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

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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吸入>C呼>C肺. 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头>C肺>C吸, but in welding areas, it was found that C肺>C头>C呼. Particles smaller than 1 μm 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-mediated 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 \( \mu m \) in metal inert gas (MIG) and gas metal arc welding (GMAW); however, Moroni\(^{10}\) observed larger particles, ranging from 0.44 to 6.16 \( \mu m \) in MIG welding fumes. Zimmer et al.\(^{11}\) observed aerosols with diameter of 6.8 \( \mu m \) produced by GMAW. These studies have shown 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\(^{12}\). Due to the high metal content and ROS within the welding environment\(^4,\)\(^13\), preventing exposure is critical to the industrial health of workers. Therefore, it is expected that our results will provide a valuable resource for developing the environmental control strategies or making the right decision 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 August and September of 2012, and the temperature range from 31–35 °C and relative humidity range from 66–82%.

**Particle size segregation**

Air samples were obtained using an eight-stage cascade impactor (Personal Cascade MarpleImpactor Model 225-50-001; SKC Inc., Eighty Four, PA, USA) with 0.8 \( \mu m \) pores and 34 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 \( \mu m \) and 50% cut-off aerodynamic (d50%) were 0.52, 0.96, 1.55, 3.5, 6.0, 9.8, 14.8, 21.3 \( \mu m \). Mucilage was sprayed on the filters prior to sampling to prevent the particles from bouncing. The filters were maintained under the same conditions of temperature and humidity during pre- and post-sampling. The filters were weighed 48 h post-conditioning and post-sampling weights were subtracted from the pre-sampling weights to determine the mass of the particles obtained during ambient sampling. Personal air pump samplers with a flow rate of 2.0 l/min were used. IOM and Marple cascade impactor sampling heads were collected from the areas associated with punching, manual welding, automatic welding, painting, and cutting. All samples were obtained simultaneously and all results are the average of three samples. Thus, this study obtained a total of 15 size segregating samples.

**Data analysis**

Particle mass concentration

Due to the log-normality of each concentration, this study adopted the method of the minimum variance unbiased estimated (MVUE) for the estimation of the arithmetic mean (AM\(_{MVUE}\)), which was used to describe the average concentrations of all sizes particles. We then obtained the 95% CI to describe the log-normal distribu-
Particle size distribution for each process of fabrication

Particle size distribution was determined 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, and GSD were reported as the coarse particles for \(d_{ae}\geq 3.5\ \mu m\) and MMAD and GSD 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, 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 (\(C_{\text{thor}}\) and \(C_{\text{resp}}\) respectively) based on concentrations of inhalable particles (\(C_{\text{inh}}\)). The concentrations of welding particles in the head region (\(C_{\text{head}}=C_{\text{inh}}-C_{\text{thor}}\)), tracheobronchial region (\(C_{\text{nh}}=C_{\text{thor}}-C_{\text{resp}}\)), and alveolar region (\(C_{\text{alv}}=C_{\text{resp}}\)) were determined using personal air samplings in accordance with the definition of inhalable, thoracic, and respirable particles.

Results

Particle size distribution

Table 1 summarizes the concentrations (including AMV and 95% CI) of inhalable (\(C_{\text{inh}}\)), thoracic (\(C_{\text{thor}}\)) and respirable (\(C_{\text{resp}}\)) 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: \(C_{\text{inh}}>C_{\text{thor}}>C_{\text{resp}}\), but the significant differences among \(C_{\text{inh}}, C_{\text{thor}}, C_{\text{resp}}\) were only observed in painting and manual welding areas.

Table 2 presents the MMAD and GSD for coarse mode (i.e., MMAD, GSD for \(d_{ae}\geq 3.5\ \mu m\)) and fine mode (i.e., MMAD, GSD for \(d_{ae}<3.5\ \mu m\)), representing the size distributions of particles in this study. MMAD 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 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.

Table 1. Mean inhalable (\(C_{\text{inh}}\)), thoracic (\(C_{\text{thor}}\)), and respirable (\(C_{\text{resp}}\)) concentrations and their 95% CI of the personal sampling in workers in different working processes (mg/m^3)

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

*: Significant differences were found among \(C_{\text{inh}}, C_{\text{thor}}, C_{\text{resp}}\) particles by Kruskal-Wallis test (\(p<0.05\))
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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 an 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_head), tracheobronchial (C_th), and alveolar (C_alv) of the respiratory tract. Once again, we see a similar pattern in the relative magnitudes of the concentrations: painting>automatic welding>manual welding>punching>cutting. Significant differences were observed among C_head, C_th, C_alv in the painting, manual welding, and automatic welding areas. However, the mass concentrations of different size intervals were not consistent among each of the work areas. In the painting area, the mass concentration was as follows: C_head>C_th>C_alv. In the welding areas, the mass concentration was as follows: C_alv>C_head>C_th. The highest levels were obtained for C_alv in the welding, cutting, and punching areas.

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.

### Table 2. Fine and coarse particle size distribution (MMAD) and geometric mean (GSD) of air samples at different working processes (mg/m\textsuperscript{3})

<table>
<thead>
<tr>
<th>Area</th>
<th>Fine particle</th>
<th>Coarse particle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MMAD\textsubscript{f}</td>
<td>GSD\textsubscript{f}</td>
</tr>
<tr>
<td>Painting (n=3)</td>
<td>1.2</td>
<td>2.76</td>
</tr>
<tr>
<td>Manual welding (n=6)</td>
<td>0.66</td>
<td>2.39</td>
</tr>
<tr>
<td>Automatic welding (n=6)</td>
<td>0.68</td>
<td>2.91</td>
</tr>
<tr>
<td>Punching (n=3)</td>
<td>0.68</td>
<td>2.04</td>
</tr>
<tr>
<td>Cutting (n=3)</td>
<td>0.84</td>
<td>2.84</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Area</th>
<th>Painting</th>
<th>Manual welding</th>
<th>Automatic welding</th>
<th>Punching</th>
<th>Cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_head</td>
<td>6.49</td>
<td>0.14</td>
<td>0.17</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>SD</td>
<td>5.07–9.09</td>
<td>0.1–0.24</td>
<td>0.1–0.21</td>
<td>0.02–0.11</td>
<td>0.03–0.06</td>
</tr>
<tr>
<td>%</td>
<td>41.7</td>
<td>27.0</td>
<td>25.1</td>
<td>35.0</td>
<td>29.7</td>
</tr>
<tr>
<td>C_th</td>
<td>5.4</td>
<td>0.1</td>
<td>0.11</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>SD</td>
<td>4.59–6.65</td>
<td>0.07–0.17</td>
<td>0.07–0.18</td>
<td>0.02–0.04</td>
<td>0.02–0.04</td>
</tr>
<tr>
<td>%</td>
<td>34.7</td>
<td>19.4</td>
<td>16.8</td>
<td>19.8</td>
<td>19.0</td>
</tr>
<tr>
<td>C_alv</td>
<td>3.69</td>
<td>0.28</td>
<td>0.38</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>SD</td>
<td>3.43–3.92</td>
<td>0.17–0.41</td>
<td>0.22–0.79</td>
<td>0.04–0.11</td>
<td>0.06–0.09</td>
</tr>
<tr>
<td>%</td>
<td>23.7</td>
<td>53.6</td>
<td>58.1</td>
<td>45.1</td>
<td>51.3</td>
</tr>
</tbody>
</table>

\*: Significant differences were found among C_head, C_th, C_alv particles by Kruskal-Wallis test (p<0.05)
(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 present study. Yu et al.⁷) 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 alloy¹¹), and the particle size may change dynamically with time²⁴).

**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 flow²⁵). Although in the point of particles size, for similar mass concentrations, welding fumes are considered more

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![Image](image-url)

**Fig. 1.** Particle size distribution of ambient particle collected from workplaces of welding, pouching, cutting and painting process in the fitness equipments manufacturing industry.

![Image](image-url)

**Fig. 2.** Cumulative mass fraction of particles with alternative particle size in workplaces of welding, pouching, cutting and painting process in the fitness equipments manufacturing industry.
harmful than the particles generated in the painting area, the hazardous effect should 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 fractionated particulate samples, with MMAD similar to the greatest impact on the spatial distribution of aerosol 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 0.7–1.0 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 impact on the spatial distribution of aerosol mass29). 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.

Acknowledgement

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26) Jenkins NT, Pierce WMG, Eagar TW (2005) Particle size distribution of gas metal and flux cored arc welding fumes. Weld J 84, 156s–63s.