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RISK ANALYSIS OF SAMPLE PREPARATION FOR TRANSMISSION ELECTRON MICROSCOPY

ANALÝZA RIZIK PŘI PŘÍPRAVĚ VZORKŮ PRO TRANSMISNÍ ELEKTRONOVOU MIKROSKOPII

MASTER'S THESIS

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TICHÝ, Milík, 2006. Ovládání rizika: analýza a management. V Praze: C.H. Beck. Beckova edice ekonomie. ISBN 80-717-9415-5.

ČSN 01 8003 Zásady pro bezpečnou práci v chemických laboratořích Praha : Úřad pro technickou normalizaci, metrologii a státní zkušebnictví, 2017. 24 stran

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ABSTRACT

This thesis presents a risk analysis of the sample preparation process for transmission electron microscopy with the aim to enhance the occupational health and safety in laboratories employed in sample preparation and analysis. The thesis focuses on identifying potential hazards, evaluating risks, and proposing effective risk mitigation strategies to mitigate or eliminate these risks. The thesis is divided into two main parts, the theoretical which provides information on different sample preparation processes and legislative requirements set by European Union and the Czech Republic, as well as the practical part where the risk analysis is conducted.

The methodology of block diagrams, Failure Mode and Effects Analysis and cause-and-effect analysis were incorporated to achieve as much information about the risk-related to sample preparation processes. In addition, the measures were proposed in order to mitigate or possibly eliminate potential risks observed. Some of the proposed risk mitigation measures encompass the use of personal protective equipment, ergonomic considerations, equipment revisions, and guidelines for handling chemical substances.

The risk analysis results demonstrate a significant reduction in risk levels, as illustrated by the decrease in the risk priority number, once the proposed measures are implemented. The findings emphasize the importance of integrating risk analysis into the sample preparation process to create a safer working environment.

Tato diplomová práce prezentuje analýzu rizik při přípravě vzorků pro transmisní elektronovou mikrosopii. Jejím cílem je zvýšit bezpečnost práce v laboratořích, které se přípravou a nalýzou vzorků zabývají. Tato práce se zaměřuje na identifikaci potenciálních nebezpečí, hodnocení rizik a navrhuje efektivní strategie na zmírnění nebo eliminaci rizik. Práce je rozdělena na dvě hlavní části. První je teoretická, která shrnuje informace o přípravě vzorků a legislativní požadavky určené Evrpskou únií a Českou republikou. Druhá, praktická část, popisuje vypracovanou analýzu rizik.

Blokový diagram, analýza příčin vad a následků i analýza příčin a následků byly použity tak, aby se zjistilo co nejvíce informací o rizicích spojených s procesem přípravy vzorků. Navíc byla navrhnuta opatření tak, aby byla zjištěná rizika eliminována nebo alespoň zmírněna. Navrhovaná opatření ke zmírnění rizik byla například: používání osobních ochranných prostředků, ergonomická opatření, revize vybavení a pokyny pro zacházení s chemickými látkami.

Výsledky analýzy rizik ukazují, že po zavedení navrhovaných opatření dojde k výraznému snížení úrovně rizika, což ilustruje snížení prioritního rizikového čísla. Zjištění zdůrazňují význam začlenění analýzy rizik do procesu přípravy vzorků pro vytvoření bezpečnějšího pracovního prostředí.

KEYWORDS

Transmission electron microscopy, risk analysis, risk, occupational health and safety, measures

Trasmisní elektronová mikroskopie, analýza rizik, riziko, bezpečnost práce, opatření

Author's Declaration

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I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the paper and listed in the comprehensive bibliography at the end of the paper.

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Introduction

Transmission electron microscopy is a powerful technique widely used in various scientific disciplines for investigating the structure and composition of materials at the nanoscale. As TEM techniques advance, the importance of ensuring safe and reliable sample preparation becomes paramount. This thesis focuses on conducting a comprehensive risk analysis of the sample preparation process for TEM, aiming to enhance safety measures regarding occupational health and safety.

The sample preparation process for TEM involves several steps, including specimen collection, handling, and manipulation, as well as the use of hazardous chemicals, equipment, and high-energy electron beams. This thesis has no ambition to describe the processing procedures to their very details but rather focuses on the practical point of view of sample preparation processes that take place at the Institute of Physics of Materials, Czech Academy of Sciences. Sample preparation activities present inherent risks to both the operators of TEM and the workers responsible for sample preparation. Understanding and mitigating these risks is crucial for maintaining a safe working environment. Therefore it is extremely important to be aware of those situations beforehand conducting them. This provides the aim of this thesis to provide, analyse and possibly suggest measures to avoid harmful consequences. In an effort to mitigate risks as much as possible risk management methods are applied to a system aiming to identify and deal with as many risks as possible.

Firstly, the theoretical part of the thesis is focused on providing information necessary for following risk analysis. The chosen methods for specimen preparation are mentioned and described for a better understanding of the sample preparation procedures. In addition, the legislative documents are researched to provide a framework for requirements in metallographic, chemical and analytical laboratories. The main focus is applied to occupational health and safety such as the primary concern of technical risks point of view, thus economic point of view is omitted. In addition, a theory behind risk analysis is provided together with a description of the risk analysis methods employed in this thesis.

The second part of the thesis provides the practical execution of risk analysis. Various risk analysis tools, such as Failure Mode and Effects Analysis, block diagrams, and Cause-and-effect diagrams, will be employed to comprehensively evaluate the identified risks and their potential consequences. In addition, for each identified risk measures are suggested to provide the best possible way how to mitigate and possibly eliminate the risks.

The main objective of this research is to identify potential hazards, assess their likelihood and severity, and develop effective risk treatment strategies to minimize or eliminate them. By conducting a systematic risk analysis, this thesis aims to provide valuable insights into the OHS-related safety vulnerabilities associated with sample preparation for TEM. The outcomes of this research are expected to contribute to the development of guidelines and best practices for safe sample preparation in TEM laboratories.

Aims of the thesis

The thesis aims to investigate the risks associated with specimen preparation for transmission electron microscopy. It aims to identify the potential risks involved in the process. Assess the likelihood and severity of every recognized risk by employing quantitative or qualitative risk analysis methods. The risks are considered mainly in metallographic, chemical and analytical laboratories where the sample preparation and analytical processes take place.

It is essential to consider the legislative perspective when establishing a safe working environment for specimen preparation, taking into account the regulations set by both the European Union and the Czech Republic. Since the risk is, according to occupational safety and health, assessed by the impact of the serenity of an event on human health the financial risks will be omitted. Finally, the ultimate goal of this thesis is to propose measures and precautions to eliminate or at least mitigate the effect of harmful events of identified risks.

State of Art

The aim of this chapter is to demonstrate the very basic principles of electron microscopy providing a reader with fundamental knowledge of the topic. In addition, the technological advancement is illustrated to enable the reader to understand the challenges and limitations encountered while displaying samples in transmission electron microscopy and scanning electron microscopy.

In order to observe and examine the outside world there has always been a need for exploring materials around us to their tiniest details. However, since the human eye can only distinguish between two points in space up to 0.072 mm micro or nanostructures are nearly impossible to be observed without additional technology [1]. Therefore several optical devices were developed providing a way to obtain higher resolution and see further into the inner structures of materials. For example, well-known light microscopes have limiting distinction length at $200 - 250$ nm [2]. The limiting factor for resolution is the wavelength of a viewing particle. As the light photon has a wavelength of $300-600$ nm, however, the size of an atom is much smaller about 0.05 nm, thus, photons are not suitable for displaying atomic structures. To achieve atomic resolution in microscopy, it is necessary for the wavelength of the imaging particles to be smaller than the size of an atom. This condition ensures that the imaging particles can interact with the atomic structure and enable the visualization of atomic-level details [3].

The idea of electron microscopy had been built on the Luis de Broglie's hypothesis stating that an electron can be perceived as both a particle and a wave motion, elaborating on Albert Einstein's idea of quantum mechanics principle of wave-particle duality from 1905, providing the fundamental principle. In addition, the impact of the magnetic and electrostatic fields on charged particles had been observed, based on a similar idea as optical lenses influence photons. Those principles enabled German engineers Ernst Ruska and Max Knoll to create the first electron microscope prototype in the 1930s. And there has been huge technological development ever since, enhancing the possibilities of exploring the inner structures of materials by electron beam exponentially. Following the Luis de Broglie's formula for the wavelength properties of an electron it is possible to establish one's wavelength.

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE_k}}[m] \tag{1}$$

Where λ is a wavelength of the particle, h represents Planck's constant which equals $6.626 \times 10^{-34}\ Js$, m stands for the mass of the particle, in this case, electron, and E_k represents accelerating voltage. As the formula suggests the electron's wavelength is inversely proportional to accelerating voltage [4]. Thus implying that the faster the particle the smaller its wavelength is, providing better resolution. The most significant wavelengths are noted in the table 1, where E_k is accelerating voltage and λ is a wavelength of the particle.

E_k **[kV]**	0.1	1	10	40	100	120	200	300	1000	3000
λ **[pm]**	122.6	38.76	12.20	6.015	3.701	3.349	2.508	1.969	0.872	0.357

Tab. 1: Wavelength of particle dependent on accelerating voltage

Depending on the application there are two major approaches to electron microscopy, scanning electron microscopes (SEM) and transmission electron microscopes (TEM). Conventional SEMs have an accelerating voltage from 500 eV to 30 keV leaving resolution to $1.5 - 0.6\ nm$ [5]. And TEMs that go even further with accelerating voltage of 300 keV reaching the resolution of 50 pm [6]. Japanese company Hitachi went even further by introducing experimental electron microscopes that are able to achieve ultra-high voltage of 1 MV and 3 MV with a point-to-point resolution of 0.16 nm and 0.14 nm. As those numbers suggest higher accelerating voltage does not automatically imply better resolution as there are many limiting parameters like optical aberrations, quality of prepared sample or type of electron gun, that play a crucial role in the final obtainable resolution of a measurement.

An electron microscope is a complex machine consisting of several magnetic and electrostatic lenses that are configured to impact the beam of fast electrons in accordance with the optical axis. However, electron microscopes are in their complexity far from being perfect, physical properties of optical elements introduce optical aberrations such as spherical aberration, distortion, coma, and astigmatism while the curvature of the field, as well as a difference in electron wavelengths, introduces chromatic aberration. Since it is impossible to completely eliminate optical aberrations the electron microscopy operators must learn a workflow of aligning and calibrating the device to reduce them as much as possible for achieving the best possible result.

If aligned properly, electrons in electron microscopes travel in a high vacuum from the field emission gun towards the sample, guided in parallel with the optical axis, ideally as close to it as possible, for a better convergence angle providing better coherence of the electron beam. In the case of TEM electron passes through the sample transmitting obtained information to detectors or camera below, while in SEM, electrons are reflected from the sample surface transferring the information to detectors mounted above. Acquired information speaks about the structural and physical properties of individual samples and is further interpreted by scientists.

1 The Sample Preparation

Electron microscopes serve humanity mainly in three respective fields - life science, material science and semiconductor industry, each one of the application fields with specific needs regarding sample preparation. Life science preparation is based on manipulating samples in cryo-conditions, while semiconductor uses mainly Focused Ion Beam (FIB) for lamellae preparation. Material science combines mechanical and chemical processing or FIB lamellae preparation depending on the sample characteristics. This thesis is solely dedicated to material science sample preparation for transmission electron microscopy.

SEMs are operating on low voltages suitable for the surface examination of various specimens. Due to the size of a microscope chamber, the specimens can have a size up to a few dozen mm. The only requirement for specimens is for them to be solid, but their nature may vary from textiles, polymers or metals to life science samples. The sample preparation for SEM microscopes usually contains of cutting, polishing and sometimes surface coating to prevent charge induction. The preparation varies with the material however, it might be much less demanding than TEM sample preparation. On the other hand, SEM analysis and techniques play a significant role in sample preparation as a tool for TEM lamellae preparation.

For TEM, the sample or specimen preparation is usually a more complex, time-consuming, high-risk activity consisting of handling materials, in order to, make them thin and electron-transparent enough for electrons to transmit through the material. The preparation requires dedicated equipment, expertise, patience and a specialised skill set, as the aim is to provide a sample which has no contamination or damage inflicted by the preparation process. It is very important to handle the specimen with great care as the results from TEM analysis can be only as good as the specimen itself. In the material science sample preparation routine, the aim is to prepare a transparent sample, with dimensions of 3.05 mm in diameter and 200 nm or lower in thickness, that are suitable to be inserted into conventional TEM holders.

For the purpose of this thesis, only several methods of sample preparation have been chosen. The chosen techniques correspond with practices used at the Institute of Physics of Materials, Czech Academy of Science. The aim of this chapter is to describe the process steps of chosen techniques, involved risks will be discussed in the following chapters.

1.1 Bulk Specimen Processing

Material science usually works with bulks of metallic materials such as lead, magnesium, iron, and nickel in the form of alloys or in their pure form. The aim of material scientists is to be able to observe the inner structure of such materials and possibly structural changes once the material is subjected to changes in temperature, fatigue loading or other deformation/reconstruction processes. In the beginning, there is a chunk of material to be analysed, since the TEM can work only with a limited sample size this bulk needs to be cut and thinned and polished into much smaller dimensions, in order to be electron transmittable at the final stage of the sample processing.

1.1.1 Plates Pre-processing

Firstly, it is necessary to obtain small, thin plates of material. The thinner the plates are, the faster they can be further processed. Since the mechanical cutting is very coarse with precision to several μm, the plates are processed further, in order to get rid of all abrasive artefacts caused by cutting.

Mechanical Cutting

Bulk materials are to be cut into thin slices by various mechanical instruments. The most often used tool for slicing is the precise metallographic circular saw either slow ($1 - 300$ rpm) or fast (up to 3500 rpm) moving. Although, several variables must be considered such as the thickness of the saw disc, pressure applied and rotation speed of the saw. A material of discs is usually chosen depending on the mechanical properties of the processed specimen. To achieve slices around 0.15 mm thin it must be cut slowly and without any pressure since the thinner slice is easier to be bent. The bending would damage the sample quality by implying unwanted artificial bending contours to the analysis results. On the other hand, the thinner the cutting disc is the less material will be lost, therefore, also the volume of the sample must be considered. In addition, the slicing process can be accelerated by applying pressure, however, the force applied must be proportionate to the sample thickness and toughness since every error causes artefacts of plastic deformation. All those variables must be taken into consideration while choosing the variables with respect to the sample characteristics.

For more fragile materials the circular saw is replaced by a wire saw. This provides better control over the cut. As the name suggests the sawing mechanism consists of a thin wire made of copper or stainless steel coated with a layer of abrasive material such as diamond dust paste. The wire moves on the surface of the specimen by variable speed (0 to 4 ms^{-1}) providing a very thin and precise cut in the material [4].

Another important aspect is the cooling of the whole cutting process since overheating might damage both sample and the cutting device. Usually, a solution of water and anti-corrosive substances is used, although, other liquids like kerosene are suitable as well.

Electrical Discharge Machining

Another technique for reducing the mass of a sample is Electrical Discharge Machining (EDM), the principle is to use the electrical discharge to remove material from a sample eliminating applied pressure or vibrations to the specimen and therefore inducing no mechanical abrasion. The principle of EDM is to submerge the material into dielectric fluid and place it between two electrodes, inducing the electricity to the electrodes, a channel of plasma of temperature from 8,000 to 20,000 °C is created melting the material intended to be removed. As soon as the induction of electric current is cut off the molten material is flushed by the fluid. The volume of removed material per discharge is $10^{-6} - 10^{-12}$ mm^{-3} usually with frequency $2 - 400$ $mm^3 min^{-1}$ varying with the application and material characteristics. This material removal method is suitable for materials of any shape and hardness. In addition, the material processed by EDM can be designed into various shapes and patterns if convenient [7].

1.1.2 Thinning

Thinning is probably the most essential step in the TEM sample preparation process as it is most time-demanding for laboratory workers and cannot be automatized since every material may be differently shaped as well as would respond differently to abrasion. Thinning plays a crucial part in the quality of obtainable results in following processing and final analysis. The aim is to make the sample as thin as possible for further electrolytic polishing. However, severe plastic deformation can be caused during this process by careless handling and thus it requires vast experience and manual skill of laboratory personnel.

Metallographic Abrasive Grinding

In order to, achieve even lower dimensions of the specimen, thinning, by mechanical abrasion on sandpapers that are attached to the working wheel and spun at a speed from 0 to 700 rpm, whereas $150 - 300$ rpm is utilized most frequently. To provide even better grinding the granularity of sandpaper is reduced during the thinning process. Sandpapers are advised to be switched for less abrasive as the specimen gets thinner at the given thicknesses mentioned in the table 1.1 below, although those data may vary with the experience and hardness of processed material. For TEM both sides of a sample should be ground equally as electrons are transmitted through the whole volume of a sample. Samples prepared by this method are usually noted as foils.

The thinned material is either glued to a device providing better support for flat abrasion or attached to a rubber since holding such a thin sample by hand would be impossible and highly dangerous as one might grind their fingers on a rotating sandpaper. As the sample gets thinner the probability of bending increases, therefore the technique must be conducted with great care and patience to prevent evoking undesired artefacts. The whole process happens in wet conditions. The water is

Sandpaper granularity	**Foil thickness [mm]**
220	0.6
400	0.4
600	0.3
800	0.25
1200	0.15 - 0.07

Tab. 1.1: Sandpaper granularity used with different sample thickness

brought in to drain away residual materials from grinding and to reduce the overheating caused by friction that would inflict artefacts in the material structure or induce bending.

The sample thickness is measured continuously by a micrometre. The cut plate must be thinned equally from both sides which ensures erasing of residual artefacts caused by cutting. In addition, thinning only from one side might cause mechanical tension which would induce plastic deformations and bend the sample. The sandpaper abrasion also implies scratches to the sample, which are erased by the use of less and less granular sandpaper. In order to get rid of the scratches as much as possible the direction of thinning should be regularly changed. As the sample gets thinner and thinner corrosion may occur since water is involved in the grinding process especially if tender metal samples are involved. Therefore the specimen is rinsed with ethanol in between the grinding and measurement interactions to prevent corrosion occurrence. Nevertheless, every material behaves differently depending on its abrasion resistance, toughness etc. All those factors must be taken into consideration while thinning the material in order to achieve the best specimen foil.

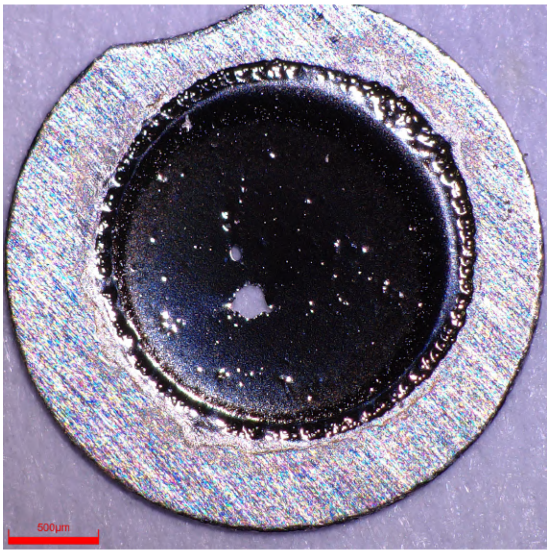
Sample Shaping

Until this point, the specimen is processed in the original shape of foils that are much larger than conventional TEM holders. In order to achieve the dimensions of 3.05 mm in diameter samples are cut by manual bench press into a circular pattern of a given size. Since the foil is already very thin the pressure necessary for the circle to be cut out can be applied by hand without the help of any hydraulic force.

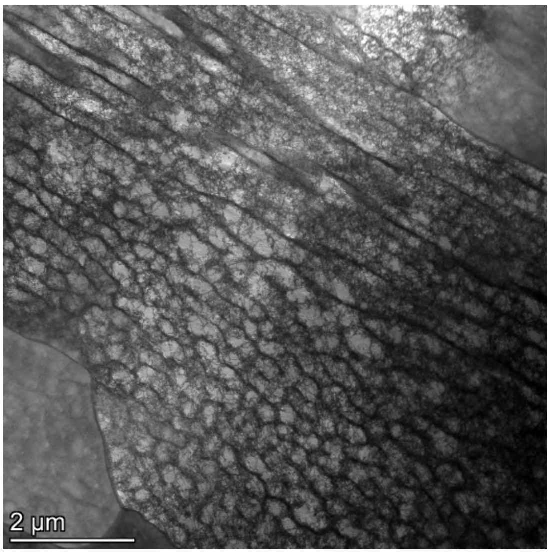
Electrolytic Polishing

Once the specimen reaches the required dimensions it is electrolytically polished. For this kind of sample preparation, the material must be conductive. The specimen is placed into a holder and submerged into an electrolyte solution, this solution differs for every material, compounds and their concentrations play a critical role in the resulting sample quality, together with temperature and applied voltage. The solution is usually a mixture of acids of given ratios and concentrations. The most used acids are perchloric acid ($HClO_4$), and nitric acid (HNO_3) in combination with ethanol or methanol. The sample is placed between two cathodes and works as an anode. Once the voltage is applied, the sample is polished from both sides. Its edges are relatively untouched, while the process is conducted as long as the area near the centre is not perforated. The perforation is recognized by a light source and corresponding photo-sensor that are placed on the opposite sides of the specimen. Once the photo-sensor obtains a signal the electrolysis is stopped. Afterwards, the sample is taken out and dipped into rinsing liquids like ethanol, methanol or deionized water [8].

The surface of the foil should appear shiny and the perforation is verified to make sure the process was successful, see Fig. 1.1a. The area around the perforated hole needs to be thin enough to be electron transmittable, that way an inner structure can be observed, see Fig. 1.1b. However, if there is any imperfection in the process like wrongly chosen voltage, old or improper electrolyte, sample with too heterogeneous structure reacting differently with electrolyte in specific areas or too thick input sample the perforation rim would be still too thick to be transmitted by electrons and therefore the sample would turn out immeasurable. The disadvantage is that the result of sample preparation cannot be verified by an optical microscope because of the small dimensions of the resulting specimen. Thus the quality of the specimen is analysed during the TEM analysis, in case of an inaccurate sample preparation a lot of time is lost and the preparation process must be optimized further.



(a) Foil of Monel alloy



(b) Detail of Monel alloy structure

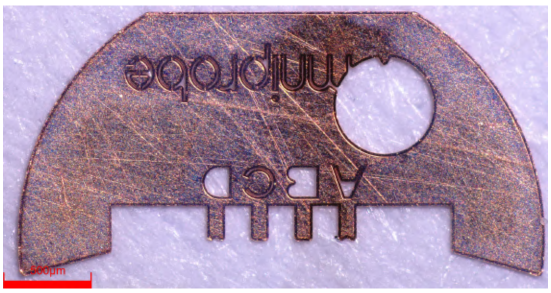
Fig. 1.1: Examples of foil samples

1.2 Focused Ion Beam Milling

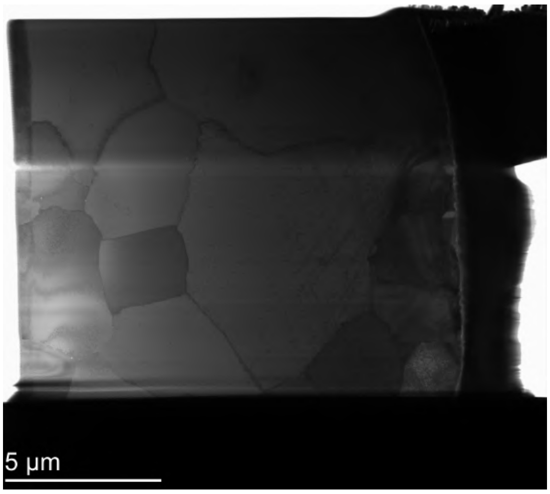
Focused Ion Beam Milling (FIB) is another frequently used sample preparation technique, mainly in the material science and semiconductor industry where the targeted area of the specimen desired to be analysed in TEM is prior studied and specifically targeted in SEM. The material of the sample is not restricted by its characteristics. The aim is to prepare a lamella from the site-specific area and protect its features from ionization damage. The principle of ion beam milling is based on depositing and misplacing material by, usually, gallium ions. However, for even faster FIB milling the plasma ions can be used. The accelerating voltage varies from 1 to 30 kV, the faster the ions are the faster the material of the sample is misplaced. On the other hand, the area hit by ions is damaged, and the radiation damage inflicted is proportional to the accelerating voltage used.

Firstly, the inert gas of platinum particles, which does not interact with the sample, is spread near its surface, and as gallium ions interact with the gas, the platinum layer is deposited at the site-specific area to protect the surface relief below it. Afterwards, the sample is rotated respectively to the microscope axis specification and two rifts are dusted off as the ions strike the atoms of the sample and displace them. This step is performed on the highest accelerating voltage in order to speed up the process. Subsequently, the sample is attached to the micro-manipulator by platinum deposition and undercut from the body of the sample creating separate lamella. The lamella is then attached to the specialized grid (half-moon) again by platinum deposition and the micro-manipulator is subsequently cut off, see Fig. 1.2a.

In the final step, the lamella is thinned from both sides. As ions interact with the sample they leave artefacts, and the accelerating voltage is gradually reduced in order to minimise the damage to the sample. At this point, the lamella is usually 10×6 nm long and 100 μm thick but the size depends on the application and examined area. In the last step, the main area of interest is then thinned to the resulting 40 μm to be electron transmittable, see Fig. 1.2b. Also, the sample's material must be considered since the longer and thinner the lamellae are, the more likely they are to bend and induce plastic deformation and bending contours to the sample.



(a) Lamela attached to half-moon, finger A



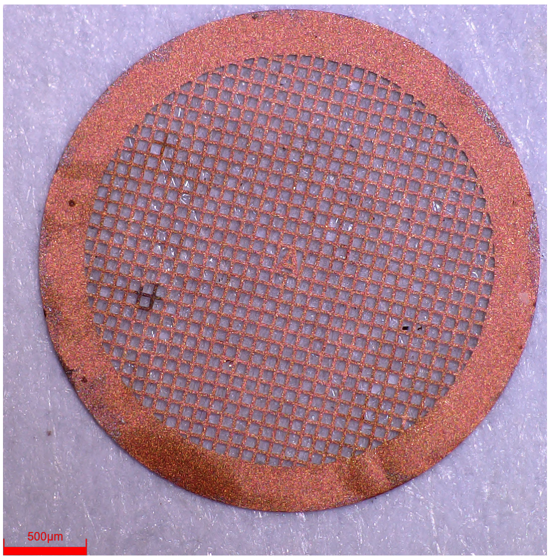
(b) Lamela of nickel-chromium dust

Fig. 1.2: Examples of lamela samples

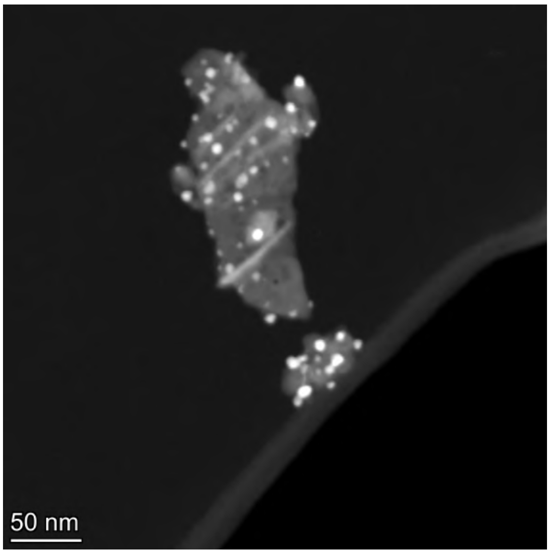
1.3 Nanoparticle Samples

As the name suggests, nanoparticles are too small to be placed in the TEM holder on their own, thus such particles must be supported by a grid or thin, usually carbon, foil. These supporting grids are usually 3.05 mm in diameter, see Fig. 1.3a. The grid is in majority made of copper but for various applications, grids can be made of nickel, copper-palladium, beryllium, stainless steel, titanium or molybdenum. The grid is a mesh structure, and the number of mesh lines varies from the application and the size of examined nanoparticles.

Nanomaterials are usually present in the form of a powder that is either spread and suffused in epoxy resin or the powder is mixed into a liquid solution, usually ethanol, and then dripped onto the grid or carbon foil. The particles get attached to the carbon foil, where they can be observed by TEM, see Fig. 1.3b. In addition, the ethanol provides an anti-corrosive layer to protect the particles, from contamination or corrosion, and due to its evaporating point, the specimen is dry in a relatively short amount of time and therefore ready to be analysed in TEM. The nanomaterials suffused in epoxy need to be further mechanically polished, however, this sample processing is used mainly for SEM analysis. On the other hand, suffused dust in epoxy can be processed by FIB in order to be TEM analysable.



(a) Grid with nanoparticles



(b) Palladium-tellurium nanoparticle

Fig. 1.3: Examples of nanoparticle samples

1.4 Analytical Work

Once the sample is finally prepared for analysis, it is carefully attached to the TEM holder. Certain manual skill is required as the sample can be bent or ruptured while manipulated. The type of holder is determined by the application to be performed, either single-tilt, double-tilt, low background, cryo or others. It is important to attach the sample properly as it might fall out from the holder while tilting in the microscope. Once the holder is inserted into the microscope the analysis can begin. As the TEM is the ultimate viewing device, it displays all the imperfections and deformations implied during the specimen preparation process and handling. The observation itself may cause damage to the sample as well as contaminate it.

It is important to emphasize that the sample after all the procedures is never the same as it was in the bulk state, yet the good sample is the one with the least induced artefacts possible. Those artefacts must be recognized by the researchers and reflected on while interpreting the experiment results. However, the artefacts may contain information on the material's response to chemical, physical and mechanical stimuli and provide a tool for understanding the structure–property–function relationship of analysed materials [9].

2 Legislative Requirements

Considering the difficulty of the whole sample preparation process, skill requirements and expertise, laboratory personnel face certain risks. Therefore, it is necessary to protect their health and ensure their safety while working. The aim of this chapter is to provide a legislative framework overview that deals with the topic of occupational health and safety, as well as to illustrate the rights and obligations of both employers and employees in that matter. Additionally, regulations in individual laboratories are discussed.

Protecting the health and ensuring the safety of employees is a legal responsibility of an employer as it is transitioned from European law and enshrined in Czech legislation. The most important legislative documents regarding occupational health and safety are *Act No. 262/2006 Coll., Labour Code, as amended* and *Act No. 309/2006 Coll. on ensuring other conditions for occupational health and safety at work, regulating other occupational health and safety requirements in employment relationships and ensuring health and safety in activities or providing services outside labour relations.* There are no direct regulations regarding sample preparation, however, the topic of work safety is covered by the *Government Regulation No. 361/2007 Coll., establishing the conditions of occupational health protection.* Together with other directives and regulations, the work conditions in laboratories and the safety of workers are ensured.

Ensure that abiding by the legislative requirements is controlled by safety audits that are performed either internally or externally by a designated and trained team. In addition, the audits provided by an external team are necessary for achieving certain types of ISO certifications to guarantee quality and working conditions.

2.1 Occupational Health and Safety

Occupational health and safety (OHS) is an obligation of the employer to ensure a safe work environment for employees and to mitigate the possibilities of injury occurrence by risk elimination as much as possible. Obligations of an employer and an employee to one another begin with the signing of a contract of employment.

Rights and obligations in the matter of (OHS) are stated in the *Act No. 262/2006 Coll., Labour Code, as amended* in sections §101 - §108. Those sections refine rights and obligations for both sides - employer and employee, together with personal protective equipment and other work-related equipment, a matter of injuries or occupational diseases and risk prevention.

Employer's Rights and Obligations

The employer has several legal obligations to ensure the safety of the work environment as well as the occupational health and safety of their employees. Since there are many obligations only the most important are listed below. The employer is by the *Act No. 262/2006 Coll., Labour Code, as amended*, considering the matter of OHS obligated to:

- ensure the safety and health protection of their employees during the work with respect to risks endangering their life and health, this applies to all neutral personnel who are knowingly present at the place of work,
- consistently look for risks endangering the life and health of employees and control the level of OHS and safety of technical equipment,
- form a list of legal regulations relevant to OHS,
- introduce the book of injuries and record every occurrence of an injury at the place of work,
- provide sufficient guidelines and information about workplace safety to every employee as well as instructions for the safe operation of machinery and equipment,
- require only the amount and difficulty of the work corresponding with the skills and capabilities of individual workers,
- provide training and related documentation in the field of OHS related to the workplace and verify related knowledge of employees at least once a year,
- provide personal protective equipment (PPE) in places and activities where risks cannot be eliminated by means of prevention.

In addition to legislation, there are several standards of practice which upon achieving serve as a guarantee of s safe workspace. In the field of OHS the international standard *ISO 45001, Occupational health and safety*, had been established. This standard was based on *OHSAS 18001, Occupational health and safety management* guideline. It became a framework to increase safety, reduce risks and enhance health and well-being at the workspace, while also providing organizations with tools to improve their OHS rules and regulations. The aim of this standard is to reduce incidents, create a healthy and safe workspace, cut insurance expenses and provide a way to adhere to legal and regulatory requirements. In order to achieve the standard, the organization is required to undergo a certification process in the form of a safety audit provided by a third-party accredited organization that will ensure the compliance of the applicant and that all the standard requirements are met [14].

Employee's Rights and Obligations

the employee on the other hand is obligated to take care of their own OHS according to their possibilities and powers as well as to take care of the OHS of other natural persons who are directly affected by their actions. That also includes being aware of their rights and obligations towards OHS enshrined in legislative documents. Some of their obligations according to *Act No. 262/2006 Coll., Labour Code, as amended* are to:

- participate in training organized by the employer, that is concerned with OHS,
- submit themselves to required occupational medical examinations,
- do not consume alcohol or any other addictive substances at the place of work and outside the place of work during working hours, additionally do not enter the workplace under the influence of addictive substances,
- follow legal and other regulations and employer's instructions in order to ensure occupational health and safety at the place of work,
- inform their employer about failures, near misses and deficiencies at the place of work and participate in eliminating those deficiencies,
- immediately inform their employer about any work-related injury,
- follow work procedures, use prescribed work equipment, means of transportation, PPE and protective devices and do not arbitrarily modify them or remove

them from service.

In addition, employees may refuse to perform tasks if there is any reasonable suspicion that it substantially endangers or restricts their life and health as well as the life and health of others. Every employee has a right to have their safety and health ensured during work and to obtain information about impending risks and possibilities to mitigate them. According to the §8 of the *Labour Code No. 262/2006 Coll.*, employees cannot be forbidden from participating in the matter of OHS [14].

2.1.1 Personal Protective Equipment

At the place where there is any risk of an injury that cannot be eliminated or mitigated by any protective measures, an employer is obligated to provide employees with PPE, to ensure that employees are protected against any risks endangering their health and life. An employer should also maintain the PPE in ready-to-use conditions, thus checking their status regularly. Employees are entitled to receive free-of-charge personal protective equipment, washing agents, detergents, disinfectants and protective beverages corresponding to the nature of their designated work, which cannot be financially compensated in order to buy their own. Also in the working environment where personal clothing is exposed to wear-down or is subjected to abrasion or tearing, employees are entitled to be supplied with work clothes and footwear. Where the type and frequency of exchanging the PPE is a decision of an employer, however, it should correspond with the nature of work.

Personal protective equipment can be sorted into several categories

- respiratory protection - respirators, face masks
- eye protection - goggles, welding masks
- hearing protection - earplugs, earmuffs
- protective clothing - vests, coats, boots, helmets, textile gloves
- skin protective - rubber, latex, nitrile or cryogenic handling gloves, face shields

2.2 Laboratory Regulations

From the sample preparation point of view, it is handled through three differently focused laboratories - mechanical, chemical and analytical. For each of those laboratories, the workers face different challenges and dangers. Laboratories are often equipped with various tools for performing experiments, measurements or gathering data. All those risks should be covered by instructions for the safe operation of the given facility provided by an employer and ensured by the person responsible for the given laboratory in the field of OHS. The work safety in the laboratories is ensured by the Laboratory Code. Laboratory Code is to be placed in every laboratory unit at a visible location. Every laboratory worker who is assigned to work in a given facility must be aware of laboratory regulations and tend to the established rules. A laboratory is a place where risks are highly concentrated thus great effort should be spent on risk detection and subsequent elimination.

Workers are obligated, together with obligations stated in the section on Employee's Rights and Obligations 2.1, to follow guidelines provided by Laboratory Code. Some guidelines should be applied to every laboratory unit, while others are use-case specific. In general, the guidelines are:

- working in laboratories is permitted only to personnel who are verifiably trained in the matter of OHS and entitled to use the equipment they are trained on and familiar with,
- follow Laboratory Code, which lays down provisions for behaviour in the laboratory,
- uninstructed person is prohibited to participate in any laboratory work or manipulation of substances,
- assigned PPE (if any) are obligatory to use in a laboratory,
- person entering the laboratory is obligated to get familiar with placement of first aid kit, fire extinguisher and escape plan instructions,
- follow work manuals and technical devices instructions,
- do not modify devices or manipulate with power transmission lines,
- always keep the workspace clean and organized, clean up the workspace after the work is finished so all the equipment is organized and in ready-to-use

conditions,

- immediately announce any occurrence of a work-related injury that is to be noted in the Book of Injuries,
- do not transport any device or material outside of a laboratory,
- do not drink, eat or smoke in a laboratory.

In addition, workers should swiftly inform their supervisor in case of any device malfunction or damage as well as a shortage of supplies. If a fire occurs it must be announced and internal fire-hazard protocol has to be followed. Every person is responsible for the work done in the laboratory and for following laboratory regulations as well as incurred damages.

2.2.1 Metallographic Laboratory

A metallographic laboratory is a place where the examined materials namely metals and their alloys are processed in order to study their physical and chemical characteristics. Machines for shaping the material like drills, or saws are present. From the sample preparation perspective, the sample is processed from the bulk form until its ready for electrolyte polishing. The aim is to reach the inner structure of the studied material without modifying it. The structure depends on chemical composition, and mechanical and thermal processing which influence is later on studied by electron microscopy.

Since people operate mainly with deformation-implying machines, there is a high injury-related risk involved. To provide a legislative outline for occupational health and safety listed documents were established, besides *Act No. 262/2006 Coll., Labour Code, as amended* and *Act No. 309/2006 Coll., on ensuring other conditions for occupational health and safety at work*:

- Act No. 258/2000 Coll., on the protection of public health,
- Act No. 350/2011 Coll., on chemical substances and chemical mixtures and amending certain other acts, known as Chemical Act,
- Act of CNR (Czech National Council) No. 133/1985 Coll., on fire protection,
- Act No. 185/2001 Coll., on wastes and on amendments of certain other acts,
- Directive No. 48/1982 Coll., notification of the Czech Occupational Safety

office to prescribe the basic requirements ensuring the safety of work and technical equipment,

- ČSN EN 61010-1 2nd ed., safety requirements for electrical equipment for measurement, control and laboratory use,
- Government Regulation No. 101/2005 Coll., on detailed requirements for the workplace and the working environment,
- Government Regulation No. 375/2017 Coll., laying down the appearance and location of safety signs and the introduction of signals, as amended.

In addition, devices and machinery placed in the laboratory adhere to technical standards to ensure their reliability and endurance to defects and thus operational safety. Technical standards include precise descriptions of the design and dimensions of components and products, details of material used, performance and measurement quality specifications. Multiple standards are usually applied in developing devices as technical standards are suited for many industries from engineering to healthcare. As well as multiple technical standards must be taken into consideration in order to establish OHS policies.

2.2.2 Chemical Laboratory

Chemical laboratories can be focused on different topics like biochemistry, the petrochemical industry, analytical work and others. Each one of those has different requirements for the expertise of their workers. A chemical laboratory is a place with a high concentration of chemical substances and mixtures used for various chemical analyses, processing or syntheses. Laboratory technicians often work with poisonous, flammable, explosive, and radioactive substances in extreme temperatures or pressures, therefore, safety and precautions are vital topics. In addition to the *Act No. 262/2006 Coll., Labour Code, as amended* and *Act No. 309/2006 Coll., on ensuring other conditions for occupational health and safety at work*, the topic of safety in chemical facilities is covered in the standard *ČSN 01 8003, on Criteria for work safety in chemical laboratories* and *Act No. 350/2011 Coll., on chemical substances and chemical mixtures and amending certain other acts*, known as Chemical Act. Other important legislative documents applied to ensure the safety of chemical laboratories are:

- Act No. 258/2000 Coll., on the protection of public,
- Act of CNR No. 133/1985 Coll., on fire protection,
- Act No. 185/2001 Coll., on wastes and on amendments of certain other acts,
- Government Regulation No. 467/2009 Coll., specifying for the purposes of the Penal Code what constitutes a poison and defining the quantities greater than small for narcotic substances, psychotropic substances, any preparations containing such substances, and poisons,
- Directive No. 428/2004 Coll., n obtaining Specialization for Manipulation with Dangerous Chemicals and Chemical Preparations Classified with High Toxicity,
- Regulation (ED) No. 1272/2008, on classification, labelling and packaging of chemical substances and mixtures (CLP regulation),
- Government Regulation No. 101/2005 Coll., on more detailed requirements on workspace and working environment,
- Government Regulation No. 375/2017 Coll., laying down the appearance and location of safety signs and the introduction of signals, as amended,
- Commission Regulation (EU) 2017/1510 amending the Appendices to Annex XVII to Regulation (EC) No. 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards carcinogenic, mutagenic, reprotoxic substances.

Personnel working in the laboratory needs to be properly educated and periodically tested on the matter of handling chemical substances as well as in the matter of OHS. Workers should be aware of all the dangers and risks they are facing in the laboratory. The acknowledgement is confirmed by signing the Laboratory Code that states principles that should be tended to by every laboratory worker in order to eliminate such risks as much as possible. Furthermore, for every chemical substance handled in the laboratory, a safety data sheet (SDS) is required. This document provides all important information, divided into 16 sections, about the properties and potential hazards of substances. The manufacturers or suppliers are obligated to provide OHS data by means of SDS to the chemical facilities they collaborate with. In addition to guidelines mentioned in section 2.2, laboratory workers should also keep in mind additional these principles related to their work:

- work only with substances that worker had been properly trained on,
- never work in the laboratory alone,
- always notify the supervisor about the presence of untrained personnel in the laboratory,
- wear adequate PPE according to handled substances,
- before the work is started get familiar with the working procedures,
- get familiar with the information stated in SDS considering the substances to be worked with
- never handle chemical substances by bare hand, use only suitable and clean tools,
- work with smoky, irritating, smelly and toxic substances only in a ventilation hood,
- observe the legal requirements for loading, handling and disposal of hazardous waste,
- in case of spill clean the substance immediately in the prescribed manner,
- adhere to space organization of the workspace and handle only labelled substances.

2.2.3 Analytical Laboratory

The place where the quality and structure of a material are observed is the analytical laboratory, also sample quality is evaluated. The quality of results obtainable is directly proportional to the quality of the prepared sample. Although TEMs are powerful machines that provide a way of examining the internal structure of materials, the results are best to be correlated with various different analytical methods such as light-microscopy, spectrometry, or SEM that are performed in analytical laboratories. That way the full context of the information on the examined material is obtained. These facilities need to adhere to several legislative documents to ensure occupational health and safety. Together with *Act No. 262/2006 Coll.,* *Labour Code, as amended* and *Act No. 309/2006 Coll., for further requirements on occupational health and safety*, the following general regulations are applied:

- Act No. 350/2011 Coll., on chemical substances and chemical mixtures and amending certain other acts, known as Chemical Act,
- Act of CNR No. 133/1985 Coll., on fire protection,
- Act No. 185/2001 Coll., on wastes and on amendments of certain other acts,
- ČSN EN 61010-1 2nd ed., Safety requirements for electrical equipment for measurement, control and laboratory use,
- Directive No. 48/1982 Coll., laying down basic requirements for ensuring safety of work and of technical equipment,
- Government Regulation No. 101/2005 Coll., on more detailed requirements on workspace and working environment,
- Government Regulation No. 375/2017 Coll., laying down the appearance and location of safety signs and the introduction of signals, as amended.

Although, the laboratory can be focused solely on one analytical method or even one device eg. electron microscopy, a unit or group of them could be placed in the analytical laboratory. However, only the electron microscopy laboratory is considered regarding the thesis topic. There is no specific legislative document which would state legal requirements for an electron microscopy facility, thus other legal documents related to this application are to be followed, together with documents ensuring the OHS:

- Act No. 263/2016 Coll., atomic act,
- ČSN EN 07 8304, on pressure vessels for gases - operating rules,
- ČSN EN 33 2180, Electrotechnical regulations ČSN - installation of electrical devices and appliances.

3 Risk Identification and Prevention

Risks are involved in every aspect of human actions, thus preventive measures must be taken to eliminate potential risks and to improve overall performance and minimize the occurrence of injuries to the least amount possible. However, from the OHS point of view, the risk prevention stated in Labour Code is considered only with regard to the work environment. Risk prevention and identification is a domain of risk management. The aim of risk identification is to identify any possible cause that might affect the operability of a subject. Risk management is regulated by *ISO 31000:2018 - Guidelines*, standards, including principles and guidelines. Several different methods for risk identification and evaluation are used in the risk management processes in order to find all the possible risks. A multidisciplinary team, either internal or external is usually involved in risk management, benefiting from a vast amount of knowledge and experience in every level of assessed process. Risk management is used as a method to ensure all OHS principles are followed and a safe environment is established.

The risk management workflow is according to ISO 31000:2018 divided into several steps:

1. Risk identification
   In this step possible risks that might affect the operability of a subject are recognized as an event. For this purpose, methods such as brainstorming, root cause analysis or Strengths, Weaknesses, Opportunities and Threats analysis (SWOT) are implemented.
2. Risk analysis
   Secondly, the probability of a risk occurrence is established as well as a possible outcome of such event. Methods used in this part are for example Bow-tie analysis, Probability/consequence matrix, what-if analysis and others.
3. Risk evaluation
   In the third step, the severity of risks is evaluated according to relevance and consequences. The impact of each risk is qualified in order to prioritize the risk response planning procedure. For evaluation, either quantitative or

qualitative analyses such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), FMEA, Hazard and Operability Study (HAZOP) and others are used.

4. Risk treatment (Risk response procedure)

   At this point, risk mitigation strategies and preventive care are planned with respect to assessed risk severity from the previous step. In an ideal world, every risk is eliminated once precautions are taken, however, in reality, some risks are impossible to be eliminated and thus such preventing steps are taken to mitigate the risk as much as possible. For every risk an approach to establishing measures is taken, either avoiding, retaining, transferring or reducing risk.

   - Avoidance - this approach is adopted in cases when an activity includes a risk behaviour that cannot be mitigated, thus reconsidering participation in such activity is considered the best solution when avoiding the risk. For example, prevent smoking as a precaution against lung cancer.
   - Retention - is an approach of accepting a risk of low severity as it is, usually because accepting small risks helps to prevent larger risks in the big picture. For example, when the cost of prevention is too high for only a small impact.
   - Transferring - to transfer responsibility for the loss in case of an occurrence of a harmful event fully or partially to a third party. Both subjects then share the risk outcome together. Insurance is an example of transferring risk mitigation strategy.
   - Reduction - in this case, the approach is about controlling the losses, where a subject can either take measures to reduce the probability of risk, reduce possible loss in case of a harmful event occurrence, or in the best case scenario mitigate the risk outcome completely [12].

5. Risk monitoring

   Risk management is a never-ending process that adapts to changes in risk evolution. As, with advancing technologies, new risks or new ways to handle them may occur. Personnel are encouraged to actively participate in risk monitoring to be agile in responding to new risks. Probably, the best way to monitor risk development is via periodical audits and revisions [13].

In summary, risk management is a never-ending iteration process that is trying to identify, assess, treat and monitor risks, enabling organizations to take effective informed decisions, adjust their risk strategies and protect themselves from undesired consequences of untreated/ unrecognized risks.

In addition, risk prevention is also mentioned in the *Labour Code No. 262/2006 Coll., as amended* in sections §101 and §102. Risk prevention is defined as *"all measures taken under statutory provisions and other regulations in order to ensure occupational safety and health protection at work and other measures taken by the employer in order to prevent or eliminate risks or to minimize the impact of risks which cannot be eliminated"* The approach of both employers and employees towards risk considering OHS is the topic of the mentioned sections. The §101 amends obligations of the employer towards risk:

- to ensure and care for the safety and health protection of their employees during the work with respect to risks endangering their life and health; this applies to all neutral persons who are knowingly present at the place of work,
- if employees of two or more employers working at the same worksite, the employers shall provide a piece of written information about discovered risks to one another,
- to ensure that the regulations of OHS apply to all individuals present at the workplace,
- all the expenses for ensuring OHS are covered by the employer only [14].

On the other hand, the §102 provides general guidelines on how to prevent risks at the workplace as much as possible, those are:

- the employer should create safe working conditions and the environment by appropriate occupational safety and health protection and by taking measures to risk prevention,
- the measures taken to prevent risk shall be updated with regard to any possible changes in previously established systems,
- if the risks cannot be completely eliminated, adequate measures shall be taken to minimize the danger,

- the employer and employees shall actively participate in seeking sources of risk and possible prevention options, eg. by monitoring established processes.

This part of the §102 provides also principles for the adoption and implementation of technical, technological, organizational and other measures, in order to prevent risks. For instance, replacing dangerous technologies with more sustainable ones or substituting physically demanding work with machines or more agile working processes. The risk should be, in the ideal case, eliminated by removing the source event (root cause), or modifying the work procedures, or conditions to avoid the harmful event. All the risk measures and prevention steps should be planned in regard to technology application, work organization, social relations and impact on the working environment. Measures ensuring collective risk prevention should be always prioritised over individual risk prevention [14].

3.1 Risk Analysis

Risk analysis is a process of identifying and evaluating potential risks, assessing the likelihood and potential impact of these risks, and developing strategies to manage or mitigate them. Depending on the point of view - economic, technical, social risks, and other risks can be recognized. However, from the technical point of view the risk, according to Tichý [10] can be defined as *"The probable value of the loss incurred by the bearer of the risk, or risk beneficiaries by a realization of a dangerous scenario expressed in monetary or other units."*. Yet multiple other interpretations suitable for different fields are available. The financial risks will not be covered by this thesis as the main focus will be given to occupational health and safety. The probability value of the risk might be enumerated as:

$$R = \frac{d}{n}\ [-] \tag{3.1}$$

where d stands for the number of risk occurrences in the monitored set, and n stands for the number of members in the monitored set. The R acquires values from 0 to 1, where the occurrence of the risk at 0 is impossible and at 1 is absolutely certain. The probability might also be converted into %. On the other hand, different definitions of risk like *"Uncertainty related to harm."* [10] imply that the risk occurrence probability might not be quantifiable. For that purpose, both quantitative and qualitative methods of risk assessment are applied in risk analysis.

Risk analysis is a tool of risk management used for risk-related decision-making. The aim is to assess identified hazardous events that may potentially trigger or lead to undesired harmful events. In order to recognize as many root causes as possible risk analysis incorporates several steps:

1. Assets identification - sets the scope of the assessed system to ensure in-depth knowledge of the topic.
2. Define value - defines the asset value from the subject point of view and evaluates the effect in case of loss. The asset value is usually based on financial value.
3. Risk identification - identifies risk events that may endanger the asset value and determines the system's weak points.
4. Threat severity and vulnerability analysis - provides further information on identified risks, and evaluates the probability of occurrence and degree of vulnerability towards harmful events.
5. Risk measurement - quantitative and qualitative methods for risk evaluation are used to estimate the risk magnitude depending on the asset value and its vulnerability.

The risk analysis is one of the steps of risk mitigation. The information collected is a vital part of adopting effective measures and consecutive risk management [11]. The aim of risk analysis is to gather as much information about the observed hazardous event as possible, thus enabling organizations to make accurate decisions in risk mitigation strategies. Incorporated in risk management, timely identification and well-informed decisions contribute to faster and cheaper risk treatment processes.

3.1.1 Chosen Methods for Risk Analysis

Methods used for risk analysis can be divided into two main categories - quantitative and qualitative, both having pros and cons that needed to be taken into consideration once a risk evaluation method is chosen. Quantitative methods provide a way to enumerate or measure an impact of a risk, thus evaluating its severity. These methods are employed if a more detailed analysis is required. While qualitative methods are rather descriptive and used to obtain as much risk-relevant information as possible.

All the information necessary for conducting the following analyses has been gathered at the Institute of Physics of Materials, Czech Academy of Sciences from the observation of processes and from the information provided by employees experienced in the sample preparation processes for TEM and their analysis.

Block Diagram

A block diagram is a graphical representation of the assessed system. This visualization tool provides a way to follow and to better understand system structures and inner interactions. The block diagram is a simplification tool that enables one to focus rather on interactions than over-complicated technical descriptions and recognize possible flaws in the system structure. The most beneficial part of this diagram is to illustrate the interconnection of individual parts of the system and to describe how they work together as a whole. Besides, every part of the system must be properly labelled to enable correct interpretation of the system processes. [15]

Failure Mode and Effect Analysis (FMEA)

FMEA is a systematical method designed for detecting possible errors in organizations, systems and processes before they occur. This analysis combines quantitative and brainstorming approaches. The method is focused on systematically defining the causes of failures and their consequences, searching for the most severe threats and their effects. Failures are ranked by the probability of failure occurrence, the probability of failure being detected, and the failure effect severity. Thus FMEA enables organisations to take specifically tailored measures necessary to protect employees from occupational accidents and other threats.

FMEA should be conducted by a multidisciplinary team of both internal and external specialists familiar with the topic. Before setting up FMEA, it is important to have gathered as much information about the assessed system as possible and establish an extent to which the system will be analysed - to divide the system into small parts is usually more beneficial than analysing the whole system at once. Subsequently, the team starts to fill in the FMEA table from left to right [16].

Failure Mode and Effect Analysis											
Process step	Failure mode	Possible consequences	Probability of failure occurrence	Probability of failure being detected	Effect severity	RPN	Proposed measures	Probability of failure occurrence	Probability of failure being detected	Effect severity	RPN

Tab. 3.1: An example of a header of FMEA table

Every failure is evaluated by three criteria illustrated in the following tables: the probability of failure occurrence, tab. 3.2, the probability of failure being detected before the failure occurs, tab 3.3, and the failure effect severity, tab. 3.4. Those criteria are estimated by team members based on their personal experience and additional information obtained from employees, manufacturers or customers, where 10 is the worst possible and 1 is the best possible scenario. For every failure mode, the most serious scenarios imaginable are considered while evaluating the individual criteria [17].

Rating	Failure occurrence	Frequency
10	Too High: Inevitable Failure	> 90 from 100 procedures
9		70 from 100 procedures
8		50 from 100 procedures
7		30 from 100 procedures
6	Intermediate: Intermittent Failure	20 from 100 procedures
5		10 from 100 procedures
4	Low: Relatively Low Failure	5 from 100 procedures
3		2 from 100 procedures
2	Very rare: Unlikely Failure	1 from 100 procedures
1		<1 from 100 procedures

Tab. 3.2: The probability of failure occurrence

Ranking	Likelihood of detection
10	Absolutely uncertain
9	Very remote
8	Remote
7	Very low
6	Low
5	Moderate
4	Moderately high
3	High
2	Very high
1	Almost certain

Tab. 3.3: The probability of failure being detected

Once criteria estimates are collected, the achieved values are multiplied together providing the final Risk Priority Number (RPN). Risks rated with the RPN > 125 are usually considered critical and should be handled with priority. For every listed risk with the RPN exceeding value 125 a measure should be proposed to mitigate

Ranking	Severity	Criteria
10	Hazardous without warning	Fatality
9	Hazardous with warning	
8	Very high	Serious injury and injury with permanent consequences
7	High	
6	Moderate	A more serious injury requiring hospitalization
5	Low	Absentee injury (with incapacity for work)
4	Very low	
3	Minor	An injury without incapacity for work
2	Very minor	
1	None	No noticeable effect

Tab. 3.4: Failure mode severity evaluation criteria

the risk as much as possible, the risks ranked lower are considered acceptable and do not require any measures. However, with the exception of OHS-related threats, they always require measures to be implemented in order to protect human health. Once the measures are suggested the risks are re-evaluated with measures considered, providing new coefficients for RPN calculation. In the ideal case, measures should be efficient enough to prevent failures from ever happening using optimization and gradually reducing the RPN to 1. In the final step, the FMEA documentation is created, including a description of imperfections found, together with a description of methods used and measures taken [16].

Cause-and-Effect Diagram

The cause-and-effect diagram, also known as the Ishikawa or fishbone diagram, is a causal tool used for root-cause analysis. The aim is to obtain as many details about the assessed problem as possible for possible risk root causes. The diagram is visually divided into 6M categories - Manpower, Mother Nature, Materials, Machines, Measurement and Methods. Those 6 categories are visualized as ribs of a fish skeleton, each provided with a potential cause, while the assessed problem is the head as illustrated in the Fig. 3.1.

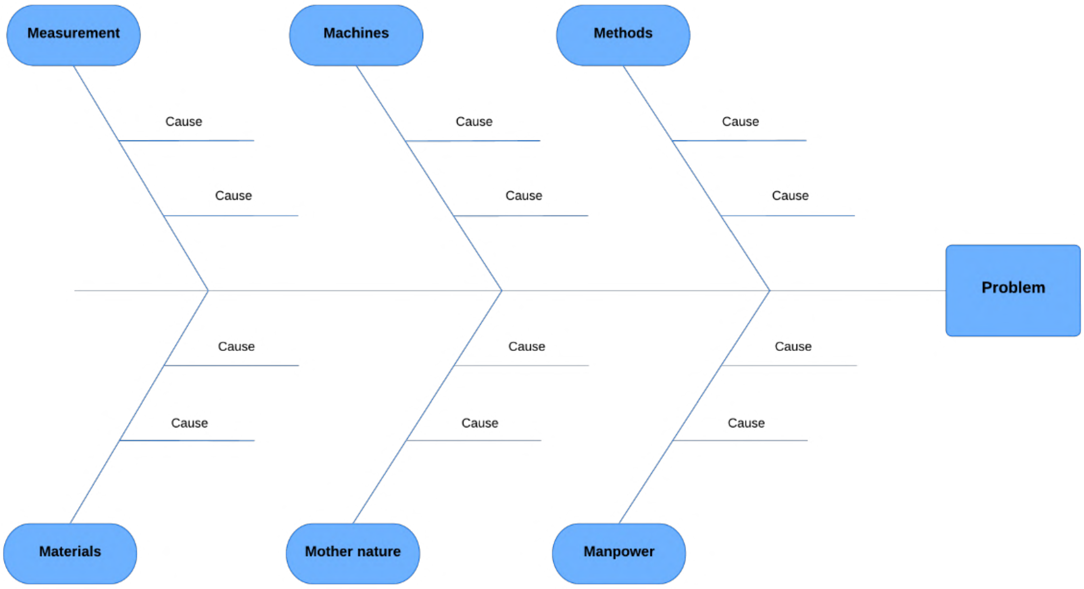


Fig. 3.1: An example of cause-and-effect diagram

Brainstorming is used as the primary tool for obtaining as much information about the defined problem as possible. The generated ideas are subsequently divided into the 6M categories and drawn into the diagram. The categories may include:

- Manpower - skills, errors and training of people involved in the problem
- Mother Nature - environmental issues influencing the assessed problem (usually unpredictable)
- Materials - the quality, and structural characteristics of materials involved
- Machines - maintenance factors, the technology used, machinery failures involved
- Measurement - used metric system, the accuracy of measurement used to assess the problem, calibrations
- Methods - process efficiency, possible bottlenecks of systems where the problem occurred

The cause-and-effect diagram can also be enhanced by additional brainstorming methods such as 5 whys, mind maps, or 5W2H asking questions: who, what, when, where, why, how and how much to ensure obtaining all necessary and crucial information.[18]

The analyses mentioned above are all interconnected together, their results provide inputs for the following analysis. Firstly, block diagrams are created for each sample preparation technique, identifying the main elements of processes. Afterwards, these elements can be analysed using FMEA which identifies potential failure modes and their consequences. Finally, identified failure modes are analyzed using cause-and-effect diagrams to identify the root causes of these failures. Overall, the interconnectivity of these analyses highlights the importance of a comprehensive risk analysis process that considers all potential risks and their impact on the assessed system. By using a combination of these tools, organizations can identify potential risks, evaluate their potential impact, and develop effective strategies to manage or mitigate these risks.

4 Risk Analysis Application

This chapter comments on the application of risk analysis carried out in this thesis. In addition, it provides the results of chosen methods used for risk analysis of sample preparation for TEM. Since there is a high probability of achieving a bad-quality sample, more than just an amount of material for one sample is usually processed at a time to provide room for error. Therefore, only aspects of OHS, as the most critical aspect of sample preparation, are considered in this thesis.

4.1 Sample Preparation Diagrams

The block diagram was chosen as the best way to illustrate the main elements of sample preparation for all foil, lamella and nanoparticles sample types. More detailed descriptions of individual sample preparation techniques are mentioned in chapter 1.

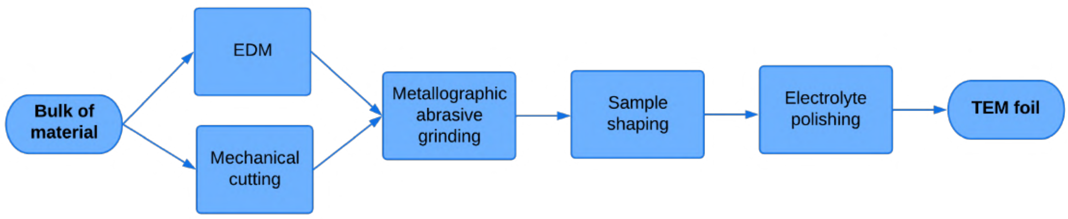


Fig. 4.1: Block diagram of TEM foil preparation from bulk

The first Fig. 4.1 follows the process of foil preparation for TEM from the original bulk form. This process includes various types of threats, including injuries caused by mechanical or electrical stimuli. In addition, the workers are exposed to chemical substances while preparing electrolytes which contributes to the overall danger of this preparation technique.

Fig. 4.2 refers to the lamella preparation technique. The majority of this process happens inside the SEM microscope, thus, mechanical dangers do not take a place in this process. On the other hand, since workers spend long hours by the computer screen ergonomic threats arise. The electrical dangers remain as the microscope is powered by a source of high voltage.

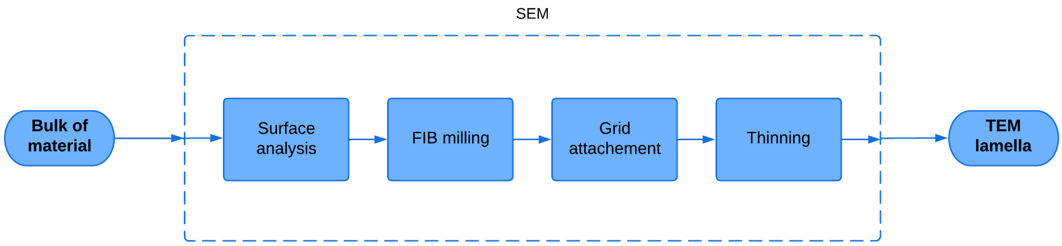


Fig. 4.2: Block diagram of TEM lamella preparation by FIB

The last block diagram 4.3 illustrates the preparation steps of nanoparticle samples. The workers come into contact with a few chemical substances that are used for dissolving the nanoparticle dust. The possibility of mechanical or electrical injury is eliminated during this process.

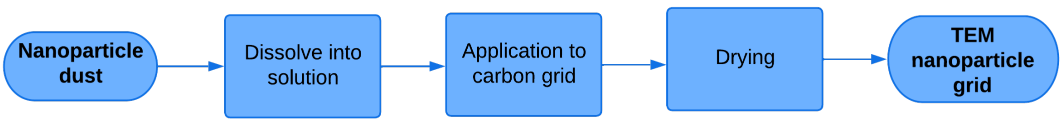


Fig. 4.3: Block diagram of TEM nanoparticle sample preparation

Once the samples are prepared either way the analytical work with TEM begins. Microscopy technicians often spend extended periods, ranging from several hours to days, analyzing sample structures and compositions. This prolonged exposure makes them more susceptible to ergonomic-related hazards. Furthermore, the use of electron microscopes, which are powered by high voltage, poses a risk of electrical hazards. The workers are also exposed to electromagnetic and x-ray radiation that emanate from the microscope. Additionally, when the microscope is being cooled down with liquid nitrogen, the technicians may be exposed to the hazardous effects of chemical substances.

4.2 Risk Identification

Since sample preparation takes place in three laboratories - metallographic, chemical and analytical, it seemed more convenient to identify specific risks for each of those laboratories rather than for each preparation technique. Therefore the measures can be subsequently implemented at the particular place. According to chapter 1 and sample preparation diagrams mentioned in chapter 4.1 the following risks have been identified. The risks listed in the sections below are sorted by their probabilities and severity.

Risks Present at Metallographic Laboratory

Sample preparation in the metallographic laboratory consists of processing bulks of material into tiny polished foils that are further processed in the chemical laboratory. Techniques of metallurgical sample processing are solely dedicated to the bulk of materials.

- Mechanical injury - since several cutting and grinding machines are used in the process of sample preparation workers can cut or grind themselves. Particularly hands and fingers are endangered.
- Chemical substances - flammable liquids and other chemical substances handled in the laboratory threaten human health, especially if consumed, inhaled or came into contact with eyes, exposed skin and tissue.
- Ergonomics - workers can spend several hours standing or sitting by the worktable which can affect one's physique.
- Fatigue - long work hours take a toll on physical and psychological health. Also, attention span decreases with worked hours increasing the chance of an accident.
- Noise - staying in noisy surrounding for an extended amount of time may cause a hearing impediment.
- Machinery failure - possible malfunction of devices endangering the health of workers. Personnel may hurt themselves (cutting; crushing or grinding fingers) once being distracted or not careful while performing destructive sample

preparation techniques.

- Injury caused by electrical current - technicians regularly work with devices (saws, metallographic grinding machine, EDM) plugged into the power source, which may cause an electric shock in case of malfunction, contact with damaged parts, violating of protective measures or improper handling. The electric shock can even lead to death.
- Slip - slipping while walking with subsequent fall of the worker causes different types of injuries.
- Fire, explosions - caused by short-circuit, static electricity discharge, or a spark that may ignite flammable chemical substances used in the laboratory.
- Fall of machinery - devices used can fall from the working table and hurt workers if not secured properly.

Risks Present at Chemical Processing

A chemical laboratory is a place where electrolytic polishing and nanoparticle specimen preparation takes place. Workers often handle and prepare electrolytes - mixtures of several acidic, alkaline or corrosive substances of various concentrations depending on the material to be polished, in the case of foil preparation. Alternatively, various mixtures of methanol and ethanol are used for preparing nanoparticle solutions.

- Chemical burns - working with solutions of acids, bases and corrosives can cause serious chemical burns in case of contact with the human body.
- Fire - caused by short-circuit, static electricity discharge, or a spark that may ignite flammable chemical substances used in the laboratory.
- Poisoning - poisoning caused by inhaling or consuming chemical substances.
- Ergonomics - workers can spend several hours standing or sitting by the worktable which can affect one's physique.
- Fatigue - long work hours affect physical and psychological health. Also, attention span decreases with worked hours increasing the chance of an accident.
- Injury caused by electrical current - the electrolytic polishing machine is plugged into a power line and thus prone to short-circuit, violating protective measures

or malfunction leading to injury by electric current.

- Slip - slipping while walking with subsequent fall of the worker causes various types of injuries including damage done by spilt chemical substances upon themselves.
- Fall of machinery - devices can fall from the working table and hurt workers.
- Cut - technicians may cut themselves while working with glass laboratory equipment in case of its breaking.

Risks Present at Analytical Laboratory

Considering only laboratory of electron microscopy, microscopes usually have dedicated entire rooms with backgrounds to ensure the operability of machines. Their function needs to be supported by various chemical substances such as liquid nitrogen or argon gas. In addition, machines are under high voltage thus technicians must be aware of electric current-related risks while working. Electrons interact with the specimen, when the secondary electrons are radiated from the atom and its position is replaced by the atom from the higher atomic shell, the x-ray is radiated. Thus precautions for X-ray safety while working with electron microscopes must be also taken into consideration. The SEM microscopy room is a place where lamellae samples are prepared before being transmitted to TEM. TEM analytical laboratory is the final step for all mentioned types of sample preparations where material structures are examined.

- Injury caused by electrical current - electron microscopes are operating at high voltages supplied by high-tension tanks, thus any short-circuit or a touch of a damaged part would have fatal consequences.
- Ergonomics - workers can spend several hours standing or sitting by the worktable which can affect one's physique.
- Chemical burns - careless handling of liquid nitrogen (-195.8 °C) can cause chemical burns in contact with anything metallic.
- Mechanical injury - hurting themselves while attaching the sample to the holder, limbs pressed by mechanical parts of a device.
- Radiation exposure - the x-ray and electromagnetic field radiations are emitted

during the analytic work.

- Slip - slipping while walking with subsequent fall of the worker causes various types of injuries including damage done by spilt chemical substances.
- Pressure vessels - the functionality of electron microscopes is ensured by pressured gasses stored in pressure vessels. Pressure vessels are subjected to a risk of explosion, or fall on a worker if not fixed properly.
- Fire, explosions - caused by short-circuit.
- Fall of parts of the device - device parts may not be secured properly, and serious injuries can be induced by the fall upon the operator.

4.3 Risk Analysis

Once potential hazards have been identified, the next step is to evaluate their likelihood of occurrence and the potential consequences if they were to occur. In this case, analytical tools like FMEA and cause-and-effect diagrams were used.

4.3.1 FMEA

Corresponding with identified risks FMEA analysis has been used. The RPN has been calculated from the evaluation criteria in accordance with the probability of failure occurrence, Tab. 3.2, the probability of failure being detected before the failure occurs, Tab. 3.3, and the failure effect severity, Tab. 3.4. The resulting RPN represents the seriousness of the identified risk, leading to the following classification, see Tab. 4.1.

The RPN obtained by coefficient multiplication can acquire values from 1 to 1000, the higher the number the more critical the risk event is. The carried-out FMEA analysis for each laboratory can be found in appendices A, B and C including proposed measures and complete evaluation, where only the regular techniques during sample preparation are considered. Workers responsible for all mentioned actions are technicians for the metallurgical laboratory, chemists for the chemical laboratory and operators for the analytical laboratory, thus the operators are not specifically

Tab. 4.1: RPN classification scale

RPN	Criteria
1 - 49	**Negligible** - low priority risk, no measures adopted, the risk is only to be observed further.
50 - 124	**Acceptable** - consequences are accepted, no need for measures implementation. Only measures with a brought value much higher than the cost of these measures can be implemented. The risk is to be monitored further.
125 - 174	**Permissible** - measure adaption is evaluated according to their cost-benefits ratio. Only measures with lower costs and higher values are recommended for implementation. The risk is observed further.
175 - 224	**Unacceptable** - the risk must be mitigated in reasonable time. The expenses spent for risk reduction should correspond with the value of assets saved.
>225	**Intolerable** - the activity is to be stopped immediately, measures mitigating the risk to an acceptable level are to be adopted as soon as possible.

mentioned in the FMEA analysis. The coefficients for acquiring RPN have been achieved by brainstorming with the involved workers.

4.3.2 Cause-and-Effect Diagrams

Based on primary FMEA results, for a better understanding of the source of risk or failure, the cause-and-effect diagram is used. The aim is to develop potential causes to a sufficient extent to find a root cause. For the purpose of the thesis, only the most crucial "Intolerable" (RPN > 225) failure modes were analysed by the cause-and-effect diagram.

The risk of injury caused by the electrical current applies to all the laboratories mentioned. The RPN has been evaluated to 250. The resulting RPN is an outcome of the multiplication of coefficients, the failure occurrence was enumerated as 5, as well as the likelihood of detection since the parts can be covered inside a device, the severity was ranked 10 as the possible consequences of contact with exposed life parts may be fatal. Possible causes of such failure mode are illustrated in the following Fig. 4.4

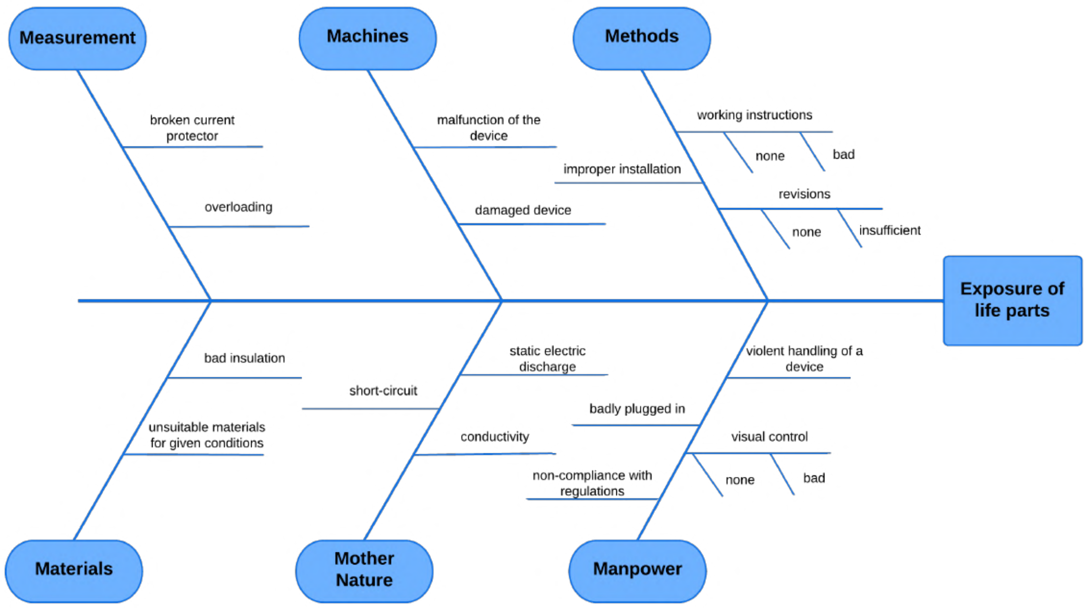


Fig. 4.4: Cause-and-effect diagram of exposure of life parts

Equally ranked became a risk of poor life parts conditions. The consequences of such a failure mode are comparable with the previously mentioned Exposure of life parts, however, a few more potential root causes were specified in Fig. 4.5.

The Long-term exposure to X-ray is analytical laboratory specific. The RPN has been evaluated to 315 since the detection is quite difficult without the use of dosimeters and the consequences of high exposure dosage are potentially fatal. Potential root causes are illustrated in Fig. 4.6.

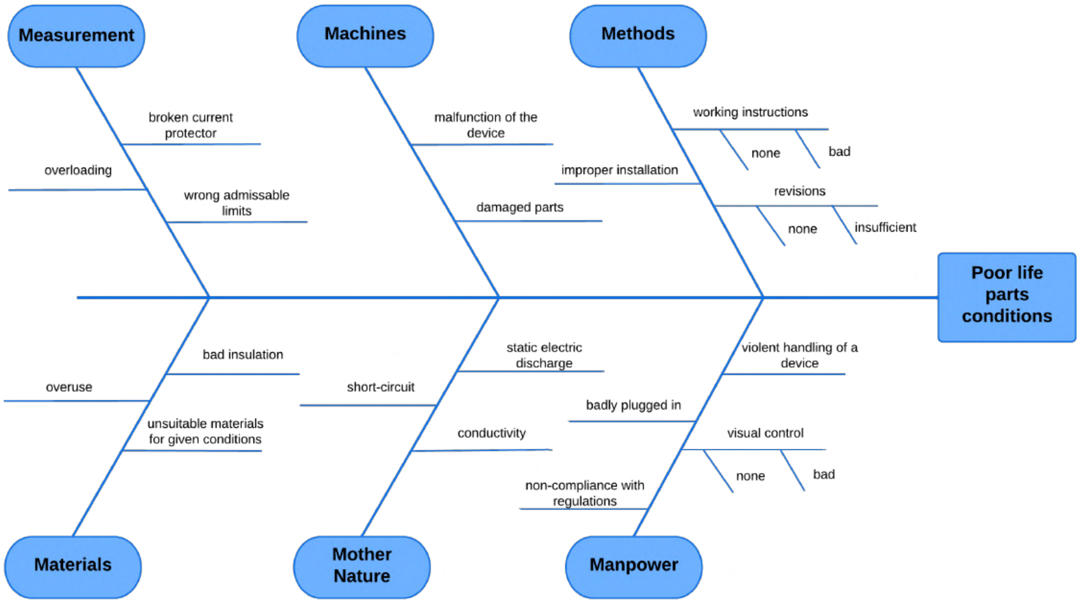


Fig. 4.5: Cause-and-effect diagram of poor life parts conditions

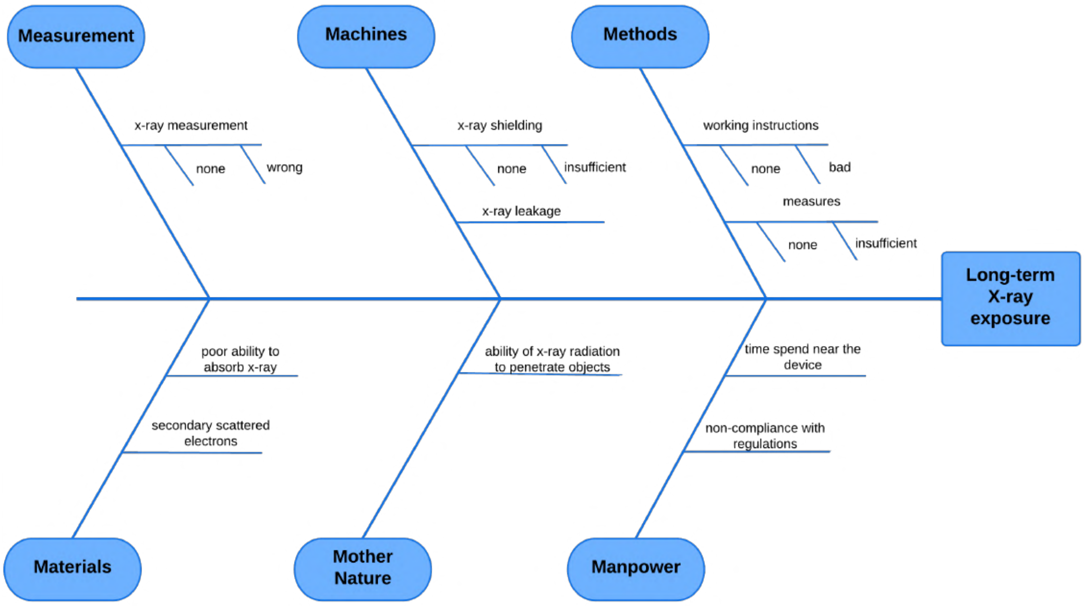


Fig. 4.6: Cause-and-effect diagram of long-term X-ray exposure

The RPN for the danger of Wrong handling of chemical mixtures and solution has been enumerated to 288. The probability of occurrence is limited only to the chemical laboratory since it is the only place where chemical substances like acids, corrosives, hydrides and others are mixed together in order to prepare an electrolyte solution. Possible causes are illustrated in Fig. 4.7.

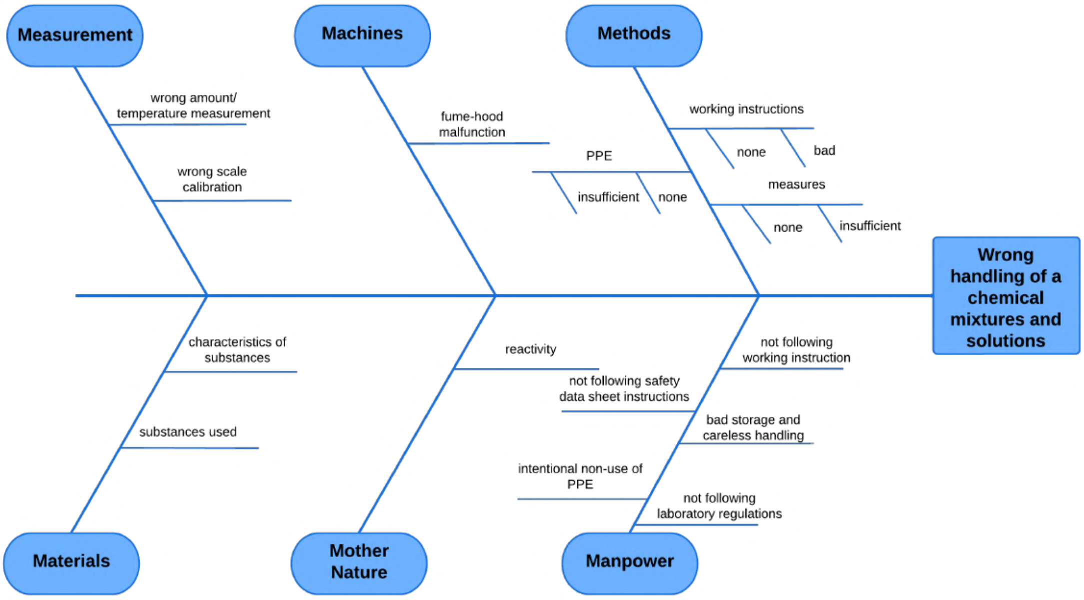


Fig. 4.7: Cause-and-effect diagram of wrong handling of chemical mixtures and solutions

4.3.3 Measures Suggested for Implementation

Based on the primary risk evaluation, measures are recommended in order to mitigate the likelihood of undesired event occurrence. The good measure should be relevant, objective, reliable, valid, implemented at the right time and able to adapt to the needs of the assessed system. After the measure is implemented, the RPN value should not exceed the "Acceptable" value (see tab. 4.1). Although, the risks rated < 125 do not require any countermeasures, in the case of OHS-related measures proposed for every failure mode. If the first round of measures fails to mitigate the risk sufficiently, the second round of measures is proposed. The following courses of action were suggested for implementation in the TEM sample preparation process with the aim to protect human health.

Suggested Measures for Metallographic Laboratory

Several measures were proposed to ensure a safe working environment while preparing the TEM samples in the metallographic laboratory. Every single measure specified for a given failure mode is itemized in appendix A. In a broader sense, the measures suggested for implementation in metallographic processing are:

- Hazardous substances - particular instructions on how to handle chemical substances have been introduced together with PPE specifications for each application in sample preparation. Also, the general principles of first aid in case of chemical burns, inhaling, or ingesting chemicals have been introduced. In addition, the importance of following safety and data sheets is emphasized. Lastly dealing with chemical waste regulations is mentioned.
- Work environment - measures ensuring the ergonomic aspects of a workplace have been suggested, together with providing information on how to secure an escape plan in case of evacuation. The measures also propose a way how to deal with fatigue and noise.
- Injuries caused by electric current - for working with Metallurgical abrasive thinning, Mechanical cutting and EDM safety information have been provided, in order to keep workers safe from the contact of live or exposed-conductive parts and subsequent injury. Also, the importance of regular revisions and careful movement around the electric devices is highlighted.
- Mechanical injuries - as mechanical injuries are the most likely to occur during metallographic processing, the usage of PPE and following working instructions have been emphasised. In addition, a way to prevent a mechanical injury caused by a fall of a device has been suggested.

Suggested Measures for Chemical Laboratory

As the name suggests measures in the chemical laboratory are mainly focused on how to handle hazardous substances. Although there have been proposed other measures for several other categories listed, that threaten the health of the chemists involved:

- Hazardous substances - hazardous substances are the most significant danger in chemical processing, thus particular instructions on how to handle chemical substances and their combinations have been introduced together with PPE specifications for each application in electrolyte polishing. Also, the general principles of first aid in case of chemical burns, inhaling, or ingesting chemicals have been introduced. In addition, the importance of following safety and data sheets is emphasized. Lastly dealing with chemical waste regulations is mentioned.
- Work environment - measures ensuring the ergonomic aspects of a workplace have been suggested, together with providing information on how to secure an escape plan in case of evacuation. The measures also propose a way how to deal with fatigue.
- Injuries caused by electric current - for working with electrolyte polishing safety information have been provided, in order to keep workers safe from the contact of live or exposed-conductive parts and subsequent injury. It is important to adhere to working instructions and be careful while working with or moving around electric devices.
- Mechanical injuries - a way to prevent a mechanical injury caused by a fall of a device has been suggested.

All measures are described in detail in appendix B.

Suggested Measures for Analytical Laboratory

The analytical laboratory may be deemed as a relatively safe environment as the operator is involved in working with only a limited amount of chemical substances and no mechanically destructive tools. However, several measures to ensure a safe working environment, as suggested below, must be taken here as well:

- Hazardous substances - the instructions on how to handle liquid nitrogen and other substances located in pressure vessels have been introduced together with PPE specifications. In addition, the importance of following safety and data sheets is emphasized.
- Work environment - measures ensuring the ergonomic aspects of a workplace

have been suggested, together with providing information on how to secure an escape plan in case of evacuation. The measures also propose a way how to deal with fatigue and for protecting operators from blue light.

- Injuries caused by electric current - for working with an electron microscope safety information have been provided, in order to keep workers safe from the contact of live or exposed-conductive parts and subsequent injury or death caused by high voltage. It is important to adhere to working instructions and be careful while working with or moving around electric devices.
- Radiation exposure - X-ray or electromagnetic field radiation is an invisible threat, the proposed measures make sure that the exposure has been limited as much as possible.
- Mechanical injuries - a way to avoid an injury caused by falling parts of an electron microscope has been suggested.

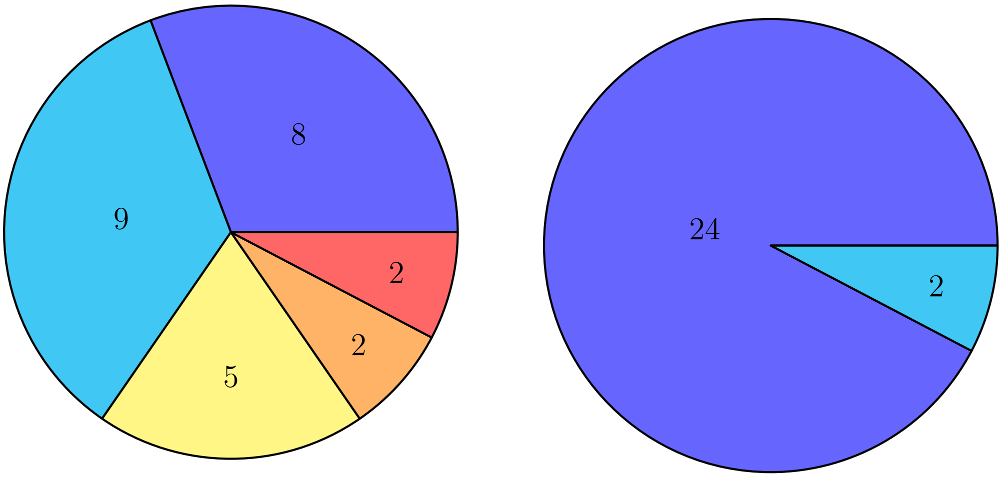
The suggested measures can be viewed in appendix C.

4.4 Results Interpretation

Through the risk analysis conducted, the aim was to identify potential risks in OHS and to evaluate their possible consequences. The analysis was conducted using a range of risk analysis methods and techniques, including hazard identification and risk assessment.

During the risk analysis, several thread events were identified, using block diagrams and subsequent FMEA analysis, for each laboratory where samples are prepared and analysed. Some of those risks were laboratory specific while others occurred across all laboratories. The results achieved by the FMEA analysis were plotted into the following pie charts. The pie charts reflect the severity of identified risks for both "before" (a) and "after" (b) the implementation of the measures. Since all recognized risks are related to OHS, measures have been proposed for each risk event.

The journey of the sample starts at the metallographic laboratory. Several common risks related to electric current-related injuries, or work with hazardous substances are encountered there. However, the metallographic laboratory is a place



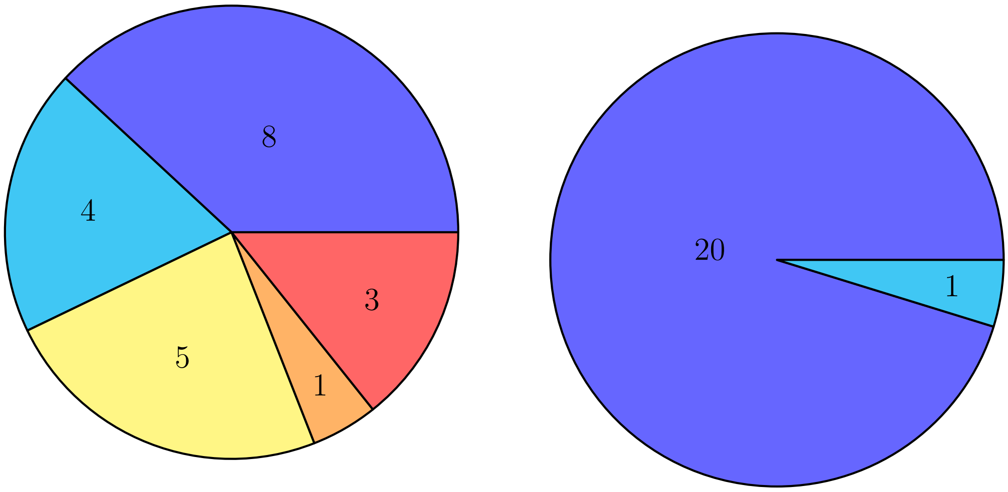
(a) before implementation of the measures (b) after implementation of the measures

$RPN < 49$ $RPN \in < 50 - 124 >$ $RPN \in < 125 - 174 >$ $RPN \in < 175 - 224 >$ $RPN > 225$

Fig. 4.8: Pie charts of identified risks in metallographic laboratory

with a high number of possible risks of mechanical injury. As illustrated in the pie chart in Fig. 4.8 26 risks were recognized in total. Only two of those risks were determined as "unacceptable" and one have a critical RPN ranking above 225. A significant reduction in the RPN evaluation occurred as the suggested measures have the potential to mitigate the risks to "negligible" and "acceptable" levels.

The chemical laboratory, the second analysed facility, faces 21 identified risks. In contrast to the metallographic laboratory, the number of "acceptable" threats decreased, on the other hand, the number of "intolerable" risks increased. As the pie chart in Fig. 4.9 illustrates, the ratio of risks rated above the RPN = 125 is around 42.86 %, while the ratio of equally ranked risks in the metallographic laboratory was around 34.62 %. This fact implies, that workers performing chemical sample preparation face a higher number of potentially more serious risks compared to metallographic sample preparation. Fortunately, similarly to the previous laboratory, the potentially highly hazardous events were treated with measures that ensure a significant decrease in the RPN evaluation. All the treated risks were established with the RPN below 50 with the exception of one risk rated in the RPN interval <50 - 124>.



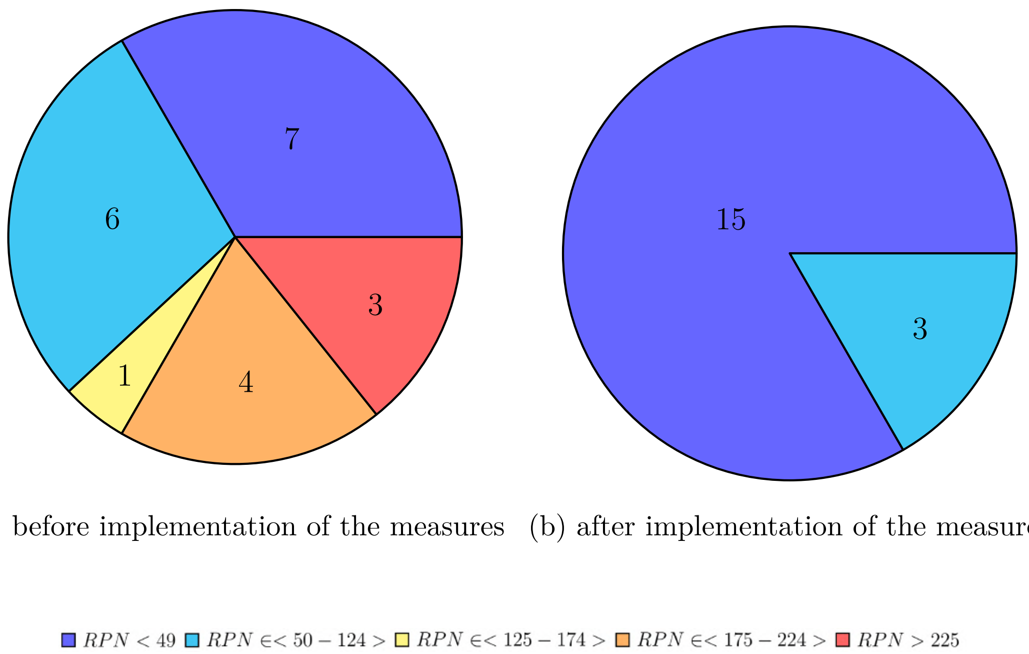
(a) before implementation of the measures (b) after implementation of the measures

$RPN < 49$ $RPN \in < 50 - 124 >$ $RPN \in < 125 - 174 >$ $RPN \in < 175 - 224 >$ $RPN > 225$

Fig. 4.9: Pie charts of identified risks in chemical laboratory

The analytical laboratory is the place with the lowest number of recognized risks as depicted in the pie chart shown in Fig. 4.10. The risks present in the analytical laboratory have also the lowest ratio of serious risk events with 38,10 % of risks ranked at the "permissible" level or worse. Similarly to previous laboratories, even in this case, the total RPN decreased significantly with the implementation of measures.

To ensure the implementation of the correct measures and to enable the organization to take a timely and informed decision the follow-up cause-and-effect diagrams were performed. Four major risks evaluated with the highest RPNs were analysed - Exposure of life parts, Poor life parts conditions, Long-term X-ray exposure, and Wrong handling of chemical mixtures and solutions. All four of them were evaluated as "Intolerable" with RPN > 225. The aim of the analysis was to find potential root causes and thus propose adequate measures. The majority of observed root causes could be controlled by regular revisions or calibrations, however, the human factor remains uncertain. Managing the risk of human error is a critical aspect of OHS risk



(a) before implementation of the measures (b) after implementation of the measures

Fig. 4.10: Pie charts of identified risks in analytical laboratory

management. This involves identifying the types of errors that are likely to occur, as well as the factors that contribute to these errors. Risk mitigation strategies may include training and education programs, and process improvements to reduce the likelihood of errors. It is important to note that the risk of human error cannot be entirely eliminated, as humans are fallible and mistakes can happen even under the best of circumstances. In addition, it is very hard for organizations to require adhering to established methodology in any other way than random control mechanisms such are Gemba walks. Therefore, human error is to be considered the most significant regarding the sample preparation for TEM.

Discussion

The aim of this thesis was to provide a risk analysis of the preparation of samples for transmission electron microscopy. The risks were evaluated for the three laboratories, described in chapter 1, where the sample preparation and analytical work occur - metallurgical, chemical and analytical. The main focus was given to the risks related to OHS since the process of sample preparation can be redone, but neither can human health. In addition, several measures were proposed with regard to the legislative regulations of the Czech Republic, which have been noted in chapter 2. The risk management methodology provides the most comprehensive way for results interpretation.

Firstly, it was necessary to identify the risks that may occur during the process. For this purpose, the block diagrams have been plotted to simplify and illustrate the individual steps for each type of sample preparation. In these simple blocks, FMEA analysis has been implemented, thus several risks could have been identified in each block of the sample preparation process. Workplace hazards such as exposure to hazardous substances, ergonomic risks, electric current exposures and physical hazards like cuts and slips were identified. FMEA analysis was worked out for every laboratory separately. The metallographic laboratory was recognized as the one with the highest number of occurring threats, however, many of those threats, have been repeatedly observed throughout all of the analysed laboratories.

In the second step of the risk analysis, possible consequences for the risk occurrence scenario were specified in the FMEA table, for each of the recognized risks. All of those illustrated consequences would possibly be health-threatening to some degree. The danger of consequences has been later on taken into consideration while evaluating the severity of risks.

Thirdly, the severity of risks was evaluated. Three criteria - the probability of failure, the probability of failure occurrence and the effect severity, were rated 1-10 depending on the seriousness, where 1 is the least dangerous outcome and 10 is the worst possible. The coefficients of criteria of each risk were multiplied together resulting in the RPN establishing the final risk severity. All the values were noted in FMEA tables (see appendices A, B and C. In addition, the most severe risks from each laboratory (with an RPN above 225) were subjected to a cause-and-effect diagram with the aim to find potential root causes of the whole assessed problem. This quantification of risk levels can help prioritize risks and allocate resources accordingly. It also enables organizations to focus their efforts on high-risk areas where the potential consequences of an incident could be significant.

Risk management proposes several ways how to deal with risks, the chosen method always depends on the cost-benefit ratio of suggested measures. In this specific scenario, it was not feasible to avoid or retain the risk due to the inherent nature of OHS-related risks. Measures must be proposed to mitigate these risks as they pose potential life-threatening consequences to the safety and well-being of workers. Sharing a risk would possibly be an option in the means of insurance. However, insurance could only provide compensation in case of injury or material losses, it plays no role in protecting the well-being of employees. Therefore the measures were suggested for every identified hazardous scenario via the FMEA analysis with the aim of reducing either risk occurrence or its effect severity.

Subsequently, the RPNs of individual risk were re-calculated with respect to the proposed measures. The good measure should be relevant, objective, reliable, valid, implemented at the right time and able to adapt to the needs of the assessed system. By adopting measures with such characteristics the best possible risk mitigation is ensured. A significant reduction in the estimated RPN of all the recognized risks was recorded. Although none of the risks were completely eliminated. Since many of the suggested measures depend on the own responsibilities of individuals, laboratory workers must remain vigilant while preparing samples for TEM and approach each procedure with caution and great care. It is always better to double-check all available information about the action, and wear all the prescribed PPE rather than make one fatal mistake. The only way to enforce adherence to the established measures seems to be random control methods and regular professional competence exams.

Finally, the risks would be further monitored, consisting of regularly reviewing and analyzing potential risks. The aim is to identify any changes in the observed risks or behaviour of implemented measures and address emerging risks before they become significant issues. Once any change of behaviour or new potential threat arises, the risk management cycle starts all over again. However, the aim of this thesis was to conduct the risk analysis and to propose countermeasures to observed risks, thus monitoring was not included.

From the results point of view, all the identified risks were significantly mitigated, however, none of them were completely eliminated. The failure modes with the worse evaluation were Exposure of life parts, Poor life parts conditions, Long-term X-ray exposure, and Wrong handling of chemical mixtures and solutions. The RPN of Exposure of life parts and Poor life parts conditions have been originally evaluated to 250. After the measures were implemented the RPN was lowered to 60 and 18 respectively. As the highest evaluated has been the Long-term exposure to X-ray radiation with RPN = 315, mainly because of the invisibility of the radiation and the severity of such exposure. The established measures enabled the RPN to be lowered to 63. Finally, the Wrong handling of chemical mixtures and solutions has been ranked RPN = 288, due to the adoption of suggested measures the value of RPN decreased to 42.

Risk analysis proved to be a systematic process of identifying potential hazards or threats, assessing the likelihood and consequences of those threats, and implementing measures to mitigate or manage those risks. It is one of the most important tools while dealing with potential threats related to OHS aiming to reduce workplace accidents to the least amount possible and enabling the company to make informed and timely decisions which could potentially prevent any degree of injury or even life losses. By identifying common risks and high-risk areas, organizations can implement risk management strategies that address these risks.

Since risk analyses are usually performed for internal purposes only and considering the very specific focus of this thesis it has been impossible to compare the findings with other research. However, every piece of literature regarding sample preparation emphasises the importance of protective measures while handling hazardous substances and cutting bulk materials. That creates an opportunity for follow-up studies that may evaluate the efficiency of proposed measures or provide whole detailed risk management strategies that can help to protect workers and minimize the risk of workplace incidents.

Risk analysis incorporates a wide range of analytical methods, each dedicated to a different purpose. The choice of tools depends on the specific context, industry, and goals of the risk analysis process. The analytical tools are hard to compare since they are often intervened together or the output of one analysis becomes an input for another. For the purpose of this thesis, and considering the information available about the sample preparation processes a few of the most commonly used and universal methods were chosen. The primary determining factors included general usability, readability, capacity to offer a quantitative evaluation of identified risks, and the ability to provide in-depth information regarding the risks ranked as the most severe.

Conclusion

In conclusion, the risk analysis of sample preparation for transmission electron microscopy has provided valuable insights into the safety vulnerabilities associated with the process of sample preparation regarding occupational health and safety. Through a comprehensive assessment of potential hazards and their potential consequences, risk treatment strategies have been proposed to mitigate or eliminate risks and enhance the overall safety of laboratories for sample preparation and analysis - metallographic, chemical and analytical. The first part of the thesis deals with gathering knowledge considering the sample preparation process as well as providing the information on legislative framework. At the end of the theoretical part, the theory of risk analysis is described. In the follow-up practical part of risk analysis, block diagrams, FMEA and cause-and-effect diagrams were combined to achieve as much risk-related information as possible.

Block diagrams serve as a visual representation of the sample preparation processes, aiming to identify potential risks at each stage. The identified risks, also known as "failure modes," were documented using the Failure Mode and Effects Analysis (FMEA) approach. To address the most critical failure modes with a Risk Priority Number (RPN) greater than 225, cause-and-effect diagrams were utilized to uncover potential root causes. Additionally, the FMEA analysis provided an assessment of the severity of the identified risks. Proposed measures were then formulated to mitigate the potential consequences of each identified risk to the greatest extent possible. Following the establishment of these measures, a re-evaluation of the risk severity was conducted. The FMEA analyses presented in the appendices illustrate the significant reduction in RPN once the proposed measures were implemented.

The results of the conducted risk analysis highlight the importance of identifying and managing risks in the context of OHS as well as their evaluation. In addition, the thesis results emphasize the need for effective risk management strategies that address these risks, minimize the likelihood and impact of incidents, and create a safer working environment for employees. The implementation of risk mitigation measures such as the use of personal protective equipment, ergonomic considerations, proper equipment maintenance, and improved training programs will contribute to creating a safer work environment for laboratory personnel involved in TEM sample preparation. As illustrated by the results the proposed measures proved themselves to be rather effective since a significant reduction in RPN evaluation of risks has been indicated.

Furthermore, this thesis has emphasized the significance of considering legislative requirements, particularly those outlined by the European Union and the Czech Republic, to ensure compliance with safety regulations and standards. Adhering to these regulations will promote safety within TEM laboratories.

Moreover, the processes of risk analysis undergo continuous improvement throughout the processes and grow with gained experience enabling organizations to adapt to changes in the workplace environment and ensure that their employees are protected from harm. Overall, the results provide insight into the OHS-related risks faced by workers on a daily basis while preparing samples for TEM and provide tools for managing those risks, creating safer working environments, and protecting the health and well-being of employees.

Further research and continuous monitoring of risk factors are recommended to be conducted to refine and improve the risk management strategies presented in this thesis. By regularly reassessing and updating safety regulations, laboratories can adapt to emerging risks and maintain a proactive approach to safety and quality assurance.

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Symbols and abbreviations

CLP	Classification, Labelling and Packaging
CNR	Czech National Council
EC	European Council
ED	European Directive
EDM	Electrical Discharge Machining
ETA	Event Tree Analisis
FIB	Focused Ion Beam
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analisis
HAZOP	Hazard and Operability Study
HRTEM	Hight Resolution Transmission Electron Microscope
ISO	International Organization for Standardization
OHS	Occupational safety and health
OHSAS	Occupational Health and Safety Assessment Specification
PPE	Personal Protective Equipment
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RPN	Risk Priority Number
SDS	Safety Data Sheet
SEM	Scanning Electron Microscope
SWOT	Strengths, Weaknesses, Opportunities and Threats

TEM	Transmission Electron Microscope

List of appendices

A FMEA - Metallographic laboratory

Process step	Failure mode	Possible consequences	RPN coefficients: Probability of failure occurence	Probability of failure being detected	Effect severity	RPN	Proposed measures	RPN coefficients: Probability of failure occurence	Probability of failure being detected	Effect severity	RPN
HAZARDOUS SUBSTANCES											
Metallographic abrasive thinning/ EDM	Wrong handling of chemical substances	* hazardous effects of chemical substances endangering human health: - danger of explosion, fire; - exposure to vapours, splashing of liquids, etc.; - chemical burns, body burns;	4	6	8	**192**	*prevent exceeding the highest permissible concentration for the working environment; for chemical compounds for which the highest permissible concentration for the working environment is not determined by the public health authority, the procedure is followed according to methodological measures for determining the highest permissible concentration for the working environment; * technical measures to exclude direct contact of workers with these substances; * use PPE according to the nature of the work; * equip workers who work with substances that corrode and irritate the skin (e.g. Corrosive substance) or decrease it (organic solvents) according to the nature of the work; * substances that are highly toxic and toxic, corrosives, flammable liquids, chemical carcinogens in the sense of the relevant legal regulations, to be labelled and handled according to regulations; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	2	7	**28**
Metallographic abrasive thinning/ EDM	Unprofessional work with alkali metals	* danger of explosion, fire; * exposure to vapours, splashing of liquids, etc.; * chemical burns, body burns;	4	7	7	**196**	* before initiating work with alkali metals prepare suitable extinguishing agents according to the instructions in case of an accident; * perform all operations with alkali metals with PPE to protect eyes and face; * check the condition of the equipment, especially the integrity of the equipment before work; * do not use water or alcohol to cool reaction vessels with alkali metals; * in the laboratory, with regard to dangerous chemical substances, main shut-offs of electricity, gas and water are placed outside the laboratory at an easily accessible place; * clearly mark the location of the electrical switches and other energy and water shut-offs; * installation of water, energy and wastewater must not be in conflict with applicable regulations; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	3	3	6	**54**
Waste dispossal	Irresponsible handling of chemical substances	* danger of explosion, fire; * exposure to vapours, splashing of liquids, etc.; * burns, burns, cuts on the body;	5	4	8	**160**	* flammable substances and other waste should be disposed of only in accordance with the Waste Act (see safety data sheets); * only minimal residues perfectly miscible with water can be poured into the sink and in such a quantity that the highest permissible concentration in water tanks is not exceeded according to the relevant regulations; * do not pour chemicals and reactive waste into sanitary facilities (toilet bowls, sinks, etc.); * at workplaces, store marked containers only in a designated place that is subject to increased preventive supervision, and empty them regularly; * immediately dispose of residues of alkali metals and alkali metal hydrides after reactions; * disposal of alkali metals in a hood with 96% ethanol, disposal of potassium with ethanol in an inert gas atmosphere; * dispose of alkali metal hydrides with ethyl acetate or acetone according to their reactivity; * do not throw substances that can cause fire or spontaneous combustion into garbage containers; * do not throw flammable material into the waste glass containers; * use metal containers with lids for garbage; * store shards and waste with sharp edges in a special container, store this waste separately at the landfill; * store waste contaminated with oil or flammable substances (textiles, sawdust, etc.) in closed metal containers, which must be emptied once a day in a fire-safe place; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	3	4	**24**

Storing	Bad storing of chemical substances	* danger of explosion, fire; * exposure to vapours, splashing of liquids, misuse, etc.; * chemical burns, burns, cuts on the body;	5	4	8	**160**	* keep flammable liquid stored in a way that they do not mix with other substances if the packaging breaks; * protect containers with liquids, where the rounding may act as a connecting lens, from sunlight; * handle FL with PPE equipped * equip warehouses with first aid supplies (including a first aid kit); * familiarize workers with the principles of providing pre-medical first aid; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	3	4	**24**
Metallographic abrasive thinning/ EDM	Unprofessional work with flammable liquids	* explosion of flammable vapors after spillage of flammable liquids and burns upon contact with the worker's body;	5	1	8	**40**	* respect the limitation of the maximum amount of flammable liquids (FL) that are allowed to be stored and handled in the laboratory; * avoid static electricity when working with non-polar solvents; * during separation work, such as filtration, extraction, sublimation, prevent the formation of explosive mixtures in the laboratory and exclude sources of initiation and fire; * if working with FL or substances with a low flash point while mixing and griding ensure there is no local overheating, similar measures apply to separation processes, grinding or mixing of solid substances, and take measures to avoid an explosion or fire caused by FL fumes; * if spilt immediately turn off gas appliances in the room (including stoves), turn off the electrical current outside the room, declare no access to unauthorized persons and ensure good ventilation (not in the corridor); * let the spilt FL soak into a suitable porous material, which can be removed to a safe place (landfill area); * do not spread spilt non-polar solvents on the floor or a plastic mat (danger of static electricity!); * workers who carry out sanitation must protect themselves against the harmful health effects of the spilt liquid, others who do not participate in the disposal must not stay in the room; * equip laboratories with fire extinguishers, or hydrants and suitable sanitation and neutralization means in case of accidents; * when spilling FL, proceed according to the measures described above; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	2	3	**12**
Metallographic abrasive thinning/ EDM	Inflammation of flammable liquids	* explosion of flammable vapors after spillage of flammable liquids and burns upon contact with the worker's body;	5	4	8	**160**	* respect the limitation of the maximum amount of flammable liquids (FL) that are allowed to be stored and handled in the laboratory; * avoid static electricity when working with non-polar solvents; * during separation work, such as filtration, extraction, sublimation, prevent the formation of explosive mixtures in the laboratory and exclude sources of initiation and fire; * if working with FL or substances with a low flash point while mixing and griding ensure there is no local overheating, similar measures apply to separation processes, grinding or mixing of solid substances, and take measures to avoid an explosion or fire caused by FL fumes; * if spilt immediately turn off gas appliances in the room (including stoves), turn off the electrical current outside the room, declare no access to unauthorized persons and ensure good ventilation (not in the corridor); * let the spilt FL soak into a suitable porous material, which can be removed to a safe place (landfill area); * do not spread spilt non-polar solvents on the floor or a plastic mat (danger of static electricity!); * workers who carry out sanitation must protect themselves against the harmful health effects of the spilt liquid, others who do not participate in the disposal must not stay in the room; * equip laboratories with fire extinguishers, or hydrants and suitable sanitation and neutralization means in case of accidents; * when spilling FL, proceed according to the measures described above; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	1	3	**6**
WORK ENVIRONMENT											

Movement around laboratory	Slipping	* slipping while walking with subsequent fall of the worker; * slipping, spraining the leg, bumping and falling of a person on the floor, on horizontal roads, staircases, etc.; * slipping while walking on wet floors (when walking or work activities);	5	3	6	**90**	* suitable workplace solution (flat, non-slippery floor surface, sufficient working space); * even and hard condition of floors and roads surfaces, without unevenness; * maintenance, removal of damaged areas, unevenness, etc. as soon as possible; * suitable work shoes, use non-slippery shoes if needed; * cleaning floors, timely removal of dirt (increasing slipperiness, especially grease), frequent cleaning, wiping floors dry using suitable cleaning and degreasing agents, etc.; * sloping the floor surface to drain the water of operating fluids so that liquid (water, etc.) does not linger on; * roughening of walking surfaces in case of their smoothing due to natural wear or unsuitability of the surface's material; * additional non-slip treatment of flooring; * floors resistant to damage, made of non-flammable material, impermeable, easily washable and without joints. In laboratories where flammable vapours, gases or dust can form an explosive mixture with air, the floors must be made of non-sparking material; * maintenance of permanently free escape routes and handling areas, including water, gas and electrical switches of electricity; * mark the entrance to the laboratory according to the nature of the work with appropriate notices, safety tables and information signs and fire tables; * a first aid kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively;	2	4	4	**32**
Movement around laboratory	Unorganised evacuation	* difficult evacuation and movement of people through escape routes in case of danger;	6	3	6	**108**	* suitable route, number, distribution and dimensions of escape routes, permanent maintenance of free escape routes and emergency exits; * opening gates and doors on escape routes in the direction of escape (outwards); * designation of defined escape routes and emergency exits; * mechanically powered doors and gates equipped with a distinct, well-recognizable and easily accessible emergency shut-off device, except in cases where they open automatically in the event of a power failure, must allow manual opening;	3	2	4	**24**
Ergonomy	Bad tables anchoring	* unwanted table movement;	5	2	3	**30**	* stable construction of the table (the table must not shake or move during work);	1	2	1	**2**
Ergonomy	Unsuitable working tables	* increased fatigue due to bending the back and arms stretching;	4	6	2	**48**	* suitable table dimensions; * table height from 800 to 1000 mm; * keep the work desk and workplace in order; * keep on the table only the tools that the worker needs for the given job; * proper storage of tools, i.e. tools that are held with the right hand on the right side of the table, tools that are held with the left hand on the left side of the table; more frequently used tools should lie closer, and less frequently used tools should be placed farther from the worker; * store unnecessary tools n a desk drawer or cabinet; * store semi-finished products, products, etc. outside the work zone of the table;	2	3	1	**6**
Fatique	Unsuitable lightning	* quick body fatigue, lack of concentration and other somatic problems;	6	6	1	**36**	* lighting must consist of two sources - daylight and artificial lighting, daylight is more suitable, but mixed lighting is most common; * in the laboratories, establish emergency lighting from a source other than the source of the artificial lighting, in particular, it is necessary to provide lighting for the emergency exit, corridors and staircases;	3	3	1	**9**
Fatique	Unsufficient ventilation	* quick body fatigue, lack of concentration and other somatic problems;	6	6	1	**36**	* operate room ventilation in a way that sufficient air exchange is ensured, but large temperature fluctuations do not occur; * laboratory ventilation must ensure that the highest permissible concentration of pollutants in the working atmosphere determined by hygiene regulations is not exceeded; * do not discharge harmful substances that can form a dangerous mixture into the common exhaust pipe; * essential laboratory equipment is a fume hood with a well-functioning extraction system;	3	3	1	**9**
Hearing	Continual exposure to noise	* hearing impairment;	6	8	3	**144**	* necessary technical measures according to the occurring noise sources; * use of PPE against noise;	1	8	3	**24**
INJURIES CAUSED BY ELECTRIC CURRENT											

Metallographic abrasive thinning/ Mechanical cutting/ EDM	Exposure of live parts	* injury by electrical current by direct or indirect contact	5	5	10	**250**	* preventive maintenance of electric devices, revisions, troubleshooting; * timely professional repairs of damaged electrical devices (sockets, plugs, movable leads, etc.); * routing of movable leads outside passages and communications; * do not operate electrical devices and equipment with wet hands; * familiarize yourself with the instructions for use; * before each use check visually the condition of the device; * do not leave the electric devices and equipment turned on after leaving the workplace and at the end of the work shift; * operation and maintenance of electrical appliances according to the instructions; * do not use damaged moving leads; prohibition of guiding them over sharp edges, tensile stress, etc.; * handle cables and power cords with care;	3	2	10	**60**
Metallographic abrasive thinning/ Mechanical cutting/ EDM	Careless handling of electric devices	* injuries due to workers being hit by electric current during regular operation, usually touching uncovered or otherwise unsecured live parts of electricity. equipment, e.g. during process on electricity devices by familiar and trained workers, shock while electric current passes through the affected person's body, followed by a fall from a height, etc.;	5	3	6	**90**	* exclusion of activities during which personnel works near electrical equipment, or can come into contact with live parts; * prevention of unprofessional intervention in the electrical installation; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular expert supervision by an authorized electrician (inspections and troubleshooting); * do not go near the electrical device, do not disable protection by position, observe the prohibition or the conditions for working near electric wiring and equipment;	3	2	6	**36**
Metallographic abrasive thinning/ Mechanical cutting/ EDM	Poor life parts conditions	* contact of persons with live parts, i.e. direct contact with live parts or parts that have become live as a result of poor conditions, especially such as: - result of insulation failure (indirect contact), imperfect protection against electric shock from non-living parts (e.g. earlier zeroing, grounding); - inadequate degree of protection against contact (accidental, unintentional, arbitrary) resulting from relevant regulations; - faulty electrical functions equipment (equipment), missing electrification equipment, (equipment) e.g. electrical parts equipment, machinery, etc.; - with unprotected live parts, e.g. in an open switchboard, damaged electrical parts installation, dismantled covers, etc.; - accessible live electrical parts equipment due to mechanical damage, e.g. switchgear, etc.;	5	5	10	**250**	* adhere to the ban on removing barriers and covers, opening access to electricity parts, disable the protective elements of covering or closure; * respecting safety messages; * exclude activities during which personnel works near electrical equipment, or can come into contact with live parts; * professional connection and repair of supply and extension cords, verification of the correctness of the connection, use of appropriate cords and cables with a protective conductor, (always performed by an electrician - knowledgeable worker with higher qualifications); * reduce strain on connections, connect extension cords with a protective conductor, the protective conductor must be longer so that it is the last to be cut when it is pulled out; * prevention of unprofessional intervention in the electrical installation; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular professional supervision by an authorized electrician (inspections and troubleshooting); * compliance with the ban on electrical wrapping cables around metal structures, railing objects, scaffolding, etc. at workplaces; * gentle handling of electricity connections by workers when handling electrical devices, switching off, plugging into sockets, etc., careful handling of cables and the connection cords; * before relocating an appliance connected to a movable supply, disconnect the appliance safely by pulling the plug out of the socket (does not apply to appliances that are specially designed and adapted for this purpose); * avoid using extension cords, use them only in the most necessary length; do not use extension cords with plugs on both sides; * before using el. devices or electric equipment make a proper inspection of its state; * do not go near electric devices, do not disable protection by position, comply with the ban or observe the conditions for working near electrical wiring and equipment;	3	1	6	**18**
Metallographic abrasive thinning/ Mechanical cutting/ EDM	Not followring working instructions	* violation of the insulation of the connected moving leads (abrasion, cutting and other mechanical damage to the insulation on the bare wire) as a result of which exposure to the risk of mechanical damage (incorrect storage or incorrect use);	2	2	9	**36**	* careful handling of cables and power cords; * adhere to the ban on electrical wiring supply cables along roads and where they could be damaged by construction sites and other equipment; * electricity maintenance cables and electricity supply lines (e.g. against mechanical damage, pulling out of terminals, etc.) - regular checks of the temporary electrical devices; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular professional supervision by an authorized electrician (inspections and troubleshooting); * compliance with the ban on electrical cables wrapping around metal structures, railing objects, scaffolding, etc. at workplaces; * gentle handling of electricity inputs by workers when handling electrical devices, switching off, plugging into sockets, etc.;	1	2	6	**12**

Metallographic abrasive thinning/ Mechanical cutting/ EDM	Inappropriate location of the main switch	* impossibility of quick power shut off in case of danger; * inaccessible main switch of the temporary electricity device;	4	2	10	**80**	* suitable location of the main switch, enabling easy and safe operation and control; * informing all construction employees bout the location of the main electrical switchboards and switches for the entire building; * maintenance of free space and access to the main switches; space in front of electrical switchboards and protection switchboards (before mechanical damage);	2	2	6	**24**
Metallographic abrasive thinning/ Mechanical cutting/ EDM	Electrocution	* electrocution by current when workers inadvertently touch parts of high-voltage lines;	1	2	10	**20**	* work near electrical device can only be carried out in cooperation with an expert under the specified conditions, including compliance with minimal distances specified in the relevant regulations;	1	2	4	**8**
Metallographic abrasive thinning/ Mechanical cutting/ EDM	Static electricity discharge	* the direct threat is usually not significant, however, accumulated electrostatic charges create a potential danger of initiating explosive concentrations or igniting vapours of flammable liquids, gases or flammable dust; * when an electrostatic charge is discharged, involuntary muscle reactions, shock, feelings of anxiety and, as a result, incorrect handling, an unexpected reaction, tripping, falling, etc. may occur; * electric charges created by physicochemical processes on electrifiable substances, e.g. by friction, rolling, mechanical separation, flow, dumping, transport, change of state, chemical processes or charges taken over by electrostatic induction, charges obtained by direct contact with another charged body;	2	8	8	**128**	Protective measures consist mainly of reducing or removing the generated electrical charges, in particular: * reducing the electability of the substances used; * increase relative air humidity; * use of neutralizers; * grounding of all conductive objects on which electrostatic charges can accumulate; * electrostatic discharge of floors; * connection of a person to grounding by a conductor or using conductive footwear and floor; * use of clothing, and equipment made of limited electrification materials;	2	3	6	**36**
MECHANICAL INJURIES											
Metallographic abrasive thinning/ Mechanical cutting	Wrong way of working with grinders and polishers	* mechanical injury – skin abrasion/burn, cut on the specimen * contact with chemical substances (polishing suspension) * splashing water/chemical substances into the eyes; splashing with water or chemicals (polishing suspension); skin contact during specimen removal and handling	4	4	5	**80**	* use of a holder, sanding the edges of the sample * proceed according to the instructions for use * wear PPE: protective gloves – latex or nitrile * wear PPE: protective glasses, protective gloves, protective clothing * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	4	2	**16**
Metallographic abrasive thinning/ Mechanical cutting	Wrong way of working with automatic / manual metallographic saw	* mechanical injury when clamping the dividing disc and the sample * spraying chemicals into the eyes; splashing with chemicals (coolant suspension - water + anti-microbial solution + anti-corrosion solution) during sample placement, sample removal and equipment washing after cutting	4	4	5	**80**	* take extra care * proceed according to the instructions for use * wear PPE: protective glasses, protective gloves, protective clothing * always divide the samples using a protective cover (according to the instructions for use) * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	4	2	**16**

Metallographic abrasive thinning/ Mechanical cutting	Wrong way of working with metallographic saw	* mechanical injury during specimen clamping * contact of chemical substances (cooling suspension – kerosene) with the skin during sample removal	4	3	3	**36**	* take extra care * proceed according to the instructions for use * wear PPE: protective glasses * always divide the samples using a protective cover (according to the instructions for use) * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	3	2	**12**
Metallographic abrasive thinning/ Mechanical cutting	Wrong way of working with automatic sander and polisher with drift head	* mechanical injury – skin abrasion/burn, cut on the specimen * contact with chemical substances (polishing suspension) * splashing water/chemical substances into the eyes; splashing with water or chemicals (polishing suspension); skin contact when taking out the sample/s	4	4	5	**80**	* use of a holder, sanding the edges of the sample * proceed according to the instructions for use * wear PPE: protective gloves – latex or nitrile * wear PPE: protective glasses, protective gloves, protective clothing * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	4	2	**16**
Sample shaping	Wrong way of working with manual bench press	* mechanical injury – skin abrasion, cut on the specimen, compressed finger	6	3	5	**90**	* sanding the edges of the sample * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations * wear PPE: protective gloves	2	3	2	**12**
Metallographic abrasive thinning/ Mechanical cutting/ EDM	Fall of a device	* mechanical injury – skin abrasion, compressed limb	2	4	7	**56**	* anchor the device to prevent any movement while the operation * check visually the position of the device before initiating work	1	2	7	**14**

B FMEA - Chemical laboratory

Process step	Failure mode	Possible consequences	RPN coefficients: Probability of failure occurence	RPN coefficients: Probability of failure being detected	RPN coefficients: Effect severity	RPN coefficients: RPN	Proposed measures	RPN coefficients: Probability of failure occurence	RPN coefficients: Probability of failure being detected	RPN coefficients: Effect severity	RPN coefficients: RPN
HAZARDOUS SUBSTANCES											
Electrolyte polishing	Wrong handling of chemical substances	* hazardous effects of chemical substances endangering human health: - danger of explosion, fire; - exposure to vapours, splashing of liquids, etc.; - chemical burns, body burns;	4	6	8	**192**	highest permissible concentration for the working environment is not determined by the public health authority, the procedure is followed according to methodological measures for determining the highest permissible concentration for the working environment; * technical measures to exclude direct contact of workers with these substances; * use PPE according to the nature of the work; * equip workers who work with substances that corrode and irritate the skin (e.g. Corrosive substance) or decrease it (organic solvents) according to the nature of the work; * substances that are highly toxic and toxic, corrosives, flammable liquids, chemical carcinogens in the sense of the relevant legal regulations, to be labelled and handled according to regulations; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	2	7	**28**
Electrolyte polishing	Wrong handling of chemical mixtures and solutions	* hazardous effect of the combination of two or more chemical substances and pollutants endangering human health - danger of explosion, fire; - exposure to vapours, splashing of liquids, etc.; - chemical burns, body burns;	6	6	8	**288**	highest permissible concentration for the working environment is not determined by the public health authority, the procedure is followed according to methodological measures for determining the highest permissible concentration for the working environment; * technical measures to exclude direct contact of workers with these substances; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations; * use PPE according to the nature of the work; * equip workers who work with substances that corrode and irritate the skin (e.g. Corrosive substance) or decrease it (organic solvents) according to the nature of the work; * substances that are highly toxic and toxic, corrosives, flammable liquids, chemical carcinogens in the sense of the relevant legal regulations, to be labelled and handled according to regulations;	3	2	7	**42**

Waste dispossal	Irresponsible handling of chemical substances	* danger of explosion, fire; * exposure to vapours, splashing of liquids, etc.; * burns, burns, cuts on the body;	5	4	8	**160**	* substances that are highly toxic and toxic and their packaging and other waste should be disposed of only in accordance with the Waste Act (see safety data sheets); * only minimal residues perfectly miscible with water can be poured into the sink and in such a quantity that the highest permissible concentration in water tanks is not exceeded according to the relevant regulations; * pour only sufficiently diluted (at least 1 + 10) and perfectly miscible with water solvents up to 0.5 liters (one time) and aqueous solutions (at least 1 + 30) of acids and hydroxides into laboratory sinks, laboratory beakers and other laboratory drains; * do not pour solvents that do not mix perfectly with water, substances that are highly toxic and toxic, poisons, explosive substances, acids and hydroxides above the stated oxidation limits, and substances that release toxic or irritating gases with water, acids or alkalis into the waste pipe; * do not pour chemicals and reactive waste into sanitary facilities (toilet bowls, sinks, etc.); * collect waste solvents, after complete removal of self-igniting substance residues and neutralization in clearly marked containers; * do not use plastic containers for collecting waste solvents; * at workplaces, store marked containers only in a designated place that is subject to increased preventive supervision, and empty them regularly; * immediately dispose of residues of alkali metals and alkali metal hydrides after reactions or drying solvents; * disposal of alkali metals in a hood with 96% ethanol, disposal of potassium with ethanol in an inert gas atmosphere; * dispose of alkali metal hydrides with ethyl acetate or acetone according to their reactivity; * do not throw substances that can cause fire or spontaneous combustion into garbage containers; * do not throw flammable material into the waste glass containers; * use metal containers with lids for garbage; * store shards and waste with sharp edges in a special container, store this waste separately at the landfill; * store waste contaminated with oil or flammable substances (textiles, sawdust, etc.) in closed metal containers, which must be emptied once a day in a fire-safe place; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	3	4	**24**
Storing	Bad storing of chemical substances	* danger of explosion, fire; * exposure to vapours, splashing of liquids, misuse, etc.; * chemical burns, burns, cuts on the body;	5	4	8	**160**	* lock highly toxic and toxic substances (with a patent lock) in a way that unauthorized personnel are prevented from accessing them; only the person responsible for working with these substances may have the key; * keep highly toxic and toxic substances in one space, clearly separated from each other (if these substances are also flammable liquids, the relevant regulations apply to them and they must be stored in a way that they do not mix with other substances if the packaging breaks); * substances that react with glass (e.g. hydrofluoric acid) or decompose in contact with it (hydrogen peroxide) should be kept in containers made of plastic, metal or in glass containers waxed from the inside; * substances that decompose with light should be stored in containers made of dark glass or opaque material; * protect containers with liquids, where the rounding may act as a connecting lens, from sunlight; * store alkali metals under a layer of inert high-boiling liquid (kerosene, paraffin oil) and white phosphorus under a layer of water, refill losses of liquids; * for the storage of alkali metals and alkali metal hydrides, reserve a metal cabinet located in a fire-safe place outside the laboratory, and mark the cabinet with an indelible inscription and the symbol "Do not extinguish with water". * store glass containers in which self-igniting substances are stored in unbreakable packaging of such dimensions that, in case of breakage of the glass container, the self-igniting substance remains under the protective liquid; * explosive substances and substances that react dangerously with each other should be stored separately, according to their chemical nature; * store containers with aggressive liquids so that they are safely accessible to all laboratory workers; * when storing bromine, prevent its vapours from escaping into the surrounding area; * equip warehouses with first aid supplies (including a first aid kit); * familiarize workers with the principles of providing pre-medical first aid; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	3	4	**24**

Metallographical abrasive thinning/ EDM	Unprofessional work with flammable liquids	* explosion of flammable vapors after spillage of flammable liquids and burns upon contact with the worker's body;	5	1	8	**40**	* respect the limitation of the maximum amount of flammable liquids (FL) that are allowed to be stored and handled in the laboratory; * avoid static electricity when working with non-polar solvents; * during separation work, such as filtration, extraction, sublimation, prevent the formation of explosive mixtures in the laboratory and exclude sources of initiation and fire; * if working with FL or substances with a low flash point while mixing and griding ensure there is no local overheating, similar measures apply to separation processes, grinding or mixing of solid substances, and take measures to avoid an explosion or fire caused by FL fumes; * if spilt immediately turn off gas appliances in the room (including stoves), turn off the electrical current outside the room, declare no access to unauthorized persons and ensure good ventilation (not in the corridor); * let the spilt FL soak into a suitable porous material, which can be removed to a safe place (landfill area); * do not spread spilt non-polar solvents on the floor or a plastic mat (danger of static electricity!); * workers who carry out sanitation must protect themselves against the harmful health effects of the spilt liquid, others who do not participate in the disposal must not stay in the room; * equip laboratories with fire extinguishers, or hydrants and suitable sanitation and neutralization means in case of accidents; * when spilling FL, proceed according to the measures described above; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	2	3	**12**
Electrolyte polishing	Inflammation of flammable liquids	* explosion of flammable vapors after spillage of flammable liquids and burns upon contact with the worker's body;	5	4	8	**160**	* respect the limitation of the maximum amount of flammable liquids (FL) that are allowed to be stored and handled in the laboratory; * avoid static electricity when working with non-polar solvents; * during separation work, such as filtration, extraction, sublimation, prevent the formation of explosive mixtures in the laboratory and exclude sources of initiation and fire; * if working with FL or substances with a low flash point while mixing and griding ensure there is no local overheating, similar measures apply to separation processes, grinding or mixing of solid substances, and take measures to avoid an explosion or fire caused by FL fumes; * if spilt immediately turn off gas appliances in the room (including stoves), turn off the electrical current outside the room, declare no access to unauthorized persons and ensure good ventilation (not in the corridor); * let the spilt FL soak into a suitable porous material, which can be removed to a safe place (landfill area); * do not spread spilt non-polar solvents on the floor or a plastic mat (danger of static electricity!); * workers who carry out sanitation must protect themselves against the harmful health effects of the spilt liquid, others who do not participate in the disposal must not stay in the room; * equip laboratories with fire extinguishers, or hydrants and suitable sanitation and neutralization means in case of accidents; * when spilling FL, proceed according to the measures described above; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	2	1	3	**6**
WORK ENVIRONMENT											
Movement around laboratory	Slipping	* slipping while walking with subsequent fall of the worker; * slipping, spraining the leg, bumping and falling of a person on the floor, on horizontal roads, staircases, etc.; * slipping while walking on wet floors (when walking or work activities);	5	3	6	**90**	* suitable workplace solution (flat, non-slippery floor surface, sufficient working space); * even and hard condition of floors and roads surfaces, without unevenness; * maintenance, removal of damaged areas, unevenness, etc. as soon as possible; * suitable work shoes, use non-slippery shoes if needed; * cleaning floors, timely removal of dirt (increasing slipperiness, especially grease), frequent cleaning, wiping floors dry using suitable cleaning and degreasing agents, etc.; * sloping the floor surface to drain the water of operating fluids so that liquid (water, etc.) does not linger on; * roughening of walking surfaces in case of their smoothing due to natural wear or unsuitability of the surface's material; * additional non-slip treatment of flooring; * floors resistant to damage, made of non-flammable material, impermeable, easily washable and without joints. In laboratories where flammable vapours, gases or dust can form an explosive mixture with air, the floors must be made of non-sparking material; * maintenance of permanently free escape routes and handling areas, including water, gas and electrical switches of electricity; * mark the entrance to the laboratory according to the nature of the work with appropriate notices, safety tables and information signs and fire tables; * a first aid kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively.	2	4	4	**32**

Movement around laboratory	Unorganised evacuation	* difficult evacuation and movement of people through escape routes in case of danger;	6	3	6	**108**	* suitable route, number, distribution and dimensions of escape routes, permanent maintenance of free escape routes and emergency exits; * opening gates and doors on escape routes in the direction of escape (outwards); * designation of defined escape routes and emergency exits; * mechanically powered doors and gates equipped with a distinct, well-recognizable and easily accessible emergency shut-off device, except in cases where they open automatically in the event of a power failure, must allow manual opening; * a first aid kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively	3	2	4	**24**
Ergonomy	Bad tables anchoring	* unwanted table movement;	5	2	3	**30**	* stable construction of the table (the table must not shake or move during work);	1	2	1	**2**
Ergonomy	Unsuitable working tables	* increased fatigue due to bending the back and arms stretching;	4	6	2	**48**	* suitable table dimensions; * table height from 800 to 1000 mm; * keep the work desk and workplace in order; * keep on the table only the tools that the worker needs for the given job; * proper storage of tools, i.e. tools that are held with the right hand on the right side of the table, tools that are held with the left hand on the left side of the table; more frequently used tools should lie closer, and less frequently used tools should be placed farther from the worker; * store unnecessary tools n a desk drawer or cabinet; * store semi-finished products, products, etc. outside the work zone of the table;	2	3	1	**6**
Fatique	Unsuitable lightning	* quick body fatigue, lack of concentration and other somatic problems;	6	6	1	**36**	* lighting must consist of two sources - daylight and artificial lighting, daylight is more suitable, but mixed lighting is most common; * in the laboratories, establish emergency lighting from a source other than the source of the artificial lighting, in particular, it is necessary to provide lighting for the emergency exit, corridors and staircases;	3	3	1	**9**
Fatique	Unsufficient ventilation	* quick body fatigue, lack of concentration and other somatic problems;	6	6	1	**36**	* operate room ventilation in a way that sufficient air exchange is ensured, but large temperature fluctuations do not occur; * laboratory ventilation must ensure that the highest permissible concentration of pollutants in the working atmosphere determined by hygiene regulations is not exceeded; * adapt the ventilation equipment so that it does not interfere with the efficiency of the fume hood; * do not discharge harmful substances that can form a dangerous mixture into the common exhaust pipe; * essential laboratory equipment is a fume hood with a well-functioning extraction system;	3	3	1	**9**
INJURIES CAUSED BY ELECTRIC CURRENT												
Electrolyte polishing	Exposure of live parts	* injury by electrical current by direct or indirect contact	5	5	10	**250**	* preventive maintenance of electric devices, revisions, troubleshooting; * timely professional repairs of damaged electrical devices (sockets, plugs, movable leads, etc.); * routing of movable leads outside passages and communications; * do not operate electrical devices and equipment with wet hands; * familiarize yourself with the instructions for use; * before each use check visually the condition of the device; * do not leave the electric devices and equipment turned on after leaving the workplace and at the end of the work shift; * operation and maintenance of electrical appliances according to the instructions; * do not use damaged moving leads; prohibit guiding them over sharp edges, tensile stress, etc.; * handle cables and power cords with care;	3	2	10	**60**
Electrolyte polishing	Careless handling of electric devices	* injuries due to workers being hit by electric current during regular operation, usually touching uncovered or otherwise unsecured live parts of electricity. equipment, e.g. during process on electricity devices by familiar and trained workers, shock while electric current passes through the affected person's body, followed by a fall from a height, etc.;	5	5	6	**150**	* exclusion of activities during which personnel works near electrical equipment, or can come into contact with live parts; * prevention of unprofessional intervention in the electrical installation; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular expert supervision by an authorized electrician (inspections and troubleshooting); * do not go near the electrical device, do not disable protection by position, observe the prohibition or the conditions for working near electric wiring and equipment;	3	2	6	**36**

Electrolyte polishing	Poor life parts conditions	* contact of persons with live parts, i.e. direct contact with live parts or parts that have become live as a result of poor conditions, especially such as: - result of insulation failure (indirect contact), imperfect protection against electric shock from non-living parts (e.g. earlier zeroing, grounding); - inadequate degree of protection against contact (accidental, unintentional, arbitrary) resulting from relevant regulations; - faulty electrical functions equipment (equipment), missing electrification equipment, (equipment) e.g. electrical parts equipment, machinery, etc.; - with unprotected live parts, e.g. in an open switchboard, damaged electrical parts installation, dismantled covers, etc.; - accessible live electrical parts equipment due to mechanical damage, e.g. switchgear, etc.;	5	5	10	**250**	* adhere to the ban on removing barriers and covers, opening access to electricity parts, disable the protective elements of covering or closure; * respecting safety messages; * exclude activities during which personnel works near electrical equipment, or can come into contact with live parts; * professional connection and repair of supply and extension cords, verification of the correctness of the connection, use of appropriate cords and cables with a protective conductor, (always performed by an electrician - knowledgeable worker with higher qualifications); * reduce strain on connections, connect extension cords with a protective conductor, the protective conductor must be longer so that it is the last to be cut when it is pulled out; * prevention of unprofessional intervention in the electrical installation; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular professional supervision by an authorized electrician (inspections and troubleshooting); * compliance with the ban on electrical wrapping cables around metal structures, railing objects, scaffolding, etc. at workplaces; * gentle handling of electricity connections by workers when handling electrical devices, switching off, plugging into sockets, etc., careful handling of cables and the connection cords; * before relocating an appliance connected to a movable supply, disconnect the appliance safely by pulling the plug out of the socket (does not apply to appliances that are specially designed and adapted for this purpose); * avoid using extension cords, use them only in the most necessary length; do not use extension cords with plugs on both sides; * before using el. devices or electric equipment make a proper inspection of its state; * do not go near electric devices, do not disable protection by position, comply with the ban or observe the conditions for working near electrical wiring and equipment;	3	1	6	**18**
Electrolyte polishing	Not followring working instructions	* violation of the insulation of the connected moving leads (abrasion, cutting and other mechanical damage to the insulation on the bare wire) as a result of which exposure to the risk of mechanical damage (incorrect storage or incorrect use);	2	2	9	**36**	* careful handling of cables and power cords; * adhere to the ban on electrical wiring supply cables along roads and where they could be damaged by construction sites and other equipment; * electricity maintenance cables and electricity supply lines (e.g. against mechanical damage, pulling out of terminals, etc.) - regular checks of the temporary electrical devices; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular professional supervision by an authorized electrician (inspections and troubleshooting); * compliance with the ban on electrical cables wrapping around metal structures, railing objects, scaffolding, etc. at workplaces; * gentle handling of electricity inputs by workers when handling electrical devices, switching off, plugging into sockets, etc.;	1	2	6	**12**
Electrolyte polishing	Inappropriate location of the main switch	* impossibility of quick power shut off in case of danger; * inaccessible main switch of the temporary electricity device;	4	2	10	**80**	* suitable location of the main switch, enabling easy and safe operation and control; * informing all construction employees bout the location of the main electrical switchboards and switches for the entire building; * maintenance of free space and access to the main switches; space in front of electrical switchboards and protection switchboards (before mechanical damage);	2	2	6	**24**
Electrolyte polishing	Electrocution	* electrocution by current when workers inadvertently touch parts of high-voltage lines;	1	2	10	**20**	* work near electrical device can only be carried out in cooperation with an expert under the specified conditions, including compliance with minimal distances specified in the relevant regulations;	1	2	4	**8**

Electrolyte polishing	Static electricity discharge	* the direct threat is usually not significant, however, accumulated electrostatic charges create a potential danger of initiating explosive concentrations or igniting vapours of flammable liquids, gases or flammable dust; * when an electrostatic charge is discharged, involuntary muscle reactions, shock, feelings of anxiety and, as a result, incorrect handling, an unexpected reaction, tripping, falling, etc. may occur; * electric charges created by physicochemical processes on electrifiable substances, e.g. by friction, rolling, mechanical separation, flow, dumping, transport, change of state, chemical processes or charges taken over by electrostatic induction, charges obtained by direct contact with another charged body;	2	9	8	**144**	Protective measures consist mainly of reducing or removing the generated electrical charges, in particular: * reducing the electability of the substances used; * increase relative air humidity; * use of neutralizers; * grounding of all conductive objects on which electrostatic charges can accumulate; * electrostatic discharge of floors; * connection of a person to grounding by a conductor or using conductive footwear and floor; * use of clothing, and equipment made of limited electrification materials;	2	3	6	**36**
MECHANICAL INJURY											
Electrolyte polishing	Fall of a device	* mechanical injury – skin abrasion, compressed limb	2	4	7	**56**	* anchor the device to prevent any movement while the operation * check visually the position of the device before initiating work	1	2	7	**14**

C FMEA - Analytical laboratory

Process step	Failure mode	Possible consequences	RPN coefficients: Probability of failure occurence	RPN coefficients: Probability of failure being detected	RPN coefficients: Effect severity	RPN coefficients: RPN	Proposed measures	RPN coefficients: Probability of failure occurence	RPN coefficients: Probability of failure being detected	RPN coefficients: Effect severity	RPN coefficients: RPN
							HAZARDOUS SUBSTANCES				
Dewar filling	Bad handling very low temperature substances	* scalds, burns when an unprotected part of the body comes into contact with coolant;	4	4	8	**128**	* do not fill containers with very cold contents to the rim; * use protective equipment against burns when handling containers containing very cold substances; * restrictions on carrying containers with very cold contents; * do not carry containers with very cold substances near the body; * the grip parts of the containers must be firm and kept clean; * do not place containers with very cold substances on the edges of tables, etc.; * professionally and correctly performed maintenance according to operating regulations; * use of PPE; * a first aid kit and an emergency kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively; * follow the instructions specified in relevant safety data sheets and local laboratory regulations	1	4	8	**32**
Pressure vessel	Careless handling of pressure vessel	* gas leakage, explosion, inhalation, poisoning, burns while handling and emptying technical gases;	2	4	10	**80**	* follow technical regulations when transporting, handling and storing bottles with compressed, liquefied or dissolved under pressure technical gasses; * place bottles only with technical gases that are necessary for operation in the laboratory; * permanently unnecessary or empty bottles must be removed; * to prevent the bottle from falling, clamps or chains must be secured in the upper half of the bottle, or they must be placed in stable or mobile stands; * mark the doors of rooms in which there are cylinders with compressed and other gases with a safety sign; * before initiating work with technical gases, ensure ventilation, prepare suitable protective, extinguishing and sanitation equipment, and check the seals and functions of the reduction valves and the seals of the apparatus; * Adhere to these prohibitions when working with technical gases: - use bottles that are expired or damaged, - use unsuitable or damaged reduction valves, - use brute force or inappropriate tools, including pipe extensions, when opening and closing valves, - use cylinders for other purposes or for other gases than for which they are intended, - repair bottles and valves or change their markings, - do heat bottles especially not with propane-butane (strictly prohibited!). * do not release gases freely in closed spaces, except when this is part of the work procedure (e.g. at gas chromatography); * know and respect the colour markings of technical gases; * PPE must be used while working with liquefied gases (air, nitrogen); * Attention!! when working with flammable substances, there is a risk of explosion by replacing liquid nitrogen with liquid oxygen or air; *metal Dewar containers should be provided with a neck cover during transport and transfer so that the gasified parts can escape, but so that the liquid cannot splash out; * follow the instructions specified in relevant data sheets and laboratory regulations when using gas appliances;	1	3	10	**30**
							WORK ENVIRONMENT				
Movement around laboratory	Slipping	* slipping while walking with subsequent fall of the worker; * slipping, spraining the leg, bumping and falling of a person on the floor, on horizontal roads, staircases, etc.; * slipping while walking on wet floors (when walking or work activities);	2	6	6	**72**	* suitable workplace solution (flat, non-slippery floor surface, sufficient working space); * even and hard condition of floors and roads surfaces, without unevenness; * maintenance, removal of damaged areas, unevenness, etc. as soon as possible; * suitable work shoes, use non-slippery shoes if needed; * cleaning floors, timely removal of dirt (increasing slipperiness, especially grease), frequent cleaning, wiping floors dry using suitable cleaning and degreasing agents, etc.; * sloping the floor surface to drain the water of operating fluids so that liquid (water, etc.) does not linger on; * roughening of walking surfaces in case of their smoothing due to natural wear or unsuitability of the surface's material; * additional non-slip treatment of flooring; * floors resistant to damage, made of non-flammable material, impermeable, easily washable and without joints. In laboratories where flammable vapours, gases or dust can form an explosive mixture with air, the floors must be made of non-sparking material; * maintenance of permanently free escape routes and handling areas, including water, gas and electrical switches of electricity; * mark the entrance to the laboratory according to the nature of the work with appropriate notices, safety tables and information signs, fire tables and tables for marking spaces with pressure vessels for gases; * a first aid kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively;	2	4	4	**32**

Movement around laboratory	Unorganised evacuation	* difficult evacuation and movement of people through escape routes in case of danger;	1	3	1	**3**	* suitable route, number, distribution and dimensions of escape routes, permanent maintenance of free escape routes and emergency exits; * opening gates and doors on escape routes in the direction of escape (outwards); * designation of defined escape routes and emergency exits; * mechanically powered doors and gates equipped with a distinct, well-recognizable and easily accessible emergency shut-off device, except in cases where they open automatically in the event of a power failure, must allow manual opening;				**0**
Ergonomy	Bad tables anchoring	* unwanted table movement;	2	4	2	**16**	* stable construction of the table (the table must not shake or move during work);	1	2	1	**2**
Ergonomy	Unsuitable working tables	* increased fatigue due to bending the back and arms stretching;	4	2	2	**16**	* suitable table dimensions; * table height from 800 to 1000 mm; * keep the work desk and workplace in order; * keep on the table only the tools that the worker needs for the given job; * proper storage of tools, i.e. tools that are held with the right hand on the right side of the table, tools that are held with the left hand on the left side of the table; more frequently used tools should lie closer, and less frequently used tools should be placed farther from the worker; * store unnecessary tools n a desk drawer or cabinet; * store semi-finished products, products, etc. outside the work zone of the table;	2	1	1	**2**
Fatique	Unsuitable lightning	* quick body fatigue, lack of concentration and other somatic problems;	6	6	1	**36**	* lighting must consist of two sources - daylight and artificial lighting, daylight is more suitable, but mixed lighting is most common; * in the laboratories, establish emergency lighting from a source other than the source of the artificial lighting, in particular, it is necessary to provide lighting for the emergency exit, corridors and staircases;	3	3	1	**9**
Fatique	Unsufficient ventilation	* quick body fatigue, lack of concentration and other somatic problems;	6	6	1	**36**	* operate room ventilation in a way that sufficient air exchange is ensured, but large temperature fluctuations do not occur; * laboratory ventilation must ensure that the highest permissible concentration of pollutants in the working atmosphere determined by hygiene regulations is not exceeded; * do not discharge harmful substances that can form a dangerous mixture into the common exhaust pipe; * essential laboratory equipment is a fume hood with a well-functioning extraction system;	3	3	1	**9**
Fatique	Continuous exposure to blue light	* eye fatique	6	2	3	**36**	* wear glasses with blue-light filter	1	1	2	**2**
INJURIES CAUSED BY ELECTRIC CURRENT												
Electron microscope	Exposure of live parts	* injury by electrical current by direct or indirect contact	5	5	10	**250**	* preventive maintenance of electric devices, revisions, troubleshooting; * timely professional repairs of damaged electrical devices (sockets, plugs, movable leads, etc.); * routing of movable leads outside passages and communications; * do not operate electrical devices and equipment with wet hands; * familiarize yourself with the instructions for use; * before each use check visually the condition of the device; * do not leave the electric devices and equipment turned on after leaving the workplace and at the end of the work shift; * operation and maintenance of electrical appliances according to the instructions; * do not use damaged moving leads; prohibition of guiding them over sharp edges, tensile stress, etc.; * handle cables and power cords with care;	3	2	10	**60**
Electron microscope	Careless handling of electric devices	* injuries due to workers being hit by electric current during regular operation, usually touching uncovered or otherwise unsecured live parts of electricity. equipment, e.g. during process on electricity devices by familiar and trained workers, shock while electric current passes through the affected person's body, followed by a fall from a height, etc.;	5	3	6	**90**	* exclusion of activities during which personnel works near electrical equipment, or can come into contact with live parts; * prevention of unprofessional intervention in the electrical installation; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular expert supervision by an authorized electrician (inspections and troubleshooting); * do not go near the electrical device, do not disable protection by position, observe the prohibition or the conditions for working near electric wiring and equipment;	3	2	6	**36**

Electron microscope	Poor life parts conditions	* contact of persons with live parts, i.e. direct contact with live parts or parts that have become live as a result of poor conditions, especially such as: - result of insulation failure (indirect contact), imperfect protection against electric shock from non-living parts (e.g. earlier zeroing, grounding); - inadequate degree of protection against contact (accidental, unintentional, arbitrary) resulting from relevant regulations; - faulty electrical functions equipment (equipment), missing electrification equipment, (equipment) e.g. electrical parts equipment, machinery, etc.; - with unprotected live parts, e.g. in an open switchboard, damaged electrical parts installation, dismantled covers, etc.; - accessible live electrical parts equipment due to mechanical damage, e.g. switchgear, etc.;	5	5	10	**250**	* adhere to the ban on removing barriers and covers, opening access to electricity parts, disable the protective elements of covering or closure; * respecting safety messages; * exclude activities during which personnel works near electrical equipment, or can come into contact with live parts; * professional connection and repair of supply and extension cords, verification of the correctness of the connection, use of appropriate cords and cables with a protective conductor, (always performed by an electrician - knowledgeable worker with higher qualifications); * reduce strain on connections, connect extension cords with a protective conductor, the protective conductor must be longer so that it is the last to be cut when it is pulled out; * prevention of unprofessional intervention in the electrical installation; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular professional supervision by an authorized electrician (inspections and troubleshooting); * compliance with the ban on electrical wrapping cables around metal structures, railing objects, scaffolding, etc. at workplaces; * gentle handling of electricity connections by workers when handling electrical devices, switching off, plugging into sockets, etc., careful handling of cables and the connection cords; * before relocating an appliance connected to a movable supply, disconnect the appliance safely by pulling the plug out of the socket (does not apply to appliances that are specially designed and adapted for this purpose); * avoid using extension cords, use them only in the most necessary length; do not use extension cords with plugs on both sides; * before using el. devices or electric equipment make a proper inspection of its state; * do not go near electric devices, do not disable protection by position, comply with the ban or observe the conditions for working near electrical wiring and equipment;	3	1	6	**18**
Electron microscope	Not followring working instructions	* violation of the insulation of the connected moving leads (abrasion, cutting and other mechanical damage to the insulation on the bare wire) as a result of which exposure to the risk of mechanical damage (incorrect storage or incorrect use);	2	2	9	**36**	* careful handling of cables and power cords; * adhere to the ban on electrical wiring supply cables along roads and where they could be damaged by construction sites and other equipment; * electricity maintenance cables and electricity supply lines (e.g. against mechanical damage, pulling out of terminals, etc.) - regular checks of the temporary electrical devices; * maintenance of temporary electrical equipment in a safe condition - initial review, regular reviews, regular professional supervision by an authorized electrician (inspections and troubleshooting); * compliance with the ban on electrical cables wrapping around metal structures, railing objects, scaffolding, etc. at workplaces; * gentle handling of electricity inputs by workers when handling electrical devices, switching off, plugging into sockets, etc.;	1	2	6	**12**
Electron microscope	Inappropriate location of the main switch	* impossibility of quick power shut off in case of danger; * inaccessible main switch of the temporary electricity device;	4	2	10	**80**	* suitable location of the main switch, enabling easy and safe operation and control; * informing all construction employees bout the location of the main electrical switchboards and switches for the entire building; * maintenance of free space and access to the main switches; space in front of electrical switchboards and protection switchboards (before mechanical damage);	2	2	6	**24**
Electron microscope	Electrocution	* electrocution by current when workers inadvertently touch parts of high-voltage lines;	1	2	10	**20**	* work near electrical device can only be carried out in cooperation with an expert under the specified conditions, including compliance with minimal distances specified in the relevant regulations;	1	2	4	**8**
							RADIATION EXPOSURE					
Electron microscope	Long term X-ray exposure	* increased risk of cancer * exposure during pregnancy carries additional risks to the developing fetus, or risk of genetic mutations * vision impairment	5	9	7	**315**	* the construction is reinforced with a lead layer * the X-ray dose of the employee is monitored by dosimeters, which are placed on the left side of the chest. * dosimeters measure the radiation dose for 3 months of operation and are evaluated by the State Institute of Radiation Protection. *operator is supposed to stay in the room with the device for the least possible time * the operator controls the device from the connected room * pregnant women are forbidden from operating the device	1	9	7	**63**
Electron microscope	Electromagnetic field exposure	* possible sleep disturbances * fatique * risk of cancer	5	8	5	**200**	* the operator controls the device from the connected room *operator is supposed to stay at the room with the device the least possible time * electromagnetic interference is installed	1	9	7	**63**
							MECHANICAL INJURY					
Electron microscope	Fall of a device part	* mechanical injury – skin abrasion, compressed limb	2	4	9	**72**	* anchor parts inside the device to prevent any movement while the operation * check visually the position and state of the device before initiating work * a first aid kit that is fully equipped and accompanied by the necessary expertise to employ its contents effectively;	1	2	9	**18**