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Characteristics of Oil Mists in Workplace Atmospheres and Their Exposures to Workers in a Fastener Manufacturing Industry

Abstract

This study was set out to characterize size distributions of oil mists in three workplace atmospheres of the forming, threading, and heat treatment in a fastener manufacturing industry and to assess their exposures to workers. Particle size distributions of oil mists in all selected workplace atmospheres were found to be “bimodal”. Oil mists of the fine mode (mass median aerodynamic diameter (MMAD) = 0.309–0.501μm) were generated through the mechanisms of evaporation and condensation of the involved metalworking fluids (MWFs), and the coarse mode (MMAD=8.16–13.0μm) were contributed by oil droplets formed via the mechanical impaction mechanism. The fractions of the inhaled oil mists exposed to different regions of the respiratory tracts for all selected workers were: alveolar (66.9-77.9%) > head (14.5-19.1%) > trachea bronchial (7.56-15.8%). Personal inhalable oil mist exposure levels were found as: threading workers (2.11mg/m³) > forming workers (1.58mg/m³) > heat treatment workers (0.0801mg/m³). The estimated respirable exposure levels for both forming and threading workers (1.34mg/m³ and 1.40mg/m³, respectively) were higher than the level known for “increased risk of pulmonary injury” (0.20mg/m³) suggesting that appropriate control measures should be taken to reduce their fine mode oil mist exposures.

Keywords: fastener manufacturing industry, oil mist, particle size distribution, exposure assessment, workplace atmosphere
1. Introduction

Base on the Taiwan governmental statistics in 2002, there were ~1,270 fastener manufacturers employed in total with ~37,000 employees in the whole country. The total fastener production rates increased from ~451,000 tons/yr in 1991 to ~1,269,000 tons/yr in 2003 accounting for ~14% world production. The manufacture of fasteners involves seven important industrial processes, including the wire drawing, forming, threading, cleaning, heat treatment, surface treatment, and packaging and shipping. Among them mineral oil-based metalworking fluids (MWFs) are used in forming, threading, heat treatment processes for cooling, lubricating, and corrosion inhibition purposes and hence might result in the emission of oil mist to the workplace atmosphere and lead to the exposures of workers [1-2].

Currently, the time-weighted-average permissible exposure limit of 5mg/m$^3$ for oil mist (mineral) is widely adopted by many agencies in the world, including US Occupational Safety and Health Administration (OSHA), US National Institute of Occupational Safety and Health (NIOSH), UK Health and Safety Executive (HSE), American Conference of Governmental Industrial Hygienists (ACGIH), and Taiwan government, with the exception of Japan Occupational Health Association (JOSH) (=3mg/m$^3$). Obviously, the above limit values are simply designated for regulating worker’s “total” oil mist exposures of the entire respiratory tract. In particular, it is well known that the so-called “total” aerosol exposures are not representative to workers’ true exposures [3].

Epidemiological and animal studies have indicated that oil mist exposures might result in the laryngeal cancer [4], asthma [5], bronchial hyper-responsiveness [6], lipoid pneumonia [7], lung cancer [8], and many other respiratory illnesses [9-10]. These suggest that oil mists deposited on different regions of the respiratory tract might lead to different health effects [11]. These also imply that, to meet a comprehensive exposure assessment purpose, we need to measure not only for those oil mists inhaled into the respiratory tract, but also need to measure those oil mists exposed to different regions of the respiratory tract. In 1997, NIOSH proposed a time-weighted-average exposure level of 0.4mg/m$^3$ for the oil mist exposure to the thoracic region [12]. Kennedy et al. found the occurrence of significant cross-shift decrements in FEV1 while workers exposed to oil mists in aerodynamic diameter <9.8µm with exposure levels >0.20mg/m$^3$ [13]. The above information further confirms the importance to measure particle size distributions of oil mists in order to assess their exposures to different regions of the respiratory tract.

To date, oil mist exposures to workers in several different industries have been assessed. These include steel millers [14], cable manufacturing workers [15], car-making workers [16], ship engine maintenance workers [17-18], and tunnel construction workers [19] (Table 1). Among them the car-making workers were found with the highest exposure level (2.6mg/m$^3$).
But to the best of our knowledge, the characteristic of oil mists exposed to fastener manufacturing industry workers has never been assessed. Therefore, this study was set out first to assess inhalable oil mist exposures to workers in fastener manufacturing industries. In addition, in order to assess the exposure levels in different regions of the respiratory tract for all involved workers particle size segregating samplings were conducted in each involved workplace. The results obtained from this study will provide useful information for fastener manufacturing industries to seek suitable control measurements for reducing workers’ exposures.

2. Material and Methods

2.1 Sampling strategies

2.1.1 Personal inhalable aerosol sampling

All workers associated with the use of MWFs in their manufacturing process were selected for conducting personal samplings. In total 17, 11 and 6 workers were selected from the forming, threading, and heat treatment processes, respectively. The IOM personal inhalable aerosol sampler (SKC Inc., Eighty-four, PA, USA) was adopted in this study which is now being widely used specifically for the inhalable aerosol exposure assessment. The sampling flow rate was specified at 2 L/min and the sampling time was designated to 7 to 8 hours for each collected sample.

2.1.2 Particle size segregating samplings

Particle size segregating samplings were conducted on the workplace atmospheres of the three selected industrial processes by using the modified Marple 8-stage cascade impactor (m-Marple). The sampler consists an inlet foam stage (φ=30mm, depth=12.5mm, 10 pores per inch, with a 50% cut-off aerodynamic diameter (d_{50%}) of 27 µm), eight impaction stages (with d_{50%} of 21.3, 14.8, 9.8, 6.0, 3.5, 1.55, 0.96, and 0.52 µm, respectively), and a back-up filter. The inlet of the m-Marple has been proven with aerosol aspiration efficiencies of unity for particles with aerodynamic diameter less than 56 µm under calm air situation (environmental wind speed < 0.5 m/s) [20]. For each industrial process, 4 particle size segregating samples were collected by uniformly placing four m-Marbles in the involved workplace. The wind velocities of the 3 selected industrial processes were measured and were consistently less than 0.3 m/s suggesting that the resultant particle size distributions could be representative to those containing in the workplace atmospheres.

2.2 Sample analysis

For all samples taken, gravimetric analysis was used to determine overall oil mist collected [21]. To reduce errors associated with moisture adsorption, all samples were conditioned prior to weighing by placing them in a desiccator overnight. The weighings were all performed using an electronic balance (Sartorius, Model RC210P, Goettingen, Germany).

2.3 Data analysis
2.3.1 Personal inhalable oil mist exposures

In this study, the log-normality of each exposure profile was examined by using the W-test [22]. The arithmetic mean was used to describe the average exposure for any given exposure profile [23]. The method of the minimum variance unbiased estimate (MVUE) is adopted to estimate the arithmetic mean (AM\textsubscript{MVUE}) and its 95% confidence interval for a log-normally distributed exposure profile. Full calculating procedures were described in the study conducted by Attfield and Hewet [24]. The above method has also been recommended by the American Industrial Hygiene Association (AIHA) Exposure Assessment Strategies Committee for exposure data with various sample sizes and geometric standard deviations (GSDs) [25].

2.3.2 Size distribution of oil mists for each industrial process

For each industrial process the averaged particle size distribution was obtained by averaging the 4 collected size segregating samples. Both the mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) were used to describe a particle size distribution. Here, GSD can be estimated by calculating either d\textsubscript{50%}/d\textsubscript{16%} or d\textsubscript{84%}/d\textsubscript{50%}, where d\textsubscript{n%} represents the aerodynamic diameter at d\textsubscript{ae} with a n% cumulative fraction for the given size distribution.

2.3.3 Oil mist exposures to the different regions of the respiratory tract

In this study we assumed that the oil mist size distribution found in a given workplace atmosphere was representative to that exposed to workers in the workplace. Therefore, the ratio of the inhalable fraction, thoracic fraction and respirable fraction could be estimated by using the inhalable, thoracic, and respirable sampling criteria which are currently adopted by the International Standards Organization (ISO), the Comité Européen Normalization (CEN), and ACGIH [26-28]. The resultant fractions were used to estimate worker’s thoracic (C\textsubscript{thor}) and respirable (C\textsubscript{resp}) exposure levels based on worker’s inhalable exposure levels (C\textsubscript{inh}) which were directly obtained from personal samplings. Finally, the exposure levels of the head region (C\textsubscript{head}; = C\textsubscript{inh} - C\textsubscript{thor}), trachea-bronchial region (C\textsubscript{tb}; = C\textsubscript{thor} – C\textsubscript{resp}), and alveolar region (C\textsubscript{alv}; = C\textsubscript{res}) for each selected worker were estimated.

3. Results and Discussion

3.1 Oil mist exposure profiles for fastener manufacturing industry workers

Table 2 shows the exposure profiles of the three selected exposure groups. The magnitude of AM\textsubscript{MVUE} shown in sequence was found as: threading workers (=2.11 mg/m\textsuperscript{3}) > forming workers (=1.58 mg/m\textsuperscript{3}) > heat treatment workers (=0.0801 mg/m\textsuperscript{3}). Obviously the above exposure levels were consistently lower than the permissible exposure level adopted by OSHA, NIOSH, ACGIH, HSE, and Taiwan government (=5 mg/m\textsuperscript{3}) and that adopted by JOSH (=3 mg/m\textsuperscript{3}). Nevertheless, the exposure levels for both threading and forming workers were much higher than that for steel millers (0.27-1.6 mg/m\textsuperscript{3}), ferry engine maintenance workers (0.45 mg/m\textsuperscript{3}), overall ship engine maintenance workers (0.24 mg/m\textsuperscript{3}), and tunnel...
construction workers (0.070-1.4 mg/m$^3$), with the exception for both cable manufacturing workers (2.25 mg/m$^3$) and car-making workers (2.6 mg/m$^3$) (Table 1). Here, it should be noted that Oudyk et al. [29] has found the occurrence of upper respiratory tract symptoms (such as asthma and sore throat, etc.) in workers exposed to total oil mist concentrations of 0.25-0.84 mg/m$^3$. Skyberg et al. [30] suggest that the possibility of inducing lung fibrosis in workers while exposed to total oil mist concentrations of 0.15-0.30 mg/m$^3$. Particularly in 2001, ACGIH proposed to lower down the oil mist threshold limit value to 0.2 mg/m$^3$ [31].

The above information warrants the need to further assess health hazards imposed on fastener manufacturing industry workers in the future.

In this study, we found that the inhalable oil mist exposure levels for threading workers were significantly higher than that for forming workers (Nonparametric Mann-Whitney test, p<0.05). But based on our field observation, the operation of the threading machine involved less mechanical impaction forces than the forming machine. In addition, the measured surface temperatures on the molder of the forming machine (=75.8±19.8°C) were higher than the temperatures on the surface of the threading gear (=69.6±17.1°C), and both workplaces shared very similar environmental temperatures (=32.2±1.48°C and 32.6±0.538°C, respectively). Apparently, it is expected that forming workers should exposed to higher oil mist concentrations than threading workers by considering the emission of oil droplets caused by impaction force, and the generation of oil mists due to evaporation and condensation processes. The above inconsistency might because (1) threading process contained more emission sources (i.e., 15 threading machines) than forming process (i.e., 13 forming machines); (2) the workplace area of the forming process (=734.4 m$^2$) was much bigger than that of threading process (=194.7 m$^2$); and (3) more enclosure could be found in each forming machine (opening= 0.60-1.82 m$^2$) than that in each threading machines (opening=3.96 m$^2$).

Finally, we found the heat treatment process had the lowest exposure levels among the three selected industrial processes (p< 0.005) warrant the need for further discussion. In fact, we did find that the temperatures measured from those MWF tanks used in the heat treatment process (=97.1±2.34 °C) were much higher than the other two process temperatures. However, we also found that all MWF tanks required only ~ 2 hrs per day on the heating condition for heat treatment purpose. The above scenario might explain why the lowest oil mist exposure levels were found in the heat treatment workers.

### 3.2 Size distribution of oil mists in the workplace atmosphere

As shown in Fig. 1, oil mist size distributions of the three selected workplaces were all in the form of “bimodal”. Table 3 shows the MMADs and GSDs for both coarse mode (i.e., MMAD$_c$, GSD$_c$) and fine mode (i.e., MMAD$_f$, GSD$_f$) for size distributions of oil mists obtained from this study. For MMAD$_c$, it can be seen that forming (=13.0µm) > threading (=9.20µm) > heat treatment (=8.16µm). The above results were quite consistent with the results obtained from a clutch manufacturing plant (>8µm) [32]. It is known that the coarse
mode oil droplets were mainly generated by the mechanical force. Therefore, the magnitude of MMADc could be affected mainly by both the magnitude of the involved impaction force and viscosity of the involved MWF. For both forming and threading processes, the viscosity of the involved MWF for the former (115.6cSt@40ºC, 12.2cSt@100ºC) was lower than that used in the later (183.7cSt@40ºC, 17.2cSt@100ºC). Based on our results, it suggests that MWF with a lower viscosity could result in the generation of oil droplets with greater particle sizes. The above inference was consistent with the observation of a study conducted by Thornburg et al. [33]. In their study they found that MWFs used in metal shearing machine with lower viscosity would result in the generation of oil droplets with greater MMAD (=21.9 µm) than those with higher viscosity (=6.10 µm). In addition, we also found that the impaction force involved in the forming process was much greater than that in the threading process. Theoretically, the greater impaction force might result in the generation of oil mists with less MMADs. Obviously, the above inference was contradictory to the results obtained from this study. Therefore, in this study it might be feasible to conclude that the magnitude of MMADs in oil droplets could be mainly affected by the viscosity of the involved MWFs rather than the impaction forces. Finally, the smallest MMADc was found in the heat treatment workplace might worth further discussion. Based on our filed observation, we found that oil droplets were generated at the center of the MWF tank (i.e., the location where fasteners dropped into the MWF tank). Because of this, oil droplets with large particle sizes might not be able to escape from the MWF tank due to the gravitational effect and the large surface area of the MWF tank.

For MMADf, it can be found that threading (=0.501 µm) > forming (=0.499 µm) > heat treatment (=0.309 µm). Theoretically, fine oil mists were generated through evaporation and condensation of MWFs during the manufacturing process. At this stage, it might not be able to know what led to the intrinsic differences in MMADfS among three studied industrial processes because factors associated with the evolution of aerosols in the field were very complicated (such as saturated vapor pressure, surface tension, and molecular weights of the involved MWFs etc.) [34]. However, our results (MMADf= 0.309–0.501 µm) are quite consistent with that found in a clutch manufacturing plant (MMADf= 0.1–1.0 µm) [32].

3.3 Estimating oil mist exposure levels at the different regions of the respiratory tract for fastener manufacturing industry workers

Table 4 summarizes the inhalable exposures (Cinh), thoracic exposures (Cthor) and repirable exposures (Cresp) for workers of the three selected exposure groups. All resultant exposure levels for heat treatment process workers were the lowest among the three exposure groups (Nonparametric Mann-Whitney test, p<0.05). Although the inhalable exposure level for the forming workers were significantly higher than that for the threading workers (Nonparametric Mann-Whitney test, p<0.05), no significance differences could be found in Cthor and Cresp (p>0.05).
Table 5 shows oil mist exposures to the head region (\(C_{\text{head}}\)), trachea-bronchial region (\(C_{\text{tb}}\)), and alveolar region (\(C_{\text{alv}}\)) of the respiratory tract for workers of the three selected exposure groups. Again, all resultant exposure levels for heat treatment process workers were the lowest among the three exposure groups (Nonparametric Mann-Whitney test, \(p<0.05\)). By comparing exposure levels for both forming and threading process workers, a significant difference could only be seen in \(C_{\text{head}}\) (Nonparametric Mann-Whitney test, \(p<0.05\)), no significance differences could be found in \(C_{\text{tb}}\) and \(C_{\text{alv}}\) \((p>0.05)\). Nevertheless, a consistent trend of \(C_{\text{alv}} > C_{\text{head}} > C_{\text{tb}}\) was found in all three studied exposure groups. The above results clearly indicate that most oil mists generated from the fastener manufacturing process might be able to reach the deep lung (i.e., the alveolar region). Here, it should be noted that \(C_{\text{alv}}\) for both forming and threading process workers (1.34 and 1.40 mg/m\(^3\), respectively) were much higher than the level known for causing “increased risk of pulmonary injury” (0.2 mg/m\(^3\)) [13]. Our results clearly suggest that appropriate control measures should be taken by the fastener manufacturing industry, particularly for the abatement of fine oil mist exposures to both forming and threading process workers.

4. Conclusions

We found that the inhalable oil mist exposure levels for workers in the fastener manufacturing industry were higher than workers in many other industries. But their exposure levels were still less than the limit value promulgated by OSHA, NIOSH, ACGIH, HSE, and Taiwan government. We found that size distributions of oil mists occurred in workplaces of the fastener manufacturing industry were “bimodal” and were dominated by the fine mode. The fraction of oil mists which can penetrate into alveolar regions account for 66.9%-77.9% of those inhaled into the respiratory tract. These results suggest the importance to apply useful control measures immediately for fastening industries in order to prevent workers exposed to oil mists with fine particle sizes.

References


### Table 1  The average oil mist exposure levels for workers in different industries

<table>
<thead>
<tr>
<th>Exposure group</th>
<th>Exposure concentration (mg/m$^3$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel millers</td>
<td>0.27-1.6</td>
<td>14</td>
</tr>
<tr>
<td>Cable manufacturing workers</td>
<td>2.25</td>
<td>15</td>
</tr>
<tr>
<td>(impregnation, sheathing, and installation of paper insulated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car-making workers</td>
<td>2.6</td>
<td>16</td>
</tr>
<tr>
<td>Ship engine maintenance workers (ferries)</td>
<td>0.45</td>
<td>17</td>
</tr>
<tr>
<td>Ship engine maintenance workers (overall)</td>
<td>0.24</td>
<td>18</td>
</tr>
<tr>
<td>Ferries</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Cargo ships</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Express ships</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Tunnel construction workers</td>
<td>0.070-1.4</td>
<td>19</td>
</tr>
</tbody>
</table>

### Table 2  Personal inhalable oil mist exposure levels for workers of the three selected exposure groups in the fastener manufacturing industry (mg/m$^3$)

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Forming (n=17)</th>
<th>Threading (n=11)</th>
<th>Heat treatment (n=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>1.12-2.16</td>
<td>1.40-2.55</td>
<td>0.0280-0.138</td>
</tr>
<tr>
<td>$\text{AM}_{\text{MVUE}}$</td>
<td>1.58</td>
<td>2.11</td>
<td>0.0801</td>
</tr>
<tr>
<td>95% C.I.</td>
<td>1.47-1.71</td>
<td>1.89-2.40</td>
<td>0.0546-0.174</td>
</tr>
<tr>
<td>Log-normality</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 3  Particle size distribution of oil mists collected from workplaces of the three selected industrial processes in the fastener manufacturing industry

<table>
<thead>
<tr>
<th>Industrial process</th>
<th>Fine mode</th>
<th></th>
<th>Coarse mode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MMAD&lt;sub&gt;f&lt;/sub&gt;</td>
<td>GSD&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Fraction (%)</td>
<td>MMAD&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>Forming (n=4)</td>
<td>0.499</td>
<td>2.02</td>
<td>73.5</td>
<td>13.0</td>
</tr>
<tr>
<td>Threading (n=4)</td>
<td>0.501</td>
<td>1.65</td>
<td>62.3</td>
<td>9.20</td>
</tr>
<tr>
<td>Heat treatment (n=4)</td>
<td>0.309</td>
<td>2.02</td>
<td>54.6</td>
<td>8.16</td>
</tr>
</tbody>
</table>

Table 4  Inhalable (C<sub>inh</sub>), thoracic (C<sub>thor</sub>) and respirable (C<sub>res</sub>) exposure levels for workers of the three selected exposure groups (mg/m<sup>3</sup>)

<table>
<thead>
<tr>
<th>Exposures</th>
<th>Forming</th>
<th>Threading</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&lt;sub&gt;inh&lt;/sub&gt;</td>
<td>1.58</td>
<td>2.11</td>
<td>0.0801</td>
</tr>
<tr>
<td>C&lt;sub&gt;thor&lt;/sub&gt;</td>
<td>1.47</td>
<td>1.62</td>
<td>0.0642</td>
</tr>
<tr>
<td>C&lt;sub&gt;res&lt;/sub&gt;</td>
<td>1.34</td>
<td>1.40</td>
<td>0.0519</td>
</tr>
</tbody>
</table>

Table 5  The exposure levels of oil mists at the head (C<sub>head</sub>), trachea-bronchial (C<sub>tb</sub>) and alveolar (C<sub>alv</sub>) regions for workers of the three selected exposure groups (mg/m<sup>3</sup>)

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Forming</th>
<th>Threading</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&lt;sub&gt;head&lt;/sub&gt;</td>
<td>0.255 (14.5%)</td>
<td>0.381 (19.1%)</td>
<td>0.0134 (17.3%)</td>
</tr>
<tr>
<td>C&lt;sub&gt;tb&lt;/sub&gt;</td>
<td>0.130 (7.60%)</td>
<td>0.222 (11.1%)</td>
<td>0.0123 (15.8%)</td>
</tr>
<tr>
<td>C&lt;sub&gt;alv&lt;/sub&gt;</td>
<td>1.34 (77.9%)</td>
<td>1.40 (69.8%)</td>
<td>0.0519 (66.9%)</td>
</tr>
</tbody>
</table>
Figure 1  Particle size distribution of oil mists obtained from the forming, threading, and heat treatment processes in the fastener manufacturing industry.