Characterization of ambient particles size in workplace of manufacturing physical fitness equipments

Chih-Chung LIN², Mei-Ru CHEN³, Sheng-Lang CHANG¹, Wei-Heng LIAO¹ and Hsiu-Ling CHEN¹*

¹Institute of Occupational Safety and Hazard Prevention, Hung Kuang University, Taiwan
²Department of Environmental Science and Engineering, National Pingtung University of Science and Technology, Taiwan
³Department of Occupational Safety and Health, Chung Hwa University of Medical Technology, Taiwan

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Abstract: The manufacturing of fitness equipment involves several processes, including the cutting and punching of iron tubes followed by welding. Welding operations produce hazardous gases and particulate matter, which can enter the alveolar, resulting in adverse health effects. This study sought to verify the particle size distribution and exposure concentrations of atmospheric air samples in various work areas of a fitness equipment manufacturing industry. Observed particle concentrations are presented by area and in terms of relative magnitude: painting (15.58 mg/m³) > automatic welding (0.66 mg/m³) > manual welding (0.53 mg/m³) > punching (0.18 mg/m³) > cutting (0.16 mg/m³). The concentrations in each of the five work areas were C_inh>C_thor>C_resp. In all areas except the painting area, extra-fine particles produced by welding at high temperatures, and further those coagulated to form larger particles. This study observed bimodal distribution in the size of welding fume in the ranges of 0.7–1 µm and 15–21 µm. Meanwhile, the mass concentrations of particles with different sizes were not consistent across work areas. In the painting area, the mass concentration was higher in C_head>C_th>C_alv, but in welding areas, it was found that C_alv>C_head>C_th. Particles smaller than 1µm were primarily produced by welding.

Key words: Welding, Particle size, Inhalable, Respirable, Alveolar

Introduction

The manufacturing of fitness equipment includes cutting and punching iron tubes followed by welding and painting. Welding produces gaseous and particulate hazards containing metals¹–³, reactive oxygen species (ROS), and gases⁴ from the base metal, welding electrode, and flux materials. A previous study identified three distinct types of welding fume particles ranging from 0.25 to 16 µm (aerodynamic diameter) in the breathing zone of welders⁵. Antonini⁶ reported particles ranging from 0.50–2.0 µm. The diameters of fume particles produced by stainless-steel welding range from 0.02 µm to 0.81 µm (with an average of 0.1 µm and geometric standard deviation of 1.42)⁷, and the mass-median aerodynamic diameter (MADD) of the particles in stainless-steel welding fumes was reported to be 0.255 µm⁸. Chung and Scott⁹ reported that the aero-
dynamic equivalent diameter ranged from 0.26–0.56 μm in metal inert gas (MIG) and gas metal arc welding (GMAW); however, Moroni\textsuperscript{10} observed larger particles, ranging from 0.44 to 6.16 μm in MIG welding fumes. Zimmer \textit{et al.}\textsuperscript{11} observed aerosols with diameter of 6.8 μm produced by GMAW. These studies have demonstrated that the particles in welding fumes range from ultrafine to fine. The fine particles produced in the high temperatures associated with welding are generally composed of spherical and aggregate particles\textsuperscript{12}. Due to the high metal content and ROS within the welding environment\textsuperscript{4, 13}, preventing exposure is critical to the industrial health of workers. Therefore, it is expected that our results even they work in different areas where exist alternative fabrication processes using an IOM personal inhalable aerosol sampler (SKC, Inc., Eighty-four, PA, USA, Institute of Occupation Medicine, IOM NO. 225-70A) with 25 mm diameter mixed cellulose ester filters (MCE, SKC) and set the flow rate at 2.0 l/min over a period of 7–8 h. The sampling site is behind the worker about 1 meter. The particles ranged in size (aerodynamic diameter) as follows: <0.4 (back-up filter), 0.4–0.7, 0.7–1.0, 1.0–3.5, 3.5–6.5, 6.5–10, 10–15, 15–21, >21 μm. Voitkevich \textit{et al.}\textsuperscript{15} identified the abundant Fe, Mn, Si, Ca, K, Na, and F in extra-fine particles, while those found in coarse particles were Fe and dissolved metals. The interactions of toxic metal components in fine and coarse particles of welding fumes have been discussed in previous studies\textsuperscript{16}. The penetration mass of ultrafine titanium dioxide particles (aerodynamic diameter=20 nm) into the pulmonary interstitium is greater than that of fine particles (aerodynamic diameter=250 nm). The 12-wk pulmonary clearance of inhaled ultrafine particles is slower (t1/2=501 d) than that of larger particles (t1/2=174 d)\textsuperscript{17}. This study sought to verify the particle size distribution and exposure concentration of atmospheric aerosols in the work areas of a fitness equipment manufacturing industry, in which the major fabrication procedure is welding. Due to the workers in this kind of industry wear the cotton-fabric mask, surgical mask or activated-carbon mask even they work in different areas where exist alternative exposure status. Therefore, it is expected that our results will provide a valuable resource for developing the environmental control strategies or making the right decision for the workers to use respiratory protective equipments to prevent particulate and gaseous hazards exposure.

**Methods**

**Air sampling**

Inhalable particles

Analysis was performed in a fitness equipment manu-
tion of particle size. This method of calculation was previously used by Chen et al. (2007)\(^{18}\).

Particle size distribution for each process of fabrication

Particle size distribution was determined according to the average of three samples from each area associated with the five processes involved in fabrication. Particle size distribution was described according to mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) estimated by \(d_{50\%}\) and \(d_{84\%}/d_{50\%}\), where \(d_{n\%}\) represents the aerodynamic diameter at \(d_{ae}\) with an \(n\%\) cumulative fraction for the given size distribution. MMAD\(_c\) and GSD\(_c\) were reported as the coarse particles for \(d_{ae}\geq3.5\ \mu m\) and MMAD\(_f\) and GSD\(_f\) were as fine mode (for \(d_{ae}<3.5\ \mu m\)).

Particle concentrations in various regions of the respiratory tract

The ratio of inhalable fraction, thoracic fraction, and respirable fraction was estimated using the data IOM and Marple cascade impactor sampling heads. This study adopted the inhalable, thoracic, and respirable sampling criteria outlined by the International Standards Organization (ISO), the Committee European de Normalisation (CEN), and ACGIH\(^{19–21}\), as follows:

a. Inhalable particles: the fraction of particles aspirated through the nose or mouth during breathing.

b. Thoracic particles: the fraction of inhaled particles that passes into the lungs below the larynx.

c. Respirable aerosol: the fraction of inhaled particles that passes down to the alveolar, the gas exchange region of the lungs.

In the present study, the ratios of inhalable, thoracic, and respirable fractions were used to estimate the thoracic and respirable fractions of welding particles (\(C_{thor}\) and \(C_{resp}\) respectively) based on concentrations of inhalable particles (\(C_{inh}\)). The concentrations of welding particles in the head region (\(C_{head}=C_{inh}-C_{thor}\)), tracheobronchial region (\(C_{th}=C_{thor}-C_{resp}\)), and alveolar region (\(C_{alv}=C_{resp}\)) were determined using personal air samplings in accordance with the definition of inhalable, thoracic, and respirable particles\(^{18}\).

### Results

#### Particle size distribution

Table 1 summarizes the concentrations (including AM\(_{AVUE}\) and 95% CI) of inhalable (\(C_{inh}\)), thoracic (\(C_{thor}\)) and respirable (\(C_{resp}\)) particles in each of the work areas. The particle concentrations in each area were as follows: painting (15.58 mg/m\(^3\)) > automatic welding (0.66 mg/m\(^3\)) > manual welding (0.53 mg/m\(^3\)) > punching (0.18 mg/m\(^3\)) > cutting (0.16 mg/m\(^3\)). With the exception of samples obtained from the painting area, all of the above concentrations were below the permissible exposure level (PEL) designated by the Taiwanese government (5 mg/m\(^3\)), as well as stands for Occupational Safety and Health Administration Permissible Exposure Level (OSHA PEL). The relative magnitude of the concentrations in each of the five work areas were as follows: \(C_{inh}>C_{thor}>C_{resp}\), but the significant differences among \(C_{inh}\), \(C_{thor}\), \(C_{resp}\) were only observed in painting and manual welding areas.

Table 2 presents the MMAD and GSD for coarse mode (i.e., MMAD\(_c\), GSD\(_c\) for \(d_{ae}\geq3.5\ \mu m\)) and fine mode (i.e., MMAD\(_f\), GSD\(_f\) for \(d_{ae}<3.5\ \mu m\)), representing the size distributions of particles in this study. MMAD\(_c\) values indicate that the particle size differed very little between work areas: cutting area (9.65 \(\mu m\)) and automatic welding area (9.93 \(\mu m\)). MMAD\(_f\) values were as follows: painting (1.20 \(\mu m\)) > cutting (0.84 \(\mu m\)) > punching≈ automatic welding≈ manual welding (0.66–0.68 \(\mu m\)). Figure 1 presents the particle size distributions in each of the work

| Areas       | Painting | Manual welding | Automatic welding | Pouching | Cutting |
|-------------|----------|----------------|-------------------|----------|---------|
| n           | 3        | 6              | 6                 | 3        | 3       |
| Inhalable   | 15.58    | 0.53           | 0.66              | 0.18     | 0.16    |
| Range       | 13.10–19.45 | 0.36–0.82     | 0.39–1.16         | 0.08–0.24 | 0.11–0.19 |
| Thoracic    | 9.09     | 0.38           | 0.5               | 0.12     | 0.11    |
| Range       | 8.02–10.36 | 0.25–0.58     | 0.29–0.97         | 0.06–0.16 | 0.08–0.13 |
| Respirable  | 3.69     | 0.28           | 0.38              | 0.08     | 0.08    |
| Range       | 3.43–3.92 | 0.17–0.41     | 0.22–0.79         | 0.04–0.11 | 0.06–0.09 |
| \(p\) value | 0.024*   | 0.023*         | 0.127             | 0.329    | 0.111   |

*: Significant differences were found among \(C_{inh}\), \(C_{thor}\), \(C_{resp}\) particles by Kruskal-Wallis test \((p<0.05)\)
areas. Two modes of particle distribution were observed in the air samples obtained in the areas of manual welding, automatic welding, punching, and cutting. As shown in Fig. 2, the cumulative mass fraction of particles with alternative particle size exhibited a obviously accumulation of mass concentration was found in large particle size in the painting area, that differed from other working areas. Estimation of particle concentration in various regions of the respiratory tract

Table 3 presents the particle concentrations in the head region (C\textsubscript{head}), tracheobronchial (C\textsubscript{th}), and alveolar (C\textsubscript{alv}) regions of the personal sampling in workers at different working processes (mg/m\textsuperscript{3}).

### Table 3. Estimated particle exposure concentrations and their 95% CI at the head (C\textsubscript{head}), tracheobronchial (C\textsubscript{th}) and alveolar (C\textsubscript{alv}) regions of the personal sampling in workers at different working processes (mg/m\textsuperscript{3})

| Area            | Painting | Manual welding | Automatic welding | Punching | Cutting |
|-----------------|----------|----------------|--------------------|----------|---------|
| n               | 3        | 6              | 6                  | 3        | 3       |
| C\textsubscript{head} Mass conc. | 6.49     | 0.14           | 0.17               | 0.06     | 0.05    |
| SD              | 5.07–9.09| 0.1–0.24       | 0.1–0.21           | 0.02–0.11| 0.03–0.06|
| %               | 41.7     | 27.0           | 25.1               | 35.0     | 29.7    |
| C\textsubscript{th} Mass conc. | 5.4      | 0.1            | 0.11               | 0.04     | 0.03    |
| SD              | 4.59–6.65| 0.07–0.17      | 0.07–0.18          | 0.02–0.04| 0.02–0.04|
| %               | 34.7     | 19.4           | 16.8               | 19.8     | 19.0    |
| C\textsubscript{alv} Mass conc. | 3.69     | 0.28           | 0.38               | 0.08     | 0.08    |
| SD              | 3.43–3.92| 0.17–0.41      | 0.22–0.79          | 0.04–0.11| 0.06–0.09|
| %               | 23.7     | 53.6           | 58.1               | 45.1     | 51.3    |
| p value         | 0.051    | 0.003*         | 0.001*             | 0.300    | 0.052   |

*: Significant differences were found among C\textsubscript{head}, C\textsubscript{th}, C\textsubscript{alv} particles by Kruskal-Wallis test (p<0.05)

Discussion

Particle concentrations of welding fume

Flynn et al.\textsuperscript{22)} reported average inhalable particle concentrations of 4.72 mg/m\textsuperscript{3} (0.003–60 mg/m\textsuperscript{3}) in welders according to data provided by Occupational Safety and Health Administration (OSHA) in 1978–2008. Those values were higher than the data obtained in the present study (0.53–0.66 mg/m\textsuperscript{3}). Variations in welding fume concentration may be due to the environment in which welding was performed (indoors vs. outdoors) as well as ventilation conditions. Lehnert et al.\textsuperscript{23)} reported the median level of respirable particles as 0.21 mg/m\textsuperscript{3} for tungsten inert gas
(TIG) welding and 1 mg/m³ for gas metal arc welding (GMAW), which are in strong agreement with the data obtained in the current study (0.28–0.38 mg/m³). In different working areas, due to the significant differences of C inh, C thor, C resp were only observed in painting and manual welding areas, it is inefficient for the workers who wore the cotton fabric mask and surgical mask in preventing occupational exposure with wide range concentration in different particle size of the two areas in the prevent study. Yu et al. reported that welding particulates with the mean particle diameter of 0.1 μm deposited in the lower respiratory tract, including bronchioles, alveolar ducts, alveolar sacs, and alveoli. Though the present result indicated that the particle size of welding particulates was <1 μm, the particle-size distribution, morphology and chemical aspects of the resultant fumes may be affected by the welding alloy, and the particle size may change dynamically with time.

Particle concentrations in various regions of the respiratory tract

In the painting area, higher particle concentrations were obtained in the head region (41.7%). The highest particle concentrations in the alveolar region were obtained in the manual welding (53.6%) and automatic welding areas (58.3%). These results indicate that fine particles produced during welding enter the tracheobronchial and alveolar regions, especially for very fine particles, which can enter alveolar regions and cannot be exhaled through expiratory flow. Although in the point of particles size, for similar mass concentrations, welding fumes are considered more
harmful than the particles generated in the painting area, the hazardous effect should be considered the chemical composition in alternative aerosols, those in the welding fume are different from that of the painting aerosol. Therefore, the particle size and chemical composition should be further analyzed simultaneously in comprehensive consideration in this kind of working characteristics.

Though the MMAD of coarse particles were nearly equal in the painting, cutting, punching, and welding areas, for MMAD of fine particles, those were less than 1 μm in cutting, punching, and welding areas (0.66–0.68 μm) except for painting area. These results match those of Jenkins and Zimmer et al.24, 26) James et al.27) reported that the MMAD of high-solids basecoat paint overspray aerosols ranged from 2.9 to 9.7 μm; this result is equal to the particle size distribution found in this study. Sowards et al.18) classified fume particles according to three distinct morphologies: spherical, irregular, and agglomerate. They observed bimodal distribution among inorganic aerosols, such as aluminum or steel; however, organic compounds presented a single or poly-dispersed mode in the size-fractionated particulate samples, with MMAD similar to that of total overspray aerosol27). In Fig. 2, the highest concentration was obtained for particles in the range of 0.7–1.0 μm in cutting, punching, and welding areas (0.66–0.68 μm) except for painting area. These results match those of Jenkins and Zimmer et al.24, 26) James et al.27) reported that the MMAD of high-solids basecoat paint overspray aerosols ranged from 2.9 to 9.7 μm; this result is equal to the particle size distribution found in this study. Sowards et al.18) classified fume particles according to three distinct morphologies: spherical, irregular, and agglomerate. They observed bimodal distribution among inorganic aerosols, such as aluminum or steel; however, organic compounds presented a single or poly-dispersed mode in the size-fractionated particulate samples, with MMAD similar to that of total overspray aerosol27). In Fig. 2, the highest concentration was obtained for particles in the range of 0.7–1.0 μm, followed by 15–21 μm, illustrating bimodal distribution. The aggregate modal may help to solve the dynamics of particles involved in generation, convection, diffusion, coagulation, and coalescence in a spatially two-dimensional flame system28). Spatial transport processes may influence aerosol dynamics, and thermophores have the greatest impact on the spatial distribution of aerosol mass29). The two main modals of the particle size in the range of 0.7–1 μm and 15–21 μm both existed in automatic welding and manual welding areas.30, 31) determined that the size and morphology of particles are strongly affected by flame temperature and transport processes within the flame. This may explain the formation of extra-fine particles produced during high-temperature welding, followed by the coagulation of these particles to form larger particles. In the punching and cutting areas, coarse particles were found to be of the highest concentration (>3.5 μm). In particular, the cutting areas exhibited a high concentration of 15–21 μm of coarse particles. Thornburg and Leith32) reported that a metal shearing machine with lower viscosity could result in the generation of large MMAD (21.9 μm) of oil droplets. In terms of extra-fine particles, the cutting fluid applied in the cutting or punching process results in a greater impaction force, which might lead to the generation of oil droplets of a lower MMAD18, 32). These small droplets may be produced by two mechanisms: atomization and vaporization condensation33). In Fig. 2, the distribution of particles in the automatic and manual welding process was coherent with three slopes. These trends could be interpreted as follows: (1) <1 μm particles might be produced from high-temperature flames; (2) 1–6.5 μm particles might be the result of extra-fine particles coagulating; (3) 6.5–21 μm particles may be formed by machine force in the cutting and punching areas25).

Conclusion

The mass concentration of welding fumes is higher than those without operating welding work. This study observed bimodal distribution in the size of welding particles in the ranges of 0.7–1 μm and 15–21 μm. The most predominant concentration is in alveolar region due to the most aerodynamic diameter of the welding particles are below than 1 μm.

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