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Field Application of a Newly Developed Personal Nanoparticle Sampler to Selected Metalworking Operations

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ABSTRACT

A personal nanoparticle sampler (PENS) that simultaneously collects respirable particles (< 4 μm) and nanoparticles (< 0.1 μm) has recently been developed and calibrated in the laboratory. This study aims to evaluate the performance of the PENS in the workplace, and to determine the exposure characteristics during selected metalworking operations. Metal polishing/buffing, spot welding, and milling operations were selected to represent sources of solid metal particles, fume aggregates and metalworking fluid mists, respectively. In each operation, personal samples of a side-by-side PENS and SKC respirable dust aluminum cyclone were taken concurrently with ambient particle number size distribution measurements. The PENS-measured respirable particle mass concentrations (PM_4) showed remarkable accuracy with respect to the reference SKC cyclone, regardless of particle type. The PENS-derived nanoparticle effective densities agreed reasonably well with the bulk densities expected for the substrate and materials in use. During the metalworking operations, the nanoparticle mass concentrations ($PM_{0.1}$) were poorly associated with the PM_4 but strongly correlated with the ambient nanoparticle number concentrations ($PN_{0.1}$), due to the persistent, elevated levels of nanoparticles formed during the operations. Overall, these results suggest that the PENS is applicable for use in the workplace to assess respirable and nanoparticle personal exposure, and that metal polishing/buffing, welding and milling generate a considerable amount of nanoparticles.

Keywords: Ultrafine particles; Personal sampling; Exposure assessment; Metalworking.

INTRODUCTION

Airborne nanoparticles or ultrafine particles are those with one dimension or diameters smaller than < 0.1 μm. Growing evidence has shown that airborne nanoparticles are harmful to human health and potentially more potent than larger particles (Donaldson *et al.*, 2005; Xia *et al.*, 2009). This is because their small sizes allow them to penetrate the respiratory tract and deposit deeply in the alveolar region (ICRP, 1994). In addition, their large surface-to-volume ratio provides more active sites for potential adverse health reactions (Nel, 2006). Although ultrafine particles have been studied for several decades, the recent exploding development and application of engineered nanoparticles in numerous fields have attracted increasing attention from not only the scientific community but also the general public. A central question surrounded by such attention or concerns is the health risk and safety of nanoparticles throughout their life cycle. To address this question, the hazard and exposure potentials need to be determined, between which the latter is the focus of this study.

According to their origin, nanoparticles can be emitted incidentally as a by-product of human activities or produced intentionally in a controlled environment as a specific material, device and product. The former is referred to as incidental nanoparticles and typical involves high temperature processes such as internal engine combustion and many industrial operations (Vincent and Clement, 2000). Diesel engine exhaust (Cheng *et al.*, 2012; Young *et al.*, 2012), welding (Lehnert *et al.*, 2012; Zimmer *et al.*, 2012), smelting (Evans *et al.*, 2008), foundry operations (Cheng *et al.*, 2008), high-speed grinding (Zimmer and Maynard, 2002) and la ser cutting (Elihn and Berg, 2009) produce high number concentrations of airborne nanoparticles. The latter is referred

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to as engineered nanoparticles and is specifically related to the application of nanomaterials in the nanotechnology industry or laboratory. Brouwer (2010) and Kuhlbusch *et al.* (2011) showed that release of engineered nanoparticles could occur during production, handling, bagging and processing; however, these nanoparticles are mostly in the form of agglomerates > 0.1 μm (e.g., Yang *et al.*, 2012) and oftentimes are difficult to differentiate from background aerosols. And such difficulty arises especially with non-selective particle number measurement techniques. Evans *et al.* (2010) have shown that particle mass is the most practical monitoring metric for handling of carbon nanofiber, whereas particle number is often influenced by other nanoparticle sources. The aggregate form of nanoparticles, on the other hand, draws criticism on the arbitrary nature of limiting nanoparticle exposure to those with diameters less than 0.1 μm. In either case of incidental or engineered nanoparticles, it is clear that the workers are of highest exposure and hence health risk due to their frequent presence in close proximity to nanoparticle emission sources. As a result, the exposure assessment of nanoparticles plays a crucial role in developing strategies for risk reduction.

The most common dose or exposure metrics of nanoparticles include number, surface area and mass. The former two, in particular, are considered to be of more biological relevance than the mass. In search of the dose metric most relevant to lung inflammation, Wittmaack (2006) illustrated that particle number is a better dose metric than joint length (i.e., the product of particle number and mean size), active and geometric surface area. On the other hand, Oberdörster *et al.* (2005b) showed that particle surface area is a more appropriate dose metric for particles of different sizes but of the same chemistry. Yet, both studies acknowledged the importance of taking the surface toxicity into account in finding the best dose metric. In this regard, particle mass may not be an appropriate surrogate for surface area and toxicity because a few number of large particles can dominant the mass but contribute little to the surface area. However, the National Institute for Occupational Safety and Health (NIOSH) and other studies have recently proposed a number of mass-based occupational exposure limits (OELs) for carbon nanotube and nanofiber, TiO_2 and fullerene (Kuempel *et al.*, 2012; and references therein). This is because the toxicity and risk assessment studies were mostly conducted on a mass basis. It is important to note that an exposure metric relevant to a specific type of nanoparticles may not be applicable to another (Maynard and Aitken, 2007). Therefore, it has been recommended that all three particle metrics be determined or derived for assessing the health risk and exposure (Oberdörster *et al.*, 2005a; HSE, 2006).

Although largely in common, exposure assessment techniques and strategies for incidental nanoparticles have been summarized by Brouwer *et al.* (2004) and Chow and Watson (2007), whereas those for engineered nanoparticle by Maynard and Aitken (2007) and Kuhlbusch *et al.* (2011). As shown in those reviews, exposure assessment of nanoparticles thus far has focused mostly on the particle number and mass/composition, whereas measurements of particle surface area are still sparse (Brouwer *et al.*, 2004; Brouwer, 2010). In particular, the incidental nanoparticles in the metalworking industry are the focus of this study. Previous studies have shown that many metal preparation, product fabrication and finishing operations produce high number concentrations of nanoparticles exceeding 10^4–10^5 cm^{-3}, compared to background levels of 10^3–10^4 cm^{-3}. The observed mass concentrations of particles with sizes less than 10 μm (PM_{10}), 4 μm (PM_4) and 1 μm (PM_1) are in the range of 50–1130 $\mu g/m^3$, 10–120 $\mu g/m^3$, 15–196 $\mu g/m^3$, respectively. Examples include smelting, melting, pouring, molding, shakeout and fettling in iron foundry (Cheng *et al.*, 2008; Evans *et al.*, 2008; Elihn and Berg, 2009), and welding, soldering, laser cutting, plasma spraying and high-speed grinding and machining in metalworking plants (Zimmer and Biswas, 2001; Wake *et al.*, 2002; Zimmer and Maynard, 2002; Peters *et al.*, 2006; Demou *et al.*, 2009).

In the above cited field studies, most of the aerosol instruments are rather bulky and thus their applications are limited to fixed-position monitoring (also known as area, stationary or environmental monitoring). In addition, the nanoparticle exposure metrics reported in previous studies are limited to number and surface area, and none measured the mass concentrations of particles with sizes less than 0.1 μm ($PM_{0.1}$). More importantly, ambient nanoparticle concentrations may differ from that presumably inhaled by the workers. The potential inadequacy of fixed-position monitoring for determining worker exposures has been well documented by NIOSH (1977). As a result, personal sampling is the recommended approach to obtaining respresentativerepresentative exposure estimate of the workers. Not until recent years, a limited number of nanoparticle personal samplers have been developed. Personal thermophoretic and electrostatic precipitators have been used to collect nanoparticles for subsequent electron microscopic analysis (e.g., Azong-Wara *et al.*, 2009; Thayer *et al.*, 2011). Although morphology, size distribution and elemental composition can be determined, the nanoparticles collected by these precipitators are not sufficient for gravimetric or detailed chemical speciation. Using a series of two inertial filters for size separation, Furuuchi *et al.* (2010) have developed a relatively high-flow (6 L/min) personal sampler to collect particles with diameters less than 0.14 μm on filters for subsequent gravimetric analysis. Also with inertia filter, Hata *et al.* (2012) have described a modified Anderson cascade impactor capable to separate nanoparticles smaller than 0.07 μm at high-flow (28.3 L/min). More recently, Tsai *et al.* (2012) have developed a low-flow (2 L/min) nanoparticle personal sampler (PENS) for simultaneous collection of respirable particles and nanoparticles on filter substrates. As such, the PENS can be used to directly determine personal exposure to PM_4 and $PM_{0.1}$, between which the latter is nearly complete lacking. In addition, it presents an alternative exposure assessment technique to that proposed for engineered TiO_2 by NIOSH (2011), in which the size distribution has to be determined by transmission electron microscopy.

The operating principles, design and calibration of the PENS have been described by Tsai *et al.* (2012). According

to the presented laboratory results, the PENS is able to sample solid or liquid PM_4 and $PM_{0.1}$ simultaneously with good accuracy. Nevertheless, the PENS has not been evaluated in the actual workplace settings. The selection of the metalworking industry as the study area is mainly because the metalworking operations produce various types (solids, fumes and mists) of nanoparticles and the elevated nanoparticle concentrations would ensure sufficient particles collected for gravimetric analysis. With that in mind, this study aims to evaluate the performance of the newly developed PENS and subsequently determine the exposure characteristics of respirable particles and nanoparticles during selected metalworking operations.

METHODS

Personal Samplers

Two types of personal sampler were used in this study, the newly developed personal nanoparticle sampler (PENS) and the SKC respirable dust aluminum cyclone (Cat. No. 225-01-02, SKC Inc., PA, USA). The operating principles, design and calibration of the PENS have been described by Tsai *et al.* (2012). In brief, the PENS operates at a flow rate of 2 L/min using a constant-flow personal pump (AirChek XR5000, SKC Inc., PA, USA). It consists of three main parts: a respirable cyclone with the median cutoff aerodynamic diameter (d_{50}) of 4 μm, a rotating micro-orifice impactor with the d_{50} of 0.1 μm, and an after-filter cassette. As a result, the 0.1–4 μm particles and nanoparticles (< 0.1 μm) are collected on the impaction plate and after-filter, respectively. According to Tsai *et al.* (2012), the mass concentrations should be less than 1.8 and 3.3 mg/m^3 for the respirable particles and nanoparticles, respectively, to avoid the PENS from overloading and changes in d_{50}. Furthermore, the nanoparticle mass concentrations should be above 2 μg/m^3 to ensure accurate gravimetric analysis. The SKC cyclone meets the ACGIH/ISO/CEN collection efficiency curve at 2.5 L/min as specified in NIOSH Method 0600, thereby serves as the reference method in this study. Its d_{50} is 4 μm at the designated flow rate maintained by a constant-flow personal pump (Airchek PCXR4, SKC Inc., PA, USA). The respirable particles penetrating the SKC cyclone are collected with a filter cassette. In this study, the filter cassette was loaded with 37-mm PTFE filter (Teflo R2PL037, Pall Corp., NY, USA), whereas the impaction substrate of the PENS impactor was silicone-oil coated PTFE/aluminum filter. Before and after the sampling, the flow rates of the samplers were verified with a flow meter (tetraCal, BGI Inc., MA, USA). The average flow rates between the start and end of sampling for the PENS and SKC cyclone were 2.02 ± 0.05 and 2.51 ± 0.05 L/min, respectively.

Ambient Aerosol Spectrometer

The ambient particle number size distributions were measured with a sequential mobility particle sizer (SMPS; GRIMM Aerosol Technik, Gmbh, Germany, Model 5.500) (e.g., Heim *et al.*, 2004). The SMPS consists of an Am-241 neutralizer (Model 5.522), a medium Vienna-type differential mobility analyzer (M-DMA; Model 55-900) and a butanol-based condensation particle counter (CPC; Model 5.403). With the default set up, the inner electrode of the M-DMA is positively charged. The CPC has a 50% counting efficiency for particles as small as 0.0045 μm, with the saturator and condenser temperature of 40°C and 15°C, respectively. The SMPS was set to down-scan 1 min and 50 s from 10,000 V to 5 V plus a wait-time of 10 s, thus producing one average particle number size distribution every 2 min. The detectable aerosol mobility diameters ranged from 0.0055 to 0.3504 μm (44 size bins) with a sheath and sample flow of 3.0 and 0.3 L/min, respectively.

Metalworking Plants

Three metalworking plants were selected to characterize aerosol exposure during metal preparation and product fabrication, namely metal finishing, spot welding and metal milling. According to the nature of generated particles, the three operations nominally represent sources of three particle types: solid particles, metal fumes and oil-water mists, respectively. These aerosols provide different challenges to the samplers and spectrometer because, unlike oil mists, solid particles are more likely to bounce upon impaction, whereas metal fumes are known to exist in the form of agglomerates instead of individual spheres. Descriptions of the plants and operations are given below.

Metal Polishing and Buffing Plant

This workplace covers an area of approximately 10-m by 15-m, as part of a larger plant of 50-m by 90-m (Fig. 1). The polishing and buffing involve workers using high-speed hand-held wheels to remove the surface imperfections off the steel-made car body parts and then buffing them to a smoother finish. Two to three grades of abrasives were used during the process, from coarse to fine ones, made of semi-friable aluminum oxide and bonded by synthetic resin. The only engineering control measure was a local exhaust ventilation (LEV) hood that was positioned near the side of each worker at waist height. The dust control was rather ineffective because the hood was not placed in a position to receive polishing dusts on their projectiles. There were 6 workers during the day shift and all of them wore gloves, goggles and surgical facemasks.

Spot Welding Plant

This workplace covers an area of approximately 25-m by 50-m (Fig. 2). The welding involves fixing multiple hexagonal nuts on aluminum engine oil pans. The weld is made by localized heating at the joint due to the resistance of base metal to the electric current flow. At this plant, there was no LEV system in place to control fume emissions but general ventilation aided by centralized supply air and pedestal fans. Instead, the ventilation was intended to control heat stress during the warm seasons. There were 28 workers operating the welding machines during the day shift and all of them wore gloves, goggles and activated-carbon facemasks.

Metal Milling Plant

This workplace covers an area of approximately 15-m by 25-m. The milling is part of a series of processes that

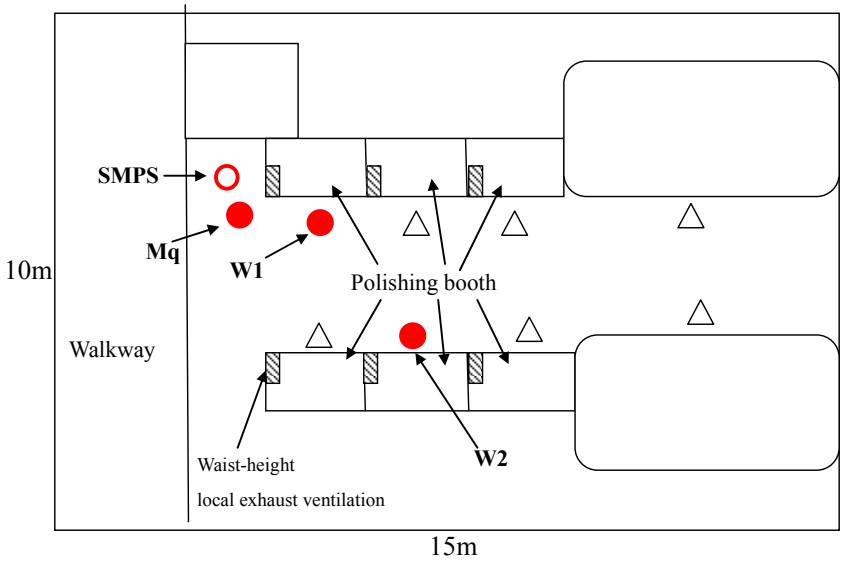

Fig. 1. Layout of the polishing operation plant. Solid circles represent workers (W) and mannequin (Mq) that wore the personal samplers, hallow circle shows the ambient air monitoring at fixed-location, and triangles represent other workers.

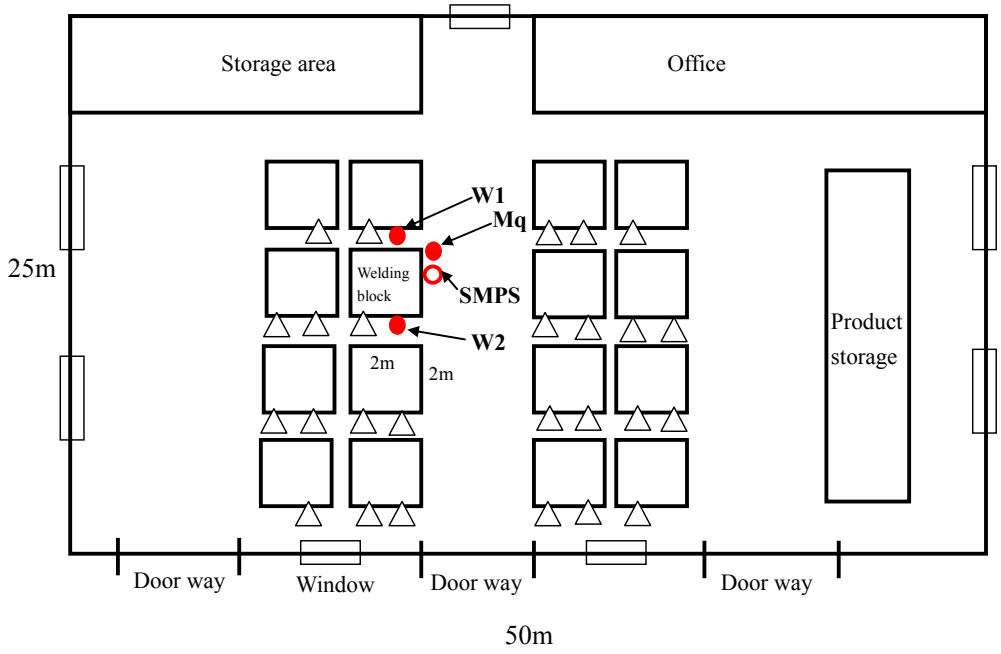

Fig. 2. Layout of the welding operation plant. The symbols are the same as Fig. 1.

machine aluminum alloy rods into camshafts for cars. During the process, water-mix metalworking fluid (MWF) is continuously sprayed onto the cutting interface to cool and lubricate and to wash away the metal debris. At this plant, the milling machines were operated manually and thus the workers were in close proximity to water-mix MWF mists. There was no LEV system in place to control mists but natural ventilation. There were 3 workers operating the milling machines during the day shift and all of them wear only surgical facemasks.

Sampling Strategy

The sampling strategy consists of workers' personal exposure measurements and fixed-location ambient air monitoring. The former specifically measures exposure in the worker's breathing zone, whereas the latter measures directly from the ambient air. In each plant, two workers (referred to as W1 and W2) at adjacent or nearby (distance within 3–5 m) workstation were selected for personal exposure measurement. In addition, a full-size mannequin (Mq) was placed statically as close as possible (within 1.5 m) to W1 to assess whether workers' movements would cause variations in the sampling results. The selection of workers was mainly constrained by the available room needed to set up the aerosol spectrometer. The W1, W2 and Mq each wore a pair of personal samplers (i.e., PENS and SKC side-

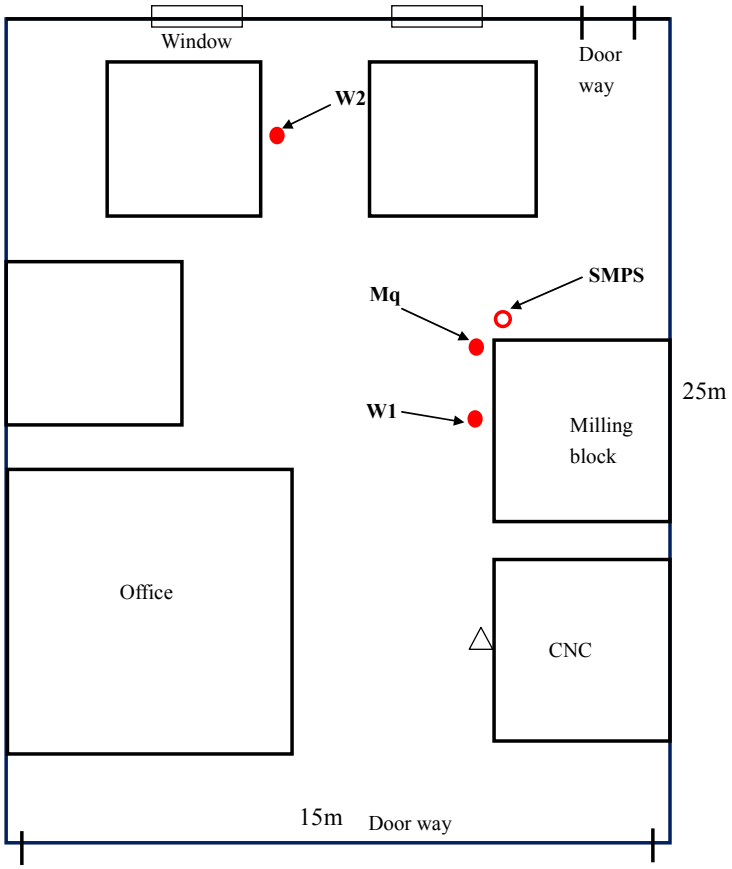

Fig. 3. Layout of the milling operation plant. The symbols are the same as Fig. 1.

by-side), attached to each side of the shirt collar. The aerosol spectrometer was placed as close as possible to the Mq (within 1.5 m), with the sampling inlet at a height of about 1.4 m.

The sampling duration of the personal and ambient air measurements covered the complete day shift of 6–8 hours, from about 8:00 to 17:00. In between short and lunch breaks, the personal samplers were taken off from the workers and then placed back on when the work resumed. The entire sampling strategy was carried out twice, over two consecutive days (D1 and D2), for each metal processing plant. As a result, we collected a total of 18 pairs (PENS and SKC) of personal samples, in which 12 were from the workers and 6 from the mannequin, and 1,346 particle number size distributions during the study.

Sample and Data Analysis

The impaction substrates and filters were conditioned at temperature of 23 ± 3°C and relative humidity of 40 ± 5% for at least 24 hours before weighing in the filter weighing room. In addition, an ionizing air blower (Model CSD-0911, Meisei, Japan) was used to neutralize the electrostatic charge of the filters. The pre- and post-weighing were carried out using a microbalance with a precision of 1 μg (Model CP2P-F, Sartorius, Germany). Because of the additional particle size cut, the respirable particle mass concentrations measured by the PENS (PENS-PM_4) were determined by summing the mass concentrations of 0.1–4 μm particles (PENS-$PM_{0.1–4}$) and < 0.1 μm nanoparticles (PENS-$PM_{0.1}$). The respirable particles measured by SKC are hereafter denoted as SKC-PM_4. In the present study, the SKC-PM_4 was used as the reference. Comparisons were made between the SKC-PM_4 and the corresponding PENS-PM_4 for examining the accuracy of PENS on collecting respirable particles in the field.

The number size distribution data obtained from the SMPS were first analyzed for outliers according to the quality control procedures proposed by Yu *et al.* (2004). In specific, the total number concentrations (TC) and the coefficient of variation (CV) were computed for each measured size distribution. Then the log(TC) versus log(CV) were plotted to reveal potential abnormal size distributions that deviated largely away from the main cloud of observations. In this study, only very small numbers of collected aerosol data (< 0.15%) were identified as outliers that typically occurred at the beginning of the instrument set up. Those outliers were not included in the data analysis. Following, size-fractionated number concentrations of nanoparticles (0.0055–0.1 μm) and total particles (0.0055–0.3504 μm) were determined. These particle number concentrations hereafter are denoted as $PN_{0.1}$ and $PN_{0.35}$, respectively. The average ratios of $PN_{0.1}$ to $PN_{0.35}$ were about 0.95 ± 0.03 during the work hours at the three metalworking plants. Unlike the respirable particles, there is currently no reference method for examining the accuracy of PENS on collecting nanoparticles in the field. In the present study, the measured particle number size

distributions were used to calculate the nanoparticle volume concentrations ($PV_{0.1}$) assuming spherical particles with mobility diameters between 0.0055–0.1 μm. And by dividing the PENS-$PM_{0.1}$ with the corresponding $PV_{0.1}$ (DeCarlo *et al.*, 2004), the derived nanoparticle effective density (ρ_{eff}) was used as an indicator for assessing the accuracy of PENS on collecting nanoparticles in the field.

RESULTS AND DISCUSSION

Assessing the Performance of the PENS

The personal exposure levels of PM_4 and $PM_{0.1}$ during two consecutive sampling days (D1 and D2) for the metal polishing/buffing (P), spot welding (W) and milling (M) are given in Table 1. The collected mass on the PENS impaction substrate and after-filter was in the range of 51.6–149.0 μg and 5.6–20.2 μg, respectively, whereas it was 70.7–179.0 μg for the SKC filters. As shown, the relative percentage difference (RPD) between the pairs of PENS-PM_4 and SKC-PM_4 ranged from –10.3% to 5.5%. The scatterplot of the pairs of PENS-PM_4 and SKC-PM_4 during the three metalworking operations is presented in Fig. 4. Regardless of the operation type, all the pairs of PM_4 fall along and in close proximity to the 1:1 line. The linear regression with the slope = 1.02 and the $R^2 = 0.98$ indicates that, on average, the difference between the two is only 2%. Considering the SKC-PM_4 as the reference, this shows that the PENS-PM_4 are of considerably accuracy. The RPD of the PM_4 between the W1 and the adjacent, static Mq (i.e., no movements) ranged from –11.9% to 20.2%, indicating that the workers' movements during metalworking operations likely did not cause substantial variations in the sampling results. In laboratory tests using liquid oleic acid and micro-sized aluminum oxide, Tsai *et al.* (2012) showed that the PENS-PM_4 agree well with that measured by the micro orifice uniform deposit impactor (MOUDI) and the IOSH respirable cyclone with the $R^2 = 0.97$. Because the three metalworking operations produce different types of particles, as described earlier, this highlights that the PENS is capable to accurately determine the personal exposure to solid, aggregate and liquid respirable particles in the real workplace settings.

Unlike the respirable particles, there is currently no reference method for personal exposure measurements of nanoparticles. As a result, the aerosol spectrometer SMPS

Table 1. Personal exposure to respirable particle (PM_4) and nanoparticle ($PM_{0.1}$) mass concentrations from paired PENS/SKC samplers during metal polishing, welding and milling.

ID*	Particle mass concentration (μg/m^3)				RPD** (%)
	SKC-PM_4	PENS-PM_4	PENS-$PM_{0.1–4}$	PENS-$PM_{0.1}$	
Polishing					
P-D1-W1	117.1	117.2	105.6	11.6	0.0
P-D1-W2	96.9	100.6	90.0	10.7	3.7
P-D1-Mq	109.3	110.4	101.9	8.5	1.1
P-D2-W1	137.8	141.0	129.0	12.0	2.3
P-D2-W2	127.9	126.7	117.5	9.2	–0.9
P-D2-Mq	143.0	130.6	119.7	10.9	–9.4
P-average	122.0	121.1	110.6	10.5	–0.5
P-SD	17.5	14.6	14.1	1.3	4.6
Welding					
W-D1-W1	102.2	103.8	86.0	17.8	1.5
W-D1-W2	107.0	108.9	85.0	23.9	1.7
W-D1-Mq	101.1	91.7	82.9	8.7	–10.3
W-D2-W1	196.7	185.4	163.8	21.6	–6.1
W-D2-W2	128.5	120.0	105.7	14.3	–7.1
W-D2-Mq	141.2	139.7	117.8	21.9	–1.1
W-average	129.5	124.9	106.9	18.1	–3.5
W-SD	36.6	33.8	31.1	5.7	5.0
Milling					
M-D1-W1	100.8	102.1	78.0	24.1	1.3
M-D1-W2	84.9	89.8	73.5	16.3	5.5
M-D1-Mq	94.4	97.2	72.8	24.4	2.8
M-D2-W1	83.9	85.5	76.9	8.6	1.9
M-D2-W2	89.8	85.4	77.0	8.3	–5.2
M-D2-Mq	73.3	76.7	66.8	9.9	4.4
M-average	87.9	89.5	74.2	15.3	1.8
M-SD	9.5	9.1	4.2	7.5	3.8

*D1 and D2 refer to sampling day-1 and day-2, respectively; W1 and W2 refer to worker-1 and worker-2, respectively; Mq refers to the mannequin.

**Relative percentage difference between SKC-PM_4 and PENS-PM_4, defined as the difference divided by the average of the two.

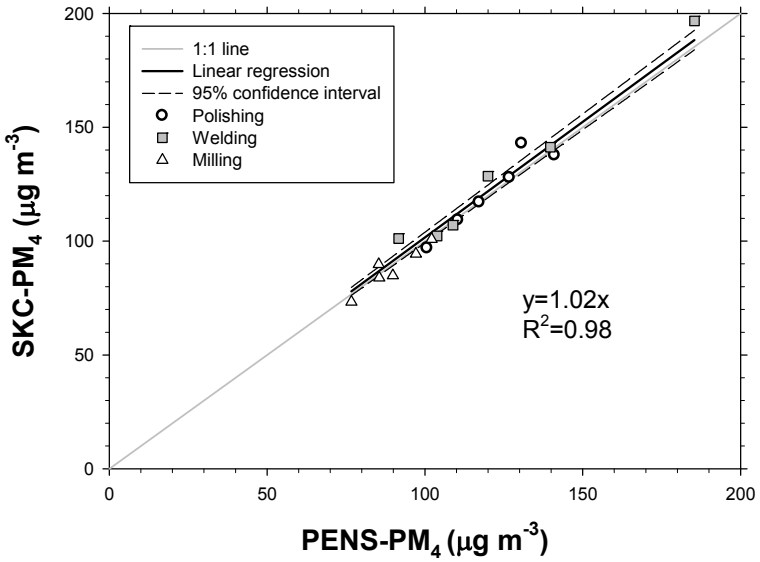

Fig. 4. Scatterplot and regression of respirable particle mass concentrations (PM_4) measured by the paired PENS/SKC personal samplers at the three metalworking plants.

was placed within 1 m next to the Mq, intended to measure the particle number size distributions and subsequently derive other nanoparticle exposure metrics. Table 2 gives the measured daily averages of ambient nanoparticle number concentrations ($PN_{0.1}$), volume concentrations ($PV_{0.1}$), nano-to-total particle volume concentration ratios ($PV_{0.1}/PV_{0.35}$) and derived nanoparticle effective density (ρ_{eff}) by the SMPS at a fixed-location during the three metalworking operations. The $PV_{0.1}$ and $PV_{0.35}$ were estimated assuming the measured particles were spheres, in which the $PV_{0.35}$ is the measured total particle volume concentration with an upper size limit of 0.35 μm. The ρ_{eff} were determined using the ambient $PV_{0.1}$ and the $PM_{0.1}$ taken from the Mq. As shown, the ρ_{eff} fall in the range of 0.94–3.51 g/cm^3 for the nanoparticles generated during the three metalworking operations. In the polishing and buffing operations, the nanoparticles could be formed by the combustion of the substrate or the volatilization of the materials at the grinding wheel (Zimmer and Maynard, 2002). The bulk densities of the steel substrate and aluminum oxide grinding material are about 7.9 and 4 g/cm^3, respectively. In the welding operation, the fumes were found to have bulk densities in the range of 3.4–5.9 g/cm^3 (Olander, 1985; Hewett, 1995). In the milling operation, the water-mix MWF mist is likely to have a bulk density of about 1 g/cm^3. Despite the potential uncertainties, the ratios of the expected bulk densities to the derived ρ_{eff} are within a factor of 0.4–3.3, with the exception for the polishing particles on Day 1 (Polish-D1) with which the ratio was 8.4. If there were particle bounce, these ratios would be substantially smaller than unity because of the "additional" particle mass and hence overestimated ρ_{eff}. On the other hand, the large ratios (> 2.3) for the solid metal particles and fume aggregates from polishing and welding, respectively, suggest that the particles were indeed non-spherical. This in turn indicates that the differences between the expected bulk density and ρ_{eff} (i.e., large ratios) may be overestimated because the ρ_{eff}, as expected, should be smaller than the bulk density for irregularly shaped particles. These results indicate that the PENS-$PM_{0.1}$ were within a reasonable range of estimated values, and there was little indication of particle bounce.

Personal Exposure Levels of PM_4 and $PM_{0.1}$

The following exposure description is limited to the PENS results to avoid repetition because the differences are negligible between the PENS and SKC as shown previously. Table 1 shows that the average PM_4 during polishing and welding were similar of 122.0 and 129.5 μg/m^3, respectively, and the PM_4 was lower of 87.9 μg/m^3 during milling. These observed PM_4 values are lower or comparable to that from earlier studies of similar metalworking operations. In a steel resistance spot welding area, Dasch and D'Arcy (2008) reported that the ambient average $PM_{2.5}$ was 250 μg/m^3. Also, Elihn and Berg (2009) showed the ambient average PM_1 was 280 μg/m^3 during steel spot welding, in which there was good general ventilation but with other welding activities nearby. The PM_4 of 460 μg/m^3 in the breathing zone of a shielded metal arc welder has been reported by Stephenson *et al.* (2003). More recently, a study of 215 welders showed the personally exposed median PM_4 was 1290 μg/m^3 during gas metal arc welding with solid wire, flux-cored wire, tungsten inert gas welding, and shielded metal arc welding (Lehnert *et al.*, 2012). A survey of occupational exposure to MWF in the engineering industry showed that the water-mix MWF mist in 298 measurements yielded a geometrical mean of 130 μg/m^3 (Simpson *et al.*, 2003). Among those measurements, they showed that milling produced lower concentrations of water-mix MWF mist with a geometric mean of 80 μg/m^3, compared with drilling, grinding and sawing. In a personal exposure study, the average respirable dust of 780 μg/m^3 was measured in 10 metal workshops using water miscible WMFs (Suuronen *et al.*, 2008). Highest oil mist exposure has been reported for threading workers in fastener manufacturing industry (e.g.,

Table 2. Daily average ambient nanoparticle number ($PN_{0.1}$), volume ($PV_{0.1}$) concentrations, volume concentration ratios ($PV_{0.1}/PV_{0.35}$) and derived nanoparticle effective density (ρ_{eff}).

	$PN_{0.1}$ (10^4 cm^{-3})	$PV_{0.1}$ ($\mu m^3/cm^3$)	$PV_{0.1}/PV_{0.35}$	ρ_{eff} (g/cm^3)
Polish-D1	25.3	9.01	0.16	0.94
Polish-D2	17.3	3.10	0.19	3.51
Weld-D1	85.5	4.83	0.22	1.81
Weld-D2	146.9	9.56	0.44	2.30
Mill-D1	164.6	9.25	0.45	2.64
Mill-D2	106.4	8.88	0.47	1.12

Hsu *et al.*, 2012). The PENS-$PM_{0.1}$ of 18.1 μg/m^3 was highest during welding, followed by that of 15.3 μg/m^3 during milling and lowest of 10.5 μg/m^3 during polishing. These $PM_{0.1}$ levels are considered quite high, given the very small sizes and hence mass of nanoparticles and in comparison to $PM_{0.1}$ levels of less than 5 μg/m^3 measured in urban and roadside air (e.g., Geller *et al.*, 2002; Ning *et al.*, 2007).

Relationship and Exposure Variability of PM_4 and $PM_{0.1}$

The relationships between the PM_4 and its two mass fractions (i.e., $PM_{0.1-4}$ and $PM_{0.1}$) measured by the PENS during the three metalworking operations are shown in Fig. 5. The linear regression between the PM_4 and $PM_{0.1-4}$ shows that, on average, 85 ± 1% of respirable particles was composed of particles in the size range of 0.1–4 μm, regardless of the operation types (R^2 = 0.95; Fig. 5(a)). However, such strong linear relationship dropped considerably for that between the PM_4 and $PM_{0.1}$ (R^2 = 0.09, now shown). Interestingly, a closer examination shows that the above relationship changes with respect to the type of operation, i.e., operation-specific (Fig. 5(b)). During polishing and welding, the linear relationships between the PM_4 and $PM_{0.1}$ dropped considerably to $R^2 < 0.28$. On the other hand, the $PM_{0.1}$ during milling were highly correlated with the PM_4 with the R^2 = 0.79. This indicates that when the formation mechanism of nanoparticles is different from that of larger particles (> 0.1 μm), the mass concentrations of the two types of particles could be unrelated. Such condition could be applicable to polishing and welding, where nanoparticles are formed via gas-to-particle conversion due to the high temperature involved, whereas larger particles are formed by mechanical attrition or welding spatter (Zimmer and Maynard, 2002; Zimmer *et al.*, 2002). In the contrary, the formation of nanoparticles as well as larger particles during milling is likely similar, both related to the mechanical breakup of the MWFs due to high shear forces.

The correlation coefficients (r) of the PENS-measured PM_4 and $PM_{0.1}$ between the workers (W1 and W2) and the mannequin (Mq) are given in Table 3. It is important to note that the distances between W1 and W2 are within 3–5 m while between W1 and Mq are within 1.5 m. With respect to the PM_4, the highest r of 0.95 was between the Mq and W1, followed by that of 0.85 between the Mq and W2 and the lowest of 0.79 between the W1 and W2. This shows that the r decreased with increasing distance to the W1. Similar trend was observed for the $PM_{0.1}$, although the r values were higher (> 0.94) between the Mq and W1/W2 and the decrease of r from 0.98 to 0.64 was slightly larger. In general, this suggests that the respirable particles as well as the nanoparticles exhibit small spatial variability within a distance of about 3 m and thus small person-to-person exposure variability. For individual workers and the mannequin, the PM_4 however showed poor correlations (0.06–0.34) with the $PM_{0.1}$, indicating that it is inappropriate to use the PM_4 as a surrogate for $PM_{0.1}$ and vice versa.

Ambient Nanoparticle Number Concentration and Size Distribution

Fig. 6 shows examples of the measured ambient particle number size distributions, total particle number concentrations ($PN_{0.35}$) and geometric mean diameters (GMD) during a work shift of metal polishing/buffing, spot welding and milling. The color contour plot clearly illustrates that all three metalworking operations produced considerably high levels of $PN_{0.35}$, with the dominant GMD in the range of 10–30 nm. The sudden drops of $PN_{0.35}$ coincided with short and noon rest hours. In addition, there were significant differences in the $PN_{0.35}$ and the dominant GMD between work and rest hours. Contributing more than 95% of the $PN_{0.35}$, the $PN_{0.1}$ during work and rest hours at the three workplaces are compared in Fig. 7. The $PN_{0.1}$ were slightly lower in the range of 10^5–10^6 cm^{-3} during polishing/buffing, whereas they were higher and comparable in the range of 10^5–10^7 cm^{-3} during welding and milling. These levels during work hours were 1–2 orders of magnitude higher than that of 10^4–10^5 cm^{-3} during rest hours. The GMD for metal polishing/buffing were mostly in the range of 0.02–0.03 μm, whereas they were in the range of 0.01–0.02 μm for welding and milling. These results show that mechanical processes such as polishing/buffing and even milling are capable to produce high levels of $PN_{0.1}$, consistent with earlier studies. For example, Zimmer and Maynard (2002) showed that high-speed hand-held grinding of steel substrate yielded an average $PN_{0.1}$ of 8.0×10^4 cm^{-3} and count median diameter of 0.01 μm. Similarly, earlier studies have found grinding activities can significant impact the ambient particle number concentration (Brouwer *et al.*, 2004; Elihn and Berg, 2009). The $PN_{0.1}$ levels for spot welding are comparable to that observed for gas metal and flux cored arc welding, but the particle mode diameters are considerably smaller than the prominent particle mode diameters between 0.1–0.36 μm during the latter two welding operations (Zimmer and Biswas, 2001; Lee *et al.*, 2006; Lehnert *et al.*, 2012).

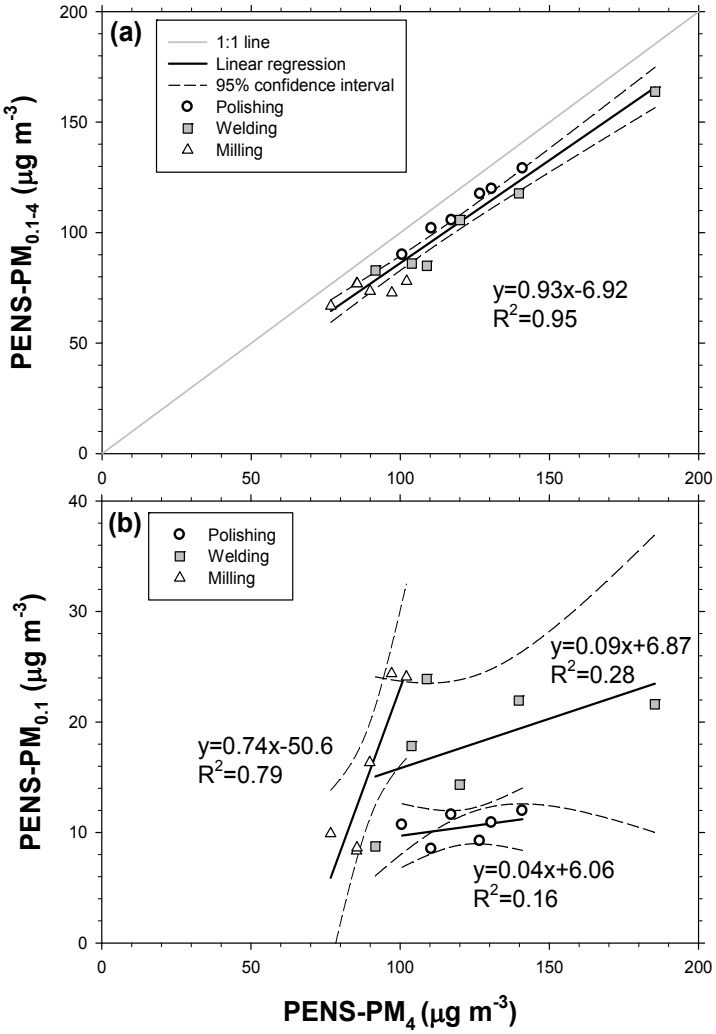

Fig. 5. Relationships between the respirable particles (PM_4) and (a) 0.1–4 μm particle ($PM_{0.1–4}$), and (b) nanoparticle ($PM_{0.1}$) mass concentrations measured by the PENS personal samplers at the three metalworking plants.

Table 3. Correlation matrix of the PENS-measured respirable particle (PM_4) and nanoparticle ($PM_{0.1}$) mass concentrations between the workers (W1 and W2, within a distance of 3–5 m) and the mannequin (Mq, within a distance of 1.5 m to W1).

	PM_4-W1	PM_4-W2	PM_4-Mq	$PM_{0.1}$-W1	$PM_{0.1}$-W2	$PM_{0.1}$-Mq*
PM_4-W1	1.00					
PM_4-W2	0.79	1.00				
PM_4-Mq	0.95	0.85	1.00			
$PM_{0.1}$-W1	0.34	0.09	0.26	1.00		
$PM_{0.1}$-W2	–0.07	0.06	–0.17	0.64	1.00	
$PM_{0.1}$-Mq*	0.34	0.00	0.22	0.98	0.94	1.00

*One single entry of $PM_{0.1}$ for the W-D1-Mq was not included in the analysis because it was a possible outlier.

Relationship between Personal and Fixed-Location Sampling

The relationships between the ambient nanoparticle exposure metrics and the PENS-$PM_{0.1}$ are shown in Table 4. As shown, the personal exposure to $PM_{0.1}$ was strongly correlated with the ambient $PN_{0.1}$ (r = 0.81). However, the correlation between the $PM_{0.1}$ and $PV_{0.1}$ dropped significantly to r = 0.49. The former suggests that the nanoparticles were generally of similar sizes, consistent with the dominant particle modes of GMD observed between 10–30 nm (Fig. 7), and the latter indicates that the assumption of spherical particle shape is inaccurate. This may be especially true for welding fumes that typically exist as aggregates; unfortunately, the limited number of personal samples did not allow us to analyze the data separately for different types of particles. In addition, the discrepancy between instruments is expected because the PENS classifies particles based on their aerodynamic properties whereas the SMPS based on

electrical mobility. After normalizing the $PV_{0.1}$ with respect to $PV_{0.35}$, the correlation between the particle volume ratio (i.e., $PV_{0.1}/PV_{0.35}$) and the $PM_{0.1}$ improved to r = 0.68. The correlation shows that the relative amount of $PV_{0.1}$, as opposed to the absolute amount, is moderately correlated with the $PM_{0.1}$. This again indicates that the PENS-$PM_{0.1}$ are

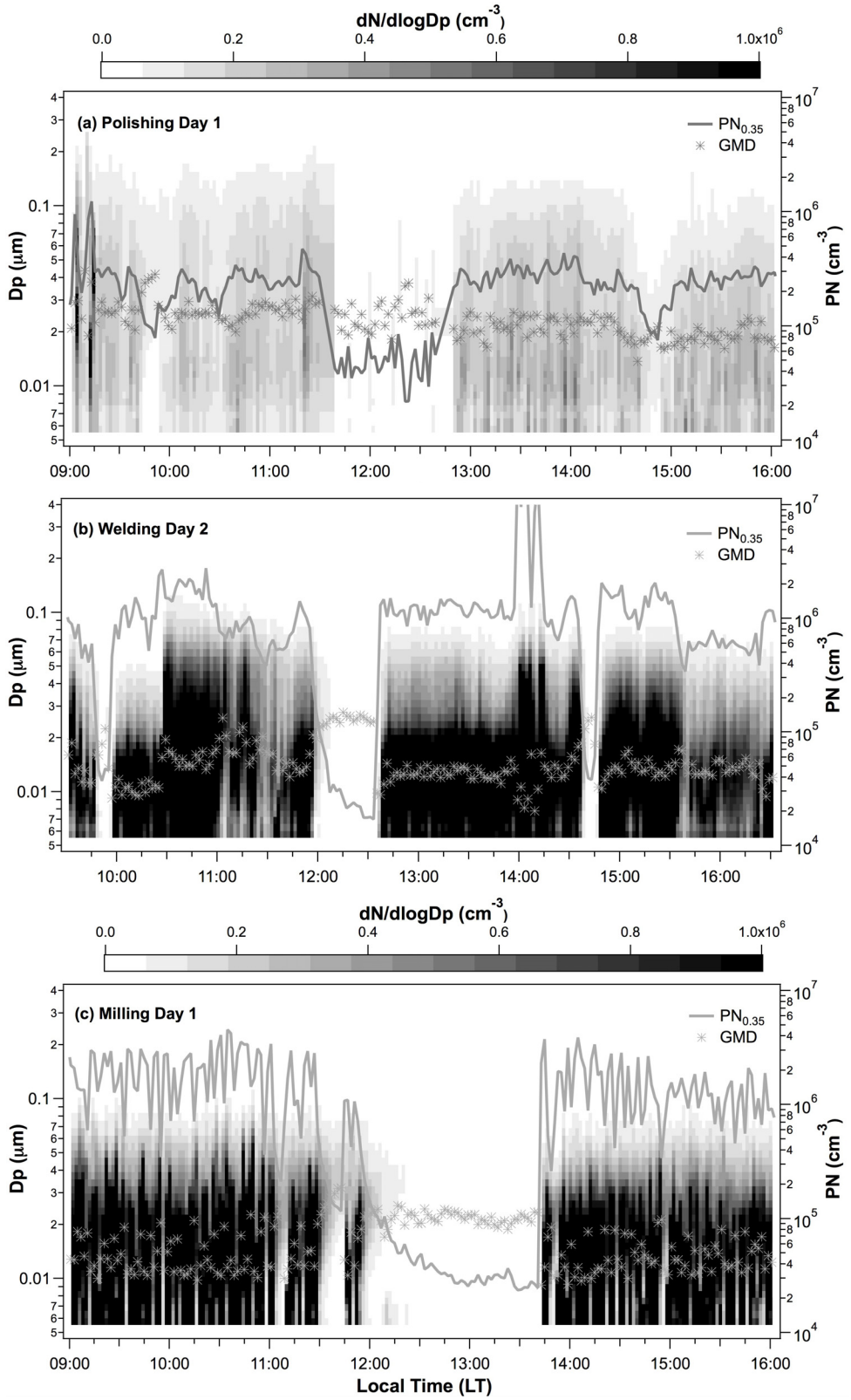

Fig. 6. Examples of the measured ambient particle number size distributions, total particle number concentrations ($PN_{0.35}$) and geometric mean diameters (GMD) during metal (a) polishing, (b) welding and (c) milling.

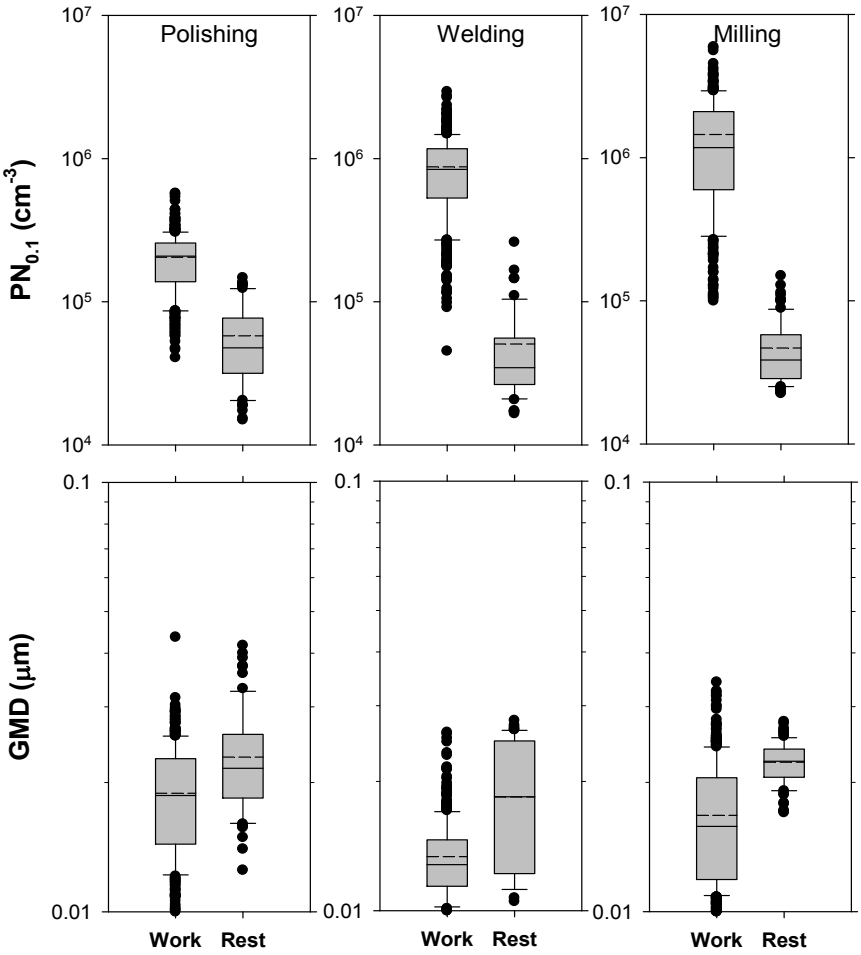

Fig. 7. Ambient nanoparticle number concentrations ($PN_{0.1}$) during work and rest periods of metalworking operations, measured by the SMPS at a fixed point in close proximity (within 1.5 m) to the mannequin.

Table 4. Correlation matrix between the PENS-measured nanoparticle mass concentrations ($PM_{0.1}$) and the SMPS-measured ambient nanoparticle number ($PN_{0.1}$), volume ($PV_{0.1}$) concentrations and volume concentration ratios ($PV_{0.1}/PV_{0.35}$).

	$PM_{0.1}$	$PN_{0.1}$	$PV_{0.1}$	$PV_{0.1}/PV_{0.35}$
$PM_{0.1}$	1.00			
$PN_{0.1}$	0.81	1.00		
$PV_{0.1}$	0.49	0.60	1.00	
$PV_{0.1}/PV_{0.35}$	0.68	0.89	0.64	1.00

in a reasonable range of estimated values, consistent with the ρ_{eff} results. Overall, the above results imply that, in the case when the nanoparticles dominate the ambient particle number, the nanoparticle number concentration could give a reasonable estimate of the nanoparticle mass concentration.

CONCLUSIONS

This study deployed and evaluated a newly developed personal nanoparticle sampler (PENS) to simultaneously assess personal exposure to respirable particles and nanoparticles during three metalworking operations. The PENS measured PM_4 showed remarkable consistency and accuracy with that measured by the conventional SKC respirable dust aluminum cyclone regardless of the particle types under study. Using the $PM_{0.1}$ and estimated nanoparticle volume concentration ($PV_{0.1}$) by a collocated aerosol spectrometer, the derived nanoparticle effective densities are in a reasonable range of expected values. Accordingly, these results suggest that the PENS is capable to accurately determine personal exposure to solid, aggregate and liquid respirable particles and also provide a reasonable estimate of the personal exposure to nanoparticles in the actual workplace settings.

The PM_4, as expected, are strongly correlated with the $PM_{0.1–4}$ but poorly with the $PM_{0.1}$. However, a closer examination shows that their relationships could improve when assessed on the basis of individual operations. For example, the $PM_{0.1}$ correlated strongly with the PM_4 during milling, but not so during polishing/buffing and spot welding. The relationship between PM_4 and $PM_{0.1}$ therefore depends on the operation types, or more accurately the formation mechanisms of 0.1–4 μm respirable particles and nanoparticles. Different mechanisms would likely lead to poor relationship. On the other hand, the moderate to strong correlations of PM_4 and $PM_{0.1}$ between workers

suggest that the respirable and nanoparticles exhibit small spatial variability within a distance of about 3 m. For individual workers and the mannequin, the PM_4 however showed poor correlations with the $PM_{0.1}$, indicating that it is inappropriate to use the PM_4 as a surrogate for $PM_{0.1}$ and vice versa. To the contrary, the ambient $PN_{0.1}$ from collocated aerosol spectrometer appears to be a better surrogate for $PM_{0.1}$ than the $PV_{0.1}$ and $PV_{0.1}/PV_{0.35}$. The strong correlation between $PM_{0.1}$ and $PN_{0.1}$ is mainly due to the persistent nanoparticle mode sizes and elevated concentrations formed during the metal polishing/buffing, welding and milling. With that being said, it is important to note that our observations may not hold true universally, especially in the cases where there are various nanoparticle emission sources and/or process-generated nanoparticles vary largely across sizes and concentrations.

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DISCLAIMER

Reference to any specific commercial products, process, service, manufacturer, or company does not constitute endorsement or recommendation by the Institute of Occupational Safety and Health (IOSH), Taiwan, R.O.C.

REFERENCES

Azong-Wara, N., Asbach, C., Stahlmecke, B., Fissan, H., Kaminski, H., Plitzko, S. and Kuhlbusch, T.A.J. (2009). Optimisation of a Thermophoretic Personal Sampler for Nanoparticle Exposure Studies. *J. Nanopart. Res.* 11: 1611–1624.

Brouwer, D. (2010). Exposure to Manufactured Nanoparticles in Different Workplaces. *Toxicology* 269: 120–127.

Brouwer, D.H., Gijsbers, J.H.J. and Lurvink, M.W.M. (2004). Personal Exposure to Ultrafine Particles in the Workplace: Exploring Sampling Techniques and Strategies. *Ann. Occup. Hyg.* 48: 439–453.

Cheng, Y.H., Chao, Y.C., Wu, C.H., Tsai, C.J., Uang, S.N. and Shih, T.S. (2008). Measurements of Ultrafine Particle Concentrations and Size Distribution in an Iron Foundry. *J. Hazard. Mater.* 158: 124–130.

Cheng, Y.H., Chang, H.P. and Yan, J.W. (2012). Temporal Variations in Airborne Particulate Matter Levels at an Indoor Bus Terminal and Exposure Implications for Terminal Workers. *Aerosol Air Qual. Res*. 12: 30–38.

Chow, J.C. and Watson, J.G. (2007). Review of Measurement Methods and Compositions for Ultrafine Particles. *Aerosol Air Qual. Res*. 7: 121–173.

Dasch, J. and D'Arcy, J. (2008). Physical and Chemical Characterization of Airborne Particles from Welding Operations in Automotive Plants. *J. Occup. Environ. Hyg.* 5: 444–454.

DeCarlo, P.F., Slowik, J.G., Worsnop, D.R., Davidovits, P. and Jimenez, J.L. (2004). Particle Morphology and Density Characterization by Combined Mobility and Aerodynamic Diameter Measurements. Part 1: Theory. *Aerosol Sci. Technol.* 38: 1185–1205.

Demou, E., Mutamba, G., Wyss, F. and Hellweg, S. (2009). Exposure to PM_1 in a Machine Shop. *Indoor Built Environ.* 18: 514–523.

Donaldson, K., Tran, L., Jimenez, L.A., Duffin, R., Newby, D.E., Mills, N., MacNee, W. and Stone, V. (2005). Combustion-Derived Nanoparticles: A Review of Their Toxicology Following Inhalation Exposure. *Part. Fibre Toxicol.* 2: 10, doi: 10.1186/1743-8977-2-10.

Elihn, K. and Berg, P. (2009). Ultrafine Particle Characteristics in Seven Industrial Plants. *Ann. Occup. Hyg.* 53: 475–484.

Evans, D.E., Heitbrink, W.A., Slavin, T.J. and Peters, T.M. (2008). Ultrafine and Respirable Particles in an Automotive Grey Iron Foundry. *Ann. Occup. Hyg.* 52: 9–21.

Evans, D.E., Ku, B.K., Birch, M.E. and Dunn, K.H. (2010). Aerosol Monitoring during Carbon Nanofiber Production: Mobile Direct-Reading Sampling. *Ann. Occup. Hyg.* 54: 514–531.

Furuuchi, M., Eryu, K., Nagura, M., Hata, M., Kato, T., Tajima, N., Sekiguchi, K., Ehara, K., Seto, T. and Otani, Y. (2010). Development and Performance Evaluation of Air Sampler with Inertial Filter for Nanoparticle Sampling. *Aerosol Air Qual. Res*. 10: 185–192.

Geller, M., Kim, S., Misra, C., Sioutas, C., Olson, B. and Marple, V. (2002). A Methodology for Measuring Size-Dependent Chemical Composition of Ultrafine Particles. *Aerosol Sci. Technol.* 36: 748–762.

Hata, M., Linfa, B., Otani, Y. and Furuuchi, M. (2012). Performance Evaluation of an Anderson Cascade Impactor with an Additional Stage for Nanoparticle Sampling. *Aerosol Air Qual. Res*. 12: 1041–1048.

Heim, M., Kasper, G., Reischl, G.P. and Gerhart, C. (2004). Performance of a New Commercial Electrical Mobility Spectrometer. *Aerosol Sci. Technol.* 38: 3–14.

Hewett, P. (1995). The Particle Size Distribution, Density, and Specific Surface Area of Welding Fumes from SMAW and GMAW Mild and Stainless Steel Consumables. *Am. Ind. Hyg. Assoc. J.* 56: 128–135.

HSE (2006). The Assessment of Different Metrics of the Concentration of Nano (Ultrafine) Particles in Existing and New Industries, RR513 Research Report, Health and Safety Executive, UK.

Hsu, H.I., Chen, M.R., Wang, S.M., Chen, W.Y., Wang, Y.F., Young, L.H., Huang, Y.S., Yoon, C.S. and Tsai, P.J. (2012). Assessing Ling-Term Oil Mist Exposures for Workers in a Fastener Manufacturing Industry Using the Bayesian Decision Analysis Technique. *Aerosol Air Qual. Res*. 12: 834–842.

ICRP (1994). Human Respiratory Tract Model for Radiological Protection, Pub. No. 66, In *Annals of the ICRP*, Smith H, (Ed.), International Commission on Radiological Protection, Tarrytown, NY, USA.

Kuempel, E.D., Geraci, C. and Schulte, P.A. (2012). Risk Assessment and Risk Management of Nanomaterials in

the Workplace: Translating Research to Practice. *Ann. Occup. Hyg.* 56: 491–505.

Kuhlbusch, T.A.J., Asbach, C., Fissan, H., Göhler, D. and Stintz, M. (2011). Nanoparticle Exposure at Nanotechnology Workplaces: A Review. *Part. Fibre Toxicol.* 8: 22.

Lee, M.H., McClellan, W.J., Candela, J., Andrews, D. and Biswas, P. (2006). Reduction of Nanoparticle Exposure to Welding Aerosols by Modification of the Ventilation System in a Workplace. *J. Nanopart. Res.* 9: 127–136.

Lehnert, M., Pesch, B., Lotz, A., Pelzer, J. and Kendzia, B. (2012). Exposure to Inhalable, Respirable, and Ultrafine Particles in Welding Fume. *Ann. Occup. Hyg.* 56: 557–567.

Maynard, A.D. and Aitken, R.J. (2007). Assessing Exposure to Airborne Nanomaterials: Current Abilities and Future Requirements. *Nanotoxicology* 1: 26–41.

Nel, A. (2006). Toxic Potential of Materials at the Nanolevel. *Science* 311: 622–627.

Ning, Z., Geller, M.D., Moore, K.F., Sheesley, R., Schauer, J.J. and Sioutas, C. (2007). Daily Variation in Chemical Characteristics of Urban Ultrafine Aerosols and Inference of Their Sources. *Environ. Sci. Technol.* 41: 6000–6006.

NIOSH (1977). Occupational Exposure Sampling Strategy Manual, Department of Health, Education, and Welfare, Pub. No. 77-173, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.

NIOSH (2011). Current Intelligence Bulletins 63: Occupational Exposure to Titanium Dioxide. Department of Human Health and Services, Pub. No. 2011–160, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.

Oberdörster, G., Maynard, A., Donaldson, K., Castranova, V., Fitzpatrick, J., Ausman, K., Carter, J., Karn, B., Kreyling, W. and Lai, D. (2005a). Principles for Characterizing the Potential Human Health Effects from Exposure to Nanomaterials: Elements of a Screening Strategy. *Part. Fibre Toxicol.* 2: 8, doi: 10.1186/1743-8977-2-8.

Oberdörster, G., Oberdörster, E. and Oberdörster, J. (2005b). Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles. *Environ. Health Perspect.* 113: 823–839.

Olander, L. (1985). Welding Fume Buoyant Plume. *Aerosol Sci. Technol.* 4: 351–358.

Peters, T., Heitbrink, W.A., Evans, D.E., Slavin, T.J. and Maynard, A.D. (2006). The Mapping of Fine and Ultrafine Particle Concentrations in an Engine Machining and Assembly Facility. *Ann. Occup. Hyg.* 50: 249–257.

Simpson, A.T., Stear, M., Groves, J.A., Piney, M., Bradley, S.D., Stagg, S. and Crook, B. (2003). Occupational Exposure to Metalworking Fluid Mist and Sump Fluid Contaminants. *Ann. Occup. Hyg.* 47: 17–30.

Stephenson, D., Seshadri, G. and Veranth, J.M. (2003). Workplace Exposure to Submicron Particle Mass and Number Concentrations From Manual Arc Welding of Carbon Steel. *Am. Ind. Hyg. Assoc. J.* 64: 516–521.

Suuronen, K., Henriks-Eckerman, M.L., Riala, R. and Tuomi, T. (2008). Respiratory Exposure to Components of Water-Miscible Metalworking Fluids. *Ann. Occup. Hyg.* 52: 607–614.

Thayer, D., Koehler, K.A., Marchese, A. and Volckens, J. (2011). A Personal, Thermophoretic Sampler for Airborne Nanoparticles. *Aerosol Sci. Technol.* 45: 744–750.

Tsai, C.J., Liu, C.N., Hung, S.M., Chen, S.C., Uang, S.N., Cheng, Y.S. and Zhou, Y. (2012). Novel Active Personal Nanoparticle Sampler for the Exposure Assessment of Nanoparticles in Workplaces. *Environ. Sci. Technol.* 46: 4546–4552.

Vincent, J.H. and Clement, C.F. (2000). Ultrafine Particles in Workplace Atmospheres. *Philos. Trans. R. Soc. London, Ser. A* 358: 2673–2682.

Wake, D., Mark, D. and Northage, C. (2002). Ultrafine Aerosols in the Workplace. *Ann. Occup. Hyg.* 46: 235–238.

Wittmaack, K. (2006). In Search of the Most Relevant Parameter for Quantifying Lung Inflammatory Response to Nanoparticle Exposure: Particle Number, Surface Area, or What? *Environ. Health Perspect.* 115: 187–194.

Xia, T., Li, N. and Nel, A.E. (2009). Potential Health Impact of Nanoparticles. *Annu. Rev. Publ. Health* 30: 137–150.

Yang, Y., Mao, P., Wang, Z.P. and Zhang, J.H. (2012). Distribution of Nanoparticle Number Concentrations at a Nano-TiO_2 Plant. *Aerosol Air Qual. Res*. 12: 934–940.

Young, L.H., Liou, Y.J., Cheng, M.T., Lu, J.H., Yang, H.H., Tsai, Y.I., Wang, L.C., Chen, C.B. and Lai, J.S. (2012). Effects of Biodiesel, Engine Load and Diesel Particulate Filter on Nonvolatile Particle Number Size Distributions in Heavy-Duty Diesel Engine Exhaust. *J. Hazard. Mater.* 199–200: 282–289.

Yu, R.C., Teh, H.W., Jaques, P.A., Sioutas, C. and Froines, J.R. (2004). Quality Control of Semi-Continuous Mobility Size-Fractionated Particle Number Concentration Data. *Atmos. Environ.* 38: 3341–3348.

Zimmer, A.T. and Biswas, P. (2001). Characterization of the Aerosols Resulting from Arc Welding Processes. *J. Aerosol Sci.* 32: 993–1008.

Zimmer, A.T. and Maynard, A.D. (2002). Investigation of the Aerosols Produced by a High-Speed, Hand-Held Grinder Using Various Substrates. *Ann. Occup. Hyg.* 46: 663–672.

Zimmer, A.T., Baron, P.A. and Biswas, P. (2002). The Influence of Operating Parameters on Number-Weighted Aerosol Size Distribution Generated from a Gas Metal Arc Welding Process. *J. Aerosol Sci.* 33: 519–531.

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