Doctoral School
Warsaw University of Technology

COURSE OFFERED IN THE DOCTORAL SCHOOL

<table>
<tr><td rowspan="2">Code of the course</td><td rowspan="2">4606-ES-000DGHL-0364</td><td rowspan="2">Name of the course</td><td>Polish</td><td colspan="3">Wstęp do skaningowej mikroskopii elektronowej i technik pokrewnych.</td></tr>
<tr><td>English</td><td colspan="3">Introduction to scanning electron microscopy and related techniques.</td></tr>
<tr><td>Type of the course</td><td colspan="6">specialized</td></tr>
<tr><td>Course coordinator</td><td colspan="2">dr hab. inż. Dariusz Jarząbek, prof. uczelni</td><td>Course teacher</td><td colspan="3">dr hab. inż. Dariusz Jarząbek, prof. uczelni</td></tr>
<tr><td>Implementing unit</td><td>Faculty of Mechatronics</td><td>Scientific discipline / disciplines*</td><td colspan="4">Mechanical engineering,
Materials science,
Biomedical engineering
Physical sciences</td></tr>
<tr><td>Level of education</td><td>doctoral studies</td><td>Semester</td><td colspan="4">winter</td></tr>
<tr><td>Language of the course</td><td colspan="6">English</td></tr>
<tr><td>Type of assessment</td><td>grade</td><td>Number of hours in a semester</td><td>26</td><td>ECTS credits</td><td colspan="2">2</td></tr>
<tr><td>Minimum number of participants</td><td>12</td><td>Maximum number of participants</td><td>30</td><td>Available for students (BSc, MSc)</td><td colspan="2">Yes</td></tr>
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<tr><td colspan="2">Type of classes</td><td>Lecture</td><td>Auditory classes</td><td>Project classes</td><td>Laboratory</td><td>Seminar</td></tr>
<tr><td rowspan="2">Number of hours</td><td>in a week</td><td>2</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>in a semester</td><td>26</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
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* does not apply to the Researcher's Workshop

1. Prerequisites

a) Basic knowledge of physics at an engineering level, in particular:
- classical mechanics,
- fundamentals of electromagnetism,
- elementary concepts of quantum physics and atomic structure.

b) Knowledge of general and materials chemistry in the field of the structure and properties of solids, including:
- fundamentals of crystallography and the structure of matter.

c) Ability to use engineering mathematics, especially in the areas of:
- linear algebra,
- function analysis,
- basics of differential and integral calculus.

d) Basic knowledge of materials science and engineering, including:
- types and properties of the main groups of materials (metals, ceramics, polymers),
- basic material characterization techniques.

e) General familiarity with electronics and vacuum technology, facilitating the understanding of equipment operation.

f) Ability to use scientific literature and read technical texts in English.

2. Course objectives

The course aims to:

a) Familiarize students with the theoretical foundations of scanning electron microscopy (SEM), including the mechanisms of electron signal generation and detection, the principles of electron optics systems, and the basics of vacuum and instrumentation electronics.
b)
c) Present related techniques used in electron microscopy, such as chemical composition analysis using EDS/WDS, backscattered electron (BSE) imaging, electron backscatter diffraction (EBSD), as well as ion and electron microscopy in FIB-SEM systems.
d) Develop the ability to interpret images and spectra obtained in SEM and correlate them with the microstructure and properties of the investigated materials.
e) Introduce students to the capabilities and limitations of SEM methods, as well as the principles of proper qualitative and quantitative analysis.
f) Provide practical knowledge on sample preparation for electron microscopy studies (conductive and non-conductive materials, coating techniques, cutting, mounting).
g) Build awareness of safety issues related to working with electron microscopes and high-vacuum systems.
h) Prepare students for the independent use of SEM in research and engineering practice, including the selection of appropriate techniques for specific research problems.

3. Course content (separate for each type of classes)

Lecture

Introduction to Electron Microscopy
- Basic differences between optical and electron microscopy.
- Principles of operation of the electron column and vacuum systems.
- Electron sources, electron optics system, and signal detectors.

Scanning Electron Microscopy (SEM)
- Principle of SEM operation.
- Types of signals: secondary electrons, backscattered electrons, X-rays.
- Image contrast and its interpretation.
- Resolution and factors affecting image quality.

Chemical Composition Analysis in SEM – X-ray Spectroscopy (EDS/WDS)
- Mechanism of characteristic X-ray emission.
- Principles of EDS and WDS detectors.
- Element identification and quantitative analysis.
- Limitations and accuracy of the method.

Electron Backscatter Diffraction (EBSD)
- Principle of operation and acquisition of Kikuchi patterns.
- Analysis capabilities: crystallographic orientation, texture, phase identification.
- Applications of EBSD in materials science.

Focused Ion Beam Techniques (FIB, FIB-SEM)
- Principle of FIB operation and types of ions.
- Use of FIB for sample preparation (e.g., for TEM).
- Applications of FIB in surface modification and 3D analysis.

Introduction to Transmission Electron Microscopy (TEM)
- Principle of TEM operation and differences compared to SEM.
- Information obtained in TEM: bright-field imaging, dark-field imaging, electron diffraction.
- High-resolution capabilities and crystal structure analysis.
- Sample preparation requirements – ultrathin lamellae (<100 nm).

Related and Complementary Techniques
- XRF – X-ray fluorescence as a method of chemical analysis.
- AFM – atomic force microscopy as a tool for surface topography imaging.
- Comparison with SEM – range of applications and limitations.

Sample Preparation for Analysis
- Conductive and non-conductive materials – sputtering, conductive coatings.
- Cutting, mounting, and polishing of metallographic samples.
- Specific requirements for sample preparation for EDS, EBSD, and FIB.
- TEM sample preparation using FIB – cutting, lift-out, and final thinning processes.

Laboratory

4. Learning outcomes			
Type of learning outcomes	Learning outcomes description	Reference to the learning outcomes of the WUT DS	Learning outcomes verification methods*
Knowledge			
W01	The doctoral student knows and understands the physical principles of electron beam–matter interactions and the mechanisms of signal generation used in scanning electron microscopy (SEM).	SD_W2	Exam
W02	The doctoral student knows and understands the structure and operating principles of a scanning electron microscope, in particular the electron optics system, vacuum systems, and detectors of electron and X-ray signals.	SD_W2	Exam
W03	The doctoral student knows and understands the capabilities and limitations of electron microscopy techniques and related methods (EDS/WDS, EBSD, FIB-SEM, TEM) in the study of material structure and composition.	SD_W3	Exam
Skills			
U01	The doctoral student is able to interpret images and signals obtained in scanning electron microscopy (SEM) and correlate them with the microstructure and properties of the investigated materials.	SD_U2	Exam
U02	The doctoral student is able to select an appropriate electron microscopy technique (SEM, EDS/WDS, EBSD, FIB-SEM, TEM) to solve a specific research problem in materials engineering or related disciplines.	SD_U1	Exam
U03	The doctoral student is able to critically analyze results obtained using electron microscopy methods and present their interpretation.	SD_U4	Exam
Social competences			
K01	The doctoral student is ready to critically evaluate results obtained using electron microscopy methods and assess their significance for the advancement of science and technology.	SD_K1	Exam
K02	The doctoral student is ready to recognize the importance of advanced material characterization techniques in solving research and technological problems.	SD_K2	Exam
K03	The doctoral student is ready to conduct research using scientific equipment in a responsible manner, with respect for research ethics and good laboratory practices.	SD_K5	Exam

*Allowed learning outcomes verification methods: exam; oral exam; written test; oral test; project evaluation; report evaluation; presentation evaluation; active participation during classes; homework; tests

5. Assessment criteria
The course is assessed on the basis of a written exam consisting of 5 open-ended questions covering the lecture content. Each answer can receive a maximum of 10 points, giving a total of 50 points. The final grade is determined based on the number of points obtained according to the following thresholds: • 0–25 pts – grade 2.0 (fail) • 26–30 pts – grade 3.0 (satisfactory) • 31–35 pts – grade 3.5 (satisfactory plus) • 36–40 pts – grade 4.0 (good) • 41–45 pts – grade 4.5 (good plus) • 46–50 pts – grade 5.0 (very good) Assessment of the answers takes into account: • substantive correctness, • ability to explain physical mechanisms and interpret phenomena, • use of appropriate scientific terminology.

6. Literature
Primary references: Scanning Electron Microscopy and X-Ray Microanalysis, Joseph I. Goldstein, Dale E. Newbury, Joseph R. Michael, Nicholas W.M. Ritchie, John Henry J. Scott, David C. Joy, DOI 10.1007/978-1-4939-6676-9, Springer New York, NY, 2017 Physical Principles of Electron Microscopy, An Introduction to TEM, SEM, and AEM, Ray F. Egerton, DOI 10.1007/978-1-4615-0215-9, Springer Science+Business Media, Inc. 2005 Secondary references: Electron Backscatter Diffraction in Materials Science, Adam J. Schwartz, Mukul Kumar, Brent L. Adams, David P. Field, DOI 10.1007/978-0-387-88136-2, Springer New York, NY, 2009 Transmission Electron Microscopy, A Textbook for Materials Science, David B. Williams, C. Barry Carter, DOI 10.1007/978-0-387-76501-3, Springer New York, NY, 2017

7. PhD student's workload necessary to achieve the learning outcomes**		
No.	Description	Number of hours
1	Hours of scheduled instruction given by the academic teacher in the classroom	26
2	Hours of consultations with the academic teacher, exams, tests, etc.	9
3	Amount of time devoted to the preparation for classes, preparation of presentations, reports, projects, homework	0
4	Amount of time devoted to the preparation for exams, test, assessments	25
	Total number of hours	**60**
	ECTS credits	**2**

** 1 ECTS = 25-30 hours of the PhD students work (2 ECTS = 60 hours; 4 ECTS = 110 hours, etc.)

8. Additional information	
Number of ECTS credits for classes requiring direct participation of academic teachers	2
Number of ECTS credits earned by a student in a practical course	0