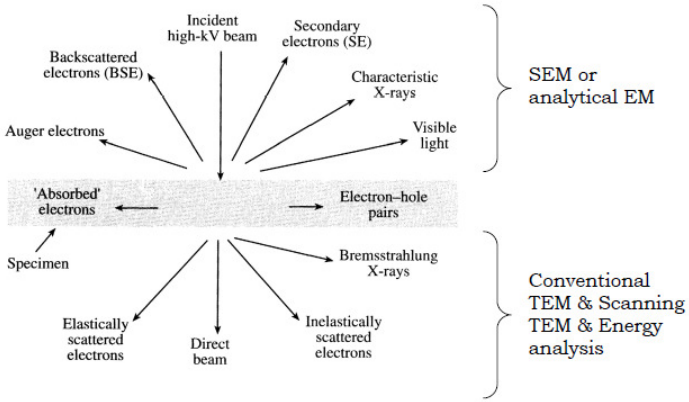


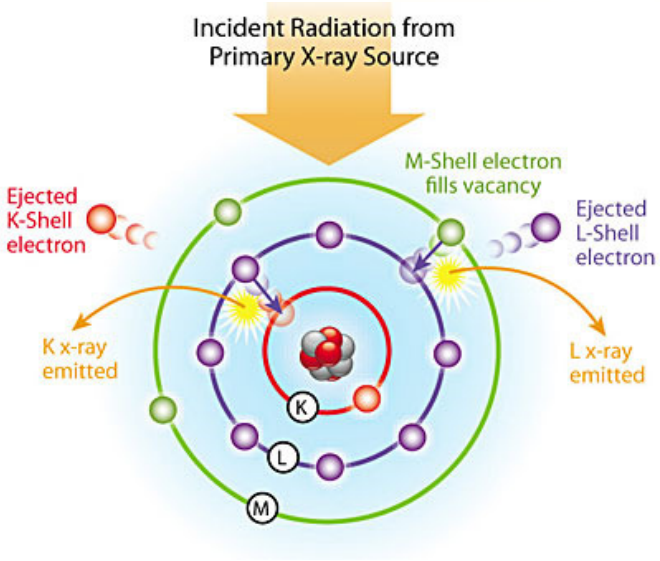
Project WND-POWR.03.02.00-00-I043/16

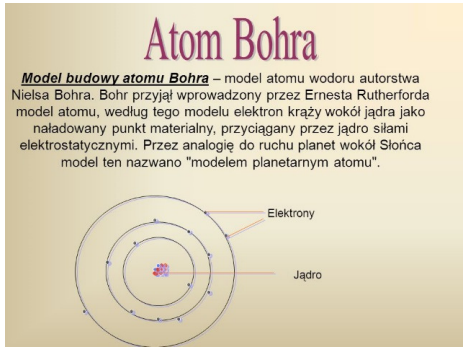
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

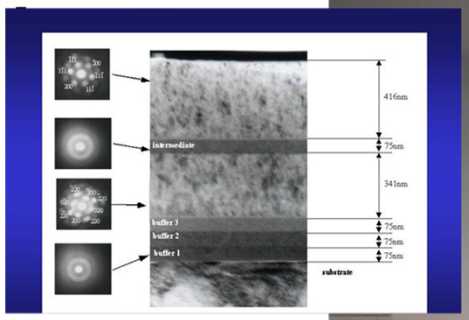
Project co-financed by the European Union within the European Social Funds

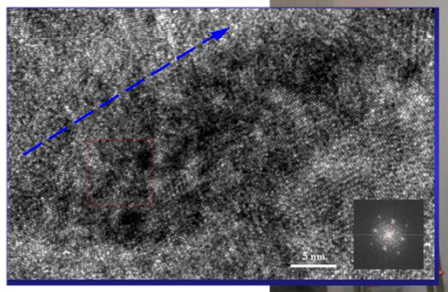
Interaction of Electron with Samples

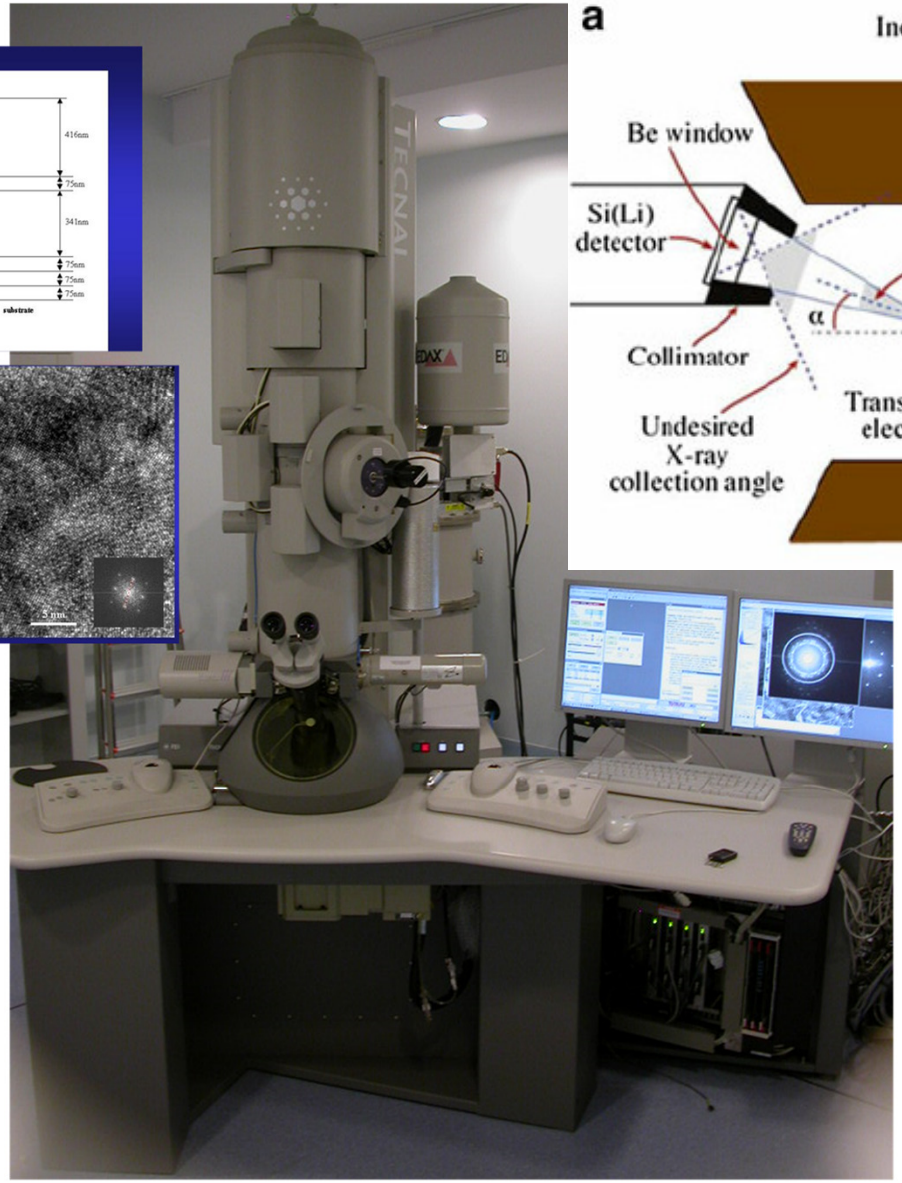


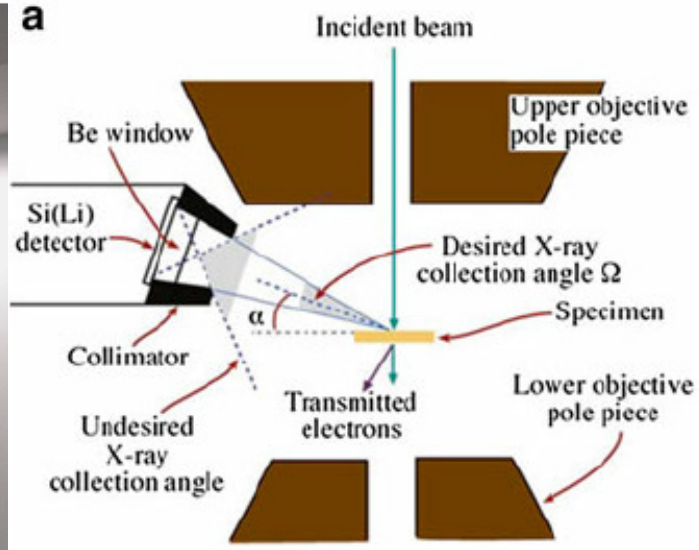


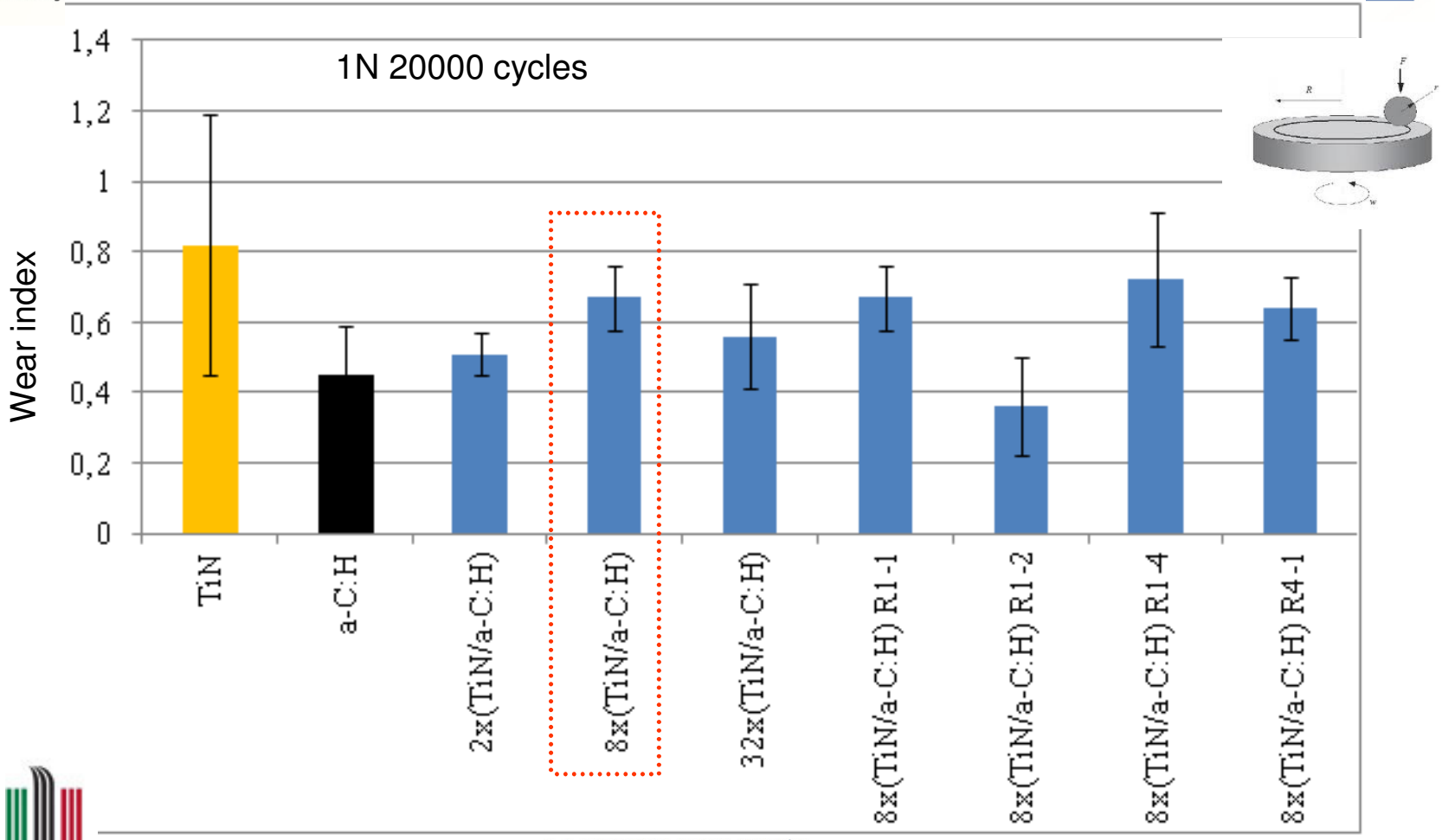



416nm
intermediate
75nm
341nm
buffer 3
75nm
buffer 2
75nm
buffer 1
75nm
substrate


5 nm


TECNAI
EDAX


a
Incident beam
Be window
Upper objective pole piece
Si(Li) detector
Desired X-ray collection angle Ω
α
Specimen
Collimator
Transmitted electrons
Lower objective pole piece
Undesired X-ray collection angle



AGH

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Multilayer 8x TiN/Ti/a-C:H coating

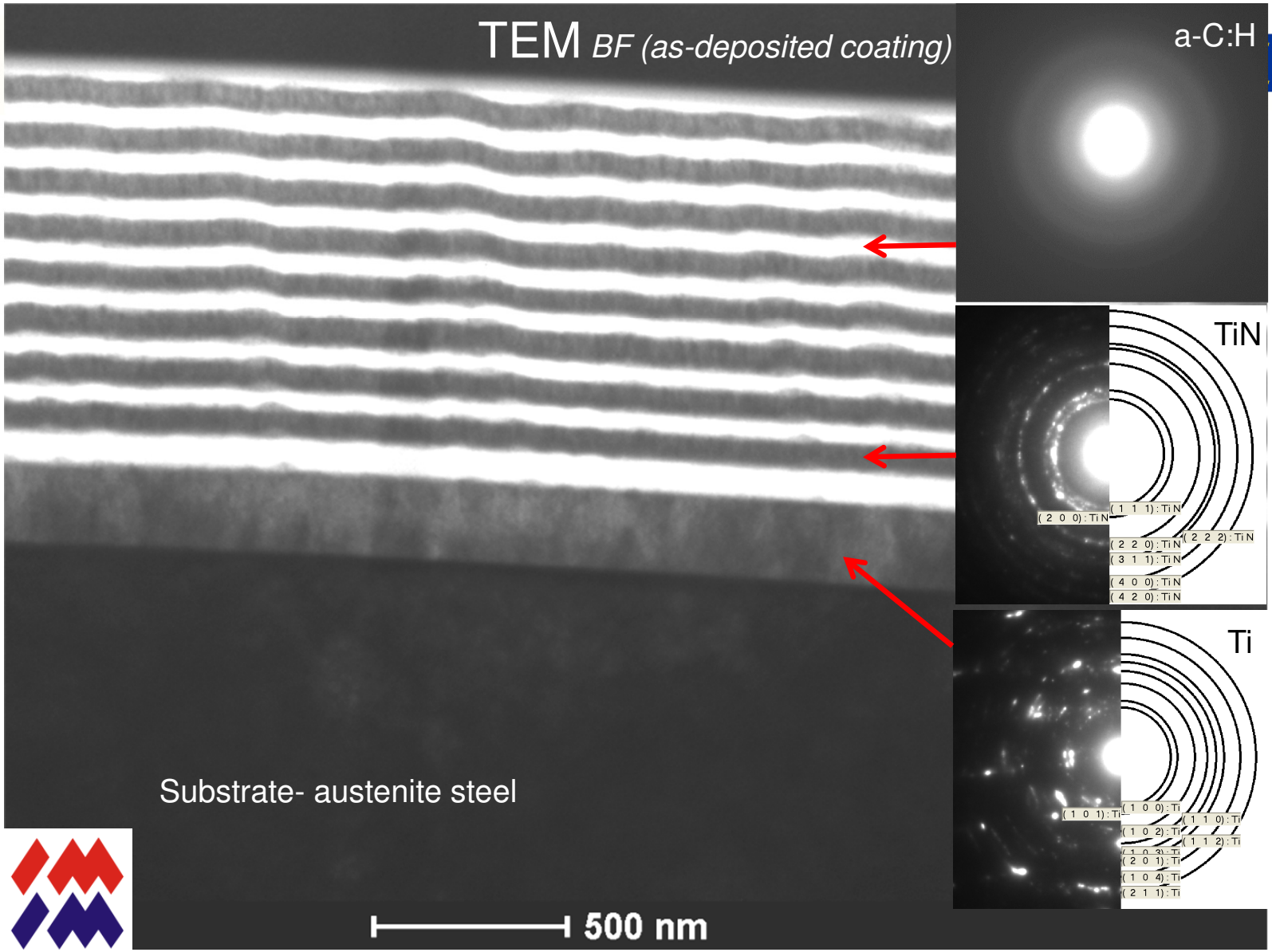
As deposited coating (Before mechnaical tests)

Microstructure characterization

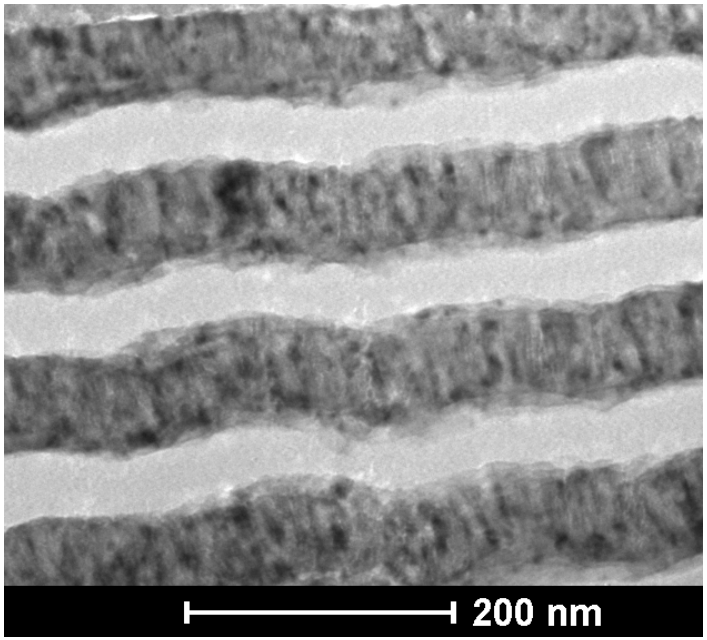
Project WND-POWR.03.02.00-00-I043/16

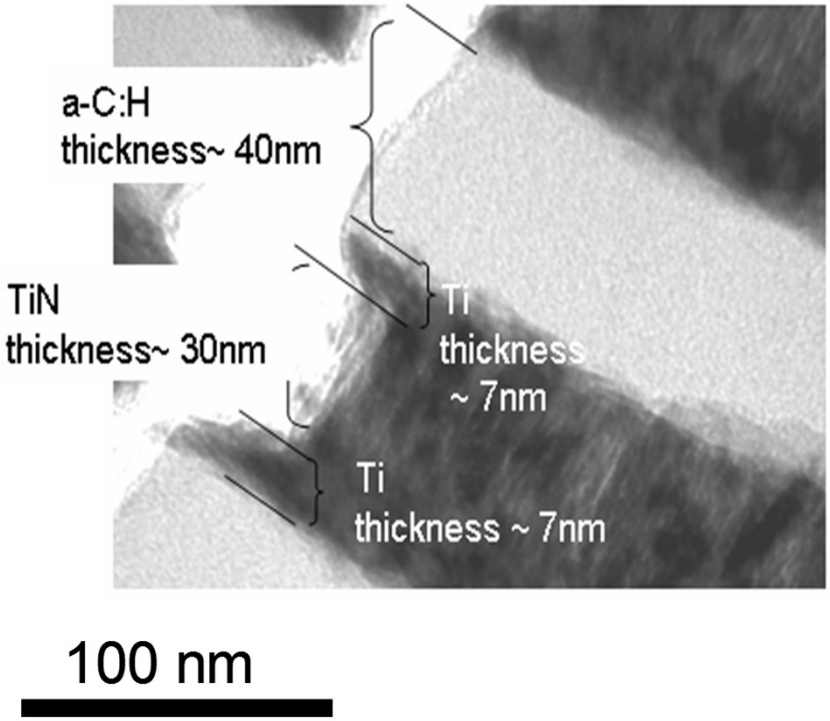
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

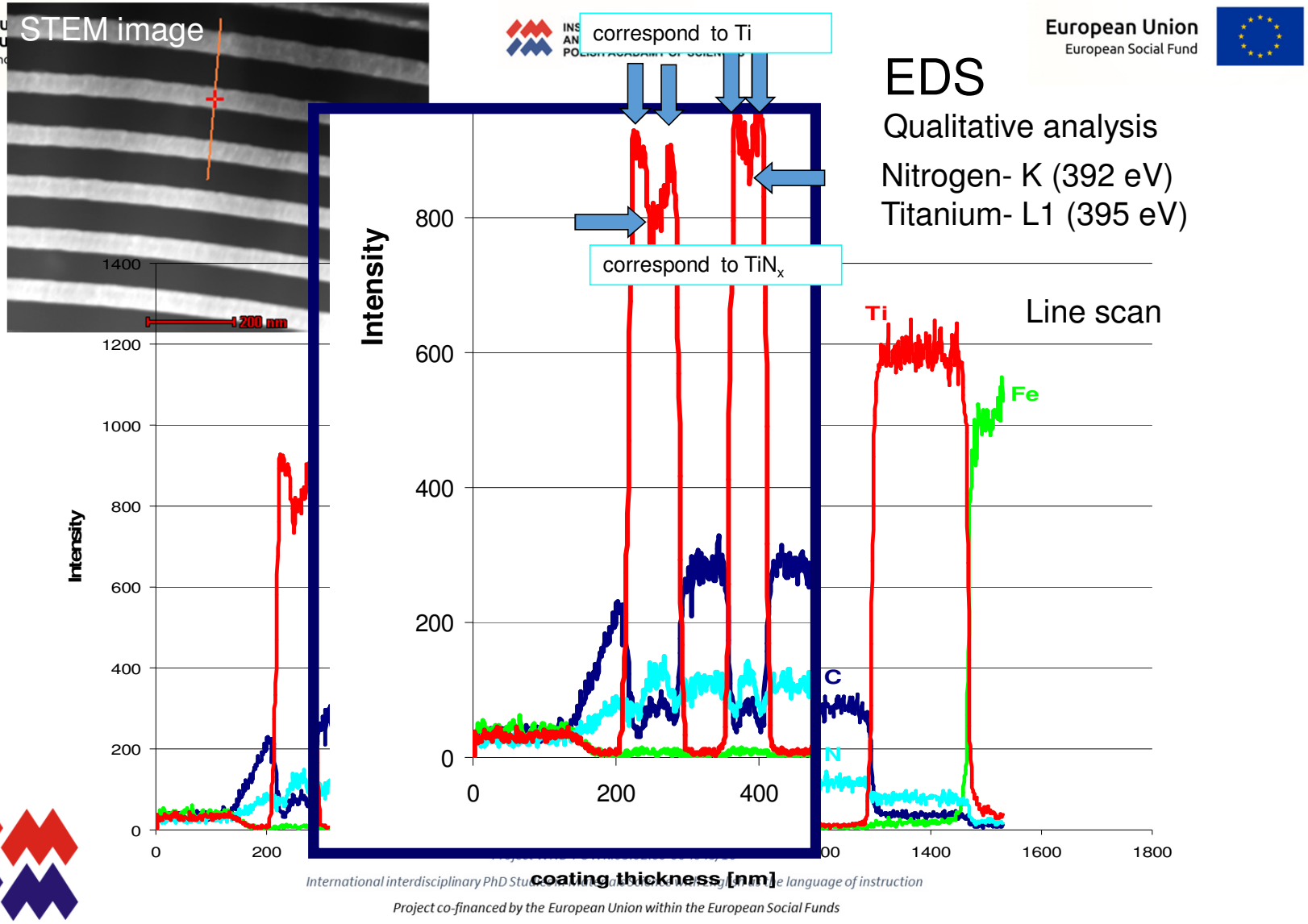

TEM BF (as-deposited coating)
a-C:H
TiN
(2 0 0) : TiN
(1 1 1) : TiN
(2 2 0) : TiN
(2 2 2) : TiN
(3 1 1) : TiN
(4 0 0) : TiN
(4 2 0) : TiN
Ti
(1 0 1) : Ti
(1 0 0) : Ti
(1 1 0) : Ti
(1 0 2) : Ti
(1 1 2) : Ti
(2 0 1) : Ti
(1 0 4) : Ti
(2 1 1) : Ti
Substrate- austenite steel
500 nm

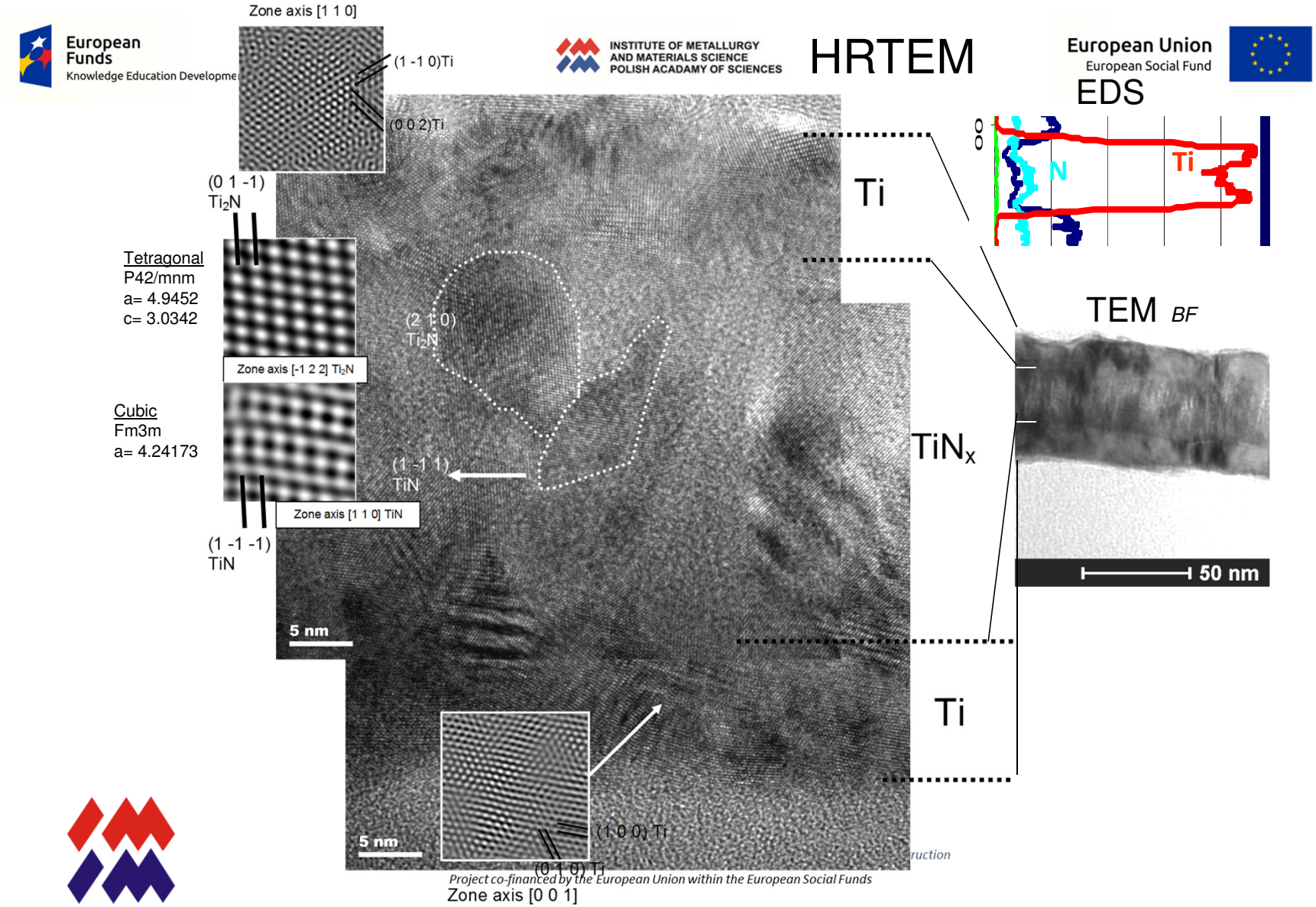
TEM *BF*

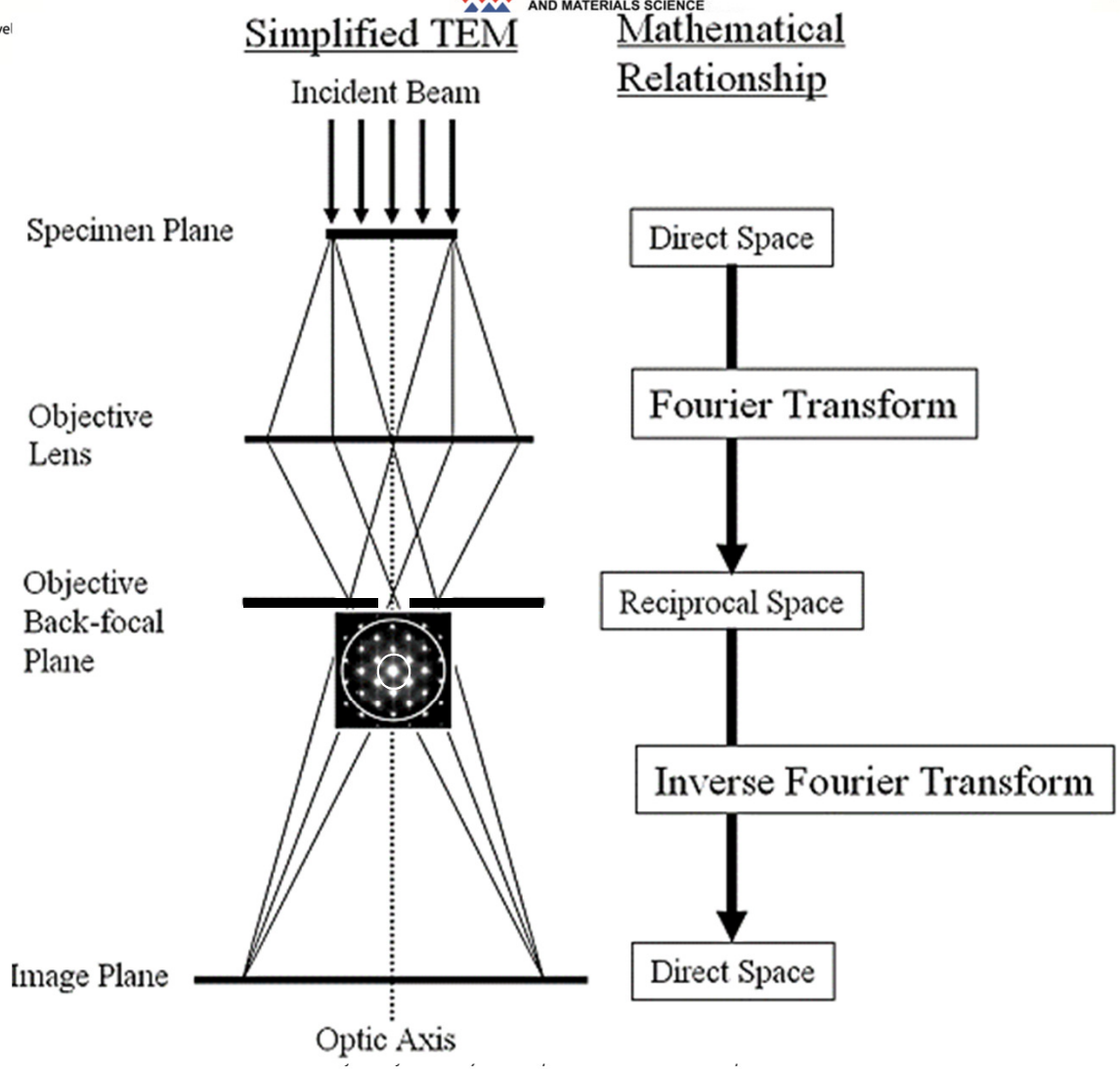


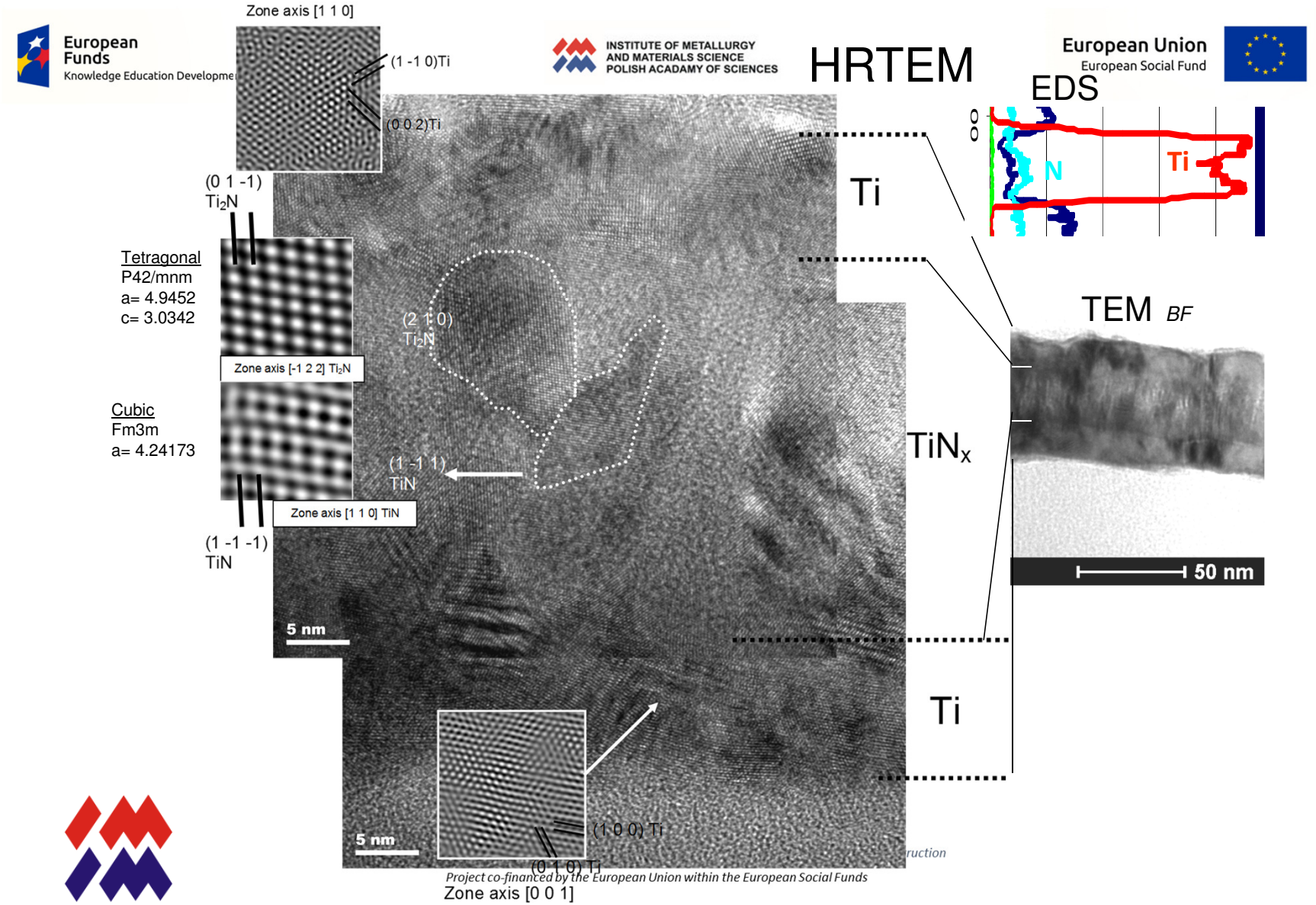


Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds


STEM image
200 nm
correspond to Ti
correspond to TiNx
EDS
Qualitative analysis
Nitrogen- K (392 eV)
Titanium- L1 (395 eV)
Line scan
Ti
Fe
C
N
Intensity
coating thickness [nm]
European Union
European Social Fund

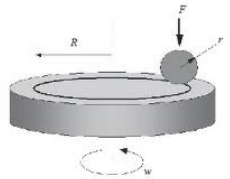

European Funds
Knowledge Education Developme
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES
HRTEM
European Union
European Social Fund
EDS
Zone axis [1 1 0]
(1 -1 0)Ti
(0 0 2)Ti
(0 1 -1)
Ti2N
Tetragonal
P42/mnm
a= 4.9452
c= 3.0342
(2 1 0)
Ti2N
Zone axis [-1 2 2] Ti2N
Cubic
Fm3m
a= 4.24173
(1 -1 1)
TiN
Zone axis [1 1 0] TiN
(1 -1 -1)
TiN
5 nm
Ti
TiNx
Ti
O
N
Ti
TEM BF
50 nm
5 nm
(1 0 0) Ti
(0 1 0) Ti
Zone axis [0 0 1]
Project co-financed by the European Union within the European Social Funds


Simplified TEM
Mathematical Relationship
Incident Beam
Specimen Plane
Objective Lens
Objective Back-focal Plane
Image Plane
Optic Axis
Direct Space
Fourier Transform
Reciprocal Space
Inverse Fourier Transform
Direct Space


European Funds
Knowledge Education Developme
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES
European Union
European Social Fund
HRTEM
EDS
Zone axis [1 1 0]
(1 -1 0)Ti
(0 0 2)Ti
(0 1 -1)
Ti2N
Tetragonal
P42/mnm
a= 4.9452
c= 3.0342
(2 1 0)
Ti2N
Zone axis [-1 2 2] Ti2N
Cubic
Fm3m
a= 4.24173
(1 -1 1)
TiN
Zone axis [1 1 0] TiN
(1 -1 -1)
TiN
5 nm
Ti
TiNx
Ti
O
N
Ti
TEM BF
50 nm
5 nm
(1 0 0) Ti
(0 1 0) Ti
Zone axis [0 0 1]
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

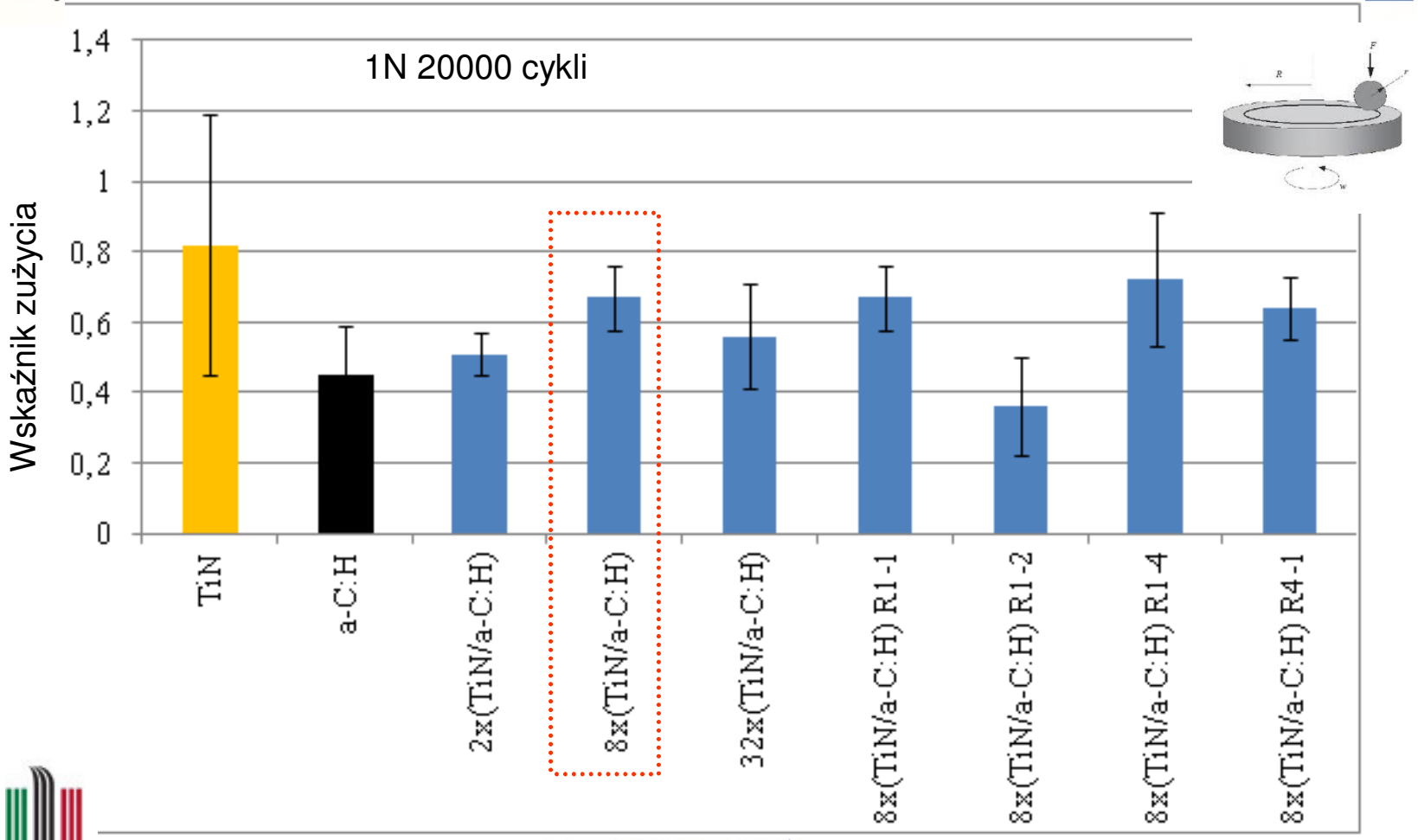
INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES



Multilayer 8x TiN/Ti/a-C:H coating

Coating after mechanical tests (Ball-on-disc 1N; 2000 cycles)
Microstructure characterization

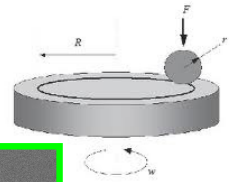
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds


1N 20000 cykli
Wskaźnik zużycia
1,4
1,2
1
0,8
0,6
0,4
0,2
0
TiN
a-C:H
2x(TiN/a-C:H)
8x(TiN/a-C:H)
32x(TiN/a-C:H)
8x(TiN/a-C:H) R1-1
8x(TiN/a-C:H) R1-2
8x(TiN/a-C:H) R1-4
8x(TiN/a-C:H) R4-1

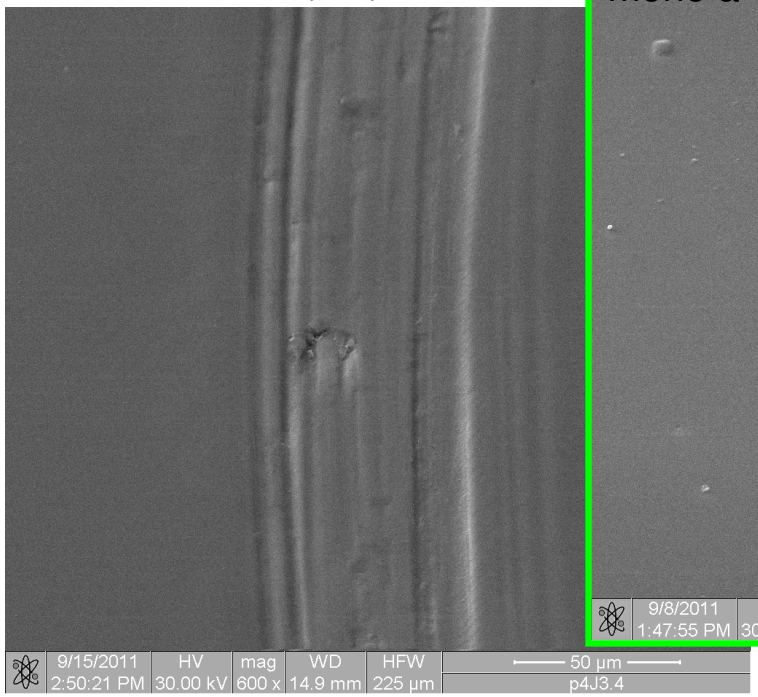
European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

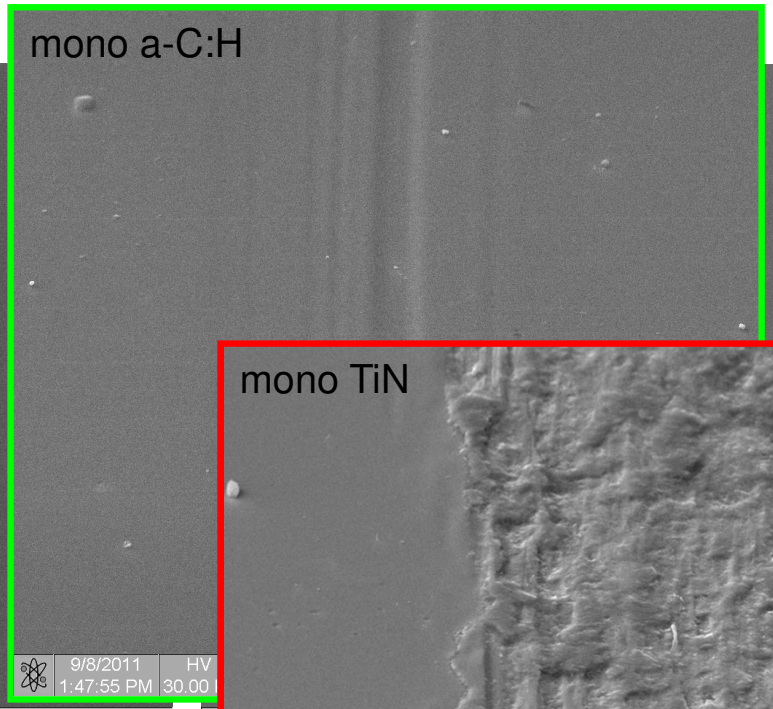
SEM



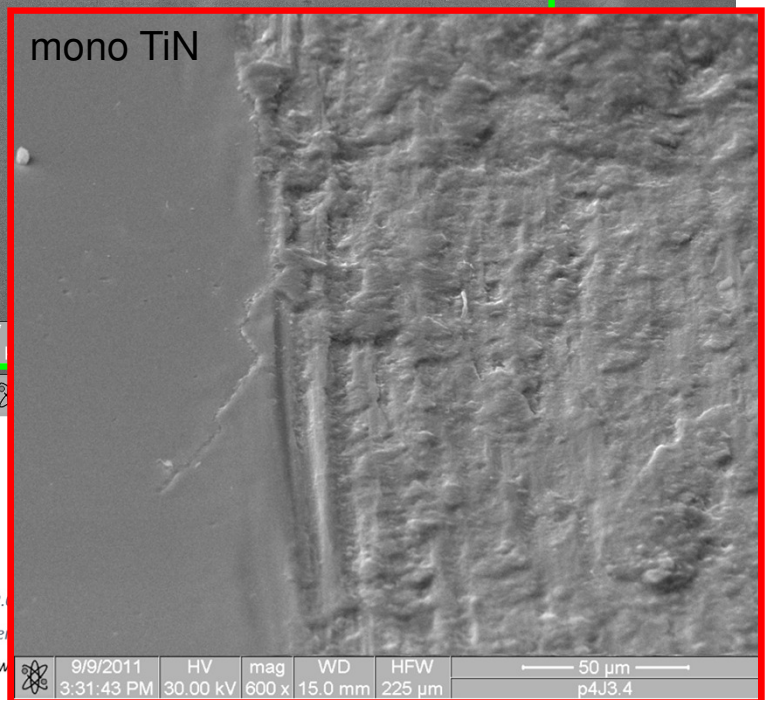
8x TiN/Ti/a-C:H (1:1)



mono a-C:H



mono TiN

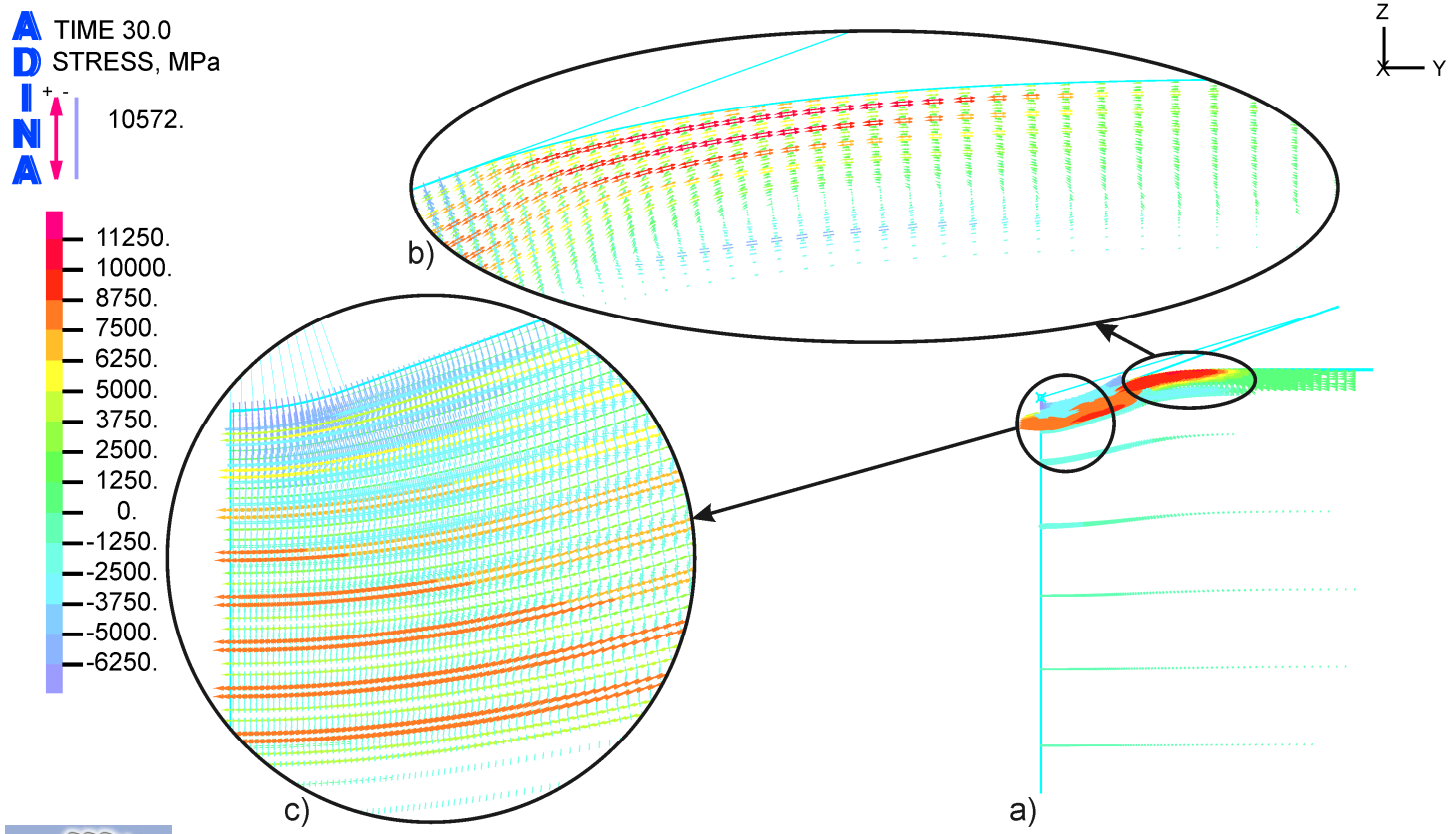


Project WND-POWR.03.02.
International interdisciplinary PhD Studies in Materials Scie
Project co-financed by the European Union w

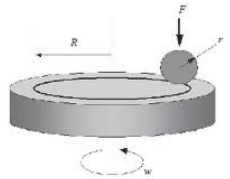
European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund



Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds



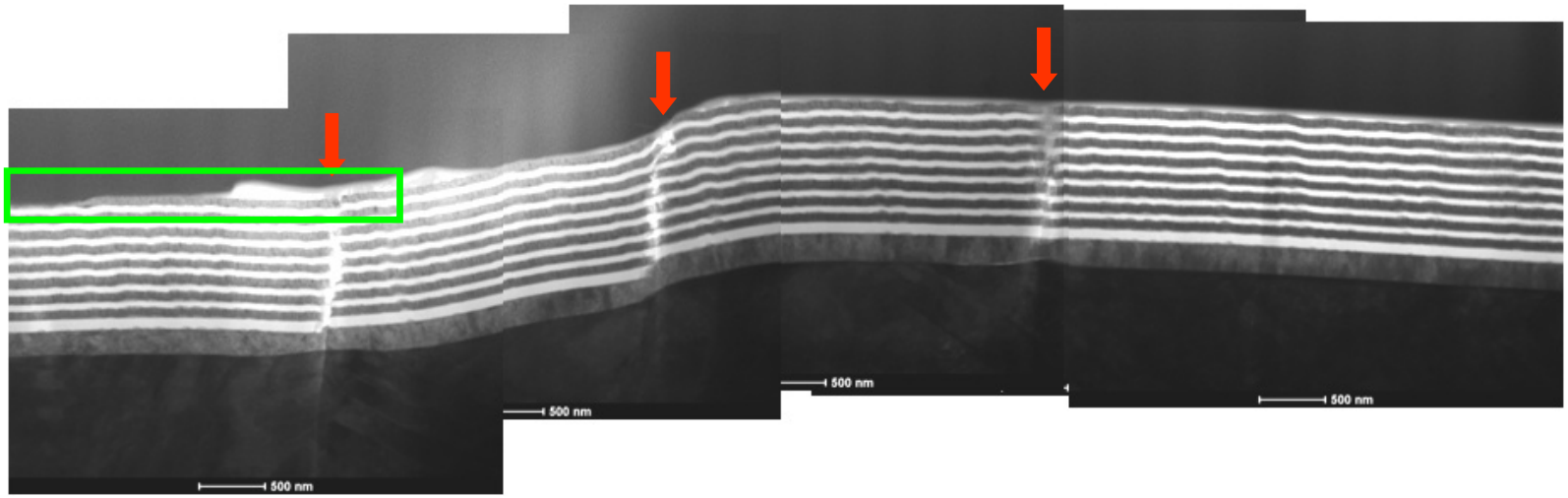
TEM *BF;*

Coating after mechanical tests

Wear mechanisms:

1) by cracking

2) by layer by layer remove + tribo-film formation



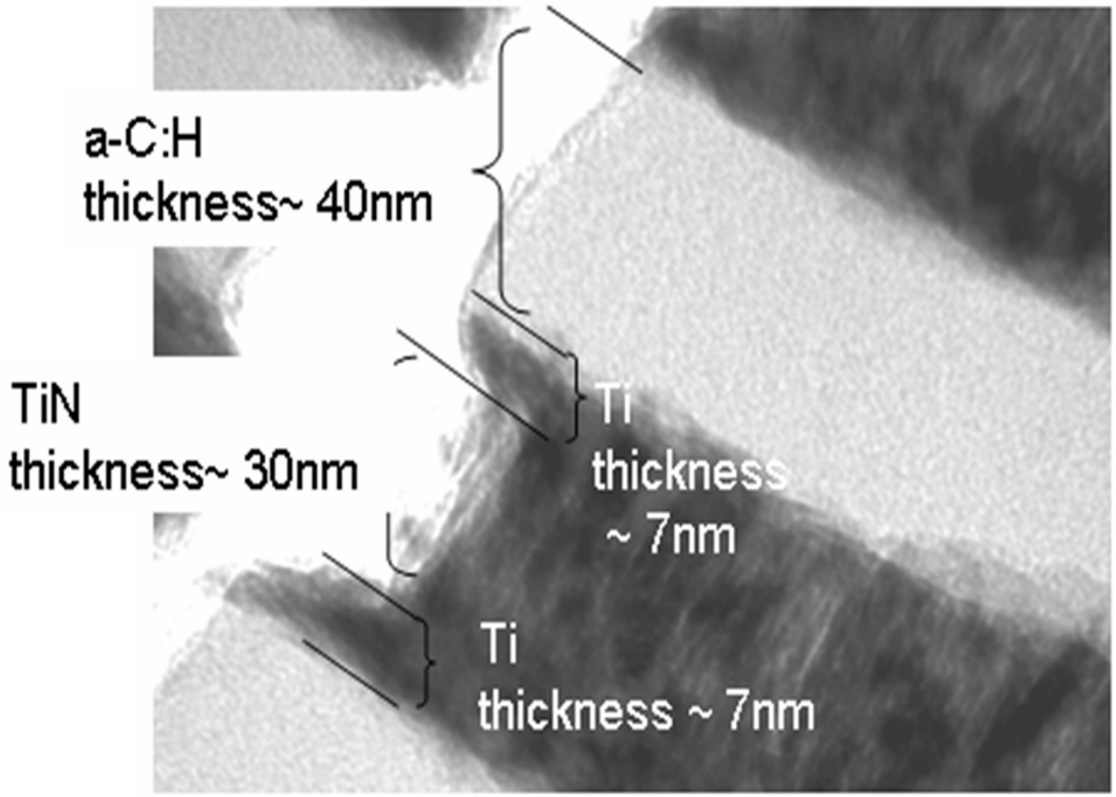
Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

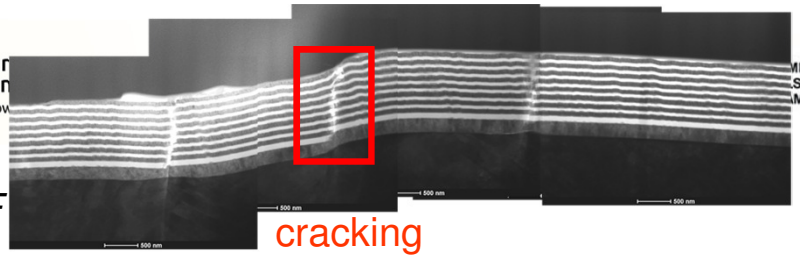
TEM *BF*

cracking

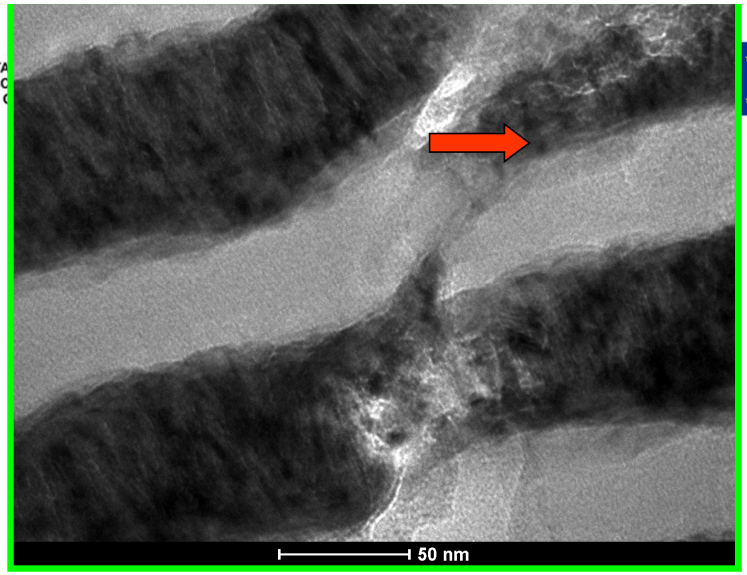


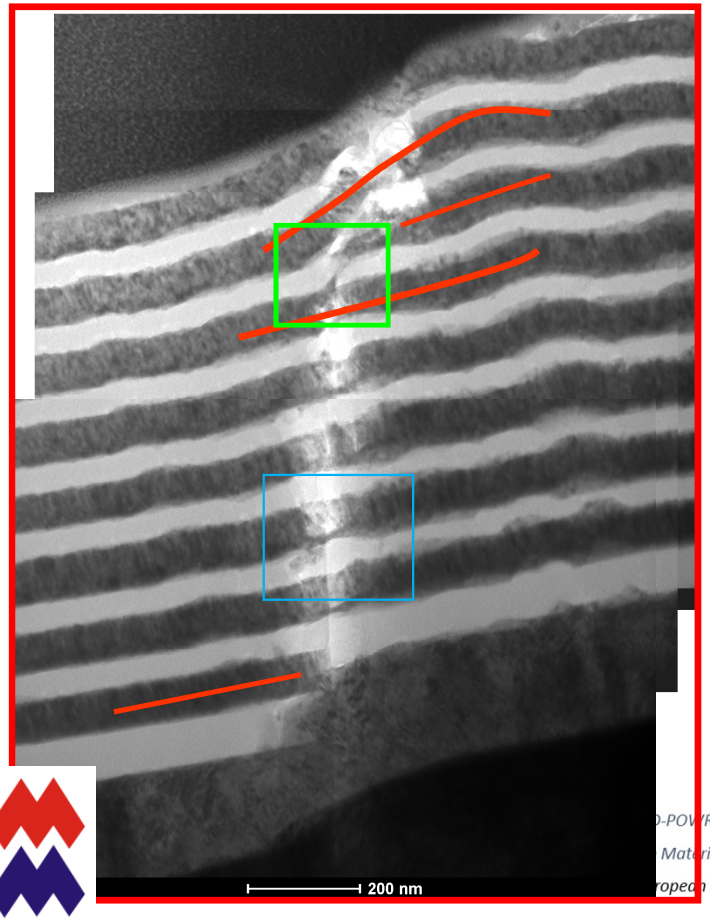
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

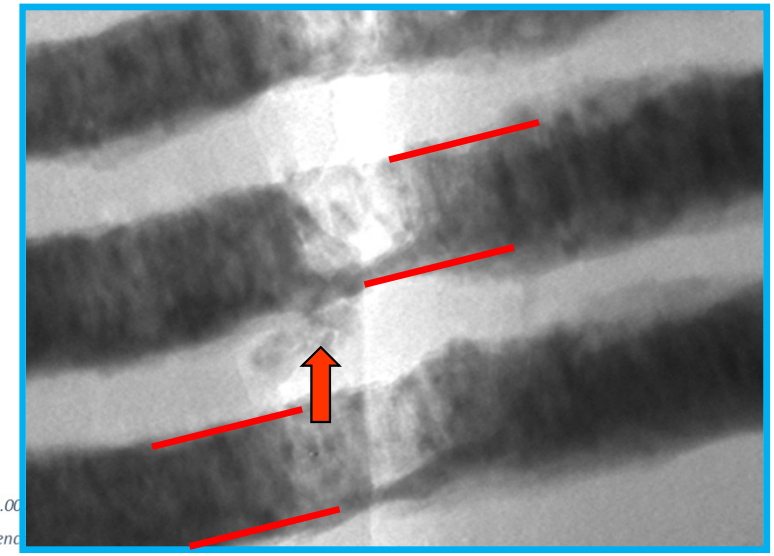
TEM *BF*



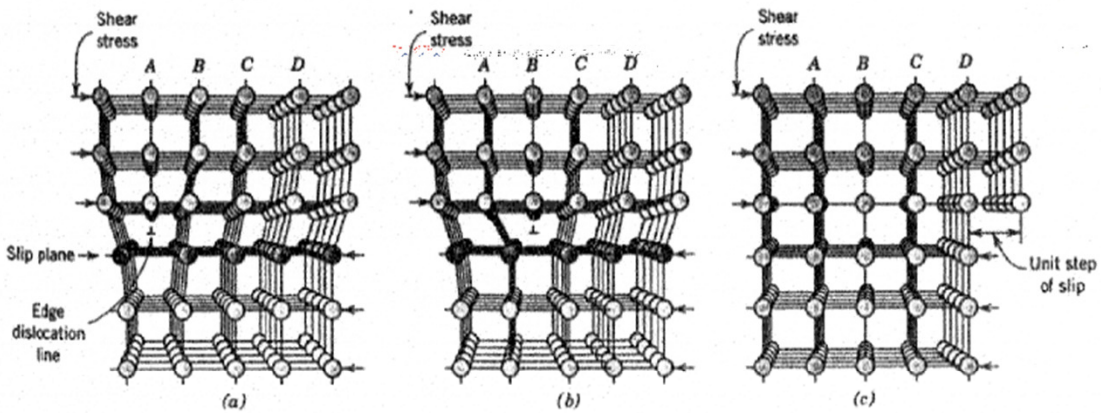
cracking

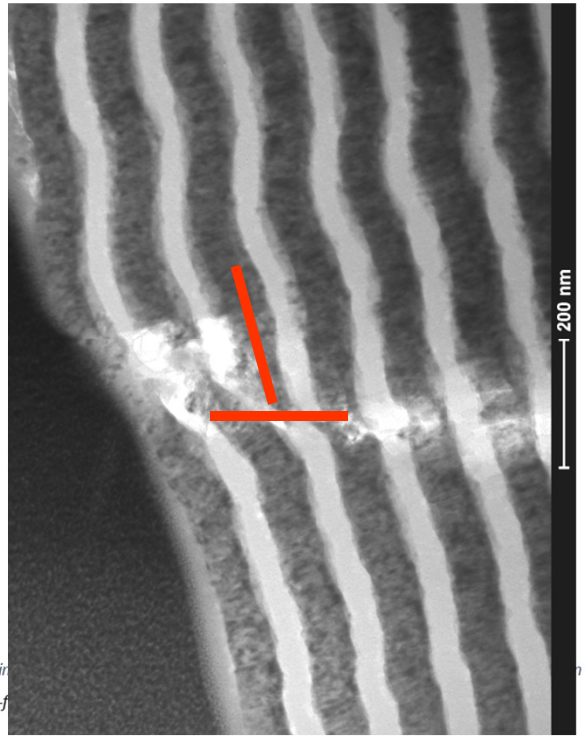






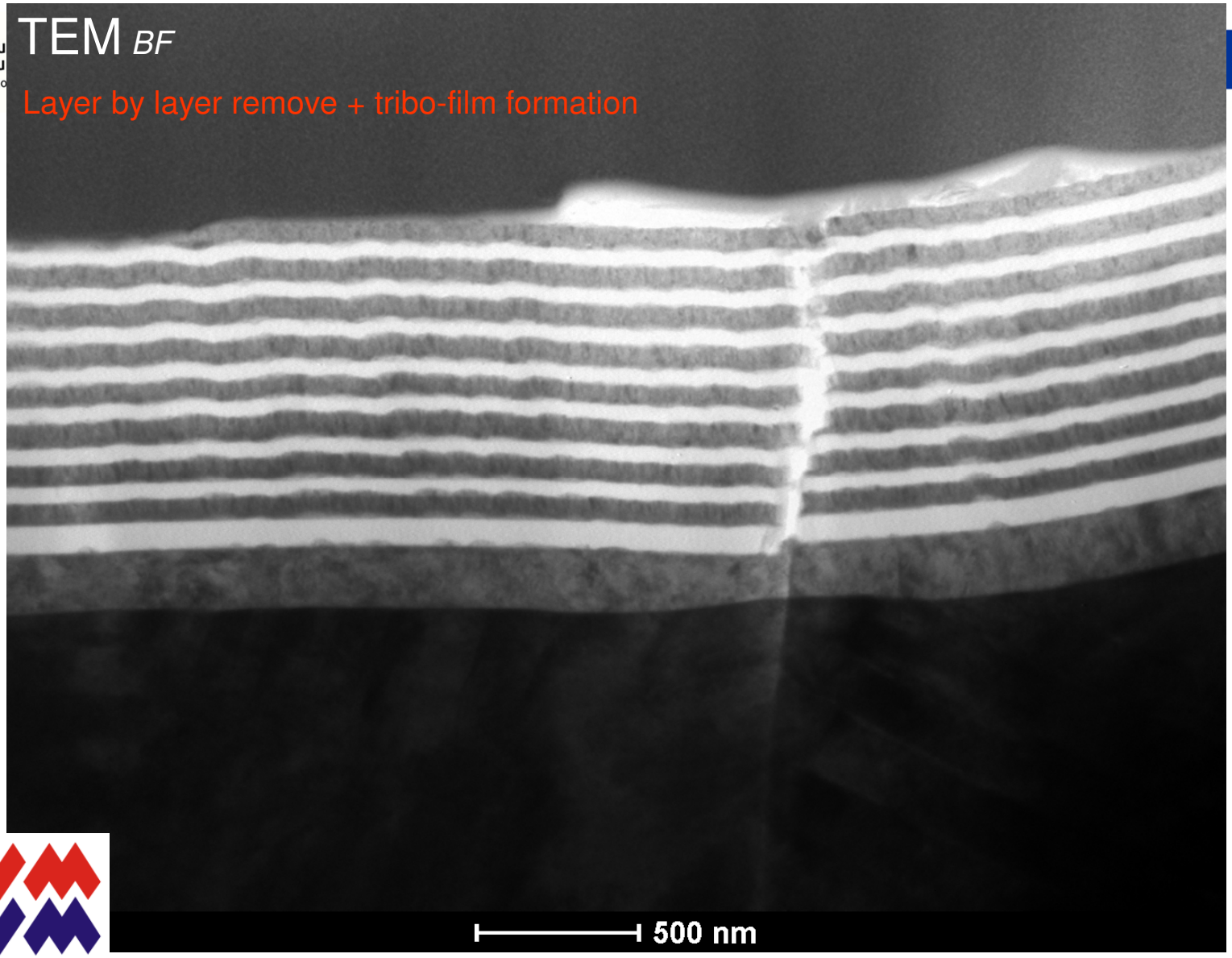
-POWR.03.02.00
Materials Scienc
ropean Union within the European Social Funds


Shear stress
A B C D
Slip plane
Edge dislocation line
(a)
Shear stress
A B C D
(b)
Shear stress
A B C D
Unit step of slip
(c)

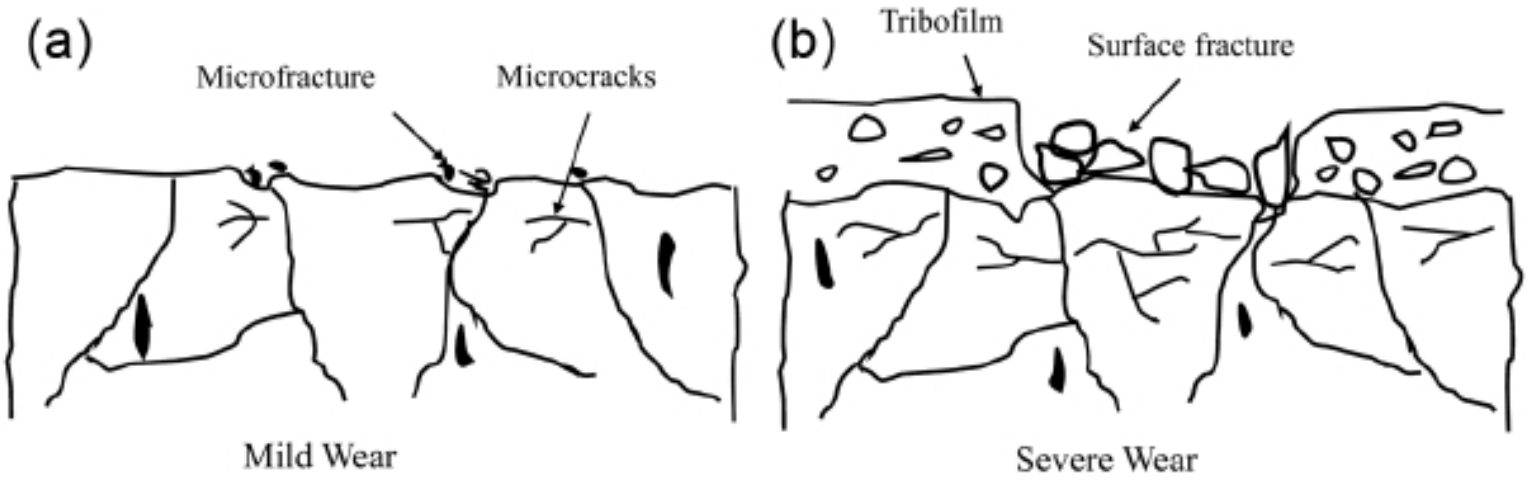

200 nm

TEM *BF*

Layer by layer remove + tribo-film formation

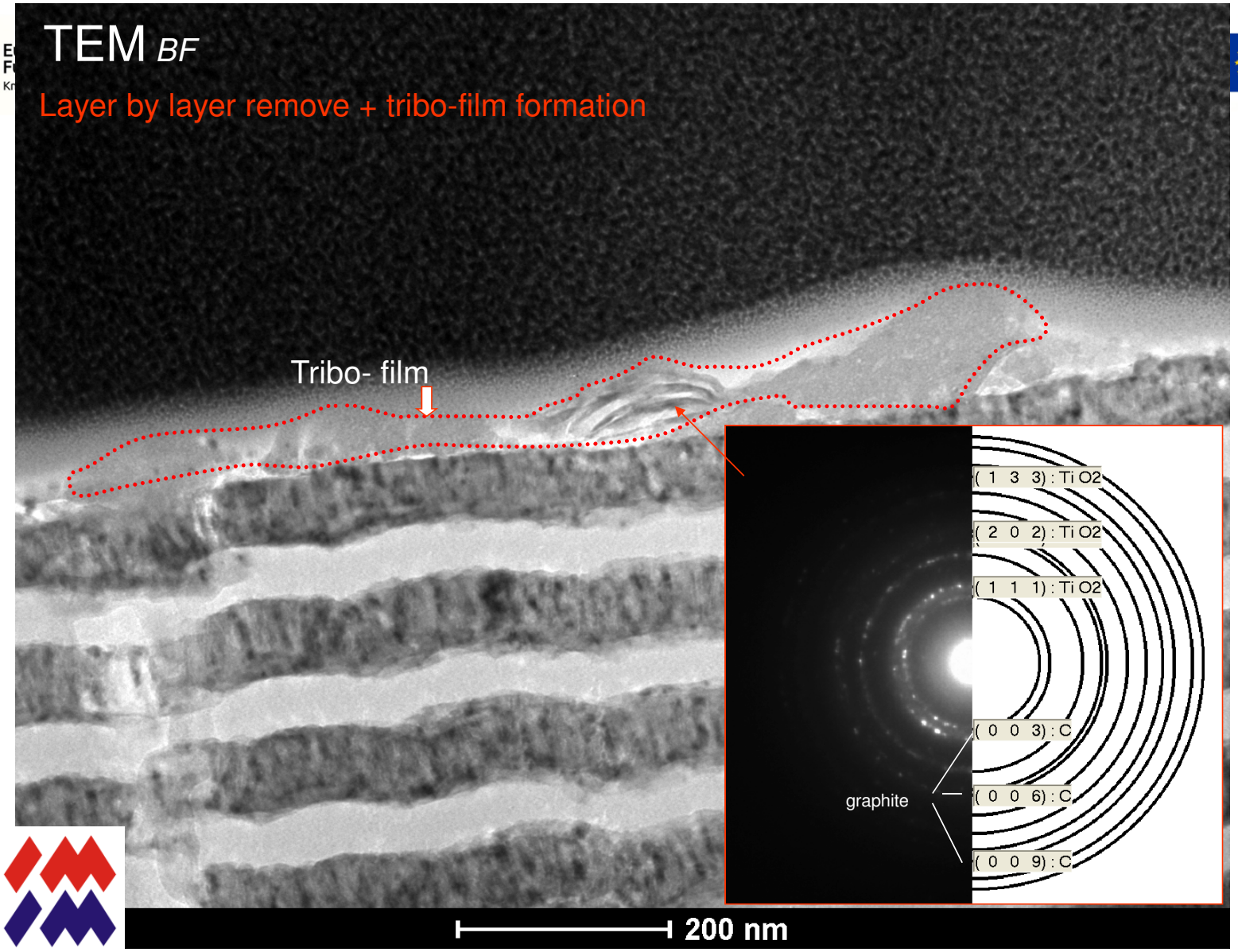


Microstructural characterization of the coatings by TEM after the wear test



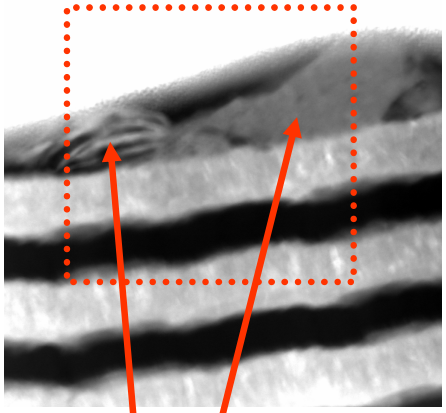
TEM *BF*

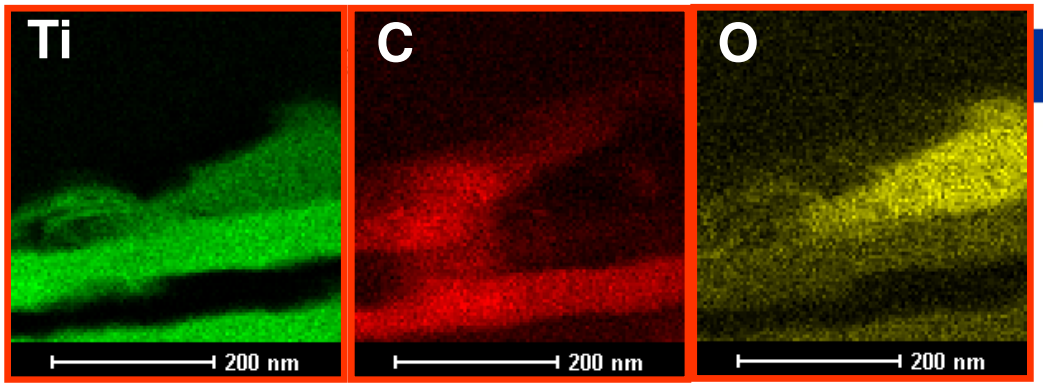
Layer by layer remove + tribo-film formation



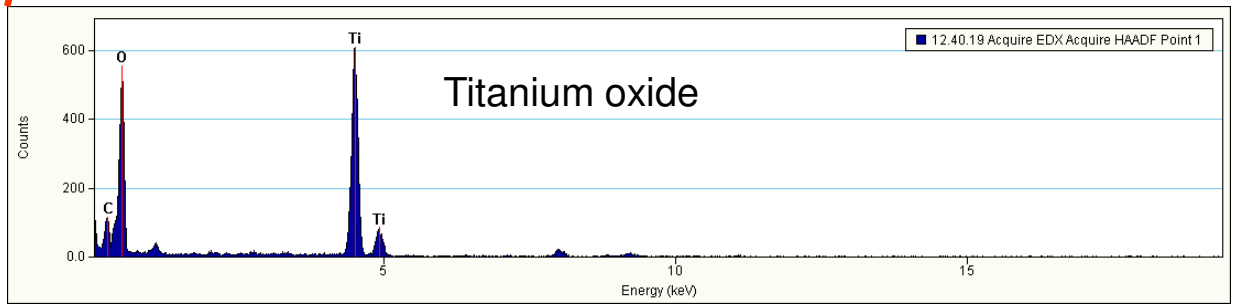
European Funds
Knowledge Education Development

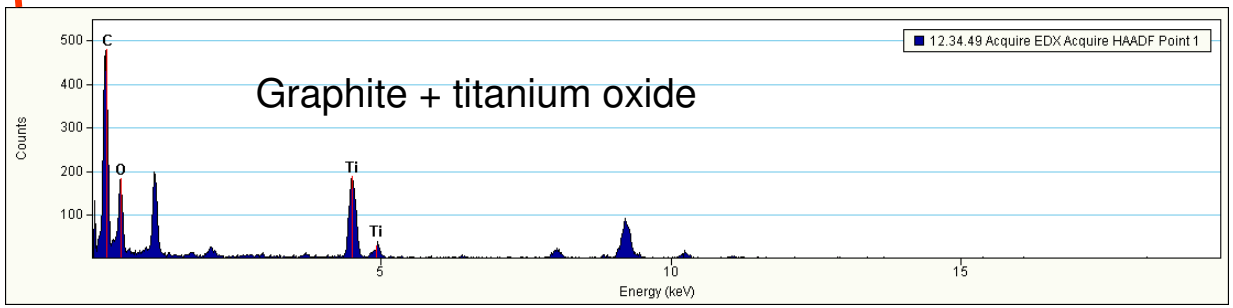
EDS



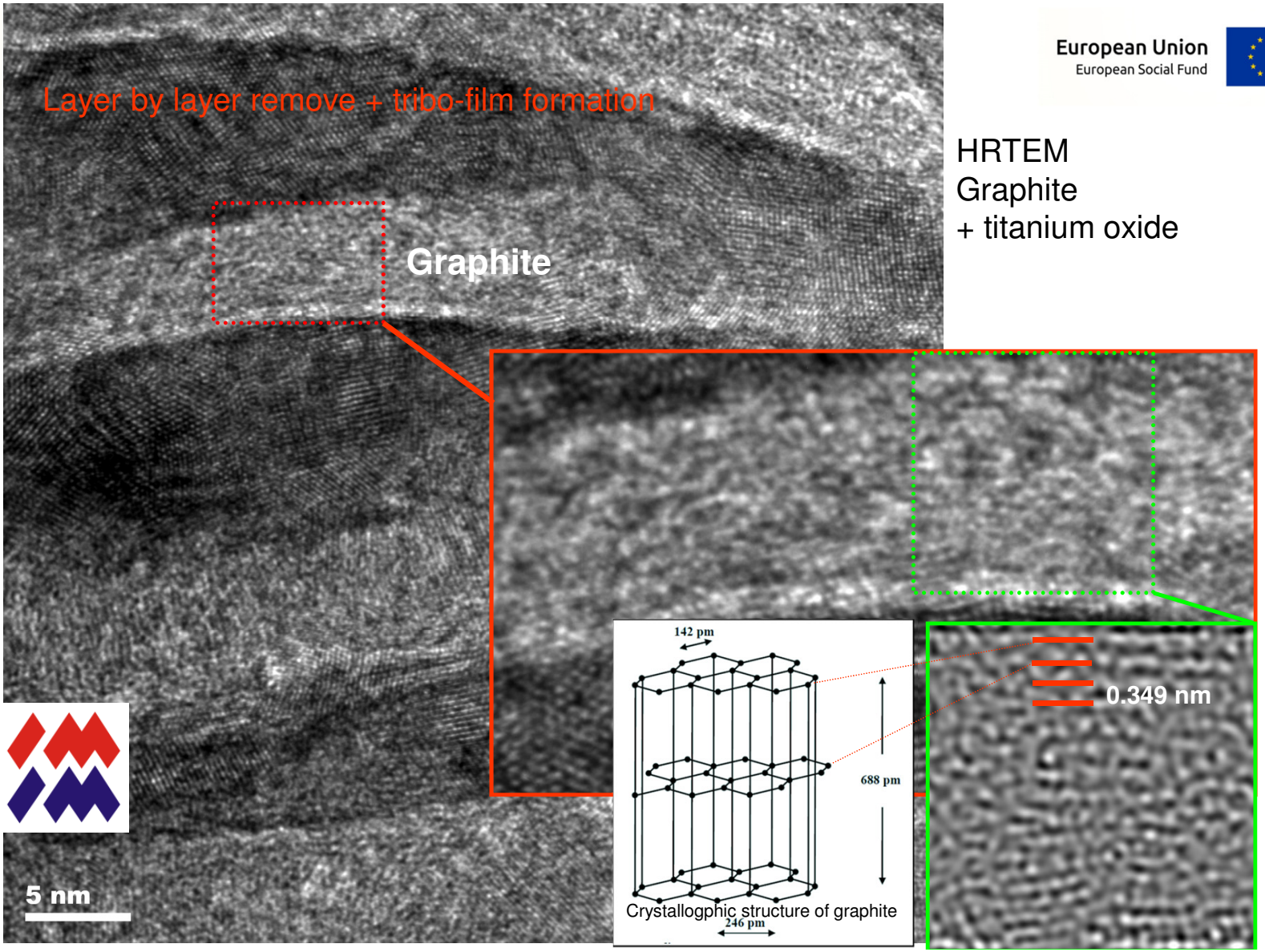


Layer by layer remove + tribo-film formation

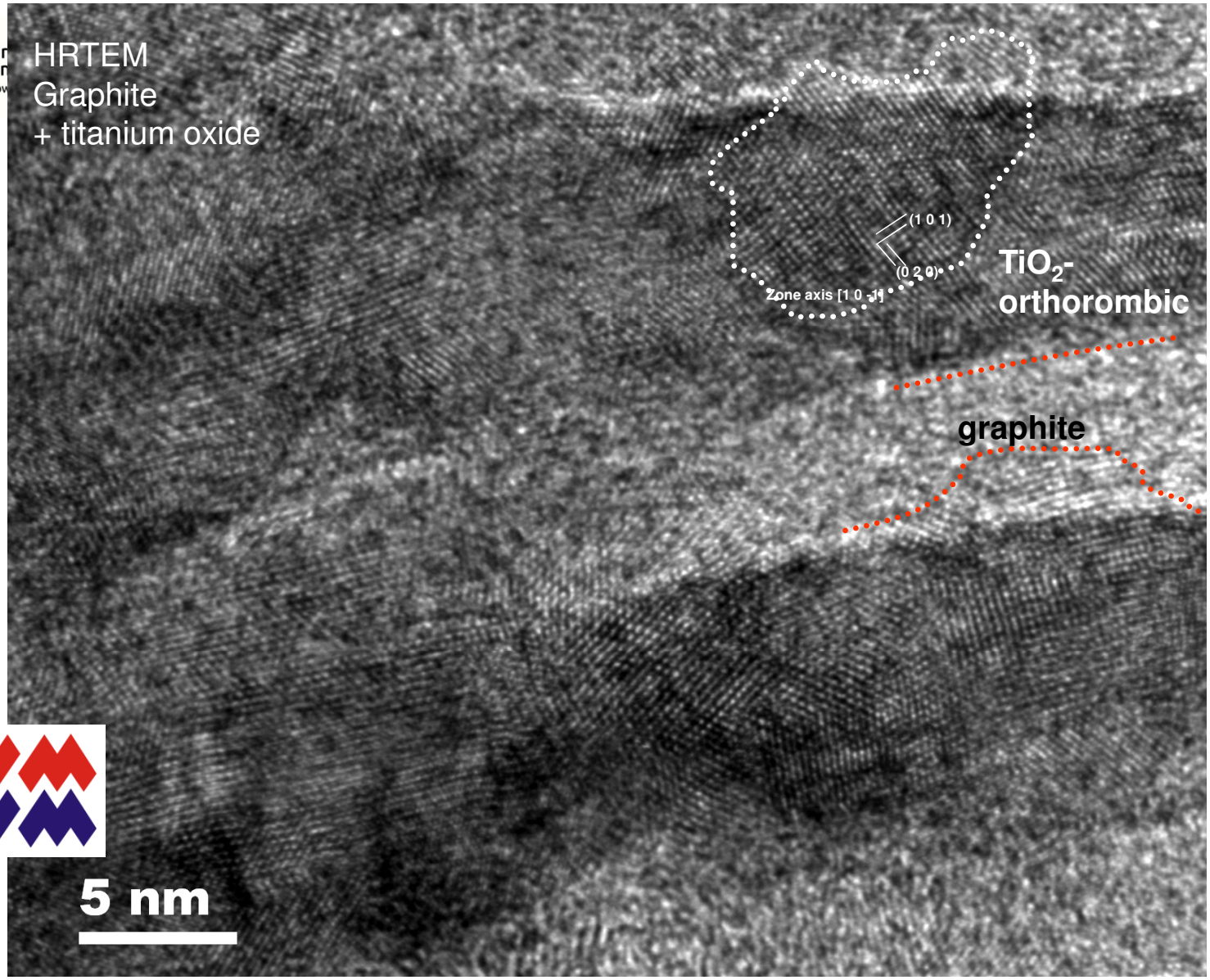




European Union
European Social Fund



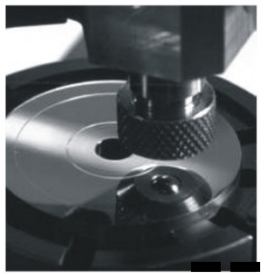
HRTEM
Graphite
+ titanium oxide

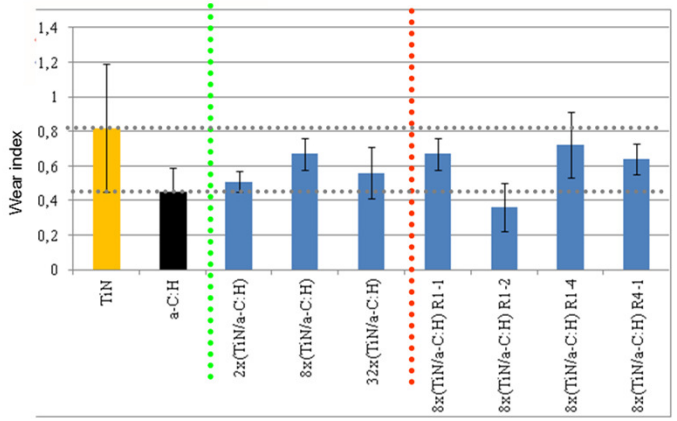

HRTEM
Graphite
+ titanium oxide
(1 0 1)
(0 2 0)
Zone axis [1 0 -1]
TiO2-
orthorombic
graphite
5 nm

European Funds
Knowledge Education Development

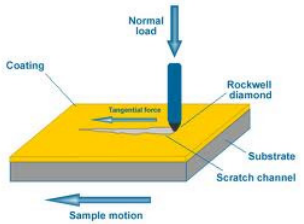
European Union
European Social Fund

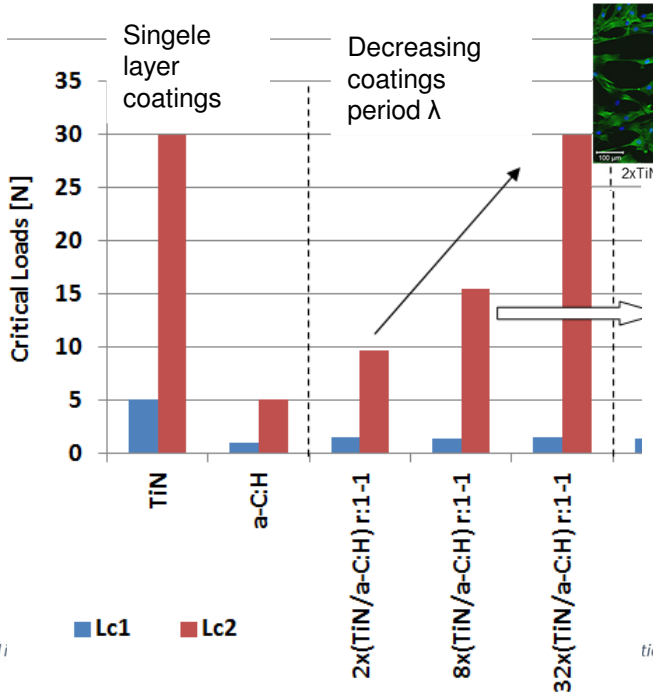
Ball- on- disc Test

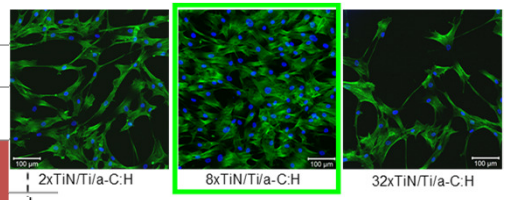




SCRATCH TEST

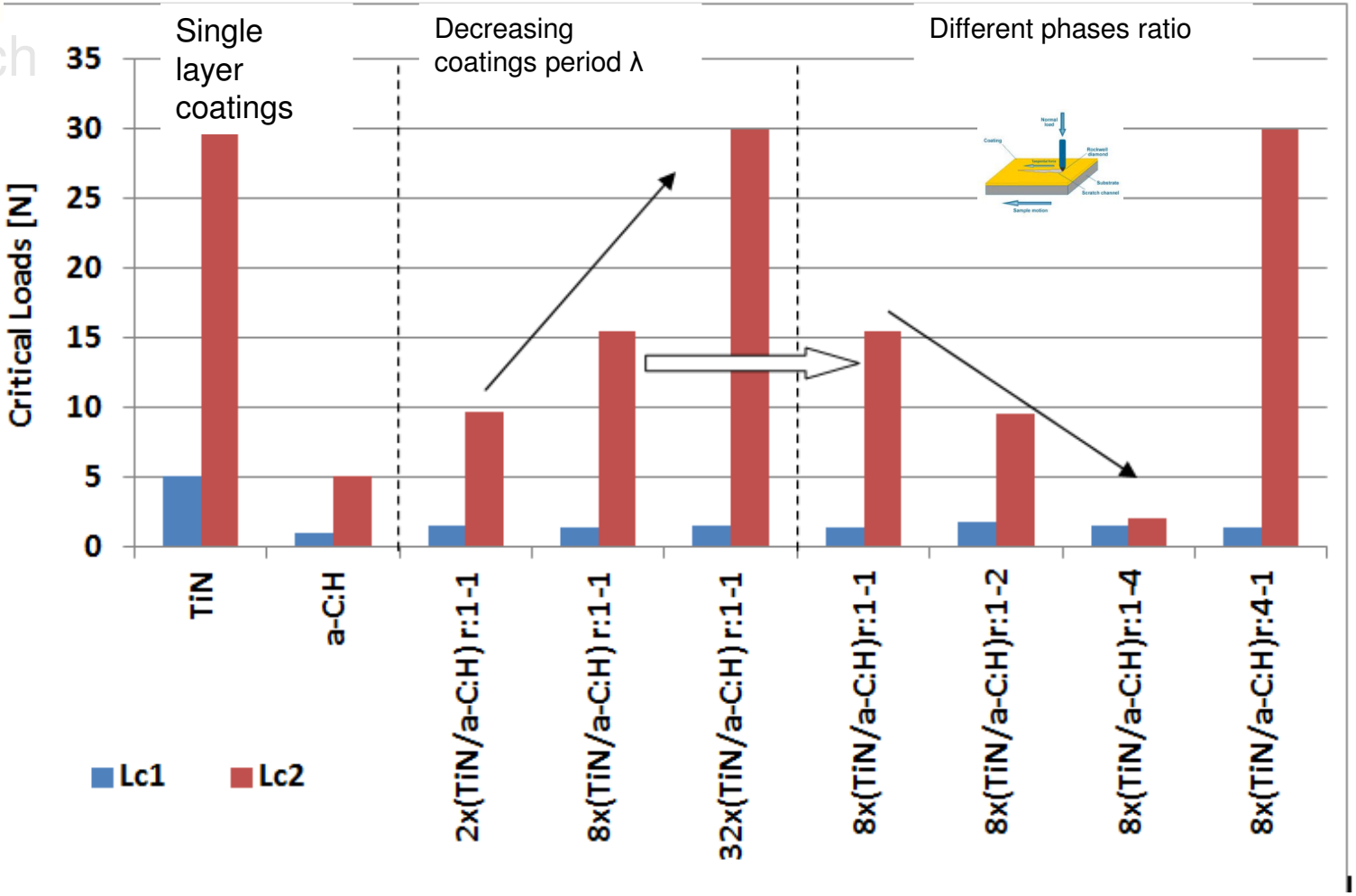






International i *tion*

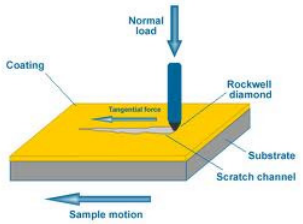
Scratch test



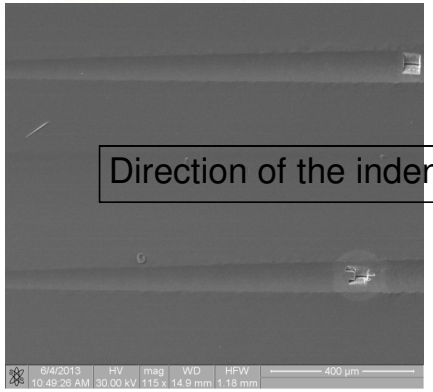
European Funds
Knowledge Education Development

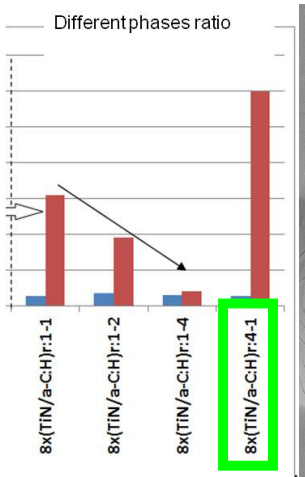
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

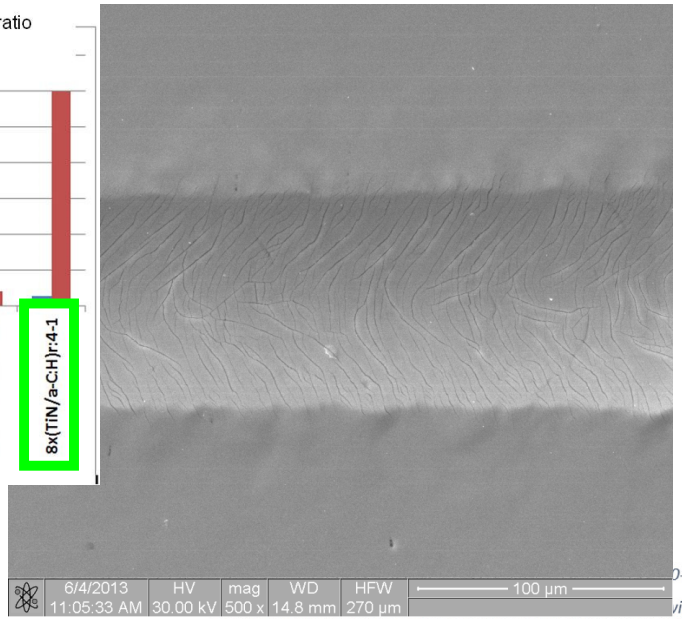
European Union
European Social Fund

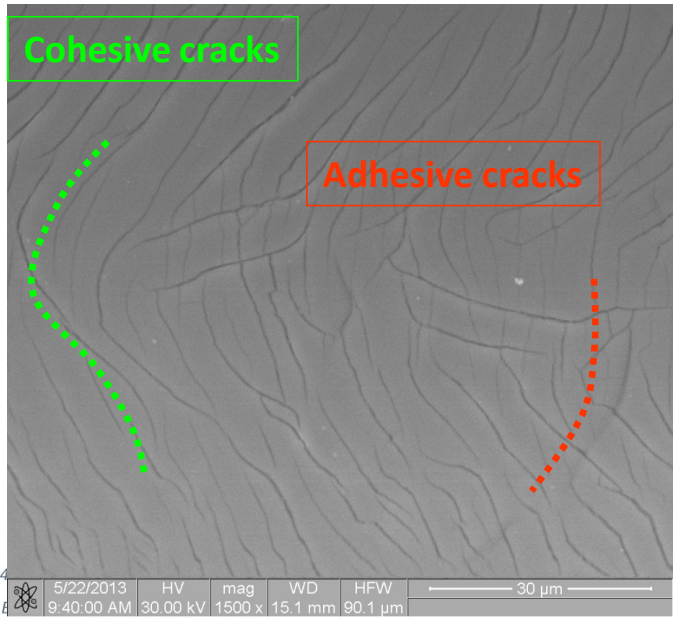


SEM







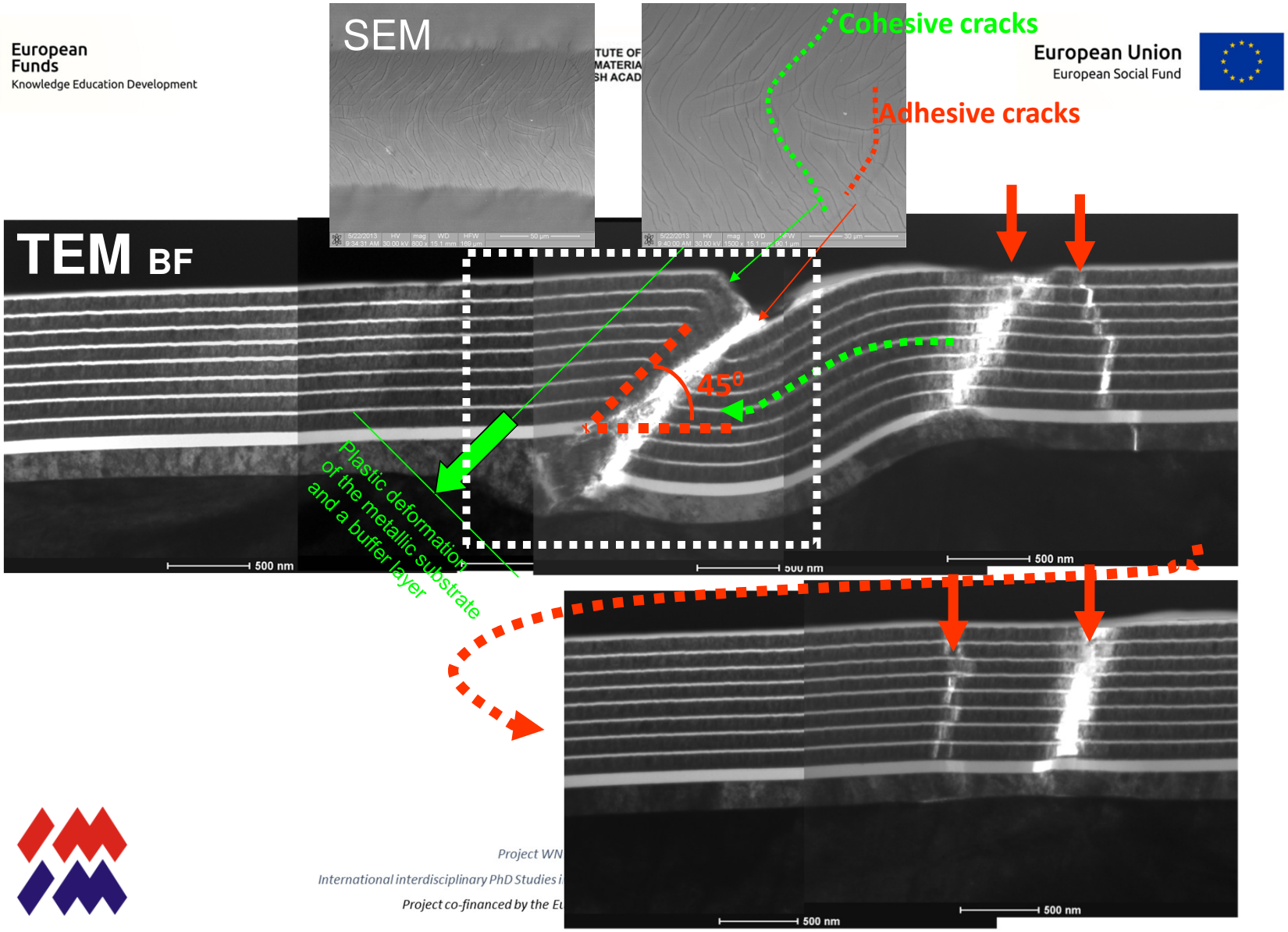


Project co-financed by the European Union within the European Social Funds

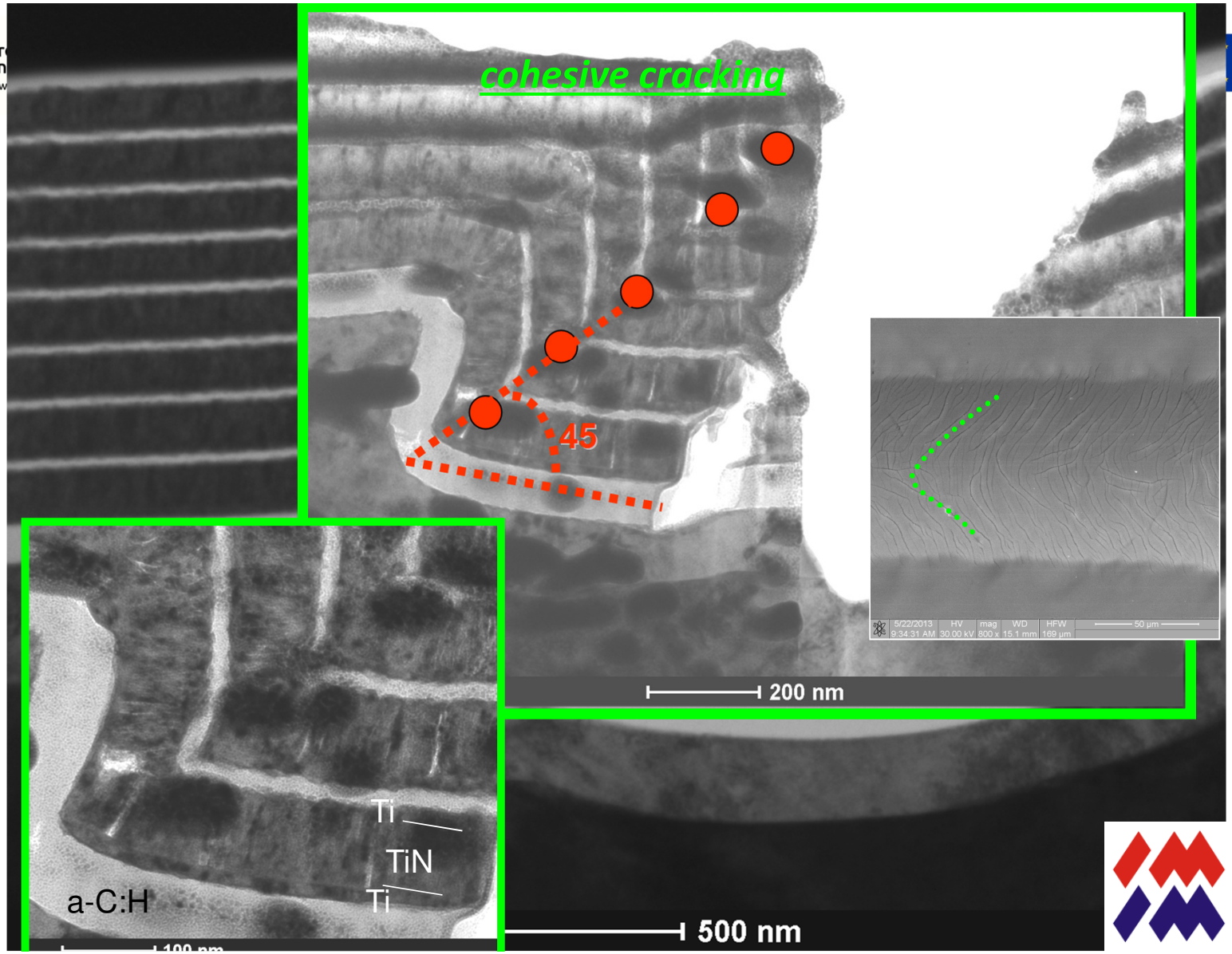
European Funds
Knowledge Education Development

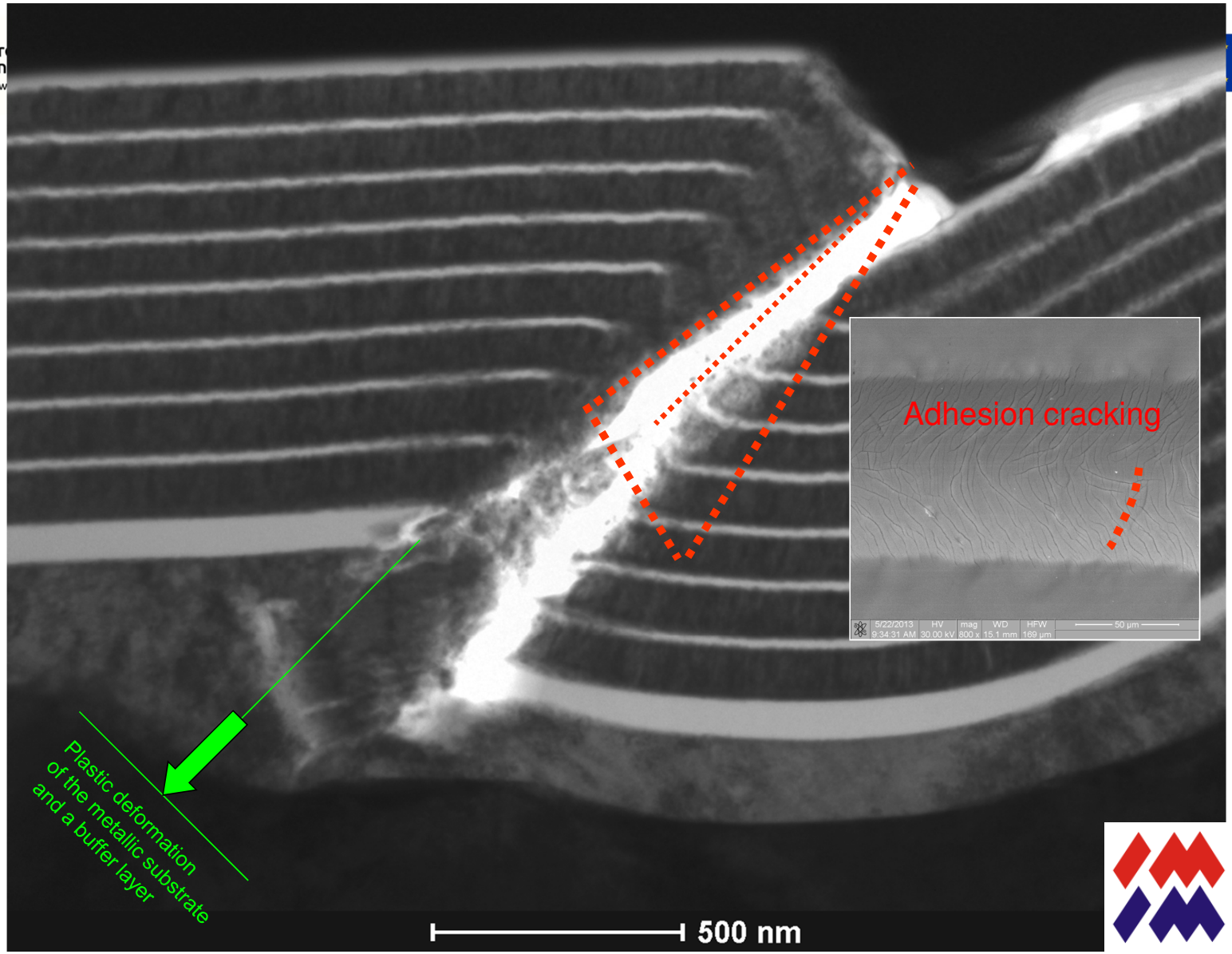
TUTE OF
MATERIA
SH ACAD

European Union
European Social Fund



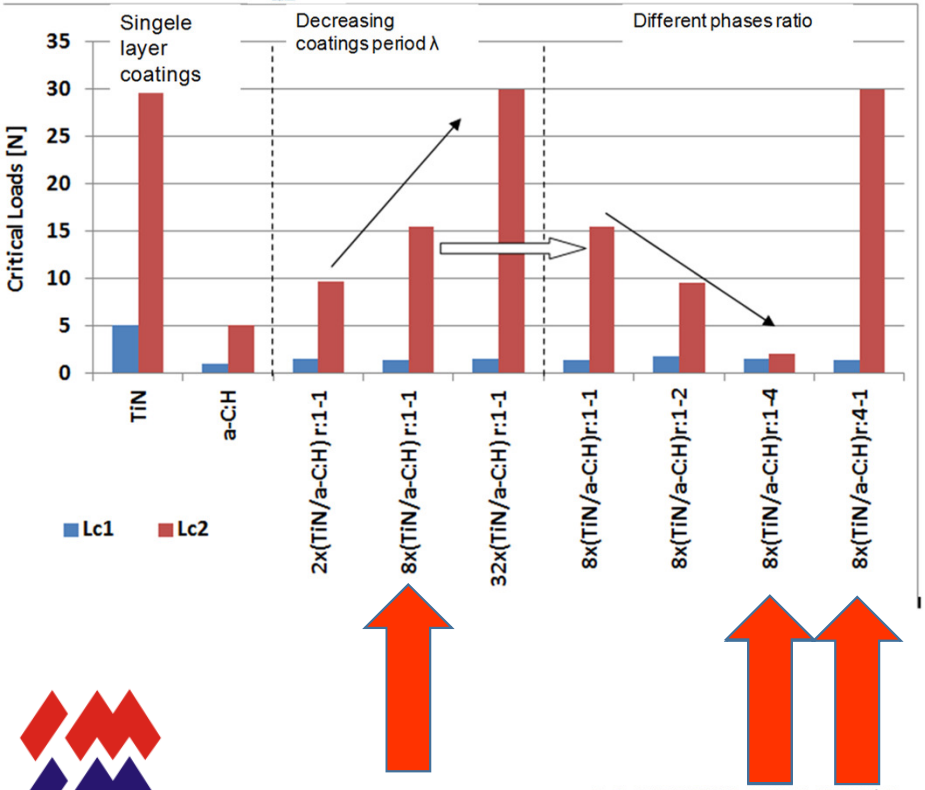
Project WN
International interdisciplinary PhD Studies i
Project co-financed by the Eu

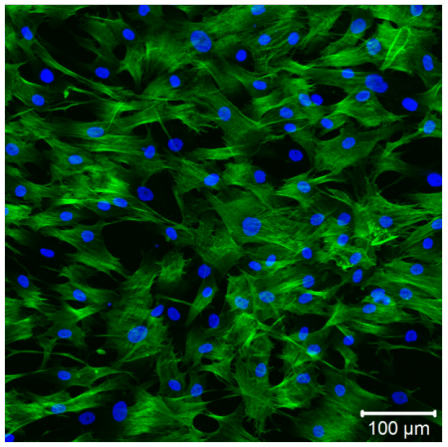

cohesive cracking
45
200 nm
Ti
TiN
Ti
a-C:H
500 nm

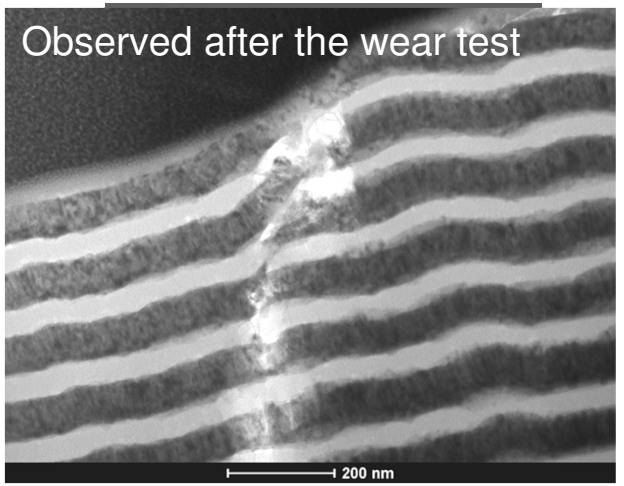

Adhesion cracking
Plastic deformation of the metallic substrate and a buffer layer
500 nm

Summary part: I

Scratch test







Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

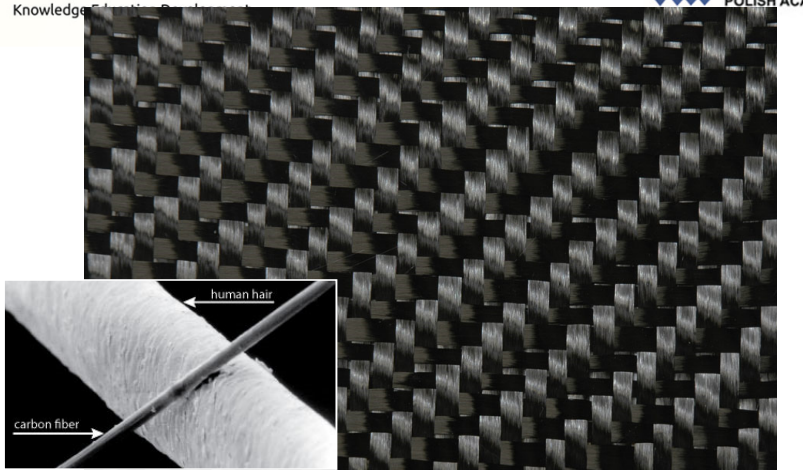
- Project NCN nr: 3066/B/T02/2011/40- *FINISHED*
- Project NCN nr: 2012/06/M/ST8/00408- *HARMONIA- FINISHED*
- Project NCN nr: 2012/07/B/ST8/03396- *OPUS- FINISHED*
- Project NCN nr: 2014/15/B/ST8/00103- *OPUS- FINISHED*
- Project NCN nr: 2015/19/B/ST8/00942- *OPUS- in progress*
- Project NCBR, number: DZP/M-ERA.NET-2015/285/2016- *in progress*

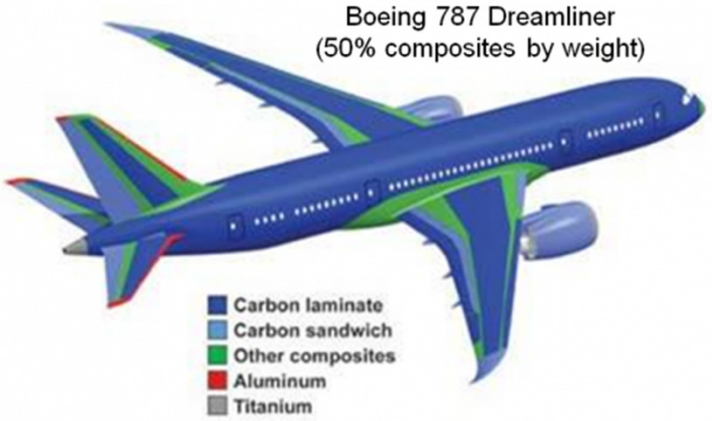
Title: Development of wear resistant multilayer protective coatings for carbon/ fiber composites

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds



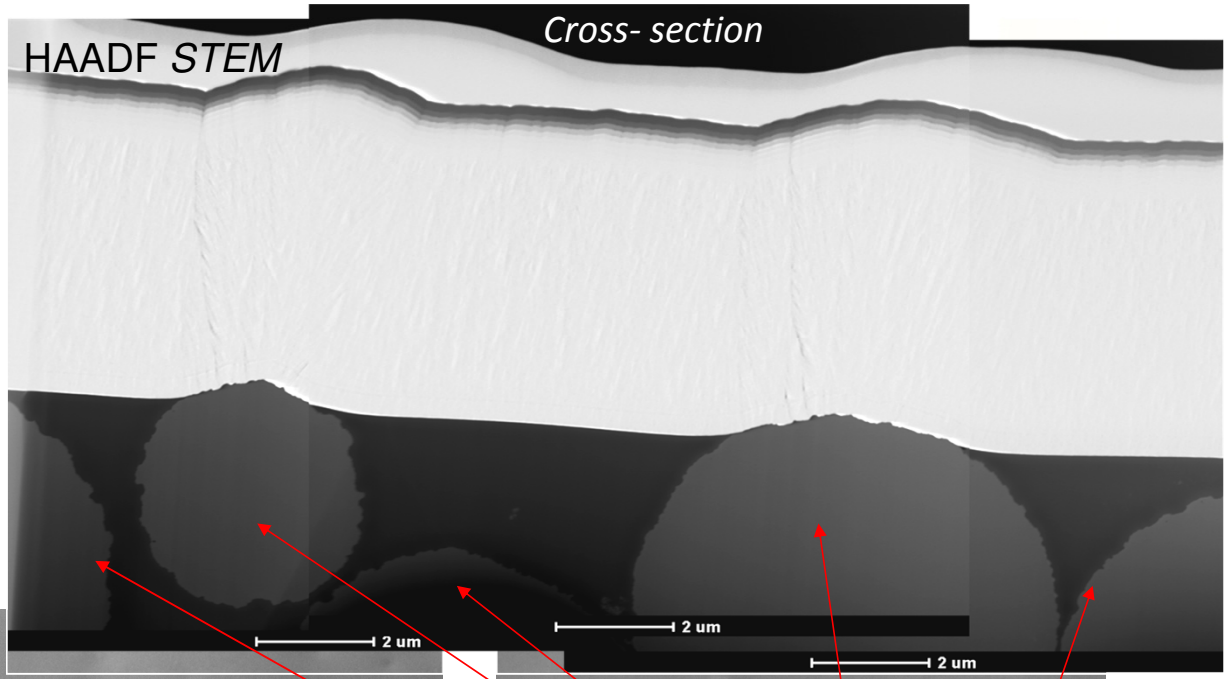


.03.02.00-00-I043/16

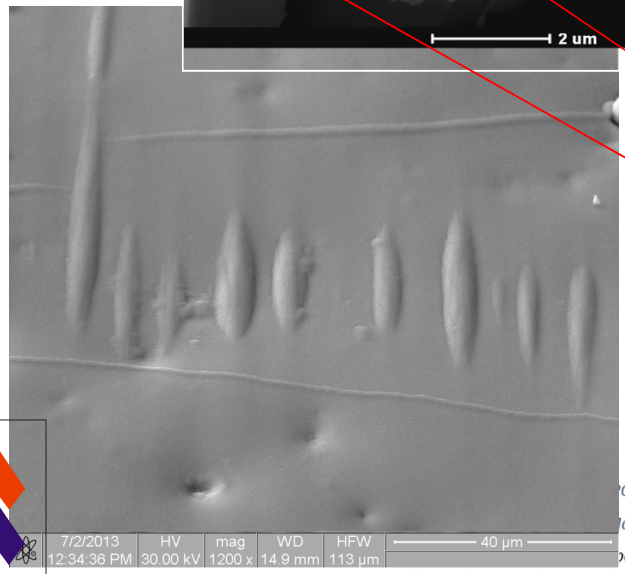
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

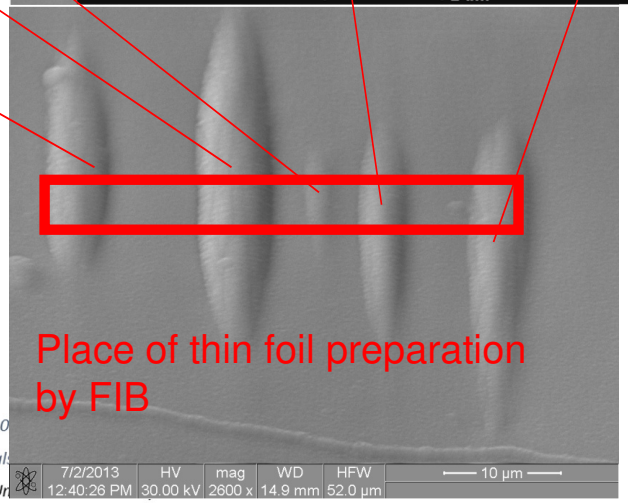
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

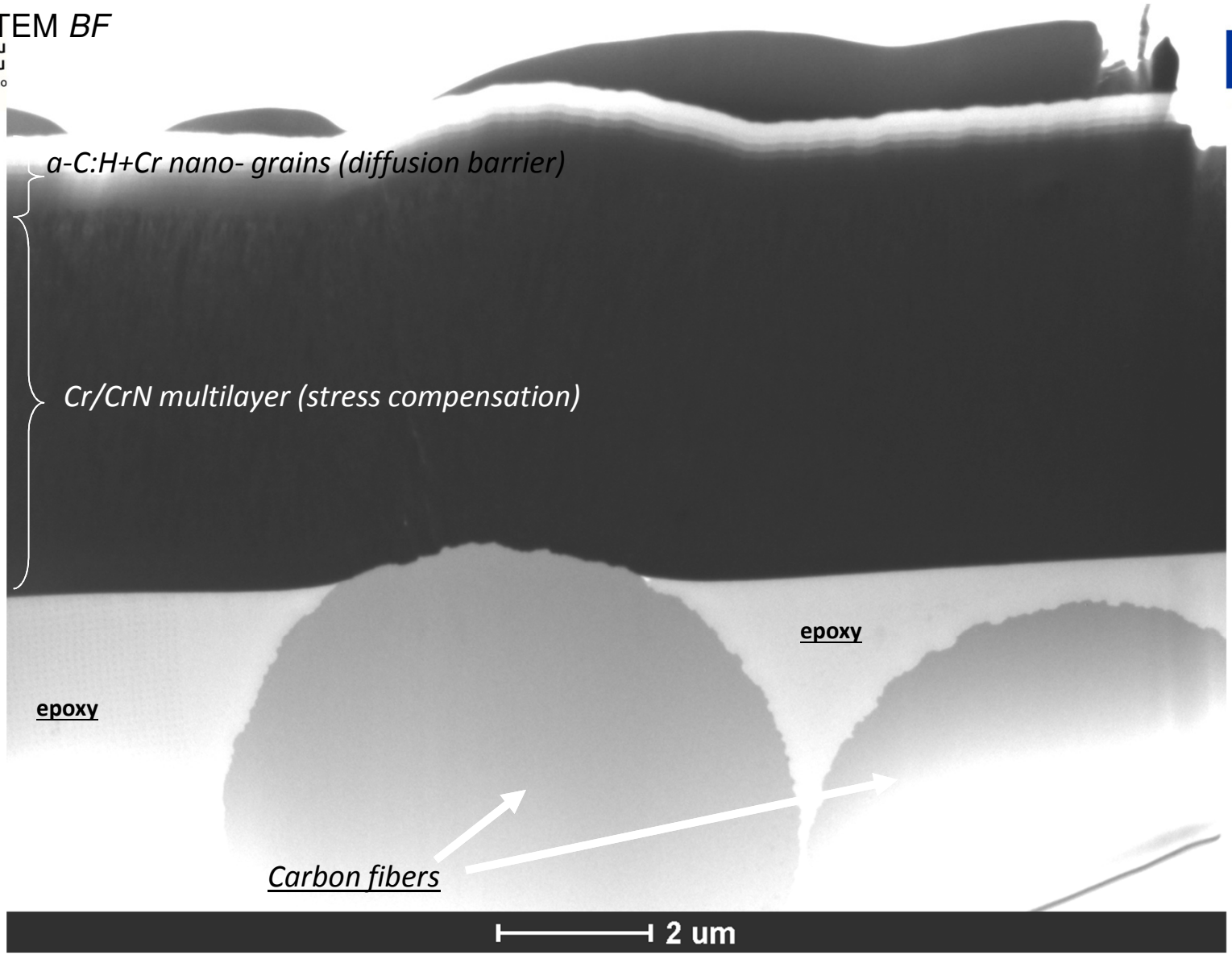


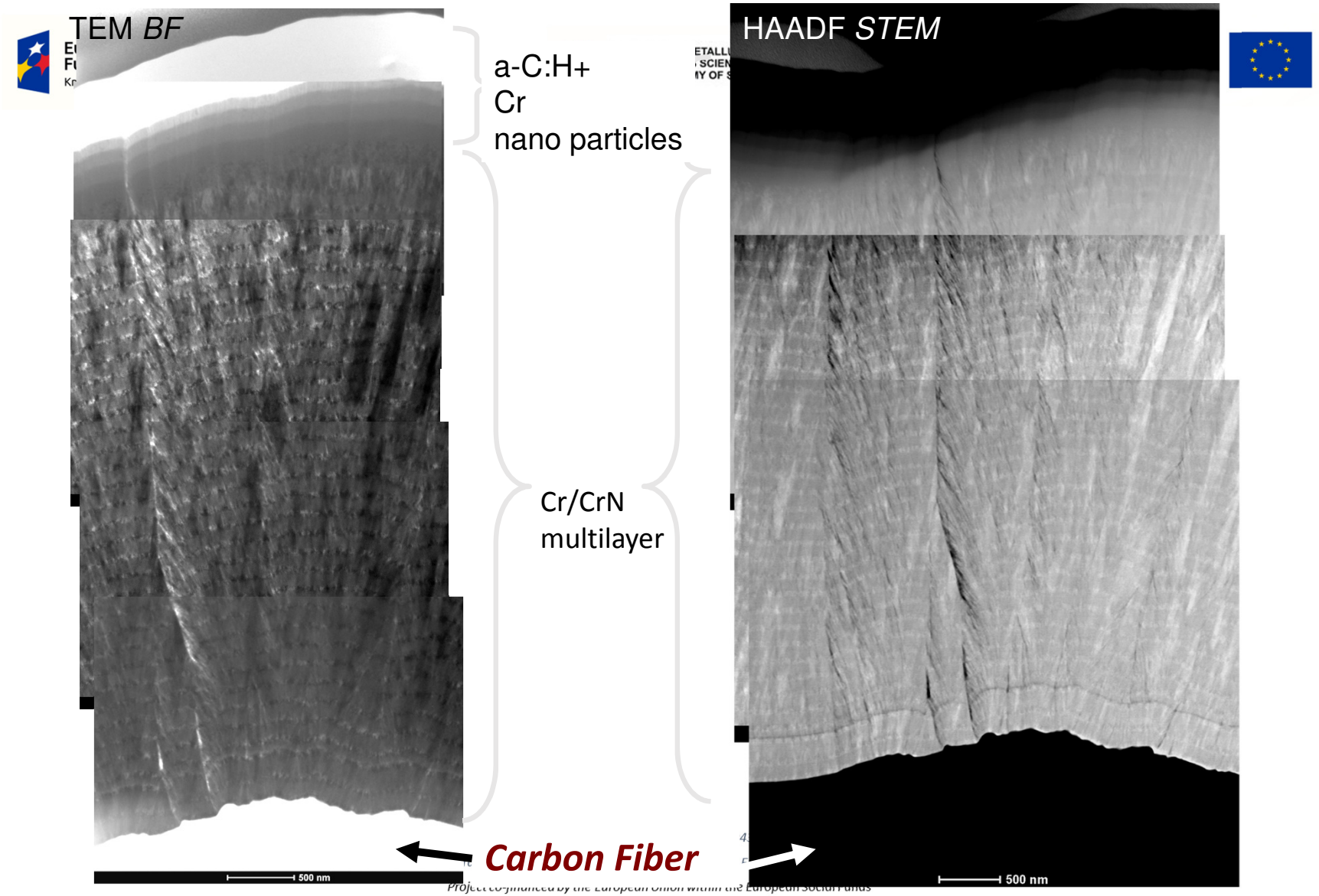
SEM

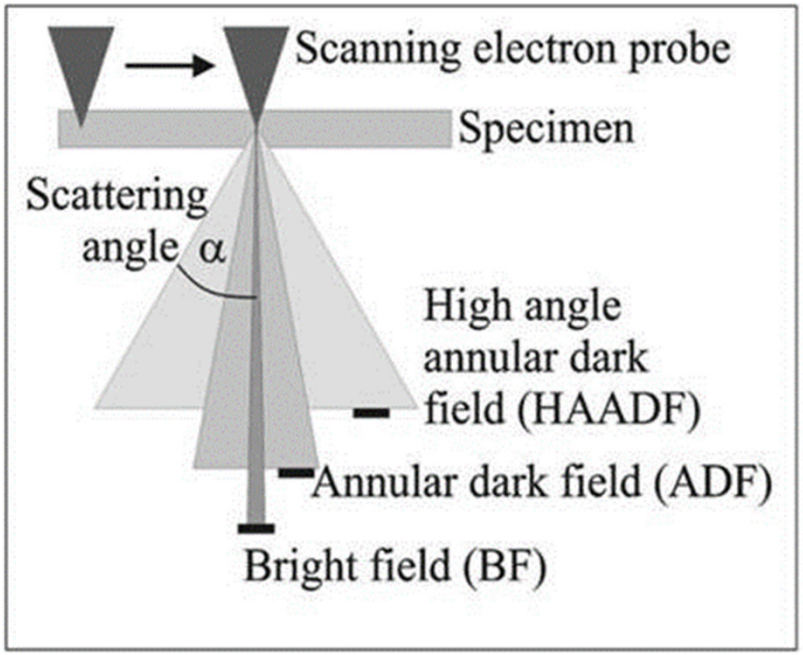


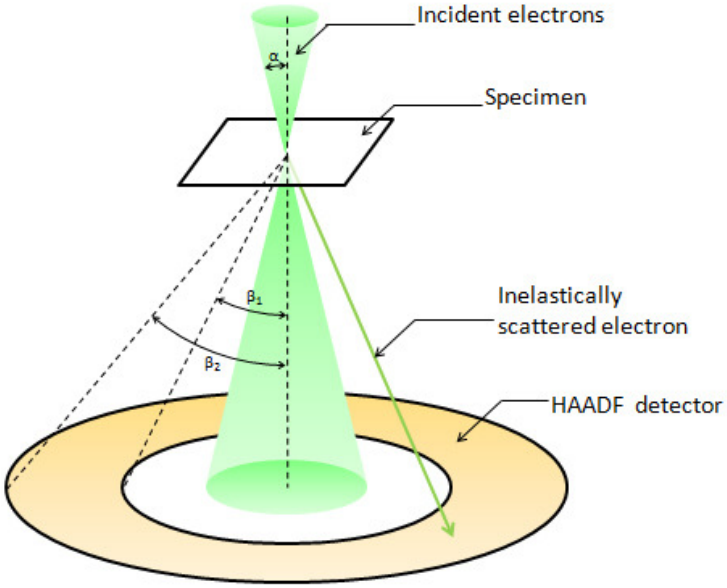


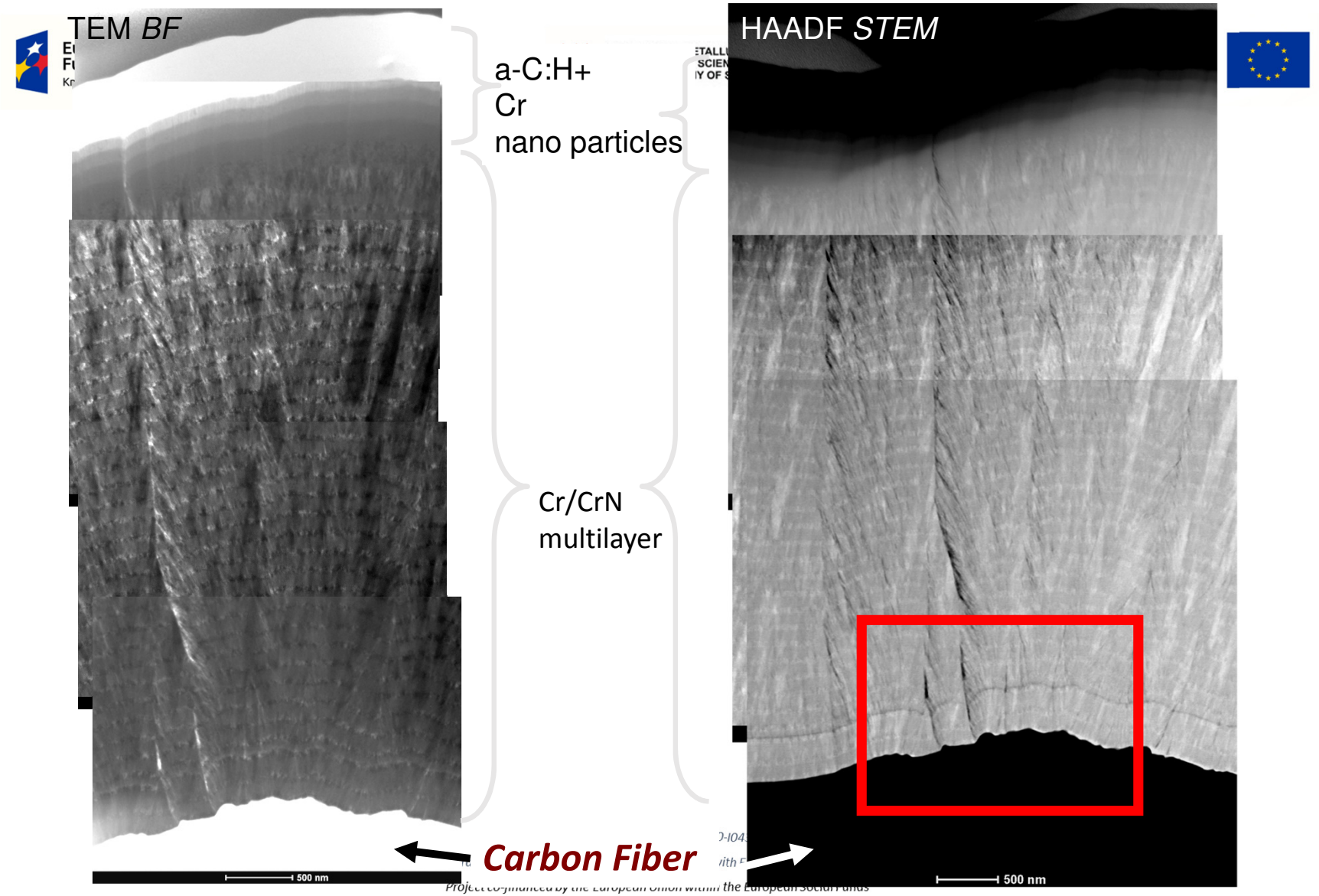
TEM *BF*

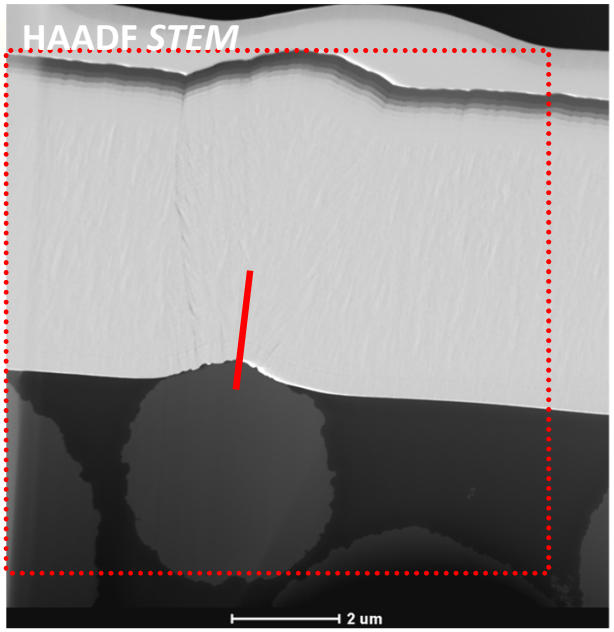

a-C:H+Cr nano- grains (diffusion barrier)
Cr/CrN multilayer (stress compensation)
epoxy
epoxy
Carbon fibers
2 um


TEM *BF*
HAADF *STEM*
a-C:H+
Cr
nano particles
Cr/CrN
multilayer
Carbon Fiber
500 nm
500 nm


Scanning electron probe
Specimen
Scattering
angle α
High angle
annular dark
field (HAADF)
Annular dark field (ADF)
Bright field (BF)

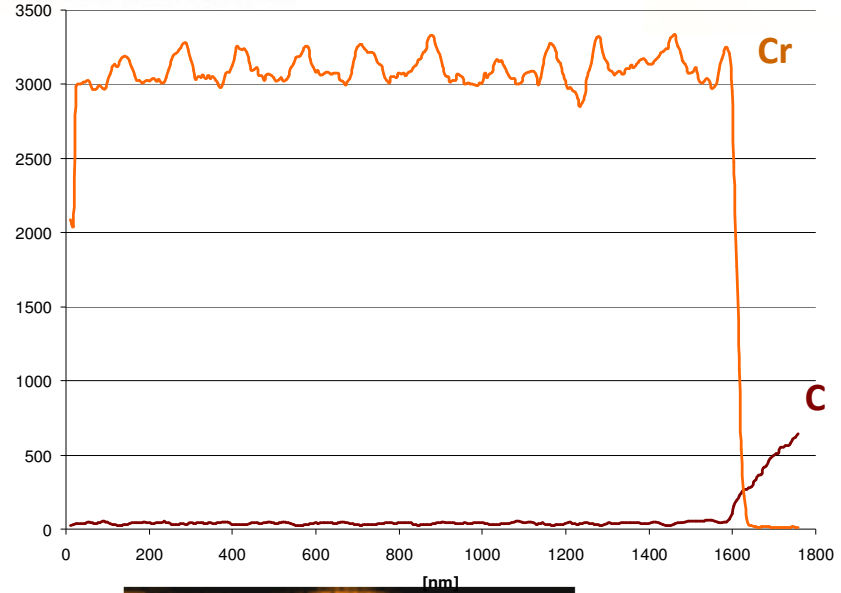

Incident electrons
α
Specimen
β1
β2
Inelastically
scattered electron
HAADF detector


TEM *BF*
HAADF *STEM*
a-C:H+
Cr
nano particles
Cr/CrN
multilayer
Carbon Fiber
500 nm
500 nm

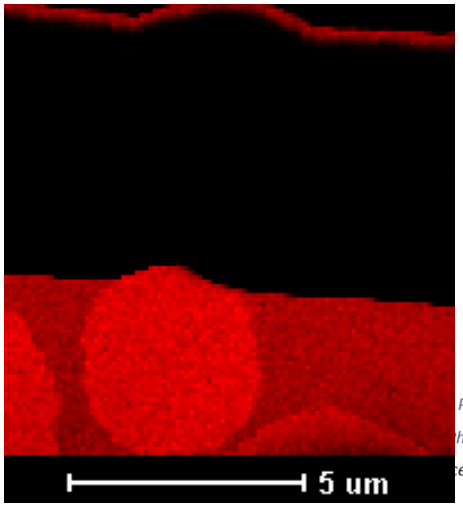


INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

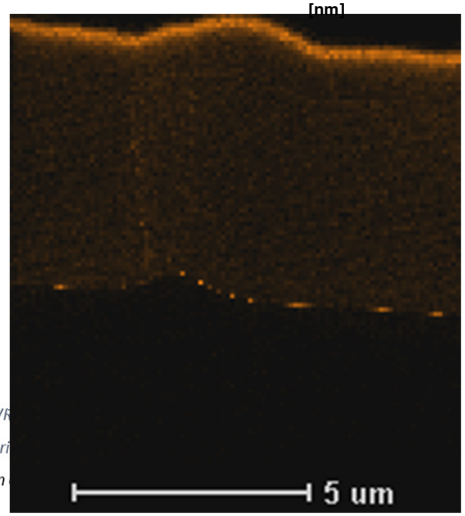
European Union
European Social Fund



C



Cr

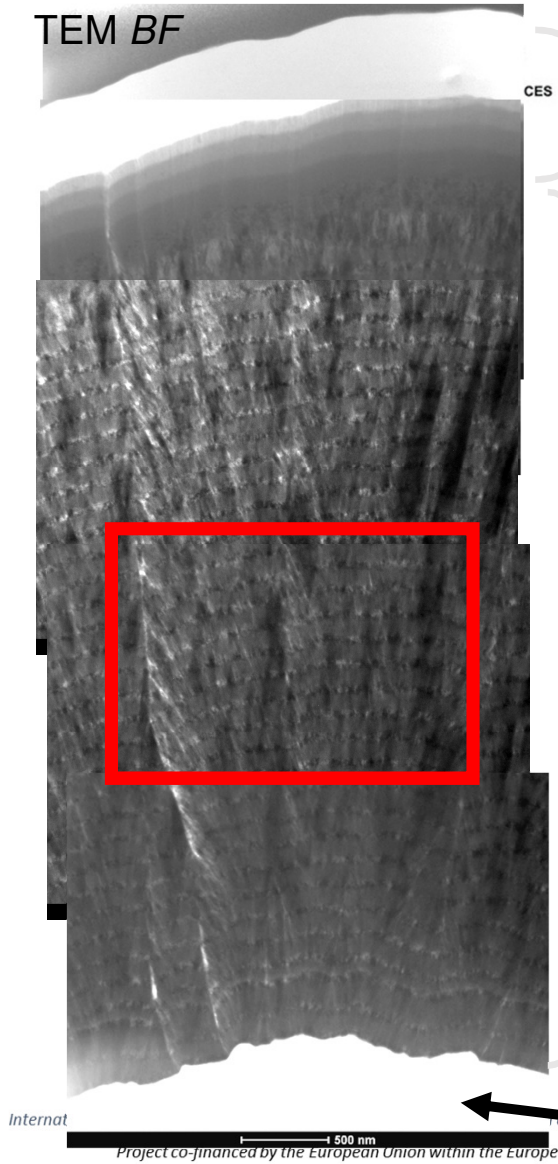


EDS

Project WND-POWR
hD Studies in Materi
ed by the European

European Funds
Knowledge Education Development

European Union
European Social Fund



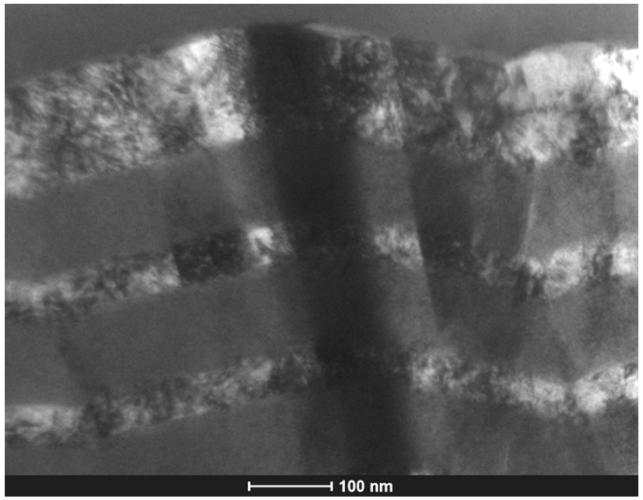
a-C:H+
Cr
nano particles

Cr/CrN
multilayer

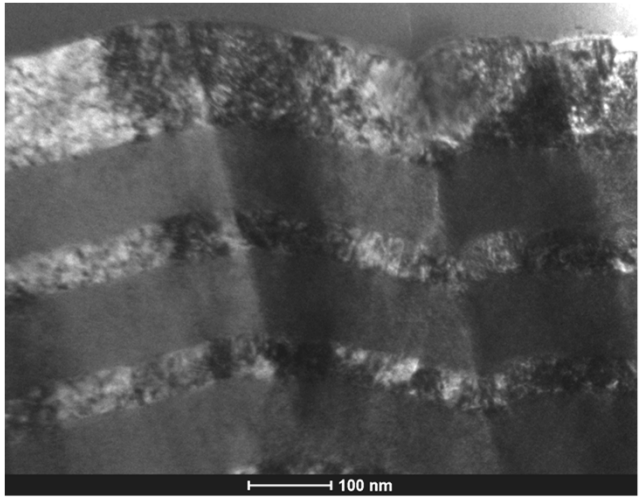
Carbon Fiber

Project co-financed by the European Union within the European Social Funds

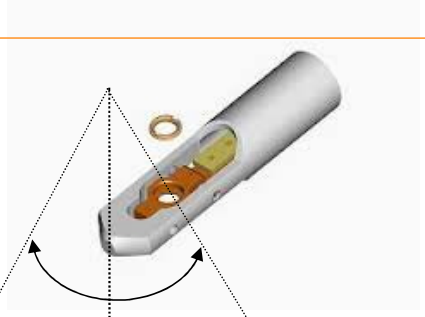
TEM *BF*



$\alpha = 0^{\circ}$



$\alpha = +2{,}14^{\circ}$



European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

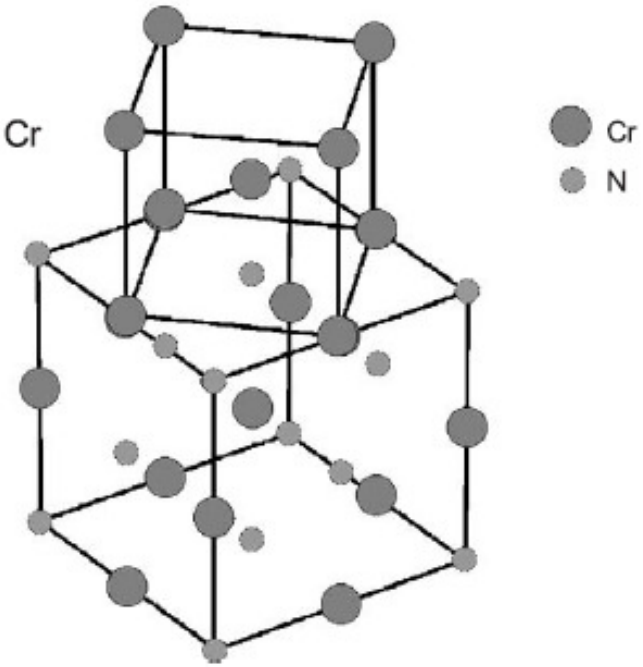
a= 2.88Å

Cr

mismatch= 1.6%
(close to epitaxial growth)

a= 4.14Å

CrN



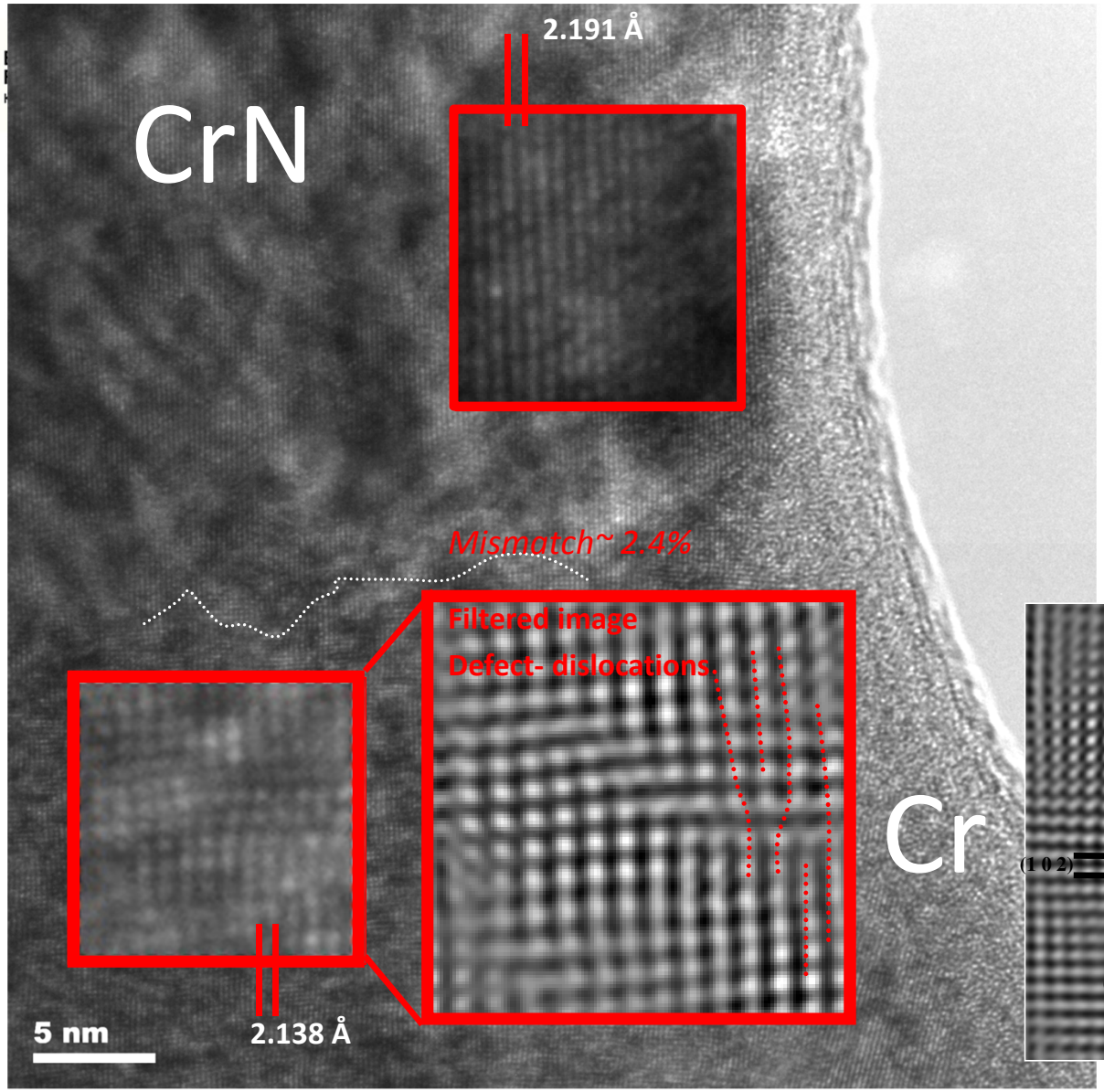
Available online at www.sciencedirect.com
SCIENCE DIRECT
Surface & Coatings Technology 188–189 (2004) 338–343
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat
ELSEVIER

Period dependence of hardness and microstructure on nanometric Cr/CrN multilayers

J. Romero*, J. Esteve, A. Lousa

Departamento Física Aplicada i Òptica, Universitat de Barcelona, Avgda. Diagonal 647, E-08028 Barcelona, Catalunya, Spain

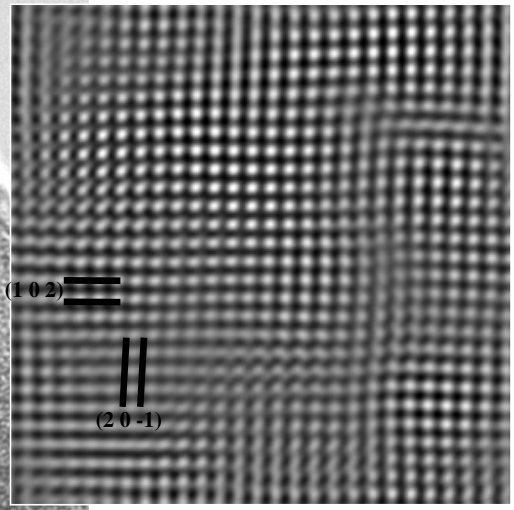
Available online 12 October 2004



European Union
European Social Fund

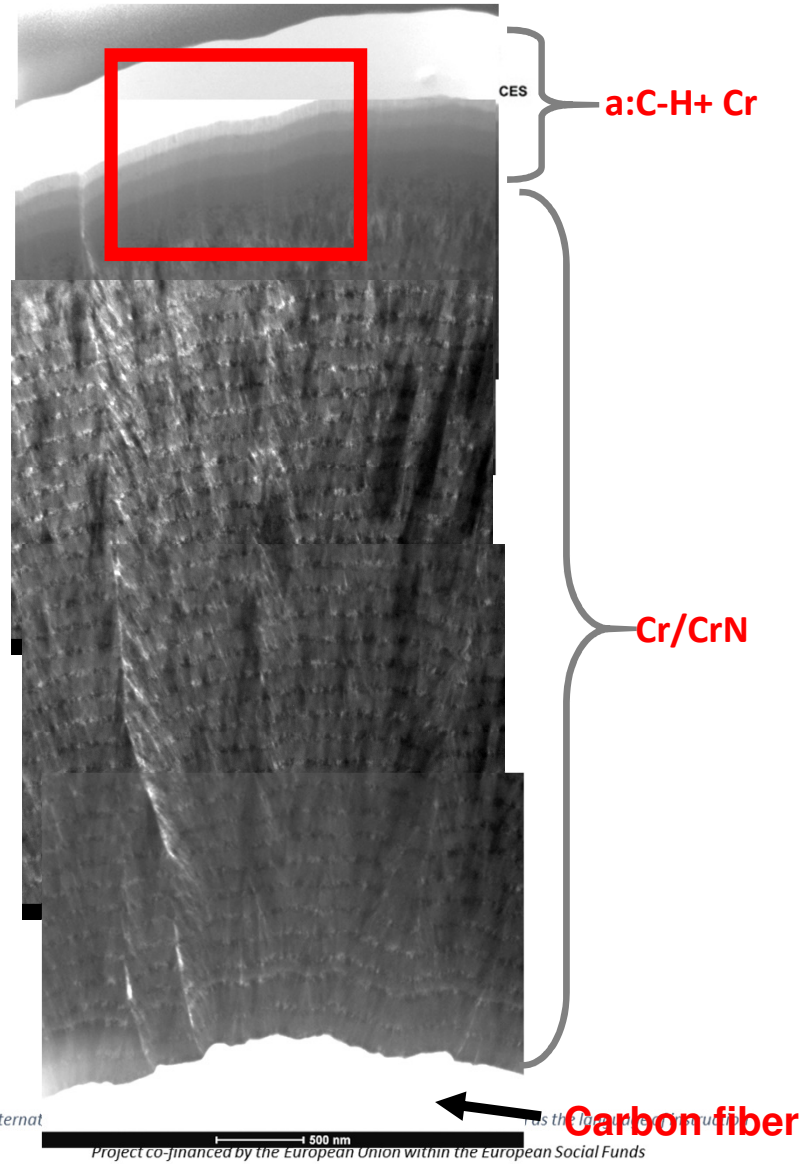
HRTEM

Zone axis [0 1 0]
Cr *cubic*



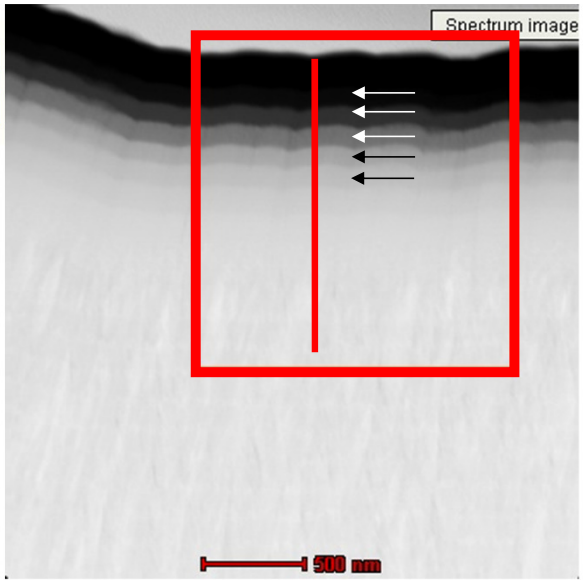
TEM *BF*

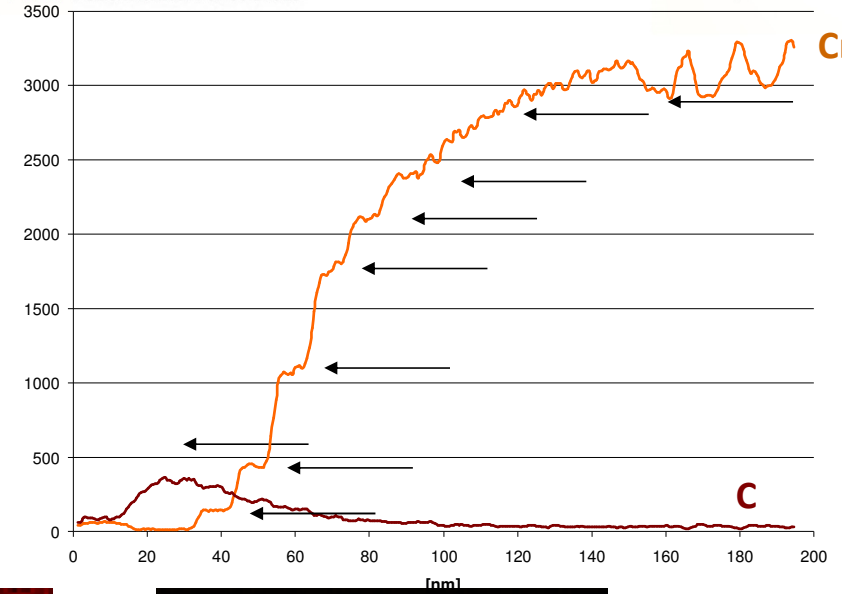
European Funds
Knowledge Education Development



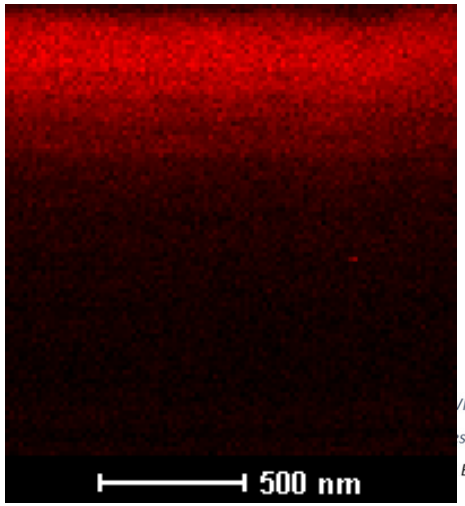
European Union
European Social Fund

Project co-financed by the European Union within the European Social Funds

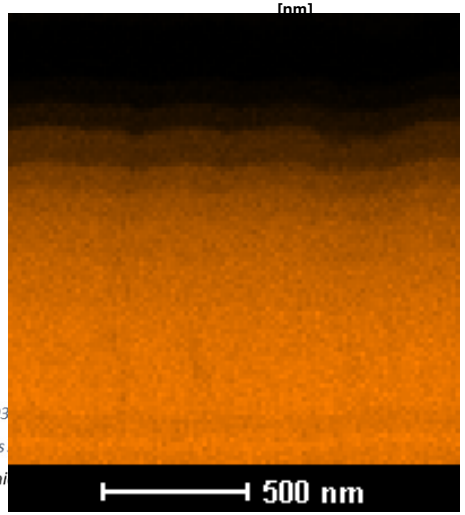

Spectrum image
500 nm


3500
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
100
120
140
160
180
200
[nm]
Cr
C

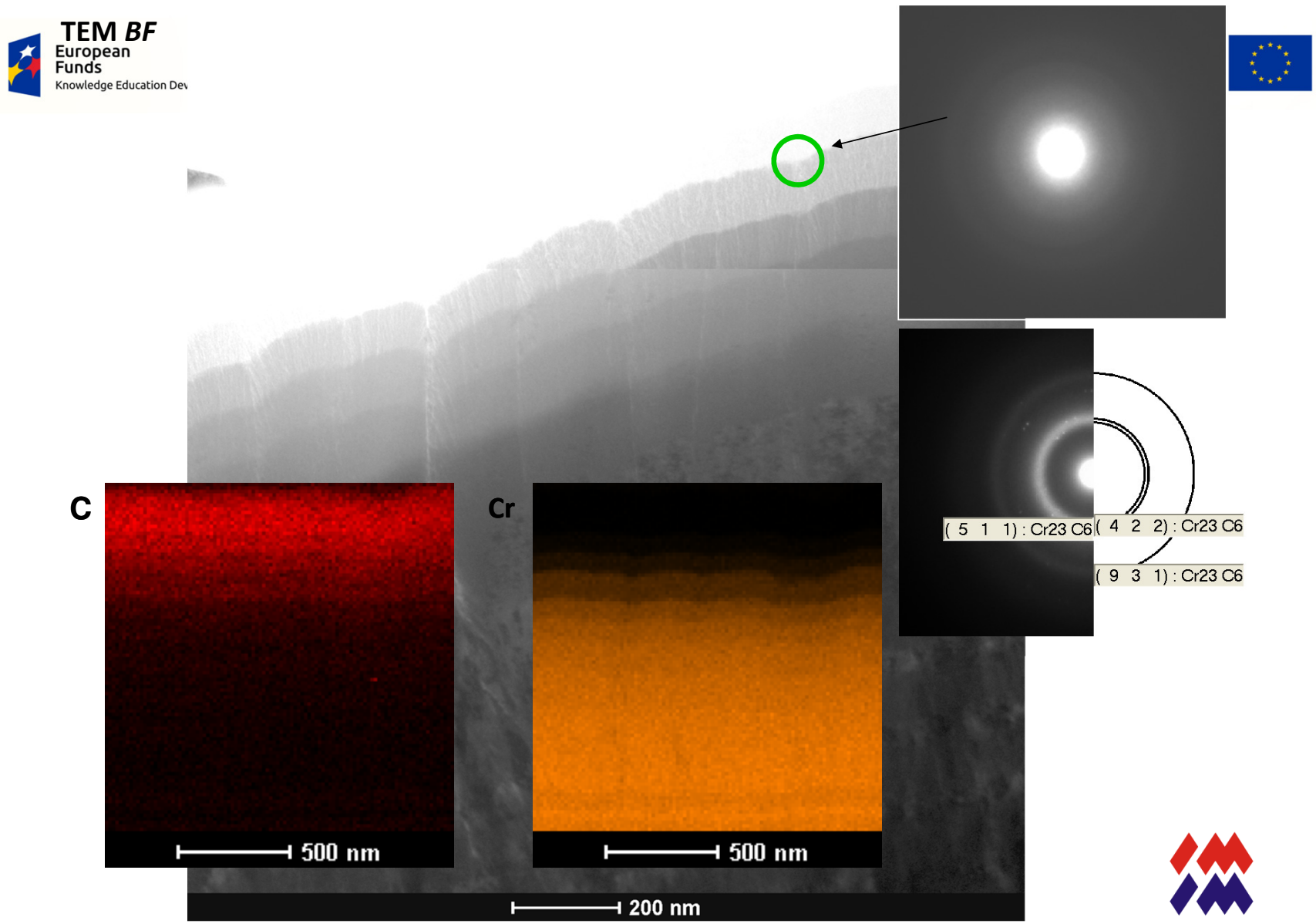
C

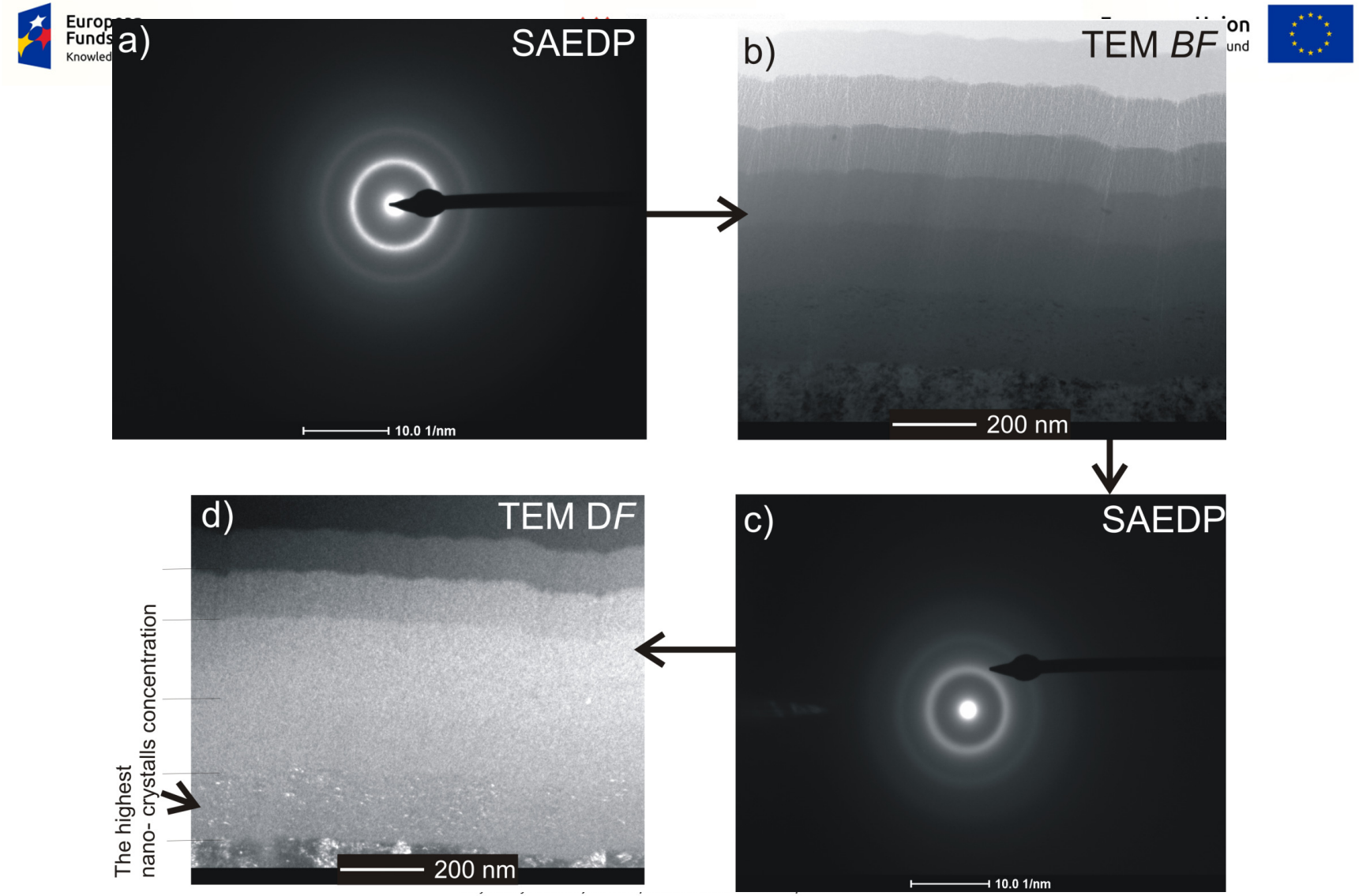

500 nm

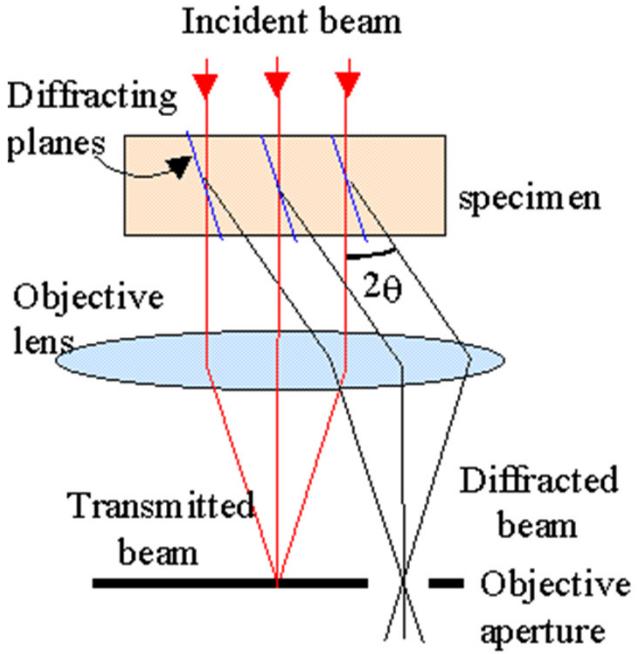
Cr


500 nm

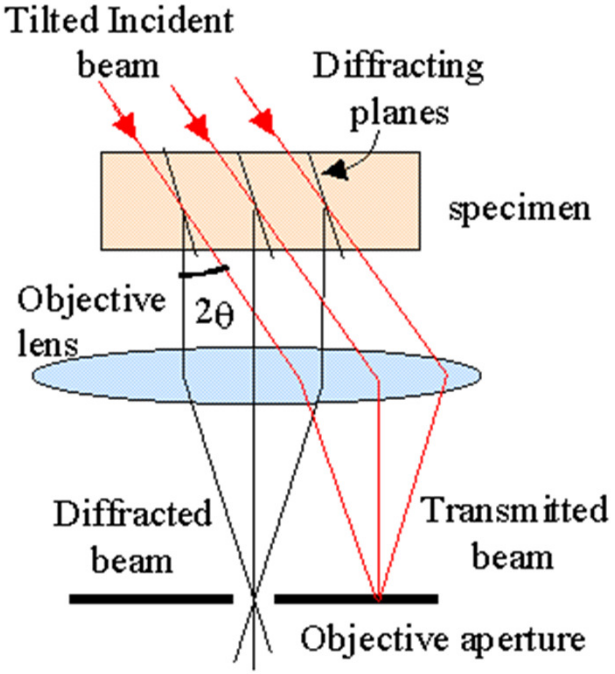
EDS


TEM BF
European
Funds
Knowledge Education Dev
C
Cr
500 nm
500 nm
200 nm
(5 1 1) : Cr23 C6
(4 2 2) : Cr23 C6
(9 3 1) : Cr23 C6

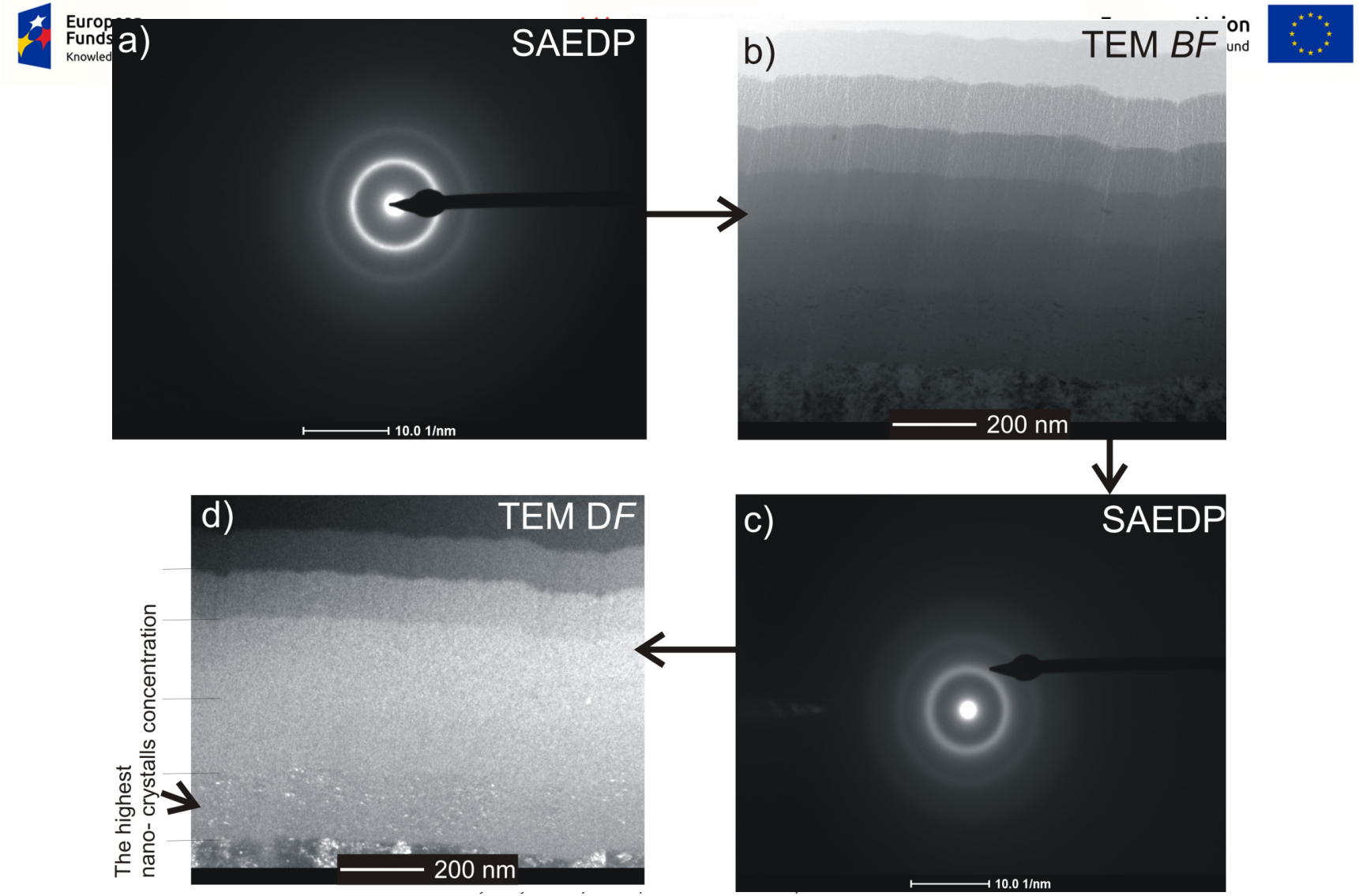

a)
SAEDP
10.0 1/nm
b)
TEM BF
200 nm
c)
SAEDP
10.0 1/nm
d)
TEM DF
200 nm
The highest
nano- crystalls concentration

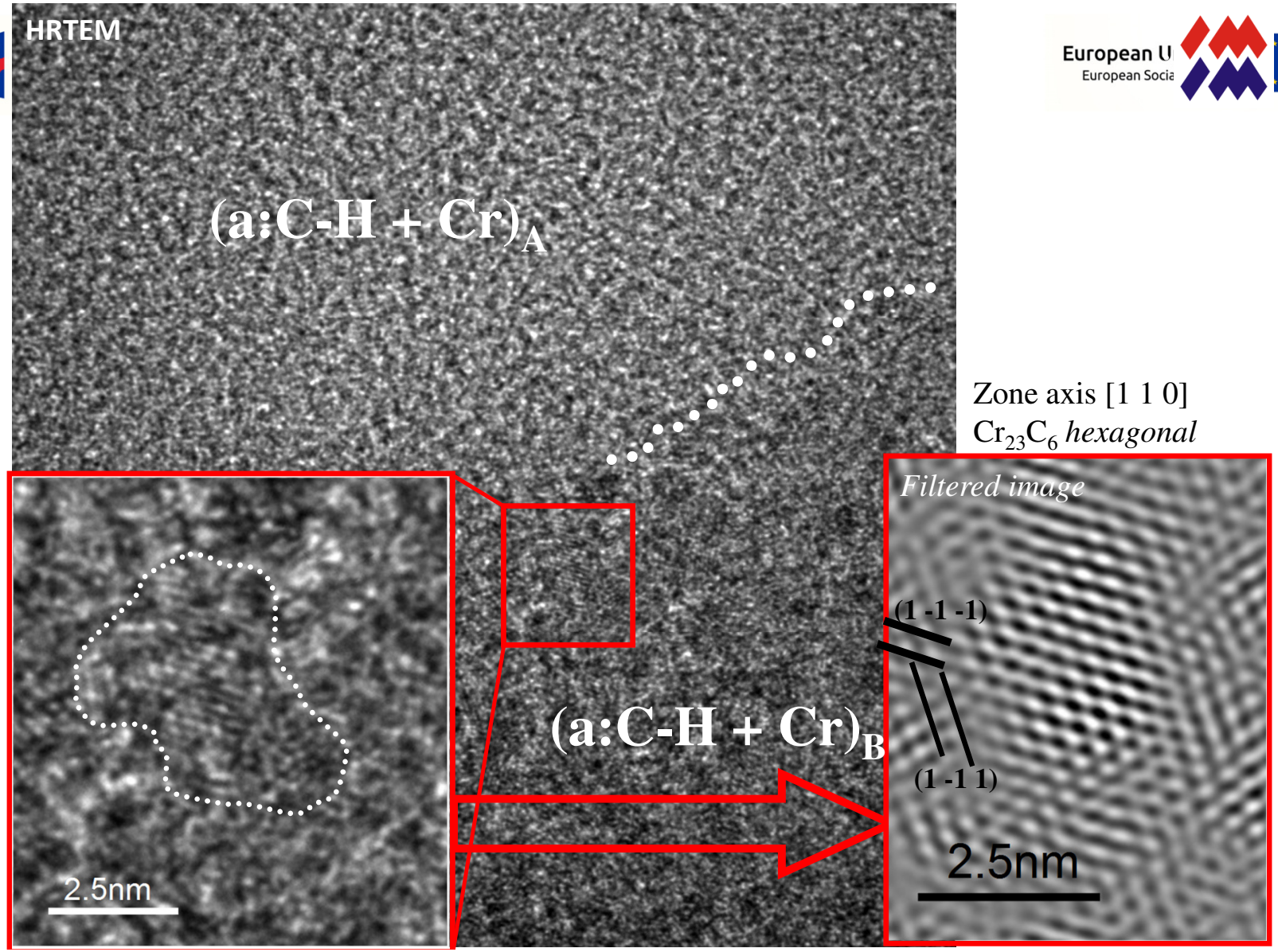


Off-axis Dark Field



On-axis Dark Field


a)
SAEDP
10.0 1/nm
b)
TEM BF
200 nm
c)
SAEDP
10.0 1/nm
d)
TEM DF
200 nm
The highest
nano- crystalls concentration

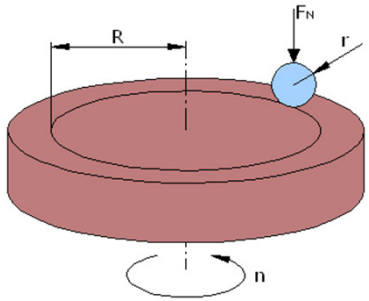

HRTEM
$(a:C\text{-}H + Cr)_A$
$(a:C\text{-}H + Cr)_B$
2.5nm
Zone axis [1 1 0]
$Cr_{23}C_6$ *hexagonal*
Filtered image
(1 -1 -1)
(1 -1 1)
2.5nm

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Tribological test– ball- on- disc
(EN 1071-3:2003.)



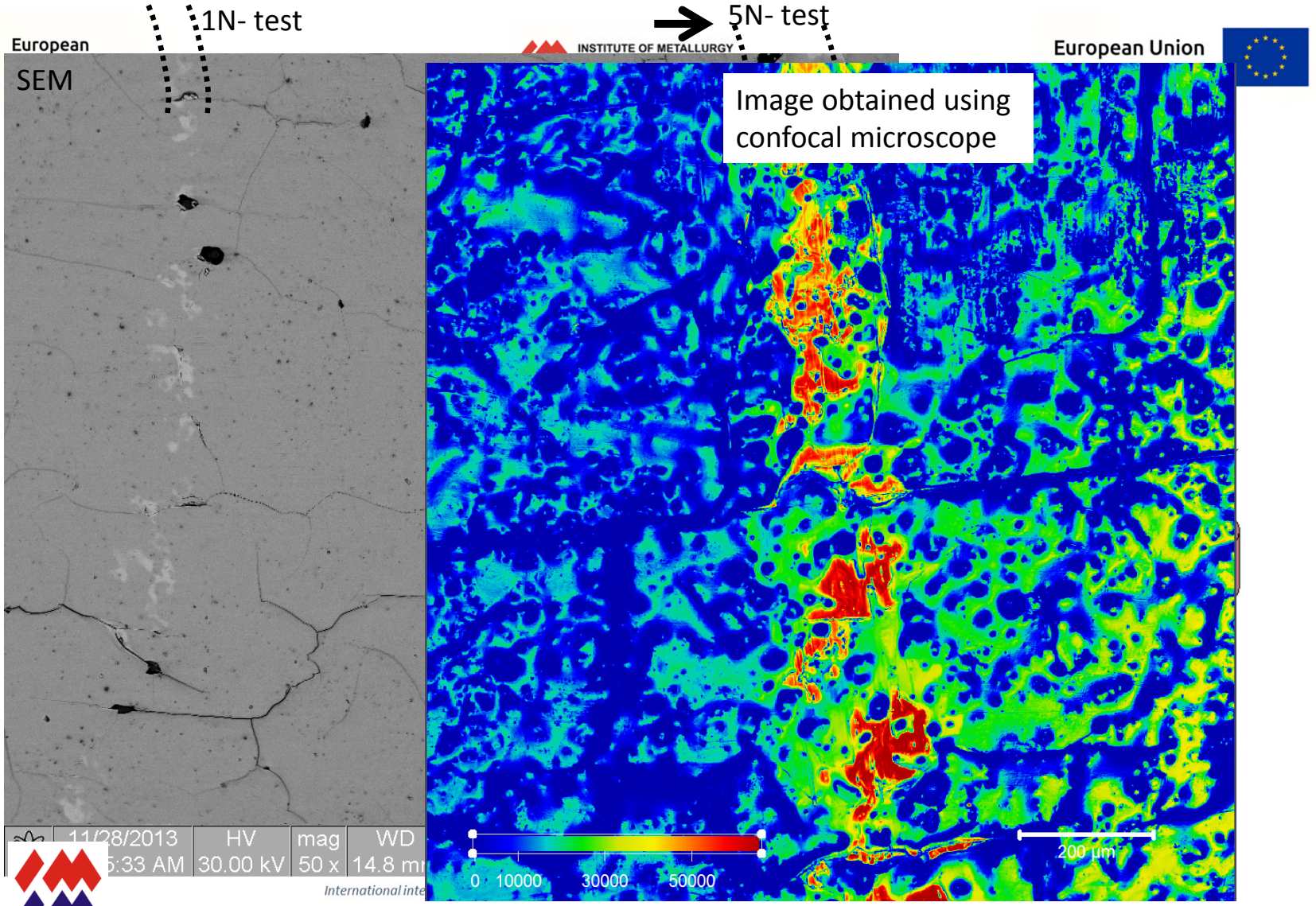
Parameter:
indenter – Al_2O_3 ball, d=1 i 6mm,

Low stress state	
Load	**F_N=1N**
Ball diameter	**R=3mm**
Cycles number	**n= 20.000**
Friction radious	**r=5mm,**
Linear speed	**v=0,06m/s**

High stress state	
Load	**F_N=5N**
Ball diameter	**R=3mm**
Cycles number	**n= 5.000**
Friction radious	**r=4mm,**
Linear speed	**v=0,05m/s**

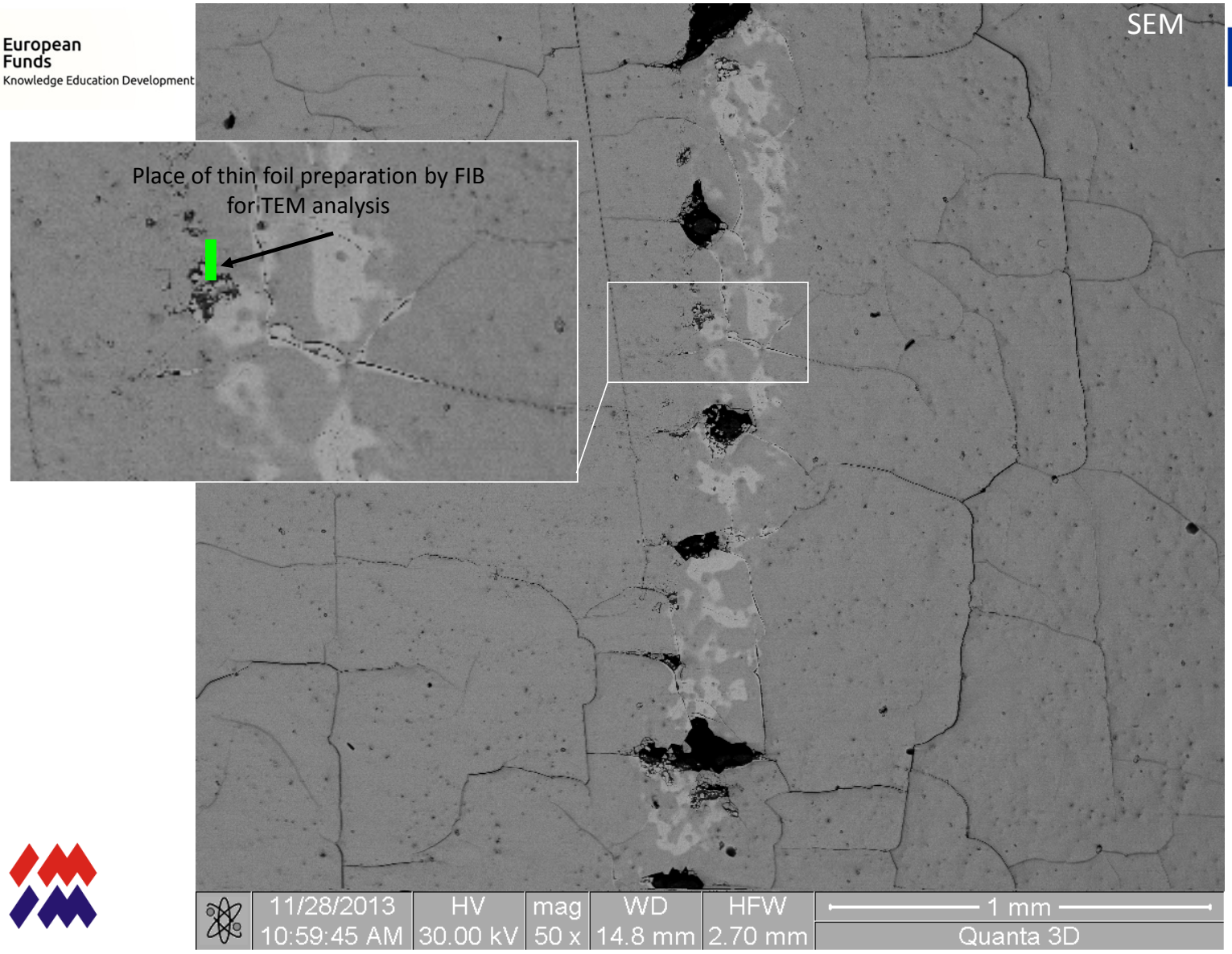
σ_H=0,45 GPa ***σ_H=0,8 GPa***

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds



Project co-financed by the European Union within the European Social Funds

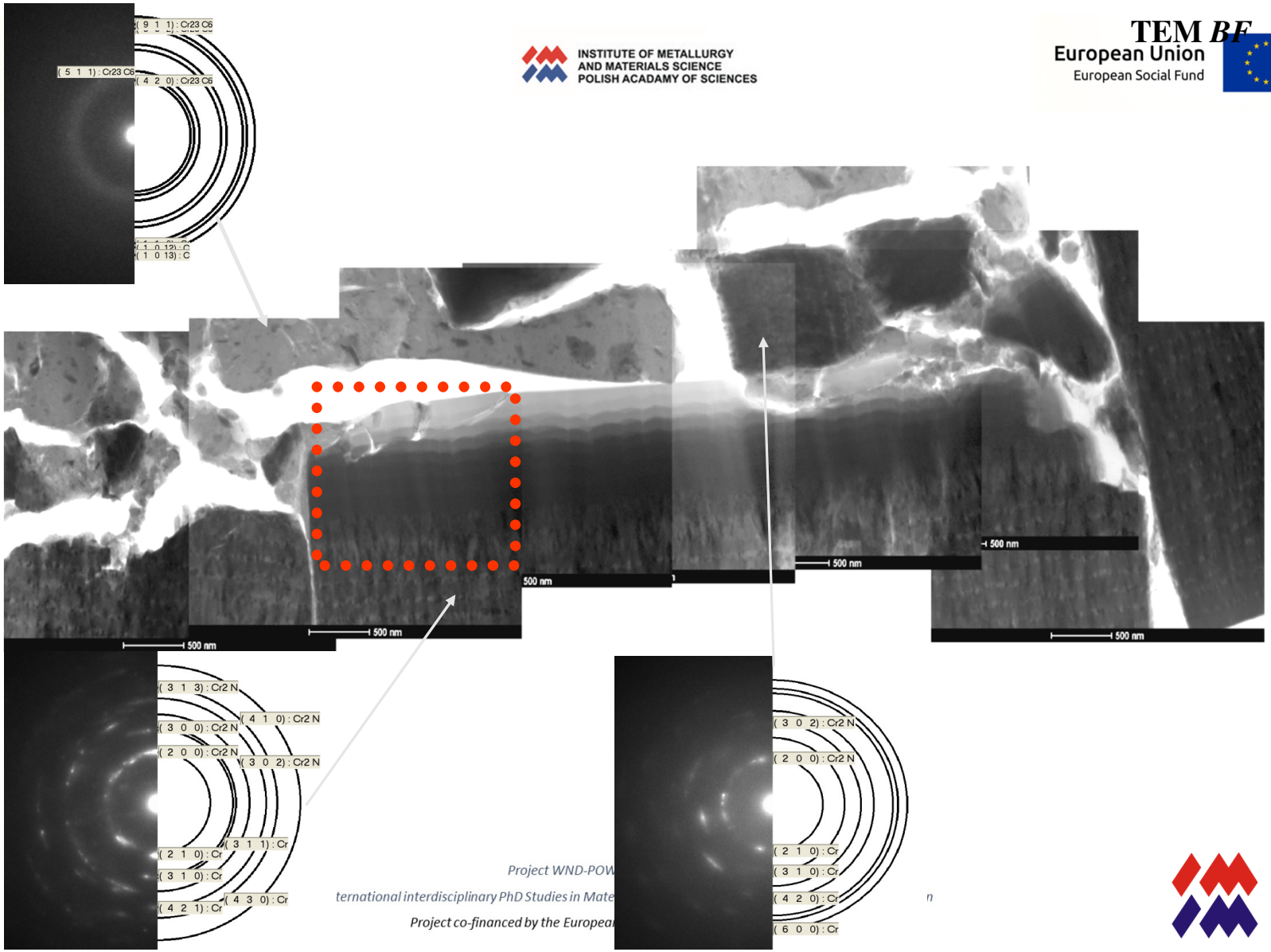
European Funds
Knowledge Education Development



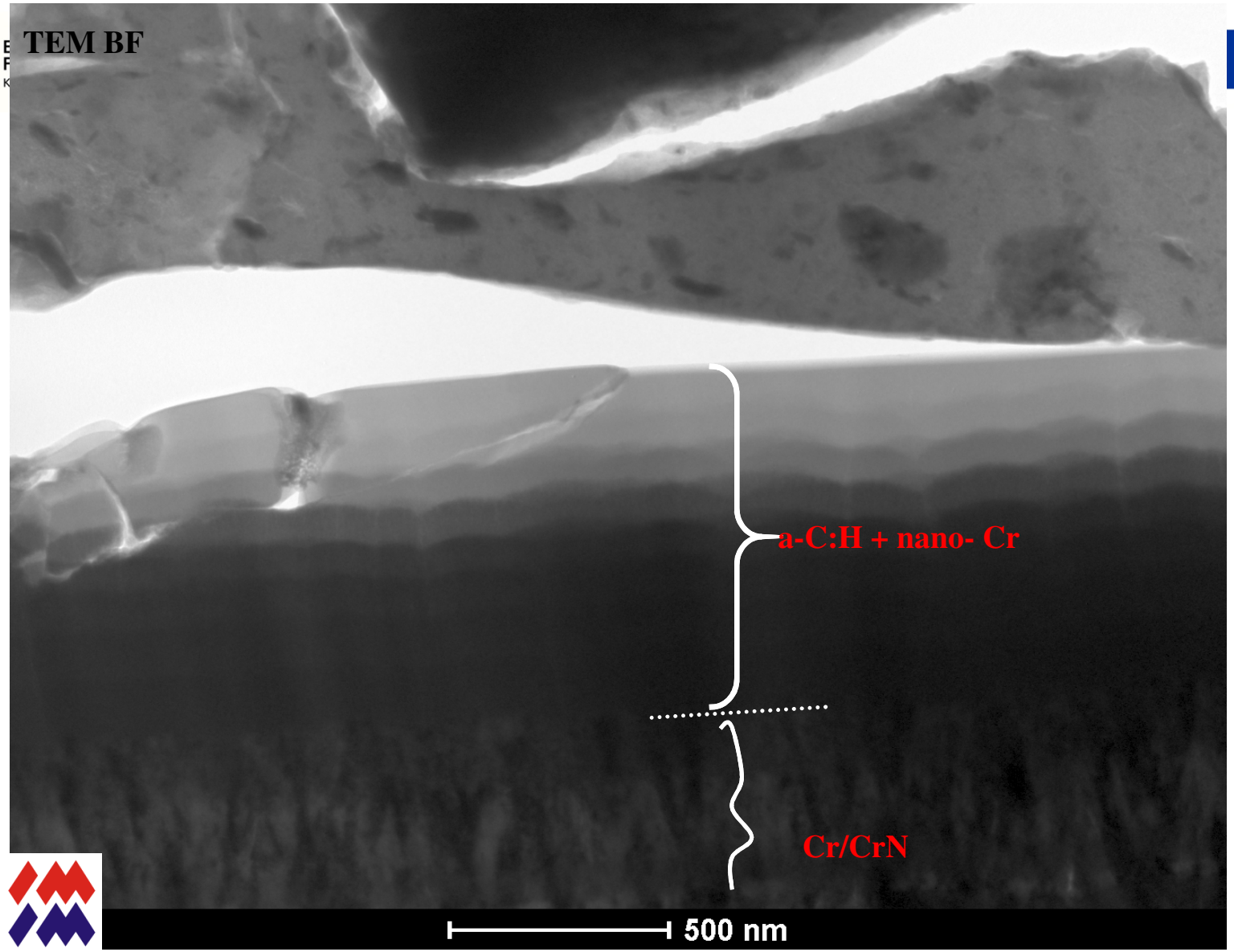
INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

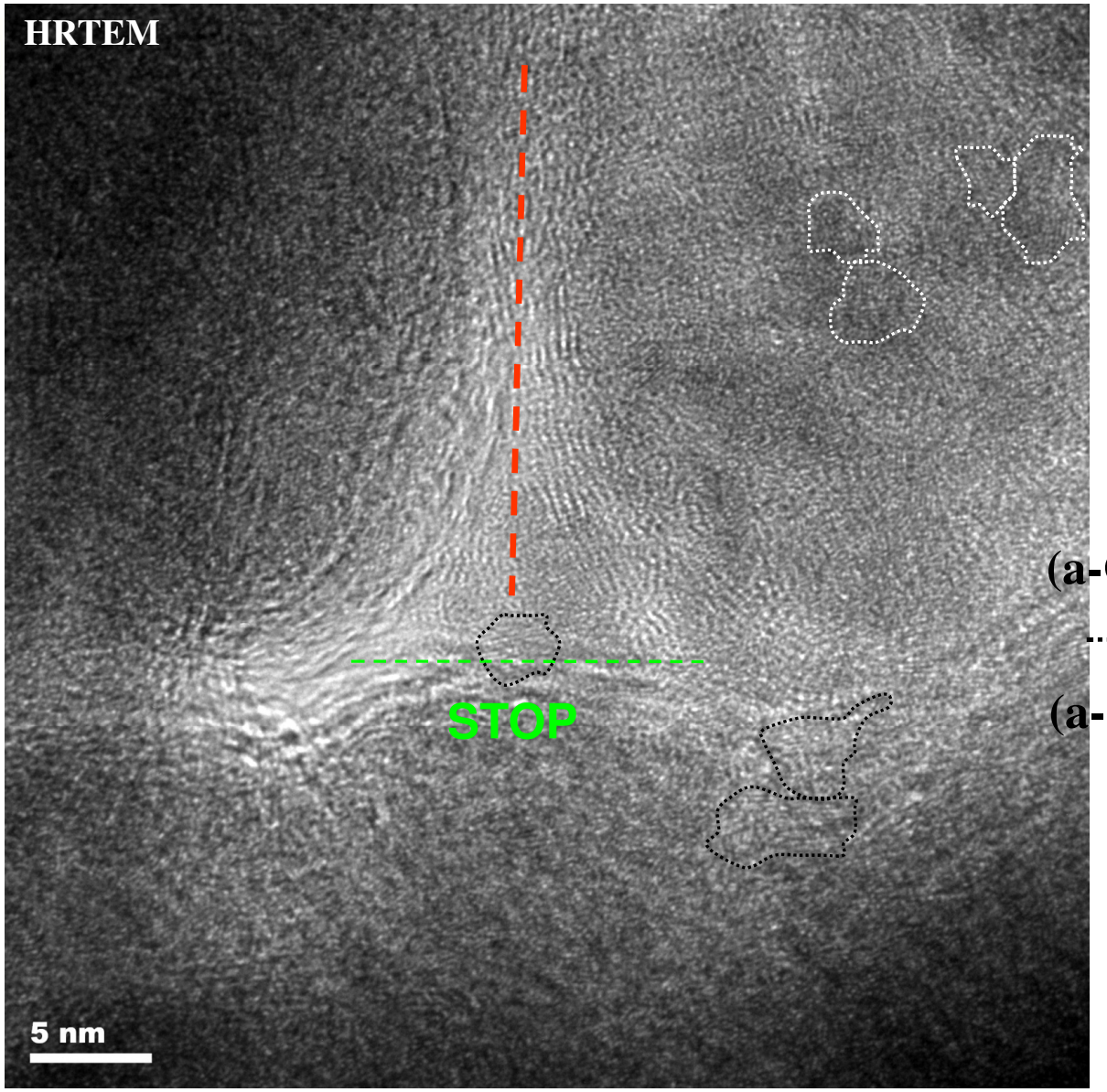
European Union
European Social Fund

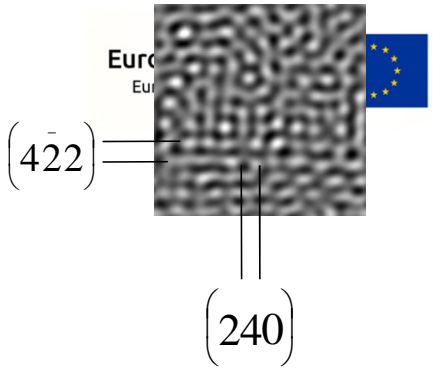
TEM *BF*



Project WND-POW
ternational interdisciplinary PhD Studies in Mate n
Project co-financed by the Europea


TEM BF
a-C:H + nano- Cr
Cr/CrN
500 nm





$Cr_{23}C_6$ *cubic-*
Zone axis $[\bar{2}15]$

$(a\text{-}C{:}H + \text{nano } Cr)_A$

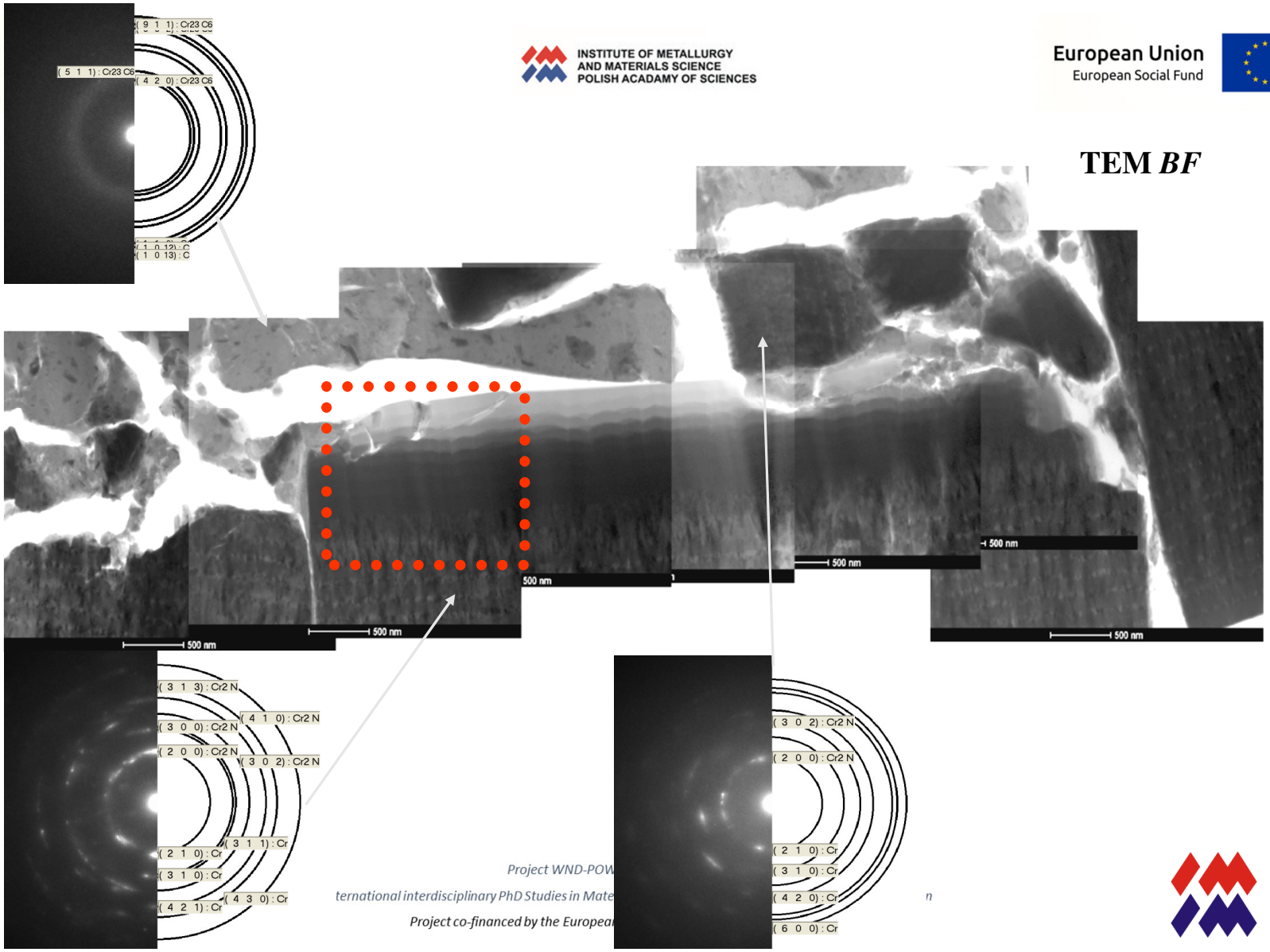
Interface

$(a\text{-}C{:}H + \text{nano } Cr)_B$

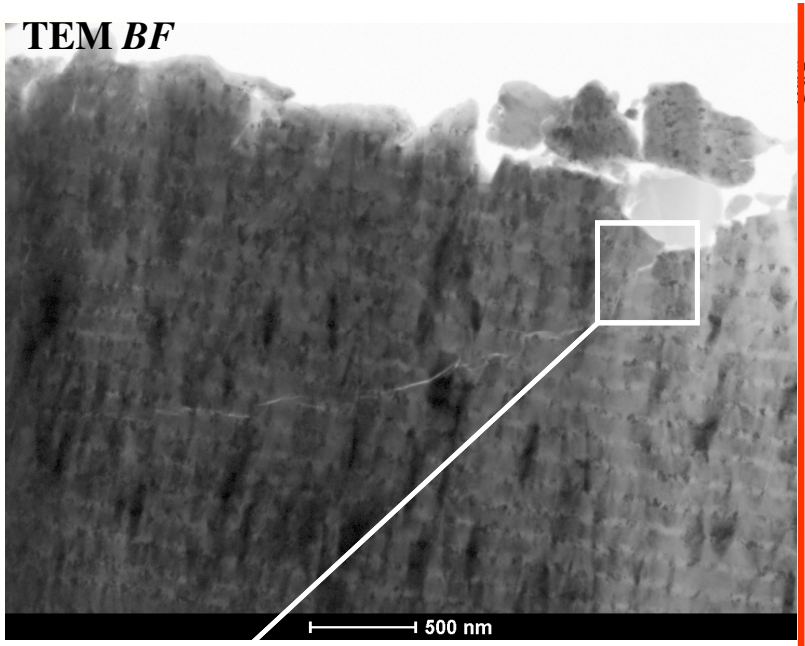
INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

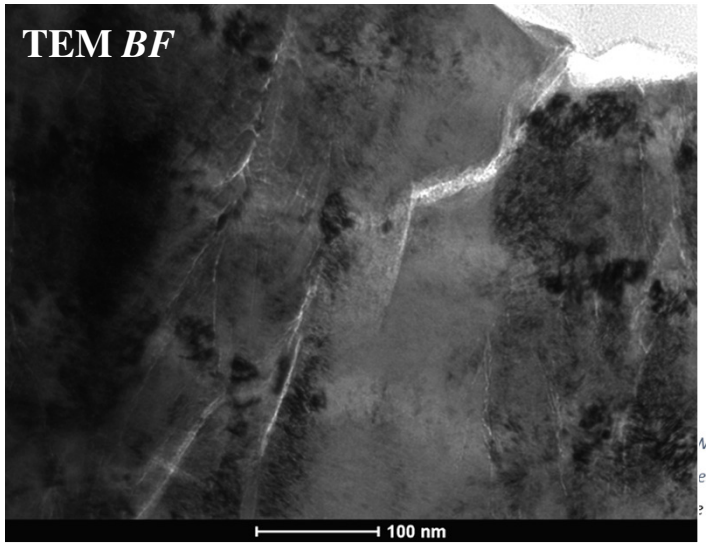
European Union
European Social Fund

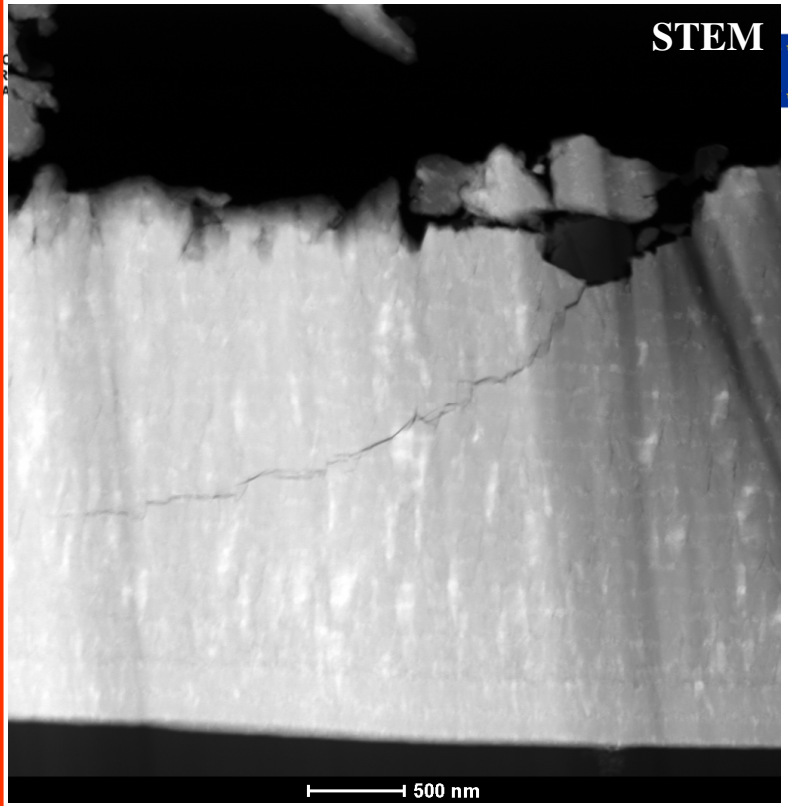
TEM *BF*



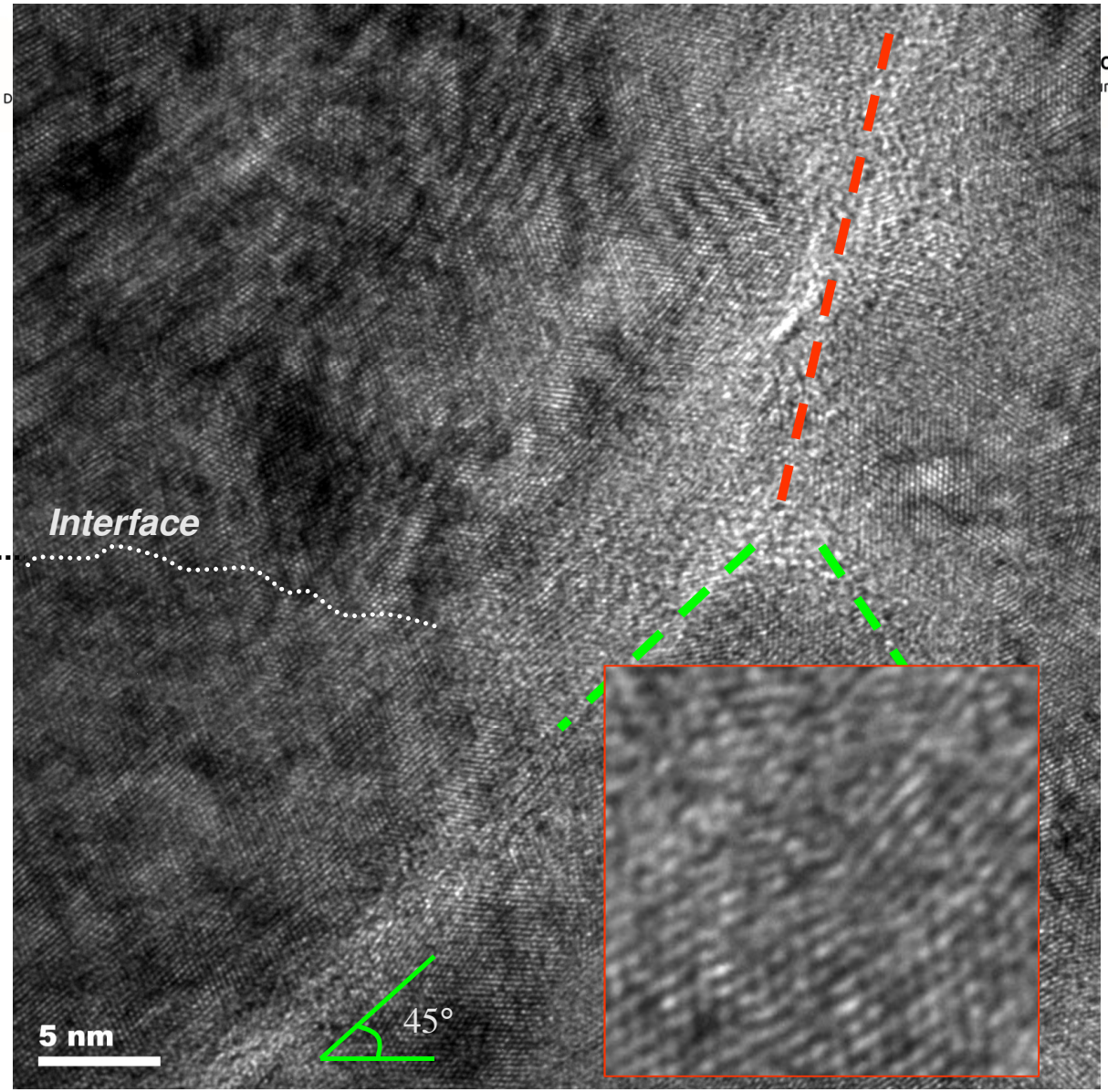
Project WND-POW
ternational interdisciplinary PhD Studies in Mate
Project co-financed by the Europea







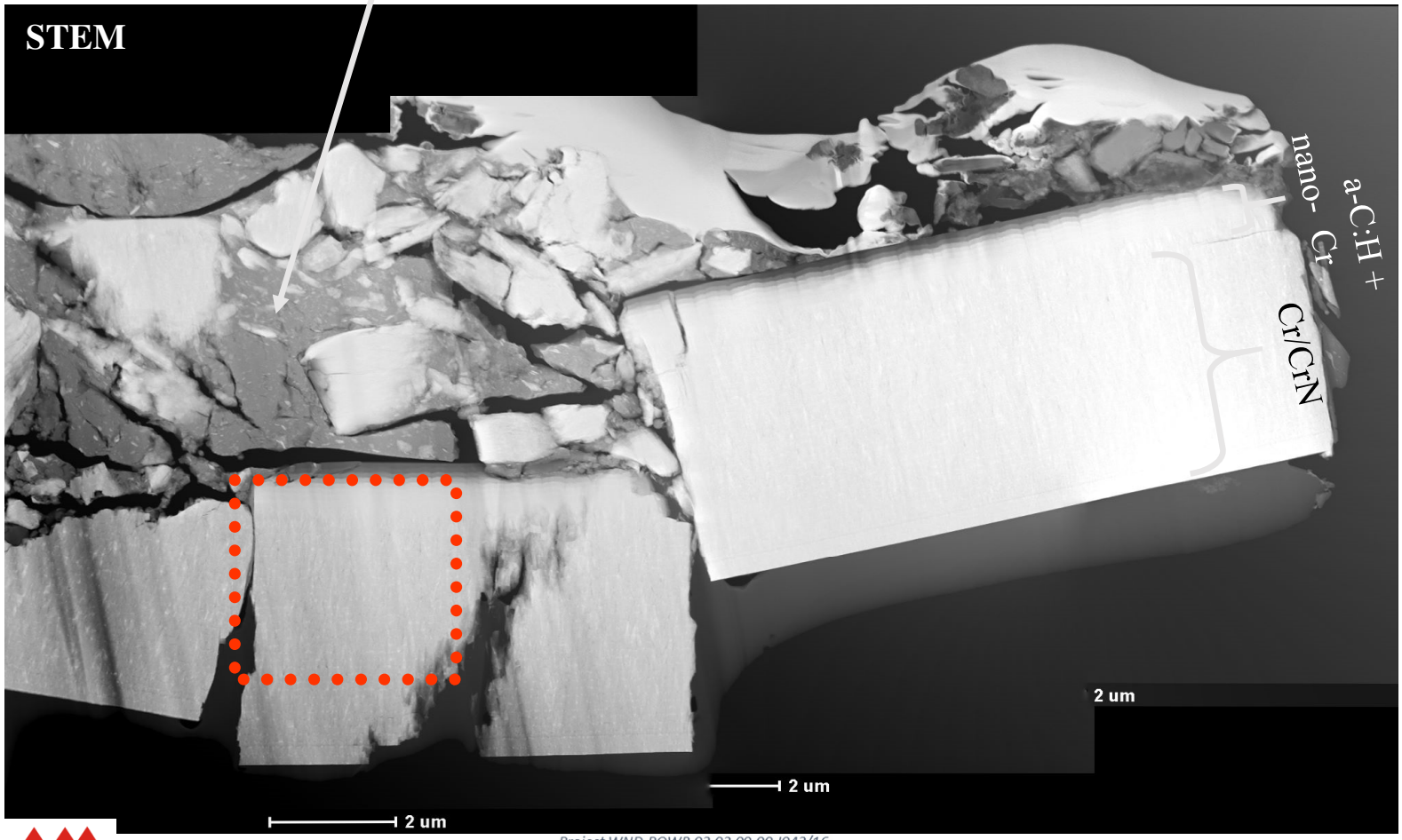
WND-POWR.03.02.00-00-I043/16
es in Material Science with English as the language of instruction
European Union within the European Social Funds


Cr_2N
Interface
Cr
5 nm
45°

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund



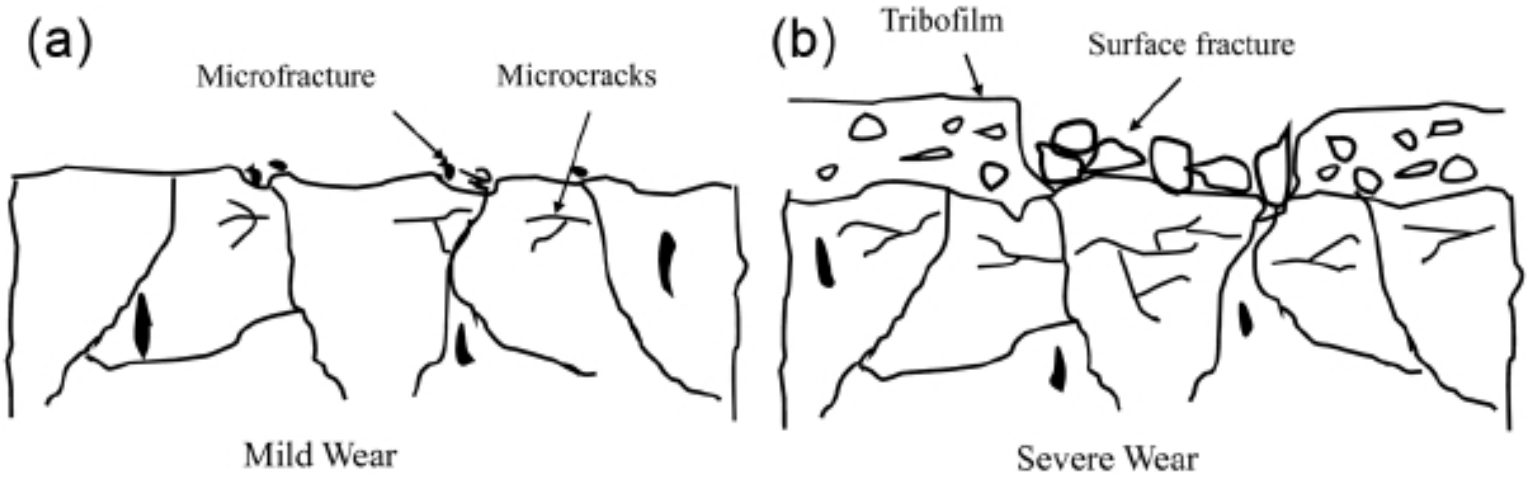
Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

Microstructural characterization of the coatings by TEM after the wear test

Soft Cr phase
+
Hard Cr_2N phase



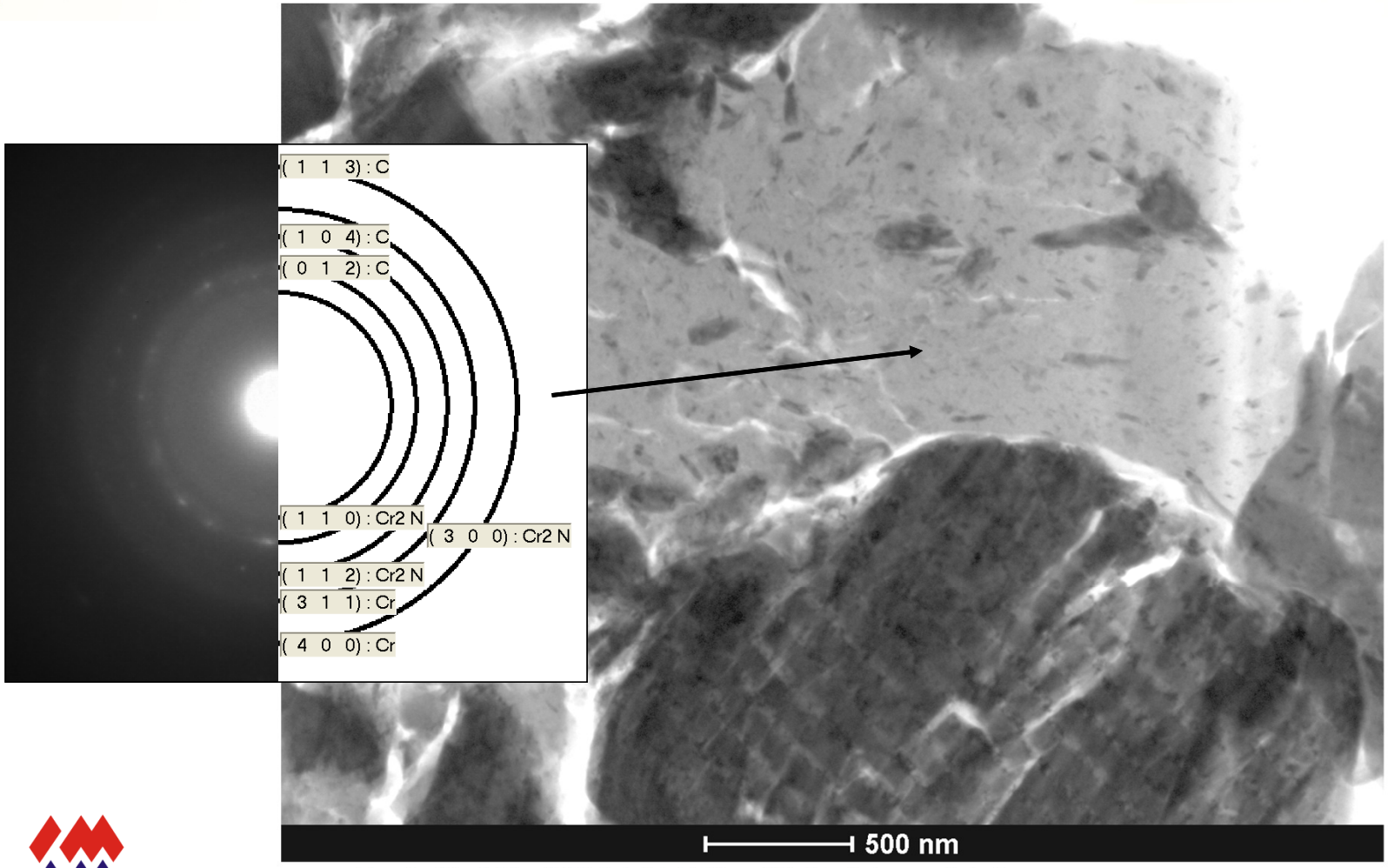
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

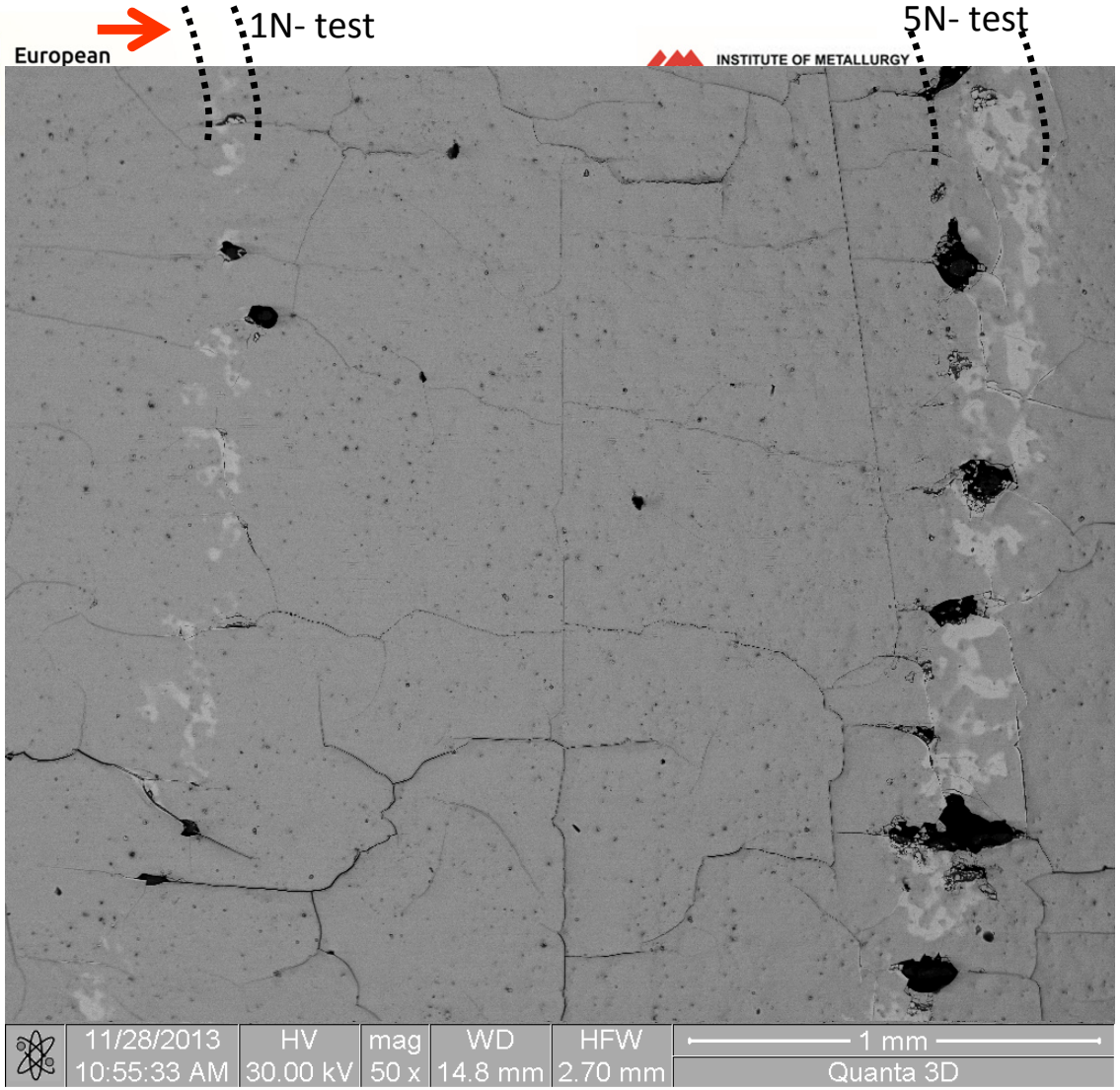
European Union
European Social Fund

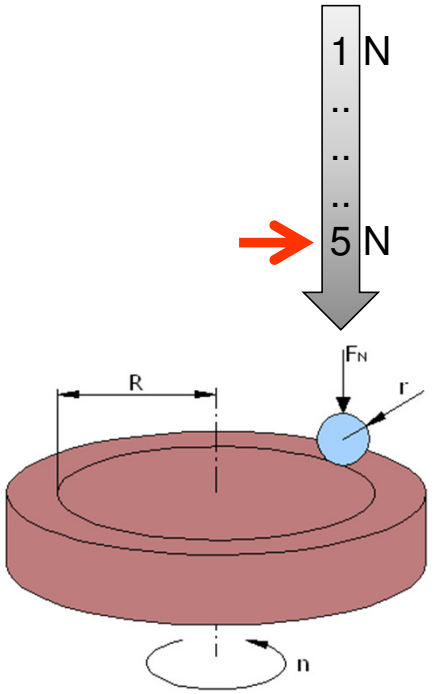
TEM *BF*

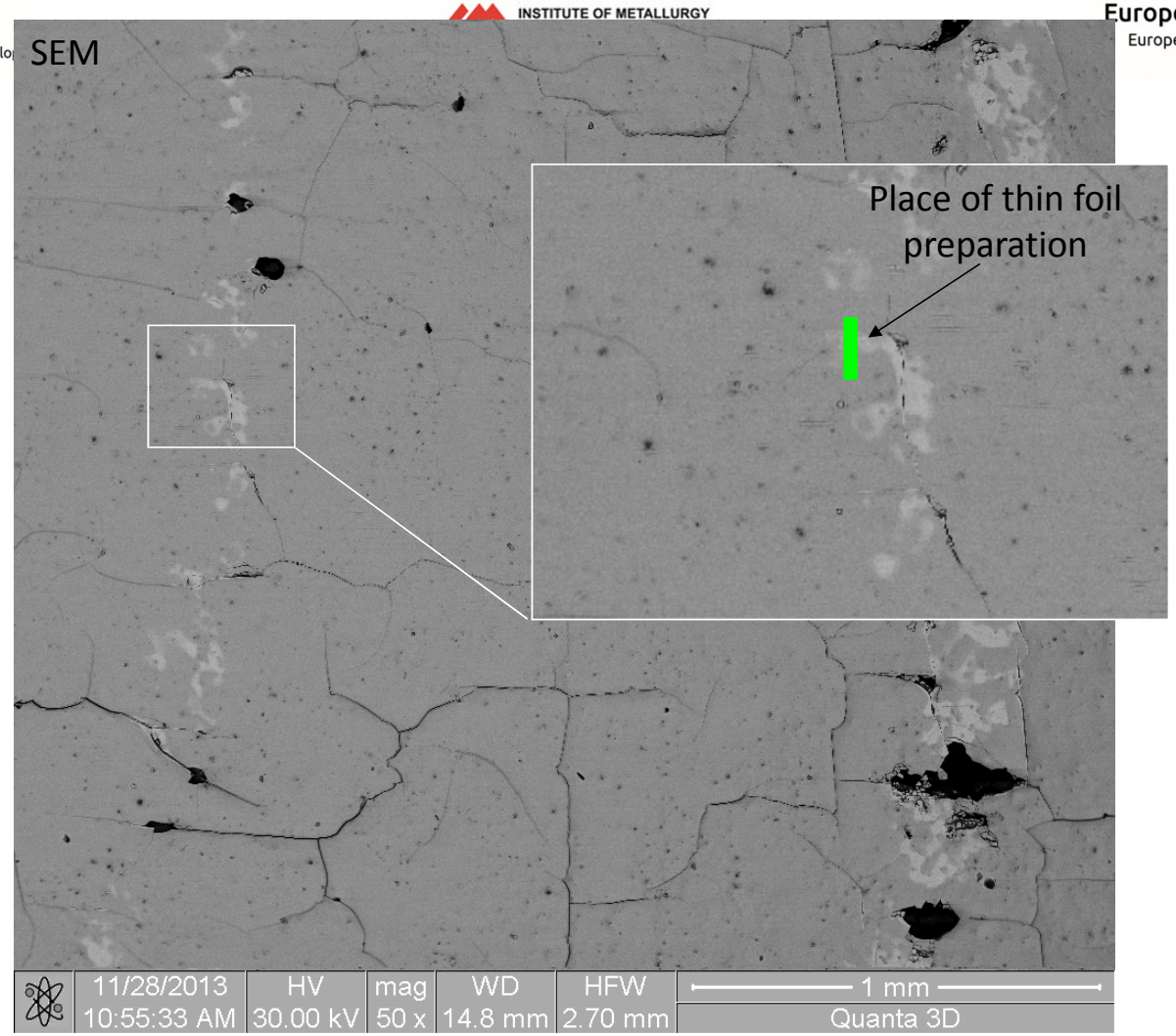


International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds


1N- test
5N- test
11/28/2013
10:55:33 AM
HV
30.00 kV
mag
50 x
WD
14.8 mm
HFW
2.70 mm
1 mm
Quanta 3D

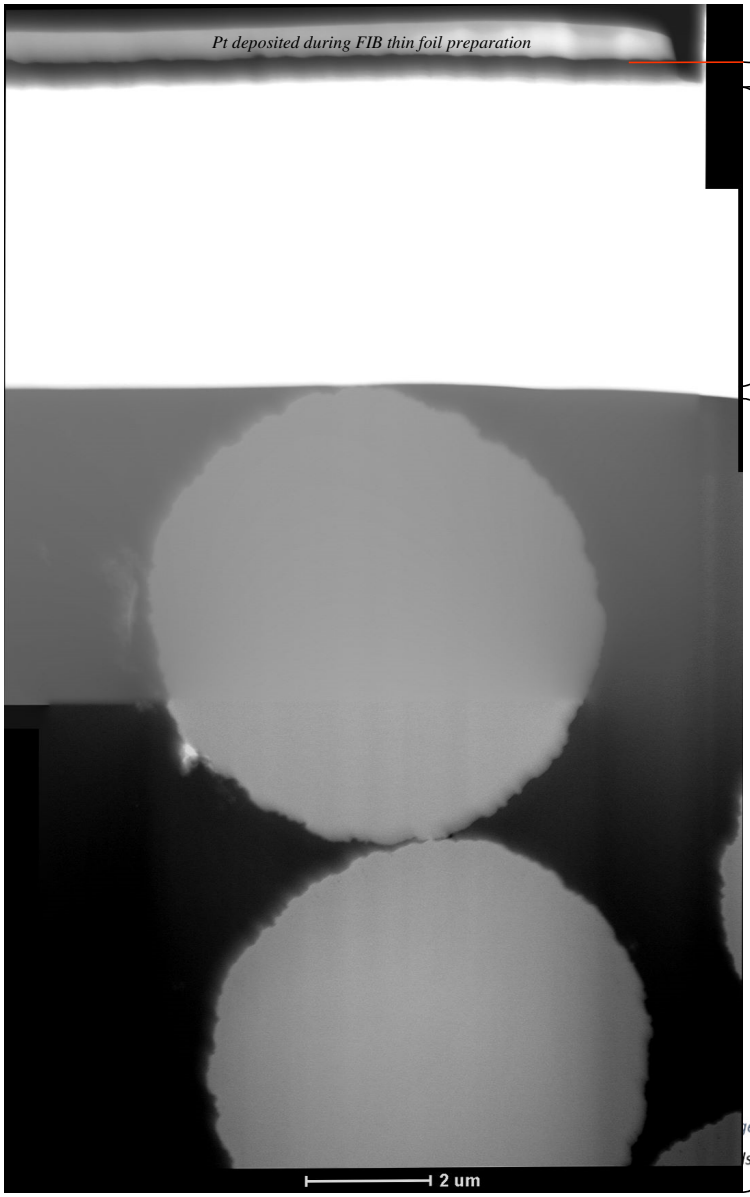

1 N
5 N
R
FN
r
n


SEM
Place of thin foil preparation
11/28/2013
10:55:33 AM
HV
30.00 kV
mag
50 x
WD
14.8 mm
HFW
2.70 mm
1 mm
Quanta 3D

European Funds
Knowledge Education Development

ean Union
ean Social Fund

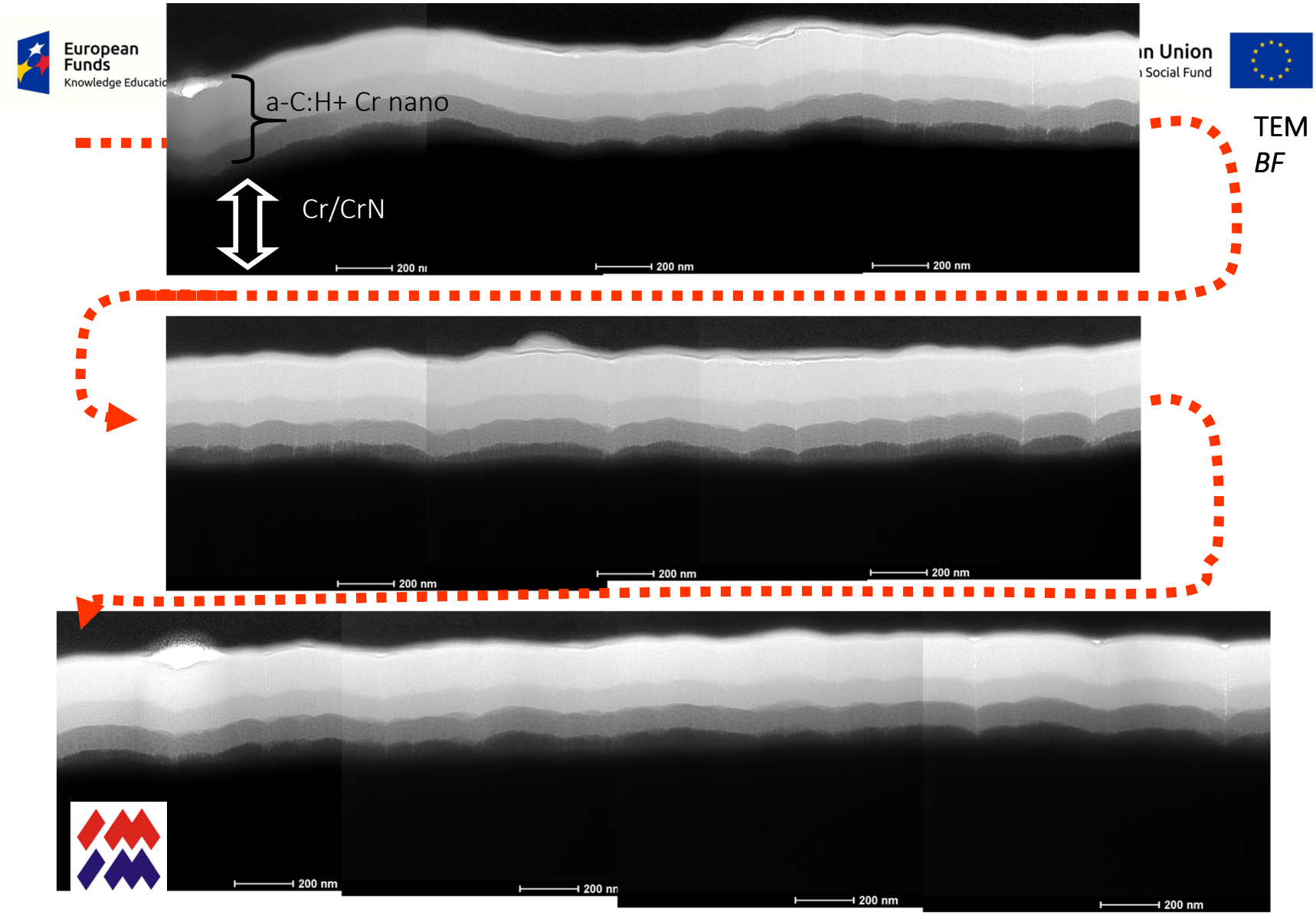
STEM



a-C:H + Cr nano

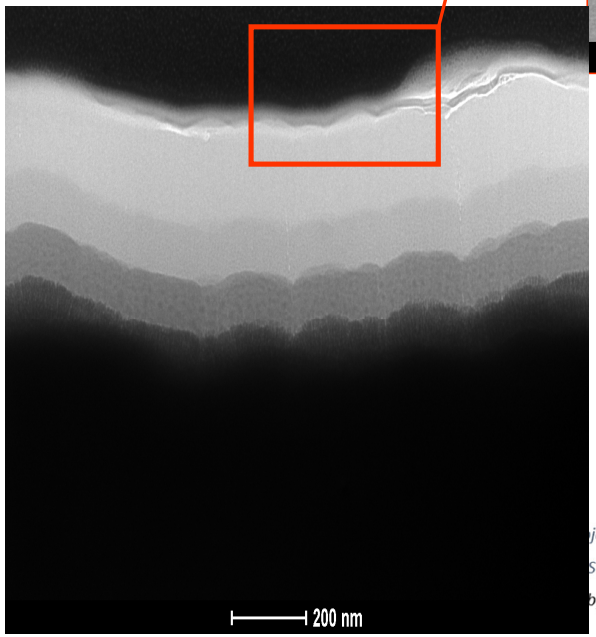
Cr/CrN

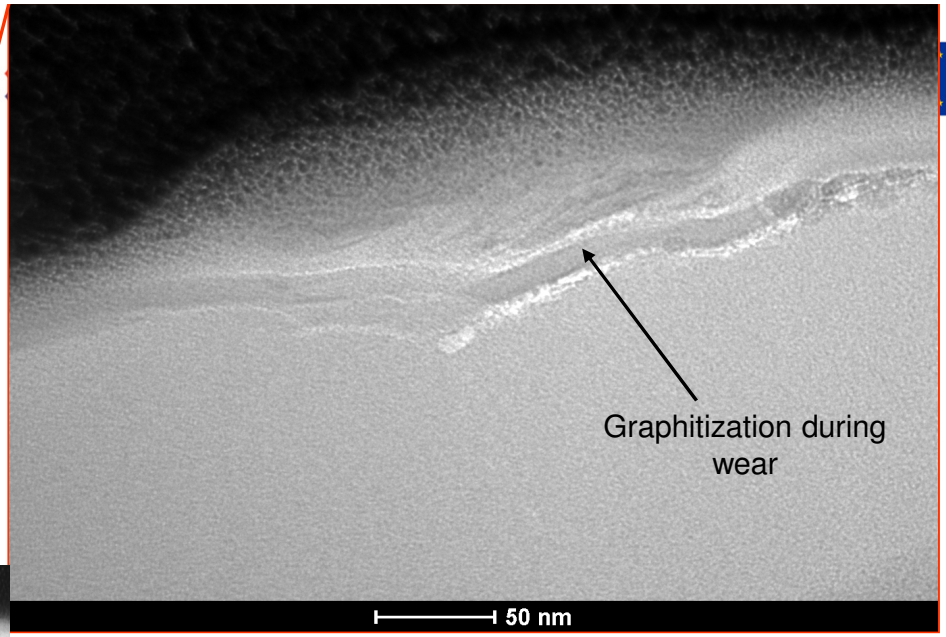
substrate CFC


European
Funds
Knowledge Educatio
n Union
Social Fund
a-C:H+ Cr nano
Cr/CrN
TEM
BF
200 nm
200 nm
200 nm
200 nm
200 nm
200 nm
200 nm
200 nm
200 nm
200 nm

European Funds
Knowledge Education Development

TEM
BF

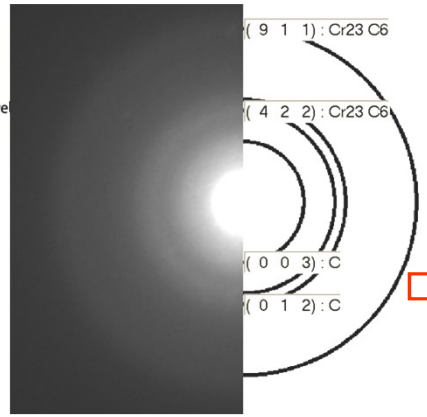


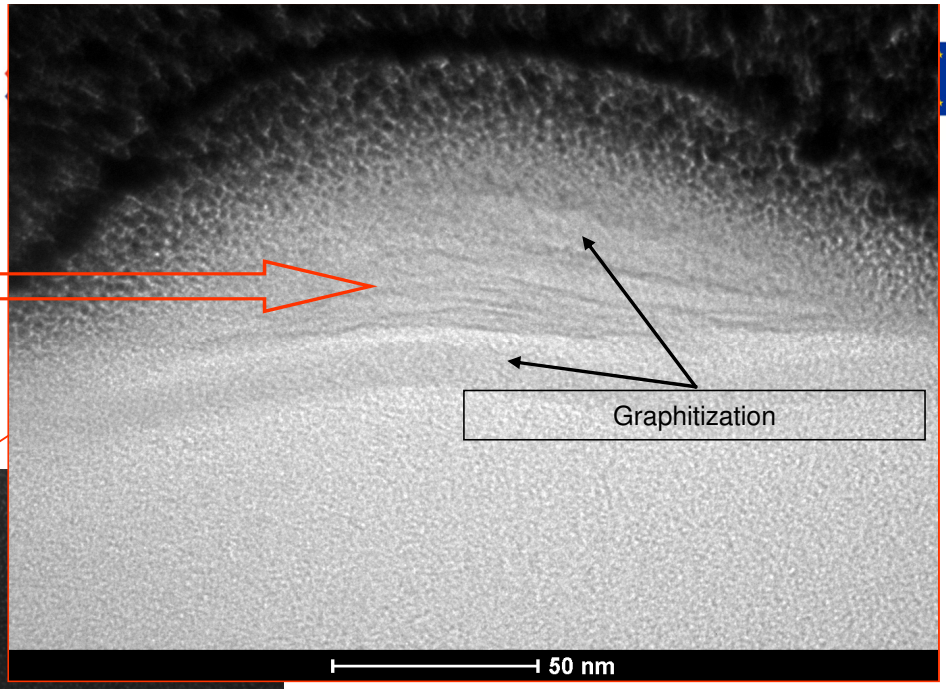


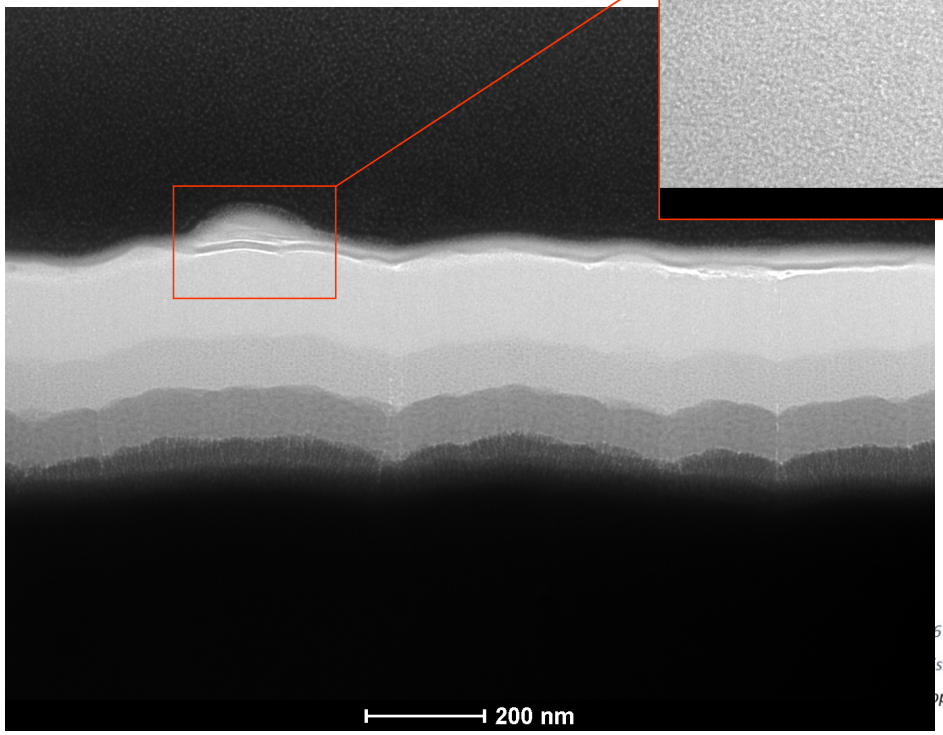
ject WND-POWR.03.02.00-00-I043/16
Studies in Materials Science with English as the language of instruction
by the European Union within the European Social Funds

European Funds
Knowledge Education Devel

TEM
BF +
SAED



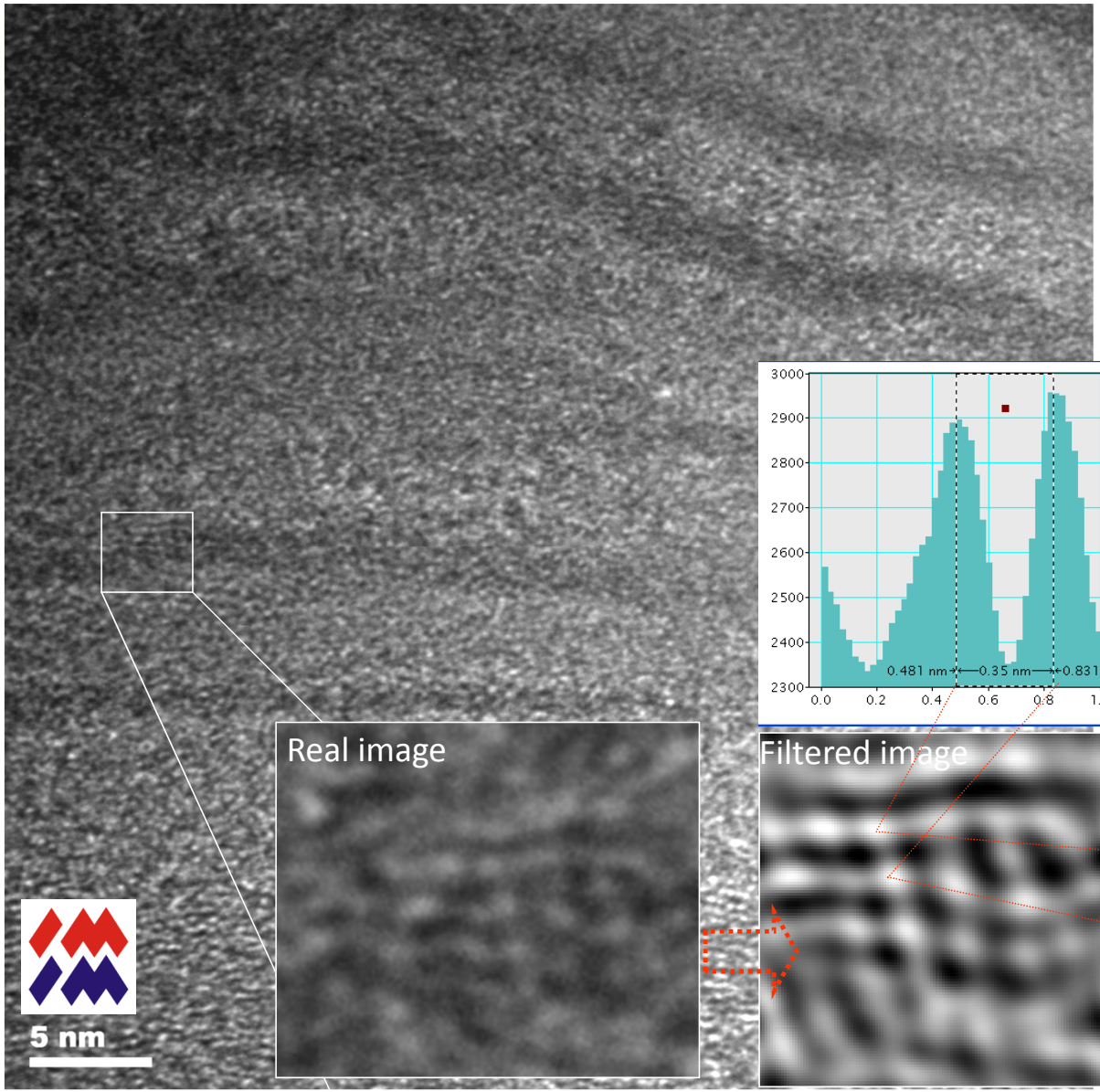




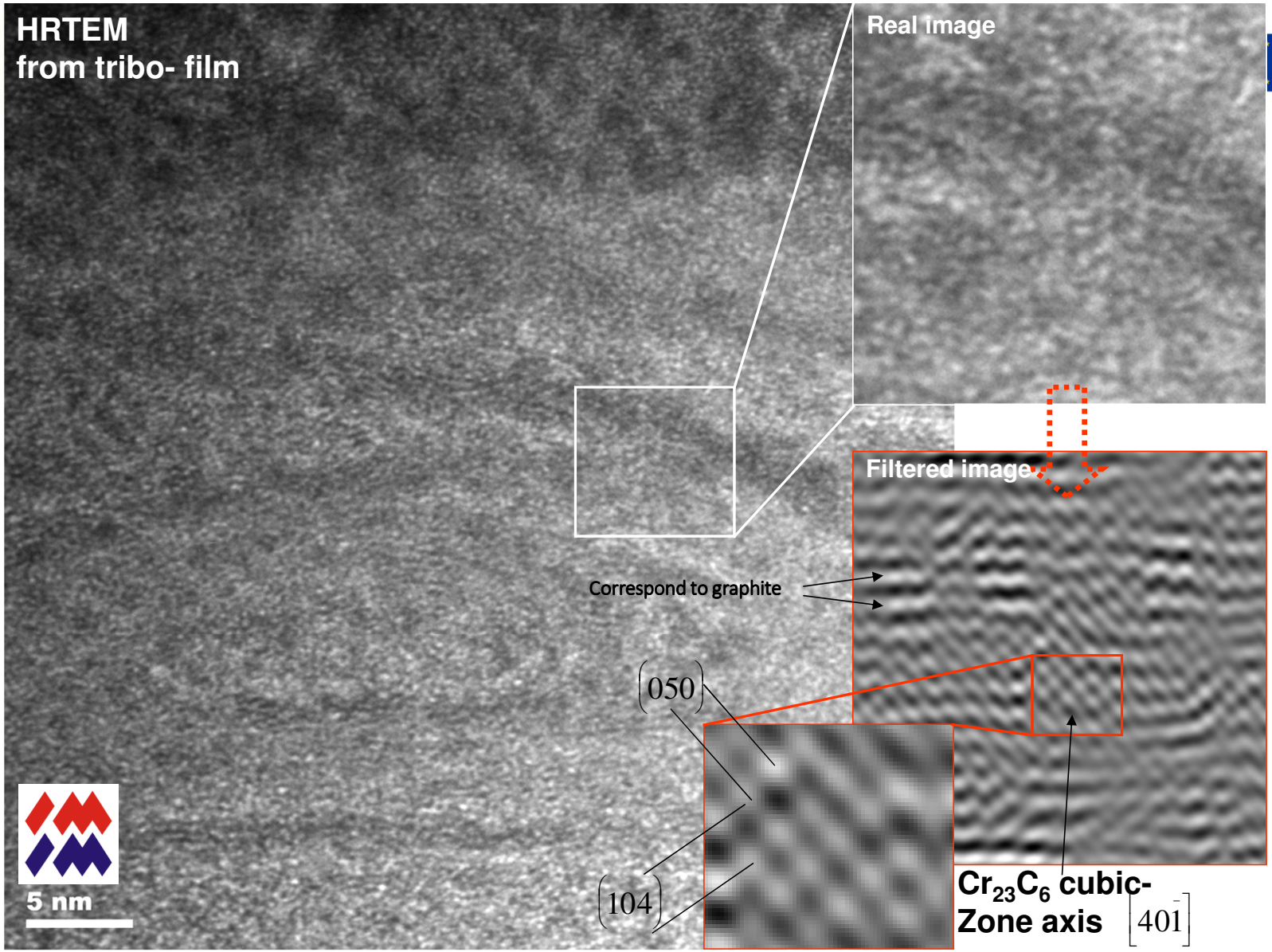
sh as the language of instruction
opean Social Funds

European Union
European Social Fund

HRTEM
graphite-
Tribo-film



Teoretical value


HRTEM
from tribo- film
Real Image
Filtered image
Correspond to graphite
(050)
(104)
5 nm
$Cr_{23}C_6$ cubic-
Zone axis [401]

- Project NCN nr: 3066/B/T02/2011/40- *FINISHED*
- Project NCN nr: 2012/06/M/ST8/00408- *HARMONIA- FINISHED*
- Project NCN nr: 2012/07/B/ST8/03396- *OPUS- FINISHED*
- Project NCN nr: 2014/15/B/ST8/00103- *OPUS- FINISHED*
- Project NCN nr: 2015/19/B/ST8/00942- *OPUS- in progress*
- Project NCBR, number: DZP/M-ERA.NET-2015/285/2016- *in progress*

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Title: Biomechanical and microstructure analysis of multilayer- nano-composite protective coatings on metallic substrates for tissue interaction

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

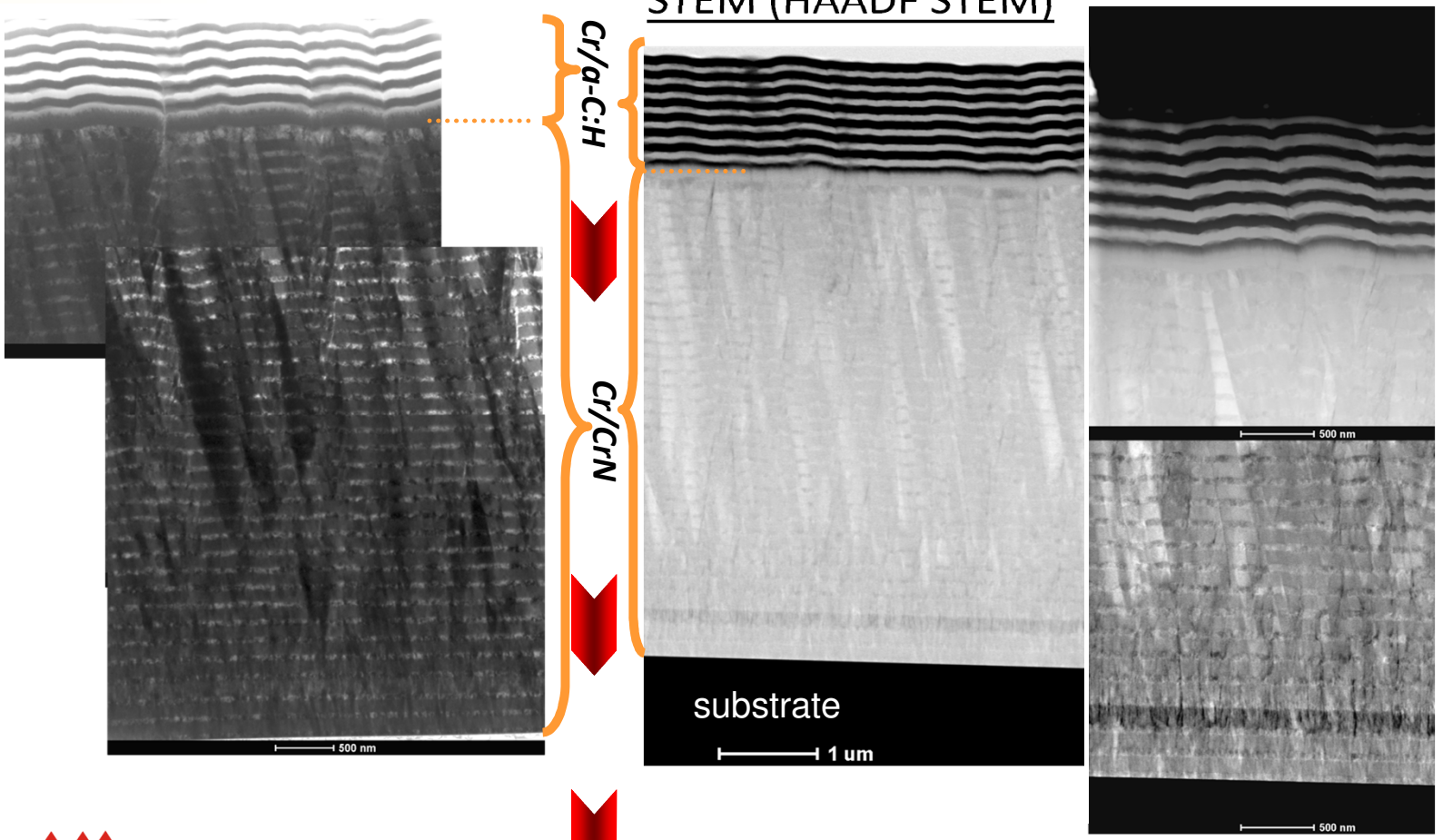
European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

TEM *BF*

STEM (HAADF STEM)



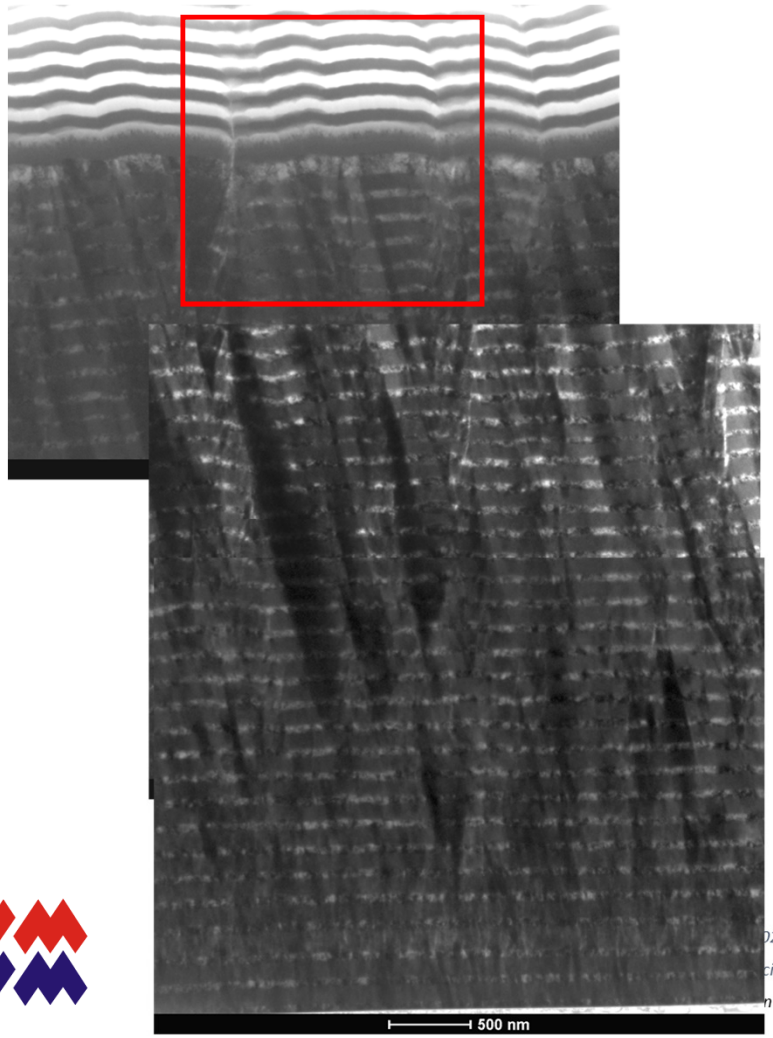
ct WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

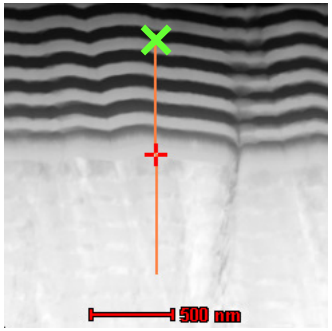
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

TEM *BF*



STEM (HAADF STEM)



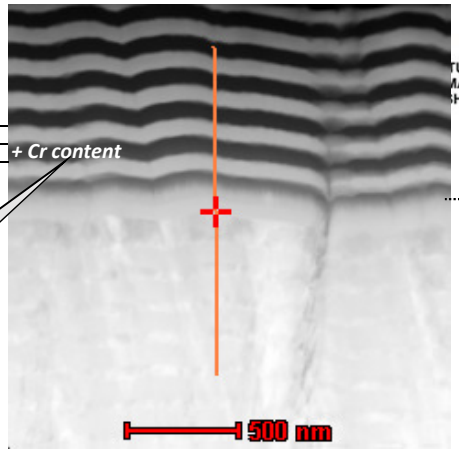
02.00-00-1043/16
cience with English as the language of instruction
n within the European Social Funds

European Funds
Knowledge Education Development

European Union
European Social Fund

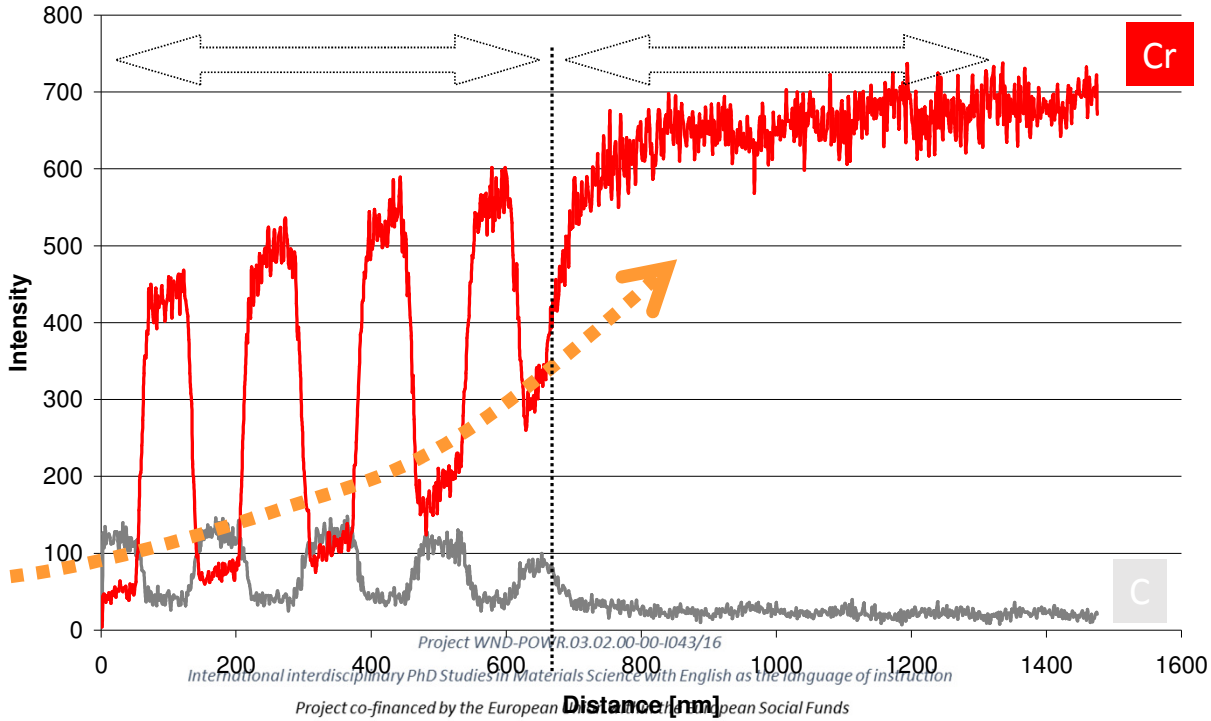
Cr
a-C:H + Cr content

Question:
How Cr
is distributed
in a-C:H areas ?

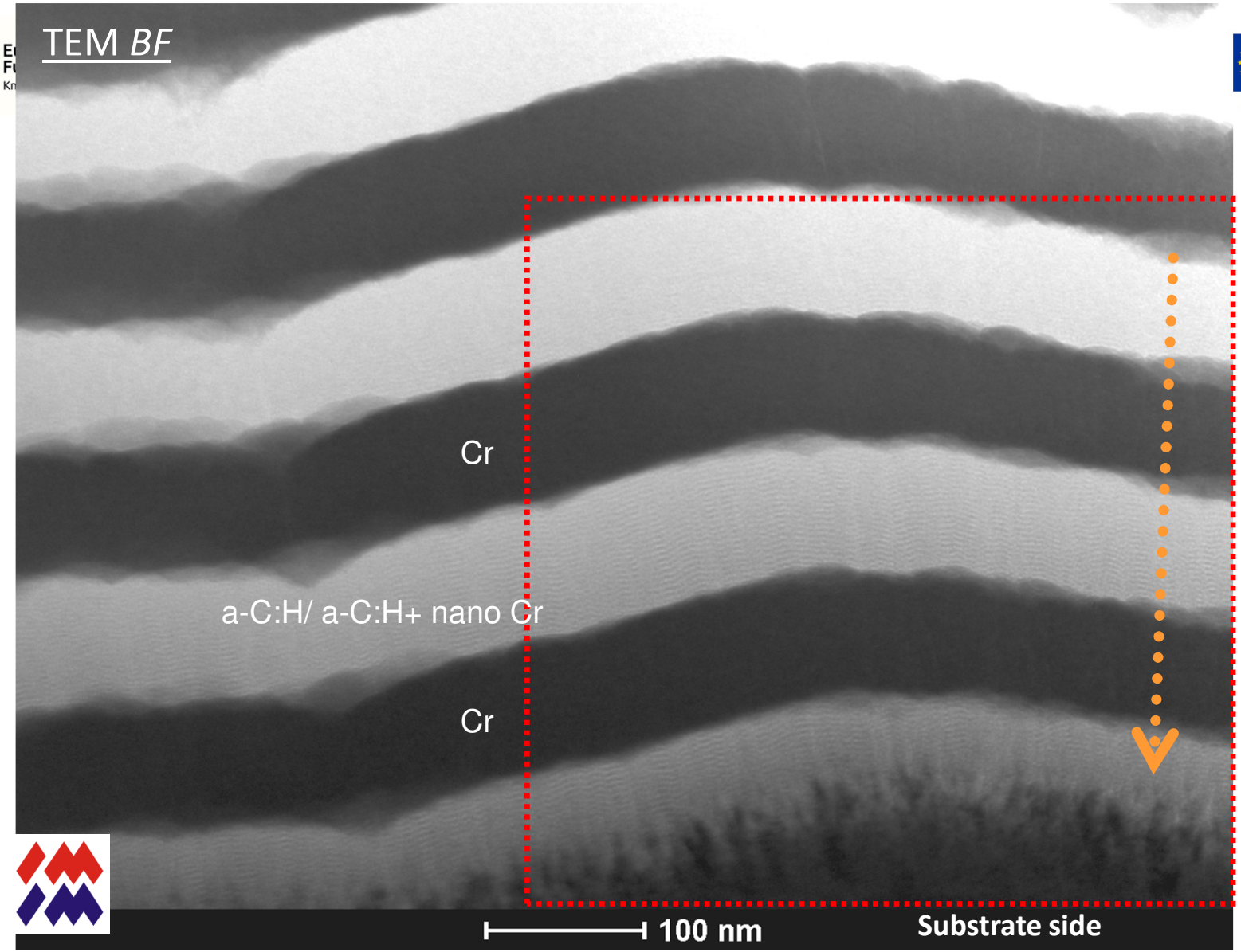


Cr/ a-C:H

Cr/ CrN



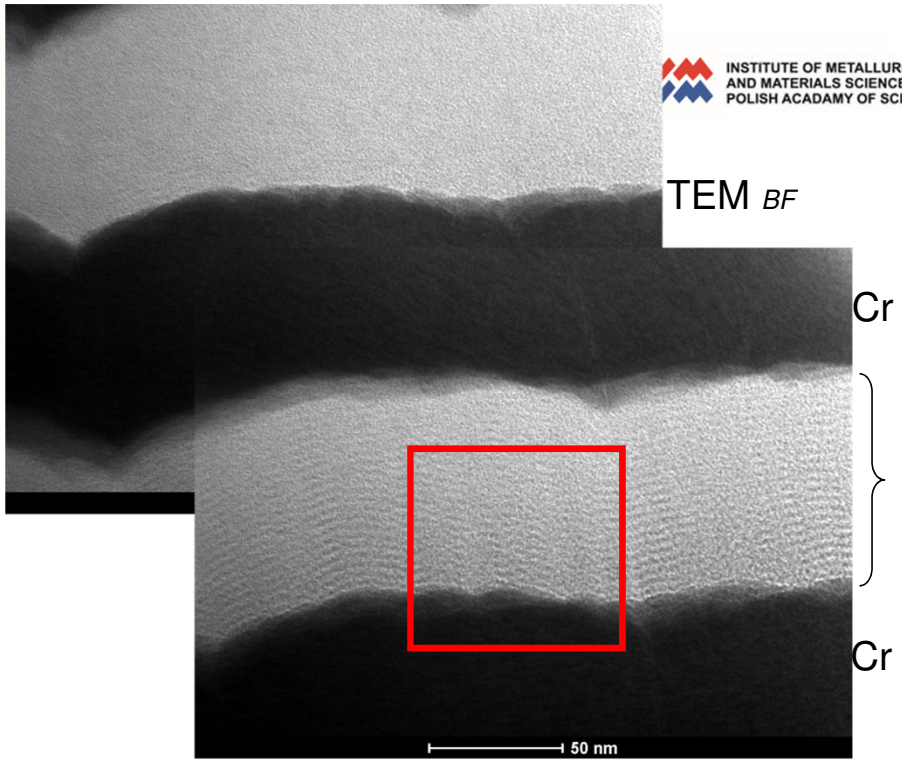
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union from the European Social Funds


TEM *BF*
Cr
a-C:H/ a-C:H+ nano Cr
Cr
100 nm
Substrate side

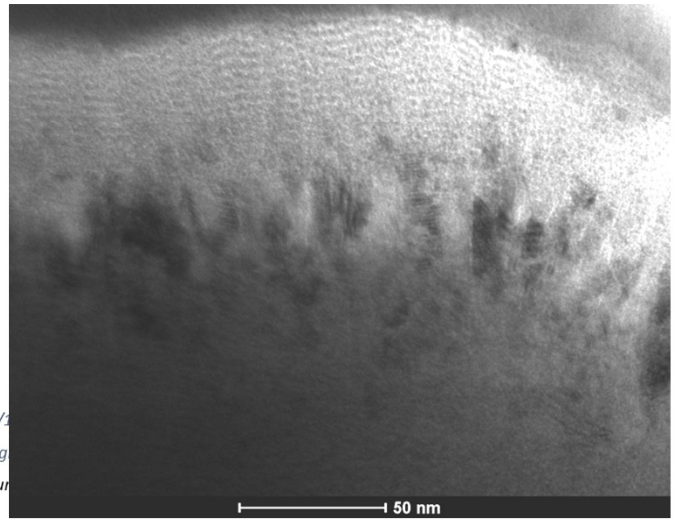
INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

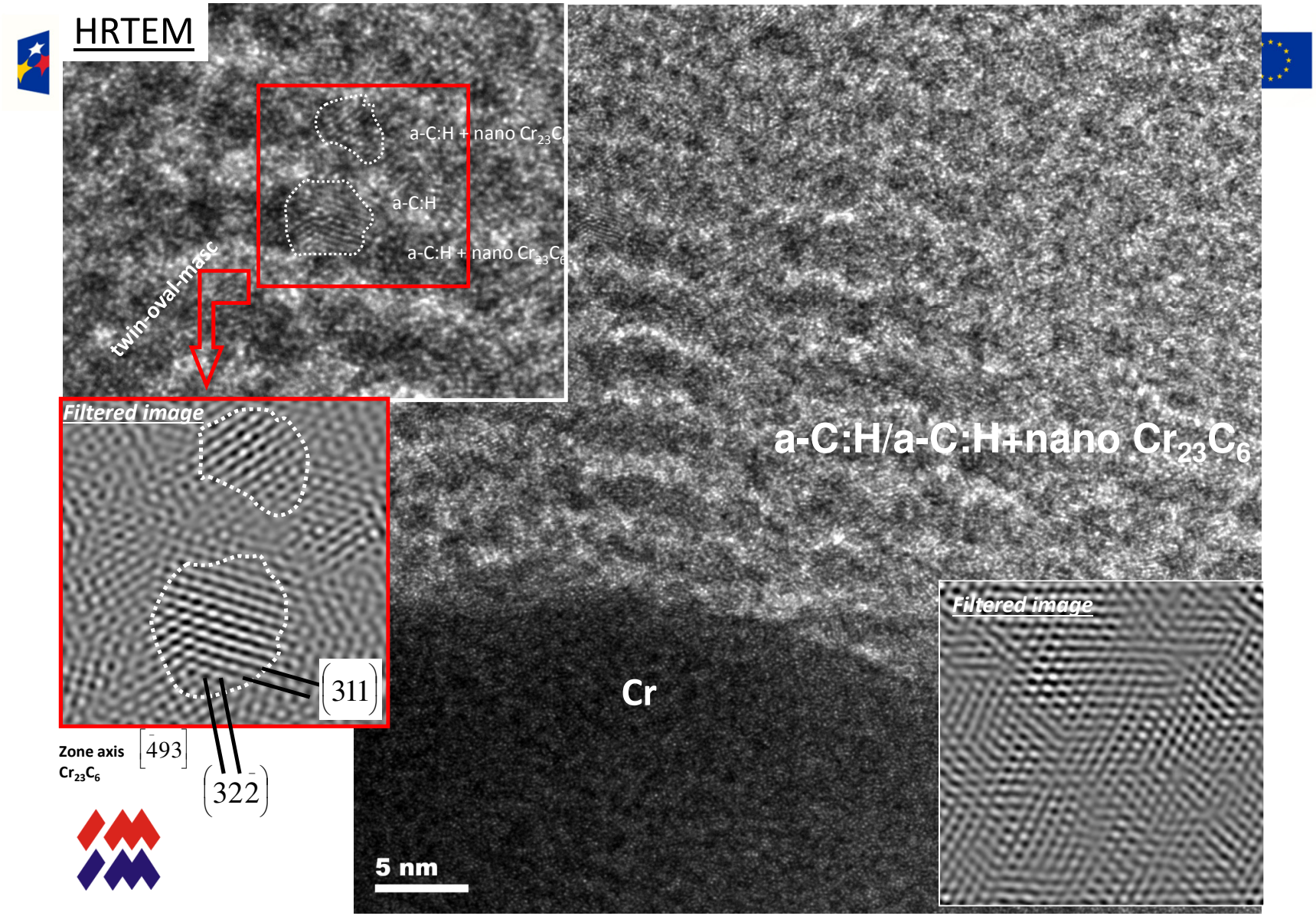
TEM *BF*

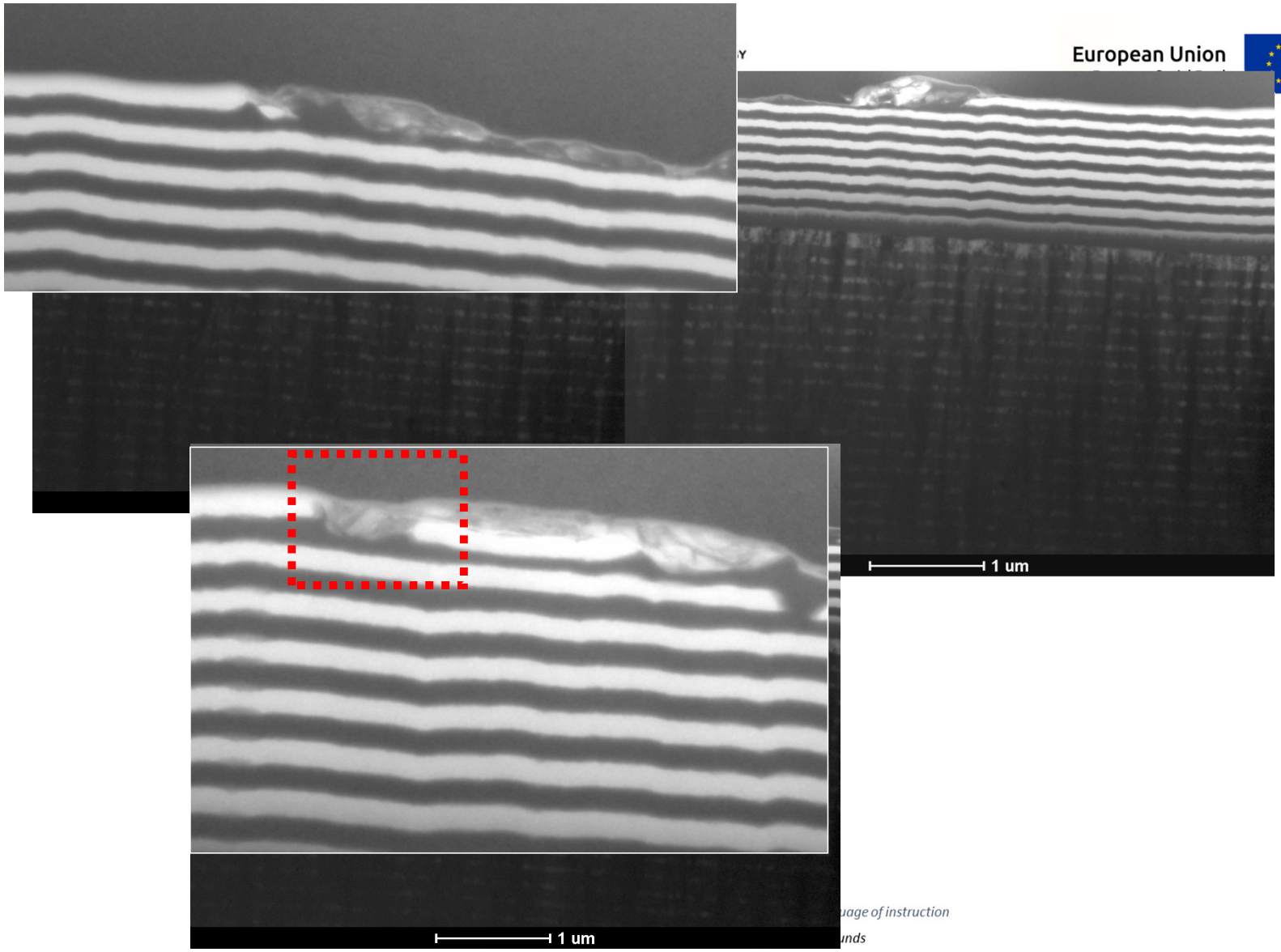


a-C:H/a-C:H+nano Cr



Project WND-POWR.03.02.00-00-I043/1
International interdisciplinary PhD Studies in Materials Science with Eng
Project co-financed by the European Union within the Eu

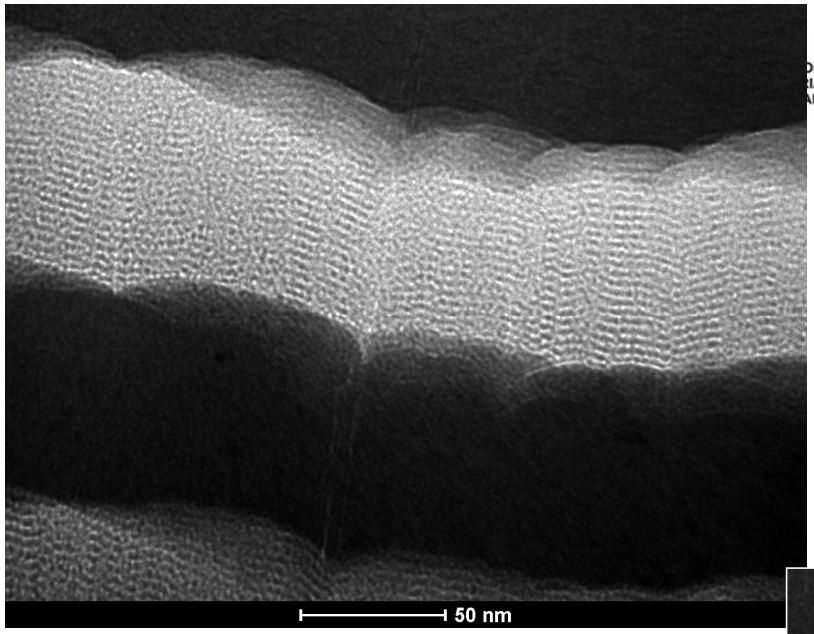

HRTEM
a-C:H + nano $Cr_{23}C_6$
a-C:H
a-C:H + nano $Cr_{23}C_6$
twin-oval-mask
Filtered image
(311)
Zone axis $[\bar{4}93]$
$(\bar{3}22)$
a-C:H/a-C:H+nano $Cr_{23}C_6$
Cr
5 nm
Filtered image



European Union

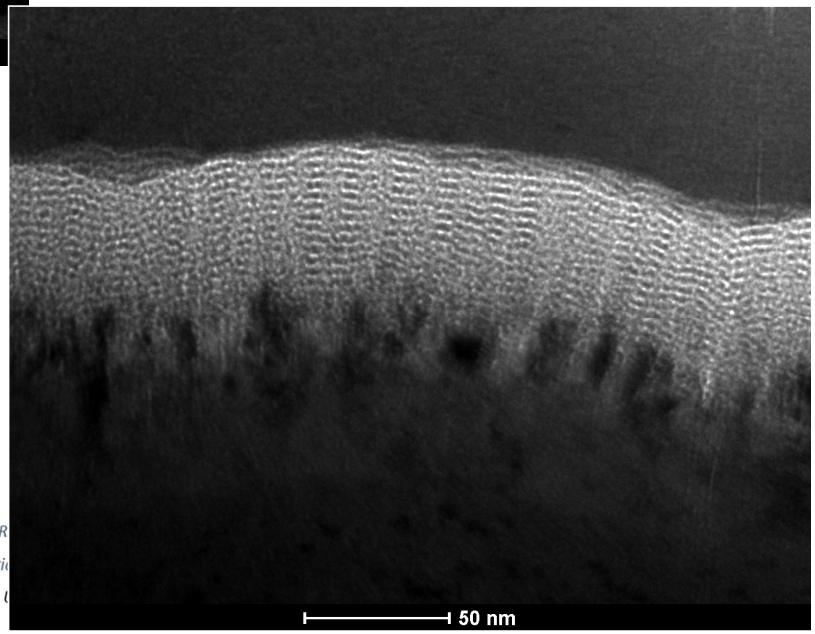
uage of instruction

unds



OF METALLURGY
IALS SCIENCE
ADAMY OF SCIENCES

European Union
European Social Fund



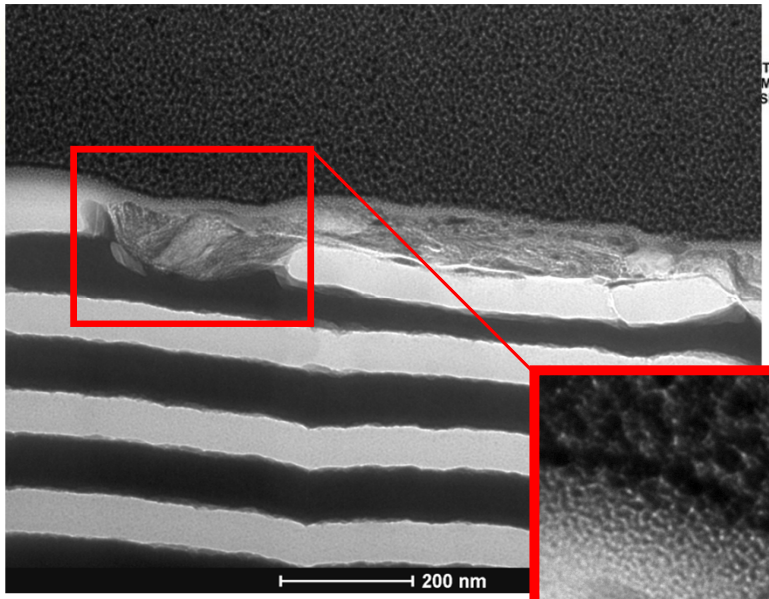
Project WND-POWR

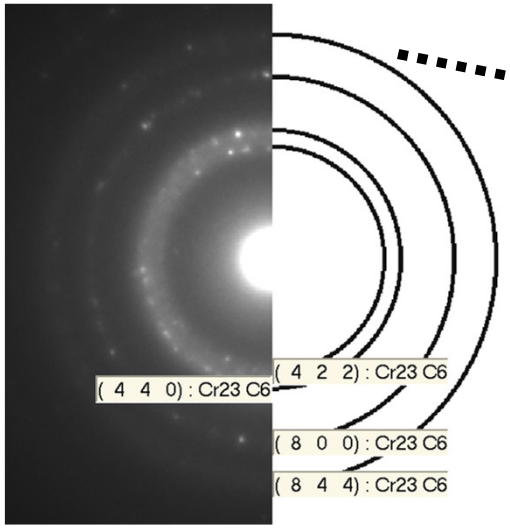
International interdisciplinary PhD Studies in Materi

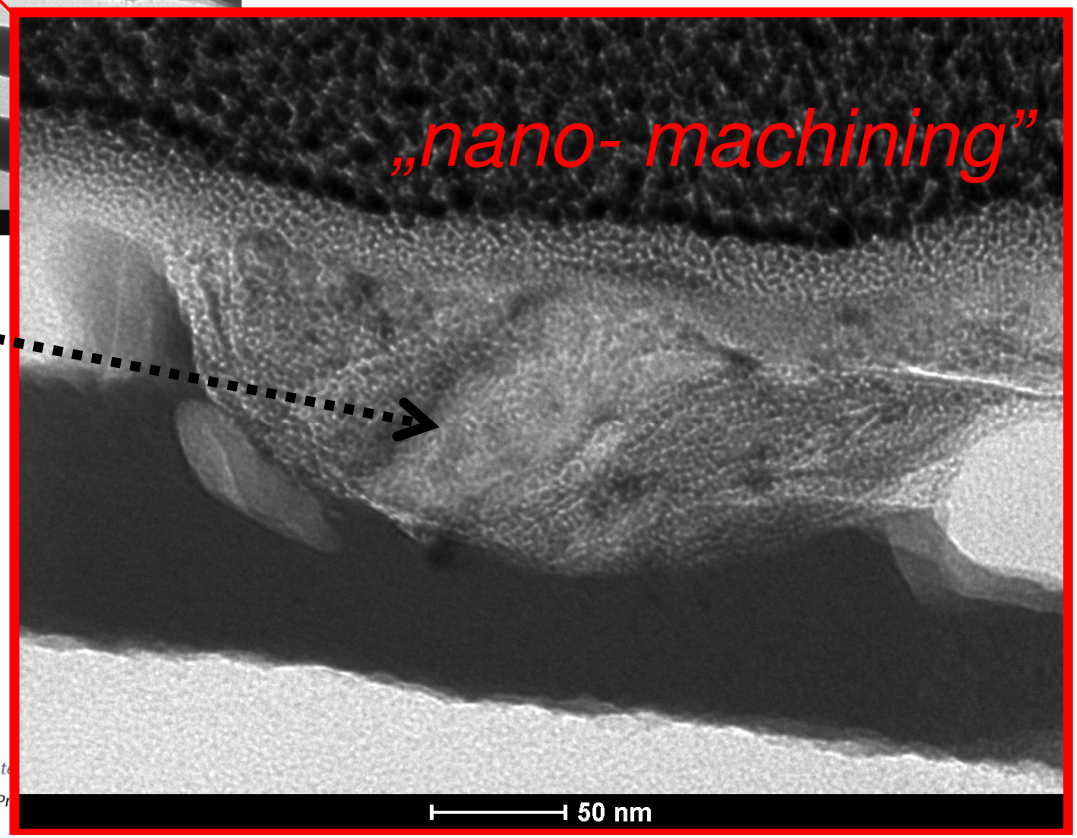
Project co-financed by the European U

TUTE OF METALLURGY
MATERIALS SCIENCE
SH ACADAMY OF SCIENCES

European Union
European Social Fund







- Project NCN nr: 3066/B/T02/2011/40- *FINISHED*
- Project NCN nr: 2012/06/M/ST8/00408- *HARMONIA- FINISHED*
- Project NCN nr: 2012/07/B/ST8/03396- *OPUS- FINISHED*
- Project NCN nr: 2014/15/B/ST8/00103- *OPUS- FINISHED*
- Project NCN nr: 2015/19/B/ST8/00942- *OPUS- in progress*
- Project NCBR, number: DZP/M-ERA.NET-2015/285/2016- *in progress*

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Title: Biomimetic, self-healing, multilayer structures elaboration on thermoplastic polymer materials

Project WND-POWR.03.02.00-00-I043/16

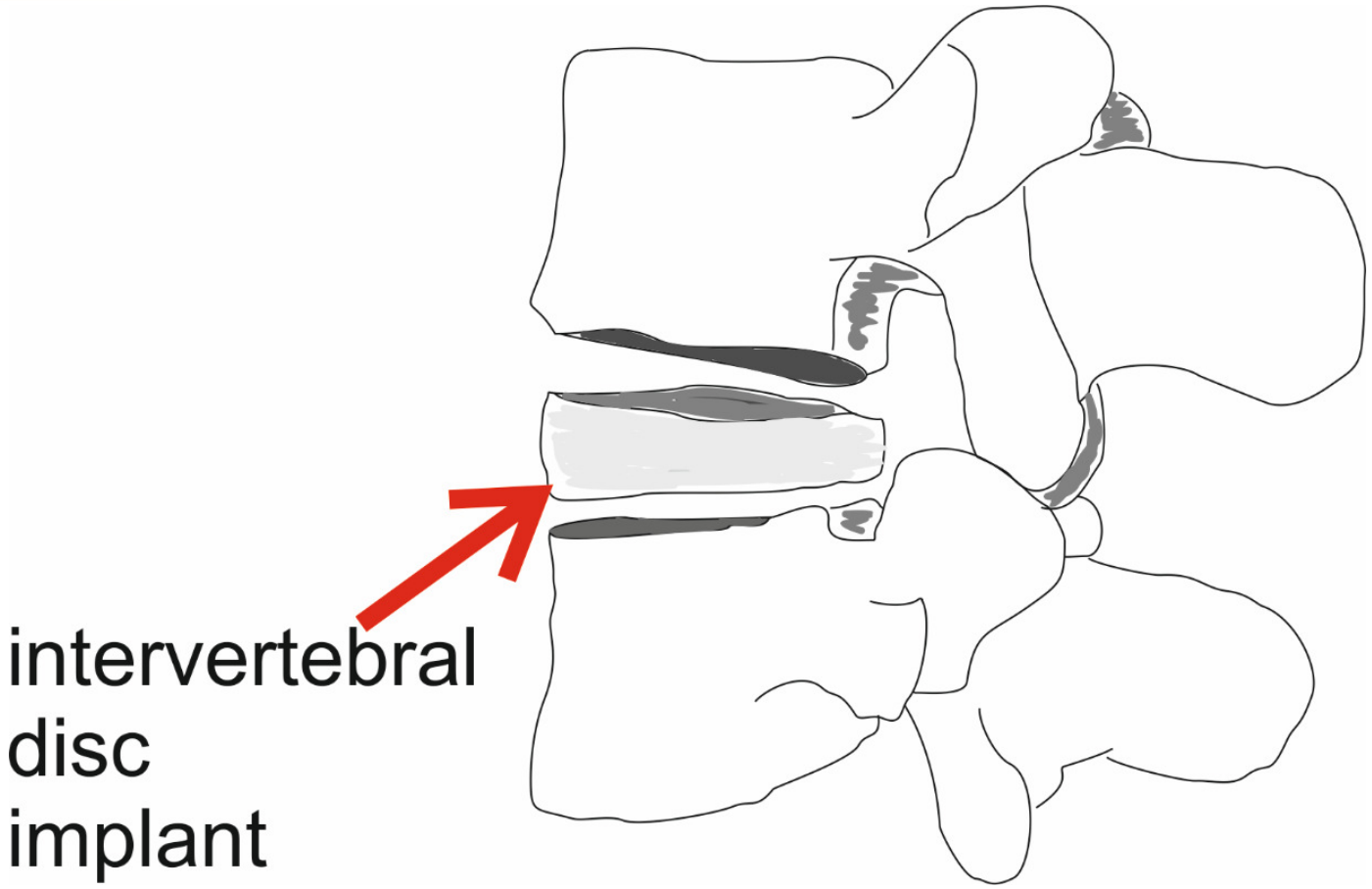
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund



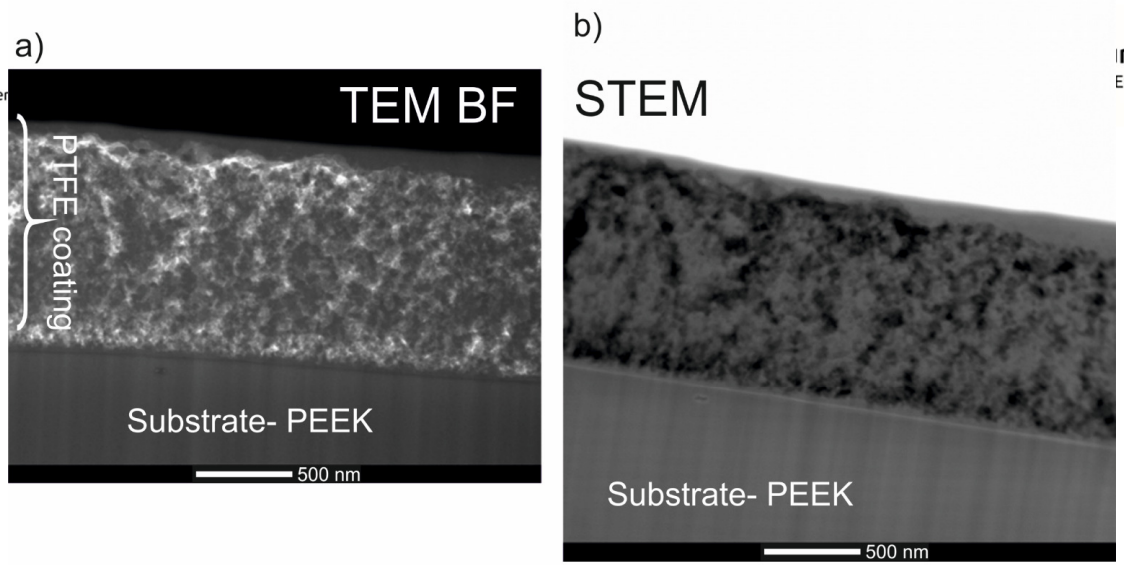
Project WND-POWR.03.02.00-00-I043/16

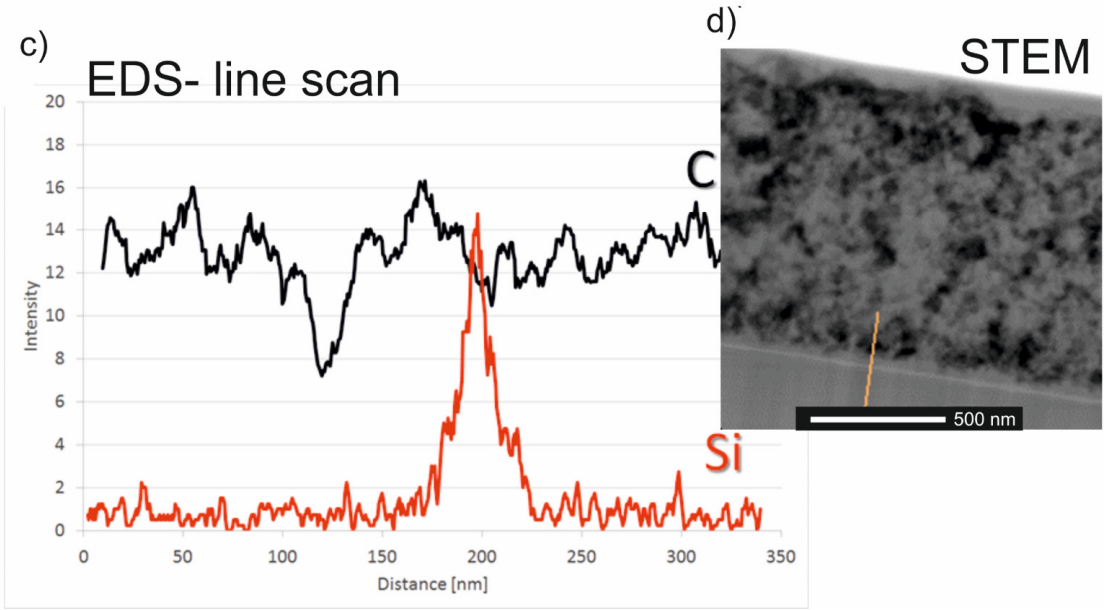
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

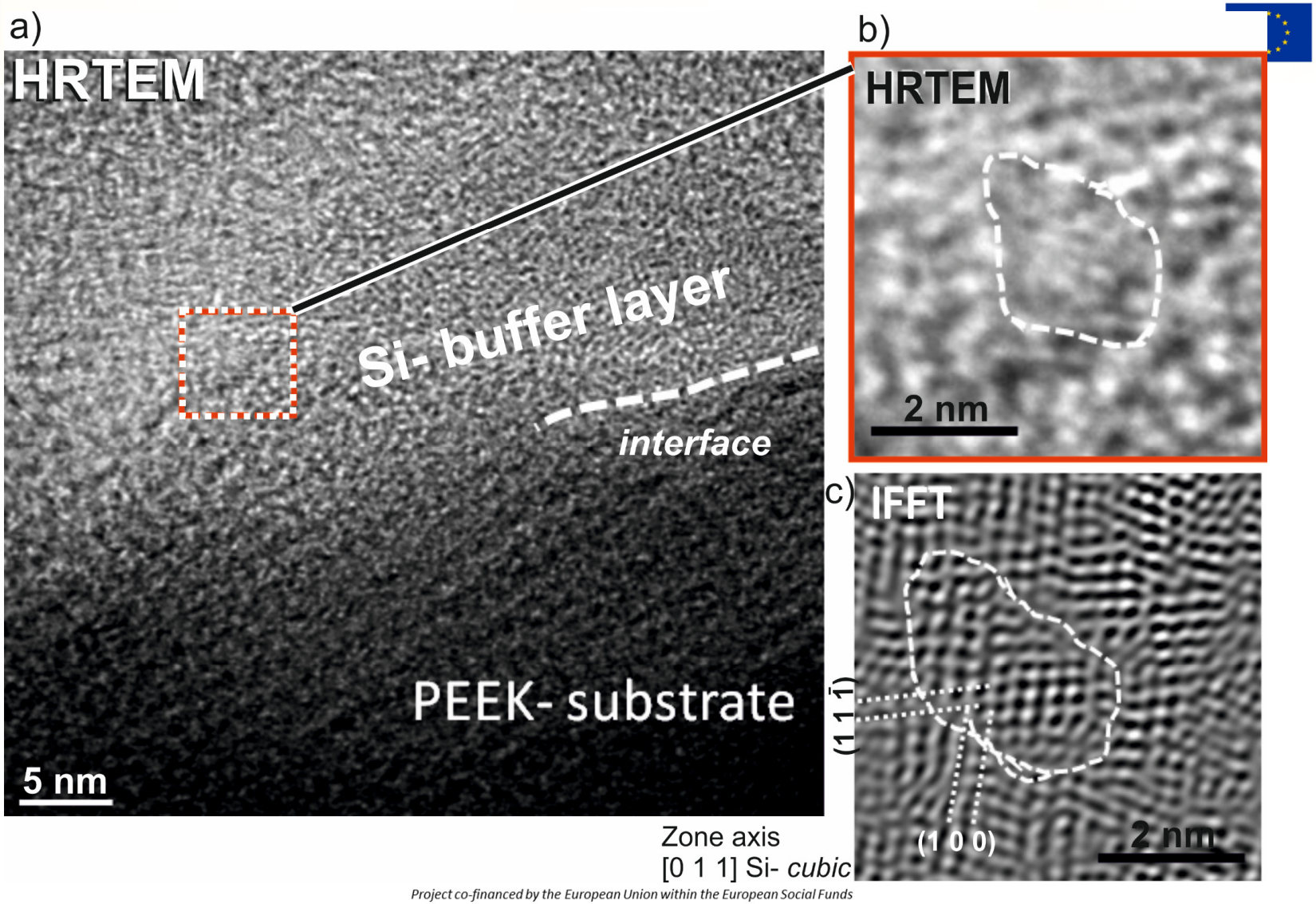
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Developmer

ropean Union
European Social Fund

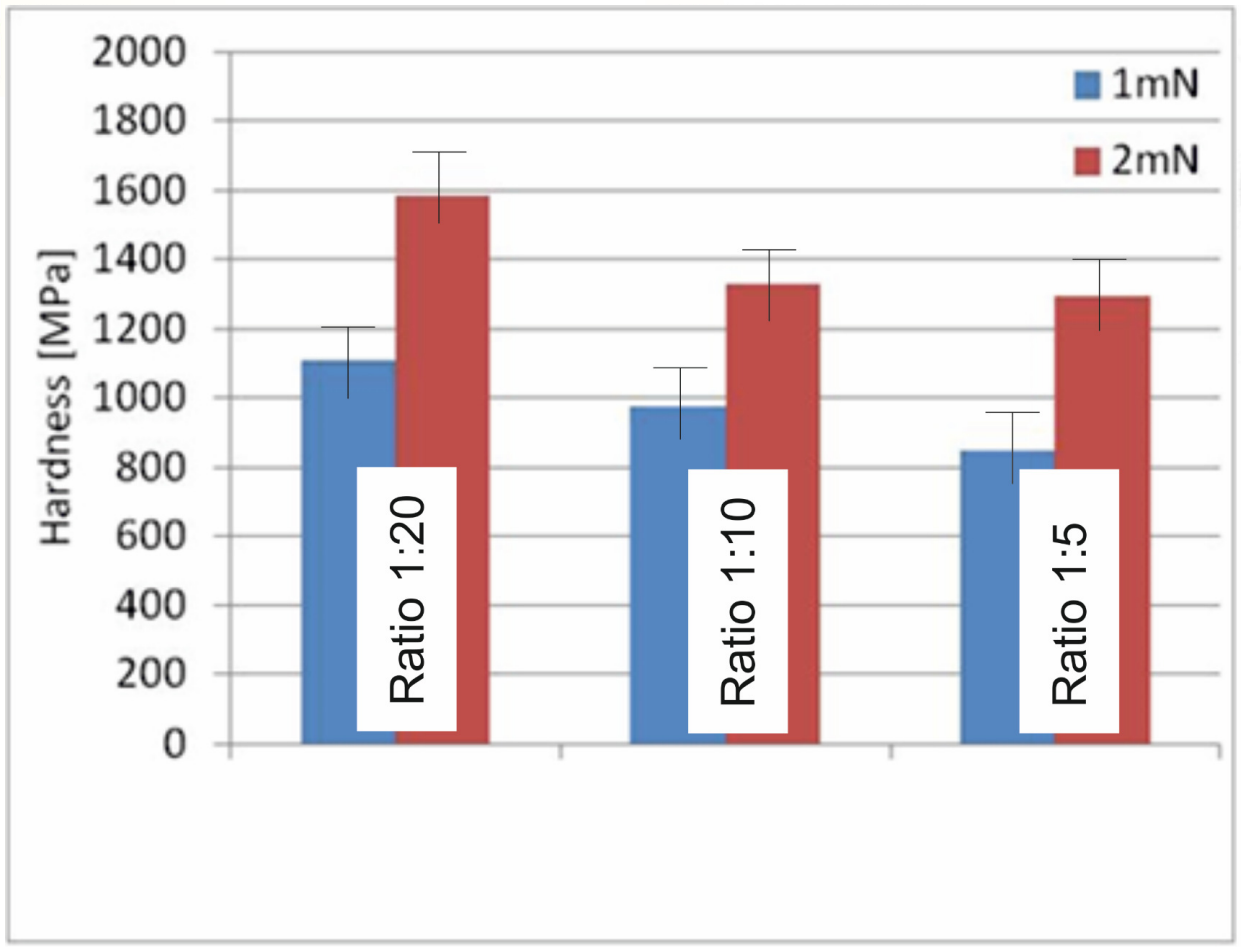


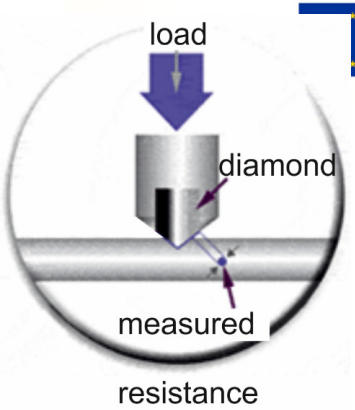




Zone axis
[0 1 1] Si- *cubic*

Project co-financed by the European Union within the European Social Funds





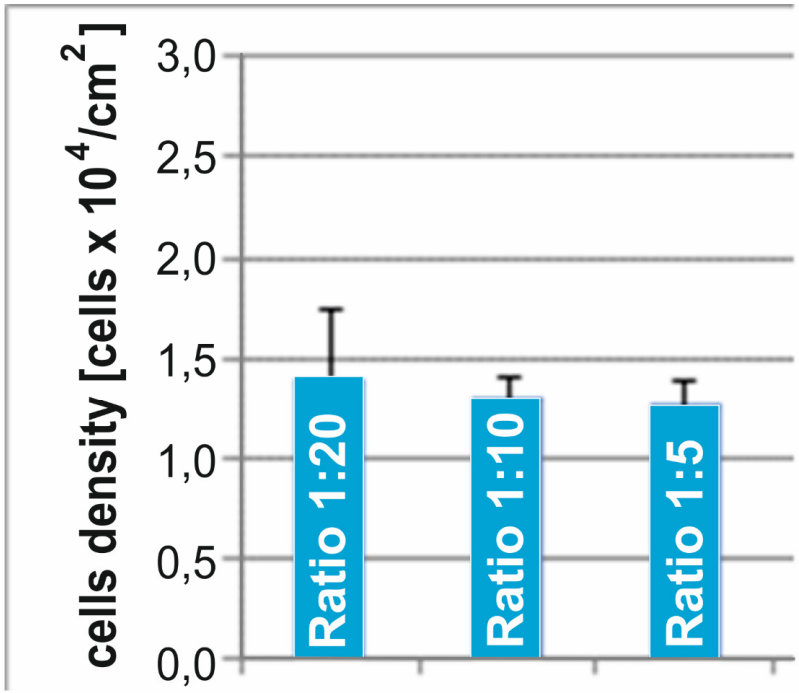
Different ratio

Project co-financed by the European Union within the European Social Funds

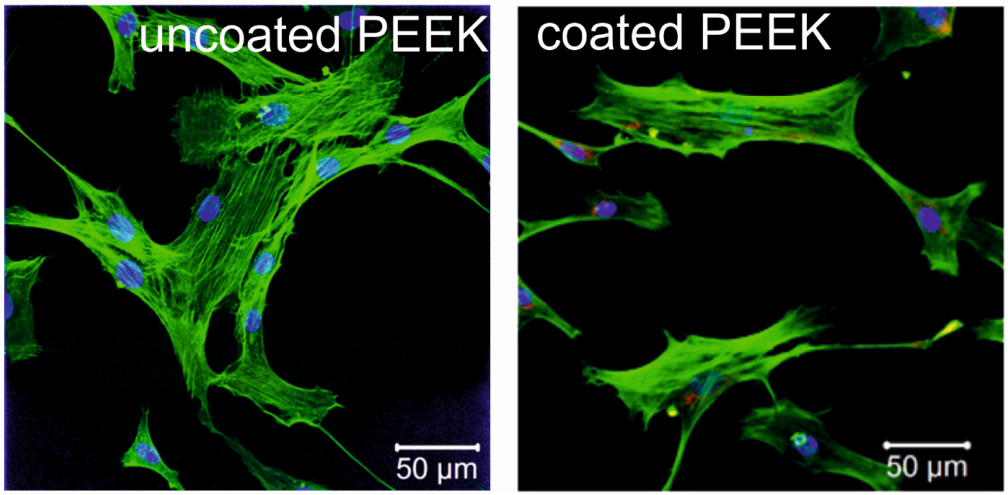
European Funds
Knowledge Education Development

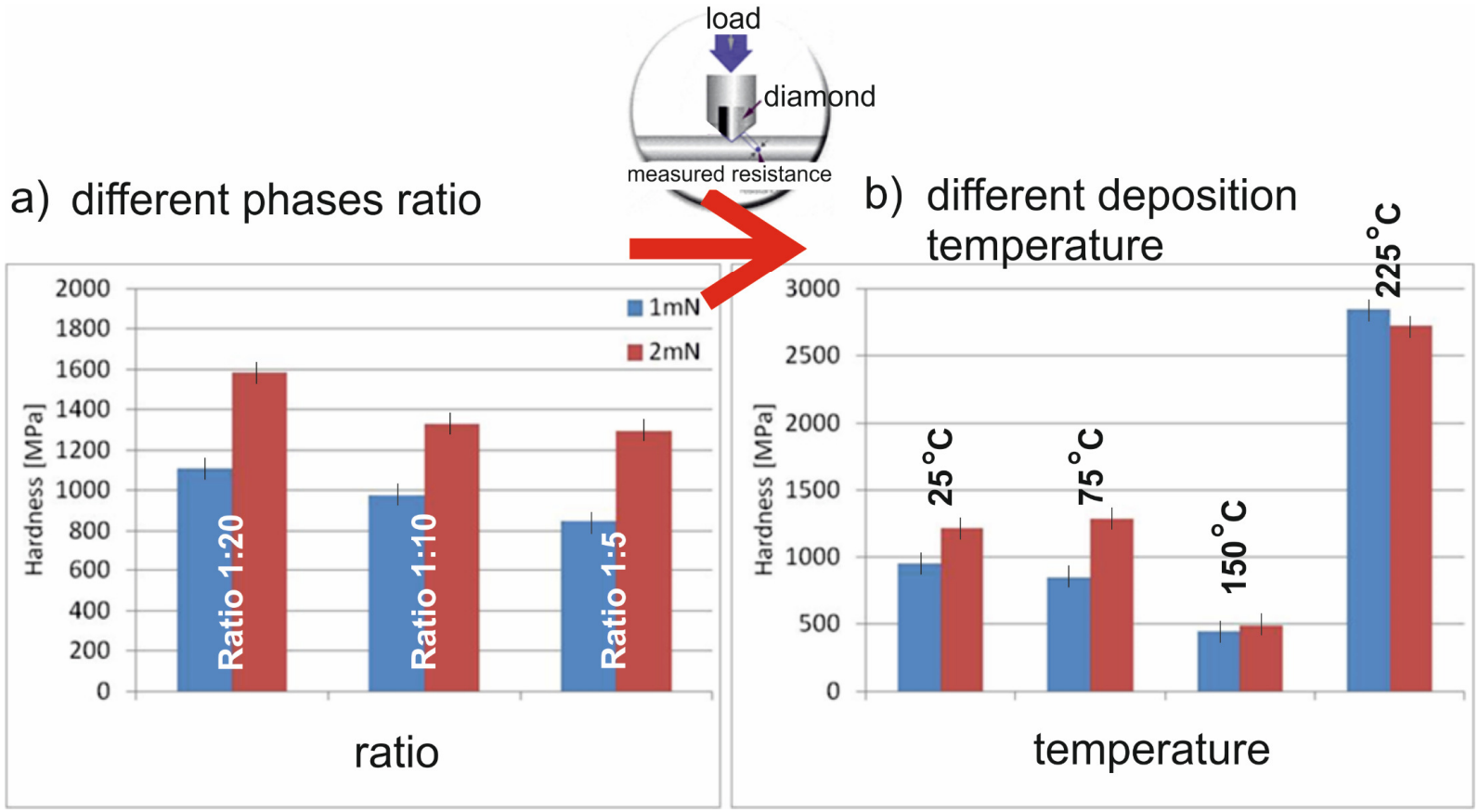
European Union
European Social Fund

a)



b)

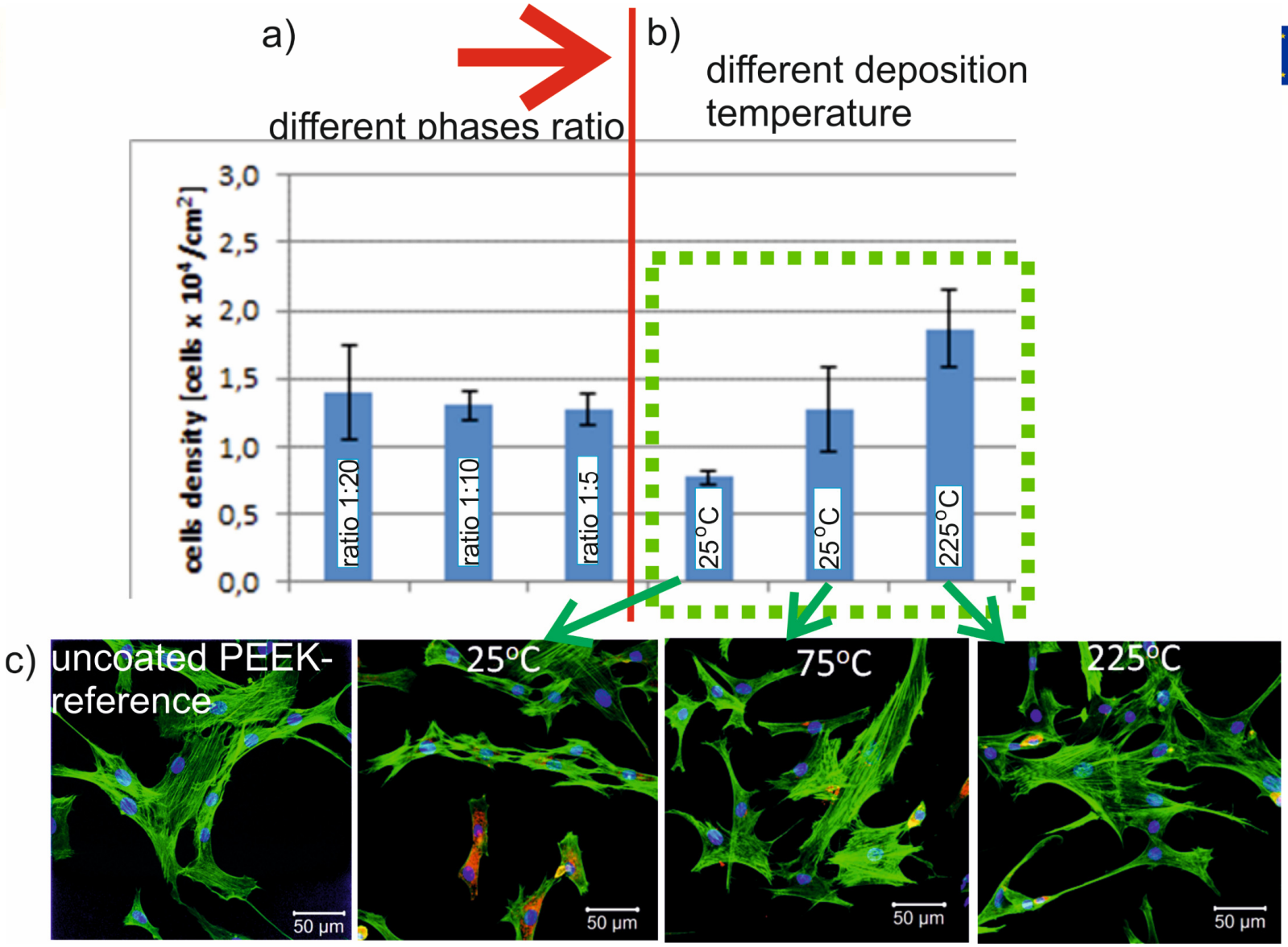




Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

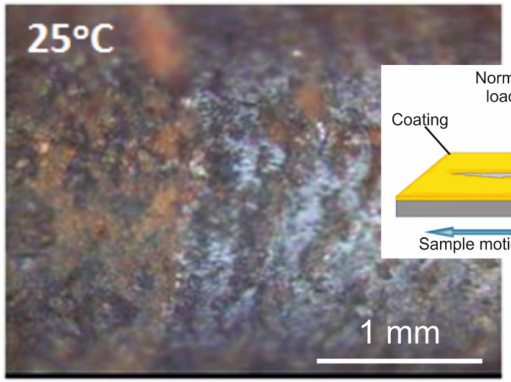
Project co-financed by the European Union within the European Social Funds


a)
different phases ratio
b)
different deposition temperature
cells density [cells x 10⁴/cm²]
3,0
2,5
2,0
1,5
1,0
0,5
0,0
ratio 1:20
ratio 1:10
ratio 1:5
25°C
25°C
225°C
c) uncoated PEEK-reference
25°C
75°C
225°C
50 µm
50 µm
50 µm
50 µm

European Funds
Knowledge Education Development

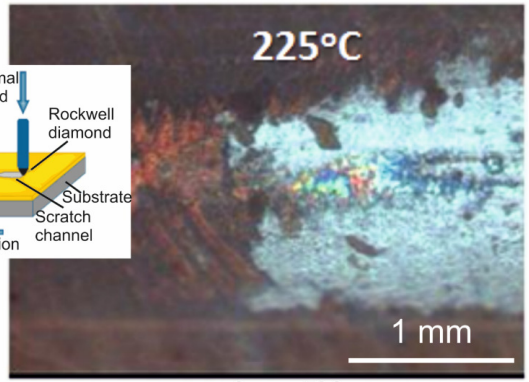
European Union
European Social Fund

a)

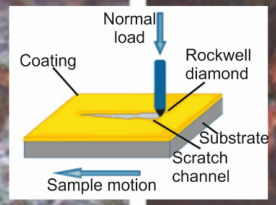


L_{C2}= 13N

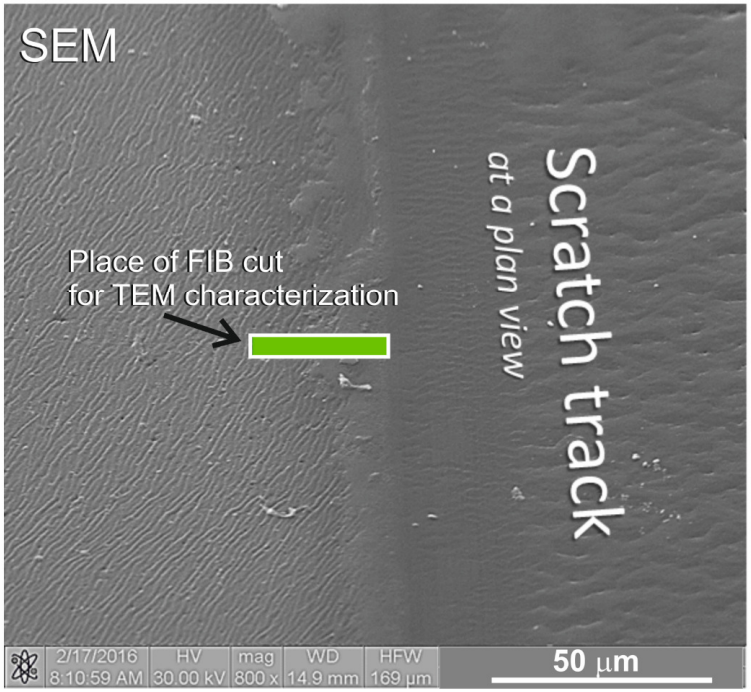
b)



L_{C2}= 5N



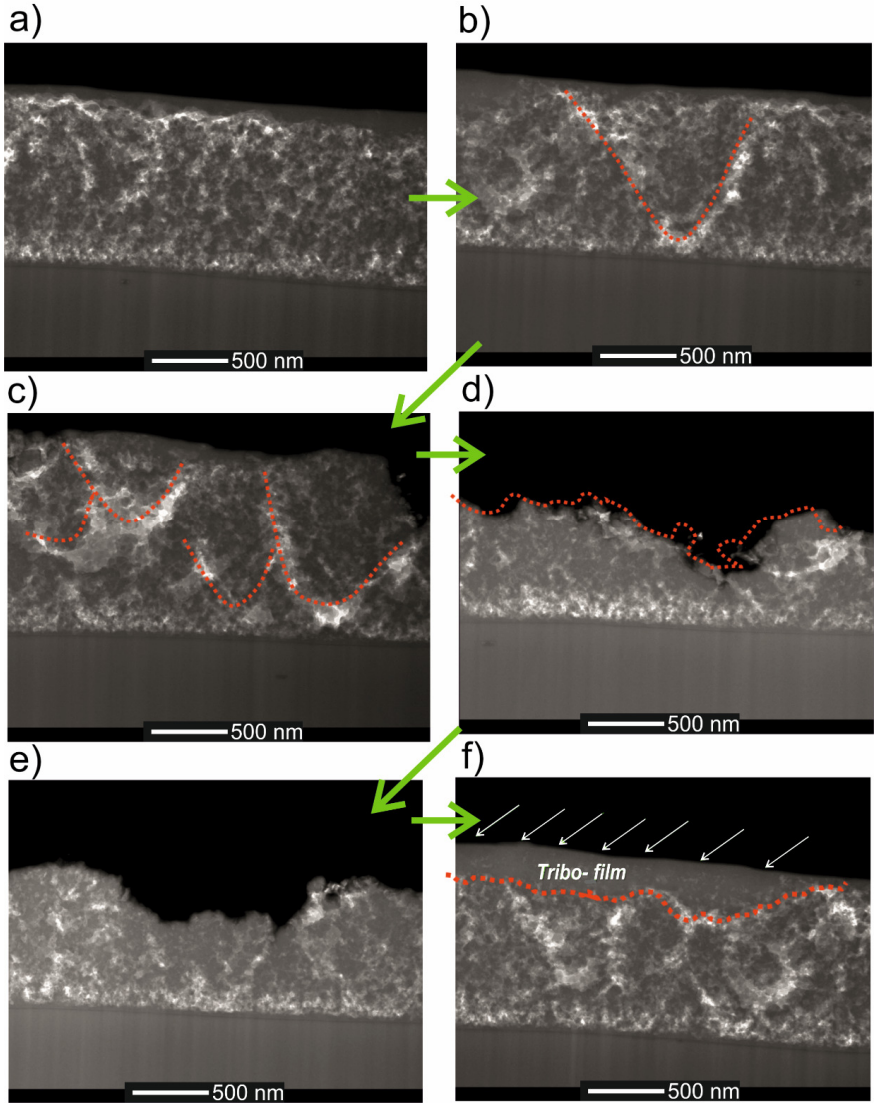
c)



European Funds
Knowledge Education Development

European Union
European Social Fund

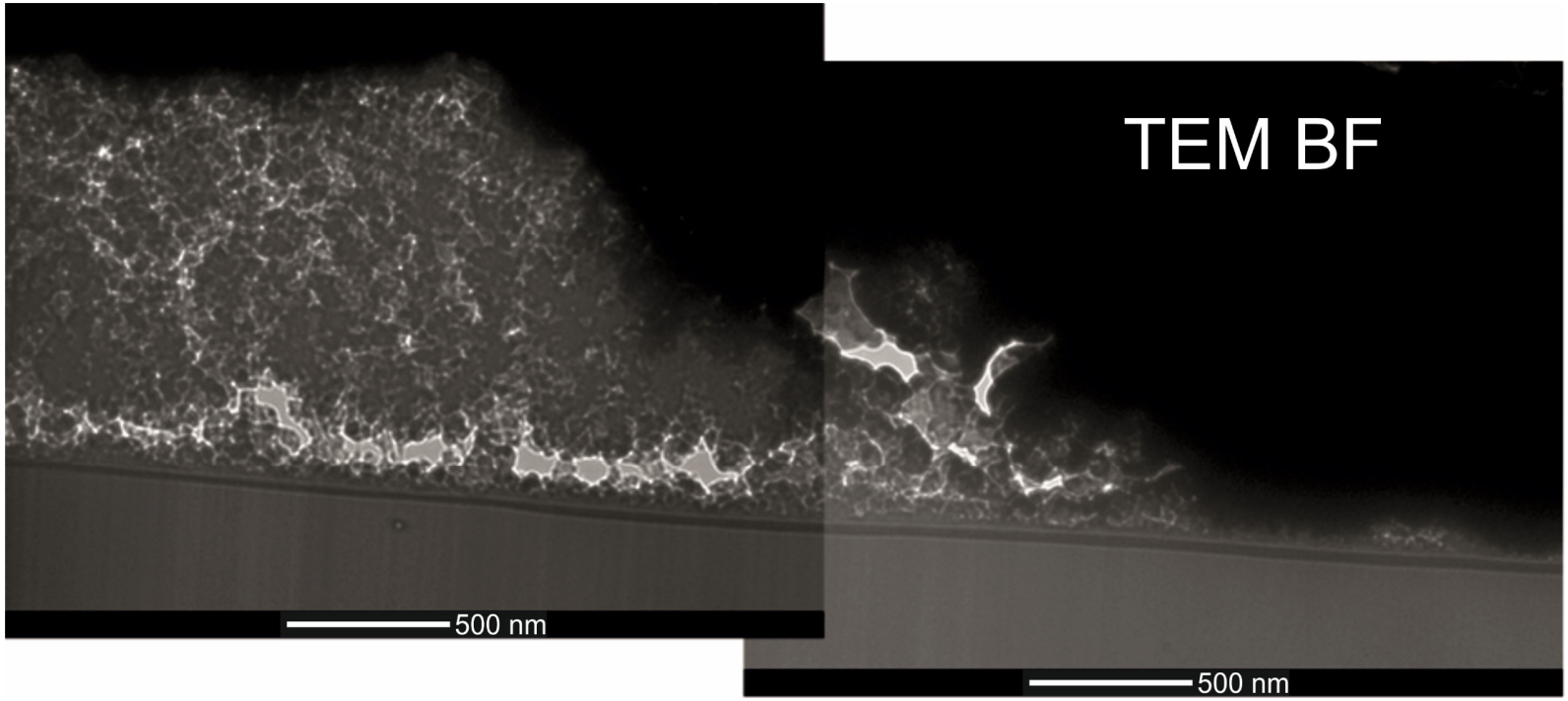
TEM BF



European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

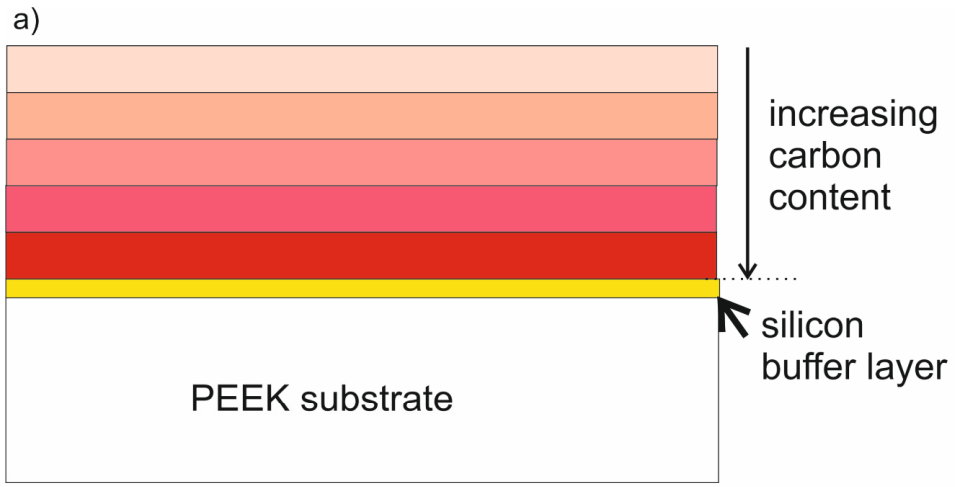
European Union
European Social Fund

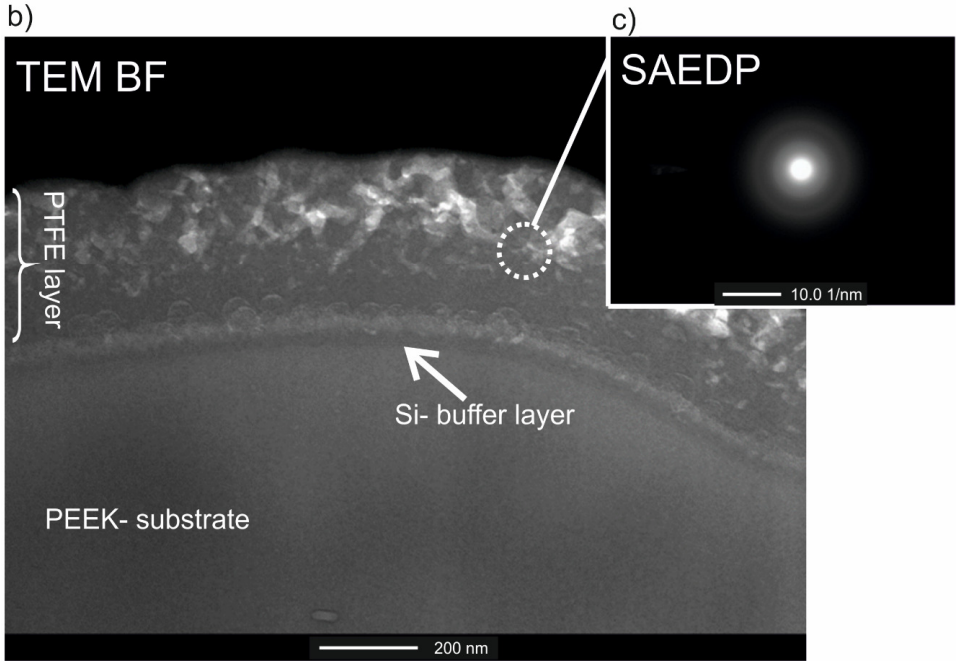


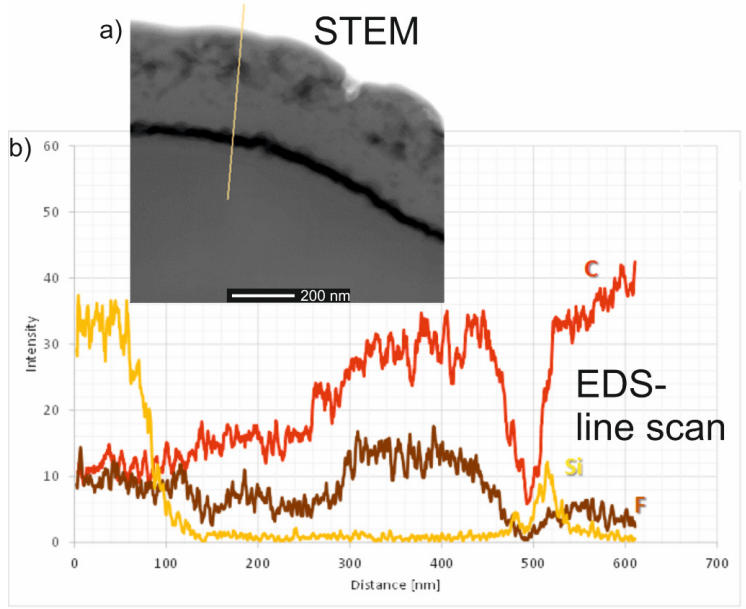
Project WND-POWR.03.02.00-00-I043/16

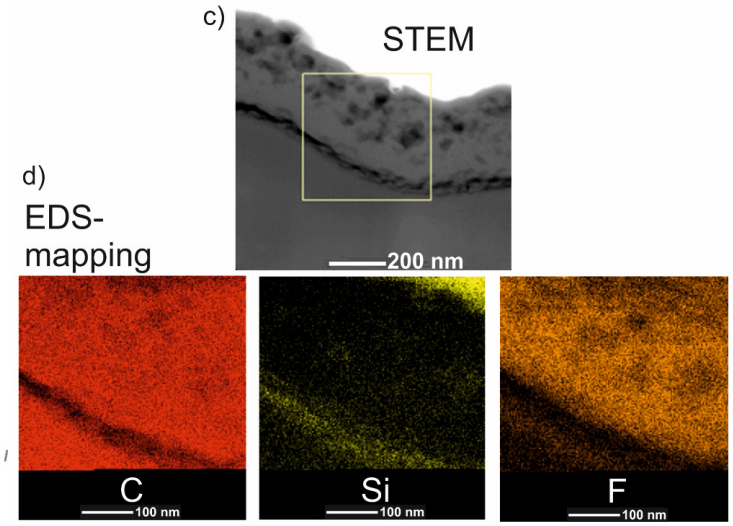
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

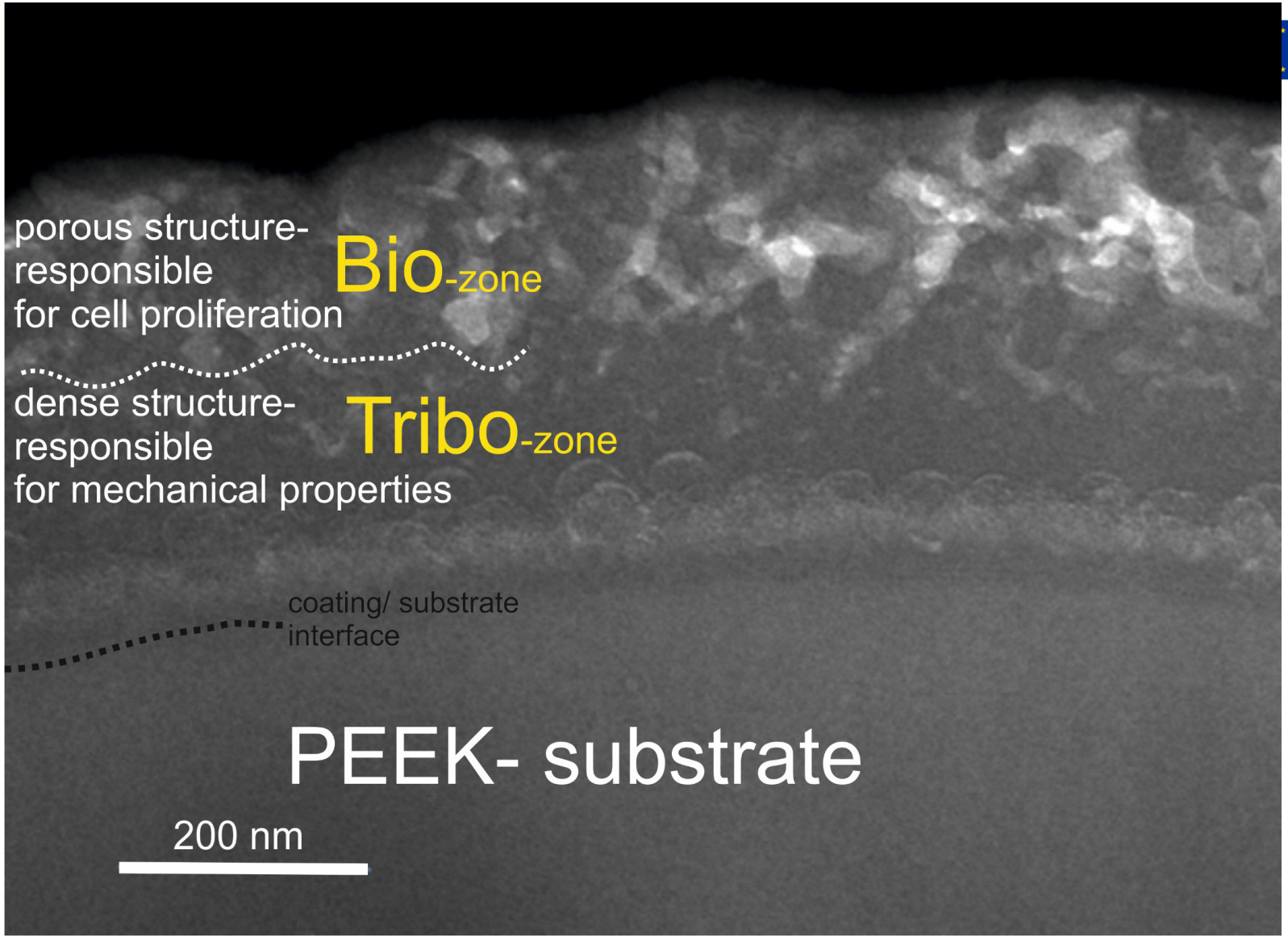
Project co-financed by the European Union within the European Social Funds



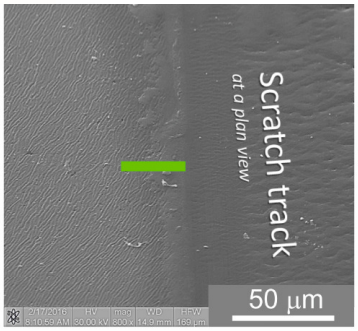


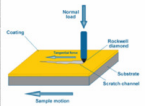

a)
STEM
200 nm
b)
Intensity
Distance [nm]
C
Si
F
EDS-
line scan


c)
STEM
200 nm
d)
EDS-
mapping
C
100 nm
Si
100 nm
F
100 nm


porous structure-
responsible
for cell proliferation
Bio-zone
dense structure-
responsible
for mechanical properties
Tribo-zone
coating/ substrate
interface
PEEK- substrate
200 nm

a) SEM

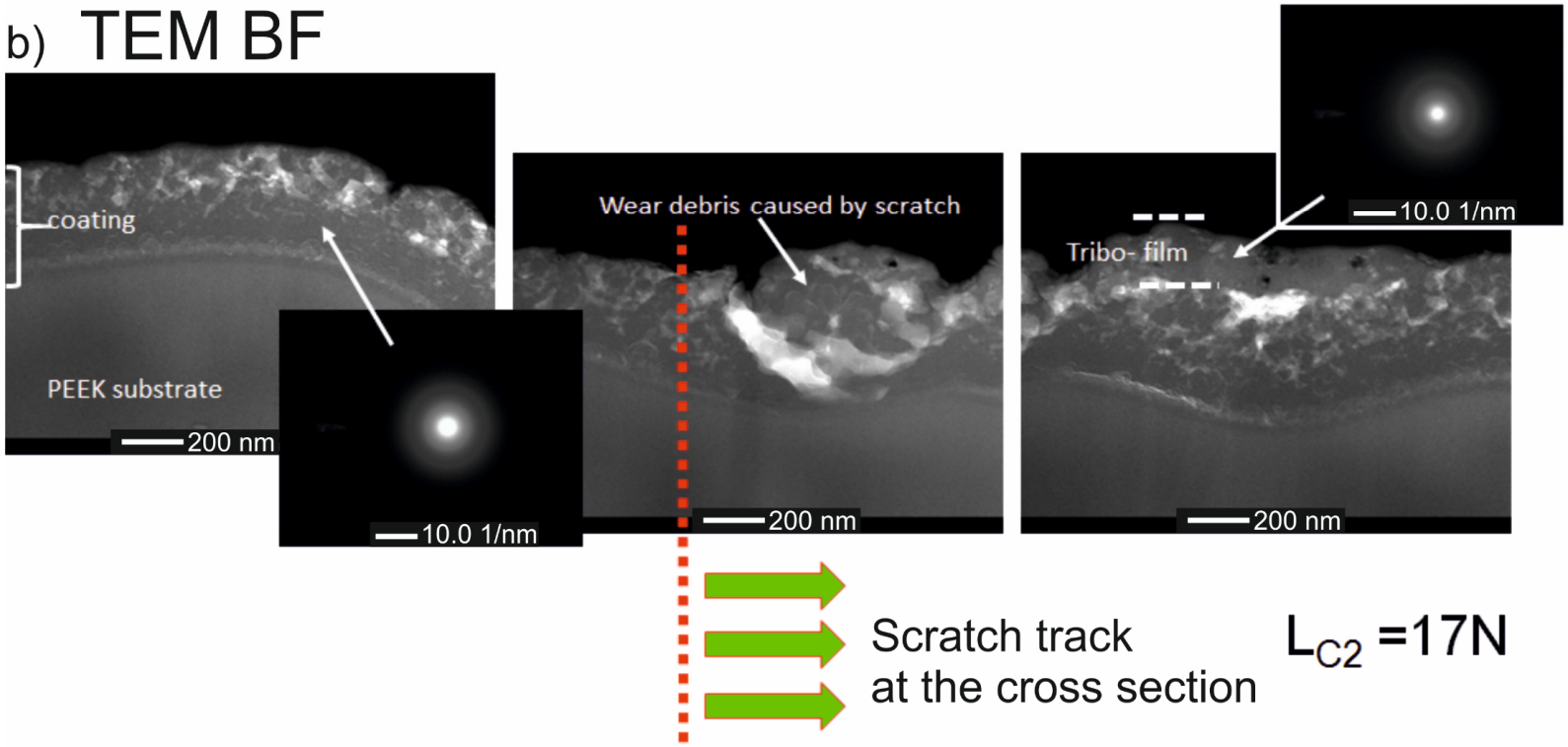




L_{C2} =17N

Scratch track-
plan view

b) TEM BF



Scratch track
at the cross section

L_{C2} =17N

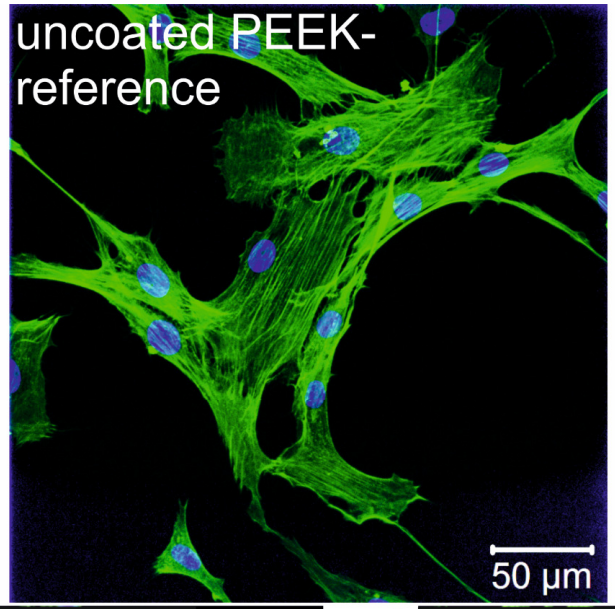
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Educati

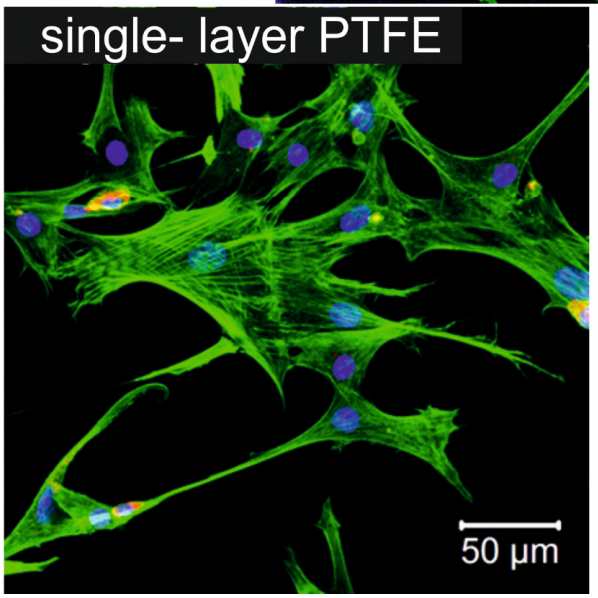
Jnion
ial Fund

a) uncoated PEEK-reference

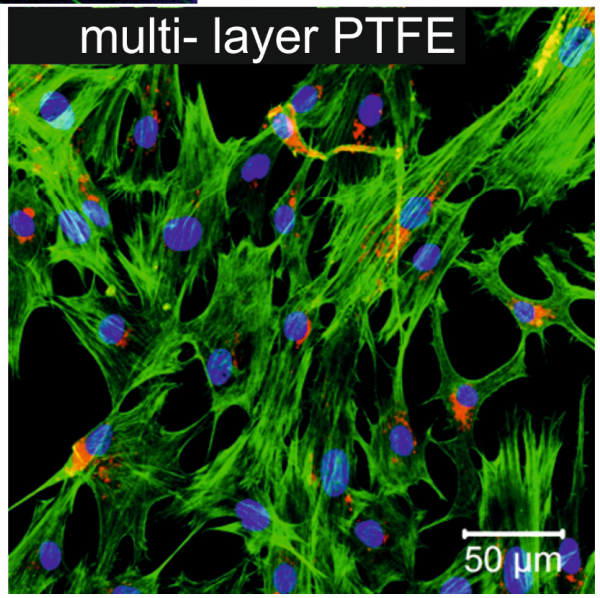
CLSM

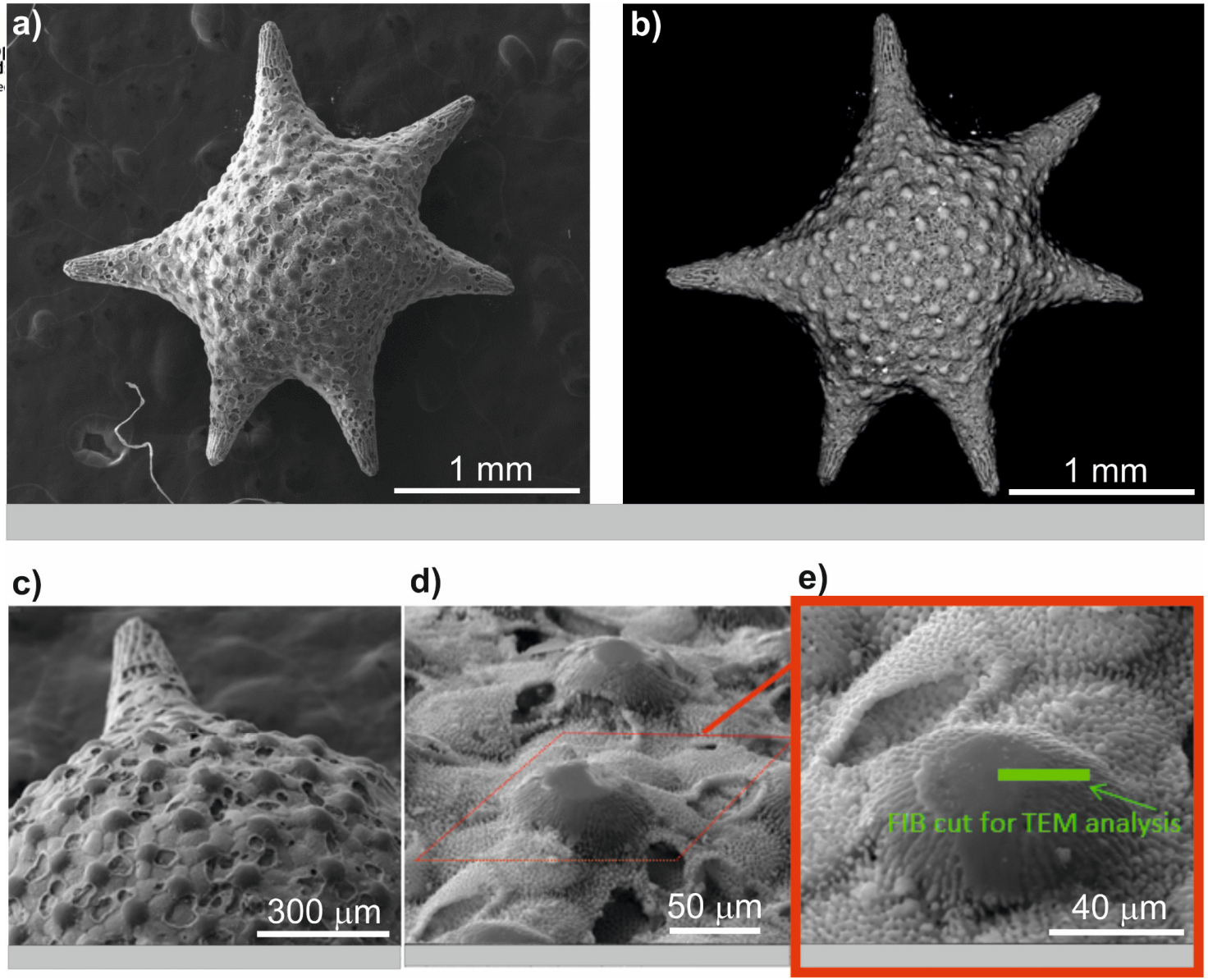


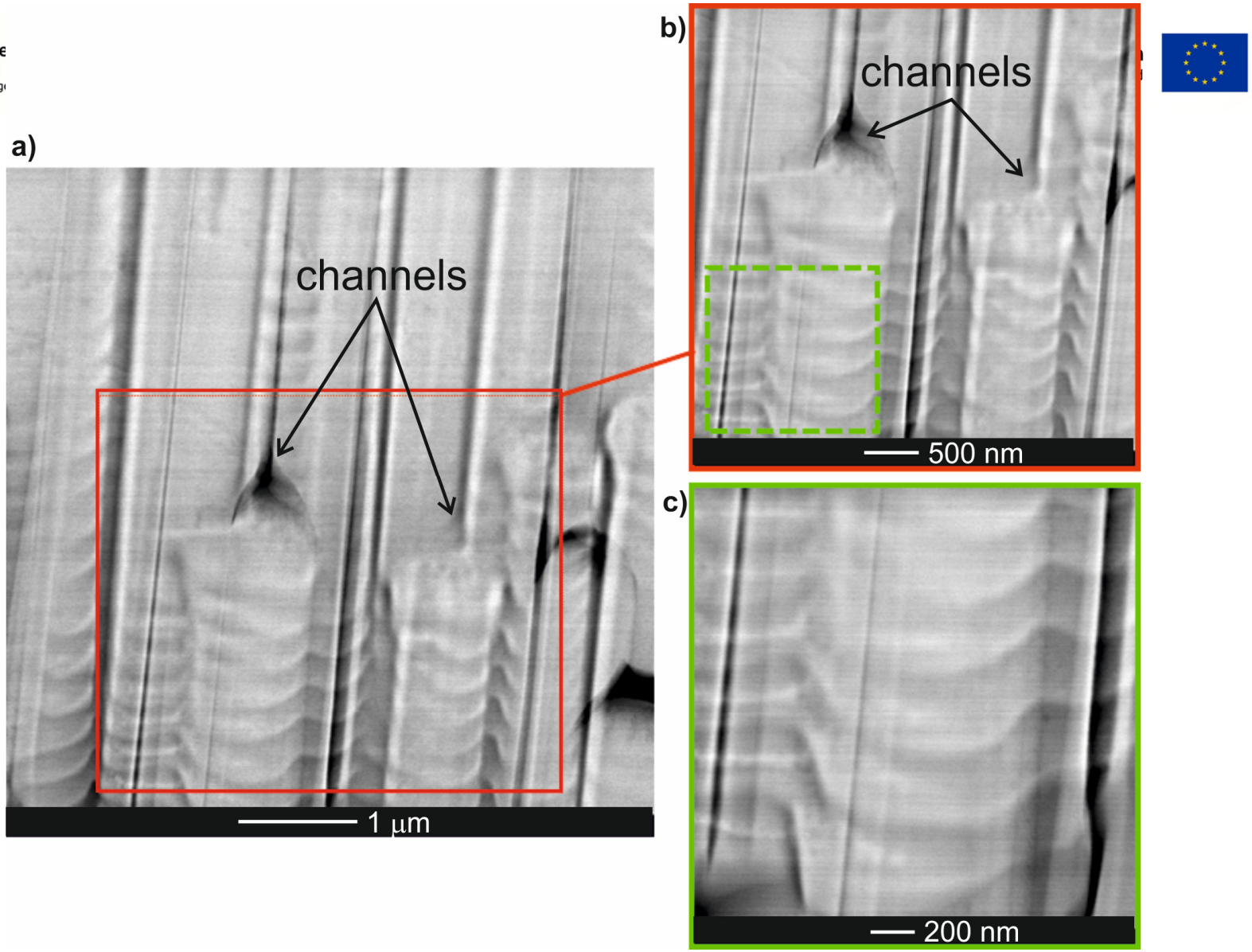
b) single- layer PTFE

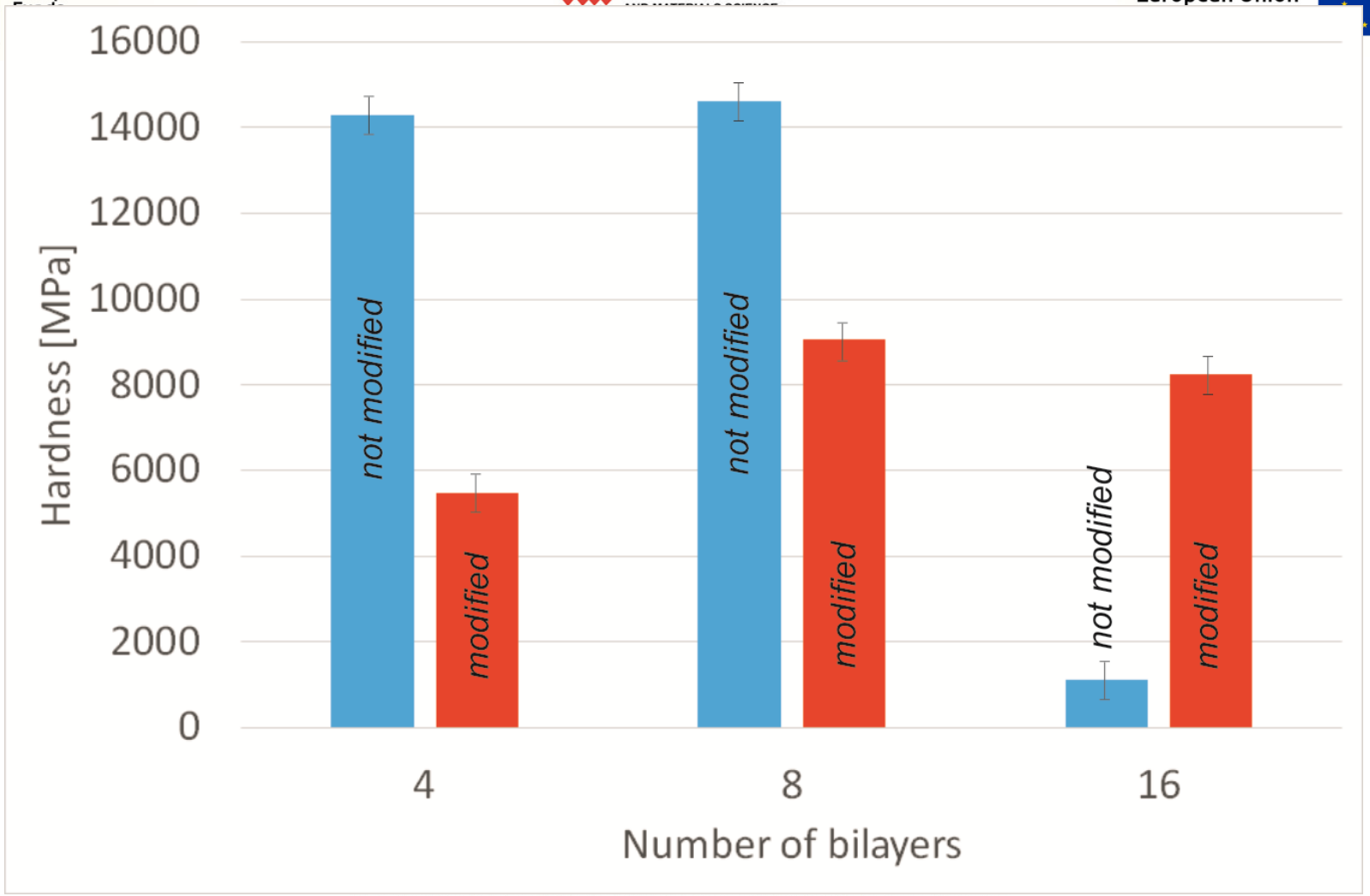


c) multi- layer PTFE



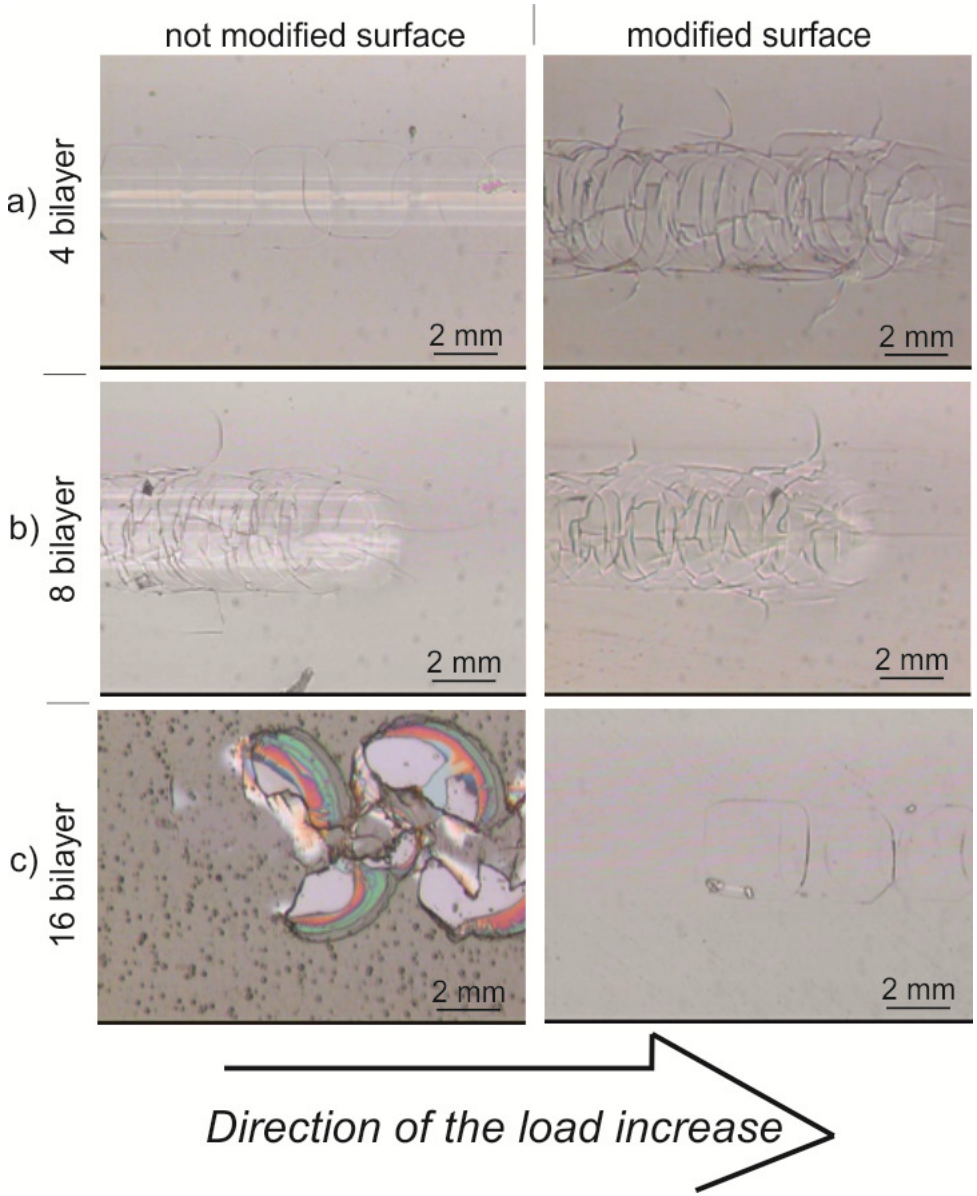

a)
1 mm
b)
1 mm
c)
300 µm
d)
50 µm
e)
FIB cut for TEM analysis
40 µm


a)
channels
1 µm
b)
channels
500 nm
c)
200 nm

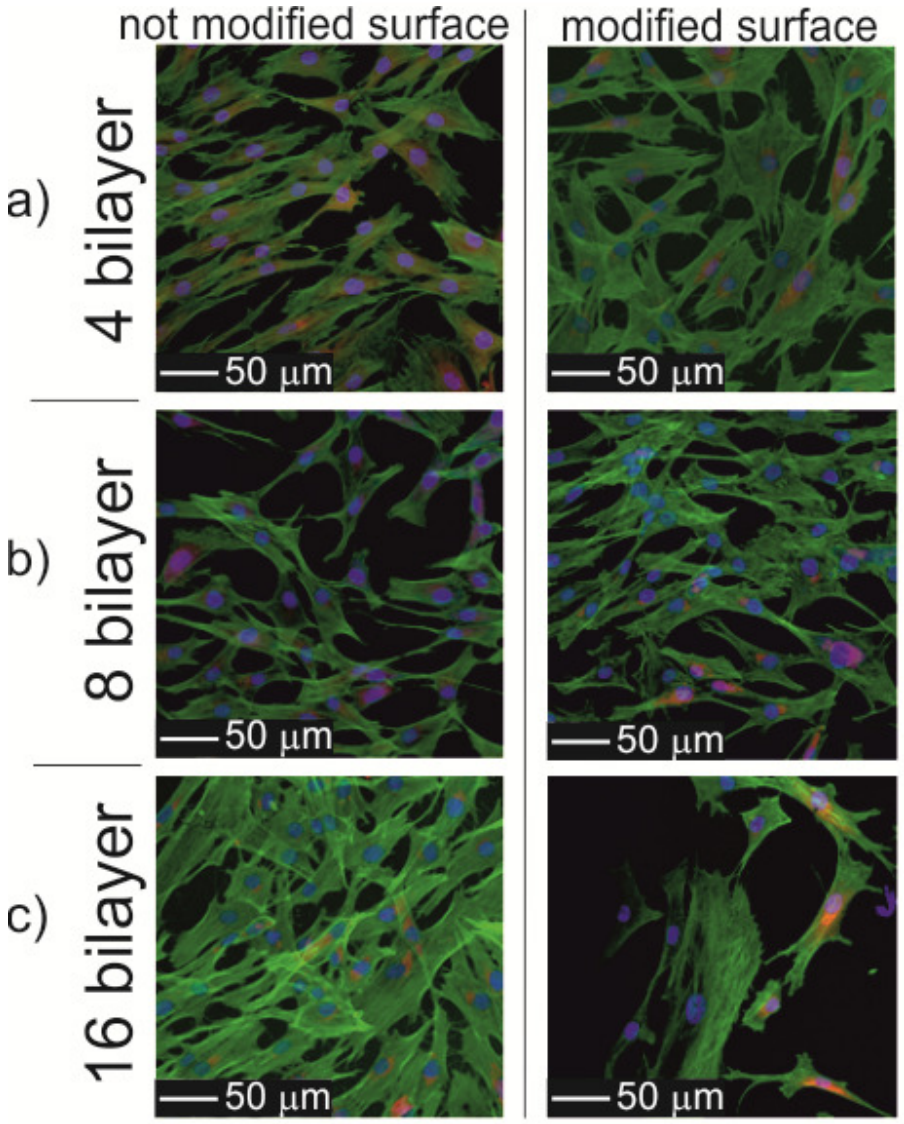

16000
14000
12000
10000
8000
6000
4000
2000
0
Hardness [MPa]
not modified
modified
not modified
modified
not modified
modified
4
8
16
Number of bilayers

European Funds
Knowledge Education Development

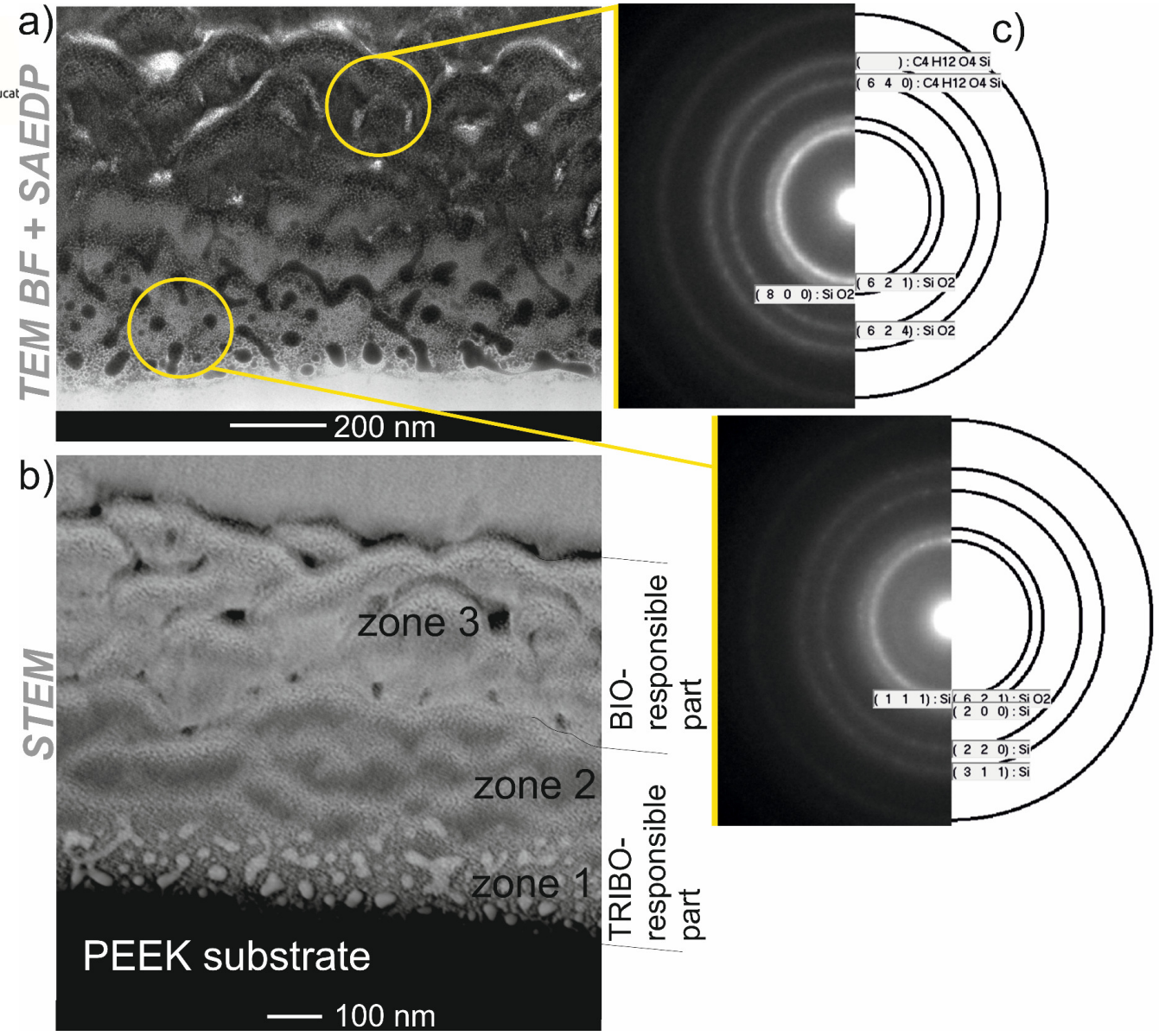
European Union
European Social Fund



European Funds
Knowledge Education Development

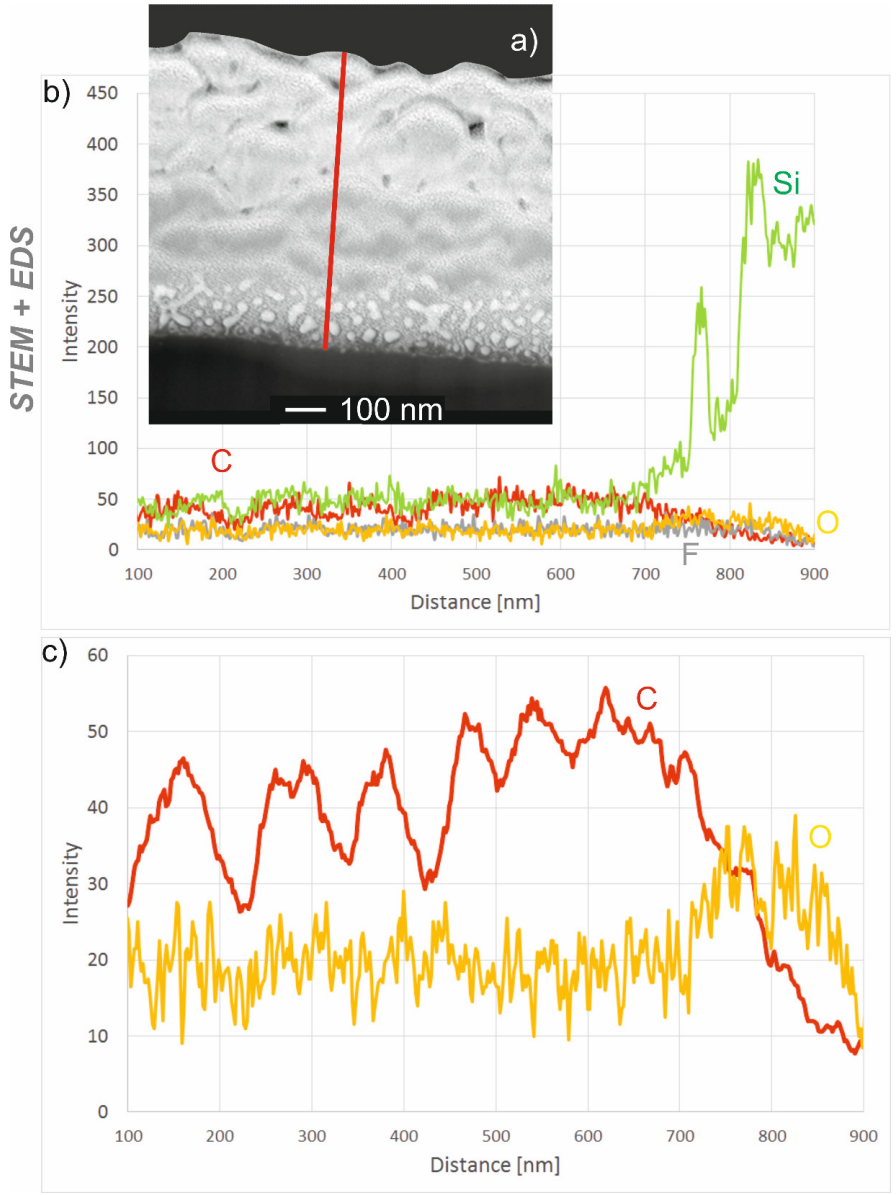


European Union
European Social Fund


a)
TEM BF + SAEDP
200 nm
c)
( ) : C4 H12 O4 Si
(6 4 0) : C4 H12 O4 Si
(8 0 0) : Si O2
(6 2 1) : Si O2
(6 2 4) : Si O2
b)
STEM
zone 3
zone 2
zone 1
PEEK substrate
100 nm
BIO-responsible part
TRIBO-responsible part
(1 1 1) : Si
(6 2 1) : Si O2
(2 0 0) : Si
(2 2 0) : Si
(3 1 1) : Si

European Funds
Knowledge Education Development

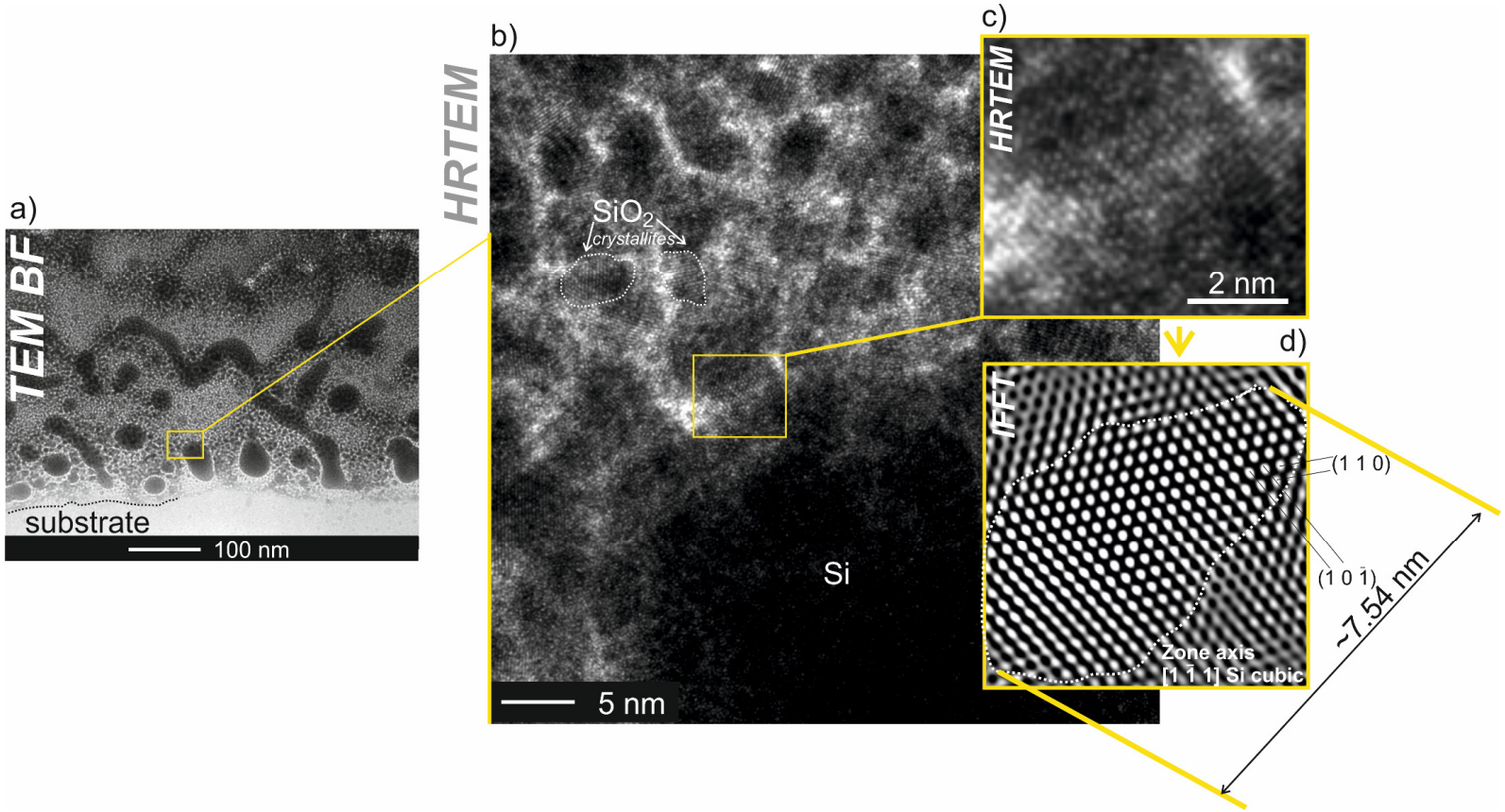
European Union
European Social Fund



European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund



Project WND-POWR.03.02.00-00-I043/16

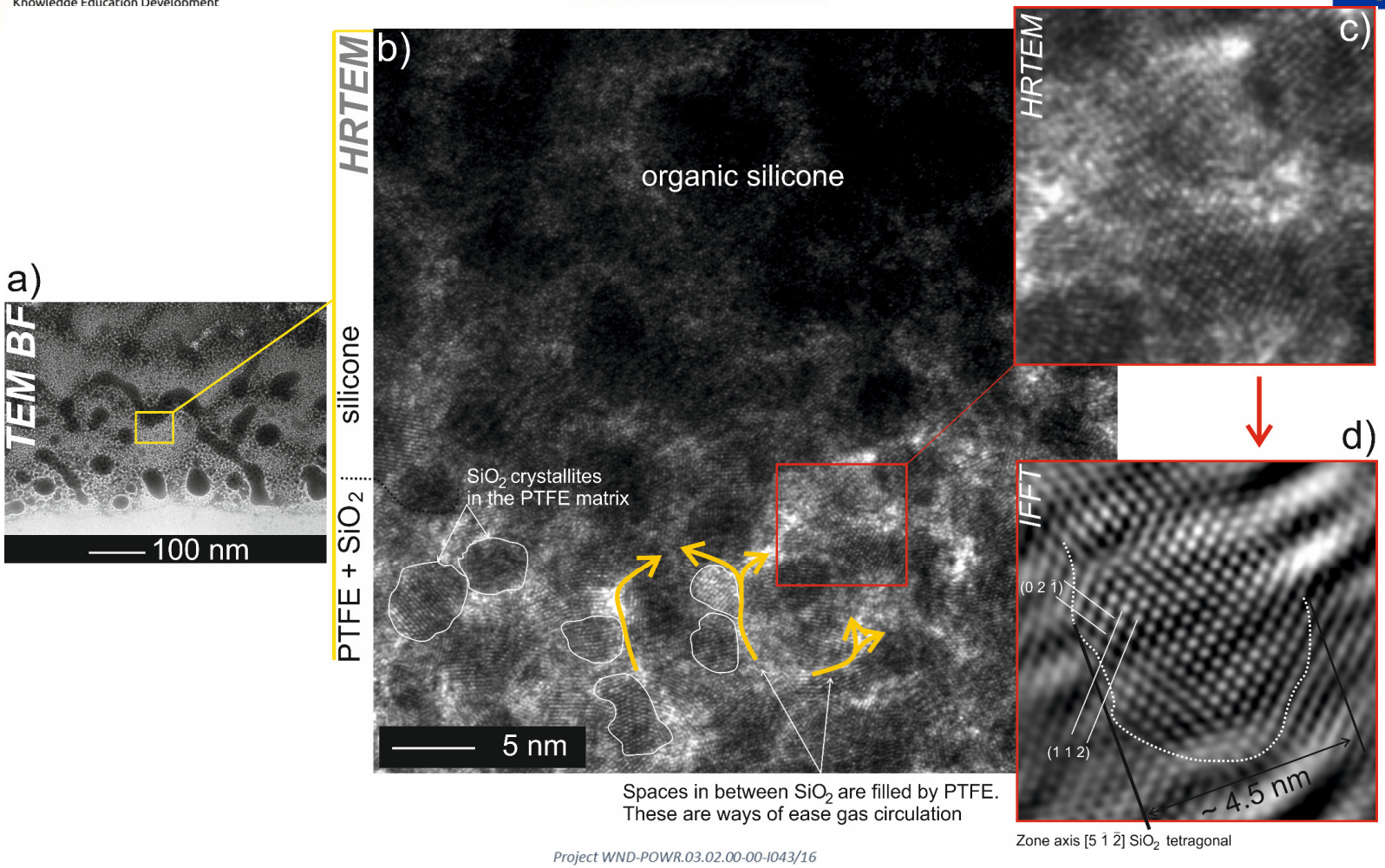
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

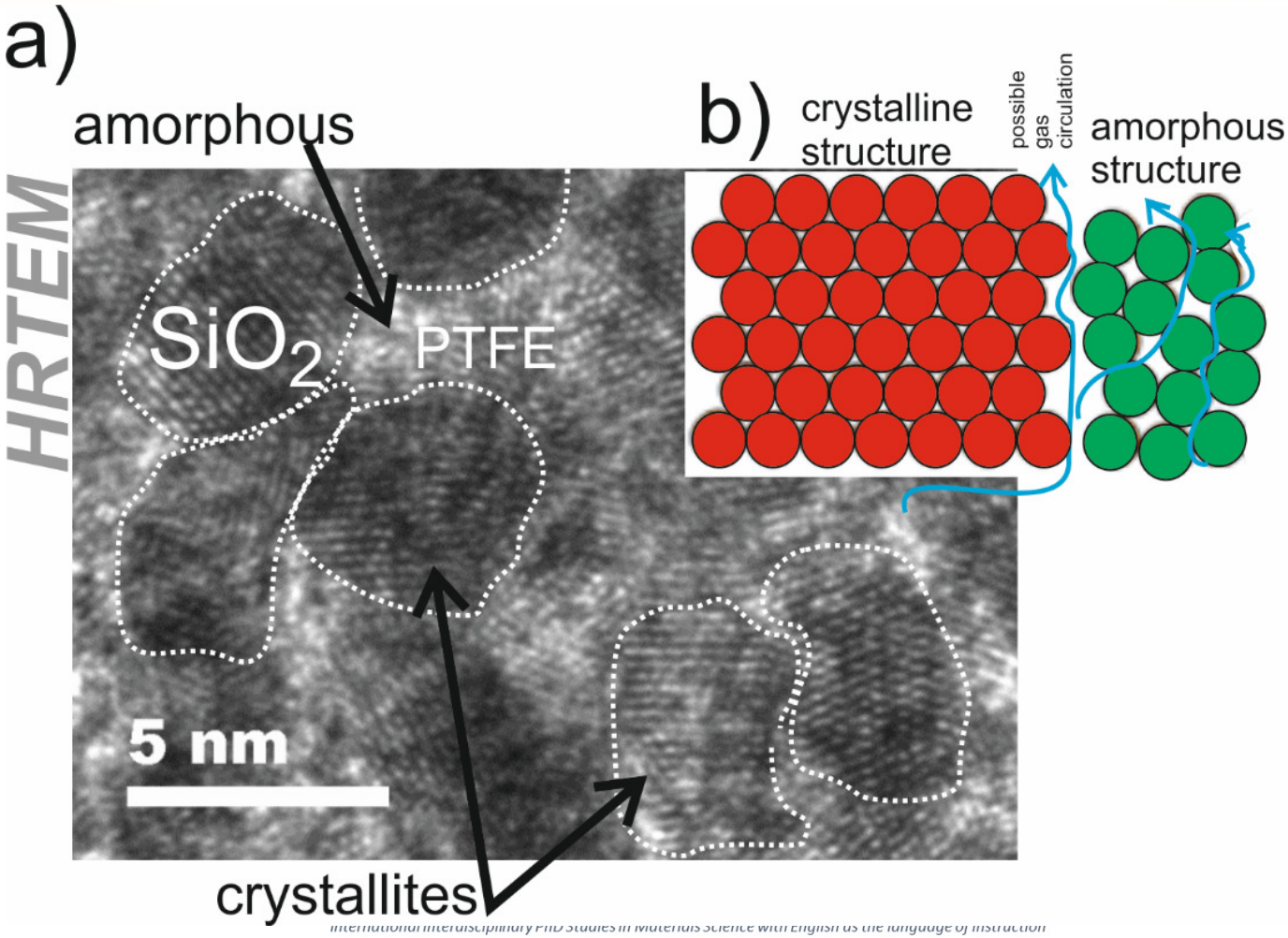
European Union
European Social Fund



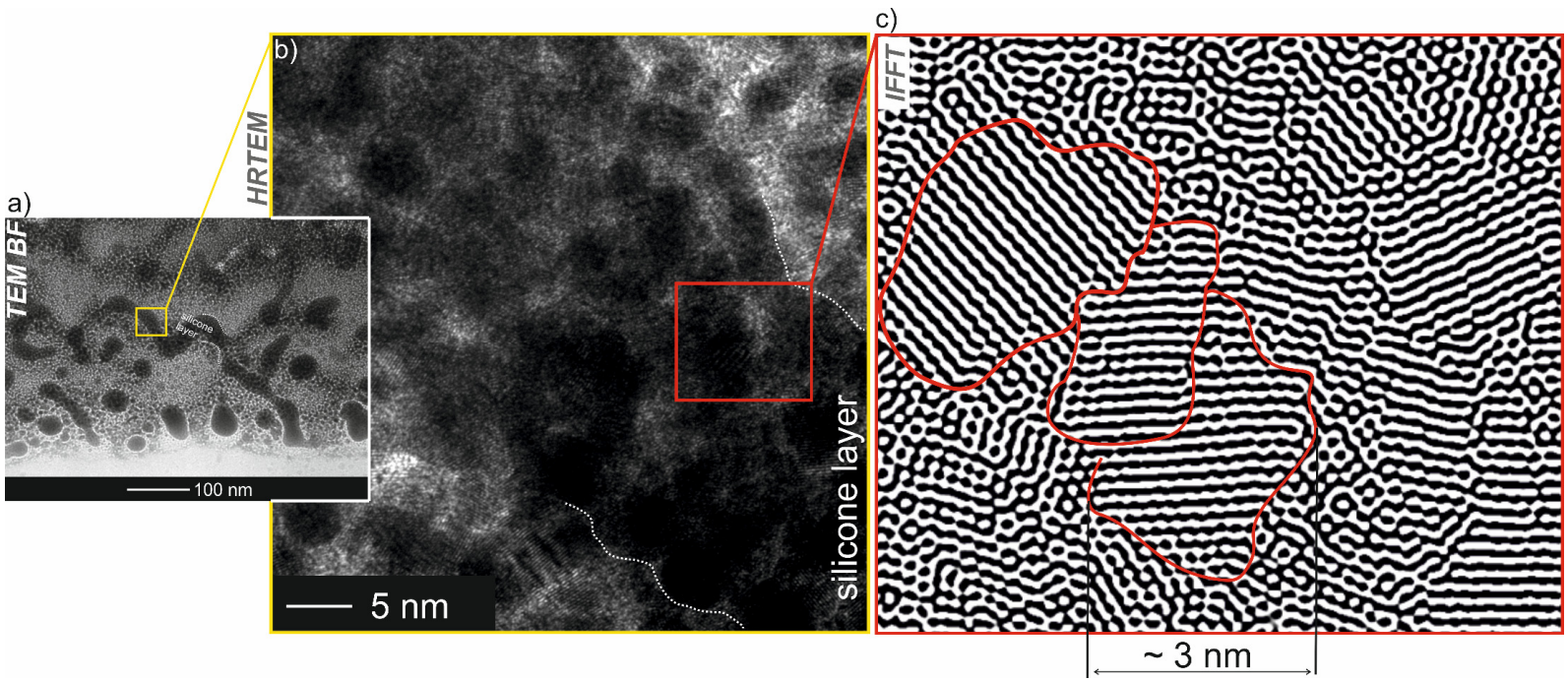
Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds



Project co-financed by the European Union within the European Social Funds



Project WND-POWR.03.02.00-00-I043/16

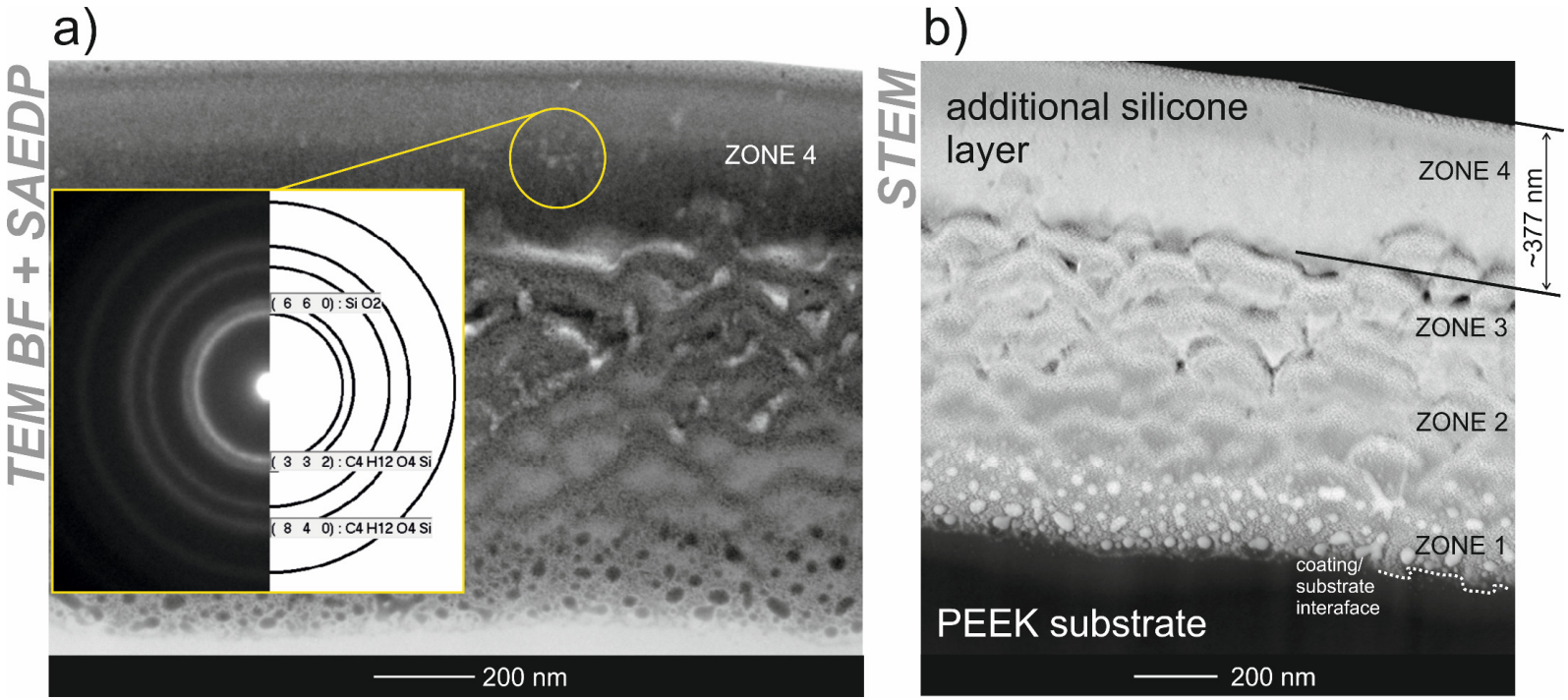
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

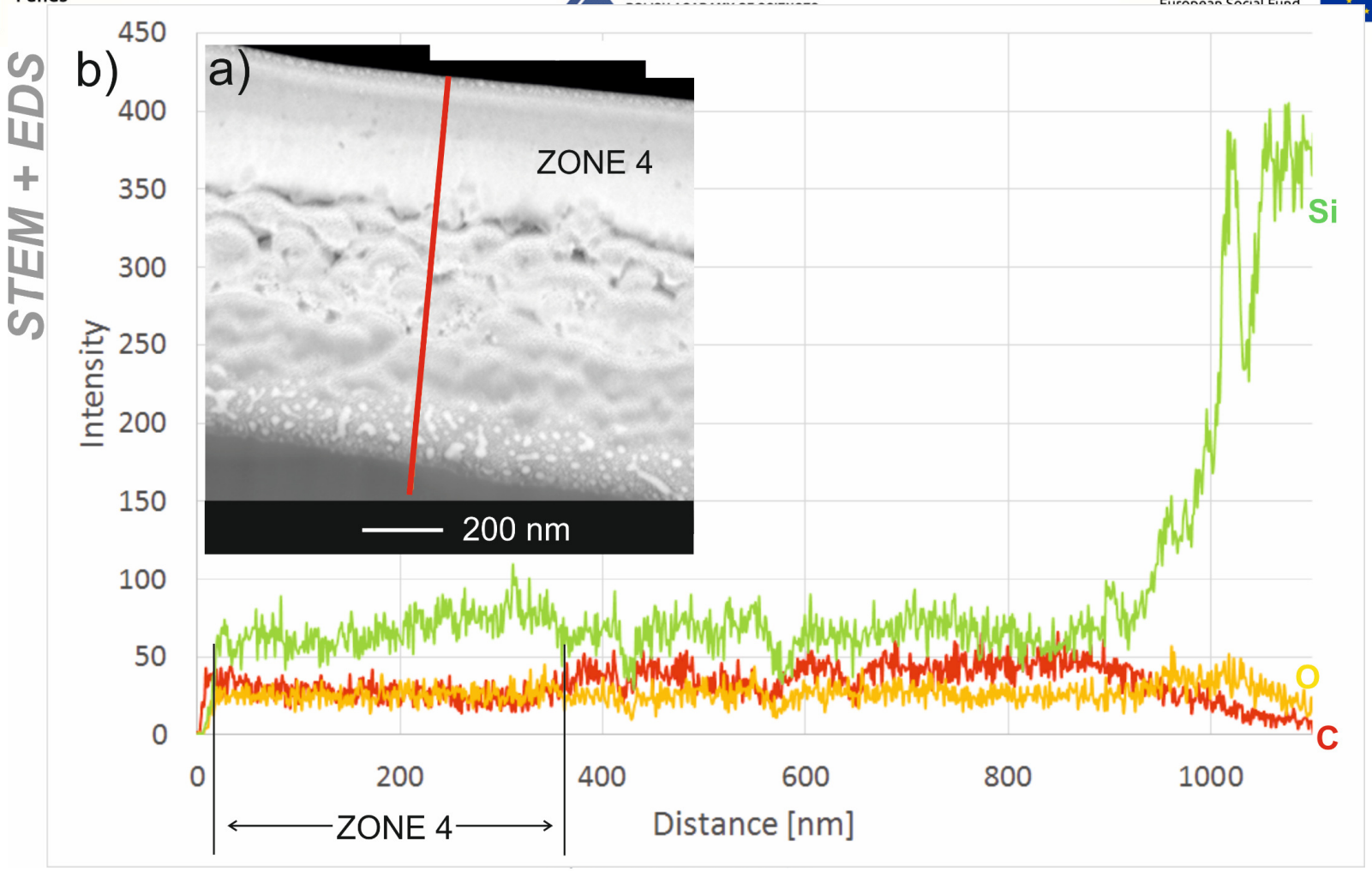
European Union
European Social Fund



Project WND-POWR.03.02.00-00-I043/16

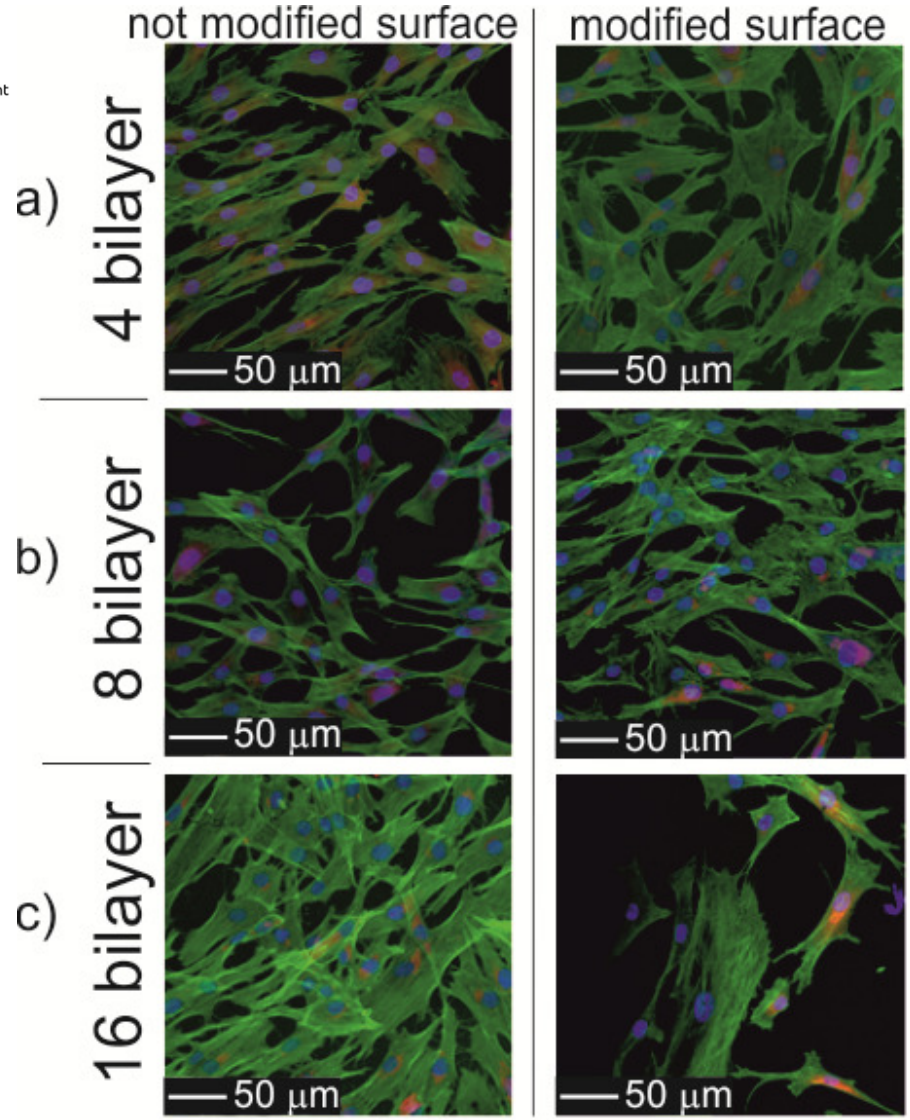
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds



Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development



European Union
European Social Fund

- Project NCN nr: 3066/B/T02/2011/40- *FINISHED*
- Project NCN nr: 2012/06/M/ST8/00408- *HARMONIA- FINISHED*
- Project NCN nr: 2012/07/B/ST8/03396- *OPUS- FINISHED*
- Project NCN nr: 2014/15/B/ST8/00103- *OPUS- FINISHED*
- Project NCN nr: 2015/19/B/ST8/00942- *OPUS- in progress*
- Project NCBR, number: DZP/M-ERA.NET-2015/285/2016- *in progress*

Title: Bio-compatibile, wear resistant, decorative coatings for biological, corrosive fluids interaction- development and their multiscale research

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Multilayer Zr/Zr_2N coatings

As deposited coating (Before mechnaical tests)

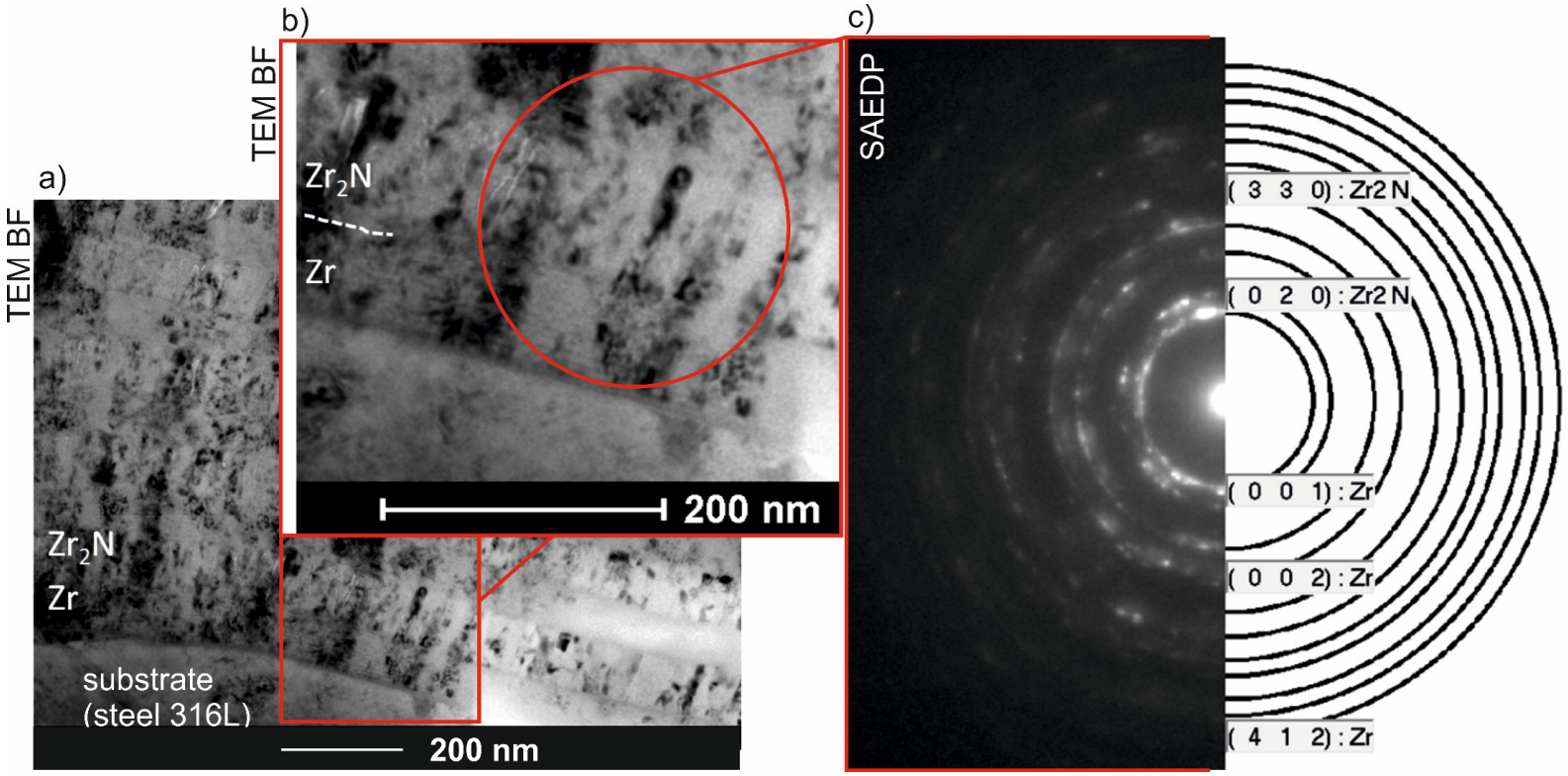
Microstructure characterization

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

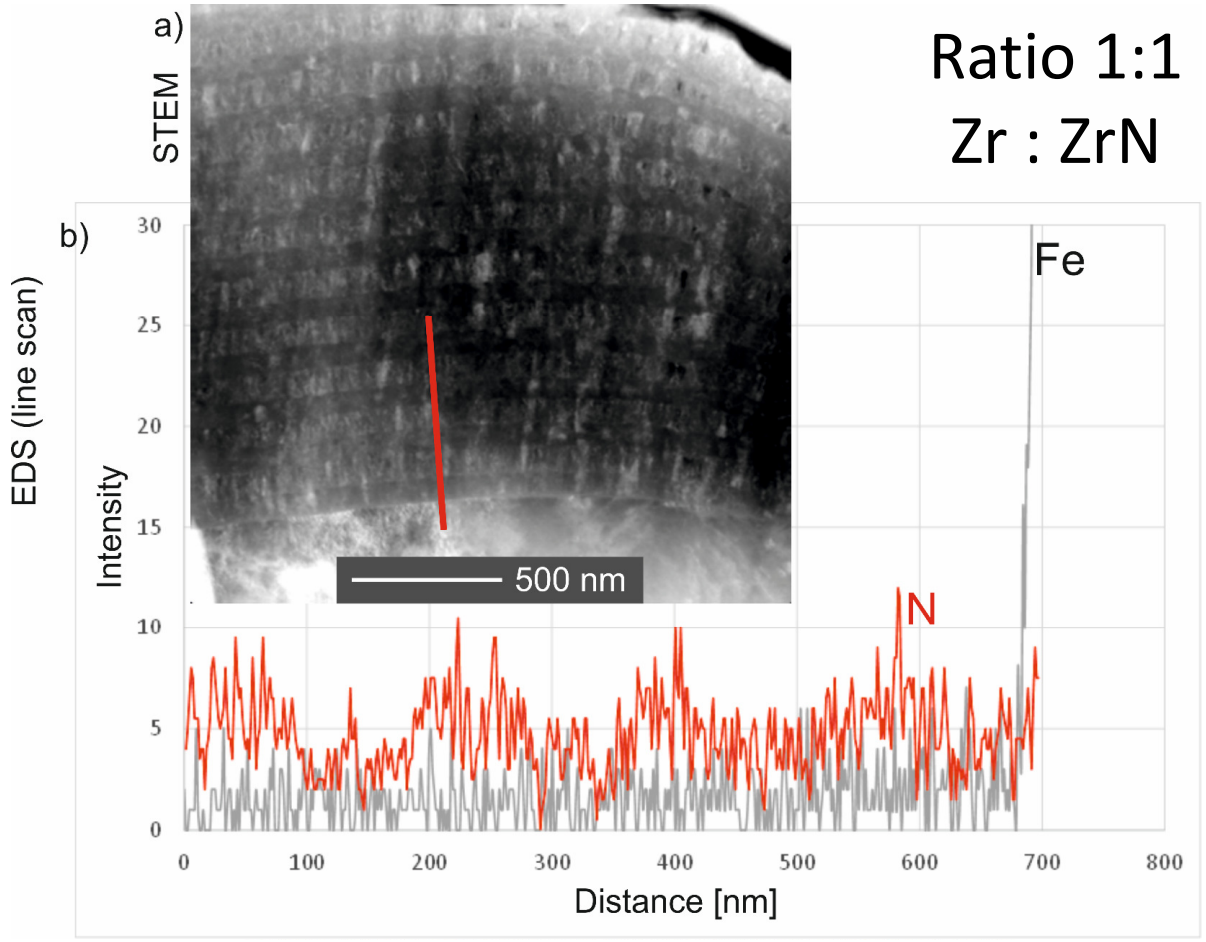
Microstructural characterization of the as-deposited coatings by TEM



Ratio 1:1

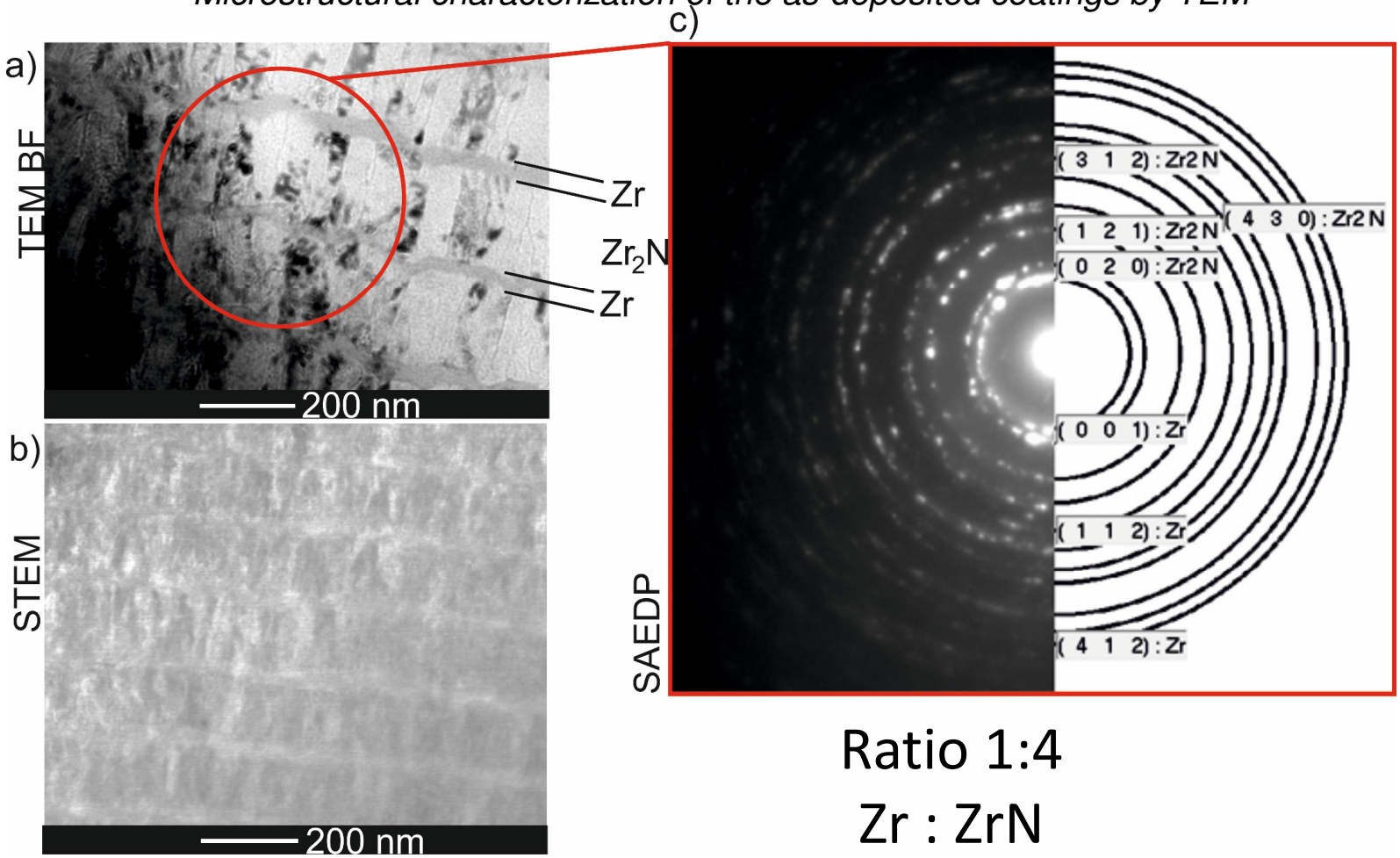
Zr : ZrN

Microstructural characterization of the as-deposited coatings by TEM



Project co-financed by the European Union within the European Social Funds

Microstructural characterization of the as-deposited coatings by TEM



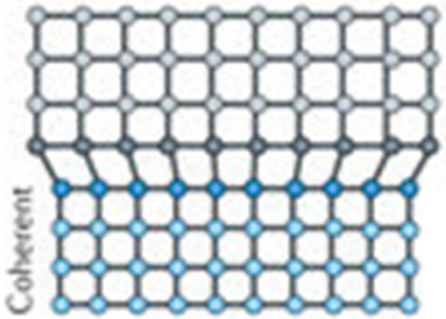
Ratio 1:4

Zr : ZrN

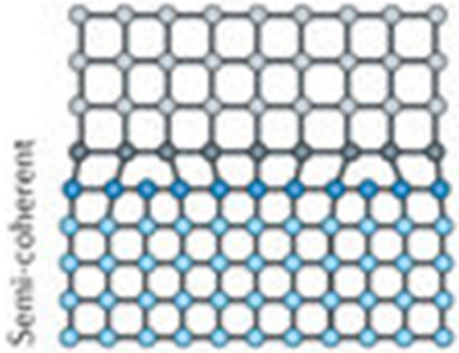
Project co-financed by the European Union within the European Social Funds

Microstructural characterization of the as-deposited coatings by TEM

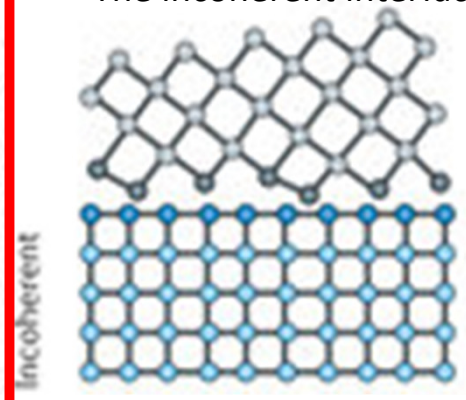
The coherent interface



The semi- coherent interfece

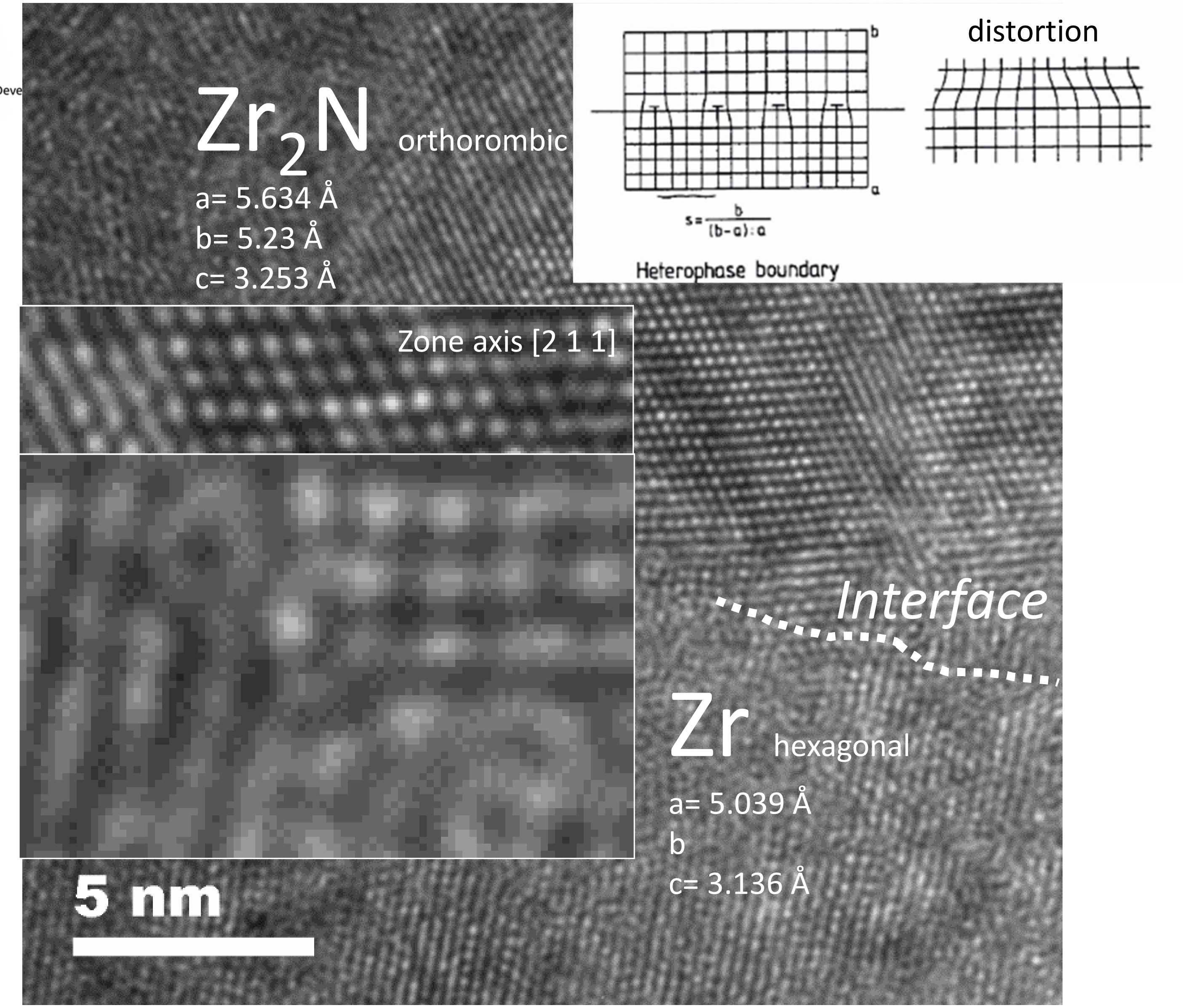


The incoherent interface

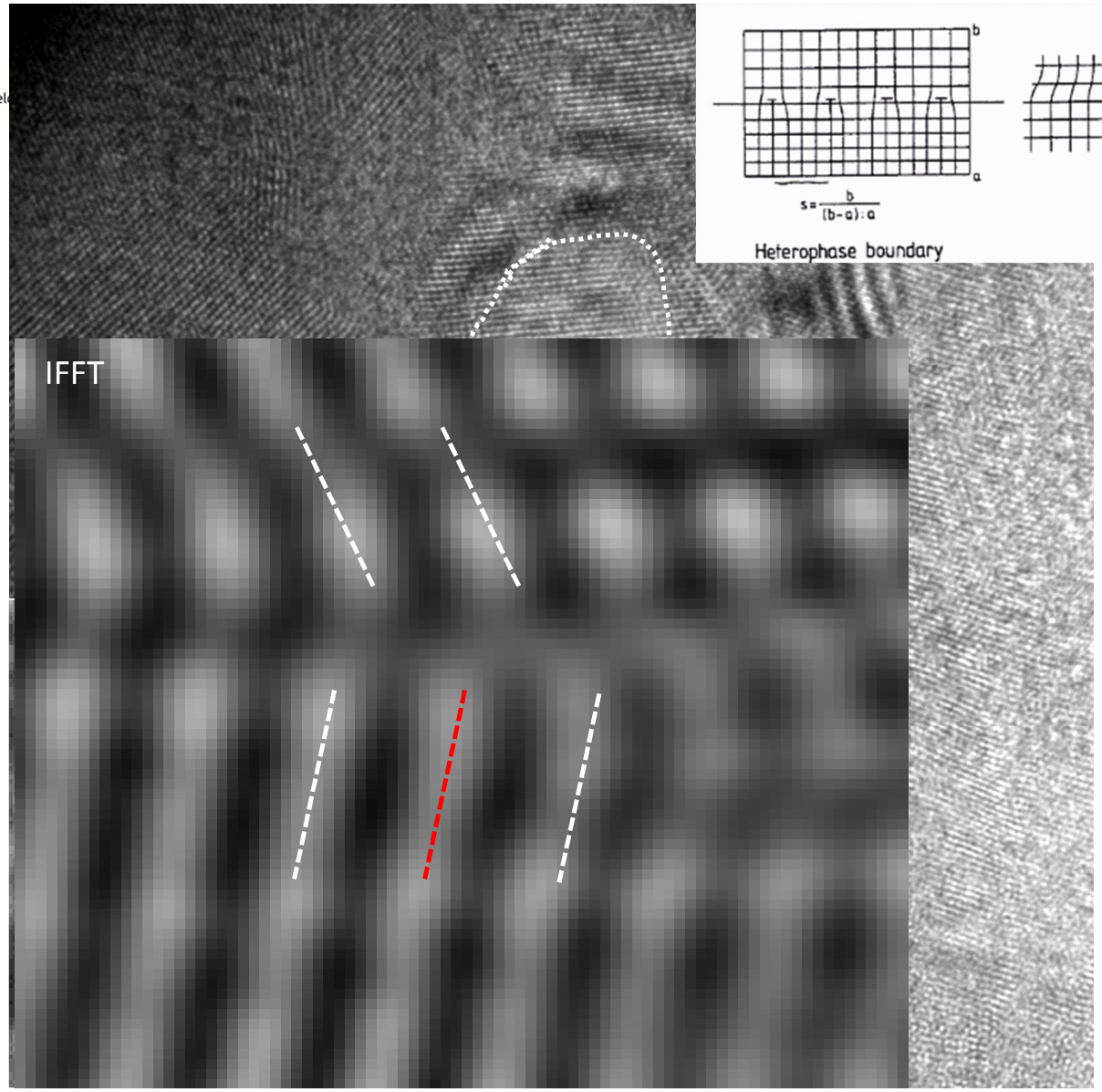


Coherency in between Zr and Zr_xN

HRTEM



HRTEM



European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Multilayer Zr/Zr_2N coatings

Coating after mechanical tests

Microstructure characterization

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

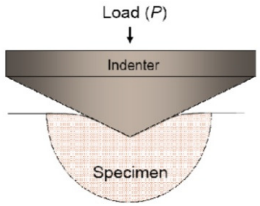
Project co-financed by the European Union within the European Social Funds

Micromechanical tests results

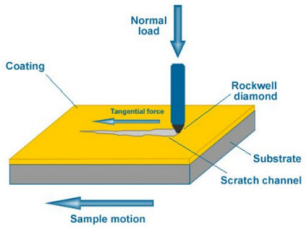
Micromechanical tests results

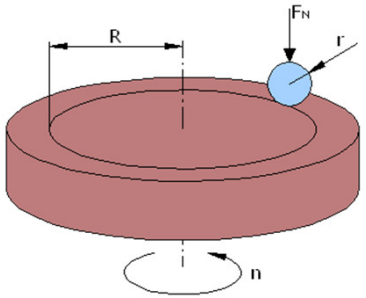
	Indentation		Critical upload		Tribological tests results		
coating	H [GPa]	E [GPa]	L_{C1} [N]	L_{C2} [N]	Coefficient of wear under F=0,25N mm^3/Nm	Coefficient of friction	Number of cycles to coating remove under the F=1N
ZrN *reference*	29,95	375	4.9	14.6	$2.92 \cdot 10^{-6}$	0.18	8200
Zr/ZrN Ratio 1:1	11,14	158	0.9	17.5	$15.55 \cdot 10^{-6}$	0.12	100
Zr/ZrN Ratio 1:2	12,43	200	1.7	**28.4**	**$5.10 \cdot 10^{-6}$**	0.1	280
Zr/ZrN Ratio 1:4	**14,59**	**221**	1	**> 30**	**$6.74 \cdot 10^{-6}$**	0.1	**750**

Indentation test (Hardness test)



Scratch test set-up

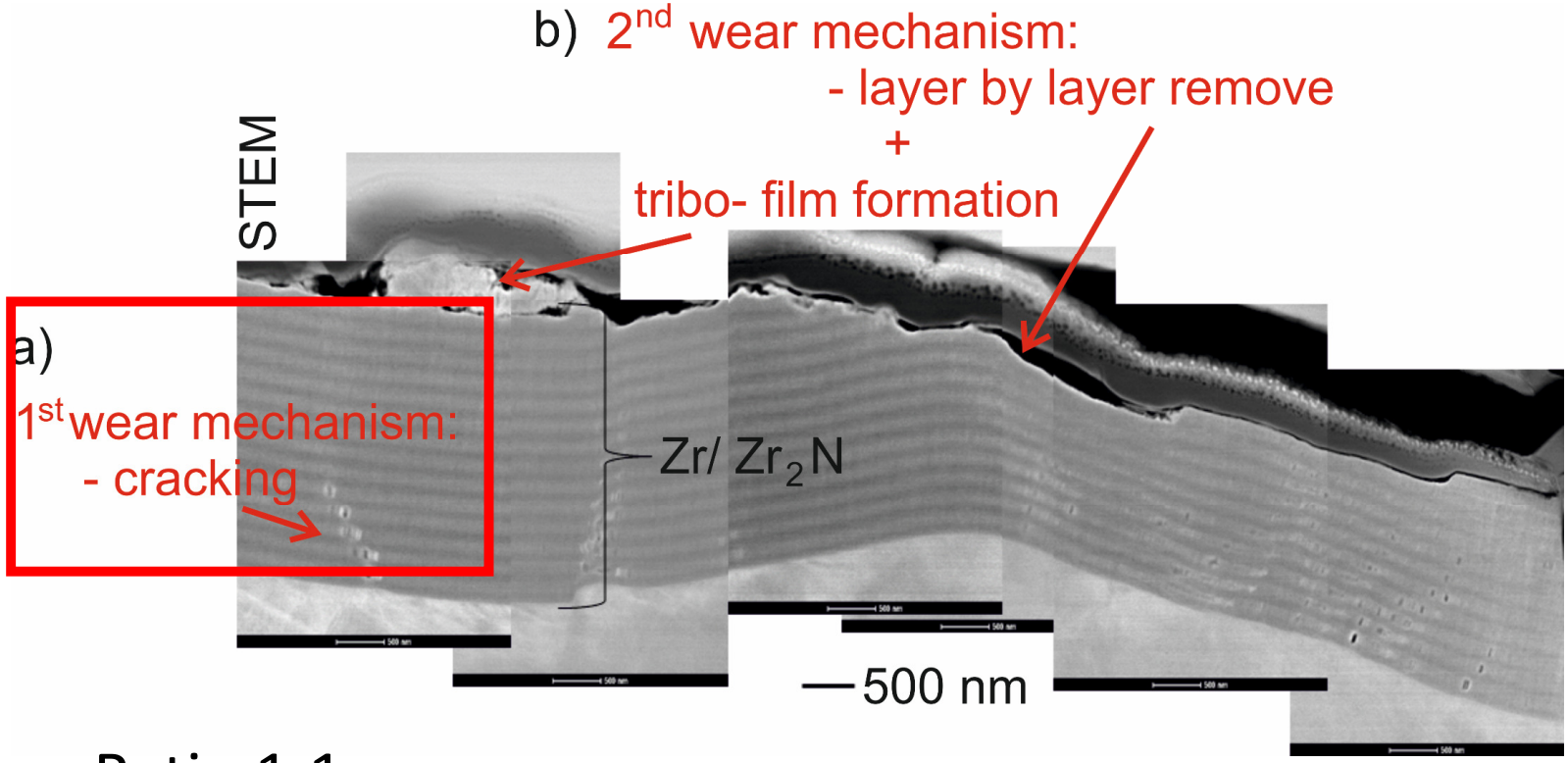




- **Hardness – resistance to penetration of a hard indenter**

Microstructural characterization of the coatings by TEM after the wear test

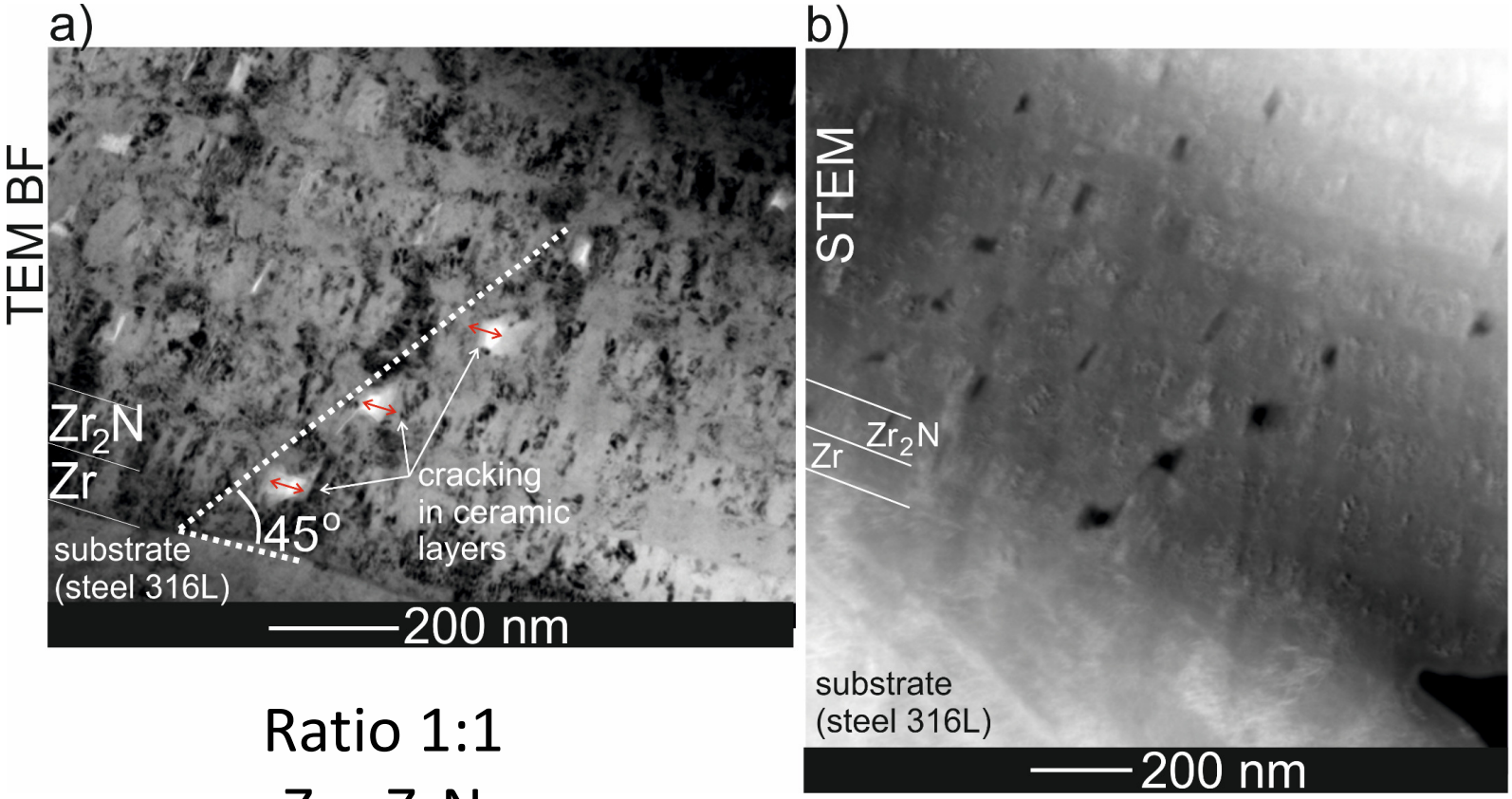
Microstructural characterization of the coatings by TEM after the wear test



Ratio 1:1

Zr : ZrN

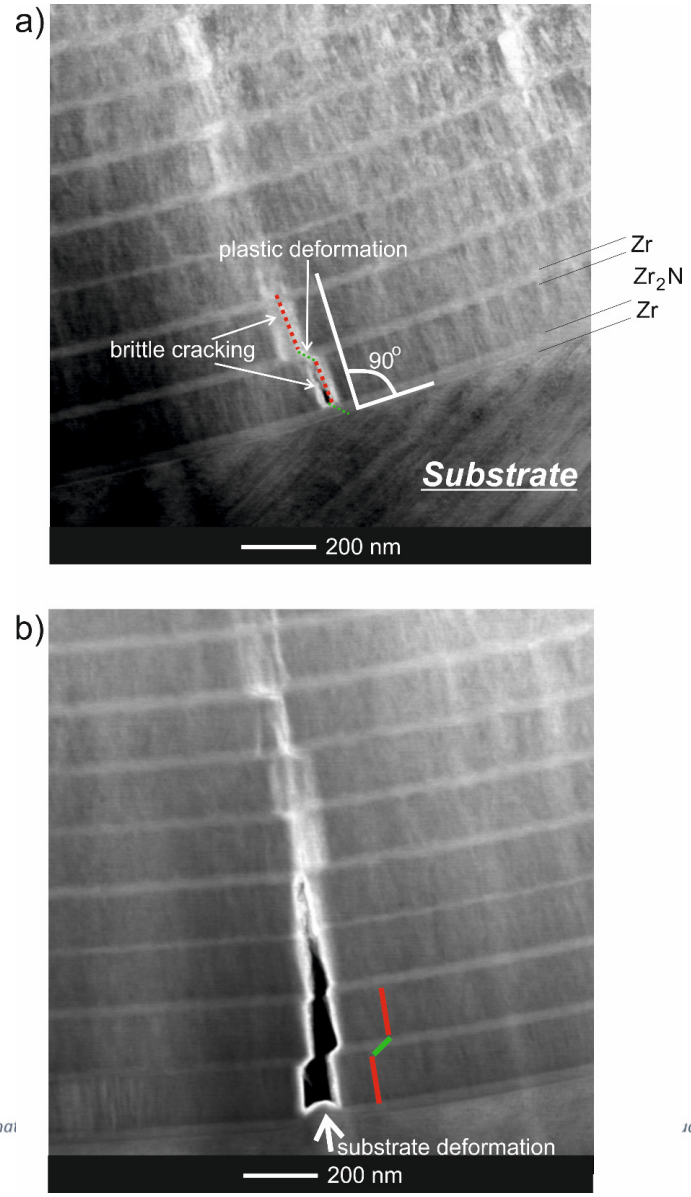
Microstructural characterization of the coatings by TEM after the wear test



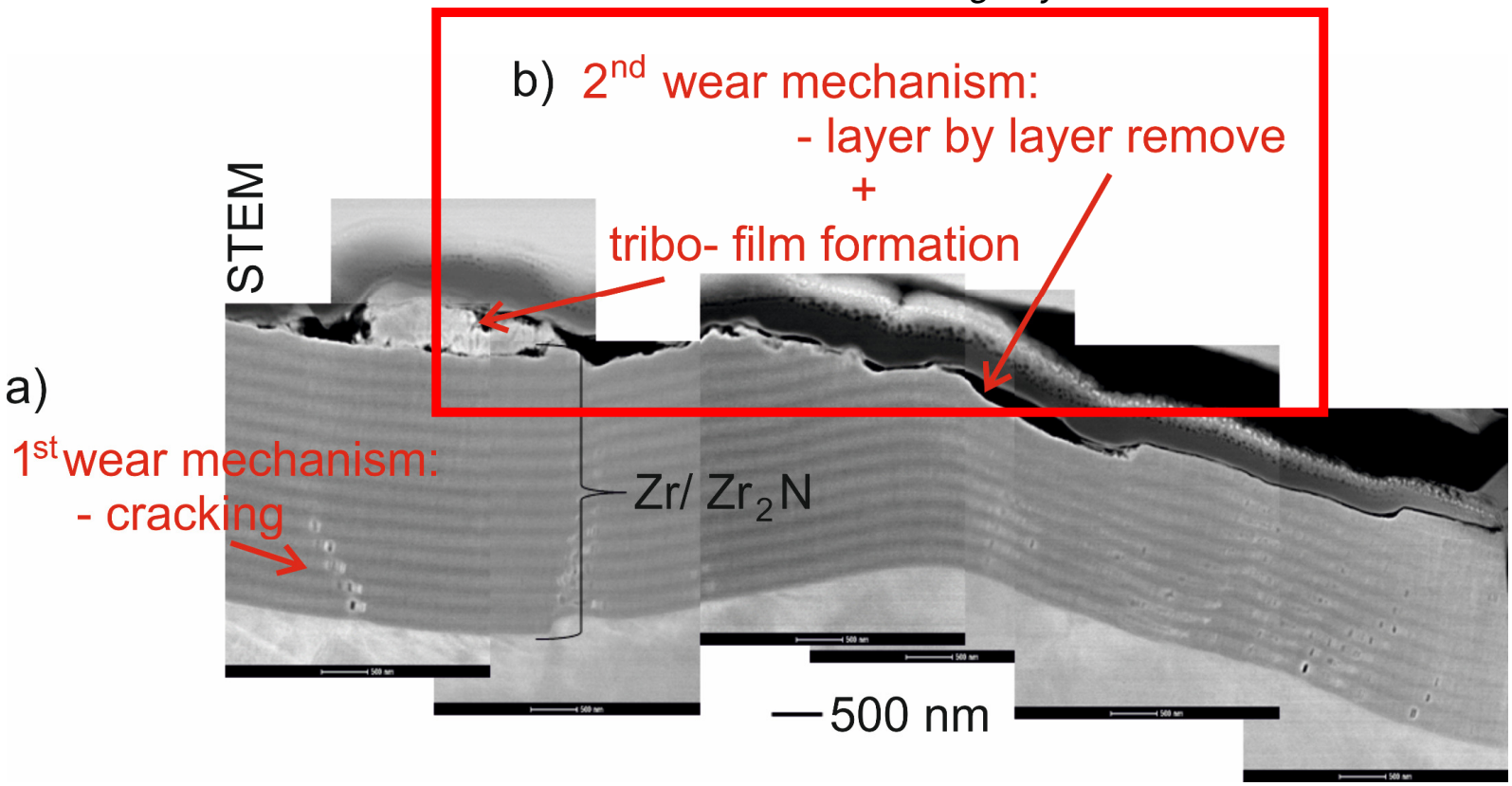
Ratio 1:1

Zr : ZrN

Ratio 1:4
Zr : ZrN

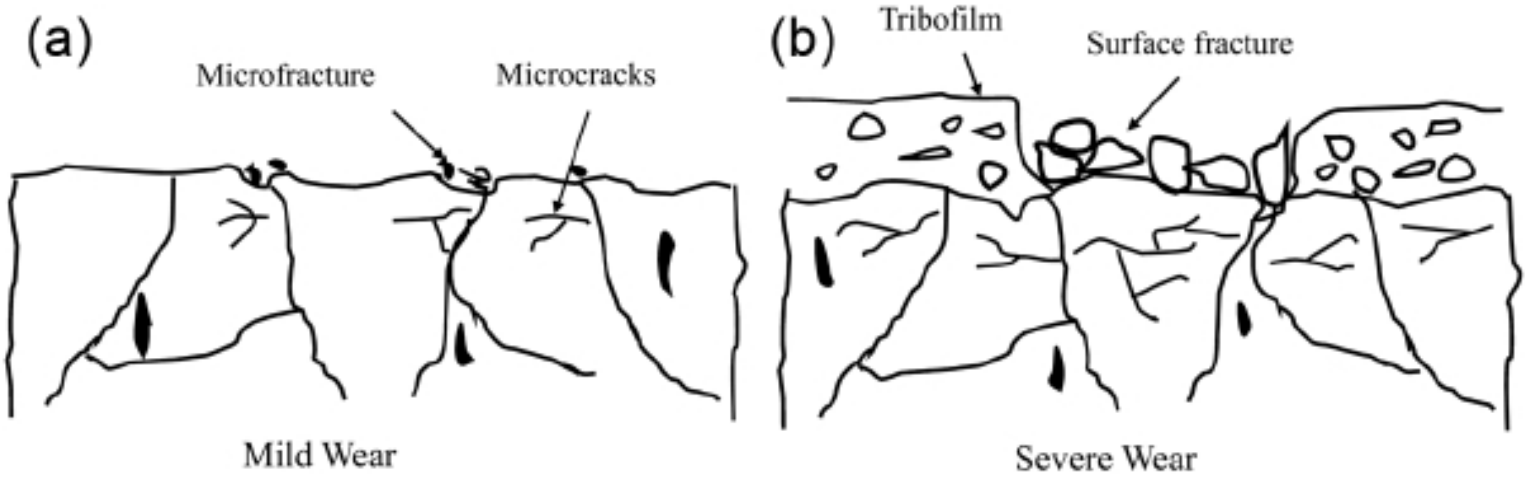


Microstructural characterization of the coatings by TEM after the wear test

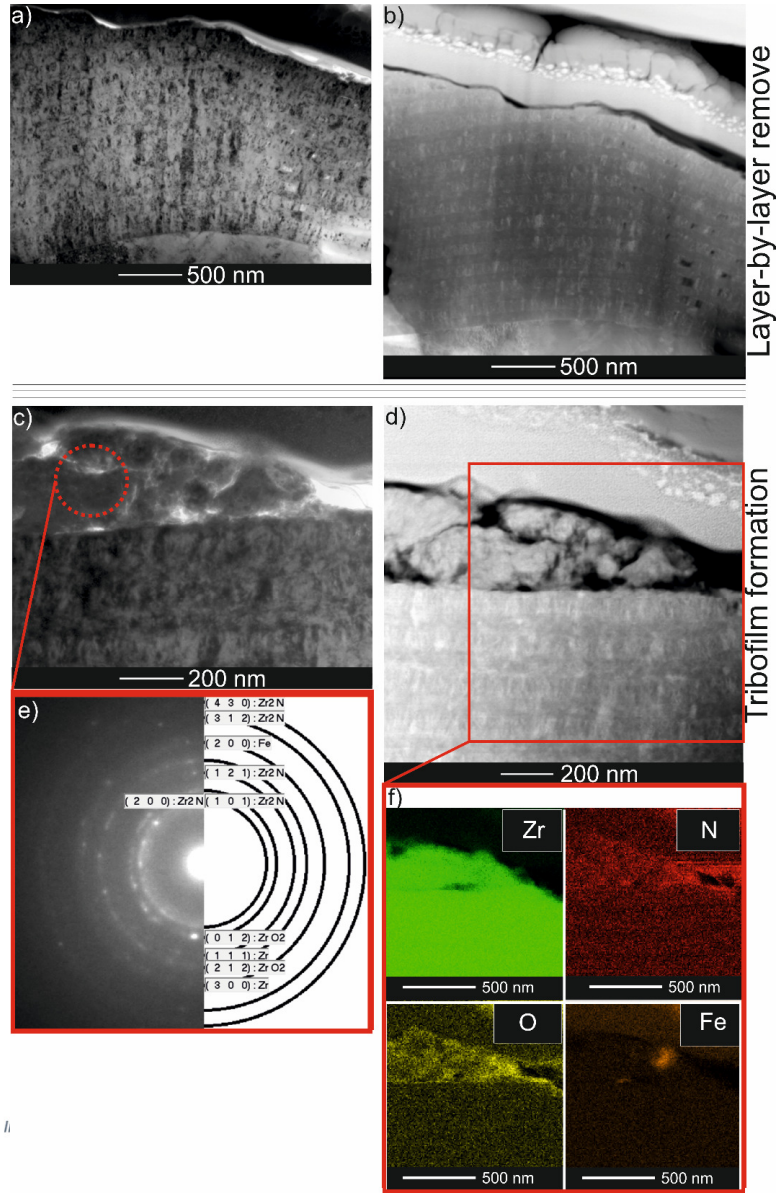


Microstructural characterization of the coatings by TEM after the wear test

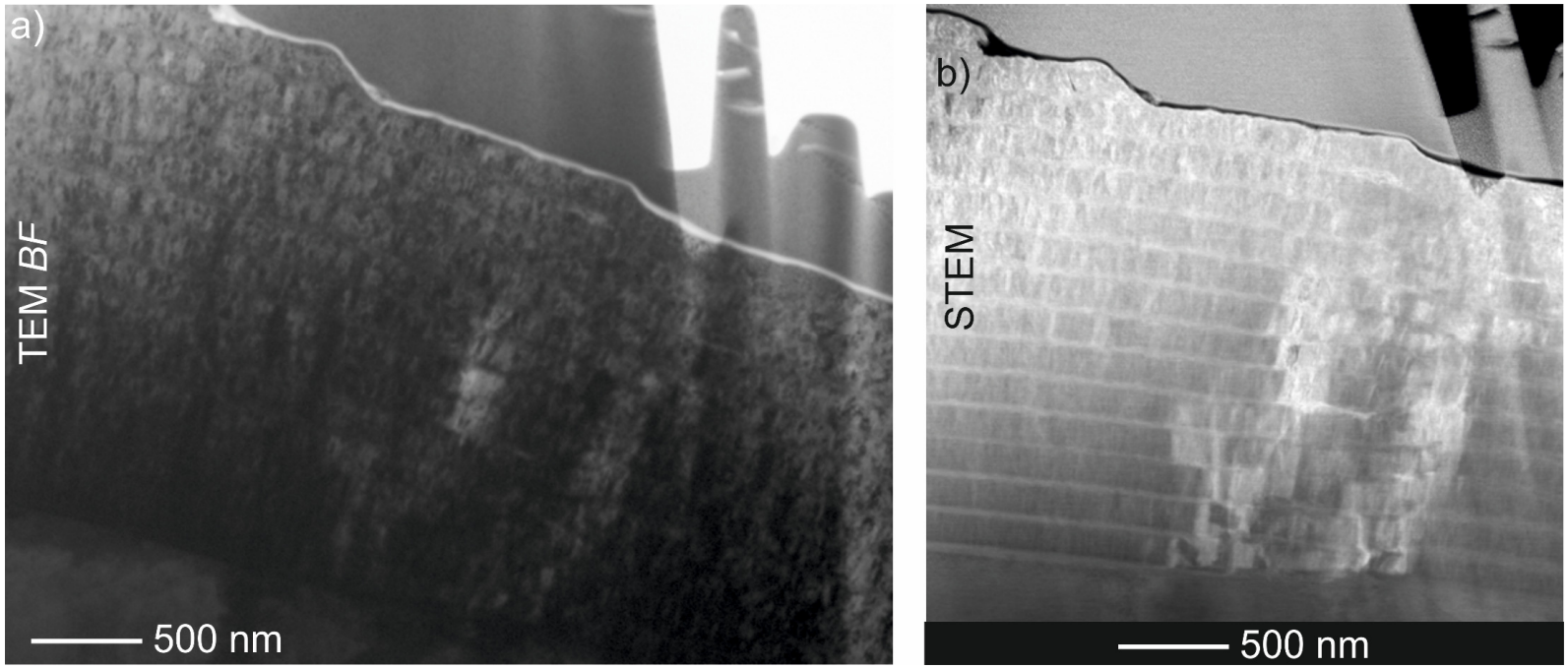
Soft Zr phase
+
Hard Zr_2N phase



Ratio 1:1
Zr : ZrN



Microstructural characterization of the coatings by TEM after the wear test



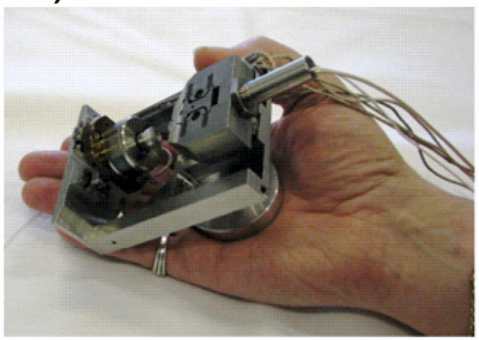
Ratio 1:4

Zr : ZrN

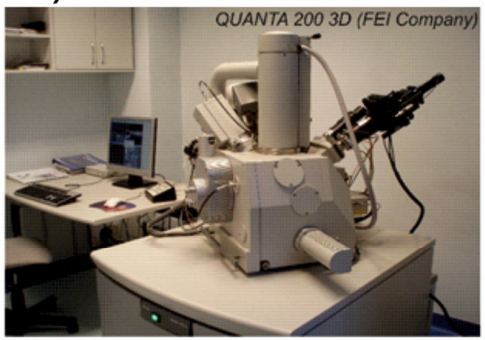
Mechanical in situ tests performed in the SEM chamber

Mechanical in situ tests performed in the SEM chamber

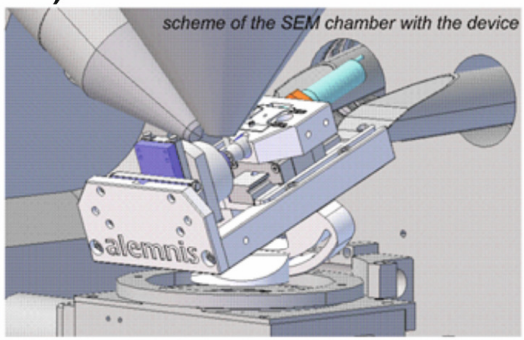
a)



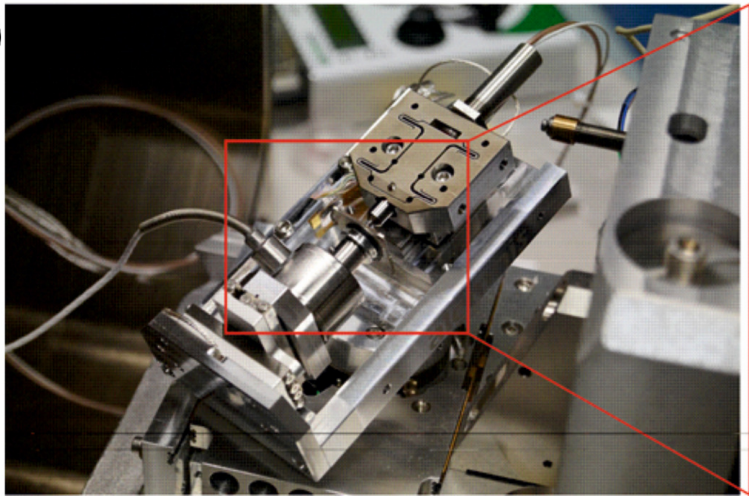
b)

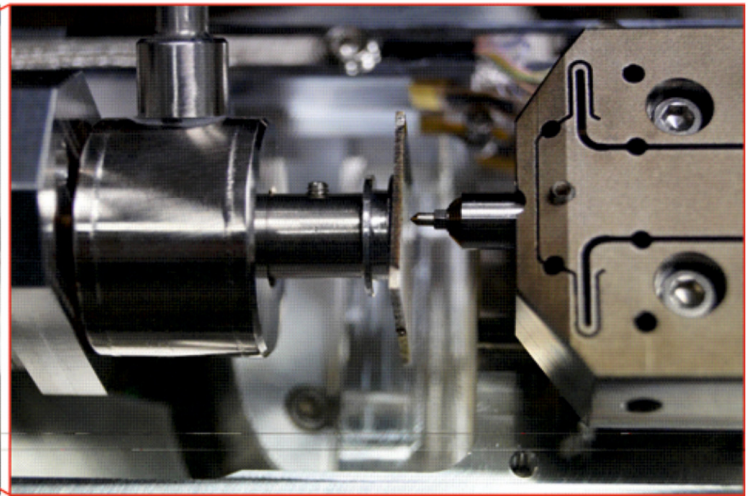


c)



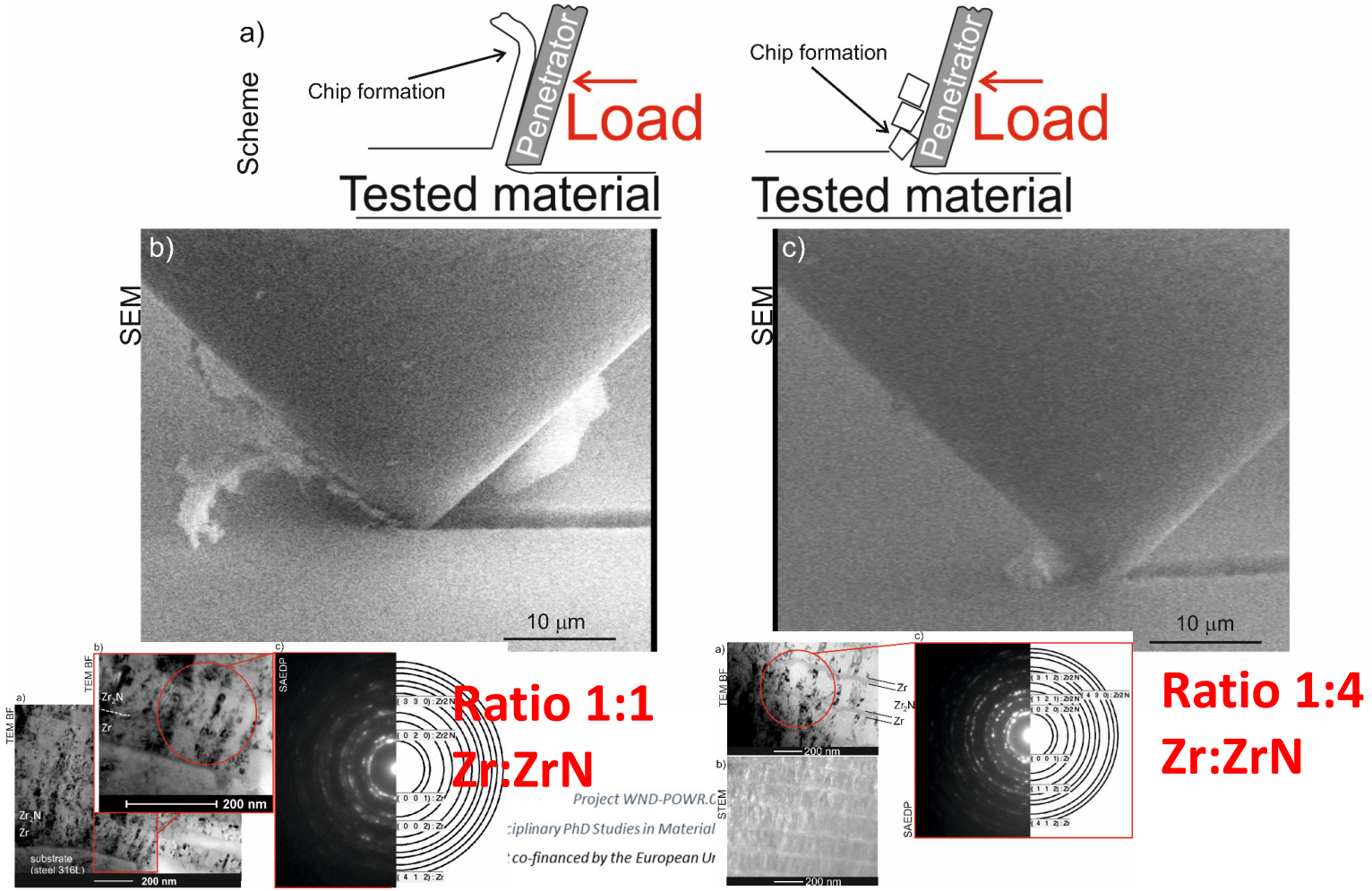
d)





e)

Mechanical in situ tests performed in the SEM chamber



Project WND-POWR.
iplinary PhD Studies in Material
co-financed by the European U

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

Multilayer Zr/Zr_2N coatings

Coating after corrosion tests

Microstructure characterization

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

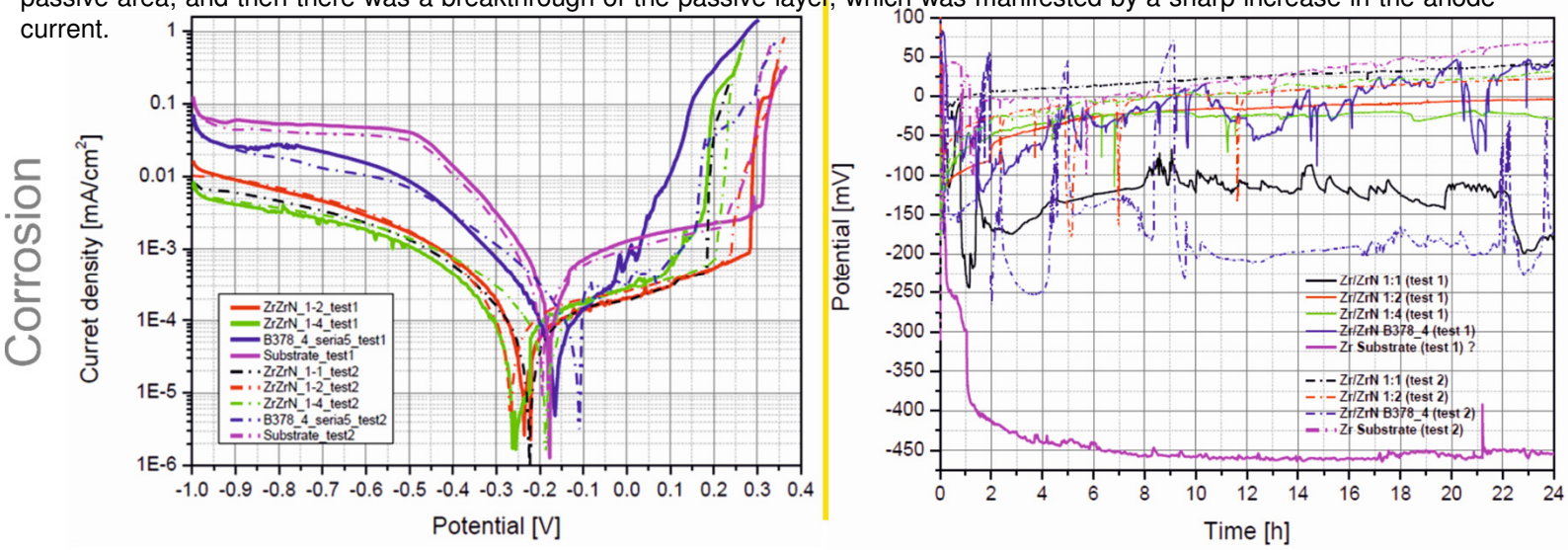
Corrosion is the destructive attack of a metal by its reaction with the environment

Corrosion test results

(Bio- corrosion in body fluids)

Linear Sweep Voltammetry – LSV

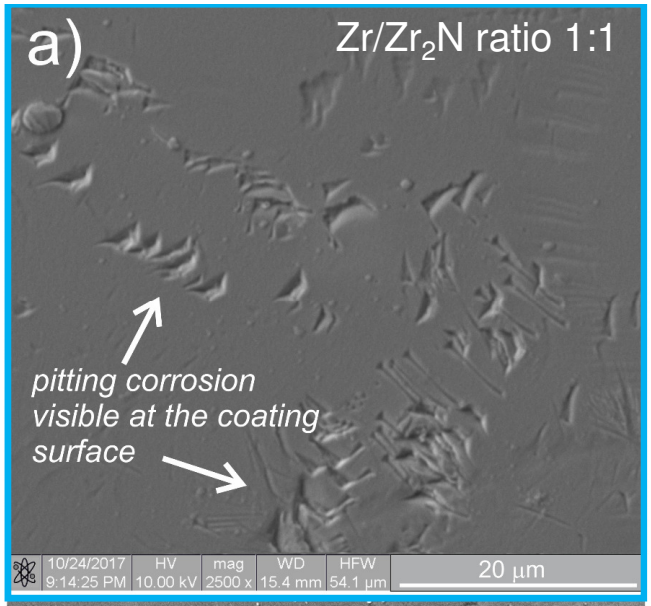
The nature of potentiodynamic curves indicates that the tested coatings and substrate (316L steel) underwent pitting corrosion in Ringer's solution. The sharp increase in the anode current, at potentials above 0 mV, indicates the formation of pitting on the surface of coatings and steel. In the cathodic area, the highest currents were recorded for the substrate (pink continuous and dotted curves). Coated substrates with all coatings showed much lower currents in the cathodic region, which indicated that the cathodic reaction (oxygen reduction reaction) was slower than on the uncoated substrate (316L). The course of the polarization curves in the anodic area of the uncoated substrate and of the samples with the coatings were very similar. They showed a passive area, and then there was a breakthrough of the passive layer, which was manifested by a sharp increase in the anode current.

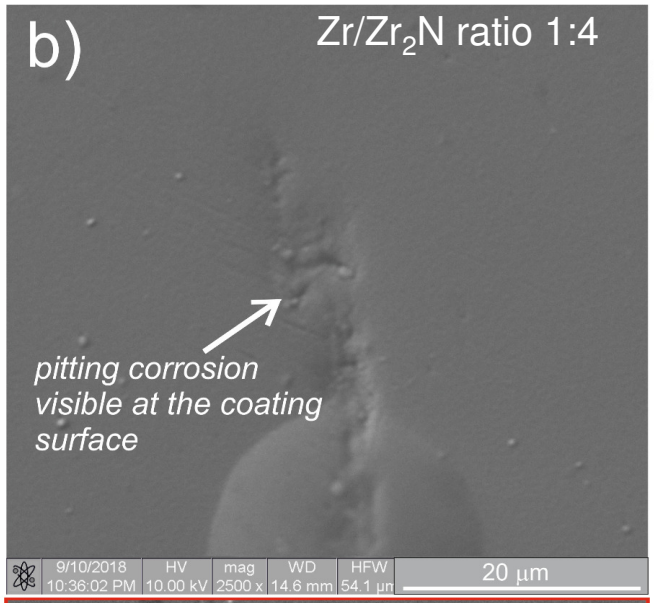


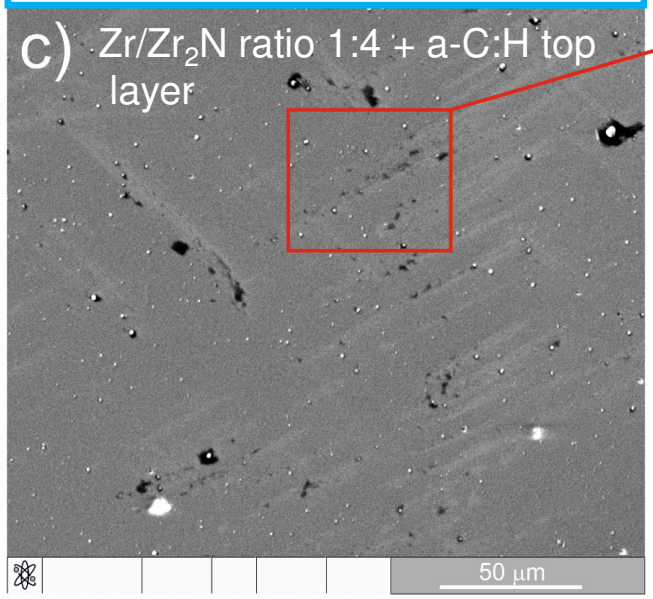
The exception was the blue curve, recorded for sample B378 (with the carbon layer), on which a continuous increase in the anode current was visible without a clear passive area. Such character of the polarization curve indicated that the B378 sample exhibited the lowest corrosion resistance in the Ringer solution. Fig. 2 showed the corrosion potential changes registered within 24 hours in Ringer's solution. The corrosion potentials recorded for the sample Zr / ZrN_B378 (blue curves) deserve attention. They showed very large potential oscillations. In 24 hours it was impossible to achieve a steady state (stable value of corrosion potential). These results suggested that the sample showed the worst corrosion resistance in the Ringer fluid environment.

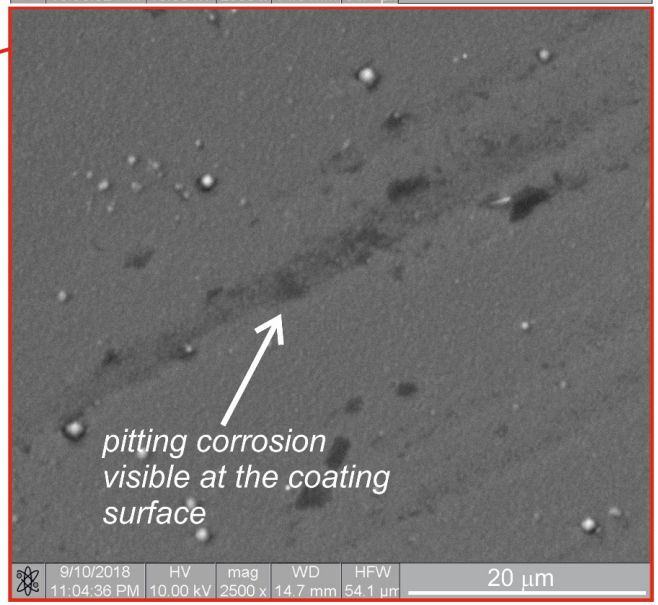
Microstructural characterization of the coatings by TEM after corrosion

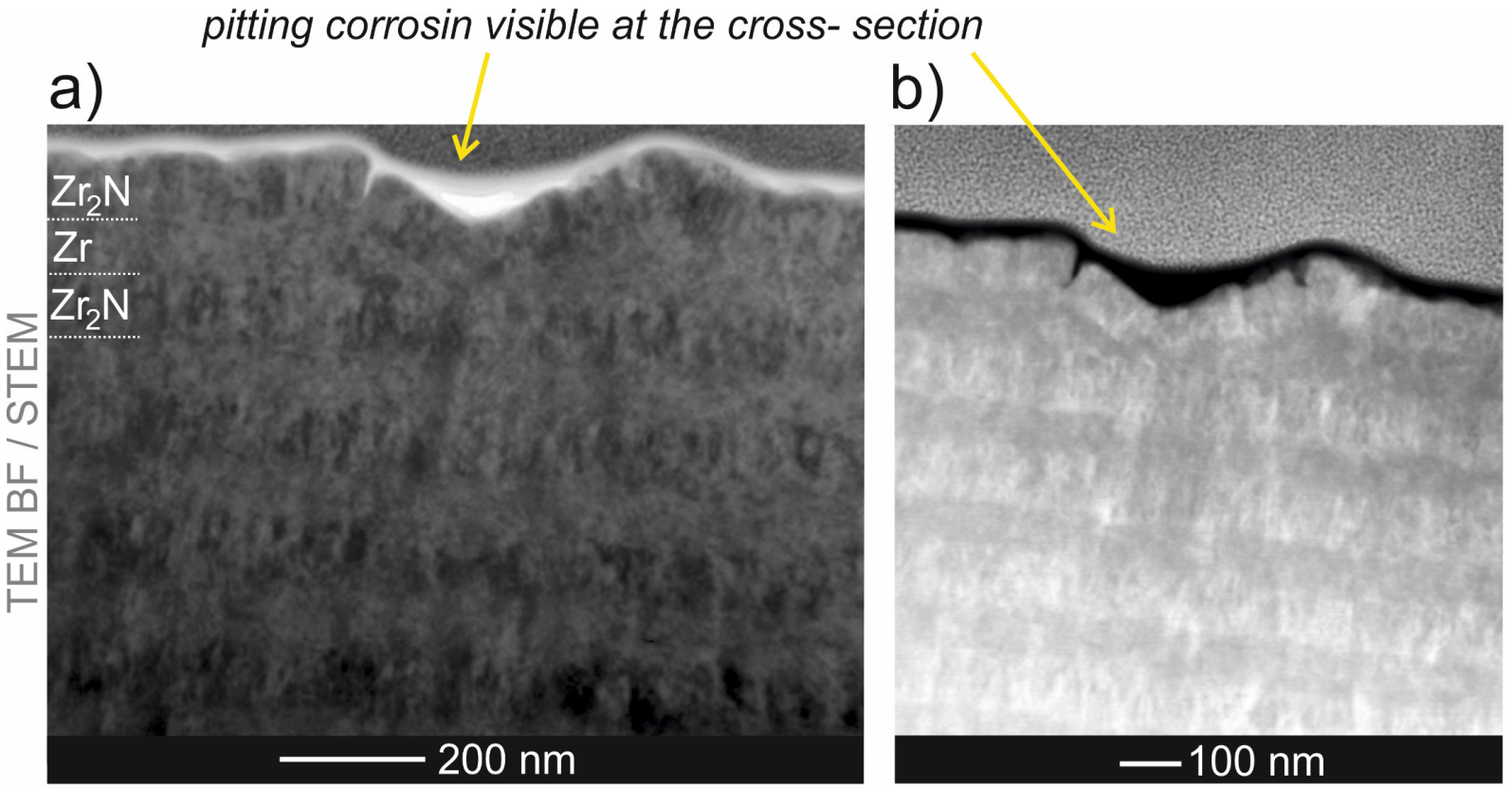
SEM


a)
Zr/Zr2N ratio 1:1
pitting corrosion visible at the coating surface
10/24/2017 9:14:25 PM
HV 10.00 kV
mag 2500 x
WD 15.4 mm
HFW 54.1 µm
20 µm

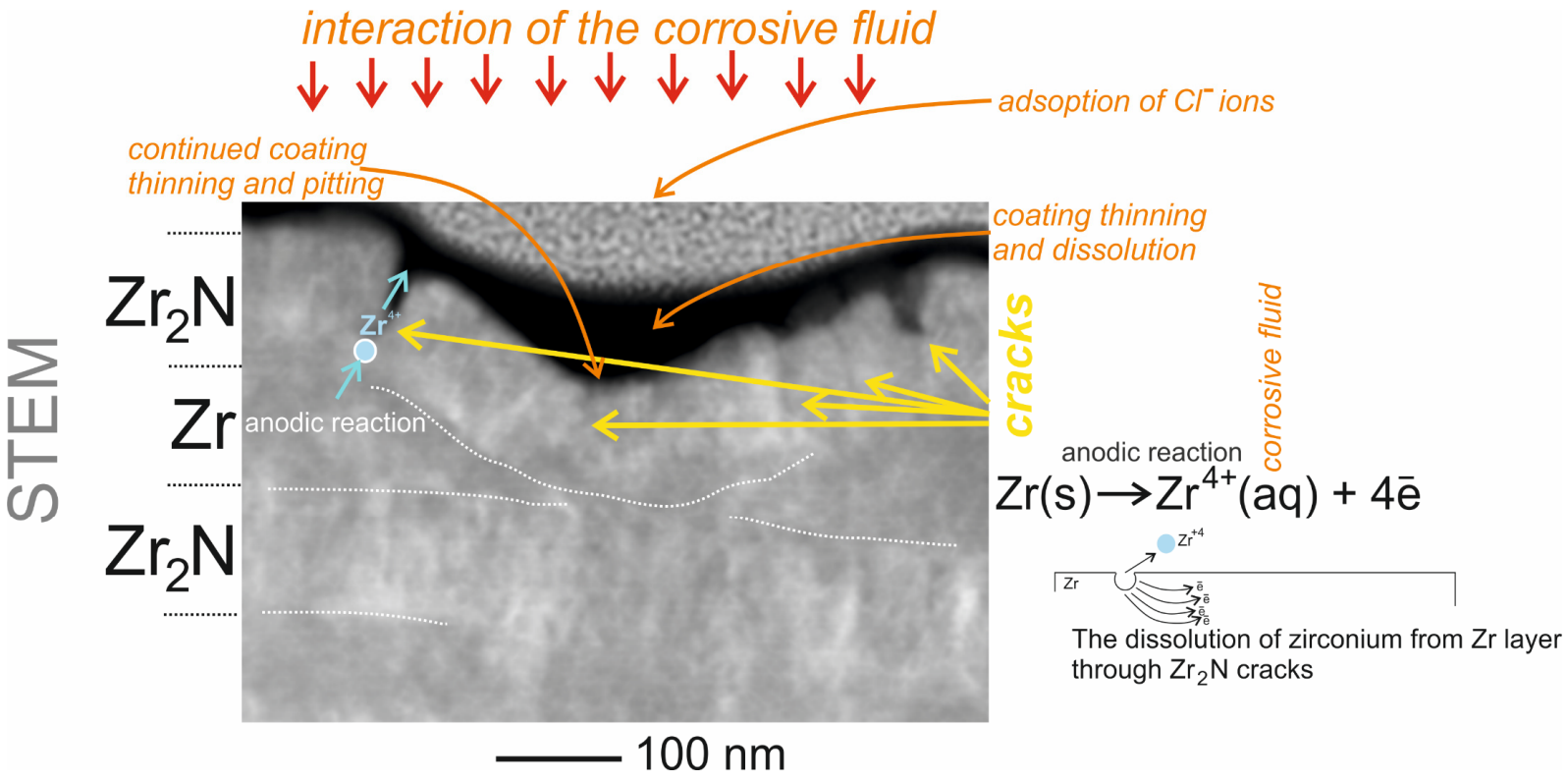

b)
Zr/Zr2N ratio 1:4
pitting corrosion visible at the coating surface
9/10/2018 10:36:02 PM
HV 10.00 kV
mag 2500 x
WD 14.6 mm
HFW 54.1 µm
20 µm


c)
Zr/Zr2N ratio 1:4 + a-C:H top layer
50 µm


pitting corrosion visible at the coating surface
9/10/2018 11:04:36 PM
HV 10.00 kV
mag 2500 x
WD 14.7 mm
HFW 54.1 µm
20 µm



Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds



Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

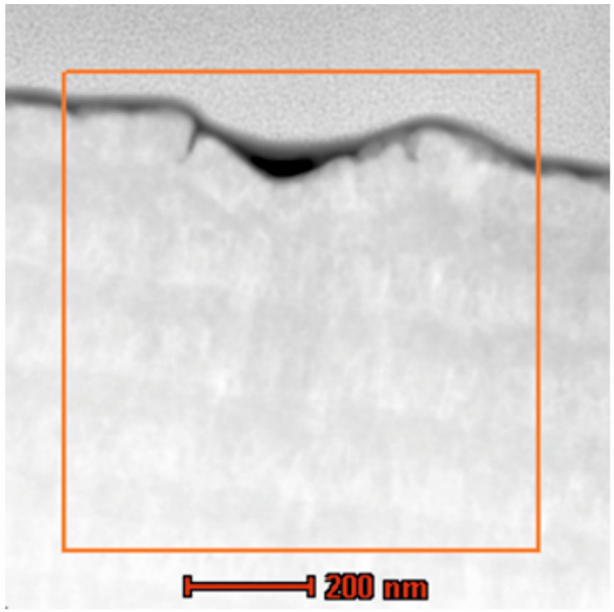
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Developmer

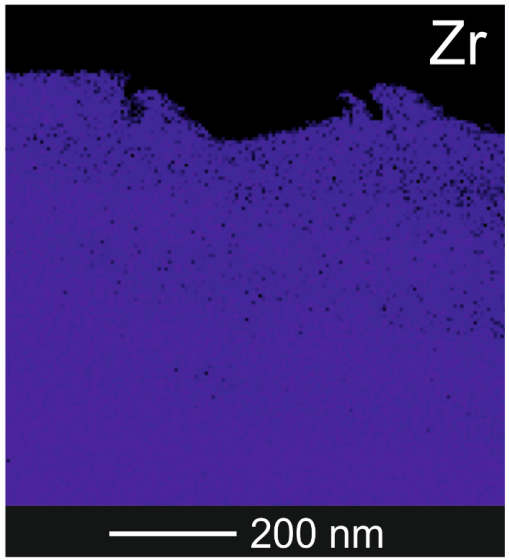
ropean Union
European Social Fund

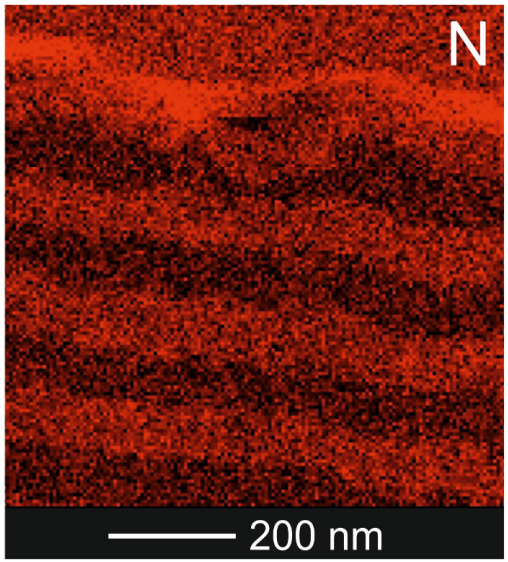
a)

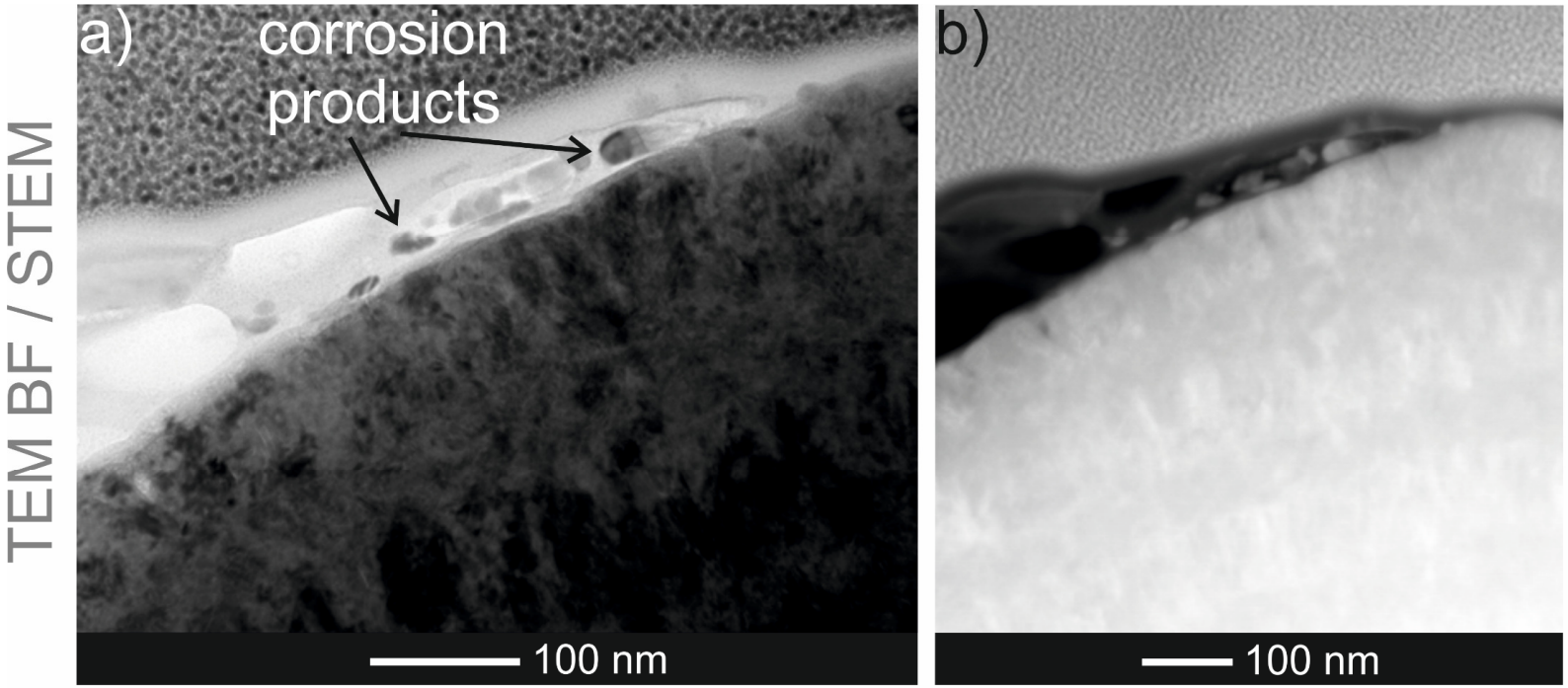
STEM + EDS



b)





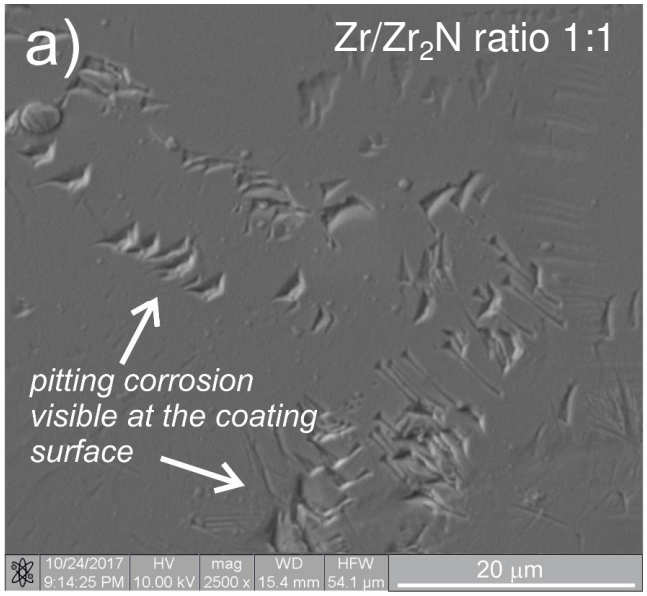


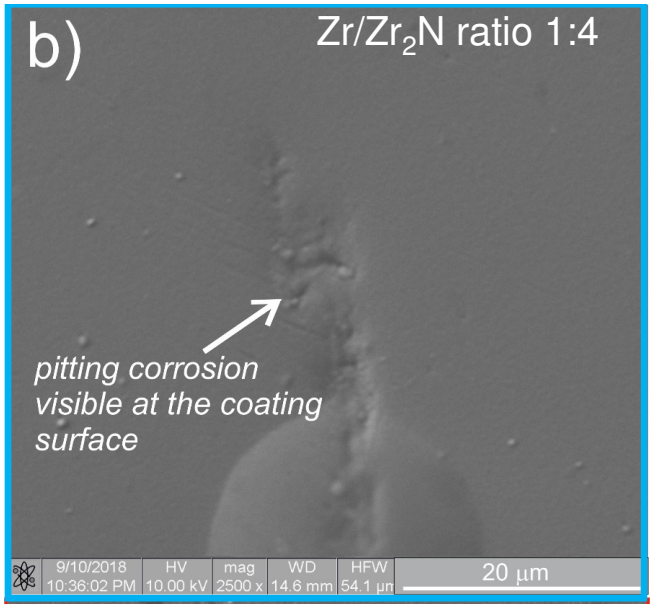
Project WND-POWR.03.02.00-00-I043/16

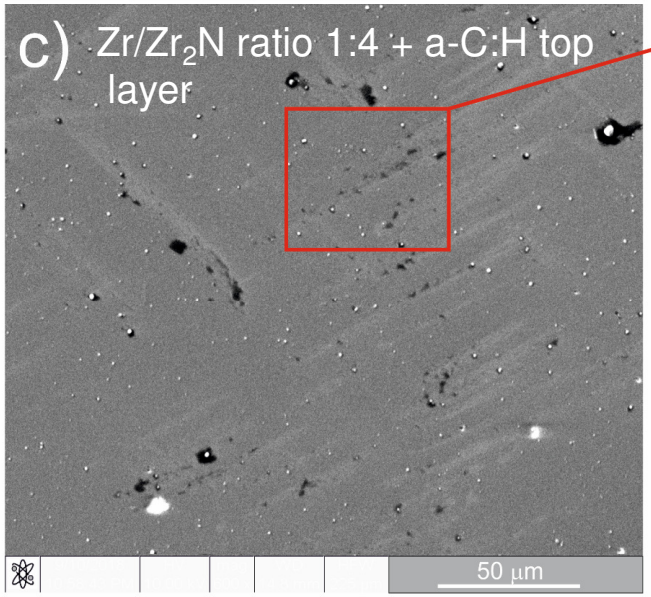
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

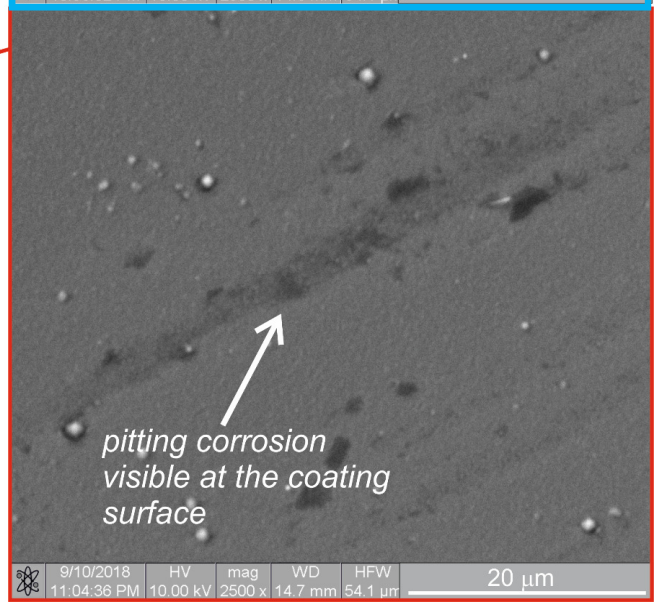
Project co-financed by the European Union within the European Social Funds

SEM


a)
Zr/Zr2N ratio 1:1
pitting corrosion visible at the coating surface
10/24/2017 9:14:25 PM
HV 10.00 kV
mag 2500 x
WD 15.4 mm
HFW 54.1 µm
20 µm


b)
Zr/Zr2N ratio 1:4
pitting corrosion visible at the coating surface
9/10/2018 10:36:02 PM
HV 10.00 kV
mag 2500 x
WD 14.6 mm
HFW 54.1 µm
20 µm

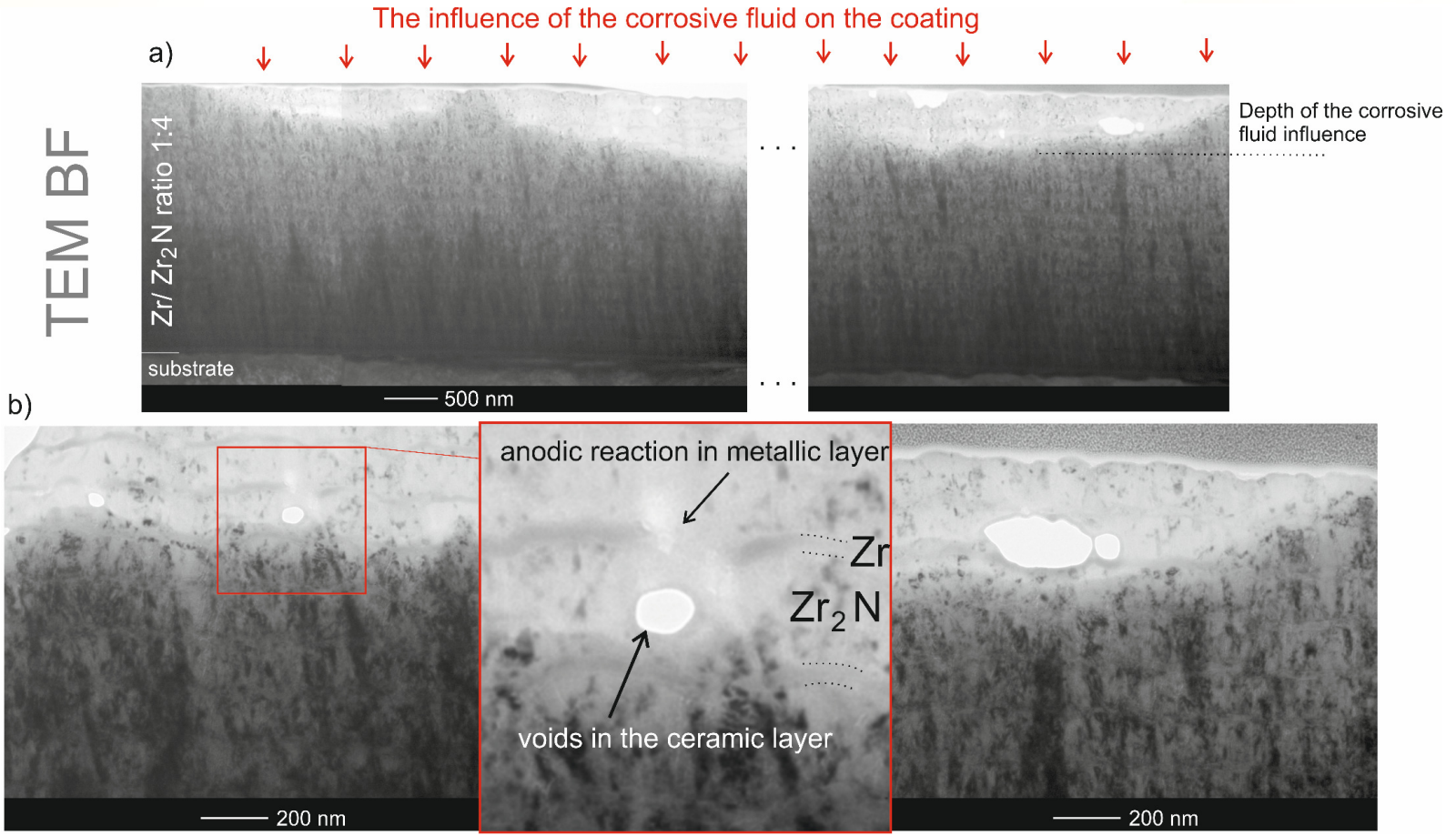

c)
Zr/Zr2N ratio 1:4 + a-C:H top layer
50 µm


pitting corrosion visible at the coating surface
9/10/2018 11:04:36 PM
HV 10.00 kV
mag 2500 x
WD 14.7 mm
HFW 54.1 µm
20 µm

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

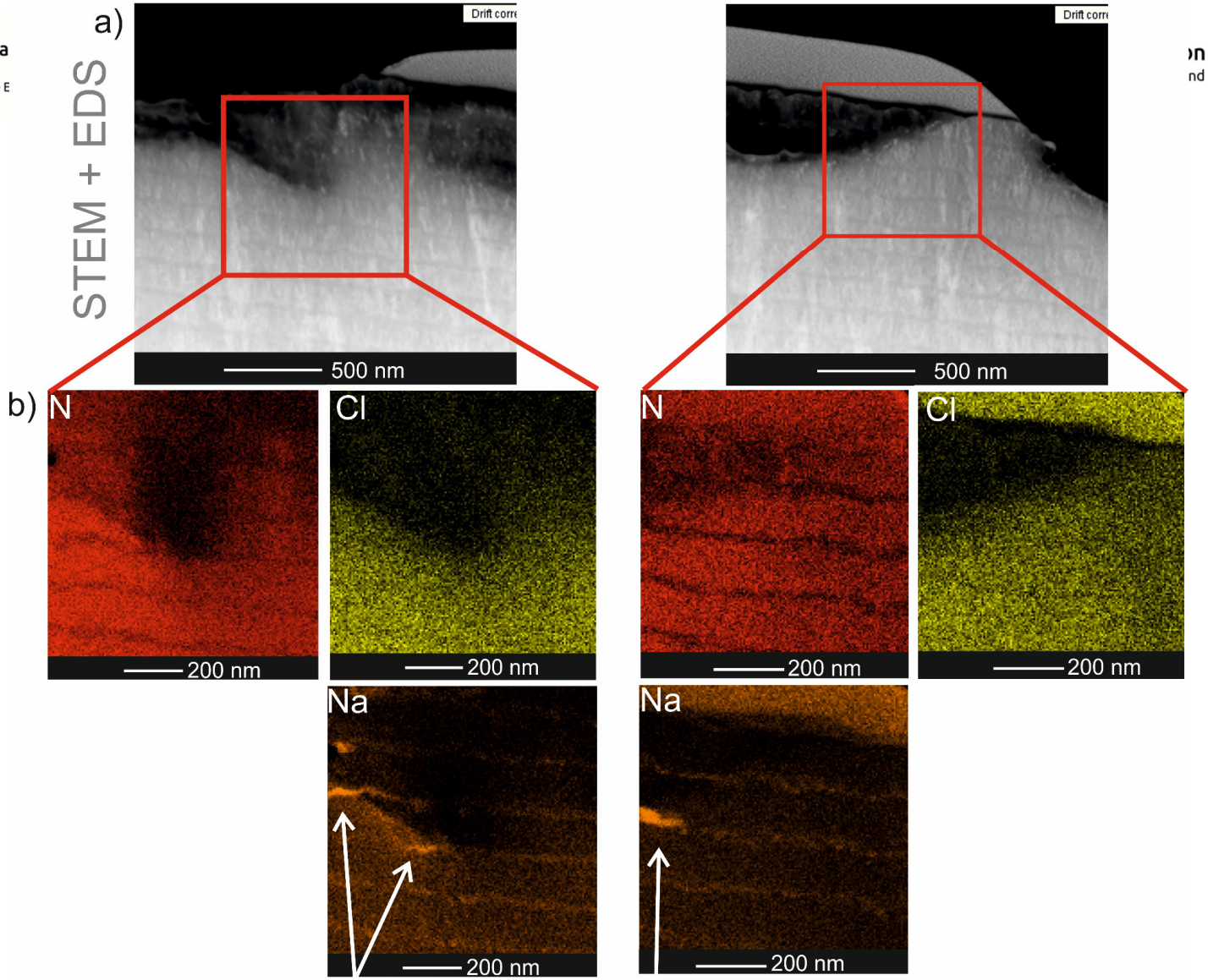
European Union
European Social Fund



Project WND-POWR.03.02.00-00-I043/16

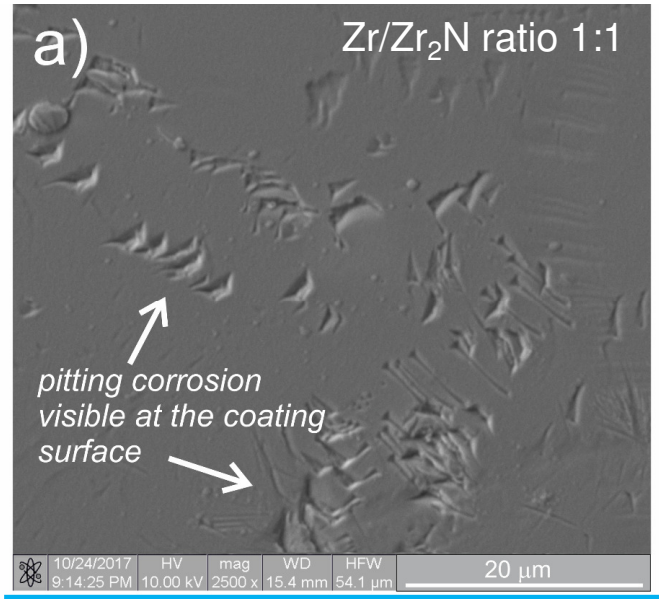
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

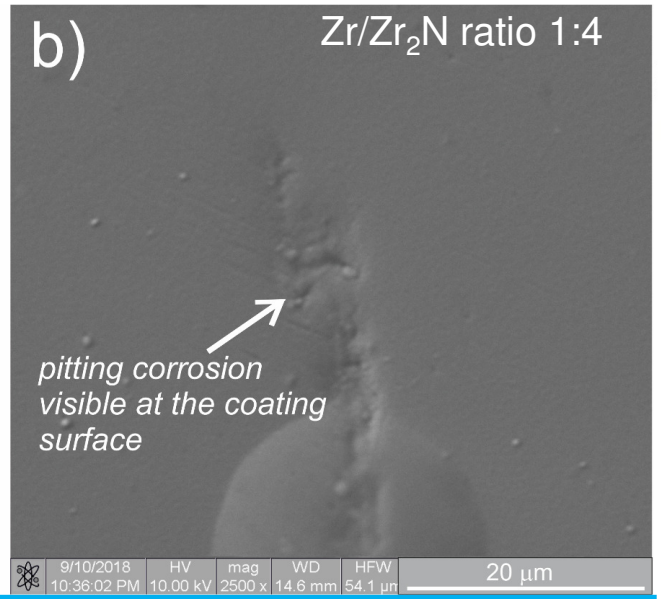
Project co-financed by the European Union within the European Social Funds

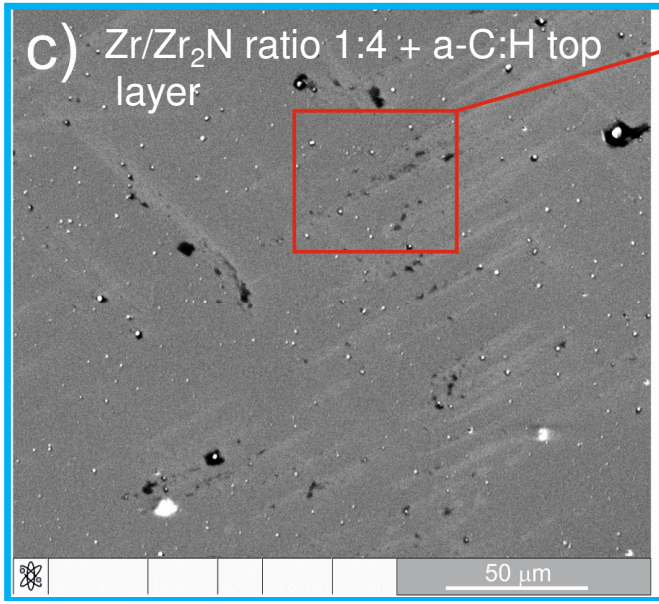


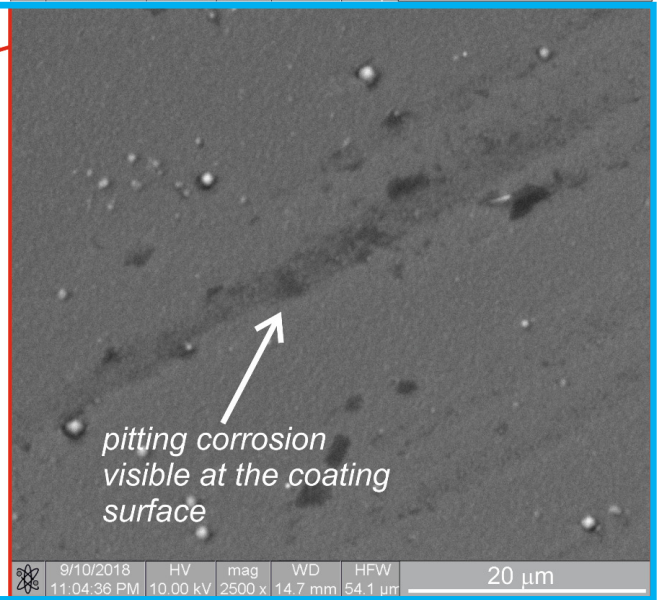
Presence of corrosive fluid components in metallic layers (increased sodium intensity)

SEM


a)
Zr/Zr2N ratio 1:1
pitting corrosion visible at the coating surface
10/24/2017 9:14:25 PM
HV 10.00 kV
mag 2500 x
WD 15.4 mm
HFW 54.1 µm
20 µm


b)
Zr/Zr2N ratio 1:4
pitting corrosion visible at the coating surface
9/10/2018 10:36:02 PM
HV 10.00 kV
mag 2500 x
WD 14.6 mm
HFW 54.1 µm
20 µm


c)
Zr/Zr2N ratio 1:4 + a-C:H top layer
50 µm

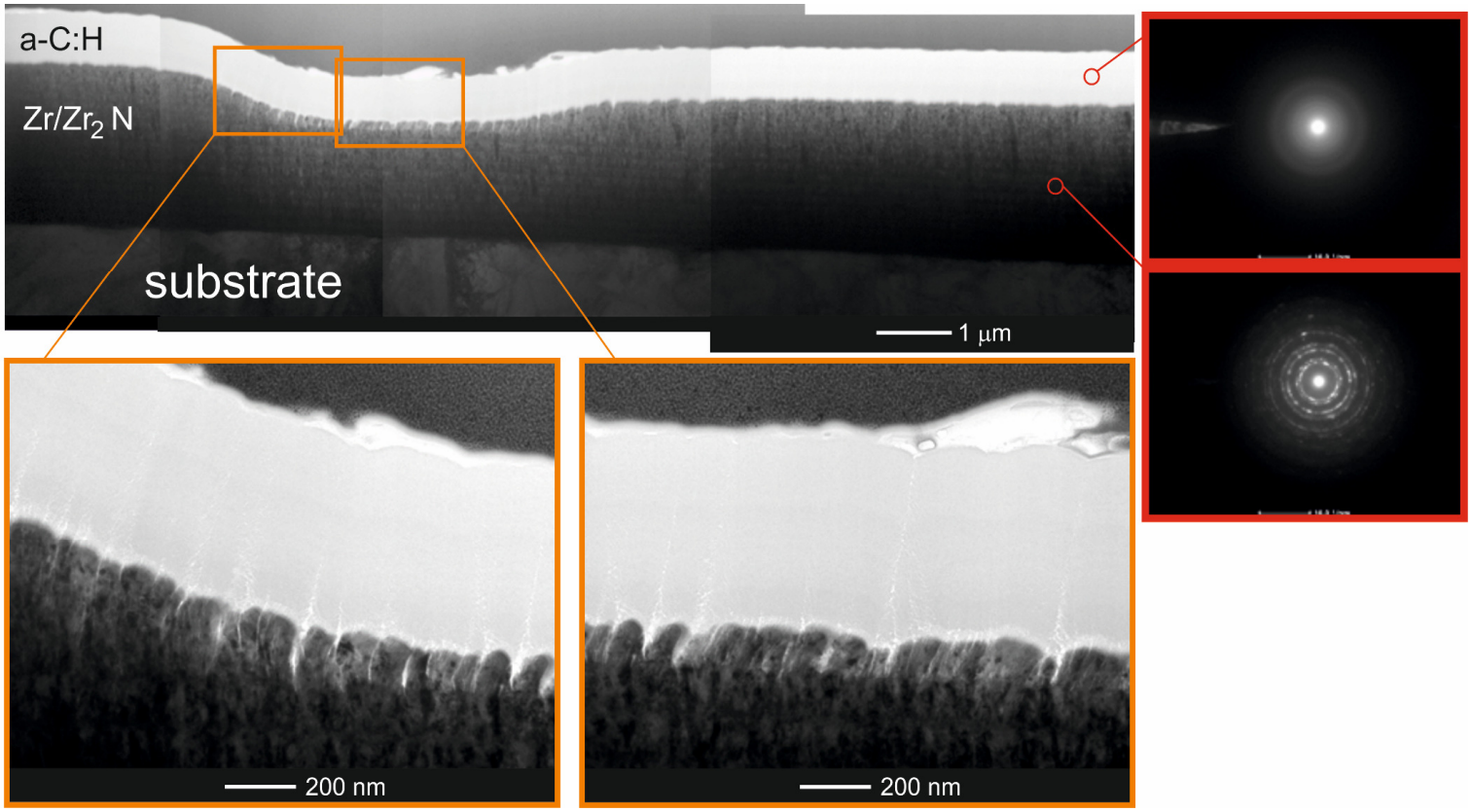

pitting corrosion visible at the coating surface
9/10/2018 11:04:36 PM
HV 10.00 kV
mag 2500 x
WD 14.7 mm
HFW 54.1 µm
20 µm

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

TEM BF + SAEDP



Project WND-POWR.03.02.00-00-I043/16

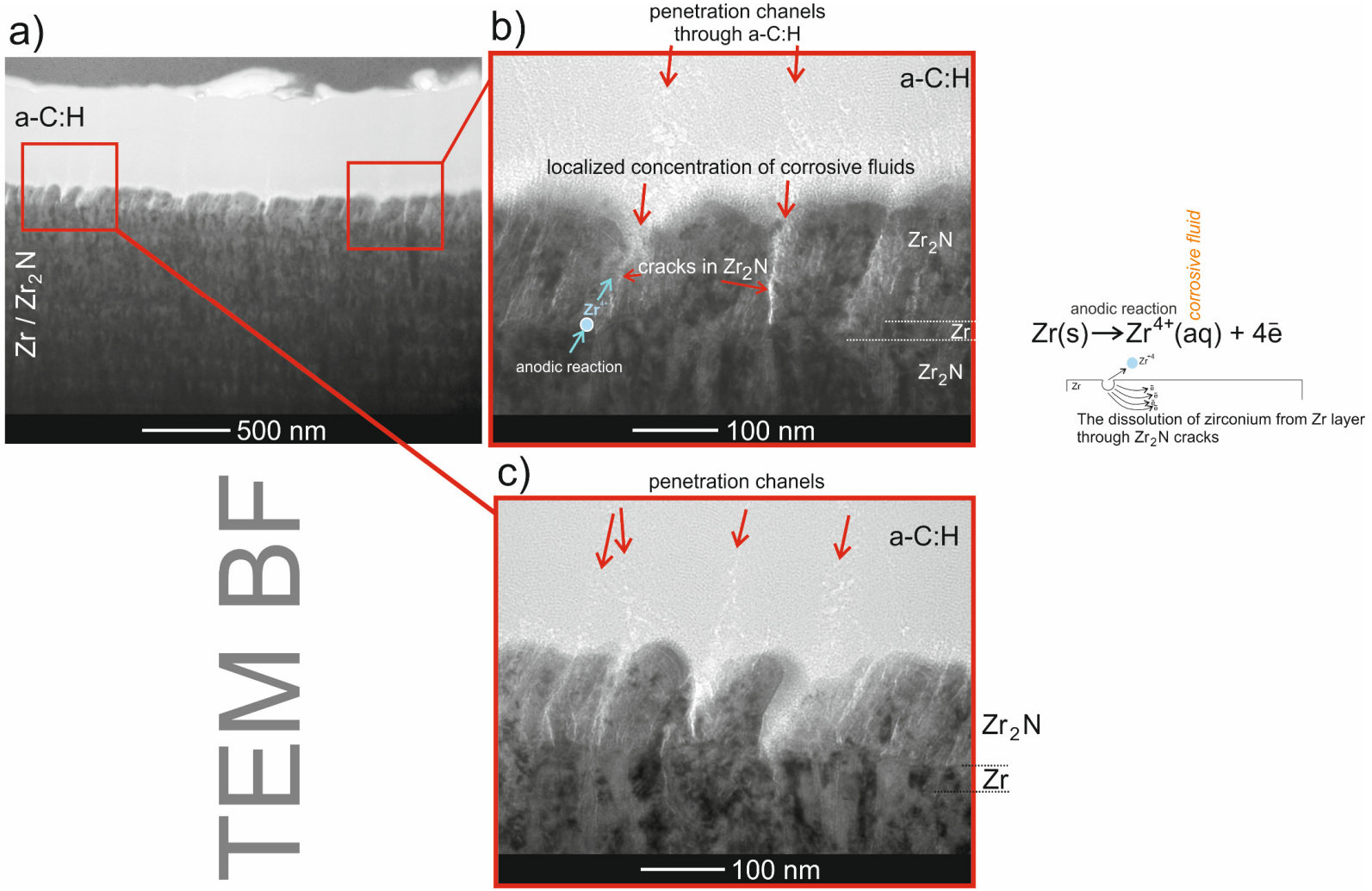
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

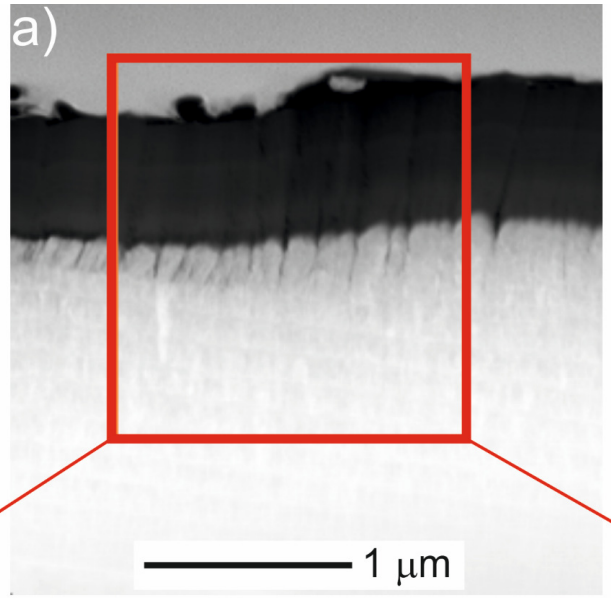
European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

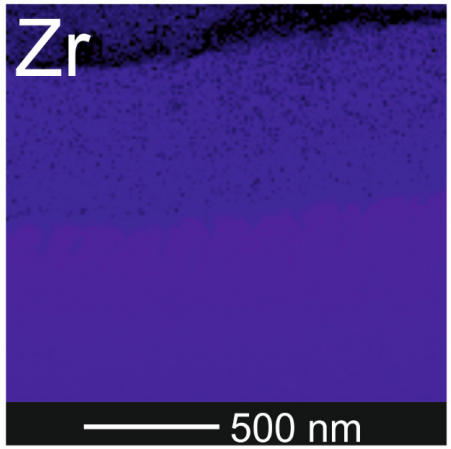


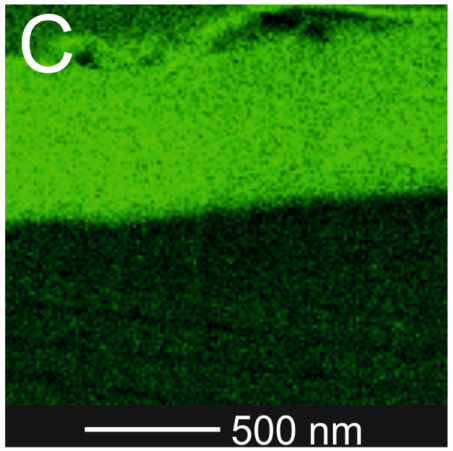
STEM + EDS

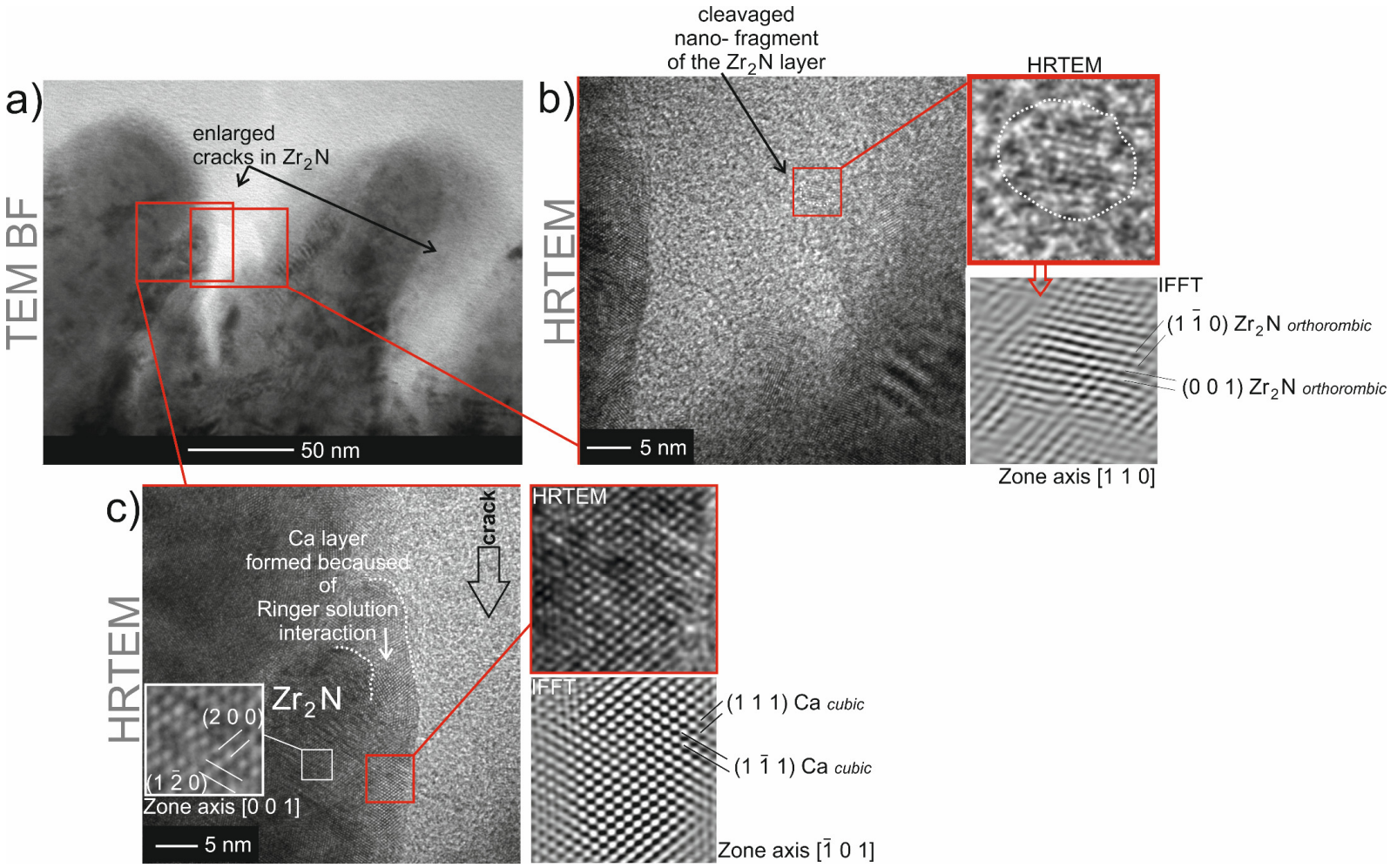


b)

zirconium content
in the a-C:H
structure
due to anodic reaction
in Zr layers



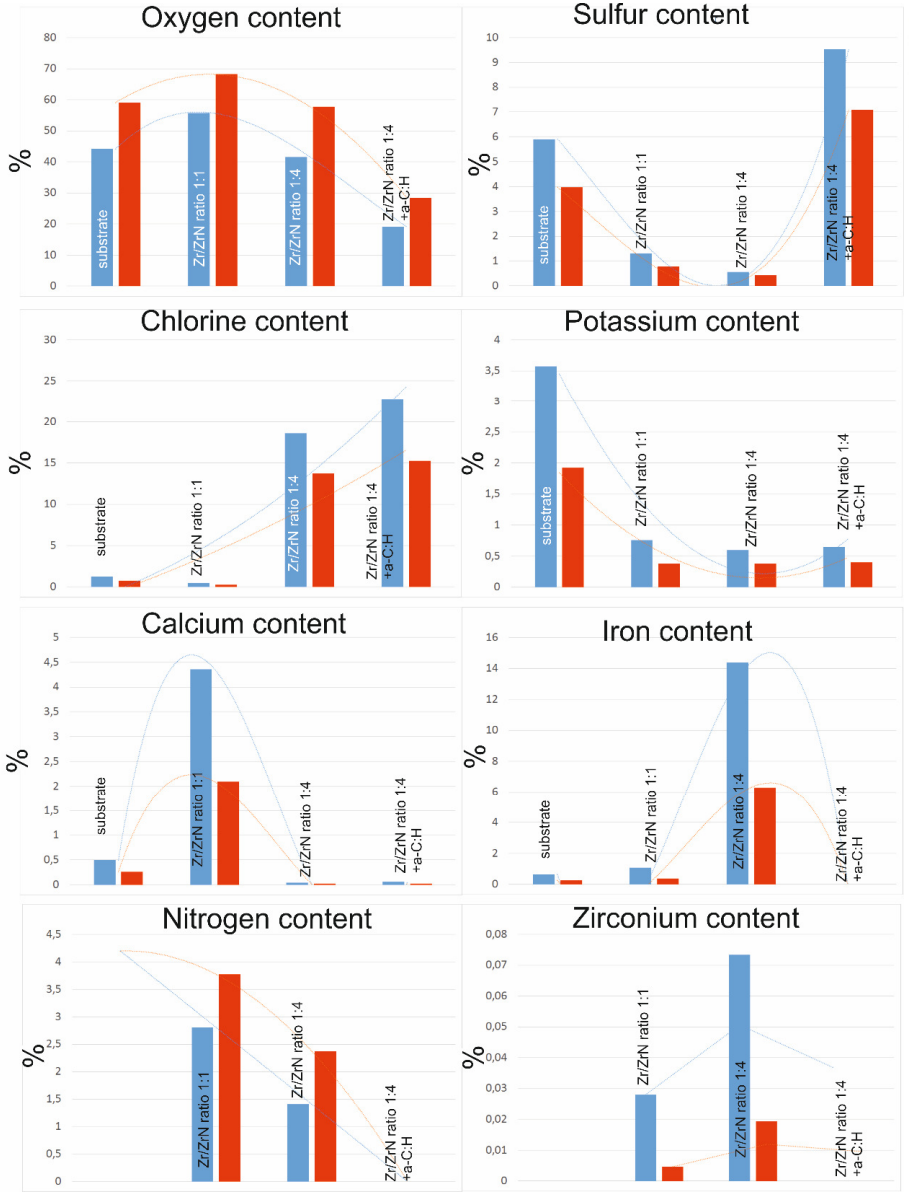



a)
TEM BF
enlarged
cracks in Zr_2N
50 nm
b)
HRTEM
cleavaged
nano- fragment
of the Zr_2N layer
5 nm
HRTEM
IFFT
(1 $\bar{1}$ 0) Zr_2N *orthorombic*
(0 0 1) Zr_2N *orthorombic*
Zone axis [1 1 0]
c)
HRTEM
Ca layer
formed becaused
of
Ringer solution
interaction
crack
Zr_2N
(2 0 0)
(1 $\bar{2}$ 0)
Zone axis [0 0 1]
5 nm
HRTEM
IFFT
(1 1 1) Ca *cubic*
(1 $\bar{1}$ 1) Ca *cubic*
Zone axis [$\bar{1}$ 0 1]

European Funds
Knowledge Education Development

European Union
European Social Fund

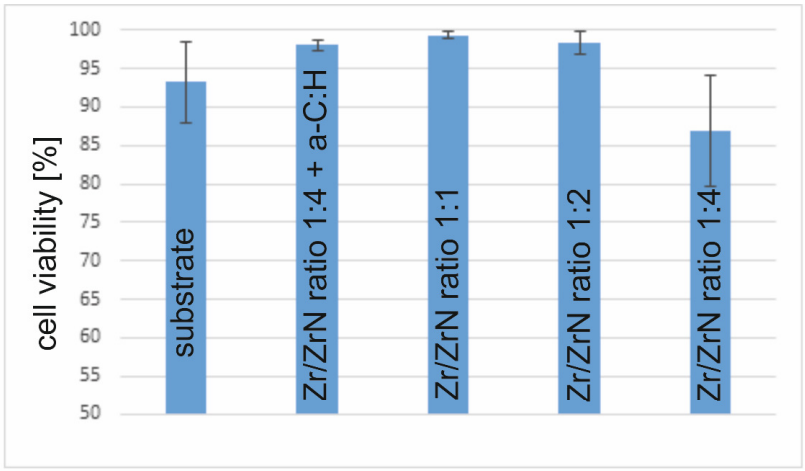
EDS



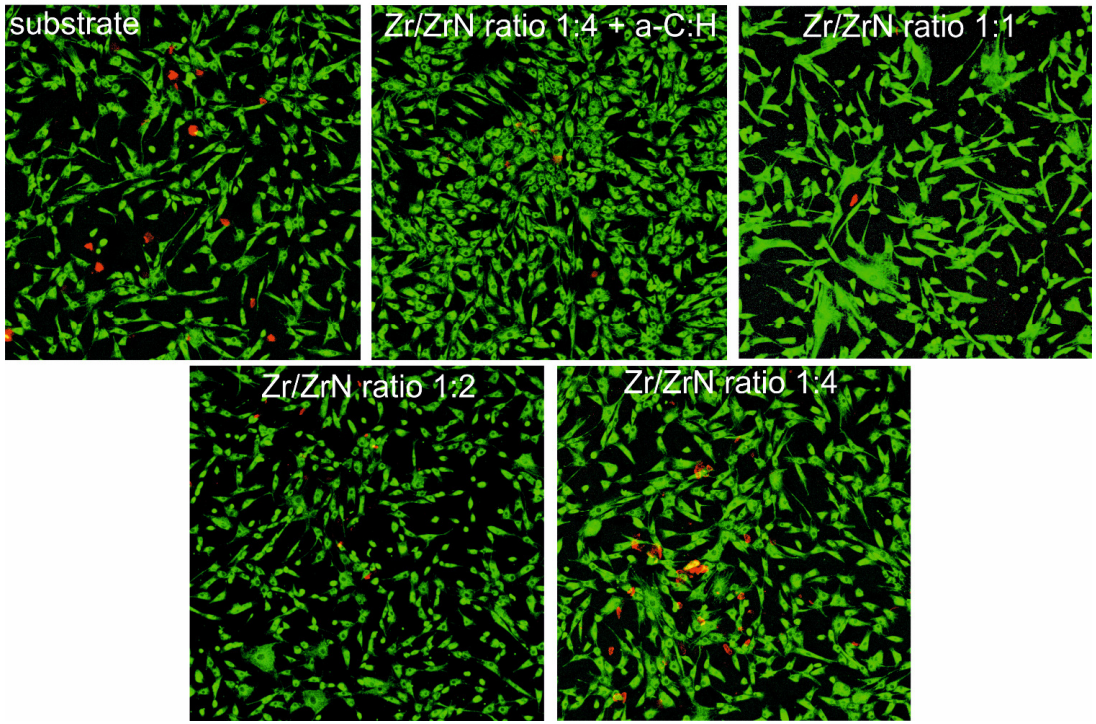
European Funds
Knowledge Education Development

uropean Union
European Social Fund

a)



b)



- Project NCN nr: 3066/B/T02/2011/40- *FINISHED*
- Project NCN nr: 2012/06/M/ST8/00408- *HARMONIA- FINISHED*
- Project NCN nr: 2012/07/B/ST8/03396- *OPUS- FINISHED*
- Project NCN nr: 2014/15/B/ST8/00103- *OPUS- FINISHED*
- Project NCN nr: 2015/19/B/ST8/00942- *OPUS- in progress*
- Project NCBR, number: DZP/M-ERA.NET-2015/285/2016- *in progress*

Title: Anti- bacterial optimization of high-strength, severe-plastic-deformed titanium alloys for spinal implants and surgical tools

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

European Union
European Social Fund

JOANNEUM RESEARCH

LIEFERSCHEIN

FABRYKA NARZĘDZI
MEDYCZNYCH CHIRMED
Andrzej Misztela
Mstowska 8
PL-42-240 **Rudniki**
POLEN

UNSER ZEICHEN: PHA/LJU/WOB
VERSAND: persönliche Übergabe durch LJU
PROJEKT: MAT.05-15.GF.010-01
LIEFERSCHEIN: 2018031

Niklasdorf, 16. Februar 2018

Pos.	Menge	EH	Art.-Nr.	Artikelbezeichnung	Ihre Bestellung:
0010	6	Pieces	C260_3 – 3D	tweezers dummies (Nr.: 5 – ~~matokiane~~) niematowane (Nr.: 6 – ~~niematowane~~) matowe coated with multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 5 atom% Ag coating thickness: 2,10 µm	according to the agreement with DDr. J. Lackner
0020	5	Pieces	C260_4 – 3D	tweezers dummies (Nr.: 5 – ~~matokiane~~) – niematowane (Nr.: 6 – ~~niematowane~~) matowane coated with multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 3 atom% Ag coating thickness: 2,30 µm	
0030	4	Pieces	C260_5 – 3D	tweezers dummies (Nr.: 5 – matokiane) niematowane (Nr.: 6 – niematowane) coated with matowane multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 7 atom% Ag coating thickness: 2,05 µm	

JOANNEUM RESEARCH Forschungsgesellschaft mbH
MATERIALS - Institut für Oberflächentechnologien und Photonik
Laser- und Plasma-Technologien

Leobner Straße 94 , A-8712 NIKLASDORF
Tel.: 0316/876-3304, FAX: 0316/876-3310
E-Mail: MATERIALSNiklasdorf-Sek@joanneum.at
http://www.joanneum.at/MATERIALS

European Funds
Knowledge Education Development

European Union
European Social Fund

CHIRMED ®
www.chirmed.pl
info@chirmed.pl

FABRYKA NARZĘDZI MEDYCZNYCH
MANUFACTURER OF SURGICAL AND MEDICAL INSTRUMENTS
ul. Mstowska 8 a 42-240 Rudniki k/Częstochowy POLAND
Tel.: +48 34 320 14 84, 320 14 34 Fax: +48 34 320 15 00, 320 14 35

Narodowe Centrum Badań i Rozwoju

M-era.Net

Rudniki k/Częstochowy dnia 15 marca 2018

Prof. Dr hab. inż. Roman Major
Instytut Metalurgii i Inżynierii Materiałowej
im. Aleksandra Krupkowskiego
Polskiej Akademii Nauk
ul. Reymonta 25
Kraków 30-059

W nawiązaniu do prowadzonej korespondencji pocztą elektroniczną w ramach projektu o akronimie SPD - bioTribo przekazuję do badań próbki w postaci pojedynczych bransz tytanowych pincet atraumatycznych z naniesionymi powłokami przez JR.

Próbki zostały poddane 18 krotnemu procesowi sterylizacji.

W załączeniu raport z ostatniego cyklu procesu sterylizacji oraz 6 szt. próbek o oznaczeniach:

STER-TEST/A5/1 i STER-TEST/A6/1, STER-TEST/B5/1 i STER-TEST/B6/1, STER-TEST/C5/1 i STER-TEST/C6/1

Znaczenie:

A5/1 - nr próbki C260_3-3D, powierzchnia narzędzia szczotkowana, sztuka pierwsza
A6/1 - nr próbki C260_3-3D, powierzchnia narzędzia matowana, sztuka pierwsza
B5/1 - nr próbki C260_4-3D, powierzchnia narzędzia szczotkowana, sztuka pierwsza
B6/1 - nr próbki C260_4-3D, powierzchnia narzędzia matowana, sztuka pierwsza
C5/1 - nr próbki C260_5-3D, powierzchnia narzędzia szczotkowana, sztuka pierwsza
C6/1 - nr próbki C260_5-3D, powierzchnia narzędzia matowana, sztuka pierwsza

Wszelkie informacje proszę o przekazywanie na poniższy kontakt:

Andrzej Misztela
Fabryka Narzędzi Medycznych - CHIRMED
Manufacturer of Surgical and Medical Instruments - CHIRMED
ul. Mstowska 8A
42-240 Rudniki k/Częstochowy
POLAND
a.misztela@chirmed.pl
Tel: +48 34 320-14-84, +48 34 320-14-34
Fax: +48 34 320-15-00, +48 34 320-14-35
GSM: 601 44 68 00

Fabryka Narzędzi Medycznych
CHIRMED®
42-240 Rudniki k/ Częstochowy
ul. Mstowska 8 A
Regon 150376074, NIP 949-146-89-57
fax 034 320-15-00, tel.034 320-14-84

DYREKTOR
Inż. Marek Dyner

No JM-11/1/2004

PN-EN ISO 9001:2001
PN-EN ISO 13485:2002
No PL-JM-11/1/2004

MELAG Vacuklav 24-B/L

Program : Program szybki B
134°C opakowane
Data : 13.03.2018
Czas : 07:32:32 (Start)
Nr. cyklu : 2
SN : 201724-BL1136

Podgrzewanie 109.4 °C
AIN6: Przewodnosc 0 µS/cm

Postep programu	Cisn. bar	Temperat. °C	Czas min
Start	0.00	64.8	00:00
1.Frakcjonowanie			
Ewakuacja	-0.92	59.9	01:15
Wlot pary	0.41	107.6	03:45
2.Frakcjonowanie			
Ewakuacja	-0.82	59.3	05:22
Wlot pary	0.40	108.9	07:14
3.Frakcjonowanie			
Ewakuacja	-0.82	59.7	08:54
Wlot pary	0.40	108.9	10:44
Wzrost cisn.	2.05	134.0	14:20
Steryl.poczatek	2.05	134.0	14:20
Steryl.koniec	2.19	135.6	19:50
Upust cisnienia	0.18	105.4	20:32
Suszenie prozniowe			
Suszenie pocz.	-0.31	91.7	20:46
Suszenie cisn.	-0.92	77.2	22:44
Suszenie cisn.	-0.94	86.2	24:44
Suszenie cisn.	-0.94	86.9	26:44
Suszenie cisn.	-0.94	85.8	28:44
Suszenie cisn.	-0.94	85.1	30:44
Suszenie cisn.	-0.94	84.9	32:44
Suszenie koniec	-0.90	85.0	32:46
Napowietrzanie	-0.28	86.1	33:04
Koniec	0.00	86.6	33:21

PROGRAM PRAWIDLOWO ZAKONCZONY!

Temperatura : 135.4 +0.3 /-0.2 °C
Cisnienie : 2.17 +0.02/-0.02 bar
Czas steryliz. : 5 min 30 s
Czas : 08:05:53 (Koniec)

77 201701136 5.15 5.06
CRC: 0x297D MF V2.008A

European Funds
Knowledge Education Development

European Union
European Social Fund

JOANNEUM RESEARCH

LIEFERSCHEIN

FABRYKA NARZĘDZI
MEDYCZNYCH CHIRMED
Andrzej Misztela
Mstowska 8
PL-42-240 **Rudniki**
POLEN

UNSER ZEICHEN: PHA/LJU/WOB
VERSAND: persönliche Übergabe durch LJU
PROJEKT: MAT.05-15.GF.010-01
LIEFERSCHEIN: 2018031

Niklasdorf, 16. Februar 2018

Pos.	Menge	EH	Art.-Nr.	Artikelbezeichnung	Ihre Bestellung:
0010	6	Pieces	C260_3 – 3D	tweezers dummies (Nr.: 5 – ~~matokiane~~) niematowane (Nr.: 6 – ~~niematowane~~) matowe coated with multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 5 atom% Ag coating thickness: 2,10 µm	according to the agreement with DDr. J. Lackner
0020	5	Pieces	C260_4 – 3D	tweezers dummies (Nr.: 5 – ~~matokiane~~) – niematowane (Nr.: 6 – ~~niematowane~~) matowane coated with multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 3 atom% Ag coating thickness: 2,30 µm	
0030	4	Pieces	C260_5 – 3D	tweezers dummies (Nr.: 5 – matokiane) niematowane (Nr.: 6 – niematowane) coated with matowane multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 7 atom% Ag coating thickness: 2,05 µm	

JOANNEUM RESEARCH Forschungsgesellschaft mbH
MATERIALS - Institut für Oberflächentechnologien und Photonik
Laser- und Plasma-Technologien

Leobner Straße 94 , A-8712 NIKLASDORF
Tel.: 0316/876-3304, FAX: 0316/876-3310
E-Mail: MATERIALSNiklasdorf-Sek@joanneum.at
http://www.joanneum.at/MATERIALS

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

C260_3_3D

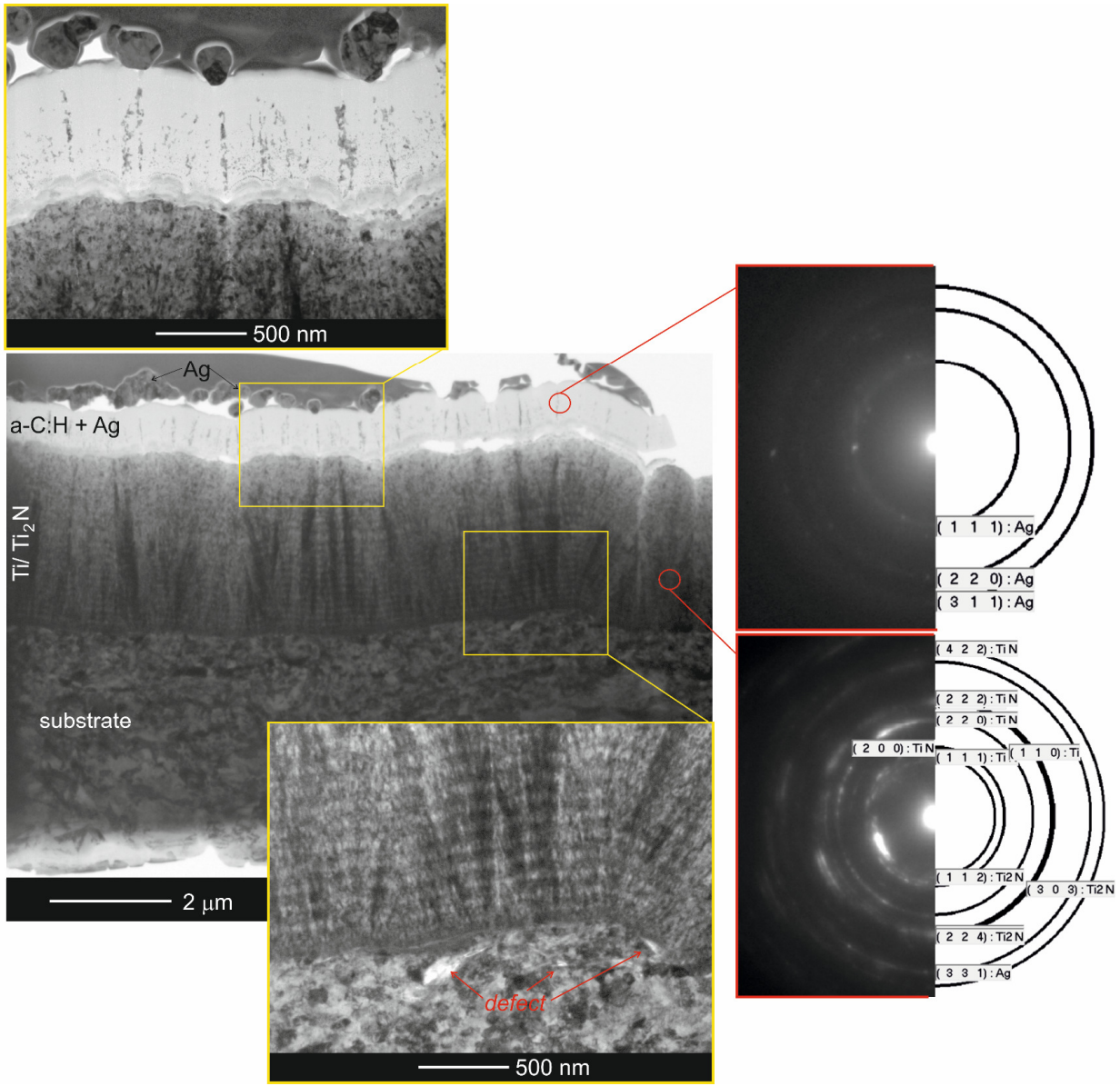
A

Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds

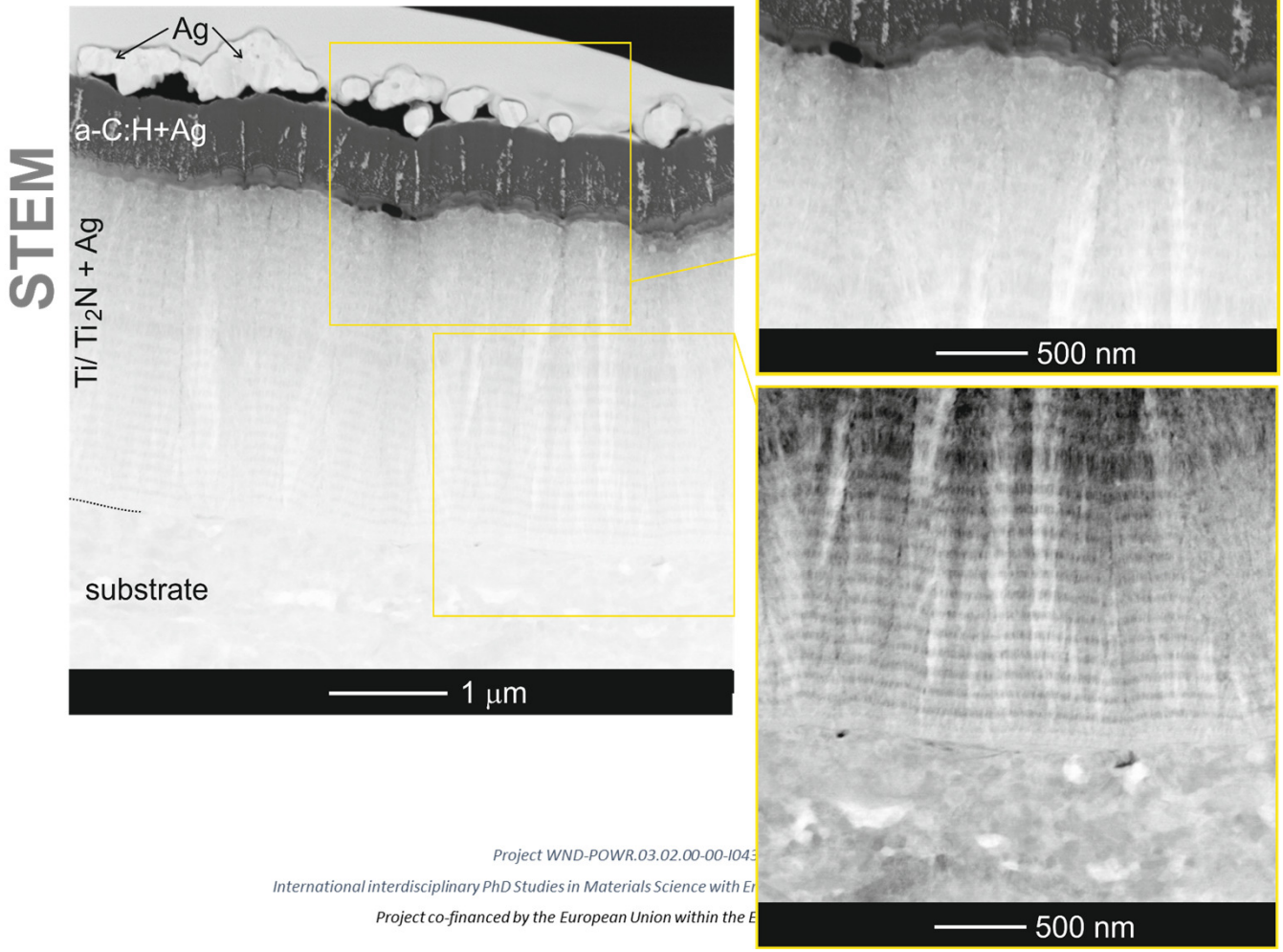
TEM BF + SAEDP



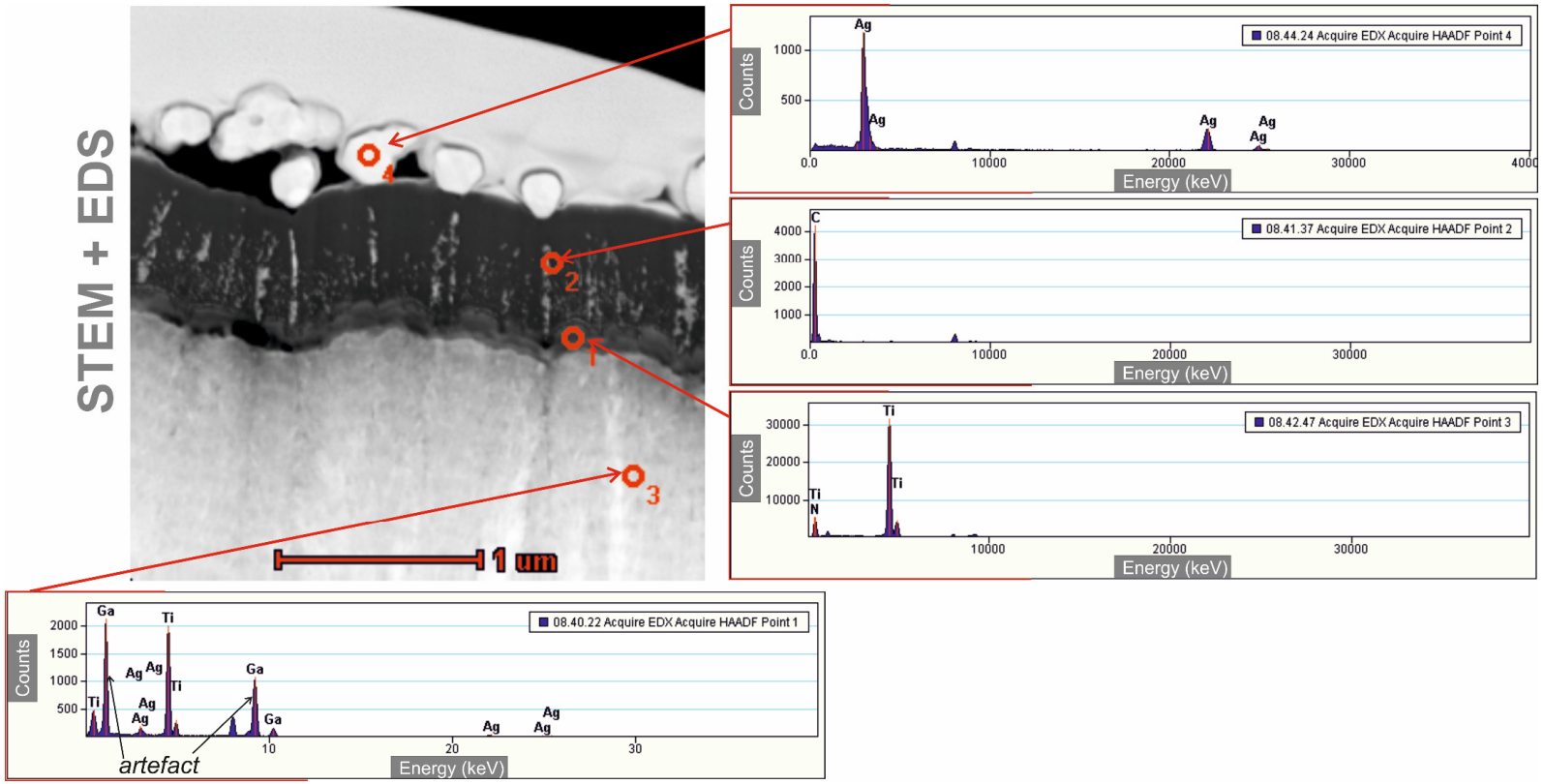
European Funds
Knowledge Education Development

INSTITUTE OF METALLURG
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIE

nion
al Fund



Project WND-POWR.03.02.00-00-I043
International interdisciplinary PhD Studies in Materials Science with Er
Project co-financed by the European Union within the E



Project WND-POWR.03.02.00-00-I043/16

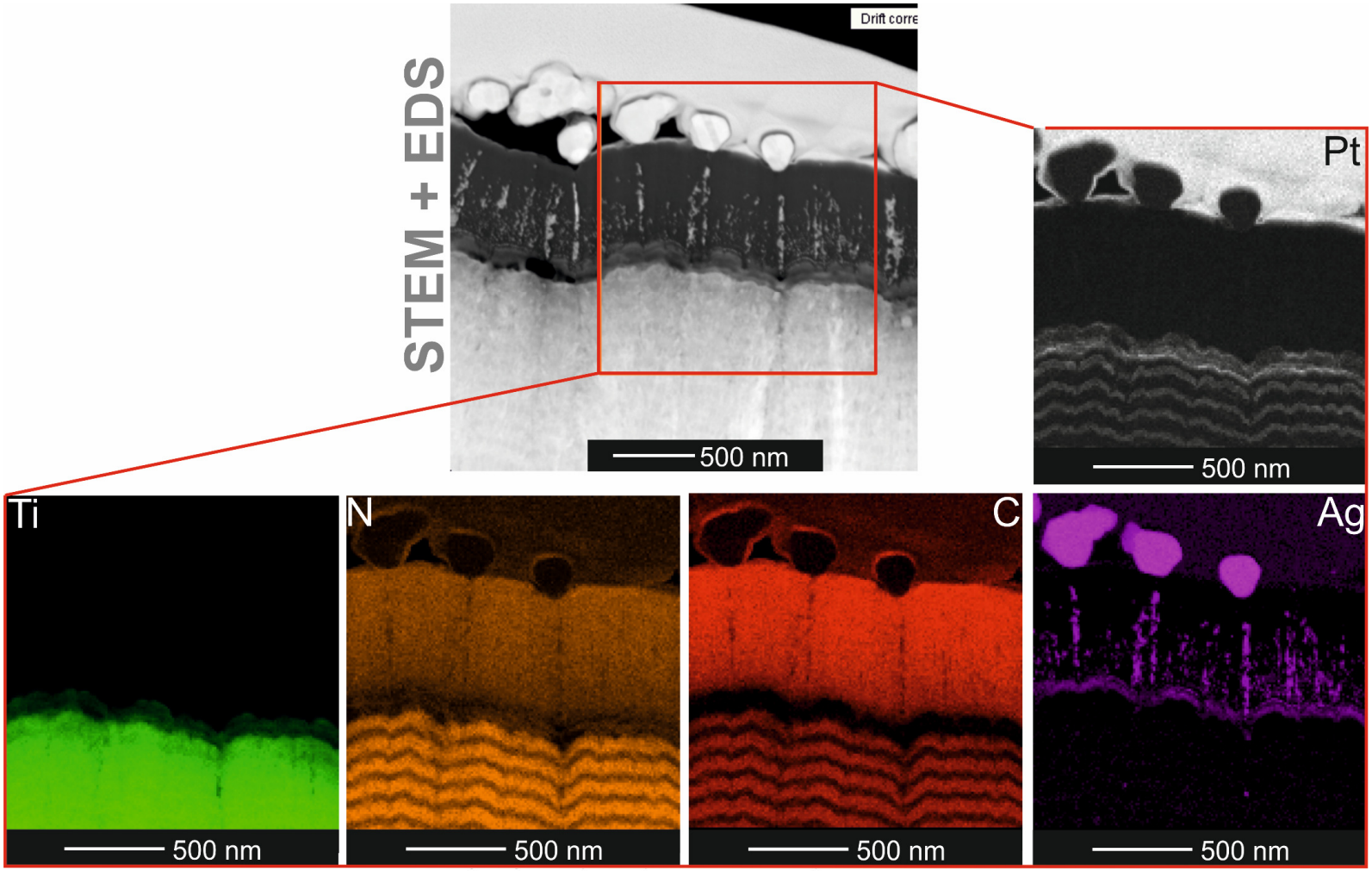
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

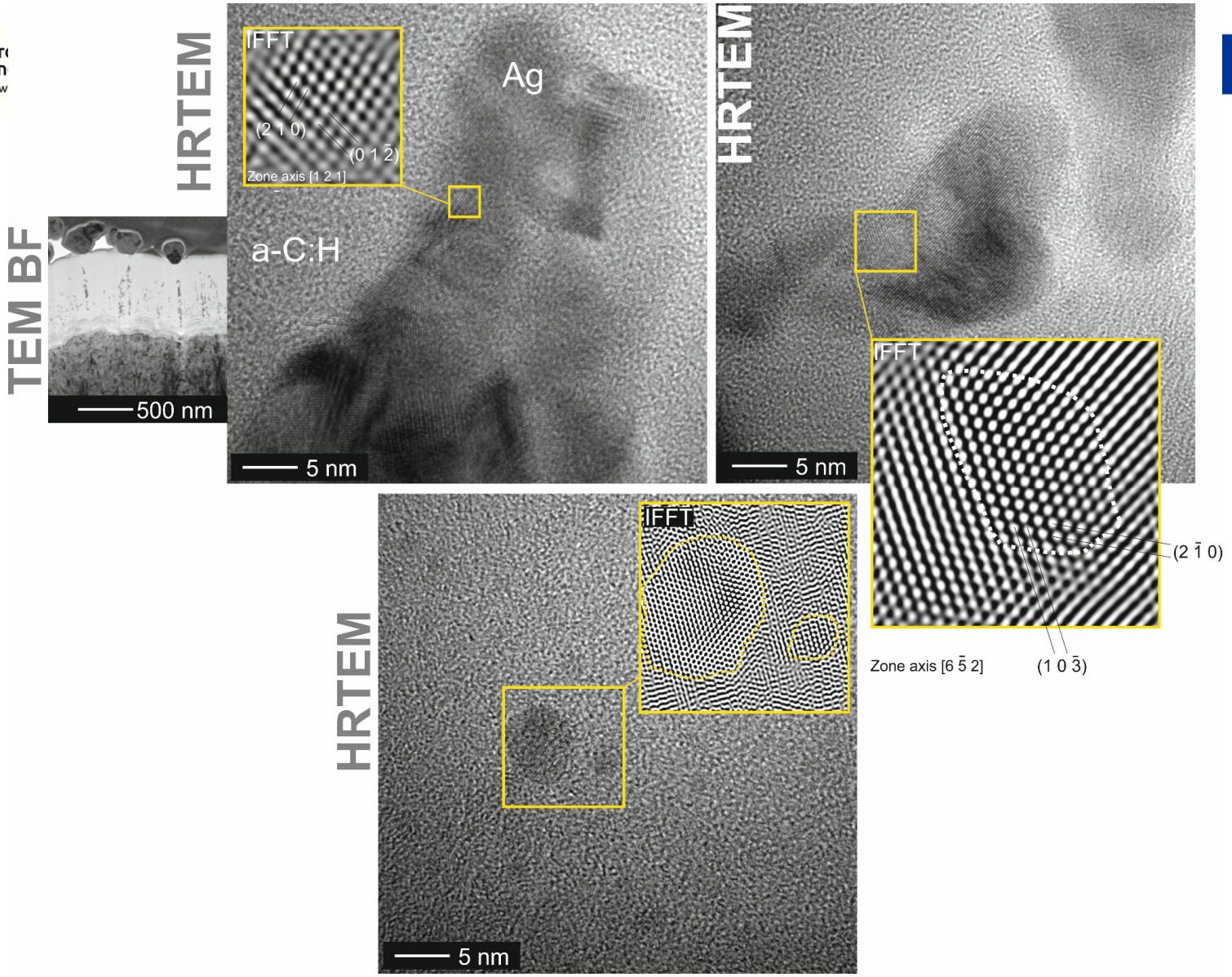
Project co-financed by the European Union within the European Social Funds

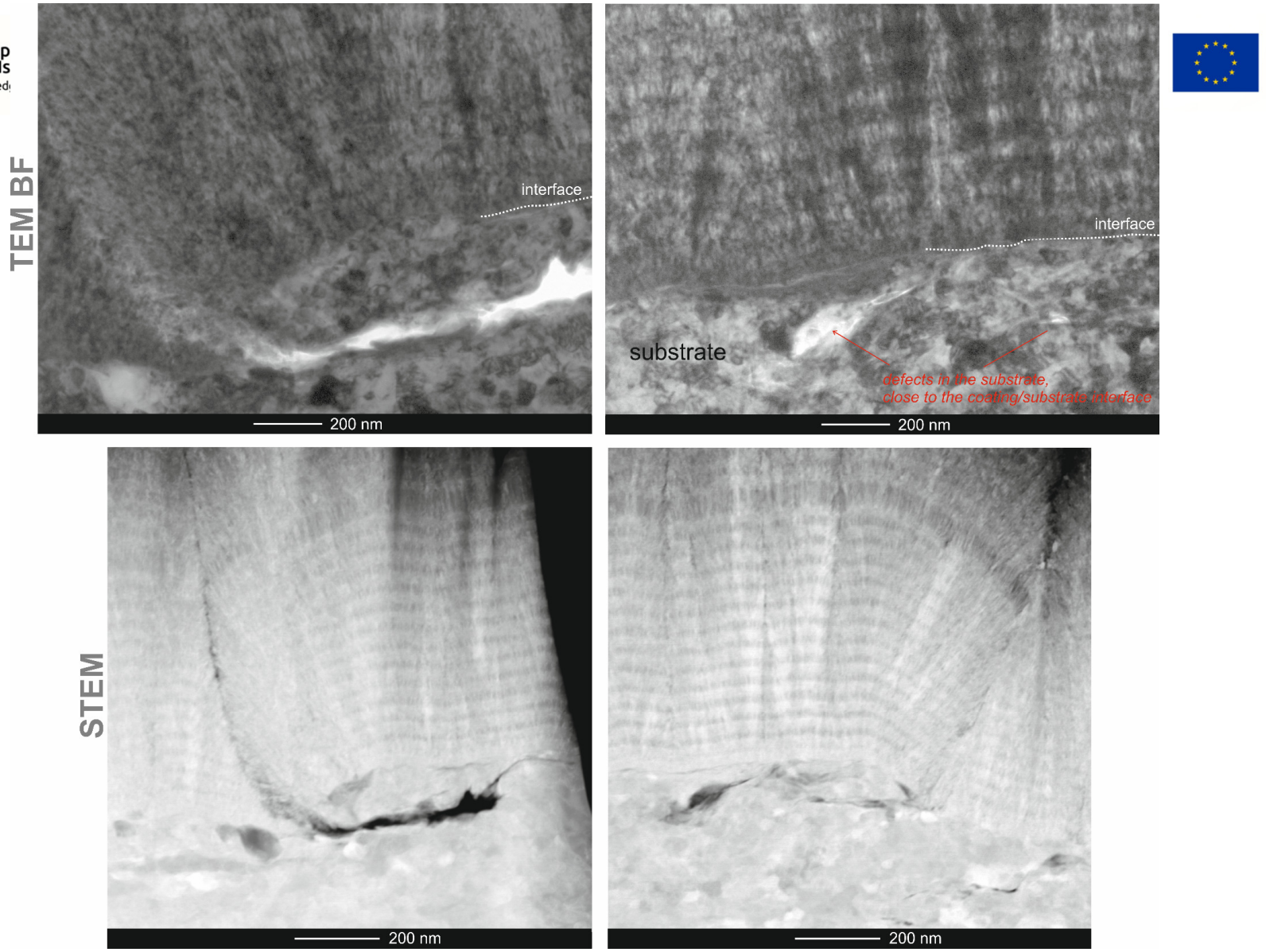
European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund




HRTEM
IFFT
Ag
(2 1 0)
(0 1 2)
Zone axis [1 2 1]
a-C:H
TEM BF
500 nm
5 nm
HRTEM
IFFT
5 nm
(2 1̄ 0)
Zone axis [6 5̄ 2]
(1 0 3̄)
HRTEM
IFFT
5 nm

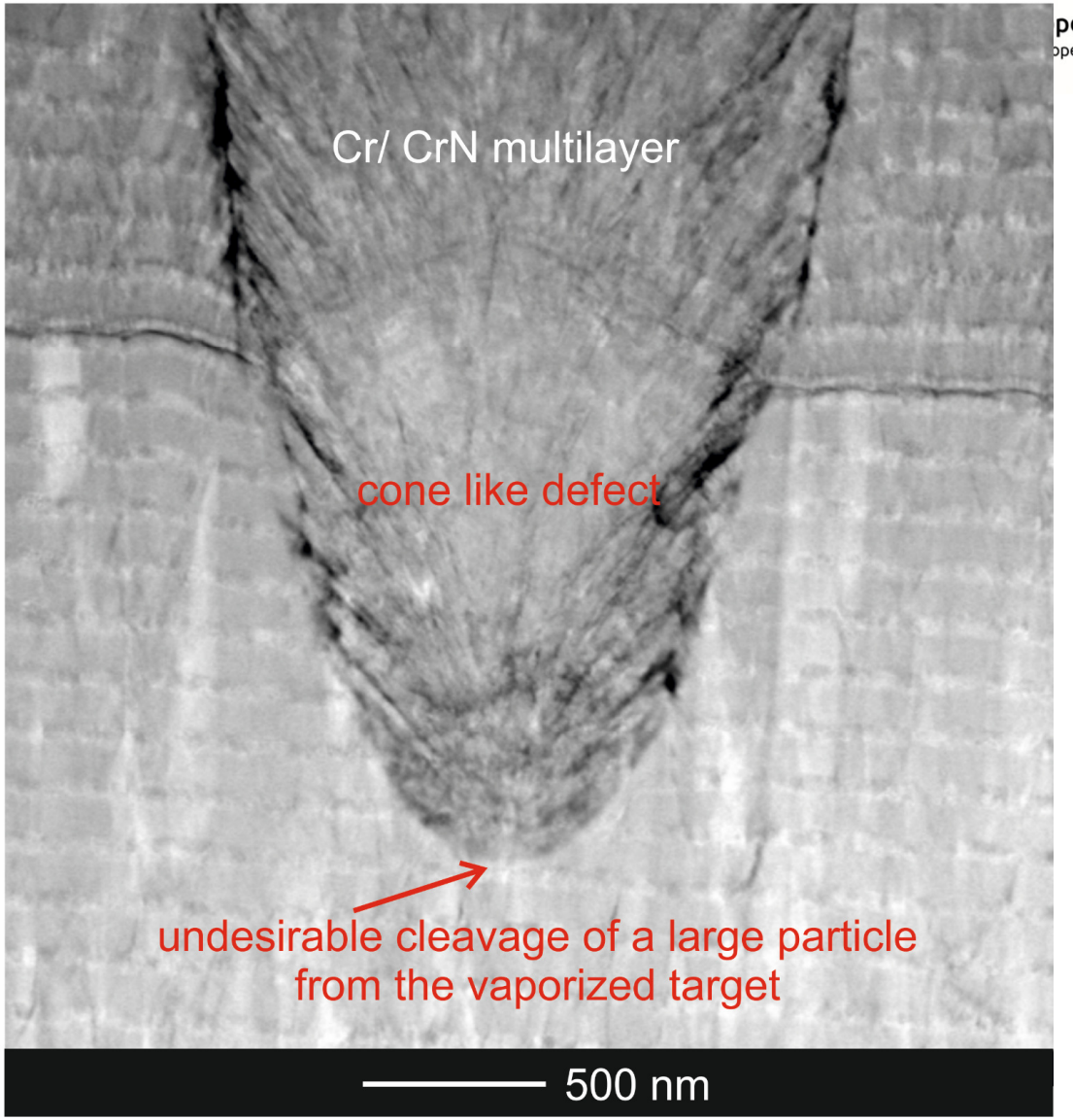

TEM BF
interface
200 nm
interface
substrate
defects in the substrate,
close to the coating/substrate interface
200 nm
STEM
200 nm
200 nm

European Funds
Knowledge Education Develop

pean Union
opean Social Fund

EXAMPLE FROM OUR PREVIOS RESERCH

STEM



European Funds
Knowledge Education Development

European Union
European Social Fund

JOANNEUM RESEARCH

LIEFERSCHEIN

FABRYKA NARZĘDZI
MEDYCZNYCH CHIRMED
Andrzej Misztela
Mstowska 8
PL-42-240 **Rudniki**
POLEN

UNSER ZEICHEN: PHA/LJU/WOB
VERSAND: persönliche Übergabe durch LJU
PROJEKT: MAT.05-15.GF.010-01
LIEFERSCHEIN: 2018031

Niklasdorf, 16. Februar 2018

Pos.	Menge	EH	Art.-Nr.	Artikelbezeichnung	Ihre Bestellung:
0010	6	Pieces	C260_3 – 3D	tweezers dummies (Nr.: 5 – ~~matokiane~~) niematowane (Nr.: 6 – ~~niematowane~~) matowe coated with multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 5 atom% Ag coating thickness: 2,10 µm	according to the agreement with DDr. J. Lackner
0020	5	Pieces	C260_4 – 3D	tweezers dummies (Nr.: 5 – ~~matokiane~~) – niematowane (Nr.: 6 – ~~niematowane~~) matowane coated with multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 3 atom% Ag	
0030	4	Pieces	C260_5 – 3D	tweezers dummies (Nr.: 5 – matokiane) niematowane (Nr.: 6 – niematowane) coated with matowane multilayer 24x (Ti / TiN) = 1:1 doped 7,5 atom% Ag + a-C:H doped with 7 atom% Ag coating thickness: 2,05 µm	

JOANNEUM RESEARCH Forschungsgesellschaft mbH
MATERIALS - Institut für Oberflächentechnologien und Photonik
Laser- und Plasma-Technologien

Leobner Straße 94 , A-8712 NIKLASDORF
Tel.: 0316/876-3304, FAX: 0316/876-3310
E-Mail: MATERIALSNiklasdorf-Sek@joanneum.at
http://www.joanneum.at/MATERIALS

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

C260_5_3D

C

Project WND-POWR.03.02.00-00-I043/16

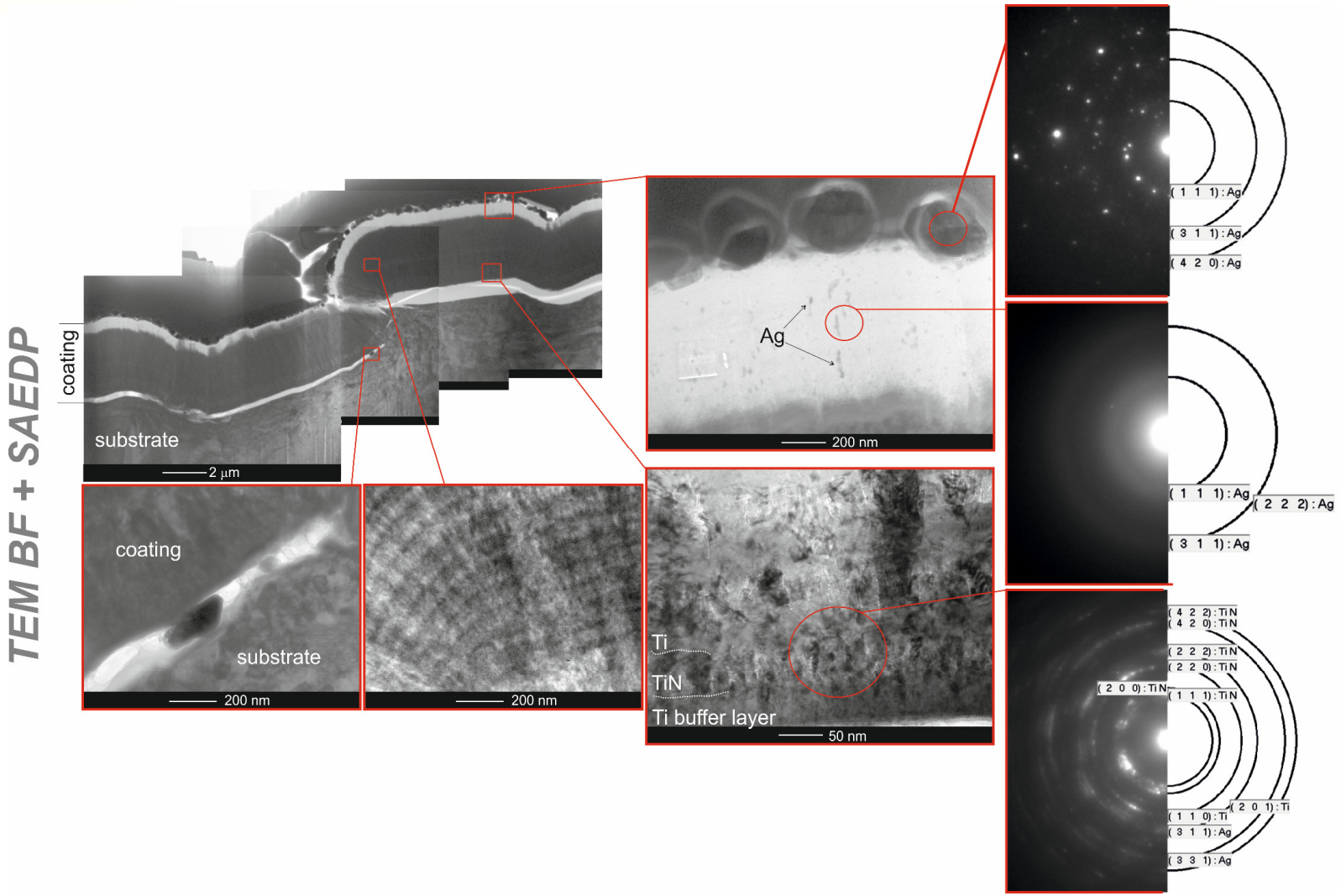
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

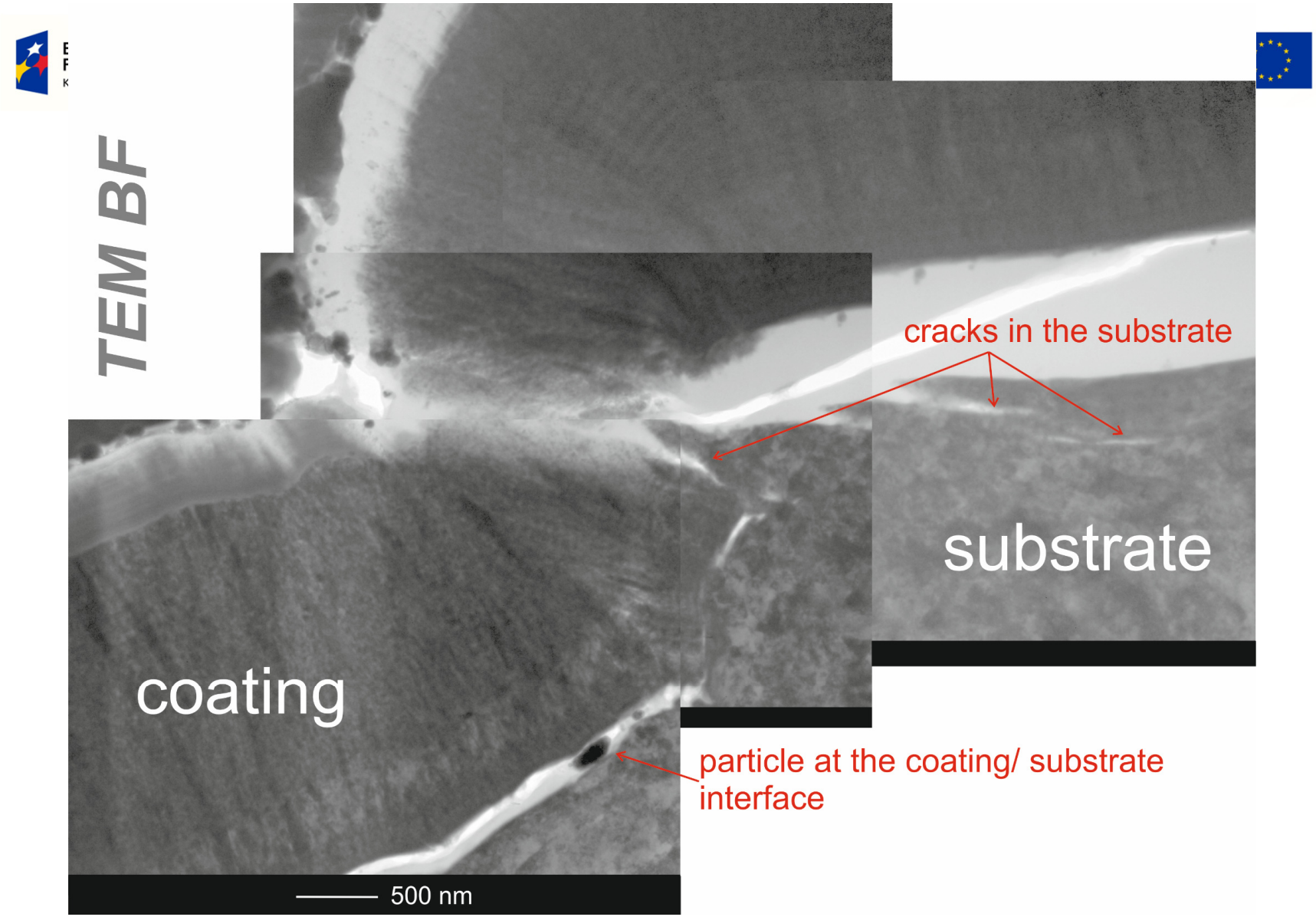
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

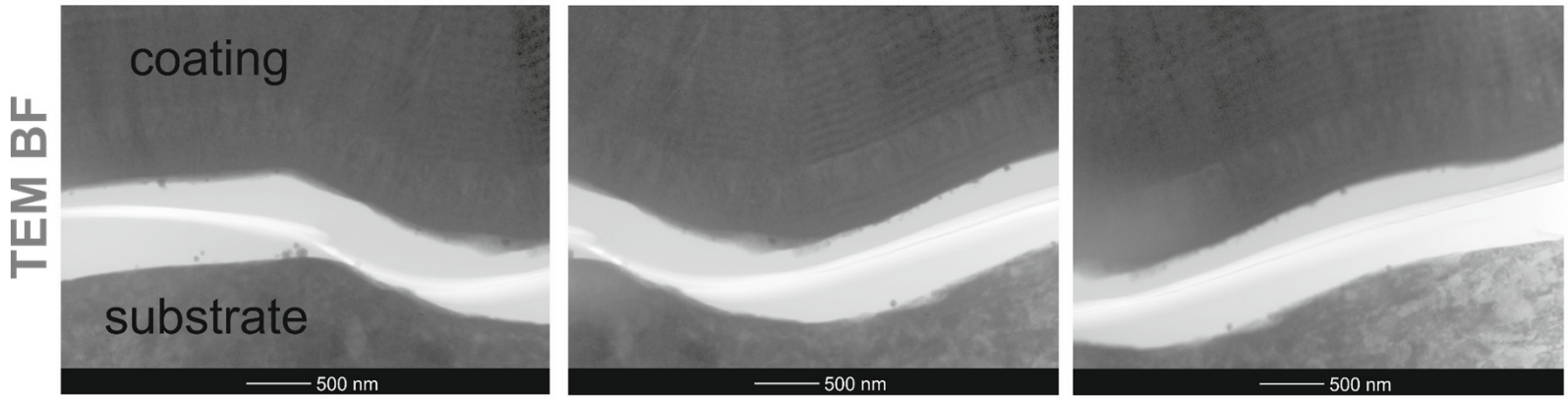



TEM BF
cracks in the substrate
substrate
coating
particle at the coating/ substrate interface
500 nm

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

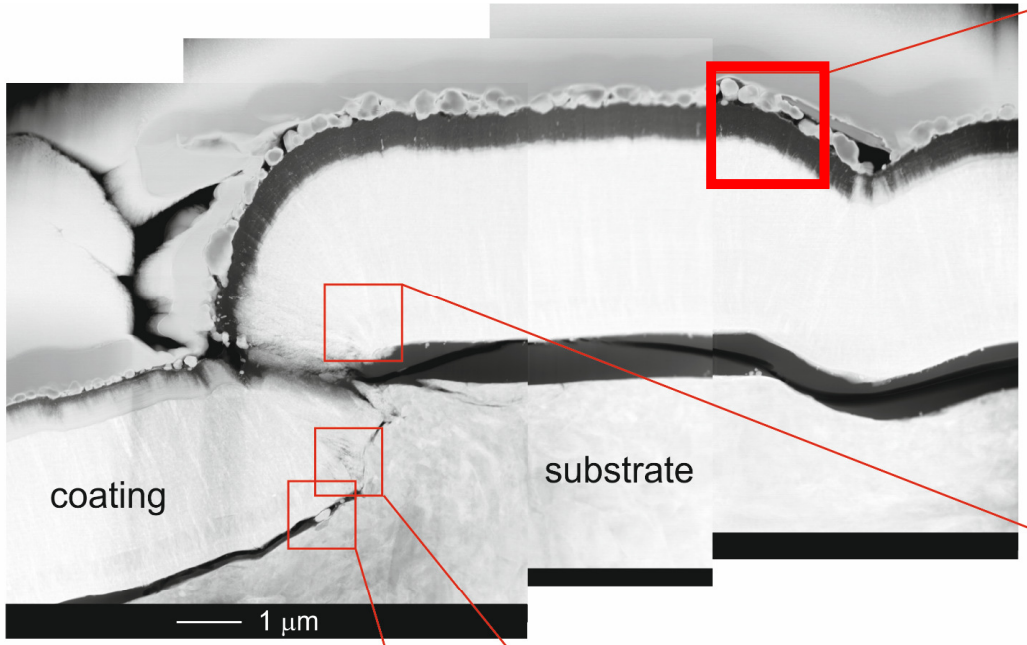


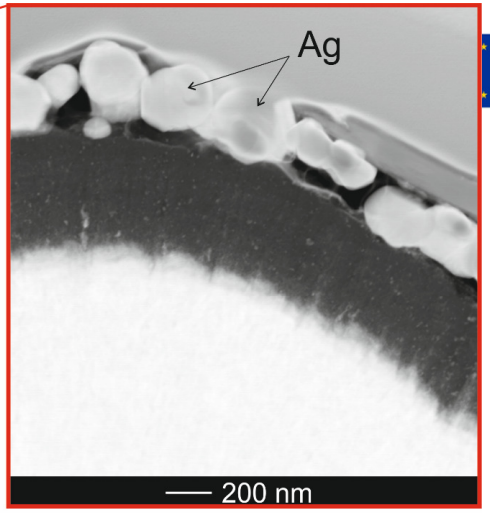
Project WND-POWR.03.02.00-00-I043/16

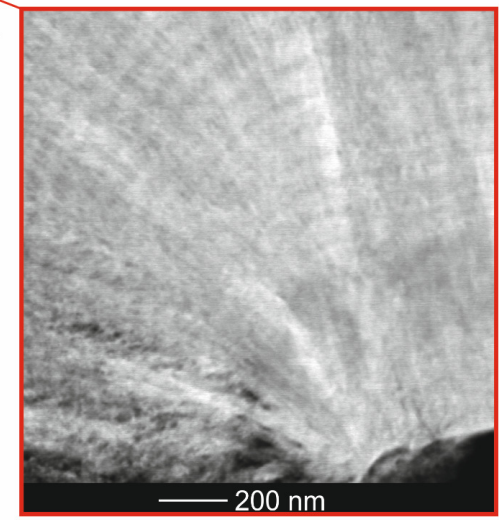
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

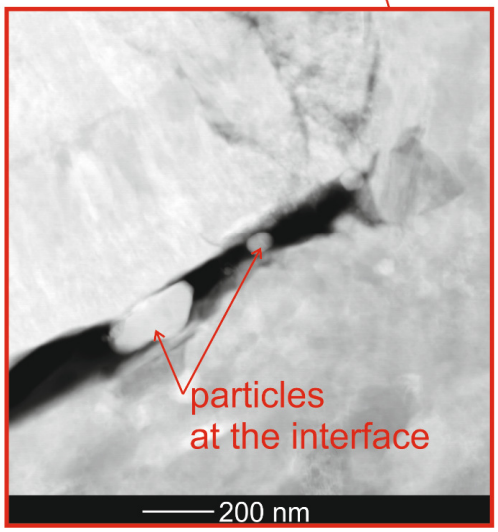
Project co-financed by the European Union within the European Social Funds

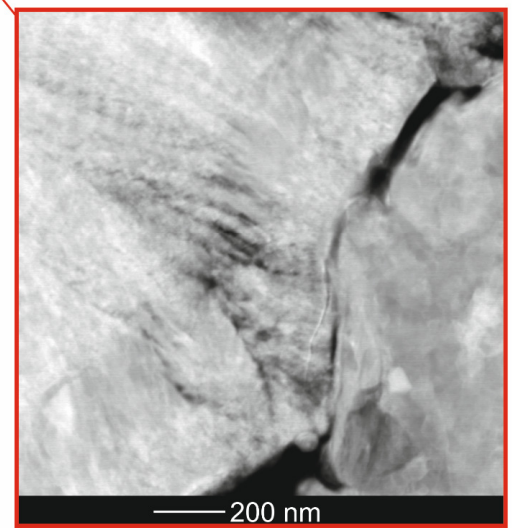
STEM


coating
substrate
1 μm


Ag
200 nm


200 nm


particles
at the interface
200 nm

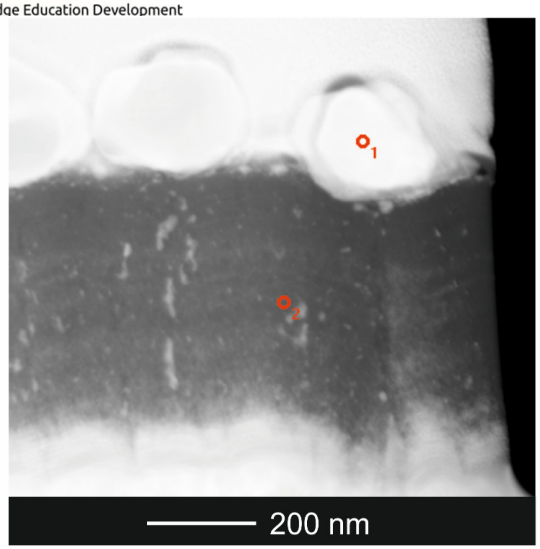

200 nm

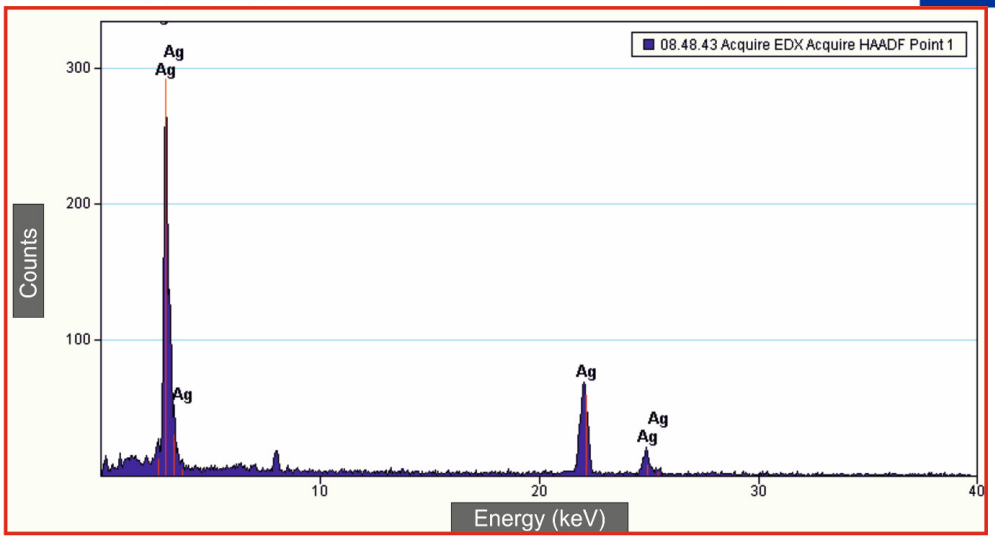
European Funds
Knowledge Education Development

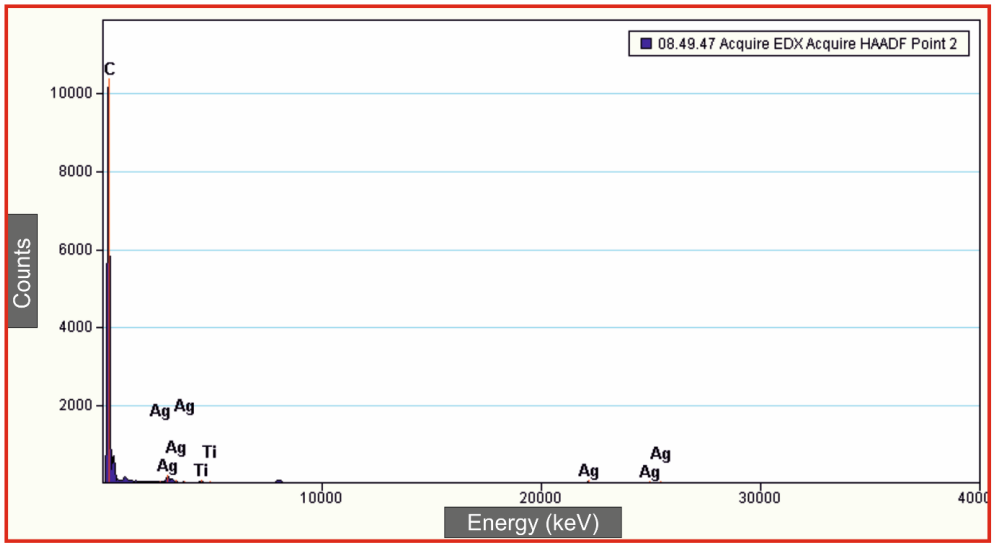
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES

European Union
European Social Fund

STEM + EDS

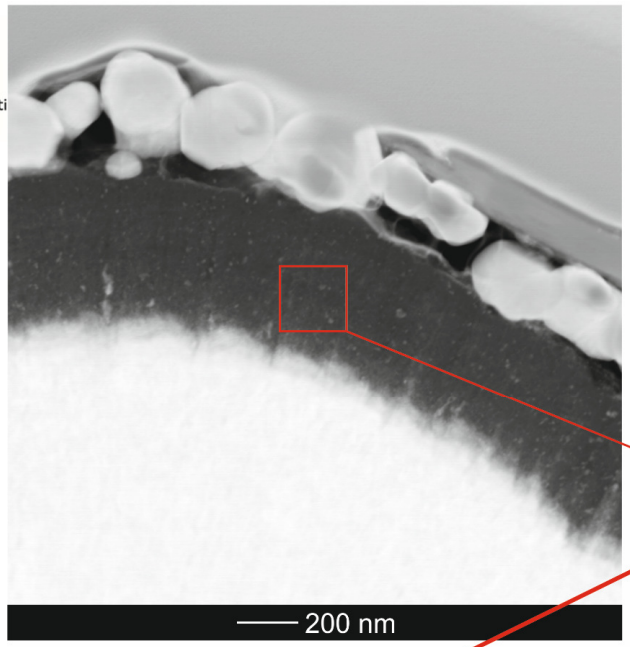


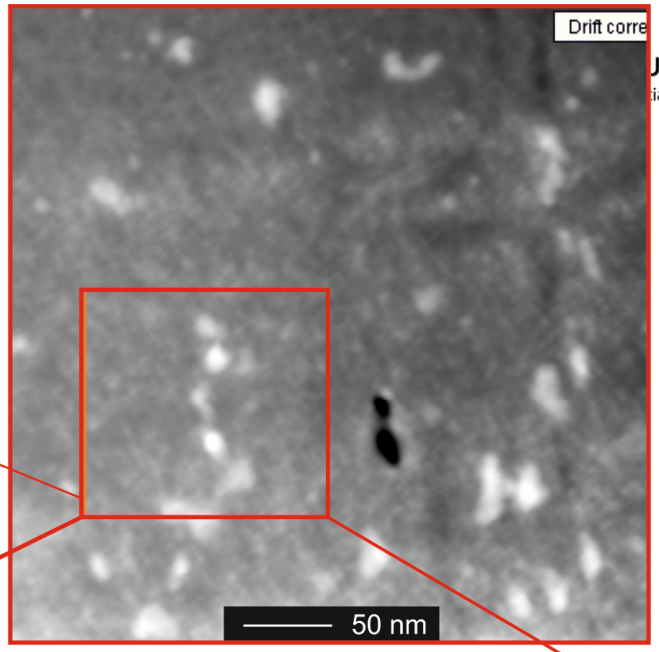




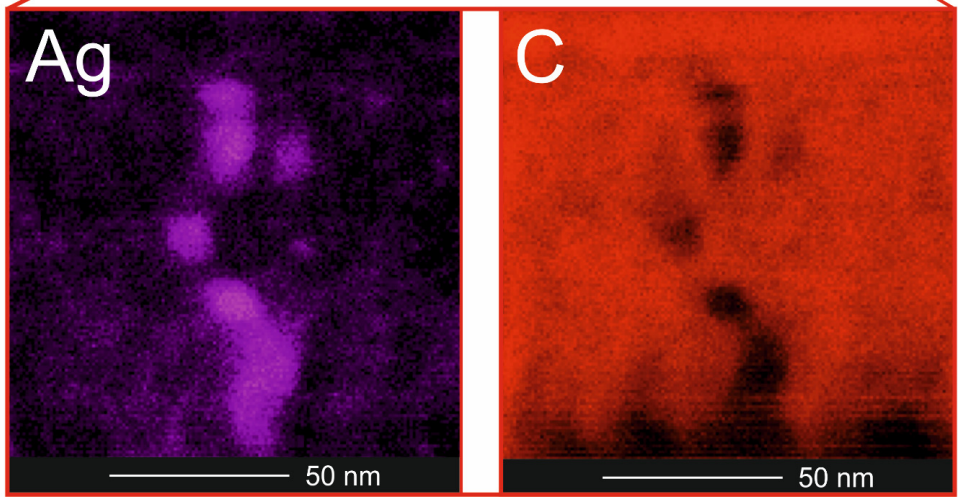
European Funds
Knowledge Educati

Union
ial Fund

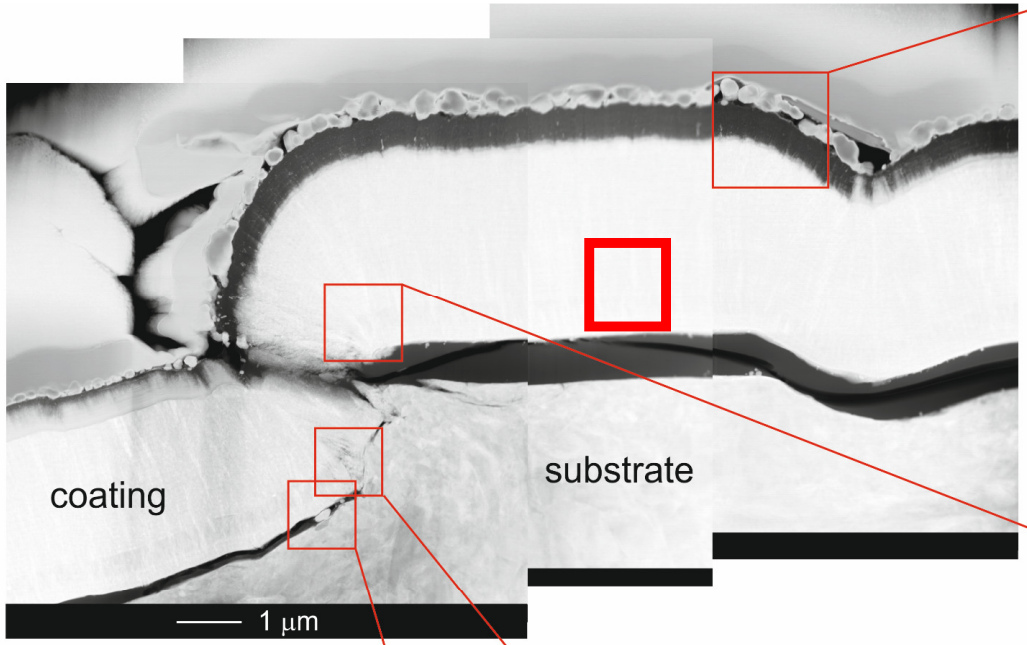


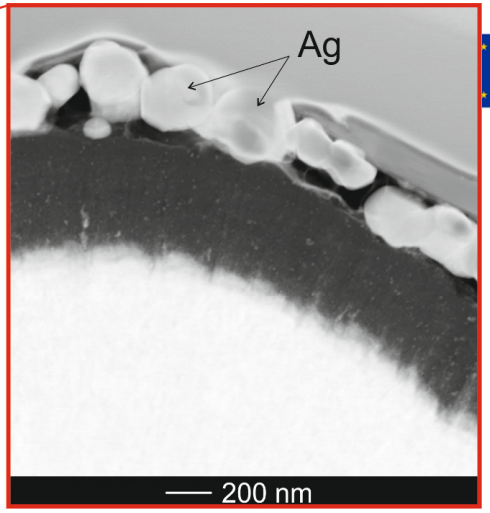


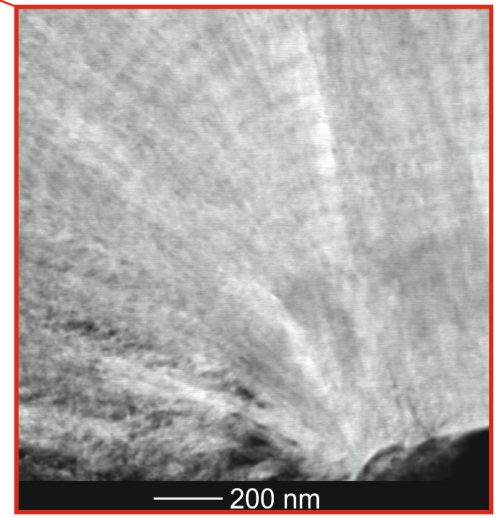
STEM + EDS

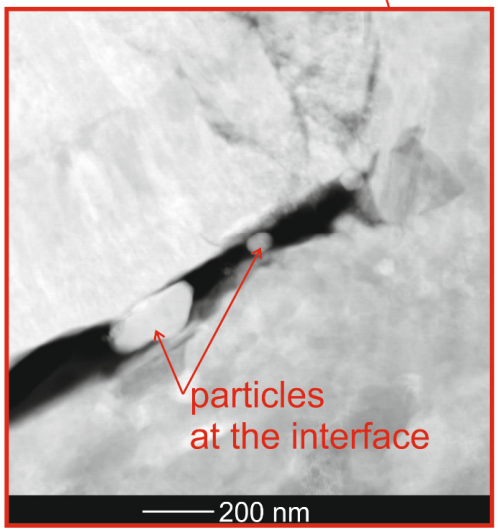


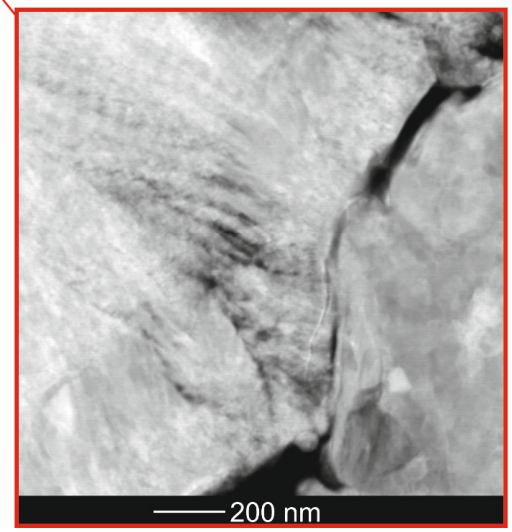
STEM

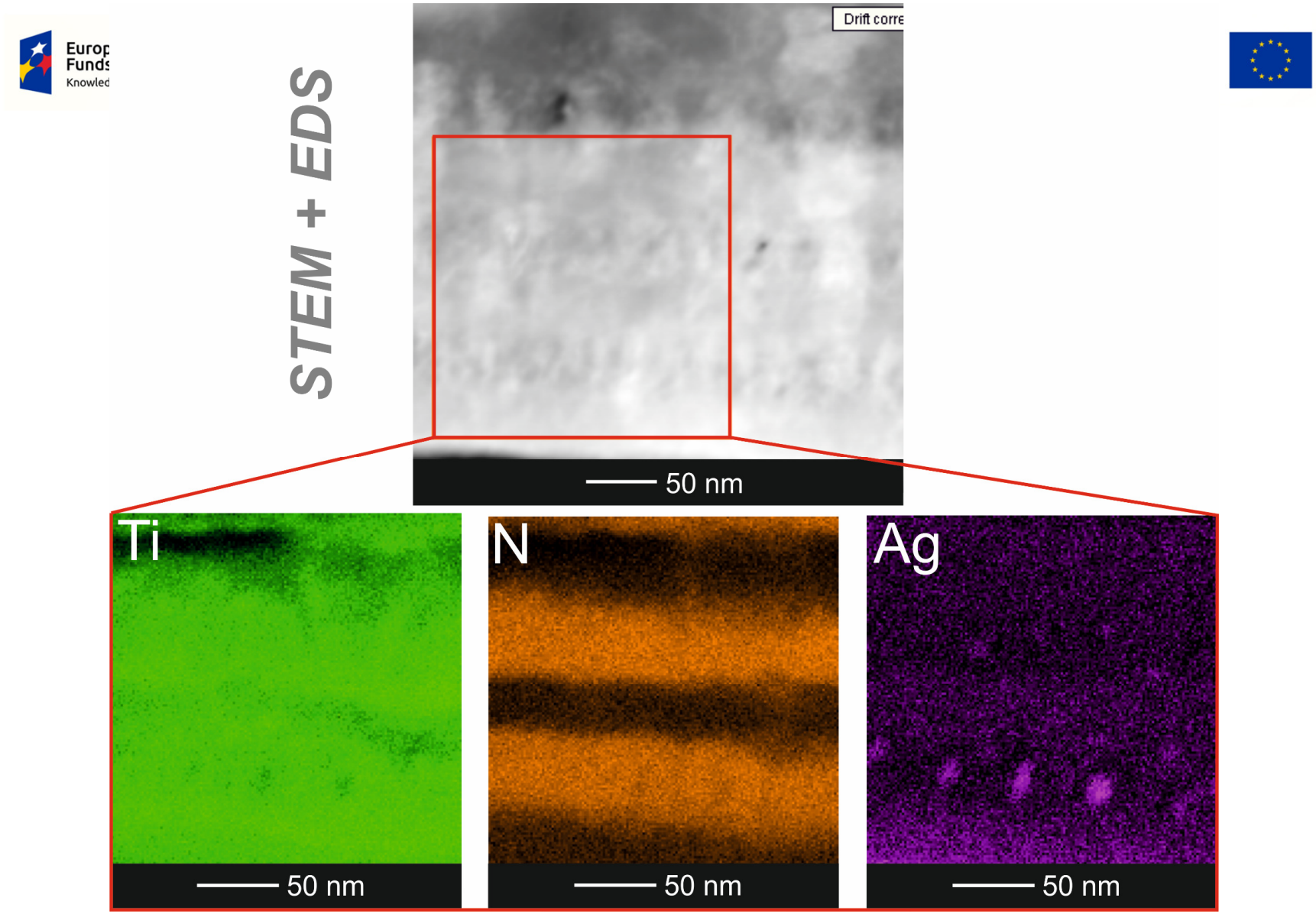

coating
substrate
1 μm

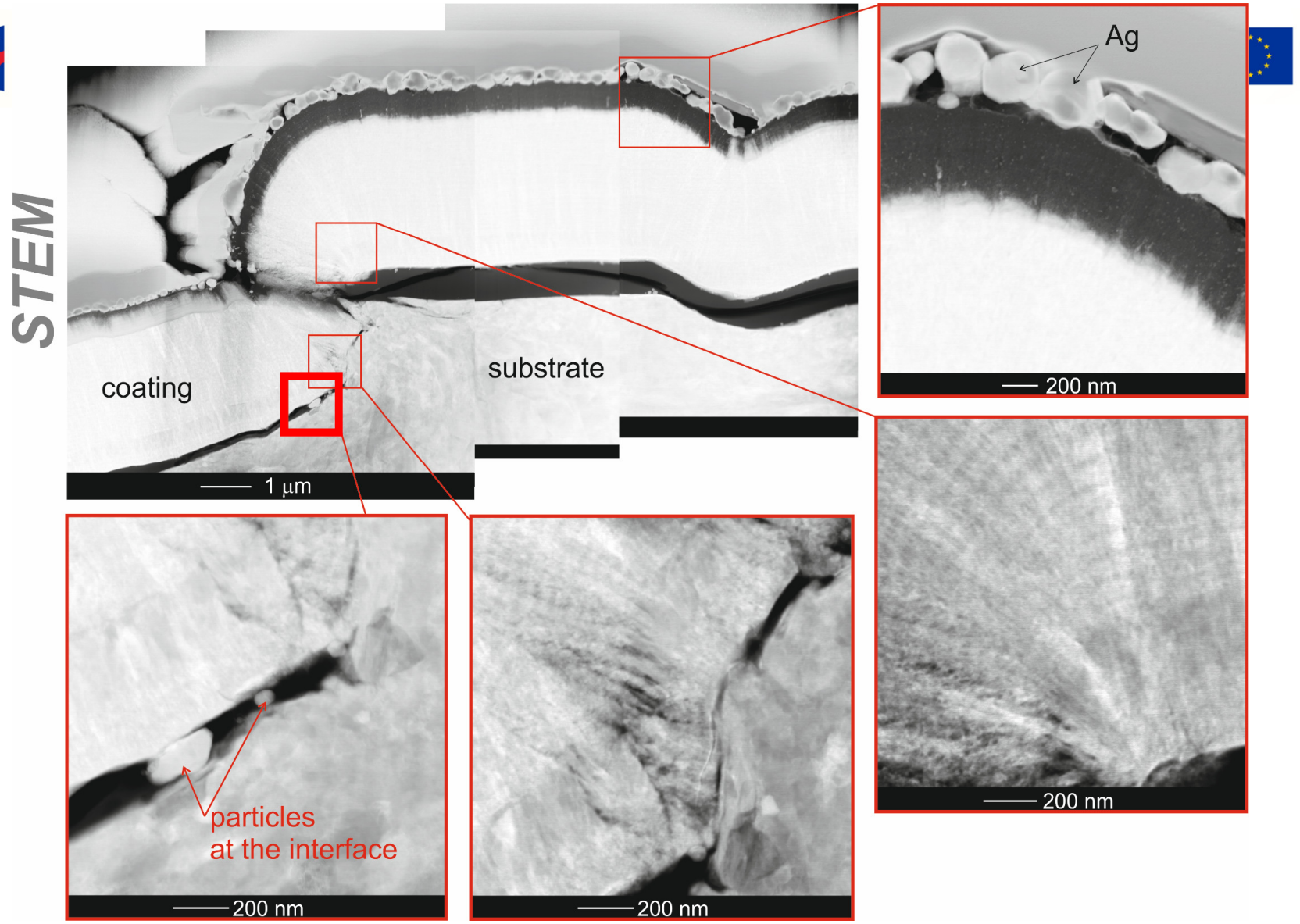

Ag
200 nm


200 nm


particles
at the interface
200 nm


200 nm

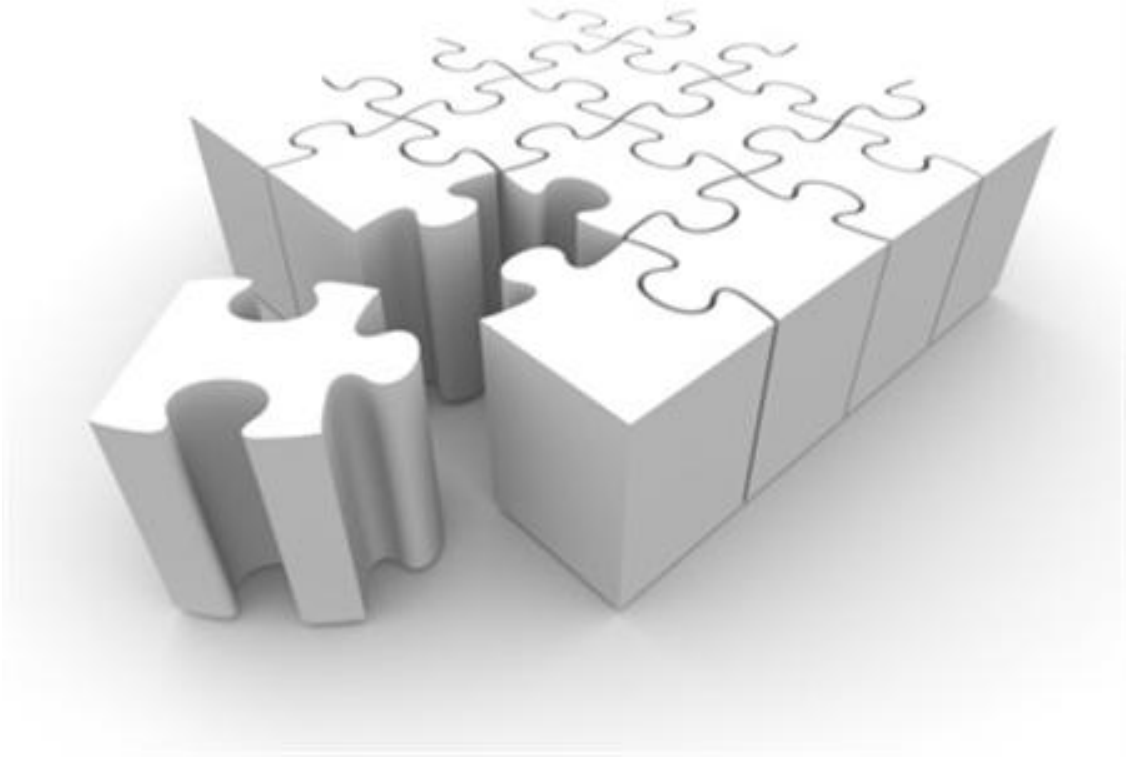

STEM + EDS
Drift corre
50 nm
Ti
50 nm
N
50 nm
Ag
50 nm


STEM
coating
substrate
1 μm
Ag
200 nm
200 nm
particles
at the interface
200 nm
200 nm

European Funds
Knowledge Education Development

INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES

European Union
European Social Fund



Project WND-POWR.03.02.00-00-I043/16

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction

Project co-financed by the European Union within the European Social Funds