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Particle size distributions of oil mists in workplace atmospheres and their exposure concentrations to workers in a fastener manufacturing industry

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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 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). We found that mass median aerodynamic diameter (MMAD) of the fine mode and coarse mode fell to the range 0.309–0.501 μm and 8.16–13.0 μm, respectively. The fractions of inhaled particles exposed to different regions of the respiratory tracts found that the alveolar region was consistently higher than both head and tracheobronchial regions in all three studied exposure groups. Personal inhalable oil mist samplings were conducted on workers in the three selected processes revealed their exposure levels as: threading workers (2.11 mg/m^3) > forming workers (1.58 mg/m^3) > heat treatment workers (0.0801 mg/m^3). The estimated respirable exposure concentrations for both forming and threading workers (1.34 mg/m^3 and 1.40 mg/m^3, respectively) were higher than the level known for "increased risk of pulmonary injury" (0.20 mg/m^3) suggesting that appropriate control measures should be taken to reduce their exposures to the oil mists of the respirable fraction immediately.
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Keywords: Fastener manufacturing industry; Oil mist; Particle size distribution; Exposure assessment; Workplace atmosphere

1. Introduction

Based on the Taiwan governmental statistics in 2002, there were ∼1270 fastener manufacturers and in total employed with ∼37,000 employees in the whole country. The total fastener production rates increased from ∼451,000 tons/year in 1991 to ∼1,269,000 tons/year 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, an 8 h time-weighted-average permissible exposure limit of 5 mg/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) with a lower permissible exposure limit (=3 mg/m^3).

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Here, it should be noted that the above limit values are simply designated for regulating workers' "total" oil mist exposures. To date, it is well known that the so-called "total" aerosols can neither reflect all aerosols existing in the workplace atmosphere (i.e., true total aerosols), nor the fractions of aerosols inhaled by workers [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 mist exposures to 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, to estimate their exposure to different regions of the respiratory tract. In 1997, NIOSH proposed an 8 h-time-weighted-average exposure level of 0.4 mg/m^3 for an oil mist exposure to the thoracic region [12]. Kennedy et al. found the occurrence of significant cross-shift decrements in FEV1 while workers were exposed to oil mists with aerodynamic diameter less than 9.8 μm with exposure levels greater than 0.20 mg/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 (2.6 mg/m^3). But to the best of our knowledge, the concentrations of oil mists exposed to fastener manufacturing industry workers has never been assessed.

The objectives of this study were set out first to assess the inhalable fraction of oil mists exposed to workers in fastener manufacturing industries. Considering several health effects are associated with the exposures of oil mists in different regions of the respiratory tract, particle size segregating samplings were conducted in each involved workplace in order to estimate workers' oil mist exposures to the head, tracheobronchial, and alveolar regions simultaneously. The results obtained from this study will provide useful information for fastener manufacturing industries to seek suitable control measurements for reducing workers' exposures in the future.

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

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

2. Material and methods

2.1. Sampling strategies

2.1.1. Personal inhalable aerosol sampling

Seven manufacturing processes, including the wire drawing, forming, threading, cleaning, heat treatment, surface treatment, and packaging and shipping were involved in for manufacturing fasteners. In order to have a smooth production, all these processes are located in one building in all fastener manufacturing industries in Taiwan. For this, only one factory was selected in this study. For the selected factory, all workers involved in the use of MWFs were selected from three manufacturing processes (including 17, 11 and 6 workers from the forming, threading, and heat treatment processes, respectively) for conducting personal samplings by using an IOM personal inhalable aerosol sampler (SKC Inc., Eighty-four, PA, USA). The sampling flow rate was specified at 2 L/min and the sampling time was designated to 7–8 h 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 a modified Marple 8-stage cascade impactor (*m*-Marple). The sampler consists an inlet foam stage (Ø = 30 mm, depth = 12.5 mm, 10 pores per inch, with a 50% cut-off aerodynamic diameter ($d_{50\%}$) of 27 μm), eight impaction stages (with $d_{50\%}$s 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. A 34 mm PVC filter with 5.0 μm pore size was used as the collection medium. 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, four particle size-segregating samples were collected by uniformly placing four *m*-Marples in the involved workplace. The wind velocities of the three selected industrial processes were measured and found to be 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

Based on a study conducted by Simpson et al., oil mist samples lost less than 5% of their weight while the viscosity of the involved mineral oils were greater than 18 cSt (at 40 °C) [21]. In our study, the viscosity of the involved MWF for the forming process (115.6 cSt at 40 °C) and threading process (183.7 cSt at 40 °C) are much greater than the above mentioned.

Therefore, we considered the loss of mass due to the evaporation could be negligible, and hence gravimetric analysis was used to determine concentrations of oil mist for all collected samples [22]. To reduce errors associated with moisture adsorption, all filters (before and after field samplings were conducted) were conditioned prior to the weighing process by placing them in a desiccator overnight then weighed by using an electronic balance (Sartorius, Model RC210P, Goettinggen, Germany).

2.3. Data analysis

2.3.1. Personal inhaled oil mist concentrations

In this study, the log-normality of each concentration profile for each exposure group was examined by using the W-test [23]. The arithmetic mean was used to describe the average concentration [24]. The method of the minimum variance unbiased estimate (MVUE) was adopted to estimate the arithmetic mean (AM_{MVUE}) and its 95% confidence interval for a log-normally distributed profile. Full calculating procedures were described in the study conducted by Attfield and Hewet [25]. 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) [26].

2.3.2. Particle size distribution of oil mists for each industrial process

For each industrial process, the particle size distribution was obtained by averaging the four 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 $d_{50\%}/d_{16\%}$ or $d_{84\%}/d_{50\%}$, where $d_{n\%}$ represents the aerodynamic diameter at d_{ae} with a n% cumulative fraction for the given size distribution.

2.3.3. Oil mist concentrations 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 de Normalisation* (CEN), and ACGIH [27–29]. Here, aerosols of inhalable, thoracic, and respirable fractions are defined as follows.

Inhalable aerosols: The fraction of particles that is aspirated through the nose and/or mouth during breathing.

Thoracic aerosols: The fraction of inhaled particles that passes into the lung below the larynx.

Respirable aerosols: The fraction of inhaled particles that passes down to the alveolar – or gas-exchanging region – of the lung.

Here, it should be noted that the above definitions for the inhalable fraction simply indicate the fraction of aerosols which can be inhaled into the respiratory tract, and both thoracic and respirable fractions represent aerosols which can penetrate to, as opposed to deposition in the thoracic and alveolar region errs on the side of being conservative.

In this study, the ratios of inhalable, thoracic, and respirable fractions were used to estimate workers' thoracic (C_{thor}) and respirable (C_{resp}) fractions of oil mist concentrations based on concentrations of the inhalable fraction (C_{inh}) that were directly obtained from personal samplings. Finally based on the definitions given above for inhalable, thoracic and respirable aerosols, the concentrations of oil mists exposed to the head region ($C_{head} = C_{inh} - C_{thor}$), tracheobronchial region ($C_{tb} = C_{thor} - C_{resp}$), and alveolar region ($C_{alv} = C_{res}$) for each selected worker were estimated.

3. Results and discussion

3.1. Oil mist concentration profiles for fastener manufacturing industry workers

Table 2 shows the concentration profiles of the three selected exposure groups. The magnitude of AM_{MVUE} shown in sequence was found as: threading workers (=2.11 mg/m^3) > forming workers (=1.58 mg/m^3) > heat treatment workers (=0.0801 mg/m^3). Obviously, the above concentrations were consistently lower than the permissible exposure level adopted by OSHA, NIOSH, ACGIH, HSE, and Taiwan government (=5 mg/m^3) and that adopted by JOSH (=3 mg/m^3). Nevertheless, the levels for both threading and forming workers were much higher than that for steel millers (=0.27–1.6 mg/m^3), ferry-engine-maintenance workers (=0.45 mg/m^3), overall ship-engine-maintenance workers (=0.24 mg/m^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. [30] 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

Table 2
Mean personal inhaled oil mist concentrations (AM_{MVUE}) and their 95% confidence intervals (95% CI) for workers of the three selected exposure groups in the fastener manufacturing industry (mg/m^3)

Statistics	Forming (n = 17)	Threading (n = 11)	Heat treatment (n = 6)
AM_{MVUE}	1.58	2.11	0.0801
95% C.I.	1.47–1.71	1.89–2.40	0.0546–0.174
Log-normality	Yes	Yes	Yes

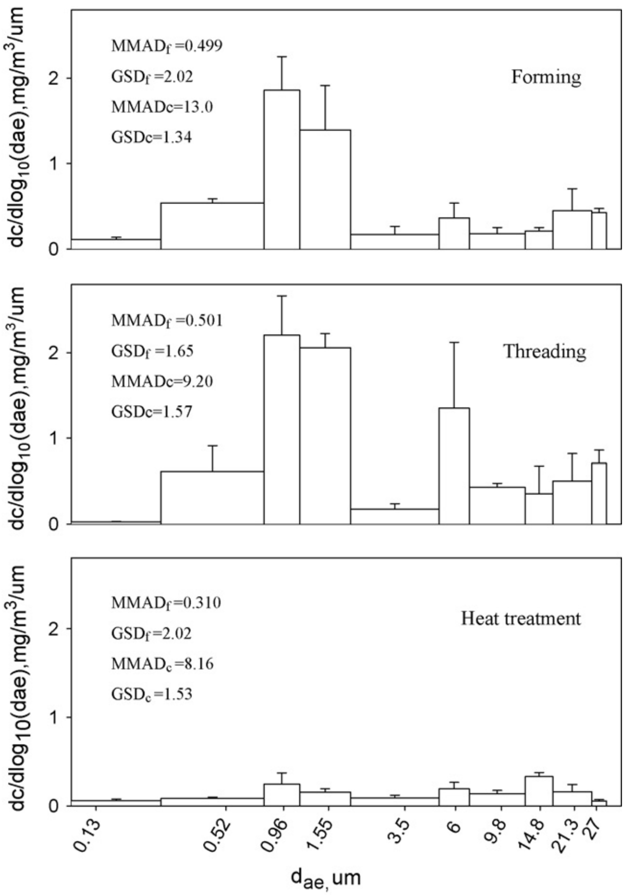

Fig. 1. Particle size distribution of oil mists obtained from the forming, threading, and heat treatment processes in the fastener manufacturing industry.

0.25–0.84 mg/m^3. Skyberg et al. [31] 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 [32]. 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 concentrations of the inhaled oil mists for threading workers were significantly higher than that for forming workers (nonparametric Mann–Whitney test, $p < 0.05$). However, we found that the operation of the treading 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). Therefore, it is expected that forming workers might be exposed to higher oil mist concentrations than threading workers by considering the emission of oil droplets caused by the impaction force, and the generation of oil mists due to the evaporation and condensation processes. The above inconsistency might result from one or more of the following facts: (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 was 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 concentration among the three selected industrial processes ($p < 0.005$), which warrants 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 were heated only ∼2 h per day to meet the heat treatment purpose. The above scenario might explain why the lowest oil mist levels were found in the heat treatment workers.

3.2. Particle size distribution of oil mists in the workplace atmosphere

Fig. 1 shows particle size distributions of oil mists in the atmosphere of the three selected workplaces. Table 3 shows the MMADs and GSDs for both coarse mode (i.e., $MMAD_c$, GSD_c for $d_{ae} \geq 3.5$ μm) and fine mode (i.e., $MMAD_f$, GSD_f for $d_{ae} < 3.5$ μm) for size distributions of oil mists obtained from this study. For $MMAD_c$, it can be seen that forming (=13.0 μm) > threading (=9.20 μm) > heat treatment (=8.16 μm). The above results were quite consistent with the results obtained from a clutch manufacturing plant (>8 μm) [33]. It is known that the coarse mode oil droplets were mainly generated by the mechanical force. Therefore, the magnitude of $MMAD_c$ 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 (115.6 cSt at 40 °C, 12.2 cSt at 100 °C) was lower than that used in the latter (183.7 cSt at 40 °C, 17.2 cSt at 100 °C). Based on our results, it suggests that MWF with a lower viscosity could result in the generation of

Table 3
Particle size distribution of oil mists collected from workplaces of the three selected industrial processes in the fastener manufacturing industry

Industrial process	Fine mode			Coarse mode		
	$MMAD_f$ (μm)	GSD_f (μm)	Fraction (%)	$MMAD_c$ (μm)	GSD_c (μm)	Fraction (%)
Forming (n = 4)	0.499	2.02	73.5	13.0	1.34	26.5
Threading (n = 4)	0.501	1.65	62.3	9.20	1.57	37.7
Heat treatment (n = 4)	0.309	2.02	54.6	8.16	1.53	45.4

Table 4
Mean inhalable (C_{inh}), thoracic (C_{thor}), and respirable (C_{res}) concentrations and their 95% confidence intervals (values in parenthesis) for workers of the three selected exposure groups (mg/m^3)

Exposures	Exposure group		
	Forming	Threading	Heat treatment
C_{inh}	1.58 (1.47–1.71)	2.11 (1.89–2.40)	0.0801 (0.0546–0.174)
C_{thor}	1.47 (1.36–1.59)	1.62 (1.45–1.84)	0.0642 (0.0438–0.139)
C_{res}	1.34 (1.25–1.45)	1.40 (1.25–1.59)	0.0519 (0.0354–0.113)

Table 5
Estimated mean oil mist exposure concentrations and their 95% confidence intervals (values in parenthesis) at the head (C_{head}), tracheobronchial (C_{tb}) and alveolar (C_{alv}) regions for workers of the three selected exposure groups (mg/m^3)

Exposures	Exposure group		
	Forming	Threading	Heat treatment
C_{head}	0.111 (0.102–0.119)	0.489 (0.439–0.557)	0.0159 (0.0108–0.0345)
C_{tb}	0.130 (0.121–0.141)	0.222 (0.197–0.250)	0.0123 (0.00838–0.0267)
C_{alv}	1.34 (1.25–1.45)	1.40 (1.25–1.59)	0.0519 (0.0354–0.113)

oil droplets with greater particle sizes. The above inference was consistent with the observation of a study conducted by Thornburg et al. [34]. In their study, they found that MWFs used in metal shearing machine with lower viscosity would result in the generation of oil droplets with MMAD (=21.9 μm) greater 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, a 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 reasonable 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 $MMAD_c$ 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 $MMAD_f$, 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 $MMAD_f$ 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.) [35]. However, our results ($MMAD_f = 0.309-0.501$ μm) are quite consistent with that found in a clutch manufacturing plant ($MMAD_f = 0.1-1.0$ μm) [33].

3.3. Estimating the concentrations of oil mists exposed to different regions of the respiratory tract for fastener manufacturing industry workers

Table 4 summarizes the concentrations (including AM_{MVUE} and its 95% CI) of inhalable (C_{inh}), thoracic (C_{thor}) and respirable fractions (C_{resp}) of oil mists exposed to workers of the three-selected exposure groups. All resultant concentrations for heat treatment process workers were the lowest among the three exposure groups (nonparametric Mann–Whitney test, $p < 0.05$). Although C_{inh} for the forming workers were significantly higher than that for the threading workers (nonparametric Mann–Whitney test, $p < 0.05$), no significant differences could be found in C_{thor} and C_{resp} ($p > 0.05$).

Table 5 shows the concentrations of oil mists (including AM_{MVUE} and its 95% CI) exposed to the head region (C_{head}), tracheobronchial region (C_{tb}), and alveolar region (C_{alv}) of the respiratory tract for workers of the three selected exposure groups. Again, all resultant concentrations for heat treatment process workers were the lowest among the three exposure groups (nonparametric Mann–Whitney test, $p < 0.05$). By comparing the concentrations for both forming and threading process workers, a significant difference could be seen in both C_{head} and C_{tb} (nonparametric Mann–Whitney test, $p < 0.05$), but no significant differences were found in C_{alv} ($p > 0.05$). Nevertheless, C_{alv} was consistently higher than both C_{head} and C_{tb} 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 the mean C_{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 oil mist exposure concentrations of the respirable fraction to both forming and threading process workers.

4. Conclusions

We found that the inhalabe oil mist concentrations for workers in the fastener manufacturing industry were higher than those for workers in many other industries. But theses values were still less than the limit value promulgated by OSHA, NIOSH, ACGIH, HSE, and Taiwan government. We found that particle size distributions of oil mists occurred in workplaces were dominated by the fine mode. The estimated mean alveolar oil mist exposures were much higher than the level known for causing "increased risk of pulmonary injury" (0.2 mg/m^3) suggesting that appropriate control measures should be taken to reduce workers' exposure to oil mists with fine particle sizes.

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