ASSESSMENT OF THE TRANSMITTANCE OF MODERN PERSONAL RESPIRATORY PROTECTION EQUIMENT FOR WELDING AND GALVANIC FUMES

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Abstract

The article focuses on the study of the filtration performance of modern respirator models when exposed to welding and electroplating fumes containing ambient particles smaller than 10 microns (PM$_{10}$*). The low filtration capacity of most modern respirators with respect to nano- and microparticles was revealed. Respirator filtration performance can be affected by a number of factors including: different filtration mechanisms, environmental parameters, filter material properties, number of respirator layers used, packing density, fiber loading density, fiber diameter, aerosol particle type and size, aerosol flow rate and concentration values, and additional factors from different human activities. Modern filtration materials and respirators are not able to provide 100% protection against the penetration of the smallest particles of industrial aerosols into the body. Respirators with multi-layer protection, fitted with carbon filters, have the highest capture capacity.*

Keywords: industrial aerosols, particulate matter, filtration capacity, electroplating, welding, nano- and microparticles, respirators

I. Introduction

Ambient air pollution by particulate matter has become a serious public health hazard in many regions [1]. Some of the main sources of pollution are exhaust gases from motor vehicles, welding, and electroplating.

According to the standard definition of nanoparticles by the U.S. National Nanotechnology Initiative (NNI) [2] and ASTM E2456-06 [3], particles smaller than <100 nm should be considered ultrafine particles. These particles are highly permeable, capable of penetrating deep into the alveoli, beyond the natural airways of bodies and settling in the lower respiratory tract [4]. These particles can trigger serious diseases such as respiratory symptoms, lung cancer, and silicosis depending on the components of particles [5]. Ultrafine particles of industrial aerosols pose toxicological hazards depending on their surface characteristics [6].

Therefore, there is a high demand for respiratory protective devices. Variants of respiratory protective devices are a face mask and a respirator.

A face mask is a loose-fitting, disposable device that creates a physical barrier between the user's mouth and nose and potential pollutants near an air pollution source. A respirator is a personal air cleaner equipped with a filter that provides a tight fit to a person's face [7]. There are several key factors that affect respirator performance: (a) filtration, (b) flow resistance (i.e., air permeability), (c) ergonomics, and (d) continuous operation in a given environment. Additionally, it is important to note that using respirators does not prevent oxygen from entering the human body. And there is no significant difference in the oxygen saturation of human lungs when using respiratory protective devices ($P > 0.05$) [8].

The filtering and separation of submicron-sized contaminants is a major challenge today. The development of modern respirator filter materials that would effectively capture suspended nano- and microscale particles requires an innovative approach. Nanofibers [9], 3D printers [10], and additive technologies [11] for manufacturing filter materials can significantly advance the technological development of respiratory protective devices.

Filter efficiency depends on several factors. It improves as the size of the filter material fibers decreases due to the high mechanical ability to trap the smallest particles suspended in the ambient air. However, it is the shape of the fibers, rather than their calculated average aerodynamic diameter, that is the dominant factor in the deposition mechanisms in the tested respirators [12].

The present study is focused on the research of the trapping characteristics of respirators exposed to aerosols of electroplating origin. Electroplating is a source of emission of heavy metal oxides into the air. It is known that exposure to aluminum, arsenic, lead, cadmium, and manganese in the workplace can increase the risk of numerous neurophysiological changes in workers and can trigger the development of Parkinson's and Alzheimer's diseases [13].

Among the technological processes of modern industrial production that have been studied so far, those that pose the most significant hygienic risks are the following:

- In electroplating it is the electrochemical process of nonferrous metals etching [14]. Used daily, this is one of the main technological processes in electroplating workshops for manufacturing parts from nonferrous metals.
- In welding production, it is manual arc welding of metal plates (construction steel, $S = 8$ mm) using electrodes with rutile covering, diameter 3 mm [15]. Emissions from manual welding are almost equivalent to the air emissions from the underwater welding [16].

For the listed technological processes, it was decided to perform a comparative analysis of the trapping characteristics of filters in 10 modern respirators in real production conditions.

It is important to understand that different types of respirators and masks have their advantages, disadvantages, capabilities, and limitations. However, for each specific type of industrial production, the most suitable and versatile masks can be developed that can provide a high level of industrial safety for workers.

In addition to the safety requirements for viral aerosol filtration tests, one of the major problems that researchers currently face is the inability to simulate or simulate true aerosol filtration scenarios through laboratory experiments, field tests, and in vitro / in vivo studies [17]. There are few studies on the effectiveness of respirators in capturing suspended particles of industrial aerosols in real production conditions [18].

For this reason, a full-scale experiment was conducted in real production conditions of electroplating and welding shops. This work is aimed at investigating the penetration ability of welding and electroplating fume particles through the filter material of modern models of respirators. For this purpose, we selected the most popular models of respirators for welding production and compared the trapping characteristics of their filter elements in real production conditions. In contrast to the works of other researchers [19], in this experimental work, only samples of filter materials were used to assess the penetration ability, not the whole respirators.

II. Experimental

Measurement of the quantitative composition of PM

The quantity of airborne PM was measured using the AeroTrak Handheld Particle Counter 9306 (TSI Incorporated, USA). This sampler meets all the requirements set out in ISO 21501-4.

Continuing the previous research of air pollution by electrochemical processes from the hygienic point of view (depending on the levels of $PM_{0.3}$ and PM_{10} in the air) [20, 21], we chose to further study the influence of the nonferrous metals etching and manual arc welding using electrodes with rutile covering on the trapping characteristics of filters in modern respirators (Table 1, Figure 1).

Filtering facepiece respirators (FFP) are commonly used in workplaces due to their low cost, comfort, ease of use, and sufficient effectiveness.

Table 1: *The list of personal respiratory protective equipment used in the experiment*

No.	Respirator/mask model	Technical specifications
1	Filtering facepiece respirator with breathing valve “Stayer Master 11118”	Protection class: FFP1 Material: textured polypropylene Manufacturer: Kraftool I/E GmbH, Germany
2	Filtering facepiece respirator with breathing valve “Zubr Expert 11160”	Protection class: FFP1 Material: textured polypropylene Manufacturer: Zubr OVK, Russian Federation
3	Filtering facepiece respirator “DEXX 11103”	Protection class: FFP1 Material: polypropylene Manufacturer: Zubr OVK, Russian Federation
4	Filtering facepiece respirator with breathing valve “Zubr Master 11163-2”	Protection class: FFP2 Material: textured polypropylene Manufacturer: Zubr OVK, Russian Federation
5	Filtering facepiece respirator with breathing valve “Rutex F1101”	Protection class: FFP1 Material: electret filtering material Manufacturer: Rutex, China
6	Filtering facepiece respirator “KN95”	Protection class: FFP2 Material: non-woven fabric and meltblown filter fabric Manufacturer: Jinhua Han Ye Daily, China
7	Filtering facepiece respirator with breathing valve “Istok”	Protection class: FFP2 Material: polyethylene foam Manufacturer: Istok, Russian Federation
8	Filtering facepiece respirator with breathing valve “Briz-1102(Y-2K)”	Protection class: FFP1 Material: polyurethane foam Manufacturer: Briz-Kama, Russian Federation
9	Facepiece elastomeric air-purifying respirator “RPG-67” with filter type A1B1	Protection class: FFP1 Material: woven fabric, charcoal filter Manufacturer: GK Rim, Russian Federation
10	Medical face mask	Material: nonwoven three-layer SMS (spunbond, meltblown, spunbond)

Air samples were taken at a distance of 1 m from the source of air pollution (Figure 1) at a constant height of 1.5 m corresponding to human breathing level.

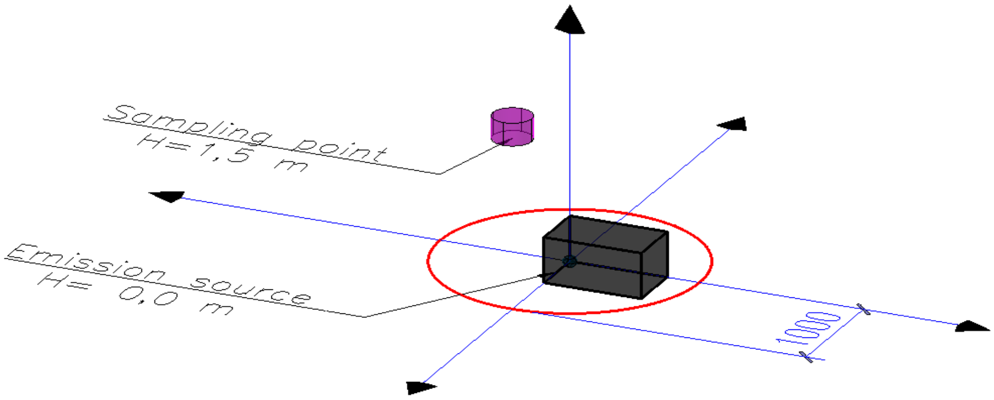


Figure 1: *Location of the sampling point in the production shops*

Two series of sampling were performed: using filters of 10 models of respirators for welding and electroplating.

Mass concentration of airborne PM

To determine the content of fine particles of industrial aerosol in ambient air, a series of air samples were taken using the aspirator-type sampler "Aspirator PU" (JSC Khimko, Russia) with filters from 10 modern respirators.

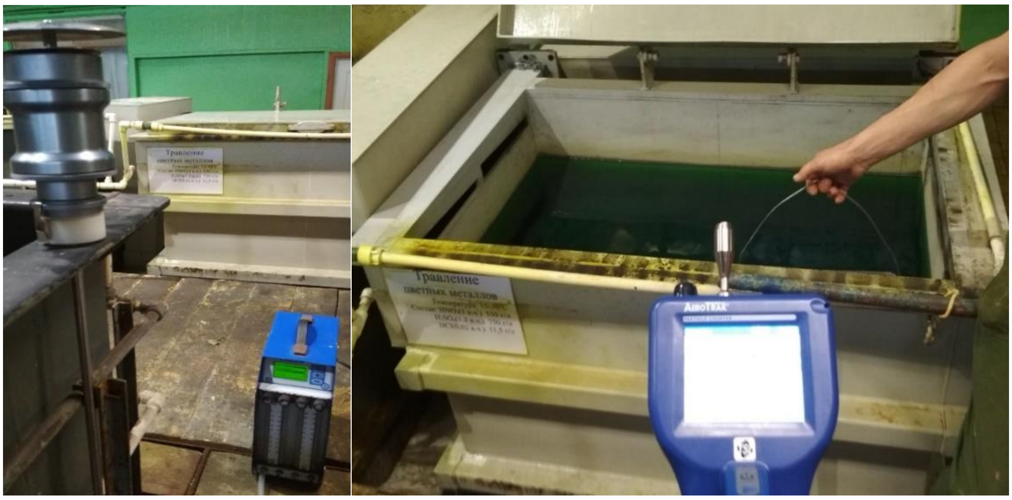
In this sampler, instead of normally used aerosol filters based on a Petryanov filtering cloth made of fibrous perchlorvinyl fabric (Gorky Kimry Factory, Russia), we used filter material taken from modern models of respirators and cut to the size fitting the sampler (Table 1).

During the experiment, this sampler was equipped with an additional attachment for sampling particles of the PM_{10} fraction, taken from a similar aspirator LVS 3.1 (Ingeniero Nobert Derenda, Germany). The range of particles for filters in this attachment is from 0.45 µm to 10 µm. The upper limit (PM_{10}) was chosen because it poses the greatest danger to human health, being the cause of respiratory diseases [22]. This reflects the current trend in the field of control of substances suspended in ambient air [23].

Before sampling, the filters were pre-dried in a TC-1/20 thermostat (Russia) for 24 hours at 40 °C (Fig. 2), then each filter was weighed three times on electronic balance CAS CAUY-120. Arithmetic mean weight was determined for each filter.

Figure 2: *Preparation of filter materials in the thermostat*

The samples were taken at the sampling points shown in Fig. 1, 3 and 4 at 1 m from the pollution source (electroplating bath or welding operator).



A) B)

Fig. 3: *Sampling air probes in the electroplating shop. A) air sampling, B) PM sampling.*

The installation height of the sampler corresponded to the level of human respiration – 1.5 m. The sampling time was 1 min for each filter. The air temperature during the experiment was 18 °C, the wind speed was 0 mps (samples were taken inside the workshop). The volume of air pumped through the sampler was 2.8 m^3/h. Filters with samples of particulate matter were transported to the laboratory of REC "Nanotechnology" of the Polytechnic Institute FEFU for further determination of the concentration of PM_{10} particles.

		
A)		B)

Figure 4: *Taking air and PM samples during welding. A) Measuring instruments, B) Welding process*

Dust content in the air was measured by weighing the filters on electronic balance CAS CAUY-120 before and after sampling. Each filter was weighed three times and arithmetic mean was determined. The resulting difference in the weight of filters before and after the air sampling procedure corresponded to the settled mass of particulate matter, including the PM_{10} fraction.

Electron microscopy of PM

To visualize airborne particles deposited on respirator filter material, a state-of-the-art stereo microscope Zeiss Stemi DV4 (Germany) was used. The microscope's features include 30x image magnification with viewing angle up to 60°.

This microscope is equipped with a high-intensity illuminator that offers three illumination modes to produce a clear image of the sample. The Zeiss dual-lens zoom system ensures excellent sharpness and high-resolution images.

Two 50x50 mm samples were cut out from each filter of 10 respirator models, corresponding to "before" and "after" the experiment on measuring the concentration of deposited industrial aerosol particles. The fibers of each filter were photographed using electron microscopy.

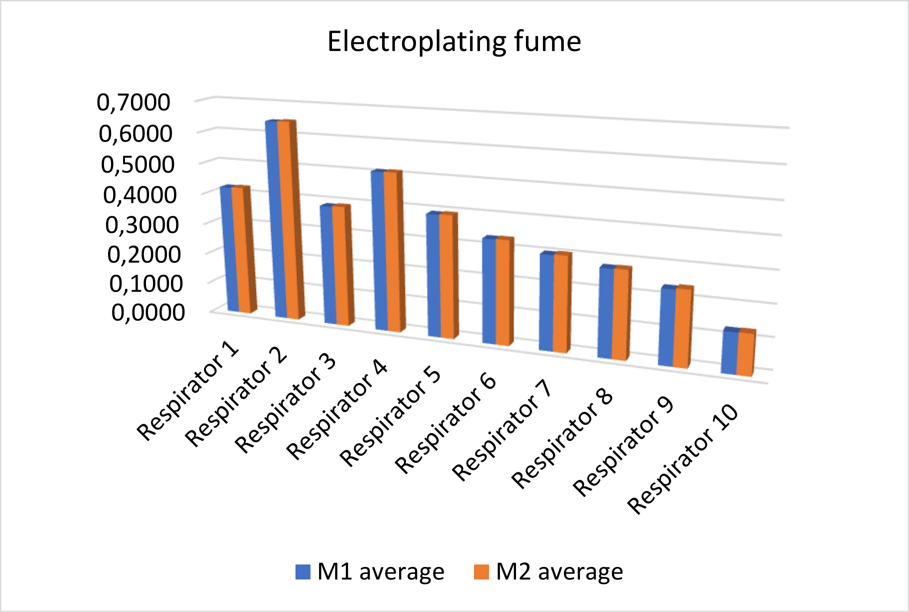
III. Results and discussion

It is known that penetration of industrial aerosol particles through the filters of respirators increases with the flow rate regardless of the type of particles, and the particle size is a significant factor influencing the penetration of combustion aerosol particles [24]. For this reason, the experiment was focused on measuring particles up to 10 μm in size, which have the greatest penetrating ability [25] and ability to settle deep into the lungs of welders and workers of related professions. Tables 2—5 summarize data on mass concentration and quantity of welding fume and electroplating fume particles.

The issue of identifying ineffective personal respiratory protective equipment is particularly relevant in the context of the pandemic [26] and the shortage of masks and respirators on sale, as well as appearance on commercial market of uncertified products with low effectiveness or even fake models [27—29].

Mass concentration of airborne particles of electroplating fume deposited on filters

Table 2: *Electroplating fume*



According to the data obtained (Table 4), the trapping capacity of filters in respirators varies depending on the PM fraction. Table 2 shows the weight data of respirator filter samples before and after the series of experiments. M1 values describe the weight of the filter sample before the experiment and M2 values – after pumping 2.8 liters of air through the respirator filter.

To obtain the values of the mass of deposited solid particles originating from electroplating aerosol, their content was recalculated to the level of 1 m^3 of air pumped through the filter.

The highest mass of deposited particles was found in respirator No. 9 (RPG-67 with filter type A1B1). This respirator can trap up to 1.6 mg when pumping 1 m^3 of air through its filter.

The second place in terms of the mass of industrial aerosol particles deposited on the filter is respirator No. 3.

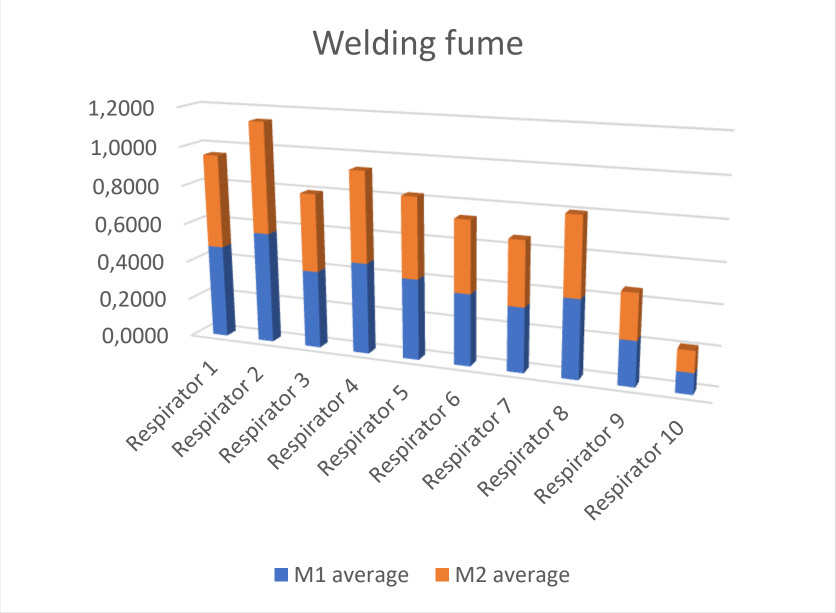
Respirators No. 2 and No. 5 show average values of deposition of industrial aerosol particles. The values for these samples range from 0.8 to 0.9 mg/m^3. Respirator No. 4 demonstrates the best trapping ability for PM_1 and PM_3 fractions. Respirator No. 5 (closely followed by respirators No. 3-7), has the highest mass of deposited PM_5 and PM_{10} particles.

Respirators No. 8, 10, 6, 4, and 1 are ineffective in trapping airborne particles of electroplating aerosol and practically do not prevent particles from freely penetrating the filtering material of respirators. The values of deposited particles on filters of these respirators range from 0.5 to 0.7 mg/m^3.

As can be seen from the data presented in Tables 2, 3, the mass concentration of airborne PM deposited on the filter elements of respirators in the electroplating shop is several times higher than the concentration of particles in the air of the work zone in the welding shop. This fact may be due to the finer size of solid particles of the welding fume, which easily overcome the filtering barrier of respirators.

Mass concentration of airborne particles of welding fume deposited on filters

Table 3: *Welding fume*

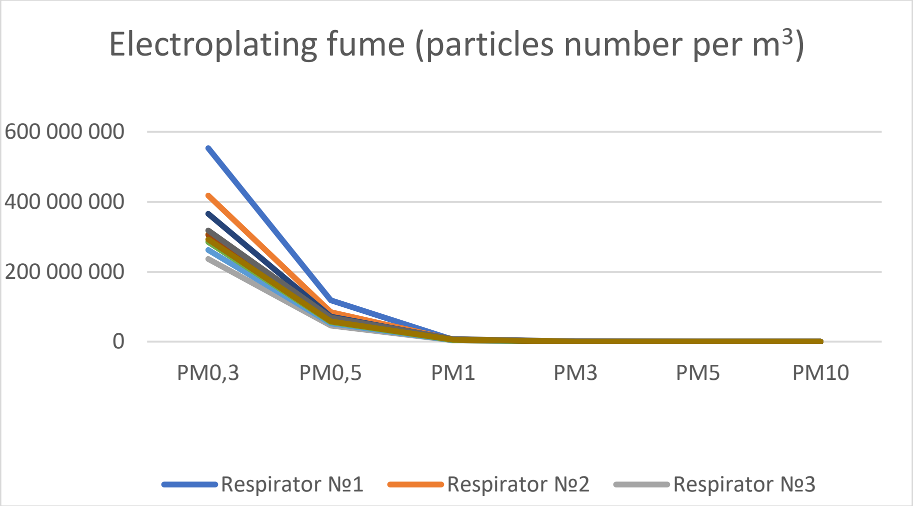


The obtained data indicate that the majority of respirators used in the experiment had low particle trapping efficiency. Respirators No. 2—6 (group 1) are barely effective in capturing solid particles of welding fume. Additionally, other 2 models of respirators: No. 8 and No. 1 (Group 2) have average efficiency against other tested respirators.

The highest mass of deposited particles was found in respirator No. 9 (RPG-67 with filter type A1B1). This respirator has several protective layers – woven fabric and charcoal filter. The filter material of this respirator trapped from 2 to 10 times more particles compared to samples from the first and second groups, correspondingly.

Quantity of airborne PM

Table 4: *Electroplating fume (particles number per m³)*



Filters do not degrade or recover after the exposure to industrial aerosols stops. Therefore, the aerosol penetration measured at any time after exposure should be equal to the maximum obtained using the respirator [30]. It should be noted that since the filter material samples were used as filters in the aspirator, they demonstrated 100% efficiency, and there was no air leakage through the end seal in different head positions when the respirator was placed against the worker's face.

The filtering efficiency of respirators depends largely on the size of solid particles, and the penetration of any dust through the mask will be critically influenced by its fractional composition.

Considering that 30-100 nm particles have the maximum penetrating ability [31], respirator No. 3 should be selected as having a clear advantage. Respirator No. 3 is most effective in trapping particles of the smallest fractions: $PM_{0.3}$ and $PM_{0.5}$. This respirator has a higher particle trapping capacity for these particle sizes compared to other respirators ranging from 20% to 234%, depending on the model.

The maximum content of aiborne PM was registered at the beginning of the experiment, with values being an order of magnitude higher than those for other repetitions. The content of particles of the smallest fraction ($PM_{0.3}$ and $PM_{0.5}$) exceeds similar indicators of other models of respirators.

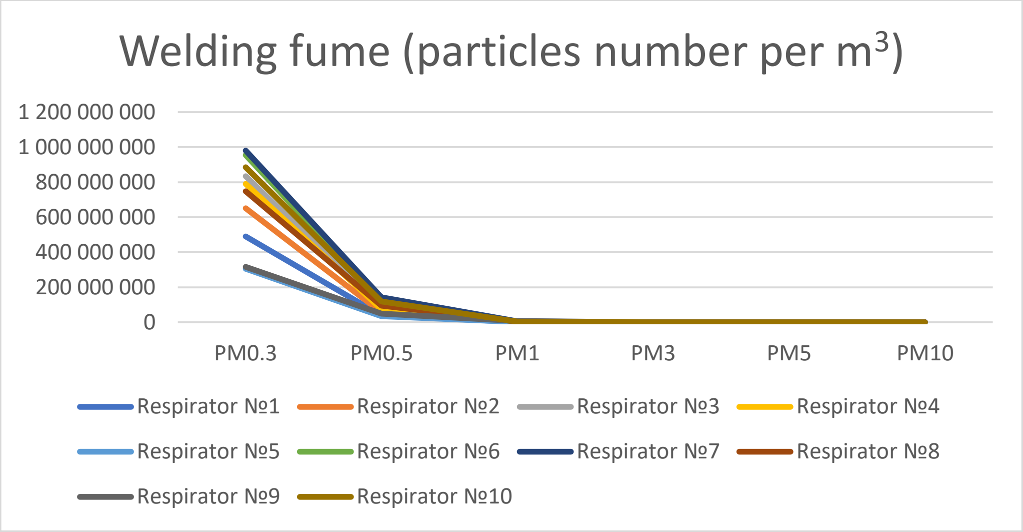
Table 5 below summarizes the measurement values for the experiments performed in the welding shop.

It is known that unlike the ultrafine fraction, larger particles (e.g., 800 nm) are almost completely trapped by the filter material in respirators with medium and high protection class [32]. That is why the numbers of nano- and micro-size particles were counted before they were deposited on the filter material inside the aspirator. The number of fine particles in welding fume ($PM_{0.3}$ fraction) reached hundreds of millions particles per 1 m³ (from 316 to 980 mln particles), which exceeded the number of PM_{10} particles several hundred-fold (from 19 to 42 thousand/m³). Nano-range particles are the most hazardous for human health as they can easily bypass alveolar protection of lungs, deeply penetrating into human internal organs and causing chronic diseases of the upper respiratory tract [33].

Compared to electroplating, a greater number of airborne particles were formed in the second half of the sampling experiment series rather than at the beginning.

As expected, the lower mass fraction of particles deposited on respirator filter elements during welding is due to their smaller size. The cells of the filter elements significantly exceed the dimensions of particles that easily penetrate the protection of respirators and penetrate into the respiratory organs. This is evidenced by the higher number of suspended particles of the $PM_{0.3}$ and $PM_{0.5}$ fractions during welding in comparison with the electrochemical process (Table 5). The average values of PM during welding are on average 1.5÷2 times higher in comparison with the electroplating process.

Table 5: *Welding fume (particles number per m³)*



Electron microscopy of ambient particles on filters

Figures 6-24 show a comparative analysis of the surface of filters from respirators before and after the experiments in the electroplating and welding shops. In the lower right corner, there is a scale bar to show the dimensions of deposited particles.

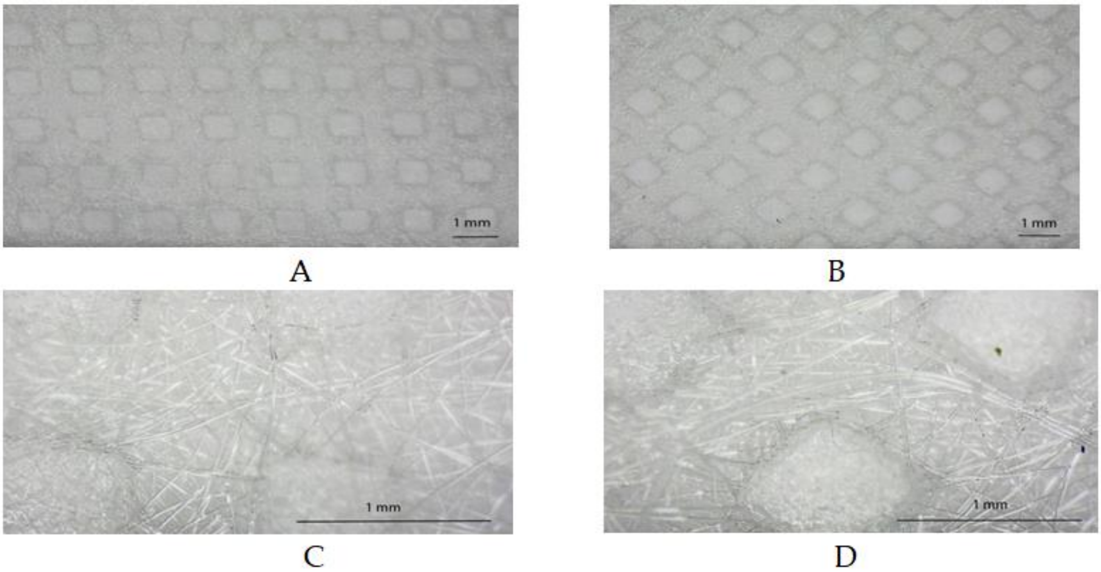
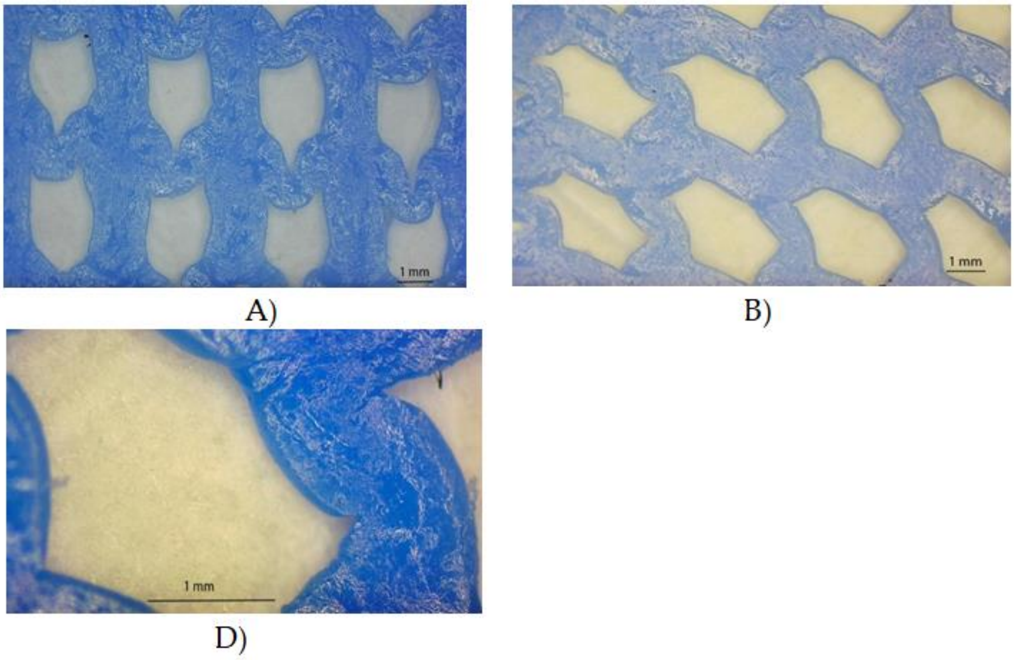
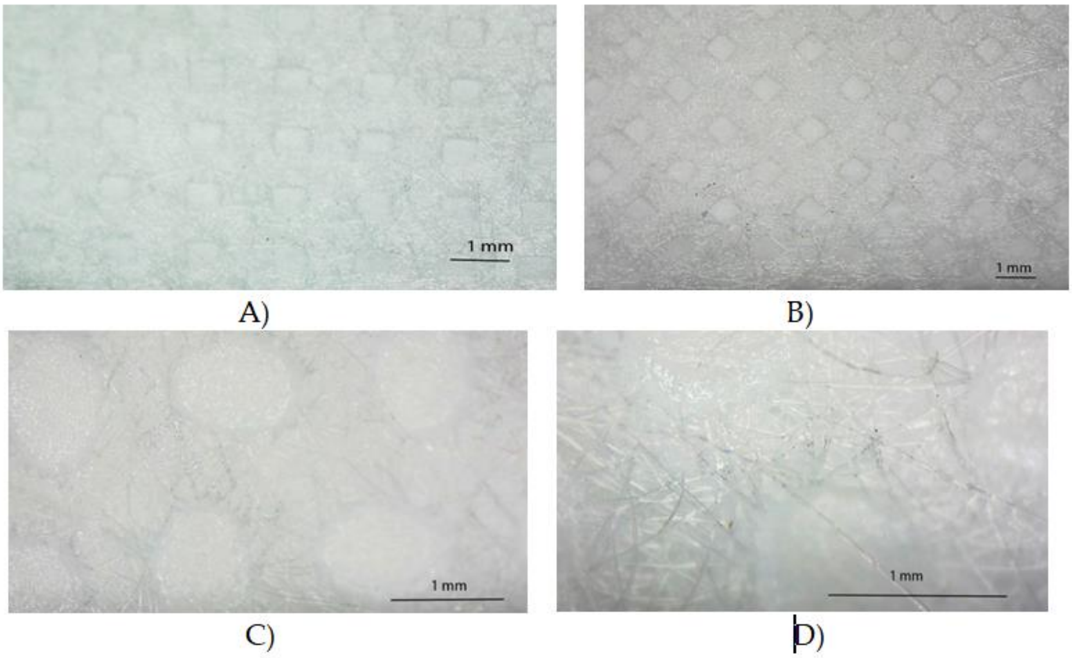


Figure 5: *Electroplating fume. Respirator 1.*
A), C) Before sampling; B), D) After sampling



A) B)
D)

Figure 6: *Electroplating fume. Respirator 2. A) Before sampling; B), D) After sampling*



A) B)
C) D)

Figure 7: *Electroplating fume. Respirator 3. A), C) Before sampling; B), D) After sampling*

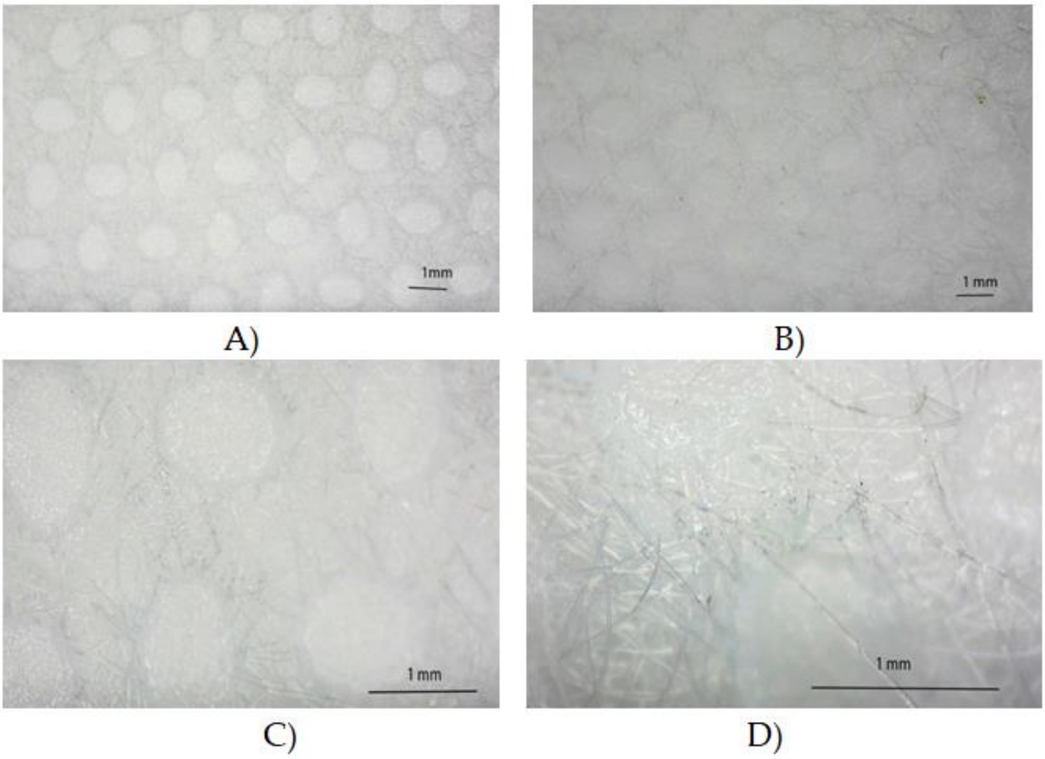


Figure 8: *Electroplating fume. Respirator 4. A), C) Before sampling; B), D) After sampling*

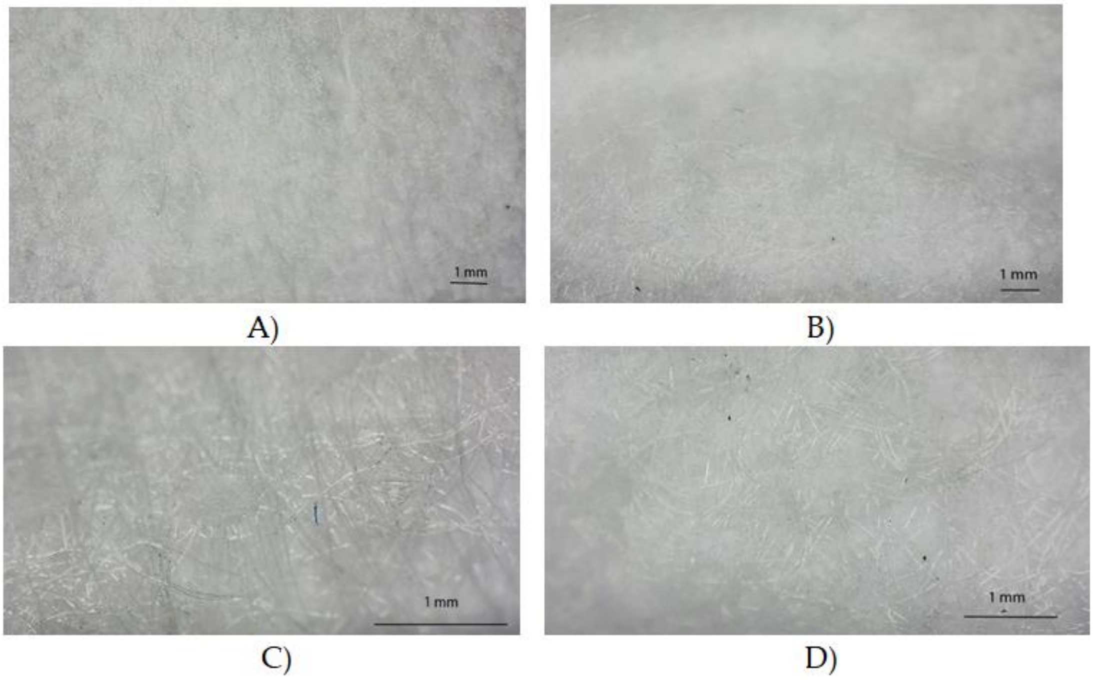


Figure 9: *Electroplating fume. Respirator 5. A), C) Before sampling; B), D) After sampling*

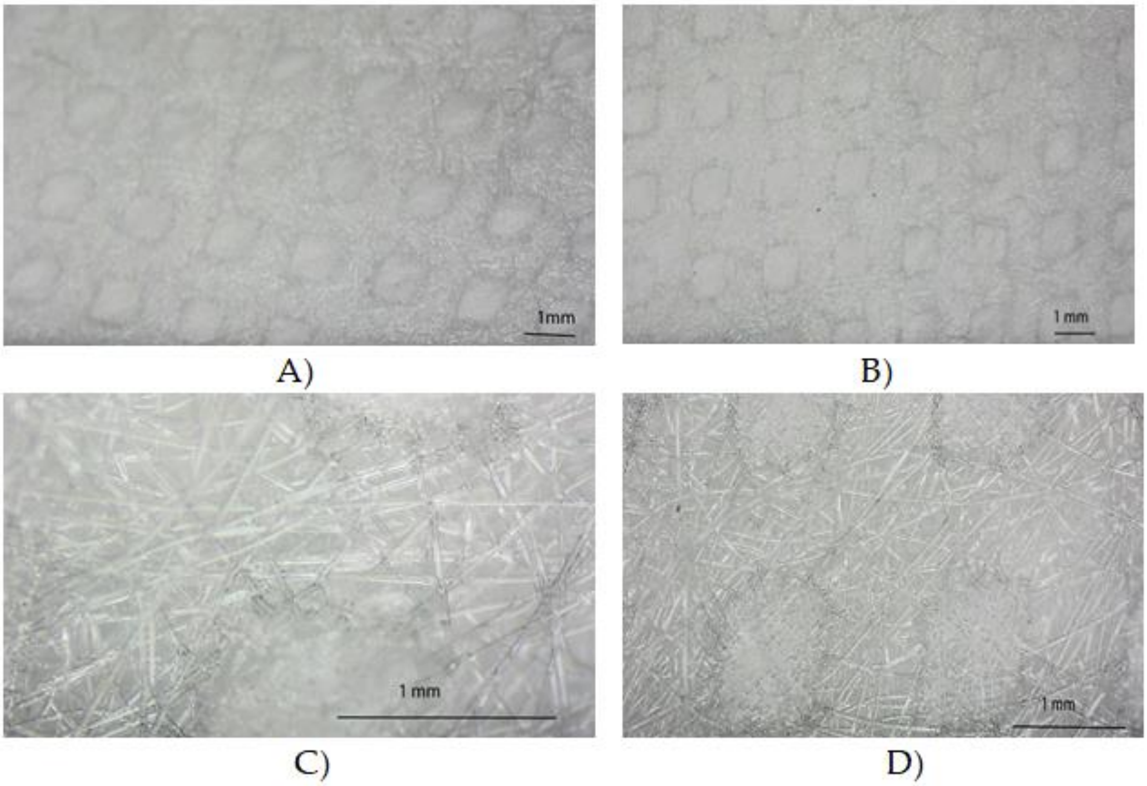


Figure 10: *Electroplating fume. Respirator 6. A), C) Before sampling; B), D) After sampling*

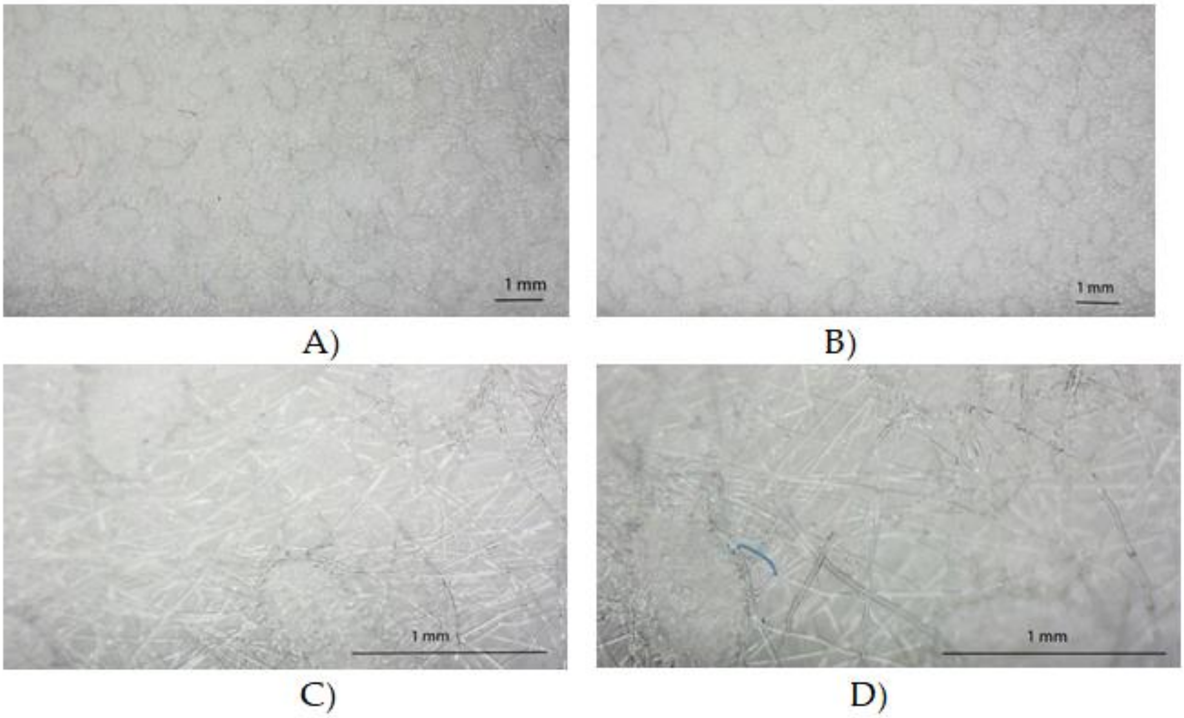


Figure 11: *Electroplating fume. Respirator 7. A), C) Before sampling; B), D) After sampling*

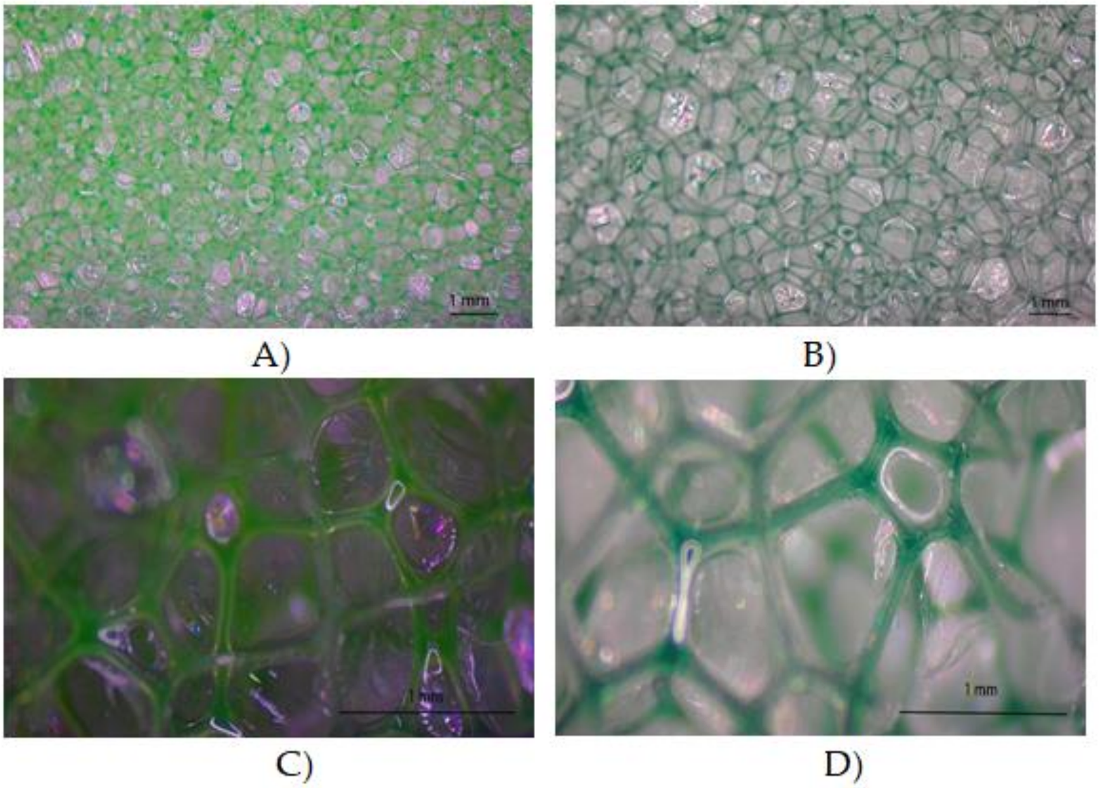


Figure 12: *Electroplating fume. Respirator 8. A), C) Before sampling; B), D) After sampling*

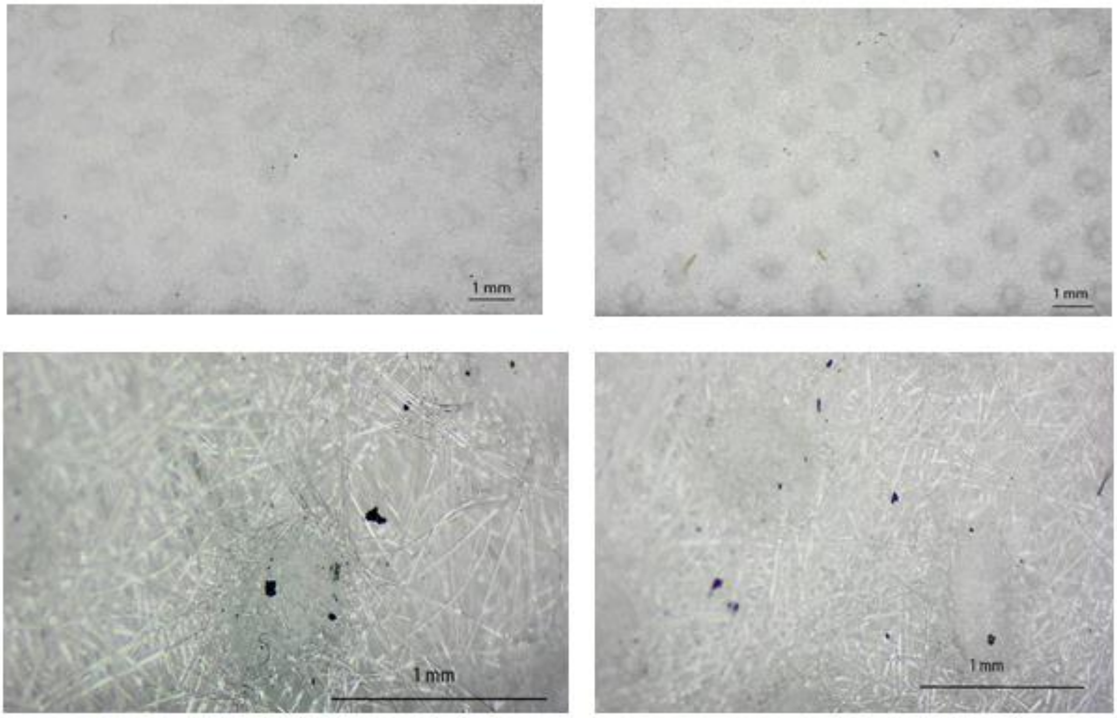
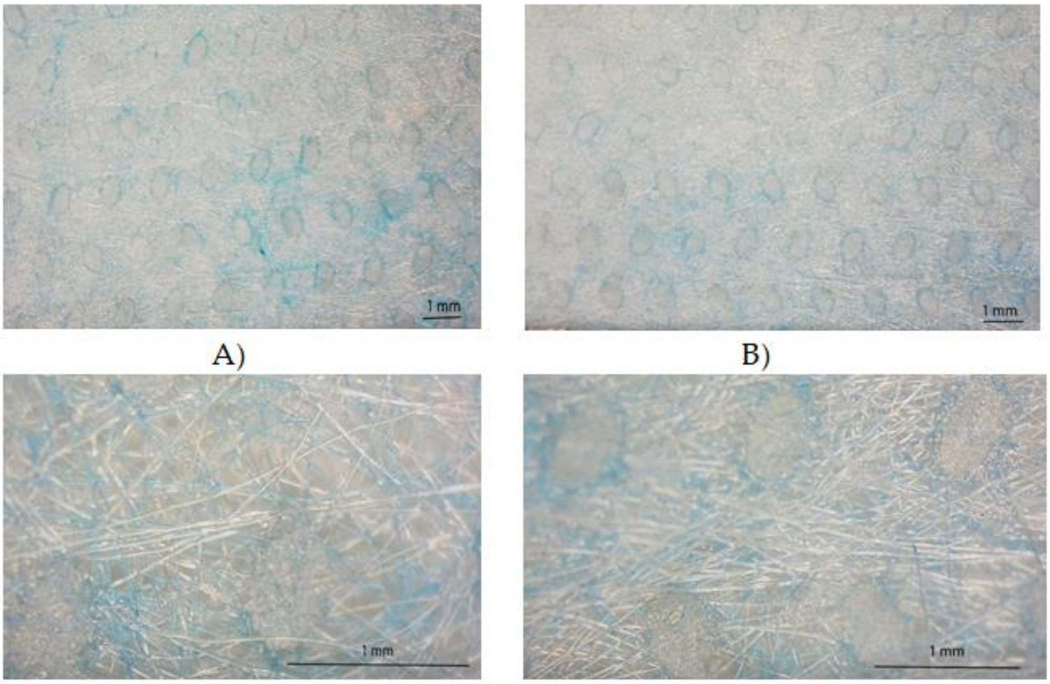


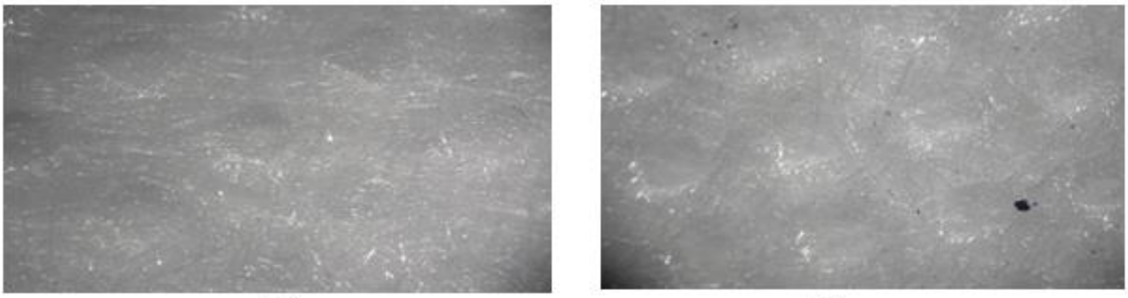
Figure 13: *Electroplating fume. Respirator 9. A), C) Before sampling; B), D) After sampling*



A) B)

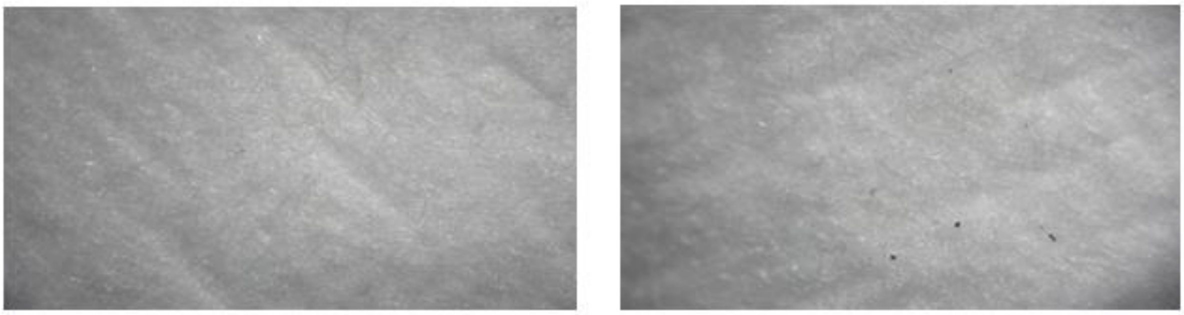
C) D)

Figure 14: *Electroplating fume. Respirator 10. A), C) Before sampling; B), D) After sampling. Comparison of the surface of filter material of the respirators before and after the experiment. Carl Zeiss Stemi DV4 stereomicroscope, magnif. 30x*



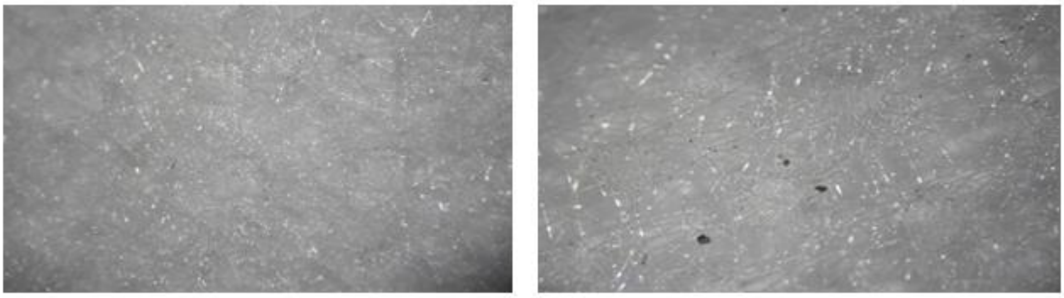
A) B)

Figure 15: *Welding fume. Respirator 1. A) Before sampling; B) After sampling*



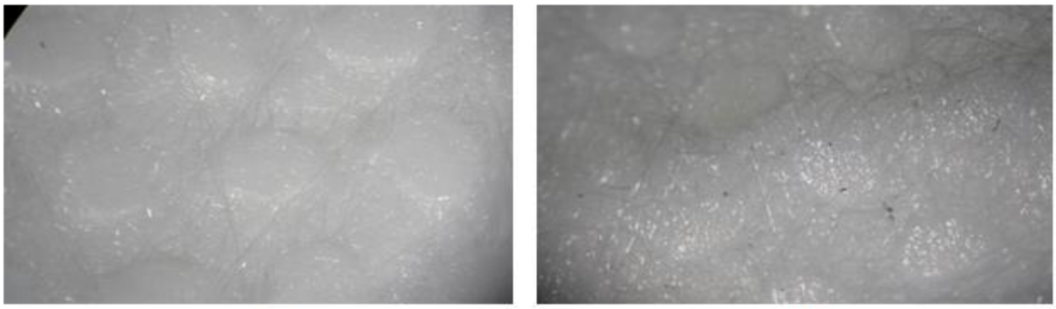
A) B)

Figure 16: *Welding fume. Respirator 1. A) Before sampling; B) After sampling*



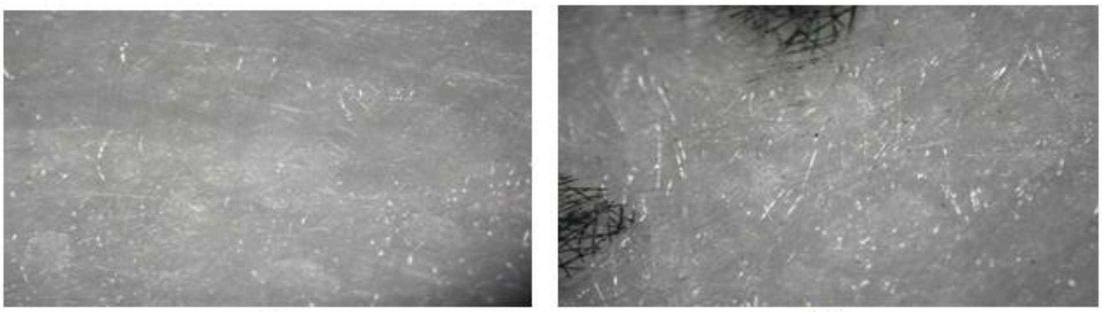
A) B)

Figure 17: *Welding fume. Respirator 3. A) Before sampling; B) After sampling*



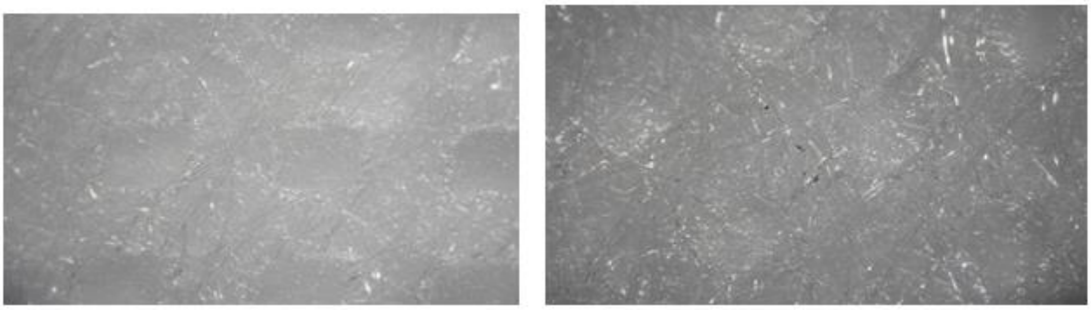
A) B)

Figure 18: *Welding fume. Respirator 4. A) Before sampling; B) After sampling*



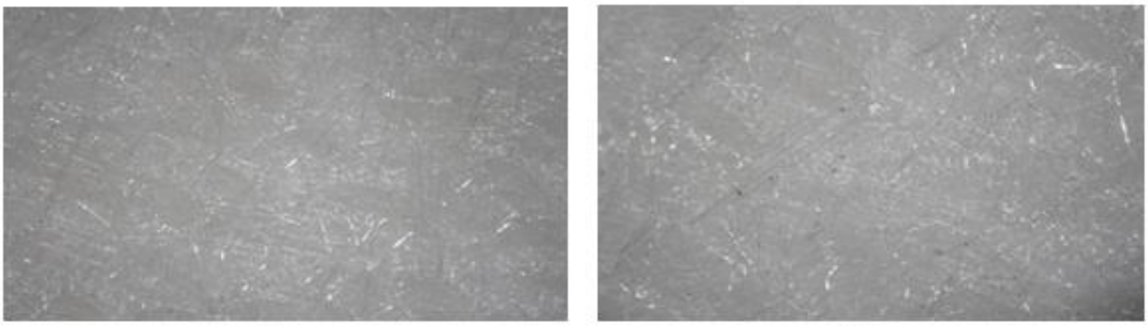
A) B)

Figure 19: *Welding fume. Respirator 5. A) Before sampling; B) After sampling*



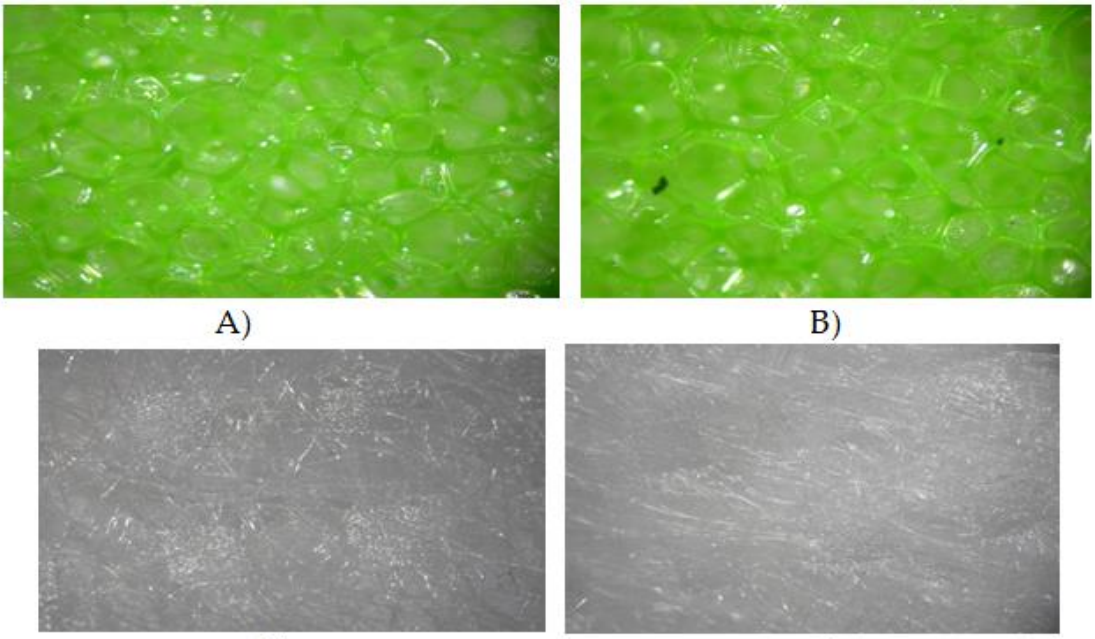
A) B)

Figure 20: *Welding fume. Respirator 6. A) Before sampling; B) After sampling*



A) B)

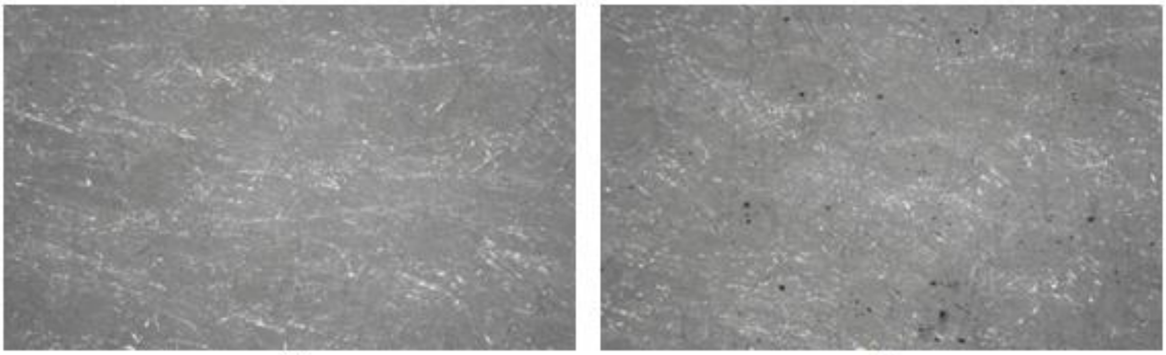
Figure 21: *Welding fume. Respirator 7. A) Before sampling; B) After sampling*



A) B)

C) D)

Figure 22: *Welding fume. Respirator 8. A), C) Before sampling; B) D) After sampling*



A) B)

Figure 23: *Welding fume. Respirator 9. A) Before sampling; B) After sampling*

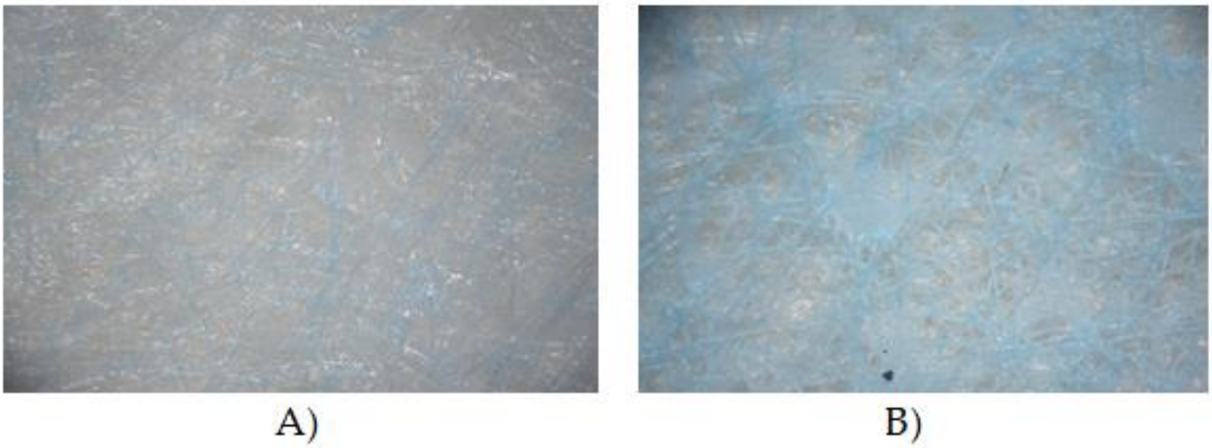


Figure 24: *Welding fume. Respirator 10. A) Before sampling; B) After sampling*

According to the results of electron microscopy, the samples of filter material from respirators No. 3 and 9 demonstrate the best trapping properties. Solid particles of industrial aerosols deposited on the filter are clearly visible (they have a dark color). The electron microscopy results correlate with the number concentration of airborne PM confirming the mechanical trapping ability of the respirator filtering material (Table 2).

The photographs of filters from respirators No. 8, 10, 6, 4, and 1 before and after the experiment are very similar because no deposited particles of industrial aerosol can be observed. These photographs and the data in Table 2 confirm the low sorption and filtration capacity of these respirators. Therefore, these respirator models are ineffective in trapping airborne PM originating from electrochemical processes in electroplating production.

The results obtained indicate the possibility of penetration of the smallest particles of industrial aerosols through the protective filtration barriers of personal respiratory protective equipment. It is known that prolonged inhalation exposure to industrial aerosols contributes to the emergence and development of occupational respiratory diseases in welders, electroplaters and workers of related professions. Prolonged exposure to industrial aerosols provokes the development of fibrogenic processes, mainly silicosis, dust bronchitis, pleurisy, pneumonia and asthma [34]. The risk of occupational diseases increases with each year of work experience, and at the age of 12-15 years the maximum rates of development of chronic diseases are reached in welders, electroplaters and workers of related professions [35].

The solution to this problem may be the introduction of new materials as filtration elements in personal respiratory protective equipment, such as composites, nonwovens, or with physical properties of magnetic fields to improve trapping characteristics.

IV. Conclusions

The results obtained indicate that there is a significant variation in the filtration efficiency of the filter elements in different respirator models.

Respirator filtration performance can be affected by a number of factors including: different filtration mechanisms, environmental parameters, filter material properties, number of respirator layers used, packing density, fiber loading density, fiber diameter, aerosol particle type and size, aerosol flow rate and concentration values, and additional factors from different human activities [17] and the fit of the respirator to the human face [36, 37].

According to the data obtained, the trapping capacity of filtering material in respirators varies depending on the fraction of airborne PM. The maximum efficiency is demonstrated by respirator No. 9 with a multilayer filter element which traps particles of the smallest fraction much better than other models used in the experiment. It should be noted that in experimental conditions, the maximum trapping characteristics of the filtering material of respirators were considered, without any leakage on edges where respirators fit to the worker's face. For models with the low trapping capacity of the filtering material (respirators No. 8, 10, 6, 4, and 1), it may be a factor that compensates for the disadvantages through better ergonomics and tight fit of the respirator to the face of the worker in real production conditions.

It should be noted that choosing the most effective respirator model that captures the maximum amount of airborne particles, thereby preventing their penetration into the human body, which can lead to occupational diseases with prolonged exposure, can solve the problem of reducing the incidence of disease among electroplaters, welders and workers in related professions. However, polymer materials used in the production of respirators and masks are usually not biodegradable which can cause serious environmental problems in most countries where waste disposal systems are ineffective. Therefore, respirator models with non-woven and non-synthetic materials have great prospects for the future if they achieve a high trapping capacity and low airflow resistance.

The results obtained for the filtration efficiency of the filter materials allow us to conclude that respirators with combined multi-layer filter elements are the most effective. Since we did not take into account a number of respirator factors, such as the tightness of the mask to the face, long-term preservation of working characteristics, and based only on the filtration capacity, it is possible that other respirator models will be more effective in real production conditions due to unaccounted for advantages.

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