Airborne Nanoparticle Pollution in a Wire Electrical Discharge Machining Workshop and Potential Health Risks

Rui Chen1§, Xiaofei Shi2§, Ru Bai1§, Weiqing Rang2, Lingling Huo1, Lin Zhao2, Dingxin Long2, David Y.H. Pui3, Chunying Chen1*

1 CAS Key Lab for Biomedical Effects of Nanomaterials and Nanosafety, National Center for Nanoscience and Technology of China, Beijing 100190, China
2 School of Public Health, University of South China, Hengyang 421001, China
3 Department of Mechanical Engineering, College of Science and Engineering, University of Minnesota, Minneapolis, MN 55455, USA

ABSTRACT

The environmental pollution associated with electrical discharge machining is not yet clearly understood. Airborne exposure to nanoscale and respirable particles were investigated with regard to the aerosol characteristics of a wire electrical discharge machining (WEDM) workshop. The total number concentration of the aerosol was multimodal, with the highest peak maxima during the working hours of 10:00 am and 3:00 pm. The majority of the released particles were smaller than \( d = 100 \) nm, with the maximum amount sized 40 nm. A large quantity of metallic elements, including Fe, Al and Cu, were found in the aerosol particulates coming from WEDM processing. Furthermore, the aerosol particles exhibited higher cellular toxicity and ROS producing ability in human alveolar epithelial cells (16HBE) when compared to the atmospheric background. Our results indicate substantial hazards arising from exposure to polluted atmosphere of a WEDM workshop. Effective exposure controls and protections are thus strongly recommended.

Keywords: Aerosols; Particle distribution; Elemental concentration; Risk assessment; Toxicity.

INTRODUCTION

Electrical discharge machining (EDM) is one of the widely used manufacturing processes for producing desired shapes of hardened metal workpieces (Liu et al., 2008). Comparing to the ‘conventional’ machining methods such as drilling, grinding, milling and any other process which is driven by mechanical forces, EDM is regarded as ‘non-conventional’ group of machining methods together with laser cutting, water jet cutting (Repp and McCarthy, 1984). There are two primary types of EDM including die-sinking EDM (DEDM) and wire EDM (WEDM) with a similar processing mechanism. Local high temperature is formed between a conductive work piece and a tool electrode, which removes material by melting and corrosion. In such process, particles including metals and/or metal oxides would probably form, even though a dielectric liquid is specially designed to avoid the particle emission in the air is used (Elihn and Berg, 2009).

The airborne particles can be classified as ambient airborne particulate material (PM) which usually is categorized into coarse, fine, and ultrafine particles with aerodynamic diameters between 2.5 and 10 µm, < 2.5 µm (PM2.5), and < 0.1 µm (PM0.1), respectively (Hinds, 1999). It had been found that particles at the nanoscale level pose more adverse health effects than larger particles with the same materials (Nalwa and Zhao, 2007; Qu et al., 2011; Chen and Chen, 2012; Gorbunov et al., 2013; Chen et al., 2014). Understanding the health risks of aerosol particles under different environmental conditions, is of major necessity for improving exposure estimates, to develop efficient control strategies, to reduce human exposure and adverse health risks. In our daily life, office printers and photocopiers have been shown to form potentially toxic nanoaerosols in the air (He et al., 2007; McGarry et al., 2011; Bello et al., 2013). Similarly, it has been proven that welding, with similar local high temperature as in the operation of EDM, generates nanoparticles in high concentrations especially close to the sources (Lee et al., 2007; Pfefferkorn et al., 2010; Gomes et al., 2012; Gomes et al., 2014). However, health risks associated with EDM air pollution are not yet clearly understood (Andujar et al., 2014). Jose et al. (2010)
evaluated the aerosol exposure of DEDM and showed that the aerosol concentration at breathing zone of the operator was above the permissible limit for repairable particulates (5 mg/m³). Unfortunately, no size fraction information was reported. Further, DEDM is an intense machine that usually generates smoke during the operation, which may constitute fire and explosion hazards. Metal-rich fumes of PM₁₀ or PM₂.₅ have been demonstrated to cause lung inflammation by producing reactive oxygen species (ROS) in some reported conventional metal processing fields (Schaumann et al., 2004; Hutchison et al., 2005; McNeilly et al., 2005; Bai et al., 2010). However, there is very limited information available on the particle emission of the WEDM machine, which considered to being safe compared with the DEDM. There is also no realistic field survey and/or sampling work reported on the working conditions that consider the air pollution caused by WEDM. Therefore, it is important to develop a deeper understanding on the air pollution from the WEDM and investigate the real situations of exposed humans, along with providing recommendations to minimize the toxicological potentials.

**METHODS**

**WEDM Workshop and WEDM Machines**

The workshop of interest was a one-floor independent room located in a regular metal processing plant. The layout of the WEDM workshop was shown in Supporting Information (Fig. S1). Briefly, the height of the workshop room was 3.8 m; total area of the workshop was about 51 m² and with no special ventilation system available. The window was closed during working time to avoid the winter’s chilly wind, but was opened at night during the survey. The door usually was also closed. One worker was in charge of the workshop and running all the machines. Three WEDM machines were working full-time in the workshop from 8:00 am to 17:30 pm during daytime, except for a lunch-break from 12:00 am to 13:30 pm. One of the machines (WEDM-1) was manufactured by Beijing AgieCharmills Industrial Electronics with model number FW2, while WEDM-2 and WEDM-3 were from Shanghai Troop Group Photovoltaic Technology with model number TP-25ZT and TP-3271, respectively. Standard WEDM dielectric fluid (DIC-206, Beijing Hua Ye Oil Limited, China) was used in the machines. Large batch of metal blocks including copper, aluminum, and stainless steel were processed during the working time within this workshop.

A suite of aerosol instruments covering the size range from 3 nm to 10 µm were used to capture the particle size distribution and number concentration in the workshop, including the Scanning Mobility Particle Sizer (SMPS, TSI model 3936, USA), Optical Particle Sizer (OPS, TSI model 3330, USA) and Hand-held Condensation Particle Counter (CPC, TSI model 3007, USA). The SMPS consists of Water-based Condensation Particle Counter (CPC, TSI model 3788, USA), an Electrostatic Classifier (EC, TSI model 3080, USA), a Nano Differential Mobility Analyzers (DMA, TSI model 3085, USA), and a Long DMA (TSI model 3081, USA). The detection range of SMPS configured with Nano DMA is from 2.89 nm to 98.2 nm, while from 14.1 nm to 615.3 nm for Long DMA at our used parameters. SMPS got an upper linear range of 10⁵ particles/cm². The detection range of OPS was from 300 nm to 10 µm with an upper linear range of 3,000 particles/cm².

CPC3007 was used to measure TNC of aerosol particles ranged from 10 nm to >1 µm in diameter. Coincidence correction was carried out with the following equation at number concentrations higher than 1 × 10⁵ particles/cm³, the upper detection limit of the CPC, according to previously described method (Hämeri et al., 2002). The equation used for coincidence correction of CPC3007 is

\[ y = 38456e^{-0.00001x} \quad \text{for} \ x > 100,000 \text{particles/cm}^3, \ r^2 = 0.817. \]

(1)

The three instruments above-mentioned were conducted “zero” calibration with high efficiency particulate air (HEPA) filter before each field application. The aerosol sample collection tubes were set at breathing zone. Detailed information including parameter setting was given in Supporting Information (Table S1). Impactor of 0.0457 cm was implied in SMPS to eliminate the particles > 1 µm, with DMA Sheath Flow was 7 L/min, CPC Sample Flow 0.7 L/min. The sample line diffusion loss is expected, although conductive rubber was used for the sampling lines. The diffusion loss evaluation on the sampling pipelines based on the penetration efficiency for aerosols was provided in Fig. S2. The SMPS data presented here have been recalculated to include the diffusion loss correction of the sampling lines. The integrated total average of the diffusion losses for the measurement of CPC 3007 and OPS were all less than 3%, which is negligible for the total particle number concentration.

Micro-Orifice Uniform-Deposit Impactors (MOUDI, Model 125B NanoMoudi-II, MSP Corporation, USA) was used to collect size-fractionated aerosol particle samples from 0.01 µm to 10 µm for gravimetric, chemical analysis and toxicological assessment. The MOUDI with internal stepper-motor stage rotation could provide uniform particle deposit on filters. The MOUDI has 13 impactor stages operating at 0.010, 0.018, 0.032, 0. 056, 0.10, 0.18, 0.32, 0.56, 1.0, 1.8, 3.2, 5.6, and 10 µm, respectively. Polycarbonate filters (Φ 47 mm, 0.22 µm, Munktell Inc., Sweden) were employed in the MOUDI to capture the airborne particles. Vacuum pump (Segevav SV10-16 B, Leybold Vacuum GmbH Co., Ltd, Germany) and flow meter (glass rotameter, LZB-10, China) were used to provide a steady flow rate of 10 L/min.

**Measurement Strategy**

The experimental design of this study includes two parts: (1) monitoring the particle number concentration of the PM₁₀ level in the selected WEDM workshop for consecutive 48 hours; (2) collecting the ambient aerosol particles in the WEDM workshop for the off-site analysis including aerosol mass concentration, physicochemical characterization and toxicological analysis. Fig. 1 shows the schematics of the whole experiments, including aerosol particle monitoring and
sampling, chemical and morphologic analysis, and cellular toxicity assessment. Real-time sampling was important to assess the potential risk of particles in the workplace. Three real-time, aerosol monitoring instruments were used in this object. The sampling point was representative of the breathing zone of the operator. Chemical and morphologic analysis, cellular experiments were carried out after integrated aerosol particle sampling. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) were adopted for inspecting the morphology of aerosol particles, while inductively coupled plasma-mass spectrometry (ICP-MS) and electron microscopy coupled energy dispersive spectroscopy (EDS) for elemental analysis. We monitored number concentrations of aerosol for consecutive 48 hours. MOUDI 125B was used to collect particles 8 hours per day for 5 working days. Grids and wafers were put on filter directly for 3 hours and collected for morphological and elemental observation.

**Particle Morphology Observation**

Electron microscopy grids were put on the filter in the MOUDI to collect the aerosol particles for morphological and elemental analysis. After putting filter on each impaction plate in the MOUDI, 2 TEM grids (200-mesh molybdenum with carbon film, Zhongxing Bairui Inc., China) and 2 SEM wafers (4 mm × 4 mm, Zhongxing Bairui Inc., China) were put on the center of filter (2 cm diameter circle). Grids and wafers were removed after MOUDI running for 3 hours continually, after which MOUDI resumed working again. The grids were inspected by TEM (T20, TECNAN Inc., USA), and wafers by SEM (S-4800N, HITACHI Inc., Japan) for particle size and morphology observation. Elemental analysis for particles of interest was conducted by the integrated EDS.

**Gravimetric Analysis**

Integrated sampling of aerosol particles by MOUDI was performed during work time from 8:00 am to 5:30 pm and lasted for consecutive 5 working days. The particle-loaded filters were carefully stored in a filter box until gravimetric analysis. The mass of particles on the polycarbonate filters was determined as mass difference between pre-and post-sampling weights of the substrates. Filters were equilibrated in desiccators for 48 hours before and after weighing, then weighted by a microbalance in National Institute of Metrology of China at a constant temperature at 20 ± 1°C and humidity of 50 ± 10%. Data was interpreted as mass concentration distribution of the room environment PM by averaging on the filtered air volume of the sampling within this survey. Taking into account the work hour and sampling length, mass was interpreted into 8 h time-weighted average concentration.

**Elemental Analysis**

We removed the particles from the filters and calculated the weight of detached particles as described in Lu et al. (2011). Briefly, filters were immersed in 4 mL DMEM after weighing and exposed to ultraviolet for 40 minutes, and sonic oscillated for 1 hour. The stock solution of collected aerosol particles was used for elemental analysis and cytotoxicity assessment. The detached filters were weighted again after dry in desiccators for computing particle elution efficiency. Chemical analysis of each stage for select transition metals was performed with the inductively coupled plasma optical emission spectrometer (ICP-OES) and ICP-MS. 1 mL stock solution of collected aerosol particles was immersed in concentrated nitric acid overnight and digested on a hot plate completely. After the digestion, the samples
were evaporated to remove the remaining nitric acid and then diluted to 4 mL using 2% nitric acid. Finally, 3 mL of diluted samples were used for ICP-MS analysis and 1 mL of diluted samples were diluted again by 3 mL of 2% nitric acid before ICP-MS test.

Cytotoxicity Assessment

300 µL Fetal Bovine Serum (FBS, HyClone), 30 µL Penicillin-Streptomycin Liquid (10,000 U/mL, HyClone) were added to the DMEM solution containing the particles. The stock solution of collected aerosol particles was used for CCK-8 cellular viability assay (Dojindo Laboratories, Tokyo, Japan) according to the manufacturer’s protocol. Briefly, a human alveolar epithelial cell line (16HBE) were maintained in Dulbecco’s Modified Eagle’s Medium (DMEM) with 10% FBS. The cells were seeded at 7,000 cells/well in 96-well culture plates in quadruples for cytotoxicity assessment. After incubated with different concentrations of aerosol particles, 10 µL CCK-8 reagent was added to cell culture medium (100 µL/well). Absorbance was recorded at 450 nm using an Infinite M200 microplate reader (Tecan, Durham, USA). The mean absorbance of cells/well in 96-well culture plates in quadruples for CCK-8 cellular viability assay (Dojindo Laboratories, Tokyo, Japan) according to the manufacturer’s protocol. 

RESULTS

The Total Particle Number Concentration in the WEDM Workshop

The total particle number concentration (TNC) was measured by CPC 3007 (particles with diameter greater than 10 nm). Fig. 2(A) shows TNC profile in the WEDM workshop over 48 hours period which include one overnight and two work shifts (Day 1 and Day 2). The highest TNC reached to 1.2 × 10⁶ Particles/cm³, about 6 times higher than the background. Background between day 1 and day 2 was relatively higher for the reason of a sandstorm at that night according to the weather record. TNC varied substantially with time, which reflects the influences of cutting activity. It is clearly shown that TNC was significantly higher during the daytime comparing to the level at night (Fig. 2(A)). TNC increased immediately after cutting activity started in the morning, and decreased after stopping the WEDM machine. The highest TNC was observed around 10:00 am and 3:00 pm in the working time, which was a result of accumulation of particles from continuous cutting activity. All machines were shut down at noon. The TNC number of the larger particle fraction monitored by OPS decreased quickly in the noon comparing to the TNC number monitored by CPC 3007 which gives the data range of PM1.0 (Figs. 2(B) and 2(C)). On the contrary, the TNC number monitored by SMPS either using nano or long DMA reflecting the small size particle fractions persisted. It indicates that the number concentration is dominated by the nanoparticles. We checked the particle emission levels of various workpieces by a simulative processes. We have shown that workpieces of aluminum could produce TNC values about 10 times more than that of copper and steel, while workpieces of copper and steel showed no obvious difference at the real-time particle emission level (Fig. S2(A) and Table S2). Similarly, particles from aluminum could produce much more particles than other elements for all particle sizes (Figs. S2(B) and S2(C)).

Particle Size Distribution

Fig. 3 exhibits a typical particle size distribution (dN/dLogDp, particles/cm³) as a function of time as measured by SMPS and OPS over a wide combined ranged of particle diameter, namely 2.89–98.2 nm for SMPS with Nano DMA, 14.1–615.3 nm for SMPS with Long DMA, 300–10 µm for OPS as described in Supporting Information (Table S1). The number concentration of nanoparticles increased dramatically at 8:30 am when cutting activity started as shown in Figs. 3(A) and Fig. 3(B). TNC was multimodal within a work day with highest maxima at 10:00 am and 3:00 pm as measured by CPC 3007 (Fig. 2(A)). Emissions of particles from the cutting activity were mainly at the PM0.1 level as illustrated in Figs. 3(A) and Fig. 3(B). The d = 40 nm size particles were present in the highest concentration range. Large particles were usually present in lower concentrations and with a sharp decrease at noon from the reason of sedimentation (measured by OPS; see Figs. 3(C) and Fig. 3(D)). The total number concentration of PM0.1 generated from WEDM operations was about 3.5 ×
10^6 particles/cm^3 during the work day (8:00 am to 5:00 pm) (Fig. 3(A)).

**Particle Mass Distribution**

Particle mass was measured by collecting the aerosol particles by MOUDI. Fig. S4 (see Supporting Information) shows the polycarbonate filter scanning images right after the finish of sampling. Particle deposits are distributed uniformly on filters where the circular impaction areas of approximately 25 mm in diameter. Filters with particle size

![Particle Mass Distribution Diagram](image)

**Fig. 2.** Total particle number concentration of two consecutive days recorded by (A) CPC 3007; (B) Day 1 recorded by CPC3007/OPS/SMPS-Nano DMA; and (C) Day 2 recorded by CPC3007/OPS/SMPS-Long DMA. Sandstorm was based on the weather record of that night.
ranging from 100 nm–1,000 nm (S6, S7, S8, S9) appears to have more particles deposited. Fig. 4 shows the mass concentration of particles which being described as dM/dLogDp, µg/cm³. The particle mass concentrations calculated for the PM < 0.1 µm, PM 0.1–1.0 µm, PM 1.0–10 µm, PM > 10 µm were 19.5 µg/m³, 204.2 µg/m³, 143.0 µg/m³ and 58.5 µg/m³, respectively. The total calculated total mass concentration was 425.3 µg/m³ (Fig. 4).

**Morphology and Elemental Analysis of Aerosol Particles**

Fig. 5 shows representative images of morphology analysis of aerosol particles in each stages of MOUDI. Black and round metal particles were observed on TEM pictures showing the existence of Fe, Al, Cu, Si, Mo and Cr elements by EDS scans (Fig. S5). Particles take different shapes and usually are in conglomerated state as illustrated in SEM images. The chemical composition determined by ICP-MS revealed large amounts of iron, aluminum and copper with trace amounts of Mg, Mn, Mo, Zn, Ni and Cr (Fig. 6). From ICP-MS results, the particle mass concentrations in the aerosols contain 60.7 µg A/m³, 135.8 µg Fe/m³, and 29.3 µg Cu/m³, respectively (Fig. S6). We concluded that these metals came mainly from the WEDM process using workpieces made of copper, aluminum, and iron respectively (Fig. S7).

**DISCUSSION AND CONCLUSIONS**

**Aerosol Emission Characteristic and Health Risk Evaluation**

Airborne particles in a WEDM workshop were collected, characterized, and tested for cytotoxicity in this research. To our knowledge, this is the first time to conduct a study with detailed characterization and biological evaluation on a WEDM working environment. This study reveals several important findings with direct concerns of indoor air pollution caused by the WEDM work process.

We concluded that aerosol particles are direct results of WEDM operation due to the high local temperature in the working process. Particle concentrations increase right after the cutting process starts, and decreases when having a break or other disturbance of the air, e.g., opening a window. The surveyed plant was not equipped with forced ventilation, so generated particles only can diffuse freely. Lack of ventilation is a common problem in small or middle size metal processing plants in developing countries. The TNC of the surveyed workshop was multimodal with peak maxima at time 10:00 am and 3:00 pm reflecting the ongoing activities. The majority of particles were smaller than 100 nm, with a maximum at 40 nm. TNC measured by CPC 3007 was as high as 1.2 × 10⁵ particles/cm³ at the peak, which was 6
Fig. 4. Particle mass distributions derived from MOUDI collected aerosol particles in the workshop.

times higher than the background (Fig. 2(A)). We provided a direct evidence that WEDM process produces particle sizes largely less than 100 nm. The average concentration of PM$_{0.1}$ (2.89–98.2 nm) reached to $3.5 \times 10^4$ particles/cm$^3$ during the workday, while its mass concentration was only about 19.5 µg/m$^3$. This TNC number is about 100 times larger than exposure limits of 20,000 particles/cm$^3$ for nanomaterials with a density of $> 6,000$ kg/m$^3$ and 40,000 particles/cm$^3$ for a density of $< 6,000$ kg/m$^3$ which was set by Institute for Occupational Safety and Health of the German Social Accident Insurance. The densities are about $2,700$ kg/m$^3$ of Al, $7,900$ kg/m$^3$ of steel and $8,900$ kg/m$^3$ of Cu workpieces used in this workshop. It should be noted that aluminum workpieces usually produce much more airborne particles than iron and copper ones, which may originate from the lower density and malleability of aluminum. However, the mass concentration observed is still much lower than the exposure limit value recommended by the National Institute for Occupational Safety and Health (NIOSH, USA), which proposed exposure limits of 2.4 mg/m$^3$ for fine (PM$_{10}$) and 0.3 mg/m$^3$ for ultrafine (PM$_{0.1}$), (although for titanium dioxide). Only titanium dioxide and carbon nanotubes had been given definite exposure limits until now, but the metal or metal oxide aerosol in this workshop was much more toxic than exposure to titanium dioxide (Ge et al., 2012; Zhang et al., 2012; Huo et al., 2015). Furthermore, lack of ventilation caused aerosols distributed widely and evenly in this workshop after long time work. Our data of the breathing zone indicates human having high level exposure at every corner in the room. At present, this NIOSH exposure limit value is much more stringent than other recommended values on TiO$_2$ exposure, i.e., 10 mg/m$^3$ from American Conference of Governmental Industrial Hygienists (ACGIH) and Korean Ministry of Labor, and 15 mg/m$^3$ from
Occupational Safety and Health Administration (OSHA) (Lee et al., 2011). Based on the mass concentration data in Fig. 4 and Fig. 6, the average human weighing 70 kg with a respiratory minute volume (RMV) of 15.5 L/min working in this environment would have approximately 2.1 mg of aerosol particles (PM2.5) deposited in the lung in an 8 hour work day. The mass of metal elements of Fe, Al, Cu were about 0.52, 0.21, and 0.034 mg, respectively. We provide a detailed evaluation of the potential exposure risk and exposure limits of associated metal NPs in the Table 1 based on our current knowledge.

**The Aerosol Particles Caused Direct Cytotoxicity**

In order to evaluate the potential health risk to the WEDM workshop aerosol, we performed cytotoxicity tests on the collected aerosol particles. Normal atmospheric background particles showed no toxicity on the 16HBE cells after 24 hours (Fig. S8(A)). However, the aerosol particles of WEDM workshop showed higher cellular toxicity both in CCK-8 cell viability assay by 16HBE cell line and ROS producing ability test by 16HBE-ARE reporter (Fig. S8). Particle sizes in the ranges of 60–100 nm, 200–300 nm and >1.0 µm of WEDM collected samples showed significant ROS producing signal in 16HBE-ARE reporter test. It should be noted that when ultrafine particles illustrated significant toxicity at a quite lower exposure concentration, only 6.8 µg/mL of 60–100 nm stage (Table, S3). Higher toxicity and ROS producing ability observed in larger size particles mean that emitted nanoparticles are unstable, easily agglomerate in aerosol. Our data shows that nanoparticles emitted from the WEDM process constitute health risk to human comparing to the background atmosphere.

**Instruments Implementation**

Four sets of instruments were employed in this study for the characterization of aerosol particles during WEDM process, making the evaluation of the most important physicochemical and morphological characteristics possible. The real-time monitoring was essential in reliably profiling the size distributions of exposures. SMPS, OPS, CPC 3007, and MOUDI could collect particles across a wide combined size range (2.89 nm–10 µm), in which nanoscale particles are well covered. In this study, two different DMA were sequential used in SMPS. SMPS with Nano DMA can capture particles diameter in 2.89–98.2 nm, while Long DMA in 14.1–615.3 nm, both of which were focusing on nanoscale particles. Hand-held, direct-reading CPC was used to evaluate the TNC of airborne particles, which also could help to take a quick pre-evaluation before a survey.

Since different instruments utilize different principles to measure particle size, it is important to make it clear that these measurements may have some disagreement (Pfefferkorn et al., 2010). However, the data tendency is apparent, even though TNC values calculated from different instruments could not be matched very well. Reasonably, the discrepancy is the result of several facts: (1) the size ranges of these instruments are different, (2.89–98.2 nm for SMPS with NanoDMA, 14.1–615.3 nm for SMPS with Long DMA, 300–10,000 nm for OPS, 10– > 1000 for CPC 3007); (2) the principles of detection are different, (electrical mobility diameter for SMPS, light scattering equivalent diameter for OPS); (3) particle settlement, agglomeration, coagulation, and/or coalescence may occur. A detailed comparison of different mobility particle sizers and their discrepancy is the result of several facts: (1) the size range of these instruments are different, (2.89–98.2 nm for SMPS with NanoDMA, 14.1–615.3 nm for SMPS with Long DMA, 300–10,000 nm for OPS, 10– > 1000 for CPC 3007); (2) the principles of detection are different, (electrical mobility diameter for SMPS, light scattering equivalent diameter for OPS); (3) particle settlement, agglomeration, coagulation, and/or coalescence may occur. A detailed comparison of different mobility particle sizers and their influence have been discussed elsewhere (Asbach et al., 2009).

**Limitations and Suggestions**

With the limitation of instruments, the two DMAs cannot be used simultaneously, which means we cannot characterize airborne particles in 2.89–615.3 nm at the same time. So, the two DMAs were operated on two different days. The
detailed assessment in this study was conducted in a real workplace the same as a two-day assessment. The detailed assessment was expected to investigate the micro-activity, so it probably influenced by many uncertain factors such as background, wind, anthropogenic, etc. Further, particles collected by the filters usually could not be detached completely, so the cell experiment can just estimate the cytotoxicity of the aerosol particles. Even under these conditions, increased ROS level and decreased cell viability were found when comparing the collected aerosol particles and background particles.

Exposure limit values expressed as mass concentration, may not reflect the significant changes of PM$_{0.1}$ aerosol exposure for chemically reactive or biologically active nanoparticles, like metal or metal oxide nanoparticles in this study. Reasonable and definite exposure limit values based on number concentrations and composition should be developed and implemented for such exposure scenarios. In the WEDM industry, it is very urgent to adopt specific approaches to protect workers’ health and make this industry develop smoothly. Before detailed regulations being enacted, we suggest that (1) forced ventilation systems should be compulsorily used; (2) number of machines installed in the workshop should be kept low; (3) workers should be mandated to wear personal protective equipment, such as special clothing, mask, gloves, and glasses; (4) it is necessary to make workers aware of the adverse health effects of such environments; (5) and regular health examinations for workers, especially of the upper respiratory tract, are indispensable. In order to evaluate the occupational safety, biological experiments are recommended to assess toxicity potential of airborne particles, for example cellular viability assays and ARE luciferase reporter for ROS producing ability test used in this research. Furthermore, unified endpoints and parameters are recommended for effective comparison among different exposure sources in the future.

In summary, we investigated the physicochemical, morphological and toxicological properties as well as the emission dynamics of aerosol particles in a realistic workplace of a WEDM workshop located in a normal metal cutting plant. Such kind of plants could be easily found in many places worldwide. Workers in WEDM take risks and are being exposed to polluted airborne particles, especially to ultrafine particles (PM$_{0.1}$). The highest total number concentration in WEDM was 6 times greater than that of background and PM$_{0.1}$ showed much higher than the exposure limit recommended by IFA. Aluminum can produce a magnitude more particles than copper and steel. The elements contained in workpieces determine the component of airborne particles, i.e., iron, aluminum and copper in this study. Ventilation by forced draft and opening windows/doors are effective ways to reduce the concentration of airborne particles and minimize the exposure risks. These findings emphasize the requirement of a better pre-design of metal workshops and associated effective exposure controls including ventilation, area, temperature, labor safety equipment and so on. For such purpose, more detailed, complete and full studies are needed to analyze the WEDM airborne pollution.

### Table 1. Results summary and exposure risk evaluation.

<table>
<thead>
<tr>
<th>Exposure limits</th>
<th>PM$_{0.1}$</th>
<th>PM$_{0.3}$</th>
<th>PM$_{0.4}$</th>
<th>PM$_{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass concentration (mg/m$^3$)</td>
<td>0.020</td>
<td>2.4</td>
<td>5.0</td>
<td>37.2</td>
</tr>
<tr>
<td>Time-weighted human lung deposition (mg/8 h)</td>
<td>0.15</td>
<td>1.76</td>
<td>17.86</td>
<td>N.A.</td>
</tr>
<tr>
<td>Time-weighted human lung deposition of metal elements (mg/8 h)</td>
<td>0.15</td>
<td>1.76</td>
<td>17.86</td>
<td>N.A.</td>
</tr>
<tr>
<td>Number concentration (particles/cm$^3$)</td>
<td>$3.5 \times 10^6$</td>
<td>N.A.</td>
<td>N.A.</td>
<td>$2 \times 10^4$</td>
</tr>
</tbody>
</table>

(a) Data of TiO$_2$ exposure from NIOSH 2011.
(b) Data of TiO$_2$ exposure from OSHA.
(c) Measured by SMPS coupled with Nano DMA (TSI Inc., USA) in this study.
(d) Data of particles with density > 6,000 kg/m$^3$ from IFA (2012).

N.A. = not available.
**ACKNOWLEDGMENTS**

We thank the financial support from the Ministry of Science and Technology of China (2011CB933401 and 2012CB934003), the National Science Fund for Distinguished Young Scholars (No.11425520) National Natural Science Foundation of China (21477029, 21277080 and 2132012003), Chinese Academy of Sciences (XDA09040400), National Major Scientific Instruments Development Project (2011YQ03013406), International Science & Technology Cooperation Program of China, Ministry of Science and Technology of China (2013DFG32340 and 2014DFG52500), Major Project of the National Social Science Fund (Grant No. 12&ZD117) “Ethical issues of high-tech”, and the European Commission through the Seventh Framework Programme for Research and Technological Development (MARINA 263215). We wish to thank the workers and the director of the plant for their help and cooperation.

**SUPPLEMENTARY MATERIALS**

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

**REFERENCES**


McGarry, P., Morawska, L., He, C., Jayaratne, R., Falk, M., Tran, Q. and Wang, H. (2011). Exposure to Particles...

Received for review, September 25, 2014
Revised, November 18, 2014
Accepted, November 30, 2014
Supporting Information

Airborne Nanoparticle Pollution in a Wire Electrical Discharge Machining Workshop and Potential Health Risks

Rui Chen1§, Xiaofei Shi2§, Ru Bai1§, Weiqing Rang2, Lingling Huo1, Lin Zhao2, Dingxin Long2, David Y. H. Pui3, Chunying Chen1∗

1CAS Key Lab for Biomedical Effects of Nanomaterials and Nanosafety, National Center for Nanoscience and Technology of China, Beijing 100190, China.

2School of Public Health, University of South China, Hengyang 421001, China

3Department of Mechanical Engineering, College of Science and Engineering, University of Minnesota, Minneapolis, MN 55455, USA

∗Corresponding author. Tel: +86-10-82545560; Fax: +86-10-62656765

E-mail address: chenchy@nanoctr.cn

§These authors contributed equally to this work.
Fig. S1. Schematic diagram of the WEDM workshop (not in scale).
Persistent measuring pattern

Flow Splitter

A: CPC 3007  
B: OPS 3330  
C: SMPS

Diffusion losses in the sampling lines (%) vs. Diameter (nm)

- Flow splitter part
- SMPS total sample line
- CPC 3007 total sample lines
- OPS total sample lines

Diameter (nm)

20 cm  50 cm  100 cm

A  B  C
Fig. S2. Evaluation on the diffusion loss of the sampling lines. The instant direct measurement on the printer particle emission by CPC 3007 was omitted for the reason of no pipe line used in the processing. The persistent measuring evaluation based on the flow rate of DMA Sheath Flow of SMPS was 7 L/min, CPC Sample Flow was 0.7 L/min, OPS inlet flow was 1 L/min. The total flow rate of 9 L/min was used for the evaluation on the diffusion loss of the flow splitter part. Diffusion loss was calculated based on the method for circular tube from Hinds (1999).
Fig. S3. Total number concentration released from machining on 3 workpieces of different elements. (A) TNC calculated from CPC 3007 (10~ >1,000 nm); (B) Diameter resolved number concentration from SMPS with Long DMA (14.1~615.3 nm); (C) Diameter resolved number concentration from OPS (300~10,000 nm).
Fig. S4. Filter images after 5 working days collection of aerosol particles of the WEDM workshop by MOUDI.
**Fig. S5.** Morphology observation of aerosol particles under SEM/TEM collected by MOUDI. Energy dispersive spectroscopy coupled to the electron microscopy was used to detect the elemental component of collected particles.
**Fig. S6.** Contents of Al, Fe, Cu elements in the aerosol of WEDM workshop by ICP-MS measurement.
Fig. S7. Elemental component of workpieces used in this workshop.
Fig. S8. Toxicity evaluations on collected aerosol particles. (A) Cytotoxicity test on 16 HBE cells; (B) ROS producing ability test on 16HBE-ARE cells.
Table S1 Summary of instruments used for characterization of airborne particles and associated parameter settings in this research

<table>
<thead>
<tr>
<th>Instrument</th>
<th>SMPS (TSI 3936)</th>
<th>OPS (TSI 3330)</th>
<th>CPC (TSI 3007)</th>
<th>MOUDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measures</td>
<td>Size distribution and TNC</td>
<td>Size distribution and TNC</td>
<td>TNC</td>
<td>Collect particles for subsequent analysis</td>
</tr>
<tr>
<td>Principle</td>
<td>Electrical mobility diameter $^a$</td>
<td>Light scattering equivalent diameter $^b$</td>
<td>—</td>
<td>Aerodynamic diameter $^c$</td>
</tr>
<tr>
<td>Size range (nm)</td>
<td>2.89-98.2 for Nano DMA</td>
<td>300-10,000</td>
<td>10-&gt;1,000</td>
<td>10-10,000</td>
</tr>
<tr>
<td></td>
<td>14.1-615.3 for Long DMA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displayed Channels /Stages</td>
<td>4,8,16,32 or 64 geometrically equal channels per decade</td>
<td>Up to 16, adjustable</td>
<td>No size resolution</td>
<td>13</td>
</tr>
<tr>
<td>Concentration range particles cm$^{-3}$</td>
<td>1-10$^8$</td>
<td>3,000</td>
<td>100,000</td>
<td>--</td>
</tr>
<tr>
<td>Sample Length (min)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>8hr</td>
</tr>
<tr>
<td>Inlet flow rate (L/min)</td>
<td>0.3</td>
<td>1</td>
<td>0.7 (0.1 for detection)</td>
<td>10</td>
</tr>
<tr>
<td>Time resolution(min)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>Time-integrated</td>
</tr>
</tbody>
</table>
Table S2. Statistic data summary on the total particle number concentrations of different workpieces measured by CPC 3007

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Steel</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM (#/cm$^3$)</td>
<td>5.1×10$^4$</td>
<td>4.87×10$^4$</td>
<td>4.65×10$^5$</td>
</tr>
<tr>
<td>GSD (#/cm$^3$)</td>
<td>1.33×10$^4$</td>
<td>2.89×10$^4$</td>
<td>3.08×10$^5$</td>
</tr>
<tr>
<td>Max. (#/cm$^3$)</td>
<td>1.15×10$^5$</td>
<td>3.23×10$^5$</td>
<td>1.36×10$^6$</td>
</tr>
</tbody>
</table>

GM: Geometric Mean; GSD: Geometric Standard Deviation; Max.: Maximum measured by the instrument.
Table S3. The particle recovery efficiency of the MOUDI filters and the final working dose used in the *in vitro* cytotoxicity tests

<table>
<thead>
<tr>
<th>PM</th>
<th>Size range (nm)</th>
<th>Recover efficiency (% Mass)</th>
<th>Dose in the medium (μg/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultrafine</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-18</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>18-32</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>32-56</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>56-100</td>
<td>15.5</td>
<td>6.8</td>
</tr>
<tr>
<td><strong>Fine</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100-180</td>
<td>91.5</td>
<td>117.1</td>
</tr>
<tr>
<td></td>
<td>180-320</td>
<td>61.6</td>
<td>99.1</td>
</tr>
<tr>
<td></td>
<td>320-560</td>
<td>88.7</td>
<td>254.5</td>
</tr>
<tr>
<td></td>
<td>560-1000</td>
<td>38.5</td>
<td>205.0</td>
</tr>
<tr>
<td></td>
<td>1000-1800</td>
<td>92.0</td>
<td>198.2</td>
</tr>
<tr>
<td></td>
<td>1800-3200</td>
<td>65.2</td>
<td>85.6</td>
</tr>
<tr>
<td><strong>Coarse</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3200-5600</td>
<td>69.9</td>
<td>132.9</td>
</tr>
<tr>
<td></td>
<td>5600-10000</td>
<td>60.2</td>
<td>141.9</td>
</tr>
<tr>
<td></td>
<td>10000-25000</td>
<td>61.1</td>
<td>193.7</td>
</tr>
</tbody>
</table>

N.A.: Not available from the reason of low mass.
Fine or coarse particles: The cut-point diameter was defined as 3.2 μm in this study for convinence, but not usually accepted value, 2.5 μm.
References


(End)