Occupational Health Risks from Welding Emissions: Exposure and Deposition of PM_{10}, $PM_{2.5}$, and Ultrafine Particles Across Welding Methods

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S1: Relative Risk (RR), Excess Risk (ER), and Attributable Fraction (AF)

The Environmental Burden of Disease (EBD) framework involves estimating key epidemiological metrics, including relative risk (RR), excess risk (ER), and attributable fraction (AF). The RR for all-cause mortality due to short-term exposure to PM_{10} was determined using the equation proposed by [1]. RR represents the likelihood of adverse health effects, such as all-cause mortality or lung cancer mortality, in a population exposed to elevated air pollution levels compared to a background level with minimal anthropogenic pollution (68 µg/m³ for PM_{10}). For all-cause mortality, RR is calculated using the following equation [2]:

$$RR = exp^{[\beta\,(X-X_0)]}$$

The RR is calculated using key parameters, including the coefficient of the risk function (β), the mean pollutant concentration (X), and the baseline concentration of PM_{10} (X_0): 68 µg/m³, which is measured before the start of the experiment. Additionally, the relative risk of cardiopulmonary and lung cancer mortality in individuals due to long-term exposure to $PM_{2.5}$ was calculated using the following approach [2]:

$$RR = \left[\frac{(X+1)}{(X_0+1)}\right]^{\beta}$$

The RR is determined based on the mean $PM_{2.5}$ concentration (X) and the baseline concentration of $PM_{2.5}$ (X_0) (40 µg/m³).

Once the RR is determined, the attributable fraction (AF) is estimated as [2]:

$$AF = \frac{(RR-1)}{RR}$$

The attributable fraction (AF) represents the proportion of disease-related deaths, such as lung cancer, that could be prevented if PM levels were reduced to 10 µg/m³ for PM_{10} and 3 µg/m³ for $PM_{2.5}$, respectively [2]. In the above expression, RR − 1 is equivalent to excess risk (ER).

Table S1 (a): $PM_{2.5}$ (µg/m^3) for shielded metal arc welding for different current intensities at welding height and breathing height (Amps representing amperes)

SMAW	Welding Height (WH)				Breathing Height (BH)			
	Average	SD	Minimum	Maximum	Average	SD	Minimum	Maximum
Ambient	56	1	55	58	55	1	54	56
50 Amps	360	142	63	530	650	228	57	980
Before 75 Amperes	70	4	66	77	50	1	49	51
75 Amps	630	205	114	992	1200	382	113	1753
Before 100 Amperes	42	3	38	46	26	3	24	32
100 Amps	1210	541	95	1916	2380	397	1502	3060
Before 125 Amperes	40	7	29	50	30	5	23	38
125 Amps	1600	760	29	2341	2780	815	201	3572
After 125 Amperes	40	8	28	52	39	8	27	51

Table S1 (b): PM_{10} (µg/m^3) for shielded metal arc welding for different current intensities at welding height and breathing height (Amps representing amperes)

SMAW	Welding Height (WH)				Breathing Height (BH)			
	Average	SD	Minimum	Maximum	Average	SD	Minimum	Maximum
Ambient	60	3	54	65	60	1	58	65
50 Amps	370	107	176	532	900	182	860	1083
Before 75 Amperes	80	3	88	99	70	1	63	76
75 Amps	630	81	485	770	1890	550	1325	2692
Before 100 Amperes	60	5	59	76	75	8	65	91
100 Amps	1260	408	549	1808	3840	953	3294	4665
Before 125 Amperes	60	24	38	90	70	19	41	91
125 Amps	1970	723	809	3020	4350	1115	1069	5928

Table S2 (a): Total number concentration (TNC) (#/cm^3) for shielded metal arc welding (SMAW) for different current intensities at welding height and breathing height (TNC values rounded to the nearest hundred and ambient reading is just before the experiment inside the workshop) (Amps is representing amperes)

SMAW	**TNC at welding height (1.1 m)**				**TNC at breathing height (1.5 m)**			
	Average	SD	Minimum	Maximum	Average	SD	Minimum	Maximum
Ambient 50 Amps	6860	370	6320	7380	8080	250	7730	8390
50 Amps	853500	738500	119000	2380000	1307800	858100	118000	3170000
Ambient 75 Amps	9600	1300	7700	11400	5130	190	4960	5460
75 Amps	1612000	992300	118000	3380000	1490200	766600	366000	3260000
Ambient 100 Amps	5900	370	5310	6430	4110	150	3870	4320
100 Amps	1383300	769900	466000	2790000	1372500	476100	651000	2440000
Ambient 125 Amps	7606	650	6870	8690	8530	1430	6760	10900
125 Amps	1569200	791700	659000	3270000	2361600	755700	1390000	4190000

Table S2 (b): Total number concentration (TNC) (#/cm^3) and $PM_{2.5}/PM_{10}$ (µg/m^3) for wire additive arc manufacturing for different current and voltage intensities (TNC values rounded to the nearest hundred and ambient reading is just before the experiment inside the workshop) (Amps is representing amperes).

WAAM	TNC (#/cm^3)				$PM_{2.5}/PM_{10}$ (µg/m^3)			
	Average	SD	Minimum	Maximum	Average	SD	Minimum	Maximum
Ambient 18 Volts 65 Amps	10710	4240	6680	16200	49/61	1/2	47/59	55/65
18 Volts 65 Amps	2720000	1090000	659000	4360000	1302/2200	169/400	1100/1260	1734/2800
Ambient 20 Volts 125 Amps	31800	14830	29700	34300	62/89	1/4	59/87	65/100
20 Volts 125 Amps	1440000	430000	902000	2180000	916/1851	163/409	763/1197	1403/2552

S1.1 Quantification of size-segregated PM deposition in the TB region

This study also evaluated the deposited mass (Figure S1) and mass per unit area (Figures S2 and S3) for SMAW and WAAM under varying current and voltage conditions. PM_{10} exhibited the peak value of deposition in the TB region due to its larger particle size compared to $PM_{2.5}$. During SMAW, peak PM_{10} deposition in the TB region across all amperages, with the 16–20 age group recording peak deposition masses of 2.8×10^{-3} µg, 5.9×10^{-3} µg, 0.0121 µg, and 0.0137 µg at 50, 75, 100, and 125 amperes, respectively (Figure S1).

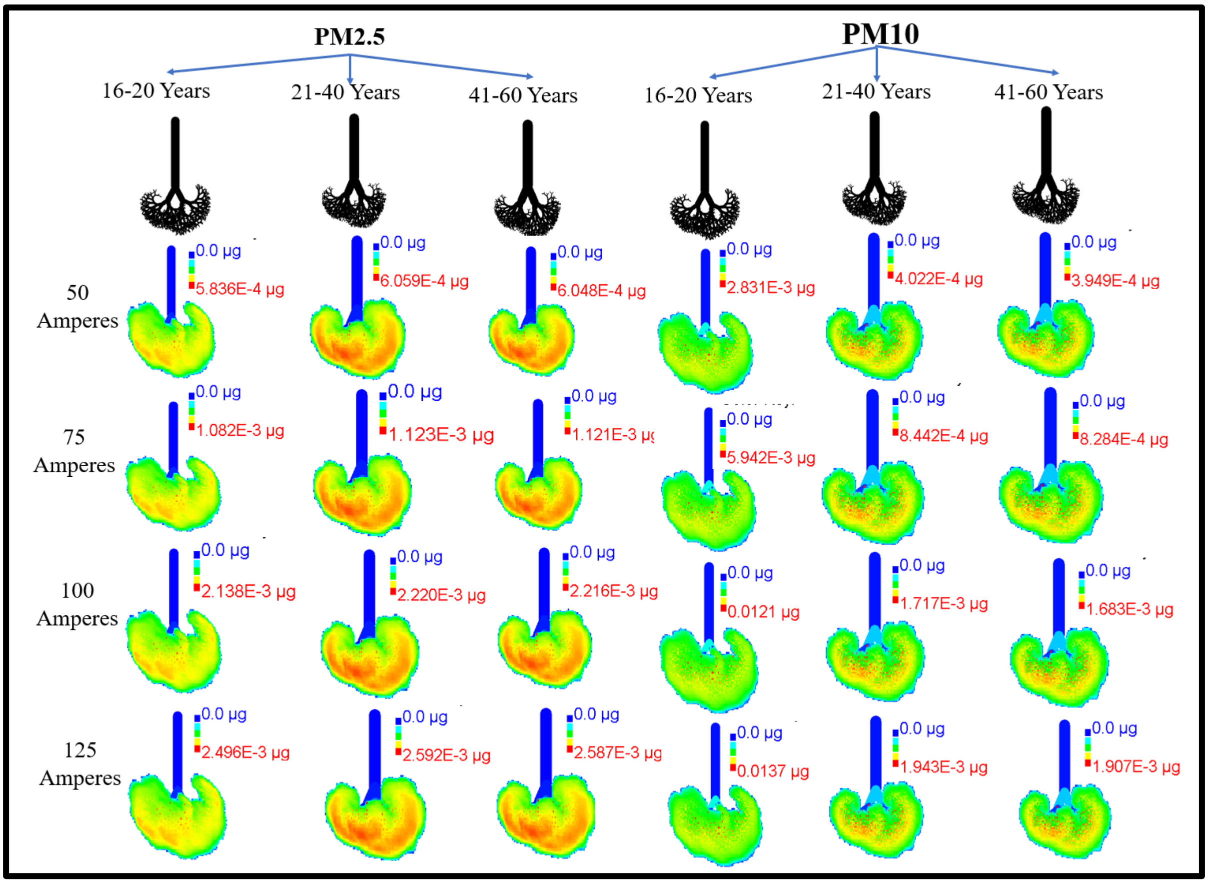


Figure S1: Visualizations of mass deposition in the tracheobronchial (TB) region for PM_{10} and $PM_{2.5}$ across different age groups (measured in µg) for shielded metal arc welding (SMAW) at different current intensities are presented. The color scales for mass deposition differ between particle sizes and age categories due to software limitations, which restricted uniform adjustment of scale settings.

The peak $PM_{2.5}$ deposition, in contrast, showed an increasing trend with age. The 16–20 age group exhibited the peak value of $PM_{2.5}$ deposition, which was lowest across all amperages, ranging from 5.8×10^{-4} µg to 2.4×10^{-3} µg, while the 21–40 and 41–60 age groups recorded average increases of 5% and 6%, respectively, for peak $PM_{2.5}$ deposition in TB region (Figure S1). For WAAM, peak PM_{10} deposition in the TB region was also highest at 18 volts/65 amperes (6.91×10^{-3} µg) and lowest for 25 volts/125 amperes (5.8×10^{-3} µg) in the 16–20 age group (Figure S3). Similar to SMAW, peak $PM_{2.5}$ deposition in the TB region increased with age, with the 16–20 age group consistently exhibiting the lowest values (1.6×10^{-3} µg and 8.2 $\times 10^{-4}$ µg under the same conditions) for WAAM at 18 volt 65 ampers, while the 21–40 and 41–60 age groups showed increases of 4% and 5%, respectively (Figure S3).

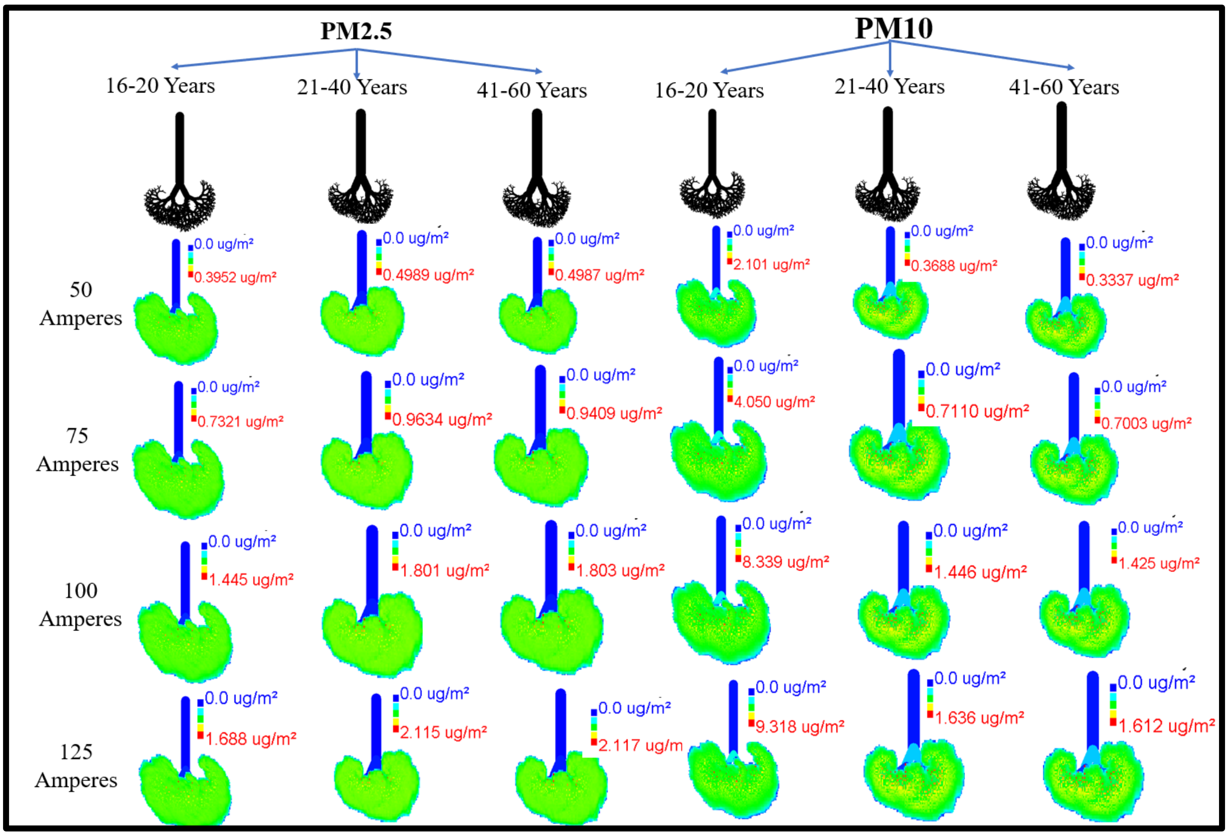


Figure S2: Visualizations of mass deposition per unit area (µg/m^2) in the tracheobronchial (TB) region for PM_{10} and $PM_{2.5}$ are presented across age groups, based on exposures from shielded metal arc welding (SMAW) at varying current intensities. The color scales for mass deposition differ between particle sizes and age categories due to software limitations, which restricted uniform adjustment of scale settings.

Deposition per unit area revealed distinct age-related trends. For SMAW, the peak PM_{10} deposition per unit area in the TB region for the 16–20 age group ranged from 2.1 µg/m² to 9.3 µg/m² across increasing amperages, significantly higher than older groups due to their larger surface area-to-volume ratio (Figure S2). Peak $PM_{2.5}$ deposition per unit area in the TB region was highest in the 40-60 age group at all amperages (Figure S2). For WAAM, the 16–20 age group recorded the peak PM_{10} deposition per unit area in TB region was highest at 4.71 µg/m² (18 volts/65 amperes) and 3.9 µg/m² (25 volts/125 amperes), while peak $PM_{2.5}$ deposition per unit area in TB region peaked in the 21–40 age group for all conditions (Figure S3). In WAAM, the peak deposition per unit area of PM_{10} was highest in the 16–20 age group, whereas for $PM_{2.5}$, the maximum deposition was observed in the 41–60 age group (Figure S3).

SMAW consistently shows peak $PM_{2.5}$ and PM_{10} deposition to be higher than WAAM in the TB region. The peak PM_{10} deposition in TB region, SMAW exhibited significant deposition across all amperages (50–125A), with the highest values in the 16–20 age group (2.1–9.3 µg/m²), surpassing WAAM (max 4.7 µg/m²). The peak $PM_{2.5}$ deposition in TB region, is increased with age, peaking in the 21–40 group for SMAW, again exceeding WAAM. While WAAM followed similar age-related trends, its overall deposition was lower. These findings highlight SMAW as a greater contributor to particle exposure than WAAM.

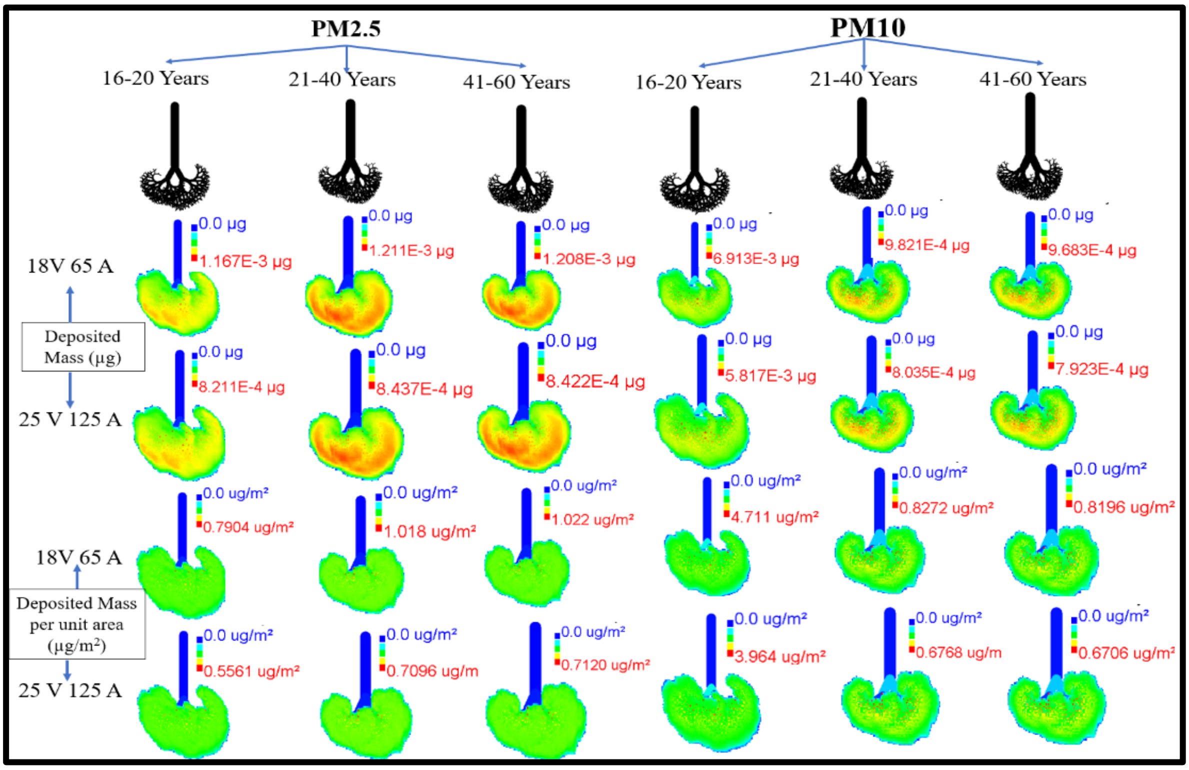
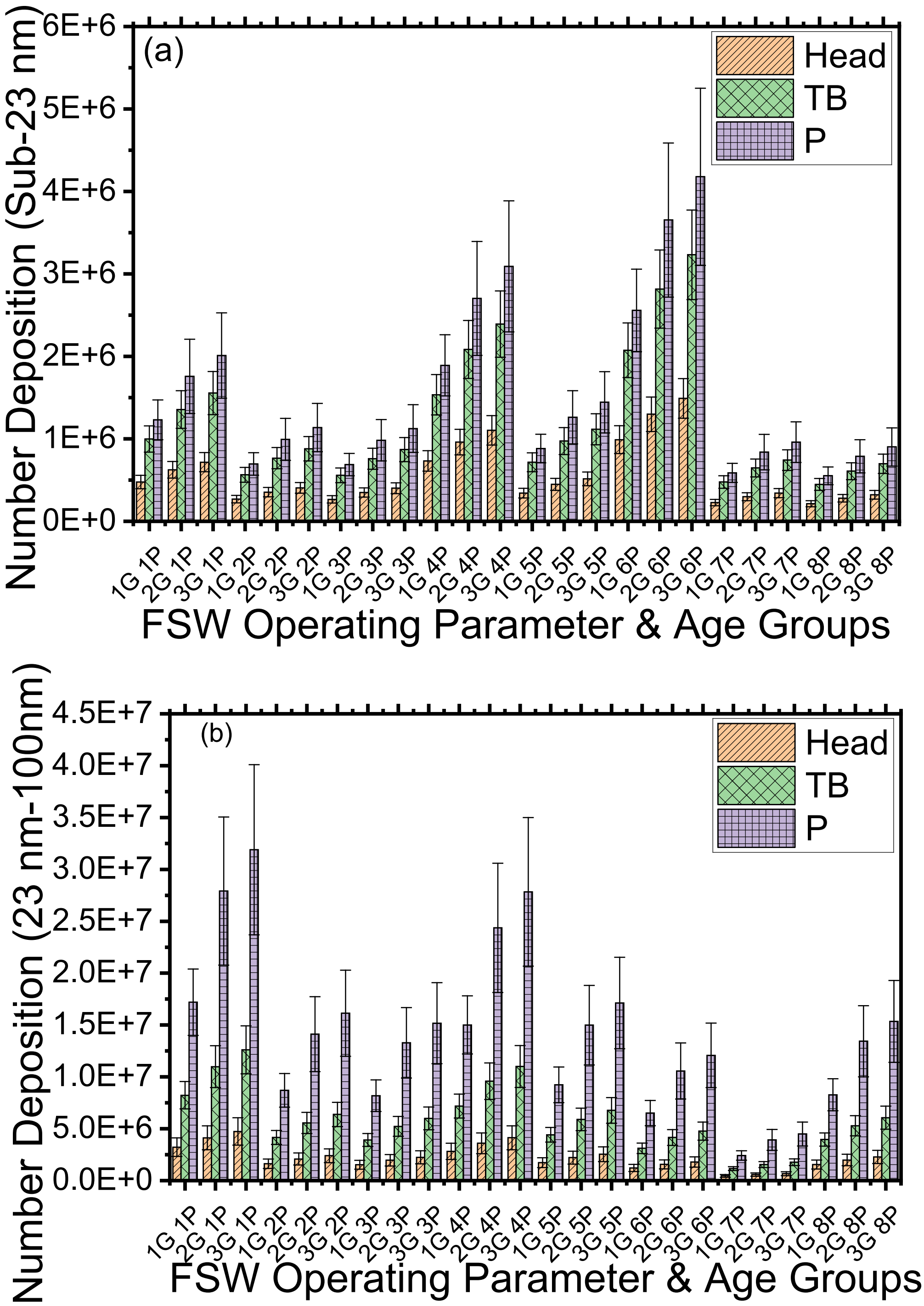


Figure S3: Visualizations of mass deposition (calculated in µg) and mass deposition per unit area (measured in µg/m^2) in the tracheobronchial (TB) region for PM_{10} and $PM_{2.5}$ across different age groups for wire additive arc manufacturing (WAAM) at different current and voltage intensities are presented. It is important to note that the color scales representing mass deposition vary between particle fractions and subjects, as software constraints limited adjustments.


(a)
Head
TB
P
Number Deposition (Sub-23 nm)
6E+6
5E+6
4E+6
3E+6
2E+6
1E+6
0E+0
1G 1P 2G 1P 3G 1P 1G 2P 2G 2P 3G 2P 1G 3P 2G 3P 3G 3P 1G 4P 2G 4P 3G 4P 1G 5P 2G 5P 3G 5P 1G 6P 2G 6P 3G 6P 1G 7P 2G 7P 3G 7P 1G 8P 2G 8P 3G 8P
FSW Operating Parameter & Age Groups
(b)
Head
TB
P
Number Deposition (23 nm-100nm)
4.5E+7
4.0E+7
3.5E+7
3.0E+7
2.5E+7
2.0E+7
1.5E+7
1.0E+7
5.0E+6
0.0E+0
1G 1P 2G 1P 3G 1P 1G 2P 2G 2P 3G 2P 1G 3P 2G 3P 3G 3P 1G 4P 2G 4P 3G 4P 1G 5P 2G 5P 3G 5P 1G 6P 2G 6P 3G 6P 1G 7P 2G 7P 3G 7P 1G 8P 2G 8P 3G 8P
FSW Operating Parameter & Age Groups

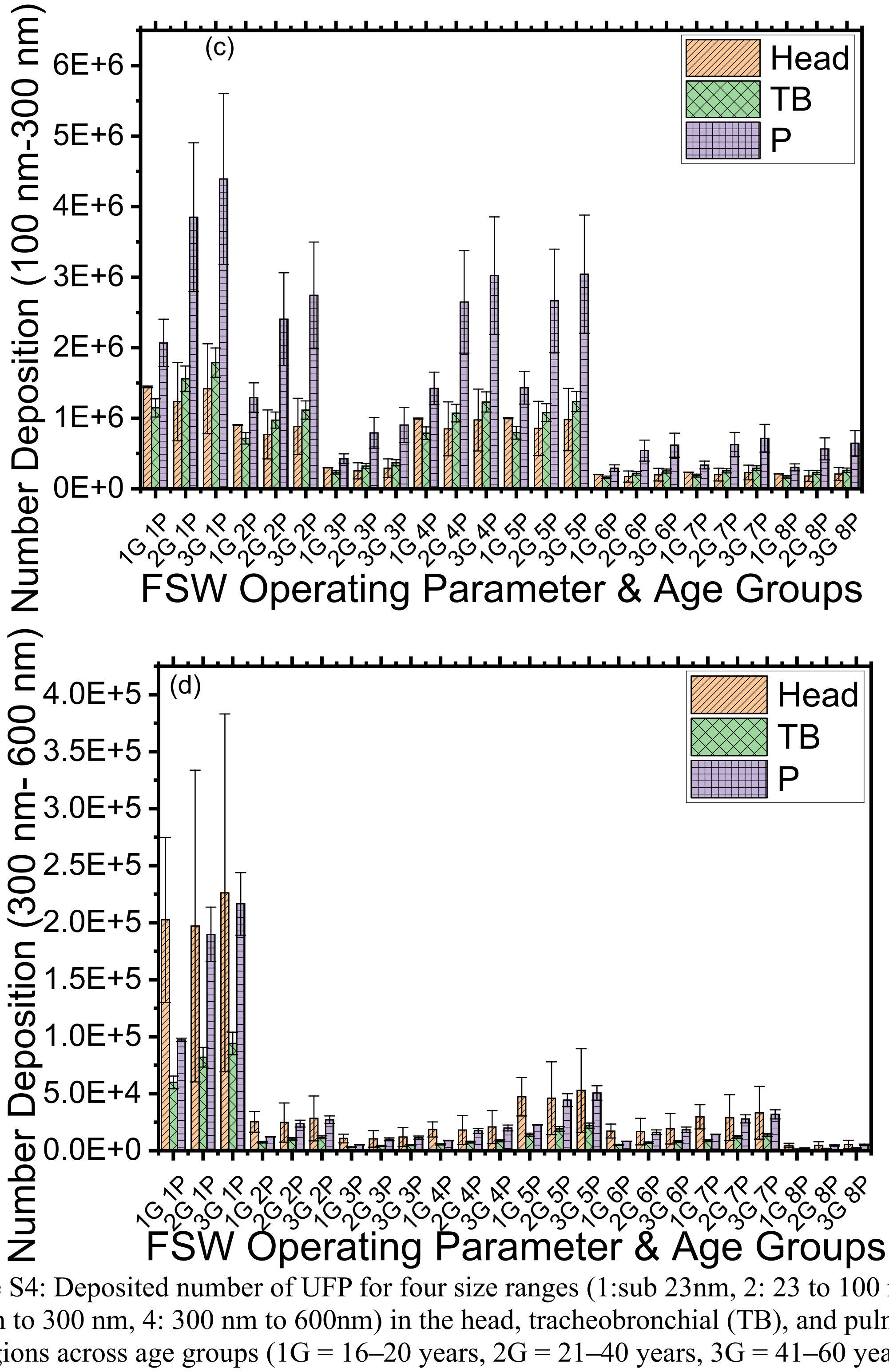
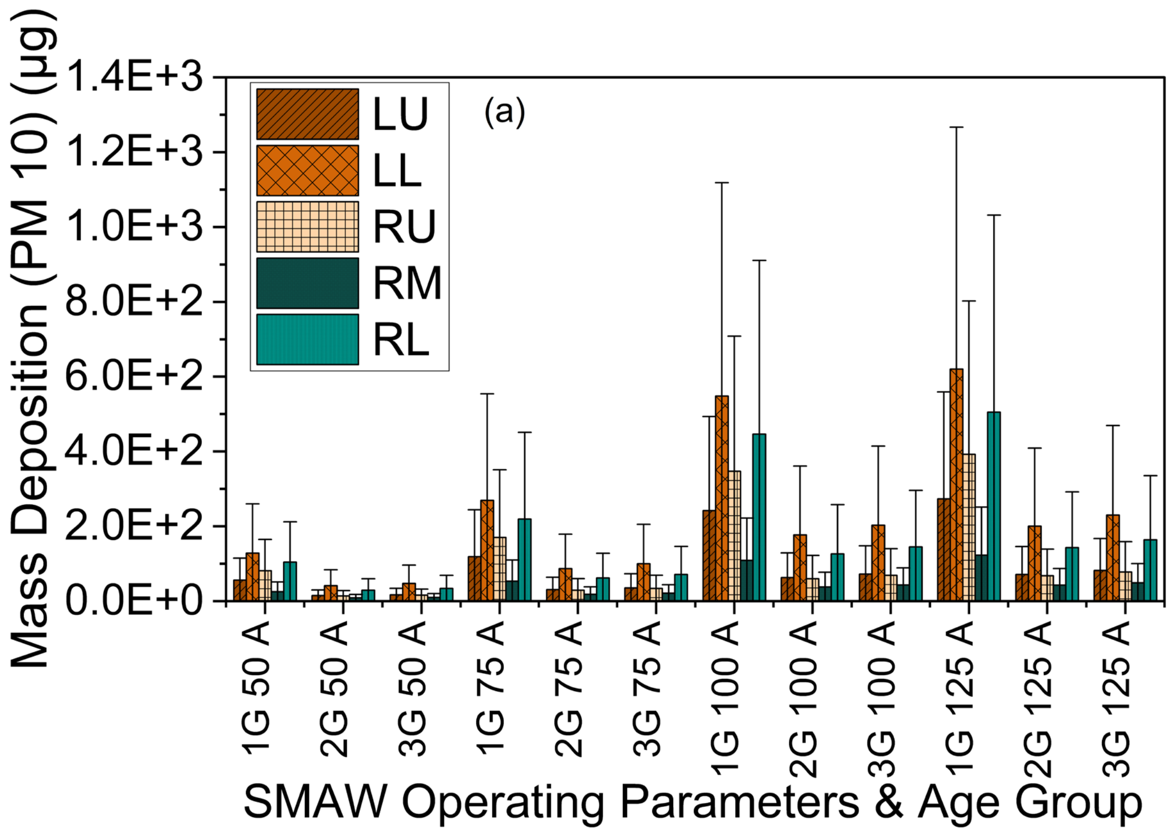
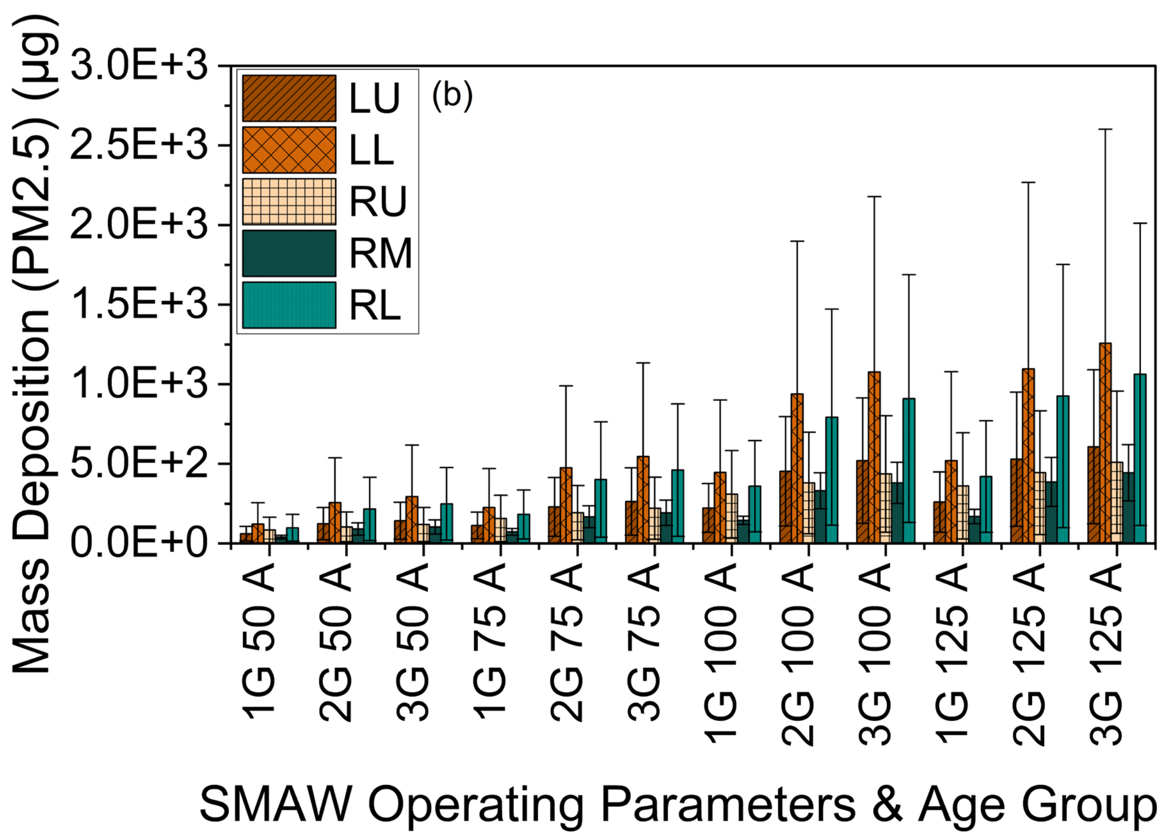


Figure S4: Deposited number of UFP for four size ranges (1:sub 23nm, 2: 23 to 100 nm, 3: 100 nm to 300 nm, 4: 300 nm to 600nm) in the head, tracheobronchial (TB), and pulmonary (P) regions across age groups (1G = 16–20 years, 2G = 21–40 years, 3G = 41–60 years) for friction stir welding (FSW) at different feed rate/RPM (38/1224 (1P), 38/900 (2P), 38/636 (3P), 98/1224 (4P), 98/900 (5P), 98/636 (6P), 58/636 (7P) and 58/1224 (8P)) (a) deposition dose for Sub 23nm UFP range from FSW (b) deposition dose for 23-100 nm UFP range from FSW (c) deposition dose for 100-300 nm UFP range from FSW (d) deposition dose for S300-600 nm UFP range from FSW


Mass Deposition (PM 10) (µg)
1.4E+3
1.2E+3
1.0E+3
8.0E+2
6.0E+2
4.0E+2
2.0E+2
0.0E+0
LU
LL
RU
RM
RL
(a)
1G 50 A
2G 50 A
3G 50 A
1G 75 A
2G 75 A
3G 75 A
1G 100 A
2G 100 A
3G 100 A
1G 125 A
2G 125 A
3G 125 A
SMAW Operating Parameters & Age Group


Mass Deposition (PM2.5) (µg)
3.0E+3
2.5E+3
2.0E+3
1.5E+3
1.0E+3
5.0E+2
0.0E+0
LU
LL
RU
RM
RL
(b)
1G 50 A
2G 50 A
3G 50 A
1G 75 A
2G 75 A
3G 75 A
1G 100 A
2G 100 A
3G 100 A
1G 125 A
2G 125 A
3G 125 A
SMAW Operating Parameters & Age Group

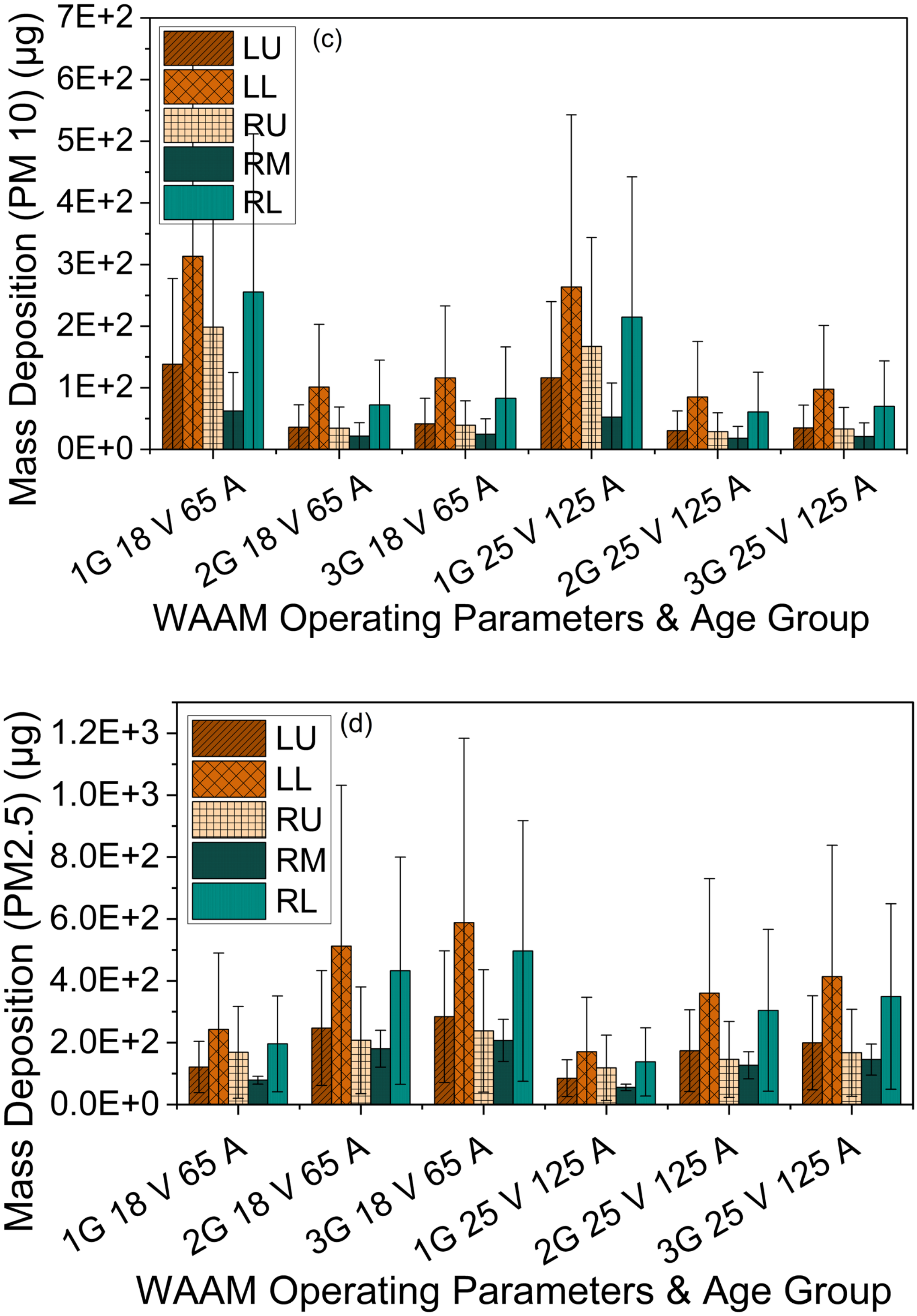
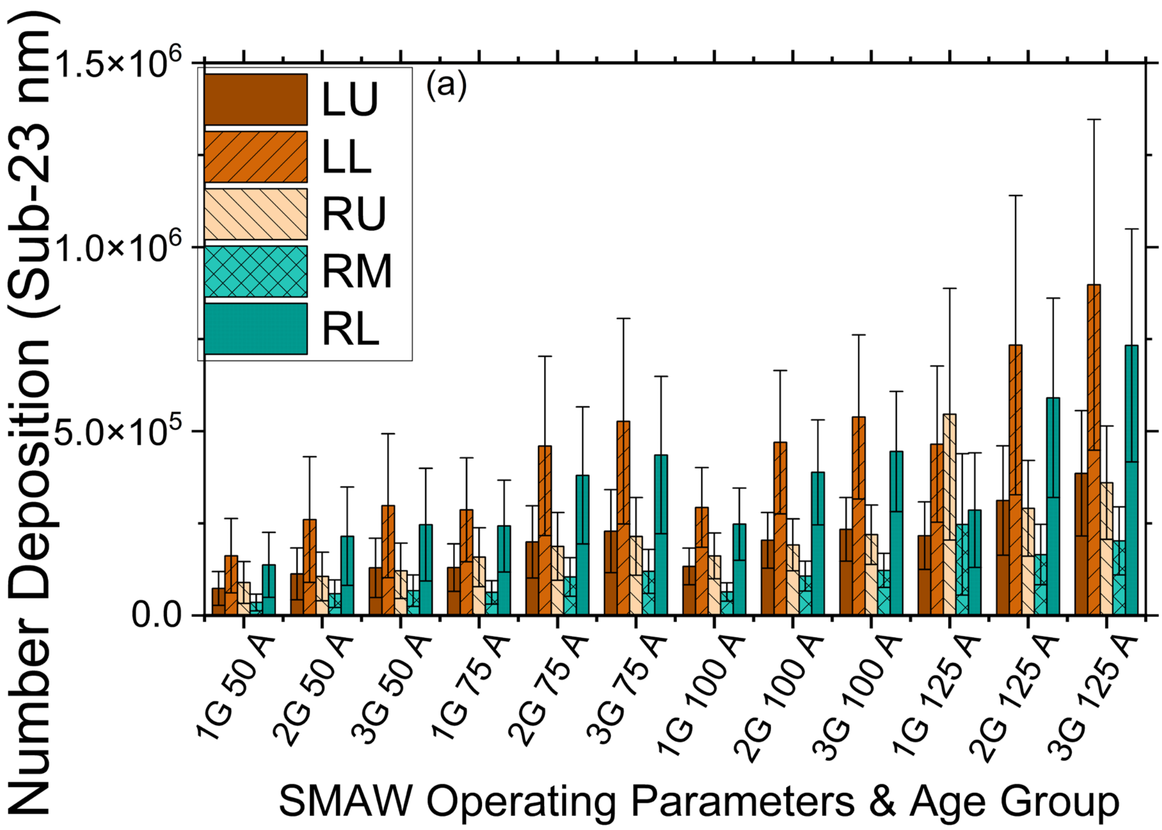
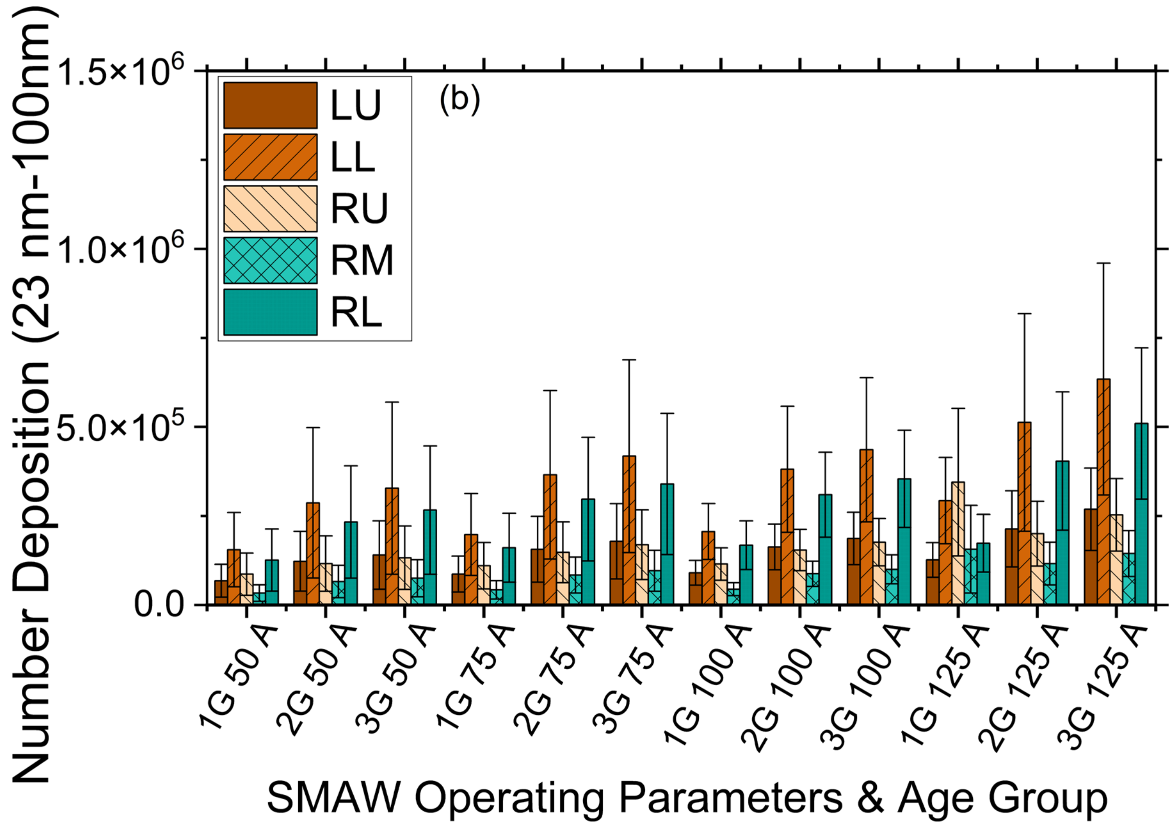


Figure S5: Deposited mass of PM in the right lower lobe (RL), right middle lobe (RM), right upper lobe (RU), left lower lobe (LL) and left upper lobe (LU) regions across age groups (1G = 16–20 years, 2G = 21–40 years, 3G = 41–60 years) for different welding techniques and parameters (a) PM_{10} during shielded metal arc welding (SMAW) at 50A, 75A, 100A, and 125A, (b) $PM_{2.5}$ during SMAW at 50A, 75A, 100A, and 125A. (c) $PM_{2.5}$ during wire additive arc manufacturing (WAAM) at 18V 65A and 25V 125A. and (d) PM10 during WAAM at 18V 65A and 25V 125A . (A= amperes, V= Volts)


Number Deposition (Sub-23 nm)
1.5×10^6
1.0×10^6
5.0×10^5
0.0
(a)
LU
LL
RU
RM
RL
1G 50 A
2G 50 A
3G 50 A
1G 75 A
2G 75 A
3G 75 A
1G 100 A
2G 100 A
3G 100 A
1G 125 A
2G 125 A
3G 125 A
SMAW Operating Parameters & Age Group


Number Deposition (23 nm-100nm)
1.5×10^6
1.0×10^6
5.0×10^5
0.0
(b)
LU
LL
RU
RM
RL
1G 50 A
2G 50 A
3G 50 A
1G 75 A
2G 75 A
3G 75 A
1G 100 A
2G 100 A
3G 100 A
1G 125 A
2G 125 A
3G 125 A
SMAW Operating Parameters & Age Group

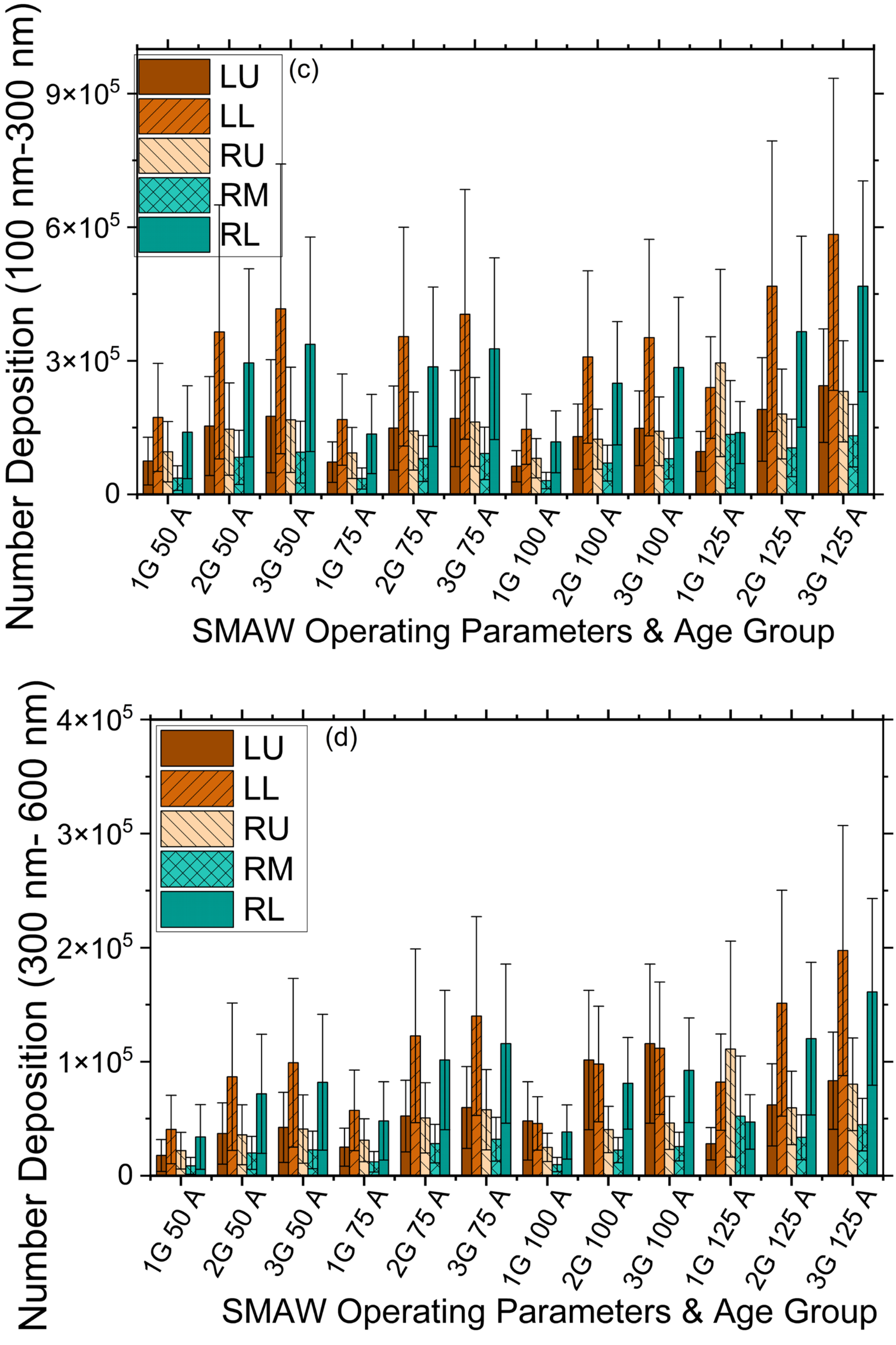
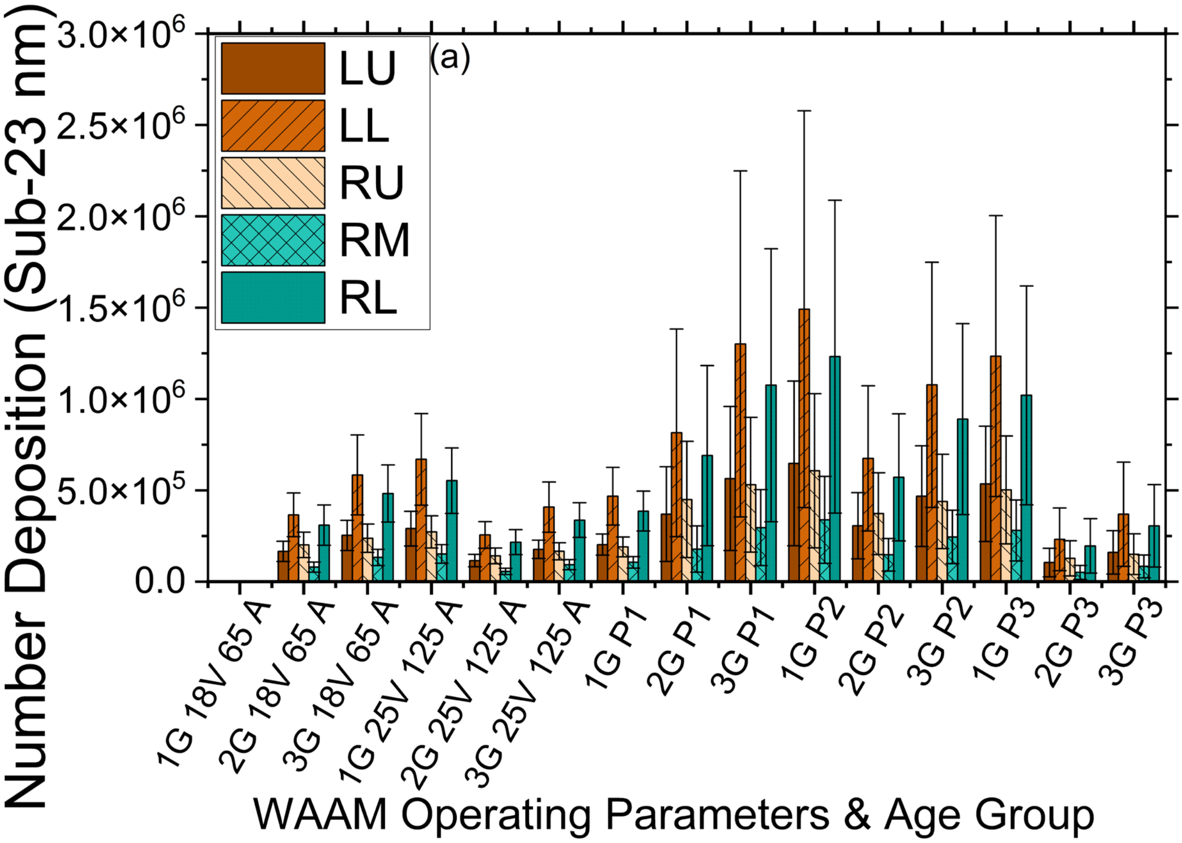
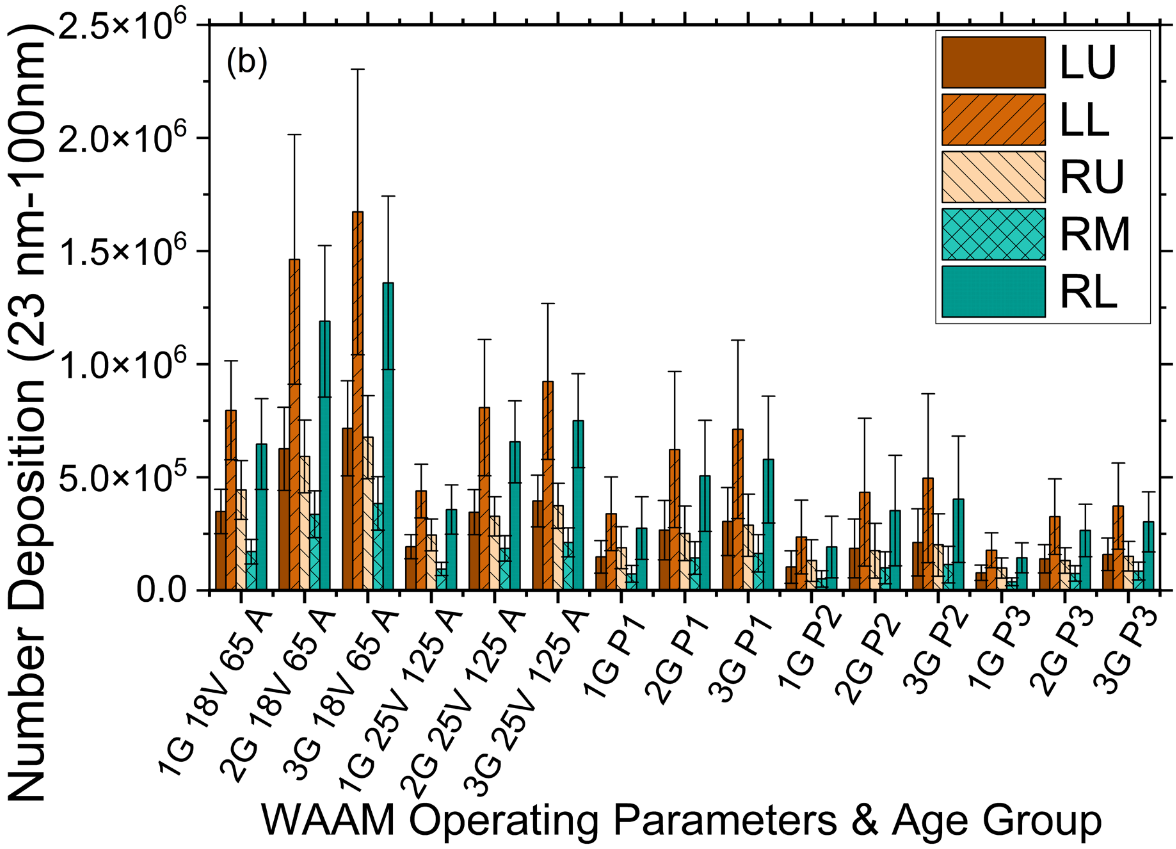
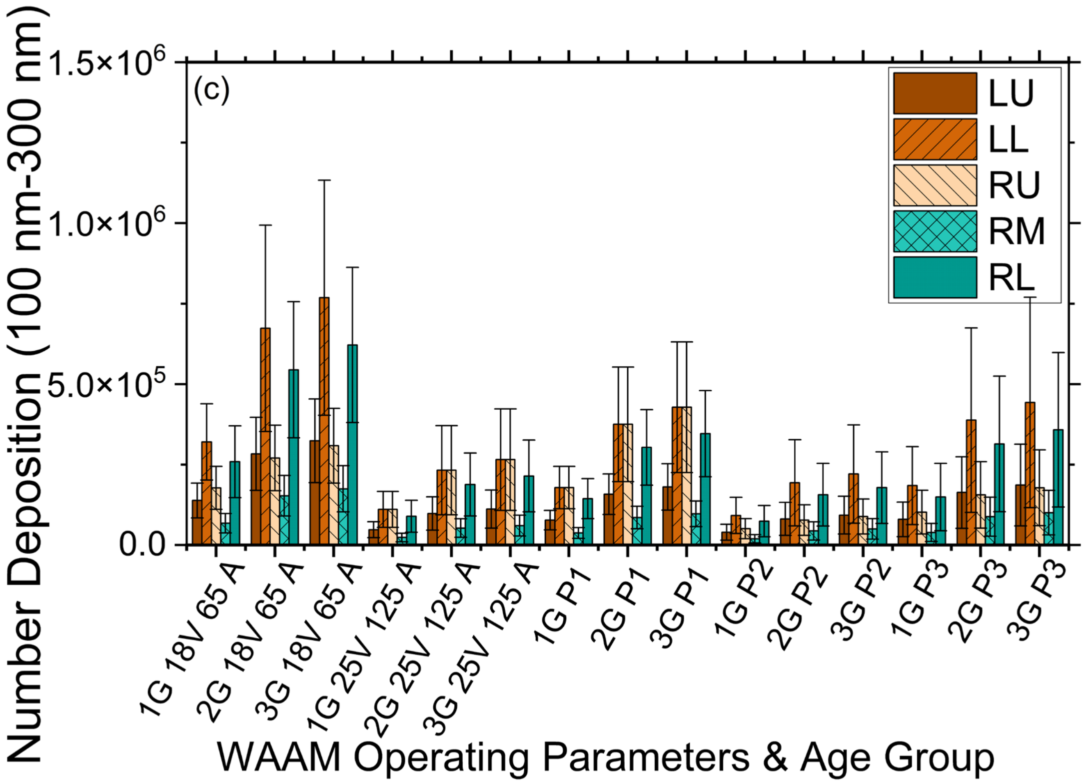


Figure S6 (a): Deposited number of UFP for four size ranges (1:sub 23nm, 2: 23 to 100 nm, 3: 100 nm to 300 nm, 4: 300 nm to 600nm) in the right lower lobe (RL), right middle lobe (RM), right upper lobe (RU), left lower lobe (LL) and left upper lobe (LU) regions across age groups (1G = 16–20 years, 2G = 21–40 years, 3G = 41–60 years) for shielded metal arc welding (SMAW) (50A, 75A, 100A, and 125A)


(a)
LU
LL
RU
RM
RL
Number Deposition (Sub-23 nm)
3.0×10^6
2.5×10^6
2.0×10^6
1.5×10^6
1.0×10^6
5.0×10^5
0.0
1G 18V 65 A
2G 18V 65 A
3G 18V 65 A
1G 25V 125 A
2G 25V 125 A
3G 25V 125 A
1G P1
2G P1
3G P1
1G P2
2G P2
3G P2
1G P3
2G P3
3G P3
WAAM Operating Parameters & Age Group


(b)
LU
LL
RU
RM
RL
Number Deposition (23 nm-100nm)
2.5×10^6
2.0×10^6
1.5×10^6
1.0×10^6
5.0×10^5
0.0
1G 18V 65 A
2G 18V 65 A
3G 18V 65 A
1G 25V 125 A
2G 25V 125 A
3G 25V 125 A
1G P1
2G P1
3G P1
1G P2
2G P2
3G P2
1G P3
2G P3
3G P3
WAAM Operating Parameters & Age Group



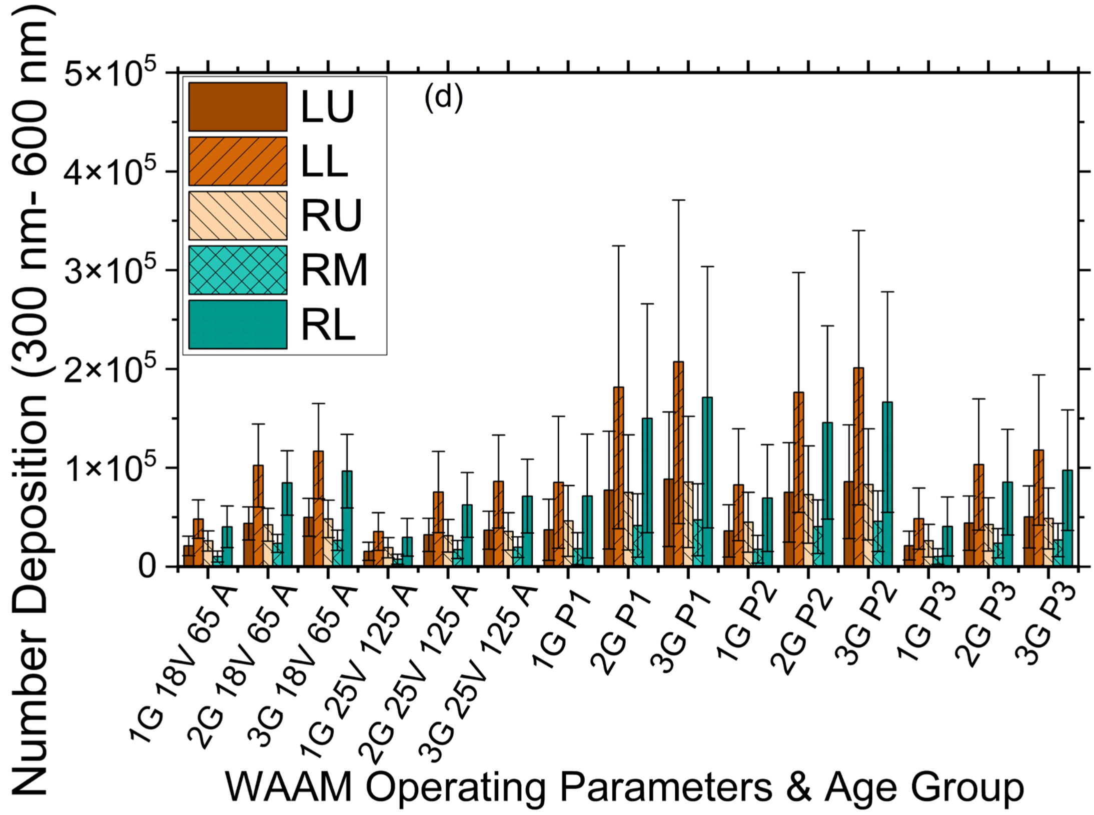


Figure S7 (b): Deposited number of UFP for four size ranges (1:sub 23nm, 2: 23 to 100 nm, 3: 100 nm to 300 nm, 4: 300 nm to 600nm) in the right lower lobe (RL), right middle lobe (RM), right upper lobe (RU), left lower lobe (LL) and left upper lobe (LU) regions across age groups (1G = 16–20 years, 2G = 21–40 years, 3G = 41–60 years) for wire additive arc manufacturing (WAAM) (18V-65A, 25V-125A, WAAM with powders (P1:95-45 µm, P2: 45-25 µm, and P3: less than 25 µm) (a) deposition dose for Sub 23nm UFP range from WAAM (b) deposition dose for 23-100 nm UFP range from WAAM (c) deposition dose for 100-300 nm UFP range from WAAM (d) deposition dose for 300-600 nm UFP range from WAAM.

S1.2 : Lungs retention for $PM_{2.5}$ from SMAW and WAAM

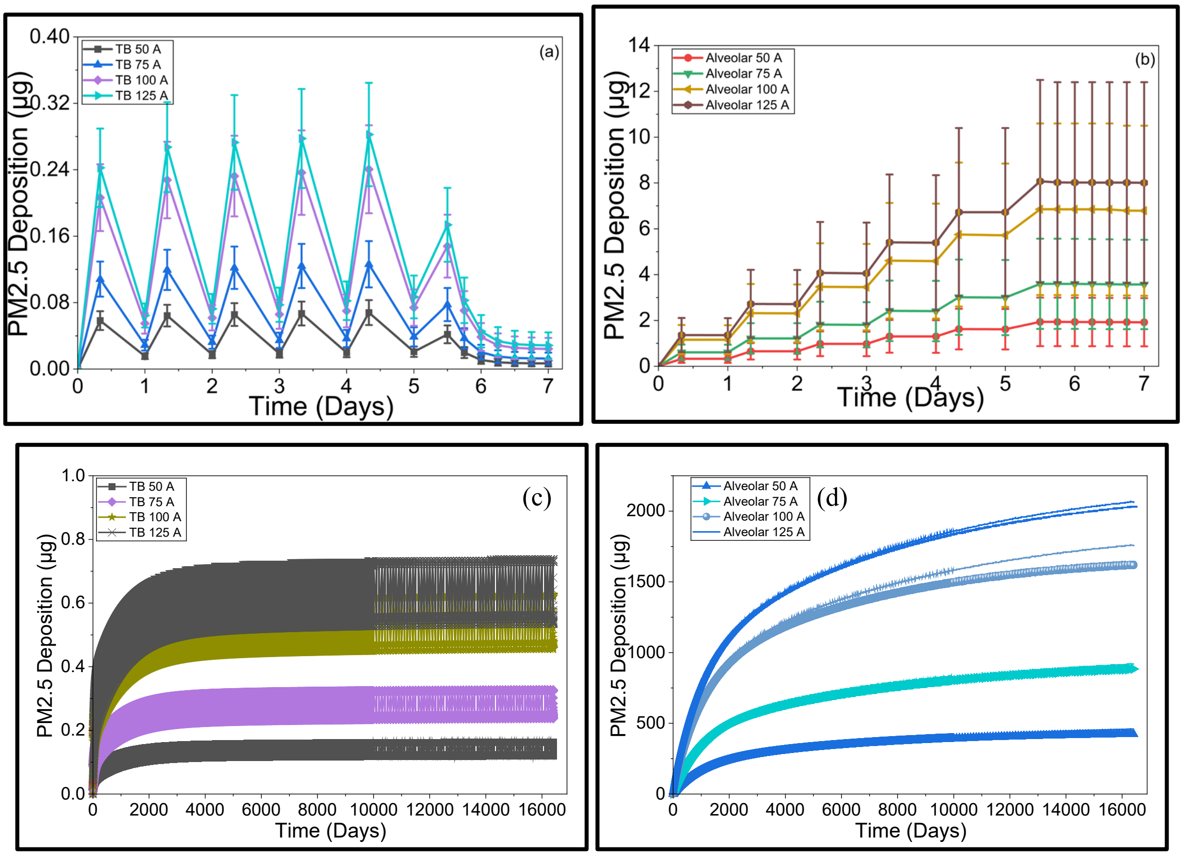
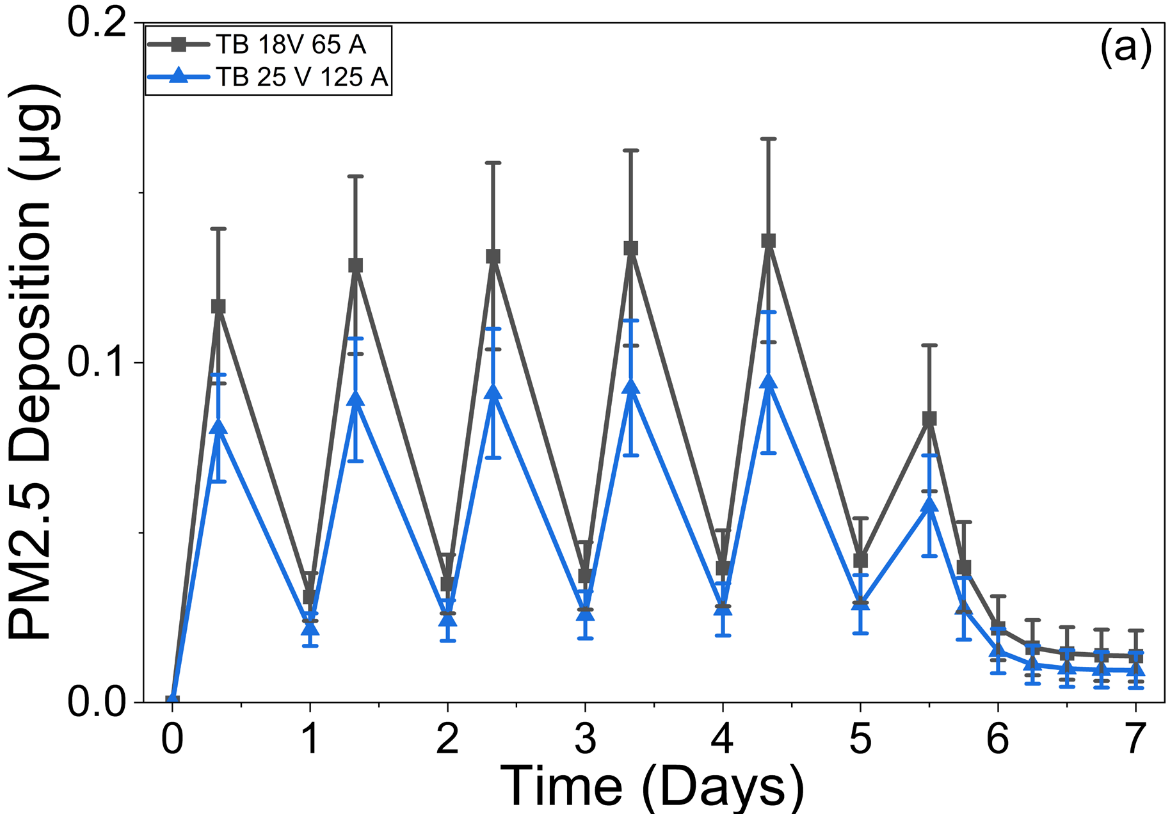
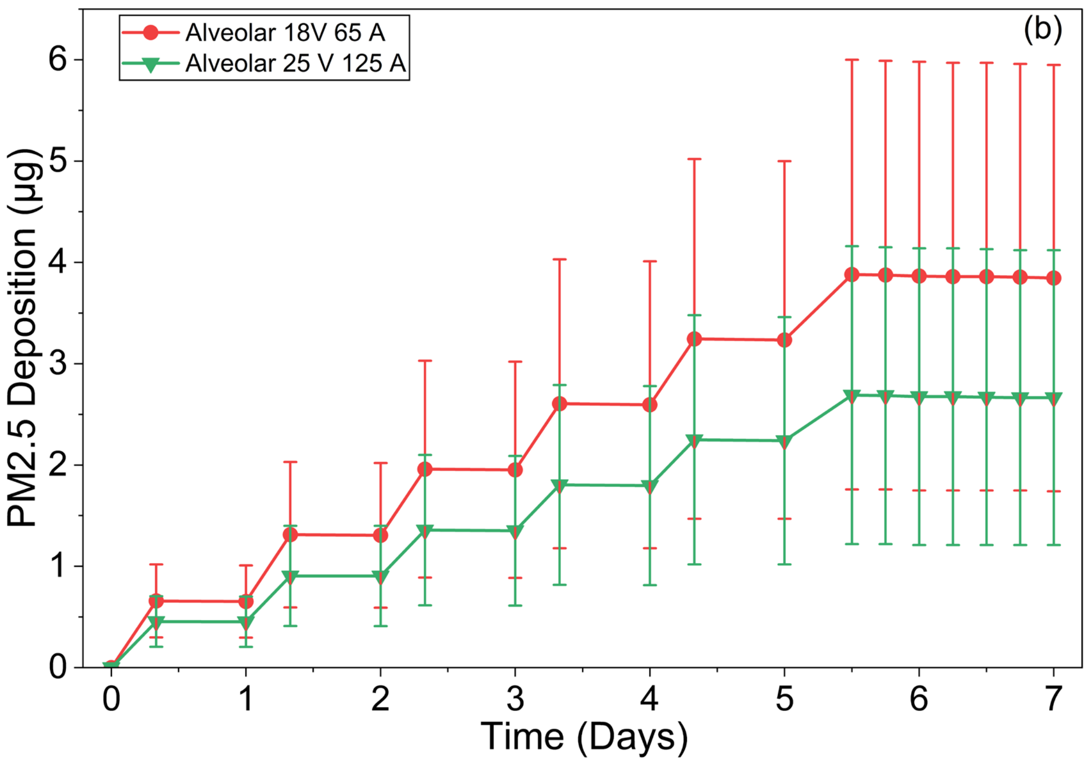


Figure S8: MPPD model predictions of welding fume mass retained in the (a) tracheobronchial (TB) and (b) alveolar regions over exposure periods of up to one week (c) tracheobronchial (TB) regions over exposure periods of up to 45 years, and (d) alveolar regions over exposure periods of 45 years. Simulations were performed using $PM_{2.5}$ concentrations measured during SMAW at 50A, 75A, 100A, and 125A for the 21–40 age group. The mean and standard deviation are shown to illustrate the variation in deposition doses across different particle densities (2 g/cm³ and 7 g/cm³).

Following the full one-week simulation, including one day without exposure, allowing only clearance, retention levels decreased to 0.028 µg/cm² in the tracheobronchial region and 8.01 µg in the alveolar region. The results presented represent particle retention values at the end of the one-week period. Detailed retention profiles for the tracheobronchial (TB) and alveolar regions, corresponding to different welding techniques, are shown in Figure S8 for SMAW and Figure S9 for WAAM. For SMAW, the highest retention doses in both the alveolar and tracheobronchial regions were observed at 125 Amperes, followed by 100 A, 75 A, and 50 A in decreasing order. In contrast, for WAAM, the 18V 65A setting resulted in greater retention doses than the 25V 125A condition in both lung regions. Figure S8 c, d shows the effects of a lifetime occupational exposure (45 years) at different concentration levels for SMAW at different current ratings. The results highlight a progressive accumulation of particles in the alveolar region, whereas retention in the tracheobronchial region tends to stabilize to a greater extent. Figure S9 c and d shows the effects of a lifetime occupational exposure (45 years) at different concentration levels for WAAM at different current and voltage ratings.





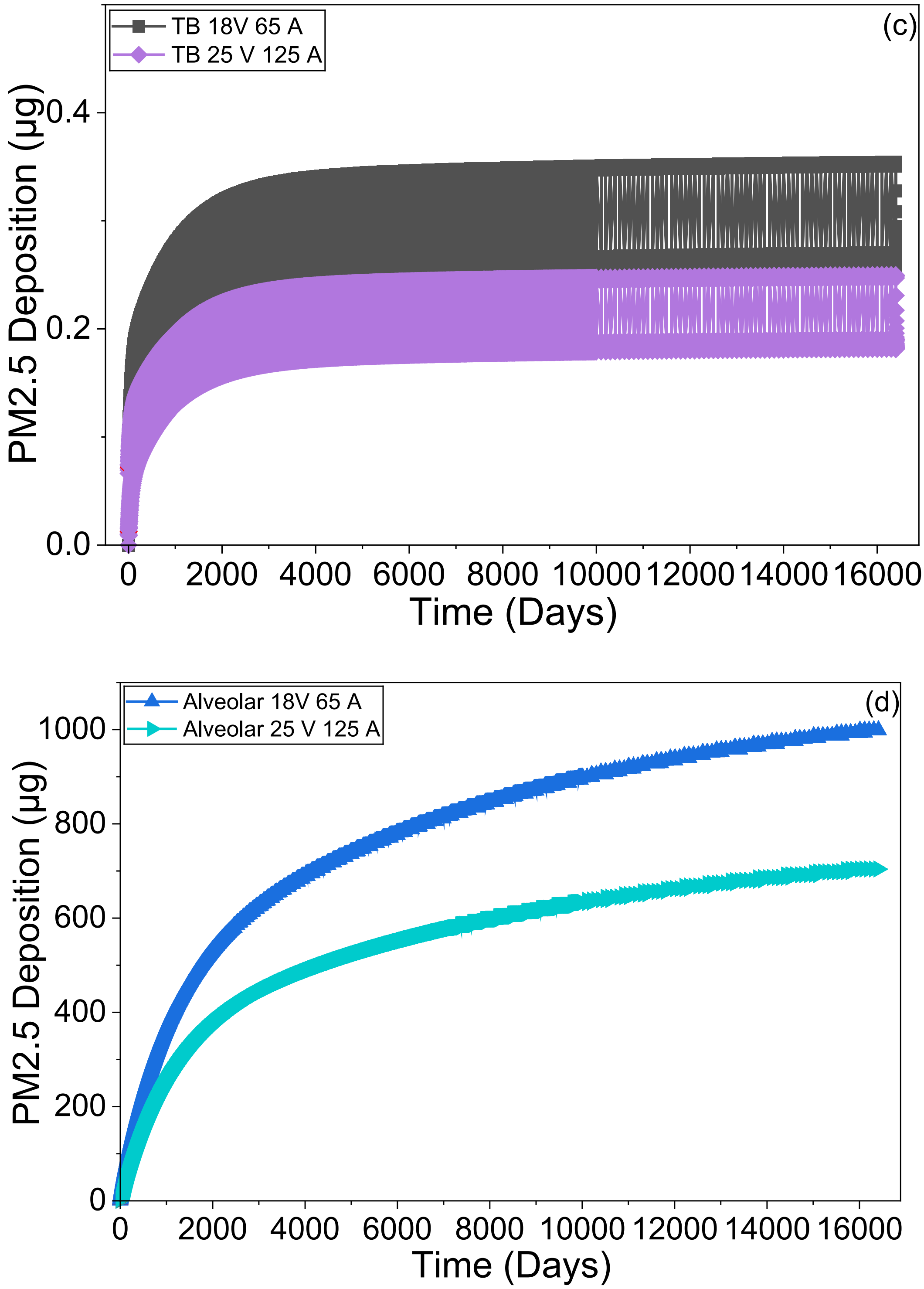


Figure S9: MPPD model predictions of welding fume mass retained in the (a) tracheobronchial (TB) regions over exposure periods of up to one week, (b) alveolar regions over exposure periods of up to one week (c) tracheobronchial (TB) regions over exposure periods of up to 45 years, (d) alveolar regions over exposure periods of 45 years. Simulations were performed using $PM_{2.5}$ concentrations measured during WAAM at 18 V–65 A and 25 V–125 A for the 21–40 age group. The mean and standard deviation are shown to illustrate the variation in deposition doses across different particle densities (2 g/cm³ and 7 g/cm³).

Table S3: The excess risk (ER) and attributable fractions (AF) for all-cause mortality associated with exposure to PM_{10}, cardiopulmonary mortality, and lung cancer mortality associated with $PM_{2.5}$

Welding processes and Parameters	**Age Groups**	**$PM_{2.5}$**			**$PM_{2.5}$**	**PM_{10}**	**All-cause mortality PM_{10}**		**Cardiopulmonary mortality $PM_{2.5}$**		**Lung cancer mortality $PM_{2.5}$**	
		LADD (μg kg^{-1} day)	**SF** (μg kg^{-1} $day)^{-1}$	**ELCR**	**HQ**		**ER**	**AF**	**ER**	**AF**	**ER**	**AF**
SMAW 50 Amperes	16-20	13.07	1.2324E-05	1.6103E-04	20.64	16.80	0.95	0.49	0.54	0.35	0.90	0.47
	21-40	15.28	8.4412E-06	1.2899E-04	20.64	16.80	0.95	0.49	0.54	0.35	0.90	0.47
	41-60	17.53	7.3566E-06	1.2899E-04	20.64	16.80	0.95	0.49	0.54	0.35	0.90	0.47
SMAW 75 Amperes	16-20	24.23	1.2324E-05	2.9856E-04	38.26	35.26	3.30	0.77	0.69	0.41	1.19	0.54
	21-40	28.33	8.4412E-06	2.3916E-04	38.26	35.26	3.30	0.77	0.69	0.41	1.19	0.54
	41-60	32.51	7.3566E-06	2.3916E-04	38.26	35.26	3.30	0.77	0.69	0.41	1.19	0.54
SMAW 100 Amperes	16-20	47.87	1.2324E-05	5.8995E-04	75.61	71.74	19.56	0.95	0.88	0.47	1.57	0.61
	21-40	55.98	8.4412E-06	4.7257E-04	75.61	71.74	19.56	0.95	0.88	0.47	1.57	0.61
	41-60	64.24	7.3566E-06	4.7257E-04	75.61	71.74	19.56	0.95	0.88	0.47	1.57	0.61
SMAW 125 Amperes	16-20	55.90	1.2324E-05	6.8890E-04	88.29	81.16	29.79	0.97	0.92	0.48	1.66	0.62
	21-40	65.37	8.4412E-06	5.5182E-04	88.29	81.16	29.79	0.97	0.92	0.48	1.66	0.62
	41-60	75.01	7.3566E-06	5.5182E-04	88.29	81.16	29.79	0.97	0.92	0.48	1.66	0.62
WAAM 18V 65 Amperes	16-20	26.13	1.2324E-05	3.2206E-04	41.28	41.06	4.50	0.82	0.71	0.42	1.23	0.55
	21-40	30.56	8.4412E-06	2.5798E-04	41.28	41.06	4.50	0.82	0.71	0.42	1.23	0.55
	41-60	35.07	7.3566E-06	2.5798E-04	41.28	41.06	4.50	0.82	0.71	0.42	1.23	0.55
WAAM 25 Volts 125 Amperes	16-20	18.38	1.2324E-05	2.2658E-04	29.04	34.52	3.16	0.76	0.62	0.38	1.06	0.51
	21-40	21.50	8.4412E-06	1.8150E-04	29.04	34.52	3.16	0.76	0.62	0.38	1.06	0.51
	41-60	24.67	7.3566E-06	1.8150E-04	29.04	34.52	3.16	0.76	0.62	0.38	1.06	0.51

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