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Personal Exposure to Metal Fume, NO_2, and O_3 among Production Welders and Non-welders

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Abstract: The objective of this study was to characterize personal exposures to welding-related metals and gases for production welders and non-welders in a large manufacturing facility. Welding fume metals and irritant gases nitrogen dioxide (NO_2) and ozone (O_3) were sampled for thirty-eight workers. Personal exposure air samples for welding fume metals were collected on 37 mm open face cassettes and nitrogen dioxide and ozone exposure samples were collected with diffusive passive samplers. Samples were analyzed for metals using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and welding fume metal exposure concentrations were defined as the sum of welding-related metals mass per volume of air sampled. Welding fume metal exposures were highly variable among similar types of welding while NO_2 and O_3 exposure were less variable. Welding fume metal exposures were significantly higher 474 $\mu g/m^3$ for welders than non-welders 60 $\mu g/m^3$ (p=0.001). Welders were exposed to higher concentrations of NO_2 and O_3 than non-welders but the differences were not statistically significant. Welding fume metal exposure concentrations for welders performing gas metal arc welding (GMAW) and shielded metal arc welding (SMAW) were higher than welders performing gas tungsten arc welding (GTAW). Non-welders experienced exposures similar to GTAW welders despite a curtain wall barrier separating welding and non-welding work areas.

Key words: Welding, Personal, Exposure, Fume, Metals, Gases

Introduction

The U.S. Bureau of Labor Statistics reports that more than 462,000 men and women in the are employed in welding, brazing, and soldering occupations[1)]. Welding is a method of permanently joining metal parts by applying heat to metal pieces and fusing them to form a permanent bond. Electric arc welding is the most common type of welding and includes shielded metal arc welding (SMAW), gas metal arc welding (GMAW or MIG), gas tungsten arc welding (GTAW or TIG)[2)]. SMAW is a process where a metal rod or stick is used as filler to join the pieces of base metal. The rod or stick is composed of a metal core surrounded by shielding material called flux. The metal core is fluidized with a high-energy current that flows between the rod and base metals while a protective inert environment is created by the shielding material. The shielding materials also vary but are generally composed of silicates and fluoride compounds[3)]. GMAW is a process where pieces of base metal are joined using a continuous feed electrode as filler where the weld is protected by shielding gas. The electrode or wire is fed through a welding gun with a nozzle for shielding gas. The shielding gas is comprised of an inert gas or combination of inert gases. The metal electrode is fluidized by a high energy current which is then protected from oxygen by the inert shielding gas ejected from the welding nozzle. GTAW is a process that uses a non-consumable tungsten electrode to create the weld, and is usually done on stainless steel using argon as the shielding gas. GTAW

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produces lower fume exposure concentrations than GMAW in controlled experiments. This difference has been attributed to the transfer of the filler metal as a spray in GMAW[4].

Welding fume is composed of solid metal suspended in air formed when vaporized metal condenses. The fume also contains relatively high levels of different toxic gases including carbon monoxide, ozone, and nitrogen oxides, that are formed during common arc welding processes[5]. The composition and generation rate of welding fume is a function of the individual welding processes, type of base metal and welding consumable rod or wire, shielding, current, voltage, and technique[4, 6, 7]. Welding fume particles are typically less than 1 μm in diameter in the fine (<2.5 μm) to ultrafine (<100 nm) respirable size fraction with the ability to penetrate deep into the alveolar regions of the lungs[8–10]. Ultrafine particles between 65 and 200 nm generate greater inflammatory pulmonary health effects than fine particles from the same source[10]. GMAW and FCAW have been observed to generate median particle diameters of 149 and 352 nm, respectively, which are close to the ultrafine size fraction of 100 nm or less. The same study observed that the concentration of particles was higher for GMAW than flux cored arc welding (FCAW)[7].

Welding fume is categorized as a Class 2B possible human carcinogen by the International Agency for Research on Cancer[11]. Welding is associated with a wide range of adverse health effects such as metal fume fever, pneumonitis, chronic bronchitis, and decrements in pulmonary function[12, 13]. In an extensive review of welding studies on workers, it was concluded that welding has been reported to cause small, transient decrements in lung function, siderosis, interstitial fibrosis, increased severity and duration of upper respiratory infection, increased mortality from pneumonia, immunosuppression, and metal fume fever[12]. Welding has been linked to significant increases in standardized mortality rates from lung cancer for those who have twenty or more years of exposure in mild steel welding but not stainless steel welding[14]. For those with greater than twenty exposure years as a welder, the risk of lung cancer has been shown to be significantly elevated. Most epidemiology studies among welders have been possibly confounded by co-exposure to asbestos or smoking[14–17].

Health effects associated with welding are also strongly related to welding fume metals and gas constituents. Fume collected from stainless steel and mild steel deposited intratracheally into the lungs of rats showed stainless steel particles remained in the lungs longer and proved to be more pneumotoxic than mild steel particles[18]. A study of 152 welding shops determined the ratio of respirable to inhalable particulate concentrations to be 53 ± 19, the highest ratio of the work type specific particulate concentration ratios observed[19].

Efforts have been made to distinguish exposures and potential health effects by welding type. It was estimated that total lung deposition from GMAW fume was 60% greater than that from SMAW and delivers three times the particle surface area to the lungs from identical exposure concentrations[20].

Many studies have analyzed particularly toxic metal components of welding fume especially Cr, Mn, and Ni[21–24], but the variability of exposures is high within and among these studies. The high variability may be attributed to large sample sizes[25, 26] or to the fact that one study was on flux-cored welders[23], as the flux-cored process is known to create generally higher and more variable exposures than processes using shielding gas. The high concentrations of Cr and Ni reported may also have been related to process parameters or may have been related to welding on high Cr and Ni containing stainless steel.

Two gaseous exposures from welding are ozone (O_3) and nitrogen dioxide (NO_2). Ozone is produced during the welding arc process and causes free radical generation in the lungs[27]. At low concentrations, ozone acts as a pulmonary irritant and can cause shortness of breath, wheezing, and tightness in the chest, and more severe exposures can cause pulmonary edema[28]. Nitrogen dioxide is also produced during welding and during most combustion processes where high temperatures can oxidize atmospheric nitrogen. The pulmonary health effects associated with nitrogen dioxide exposure have been documented as lung function disorders from diesel exhaust exposure[29] and decrements in peak expiratory flow rate from welding fume exposure[30].

NIOSH recommended that advanced studies and data were needed to better characterize welding fume exposure and associated health effects[31]. Our study was conducted in a work environment where a relatively large number of employees were involved exclusively in production welding. Our study expands on previous attempts by monitoring exposures among several types of welders and analyzing exposure samples for several metals that were determined to be welding-related. Unique aspects of this study include the collection of personal metal fume samples from welders and non-welders under different working conditions and the subsequent analysis for a spectrum of individual metals. The analysis of several component metals to estimate exposure to welding fume is a novel approach and attempts to more thoroughly evaluate the magnitude and potential impact of welding-related metal fume exposure.

Subjects and Methods

Study objectives

The overall objective of the study was to ascertain welding-related occupational exposure to welding fume metals and irritant gases. The specific objectives of this study were: 1) to measure eight hour time weighted average (TWA) exposures to welding fume metals, NO_2 and O_3 in a group of welders and non-welders in a manufacturing facility, and 2) to describe differences in concentration of welding fume metals and gases for different welding processes and between welder and non-welder exposures.

Study location

The study was performed at a facility that manufactures large electromotive engine crankcases and employed approximately sixty full-time welders in suburban Chicago. Engine crankcases are welded from mild steel plates. Many welders performed GMAW with a continuous feed welding electrode and a composite shielding gas consisting of approximately 80% carbon dioxide and 20% argon. SMAW, GTAW, and specialty welding were also done using various electrodes. GMAW and SMAW were performed primarily on mild steel in the welding of crankcases. The GTAW process was semi-automated and performed on stainless steel and this process area was not adjacent or near the other welding processes. In addition to welders, electricians and other trades necessary for large engine manufacturing are employed. The facility areas investigated consisted of welding and electrical assembly bays. Welding bays were dedicated to crankcase assembly welding, while the electrical bay area was dedicated to electrical assembly and separated from welding areas by a curtain wall. The facility was ventilated by a mix of natural ventilation from open windows and bay doors and independent mechanical ventilation systems for the welding and electrical bays and provided one hundred percent filtered outdoor make-up air. Local exhaust ventilation was generally absent or not in use near the welding areas. Some individual welding stations used portable fans for welding fume dilution and dispersion. No other exposure controls were observed in the welding areas. The welding cohort in this study was relatively mature with an average of 20 yr of welding experience.

Personal sampling

A cohort of thirty-eight participants consisting of welders, non-welder electricians, and other non-welders was recruited from the facility workforce. Workers were recruited and consented into the study prior to sampling during daily pre-shift safety meetings. This study was reviewed and approved by the University of Illinois at Chicago (UIC) Intuitional Review Board (IRB), protocol #2001-0364. Workers were sampled over five sequential weeks on Monday following a non–working weekend; each worker was monitored once. The exposure monitoring was conducted under typical working conditions although the facility was at a relatively low volume of productivity according to employees and management.

Personal samples were collected in the breathing zone of each worker for welding fume metals, NO_2, and O_3. Samplers were attached to the workers' uniforms and located approximately 20 cm from the mouth and nose. For the welders, samplers were initially attached to uniforms outside of the welding helmet. However, workers frequently raise or lower their welding helmet in combination with changes in posture which can cause samplers to be covered by the helmet. Integrated samples were collected for the entire work period including breaks and lunch. Welding fume metals samples were collected on 37 mm cellulose ester membrane 0.8 μm pore size filters (SKC, Inc, Eighty Four, PA) at a nominal flow rate of 2 liters per minute (lpm) in accordance with NIOSH method 7300. All sampling pumps were calibrated prior to deployment with representative sampling media in-line and flow rates were verified with calibrated rotameters several times during the sampling. Sample volumes were calculated by the summation of flow rates multiplied by the specific time interval and then correcting the volume to standard temperature and pressure. Two field blanks (>25%) of each sample type were used per set of daily samples. NO_2 and O_3 samples were collected using Ogawa & Company model 3300 passive diffusion samplers. Each worker was observed during the sampling period, and welding type, materials used, and welding duration in minutes were recorded.

Metals analysis

Personal welding fume metals samples were analyzed for the presence and quantity of forty metals species using inductively coupled plasma mass spectrometry (ICP-MS). Analysis was performed with a Thermo Instruments PQ-ExCell III ICP-MS (Thermo Electron Corporation, Waltham, MA) at the Wisconsin Occupational Health Laboratory (WOHL, Madison, WI), an American Industrial Hygiene Association (AIHA) accredited laboratory. Sample filters were prepared for analysis using a Milestone Ethos+ (Monroe, CT) microwave lab station for acid digestion and sample extraction. Filters were digested with 1.5 ml nitric acid, 0.5 ml hydrochloric acid, and 0.2 ml hydrofluoric acid, all metals-free reagent grade quality. Reagent blanks, check blanks, continuing calibration verification standard, laboratory control sample, and National Institute of Standards and Technology (NIST) Standard Reference Materials® (#2556, #1649a, #2709) were used for laboratory and instrument quality control. The correlation coefficient exceeded 0.99 for each isotope calibration plot. Sample error was calculated based on the standard deviations of the digested blanks along with the calculated deviations of the sample replicates. Mass of each metal element in each sample with the corresponding error was reported and used to calculate concentration and evaluate the validity of individual mass measures and distributions. Personal exposure samples were not evaluated by gravimetric analysis.

NO_2 and O_3 analysis

Samples of NO_2 and O_3 were collected on agent specific filter pads pre-treated with triethanol-amine and nitrite solutions respectively; all samples were blank corrected. High precision and good correlation with standard methods has been found using these samplers[32, 33]. Passive sampler components were cleaned by sonication and rinsed with high purity water prior to sampling. Sample filter media pads were loaded prior to sampling and samplers were stored in refrigerated airtight containers before and after sampling. Sampling media was shipped for analysis in individual airtight Teflon containers.

Sample analysis for NO_2 and O_3 concentrations was conducted at Research Triangle Institute (RTI Inc., RTP, NC). Spectrophotometry for NO_2 analysis and ion chromatography (IC) for O_3 analysis were conducted according to procedures outlined by Ogawa & Co[34].

Data analysis

Data analysis was performed using the SAS software program (Cary, NC). We determined which of the metal species were welding-related by applying two criteria: 1) where the distribution of mass in the blanks was not significantly different from distribution of mass in the samples, the metal species was determined to be unrelated to welding; and 2) in cases where mass and error distributions for metal species were determined to be not significantly different, the metal species was excluded from the summation of total welding fume. Ten metals that did have overlapping distributions with blank and error values were determined to be unrelated to welding and were excluded from further analysis. The sum of the mass of the 30 metal species determined to be welding-related is defined in this study as welding fume metals. Descriptive statistics were generated as geometric means (GM) and geometric standard deviation (GSD) in order to reduce the influence of extreme values and skewed data on measures of central tendency.

Data analysis and statistical testing were performed on natural log transformed data to accommodate non-normal data distributions and is consistent with the use of geometric means and standard deviations.

Results

Welding fume metals exposure

In this study, thirty metals were determined to compose total welding fume metals exposure. Welding fume metals exposure measurements (GM) are presented in Table 1. The single maintenance welder is not included in Table 1 data or any analysis or statistical testing and is addressed in the subsequent section. The GM welding fume metals exposure concentration was 420 $\mu g/m^3$ for welders and 60 $\mu g/m^3$ for non-welders.

Welding fume metal exposures were significantly ($p<0.05$) higher for welders than non-welders according to the *t*-test. Individual metals Al, Cr, Cu, Fe, Mn, and Zn were also significantly ($p<0.05$) higher for welders than non-welders. Exposures by welding process for welding fume and individual metal measurements are also detailed in Table 1.

Compared by welding process, GM exposure concentrations were 630 $\mu g/m^3$ for SMAW, 510 $\mu g/m^3$ for GMAW, and 59 $\mu g/m^3$ for GTAW. The three main welding process types were compared by exposure concentration using the general liner model (GLM) procedure[35]. When comparing exposures across the three welding process types simultaneously, metal fume exposures were not significantly different. The results from the GLM procedure showed there was a significant difference in welding fume exposure concentrations between SMAW and GTAW welders. There was no statistically significant difference in metal fume exposure concentrations across the different weeks of the study among welders or non-welders.

Welding fume metals exposure was composed predominantly of iron (Fe), which accounted for an average of 86% of the total welding fume metal mass among the welders and 85% among the non-welders. By welding process, Fe composed 90%, 89%, and 83% by mass for SMAW, GMAW, and GTAW respectively. Following Fe, the most abundant metals measured for SMAW, GMAW and non-welders were, in descending concentrations: Mn, Al, Cu, Zn, and Cr. For GTAW, the order of abundance following Fe was different: Mn, Zn, Cr, Al, and Cu.

Welders experienced six times the Mn concentration; four times the Al, Cu, Ti, and Zn concentration; and twice the concentration of Ni as non-welders.

Table 1. Welding exposures for welders and non-welders

Exposure	Welder (n=15)	Non-welder (n=22)	*p*-value
Fume, μg/m^3	420 (46–2,100)	60 (3.8–370)	<0.05
Fe	370 (38–2,000)	52 (2.4–330)	<0.05
Mn	31 (4.5–150)	4.8 (0.11–32)	<0.05
Al	2.4 (0.32–17)	0.60 (0.15–2.2)	<0.05
Cu	1.9 (0.37–9.5)	0.35 (0.042–2.6)	<0.05
Zn	1.3 (0.35–4.9)	0.29 (0.036–0.88)	<0.05
Cr	1.2 (0.051–1.9)	0.16 (0–0.78)	<0.05
Ti	0.57 (0.13–7.6)	0.13 (0–0.44)	0.38
Sn	0.43 (0.048–0.68)	0.11 (0–0.48)	0.75
Ni	0.25 (0.11–2.5)	0.092 (0.0018–0.51)	1.0
Ba	0.19 (0–1.8)	0.048 (0–0.16)	0.43
Pb	0.13 (0.052–0.53)	0.041 (0.00057–0.26)	0.08
Zr	0.086 (0.014–0.39)	0.035 (0.0035–0.66)	0.60
Mo	0.064 (0.023–0.66)	0.023 (0.00094–0.66)	0.51
Sb	0.047 (0.0057–0.095)	0.017 (0.00053–0.36)	0.25
Sr	0.034 (0–0.38)	0.0092 (0–0.035)	0.98
Li	0.032 (0–1.3)	0.0067 (0–0.050)	0.75
Co	0.024 (0.0060–0.15)	0.0059 (0.00011–0.033)	<0.05
V	0.020 (0.0043–0.090)	0.0031 (0.00096–0.013)	0.32
Cd	0.011 (0.0019–0.020)	0.0026 (0.00042–0.0081)	0.60
Rb	0.0091 (0.0016–0.15)	0.0022 (0.00012–0.0094)	0.13
Ag	0.0076 (0–0.0093)	0.0022 (0–0.043)	0.54
Ce	0.0062 (0.0019–0.086)	0.0016 (0–0.0050)	0.24
W	0.0052 (0–0.025)	0.0015 (0–0.0041)	0.25
Nb	0.0038 (0.00091–0.096)	0.0012 (0.000079–0.0072)	0.14
Hf	0.0031 (0.00023–0.0074)	0.0010 (0–0.014)	0.39
La	0.0025 (0.0012–0.034)	0.0009 (0–0.0032)	0.72
Tl	0.0014 (0.00029–0.0073)	0.00044 (0–0.0011)	0.80
Y	0.0010 (0–0.0013)	0.00024 (0.00052–0.018)	0.15
U	0.00045 (0.00010–0.0039)	0.00011 (0–0.00085)	0.53
Ho	0.000093 (0–0.00071)	0.000040 (0–0.00097)	
NO_2, ppbv	50 ()	37 ()	0.06
O_3, ppbv	7.3 ()	3.2 ()	0.07

Exposures concentrations to nickel and total chromium were relatively similar among GMAW and GTAW welders. For nickel, GTAW resulted in the highest exposure followed by SMAW and then GMAW. For total chromium, SMAW resulted in the highest exposure to followed by GTAW and finally GMAW. Manganese exposure for GMAW was nearly two times higher than for SMAW and nearly ten times higher than for GTAW. Manganese was approximately 10% of total metal fume concentration and the percent exposure to manganese in the total sample was not significantly different between welders and non-welders.

There were two welders with very different welding fume metals exposure concentrations and metals compositions. One was a maintenance welder and another was a SMAW welder. The maintenance welder's exposure to welding fume metals concentration of 2,572 μg/m^3 was composed of only 38% of the Fe versus 83–90% for other welding process types. The maintenance welder was exposed to higher concentrations and higher percentages of Al, Cr, Ni, Sr, and Zn than all other welders. The SMAW welder had a total welding fume metals exposure of 2,077 μg/m^3, similar to the maintenance welder. This SMAW welder was exposed to welding fume metals at nearly six times the average level of all other welders. Factors influencing this SMAW welder's high and different exposures may be that they were observed performing carbon-arc gouging and grinding. Carbon-arc gouging is a physical process of removing metal from a work piece using an electric arc from a carbon electrode to melt metal while air moves through the arc and blows away the molten metal. These activities may also have contributed to the high percentage (95%) of iron in the exposure concentration relative to other welders in the study.

NO_2 and O_3 exposure

Welders experienced higher exposure concentrations of NO_2 than non-welders, 50 and 37 ppb, respectively, but the difference was not statistically significant. The same was true for exposure to O_3 at 7.3 ppb for welders and 3.2 ppb for non-welders. The ACGIH TLV for ozone and nitrogen dioxide are 0.08 ppm (moderate work load) and 3 ppm, respectively. It is notable how-

Table 2. Welding exposures by type of welding

Exposure	SMAW (n=7)	GMAW (n=6)	GTAW (n=2)	Maintenance (n=1)
Fume, μg/m^3	630 (150–2,100)	510 (140–1,700)	46–77	2,600
Fe	570 (130–2,000)	450 (120–1,500)	38–64	990
Mn	32 (8.0–75)	51 (15–150)	4.5–6.7	120
Al	4.0 (1.1–9.6)	2.3 (0.32–16)	0.33–0.76	110
Cu	3.3 (0.74–9.5)	2.0 (0.66–4.6)	0.37–0.53	4.1
Zn	2.6 (0.95–3.7)	0.78 (0.35–4.9)	0.96–1.2	8.1
Cr	1.8 (0.051–1.90)	0.46 (0.14–1.6)	0.29–1.8	160
Ti	0.65 (1.4–7.6)	0.79 (0.33–2.8)	0.13–0.23	22
Sn	0.57 (0.082–0.68)	0.10 (0.047–0.42)	0.081–0.24	0.47
Ni	0.36 (0.14–2.5)	0.29 (0.11–1.2)	0.18–1.7	390
Ba	0.34 (0.088–1.2)	0.22 (0–1.8)	0.11–0.16	380
Pb	0.15 (0.074–0.33)	0.12 (0.052–0.53)	0.057–0.10	1.1
Zr	0.14 (0.037–0.39)	0.035 (0.014–0.13)	0.028–0.084	0.16
Mo	0.12 (0.036–0.66)	0.075 (0.027–0.32)	0.023–0.029	1.7
Sb	0.10 (0.016–0.080)	0.024 (0.012–0.095)	0.0057–0.0098	0.057
Sr	0.067 (0.017–0.38)	0.037 (0–0.18)	0.017–0.026	380
Li	0.047 (0.013–1.3)	0.010 (0–0.28)	0.0098–0.010	3.1
Co	0.037 (0.012–0.15)	0.037 (0.014–0.13)	0.0060–0.014	0.16
V	0.034 (0.016–0.090)	0.014 (0.0053–0.034)	0.0043–0.010	0.30
Cd	0.025 (0.0020–0.019)	0.0037 (0.0019–0.015)	0.018–0.020	0.030
Rb	0.023 (0.0073–0.15)	0.0058 (0.0016–0.036)	0.0034–0.0048	0.94
Ag	0.013 (0–0.0093)	0.0027 (0.00044–0.0063)	0.0023–0.0034	0.043
Ce	0.0081 (0.0038–0.086)	0.0063 (0.0024–0.028)	0.0019–0.0022	0.11
W	0.0065 (0.0039–0.025)	0.0035 (0–0.016)	0.0064–0.015	0.36
Nb	0.0049 (0.0076–0.096)	0.0061 (0.0014–0.021)	0.00091–0.0015	0.12
Hf	0.0049 (0.00070–0.0074)	0.00072 (0.00023–0.0034)	0.00072–0.0022	0.0042
La	0.0037 (0.0019–0.034)	0.0030 (0.0012–0.013)	0.0012–0.0013	0.056
Tl	0.0027 (0.00029–0.0034)	0.0013 (0.00030–0.0073)	0.00061–0.00061	0.020
Y	0.00091 (0.0015–0.018)	0.0017 (0.00052–0.013)	0.00059–0.00089	0.32
U	0.00078 (0.00022–0.0039)	0.00034 (0.00013–0.0013)	0.00010–0.00020	0.0048
Ho	0.00024 (0–0.00071)	0.000074 (0.000027–0.00041)	0.000043–0.000051	0.0054
NO_2, ppbv	64 (52–220)	38 (37–61)	48–52	33
O_3, ppbv	4.7 (0–20)	12 (0–37)	0.46–0.75	1.8

ever that the maximum exposure concentrations for both NO_2 and O_3 were nearly three times higher in welders than in non-welders. No statistically significant differences were found in exposure concentrations of NO_2 or O_3 among different types of welding. No statistically significant correlations were found between NO_2 and O_3 exposures or between each gas and welding fume metals exposure.

Discussion

The differences in welding fume metals exposure concentrations can be attributed to status as welder or non-welder and further differentially characterized by type of welder. Welders in this study experienced significantly higher welding fume metals exposure concentrations than non-welders. A similar study of welders and non-welder controls by Kim *et al*. reported cyclone-collected PM2.5 exposures of 1,660 μg/m^3 for welders and 40 μg/m^3 for controls[36]. This exposure concentration for welders is in relatively close agreement with the results of our study. The exposure differences between the Kim study and our results could be due to the fact that our study defined welding fume metals as the sum of 30 welding-related metals rather than the entire mass collected.

The welding fume metals exposure concentrations in this study did follow a pattern reported by previous studies where SMAW produced higher welding fume exposures than GMAW. The range of exposure concentrations was similar between the SMAW and GMAW groups for our study: SMAW range was 150 to 2,100 μg/m^3 and the GMAW range was 140 to 1,700 μg/m^3.

In comparison with other welding types, GTAW produced relatively low welding fume metals exposures with a range of 45–77 μg/m^3. The non-welder electricians actually experienced similar welding fume metals exposures to GTAW welders. This may reasonably be explained by the fact that the non-welder electricians were adjacent to the main welding bays and separated by a curtain wall, which may have provided inadequate abatement of fugitive welding fume metals. The GTAW area was in a separate part of the facility and was not adjacent to the SMAW/GMAW area. The GTAW process was semi-automated where welders set up the process but the welding was performed in a way in which the welders were not located in the welding plume like those individuals performing GAMW or SMAW welding. This combined with the fact that GTAW does not use a consumable electrode, likely contributed to lower exposures.

One finding of importance from this study is that those welders involved in maintenance or non-typical welding applications may experience exposures of much higher concentrations of more toxic metals for the same welding duration as those doing production SMAW, GMAW, and GTAW. Another finding is that non-welders working adjacent to welding areas may experience exposure to welding fume metals, with proportions of metals similar to welder exposures. In this study, the non-welders experienced higher average exposures than those doing GTAW and approximately one-fifth the exposure of those doing GMAW. This suggests that welding fume metals may have migrated from areas of high welding activity and were not well controlled by curtain walls or separate dilution ventilation systems.

In this study, chromium was measured at geometric mean exposures of 0.16 μg/m^3 for non-welders and 1.2 μg/m^3 for welders. These exposures are in agreement with previous studies in shipyard SMAW with chromium exposures at 1–2 μg/m^3, [37]. The welders in this study may be exposed to chromium below the level of boilermakers involved in cutting, grinding, and welding. A recent study reported exposure to chromium among boilermakers at 4.7 μg/m^3, [38]. This seemingly high concentration may be attributed to the semi-confined and close-to-source working conditions of boilermakers.

Manganese is a metal of high toxicity and concern among welders. In this study the geometric mean exposure concentration of manganese among non-welders was 4.8 μg/m^3 and 31 μg/m^3 among welders. A similar study measured breathing zone concentrations of manganese among welders to be 22.2 μg/m^3 before and 8.2 μg/m^3 after the introduction of local exhaust ventilation (LEV)[39]. These study observations are in strong agreement but alarming, as the non-welders in this study were exposed at close to the same level as other welders utilizing LEV. Additionally, welders in this study have average exposures higher than the pre-LEV intervention study welders. The relatively high levels of manganese are likely due to the high manganese content of the mild steel base metals and consumables used by this group of welders. The geometric mean exposure to manganese of 51 μg/m^3 for GMAW, 32 μg/m^3 for SMAW, and 5.5 μg/m^3 for GTAW may be influenced by welders who experienced high exposures. One GMAW welder had an exposure concentration of 150 μg/m^3 manganese, which was higher than the maintenance welder. One SMAW was exposed to manganese at 75 μg/m^3. These exposures are considerably lower than the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value-time weighted average (TLV-TWA) of 0.2 mg/m^3 for manganese. Despite manganese exposures in our study being below current recommended standards, these exposures should be considered candidates for control measures given the severity of the associated irreversible toxic neurological effects[40–42].

The most interesting result in this study was the exposure concentrations of the single maintenance welder. The maintenance welder welded for a total of fifty minutes, in the lowest third of all welding times, but experienced the highest exposure concentration and a much different exposure profile than other welders. The welding fume metals concentration exposure of the maintenance welder was approximately four times higher than the average exposure for SMAW welders. The maintenance welder experienced double the concentration of manganese, 140 times the chromium concentration, and over 400 times the nickel concentration than the next highest welding type. The maintenance welder experienced high percentages of Ba, Cr, Ni, and Sr of total welding fume metals relative to other welders and non-welders. A major drawback is that only one maintenance welder was observed in this study, but this may serve as a precautionary example when conducting exposure assessments on welders doing similar work or using a combination of several welding techniques.

Other factors that likely influenced exposures, but were uncontrollable, were the use of fans and non-uniform ventilation. Fans were used and windows and bay doors were opened intermittently. Welders often did more than one type of welding in addition to their primary welding type. Welders also performed grinding, gouging, and blowing that may have affected their exposure concentrations and profiles. The specific nature of the welding operation being performed may have added to the variability of exposures between welding types. For example, some welders doing SMAW were able to weld in a standing position with the work pieces in front of them where they were able to maintain a distance from the welding plume. Other welders doing SMAW were required to kneel or work over their work pieces to perform welding tasks placing them directly into the cloud of freshly formed welding fume. Another example with GMAW welders is that some performed welding tasks in very close proximity to and nearly inside of engine crankcases, while others performed GMAW on more easily accessible locations out of the welding fume. The variability in work practices is likely the cause of the large range of exposure concentrations for those doing the same types of welding. Any attempt to estimate emission rates in terms of welding time would likely be confounded by differences in welding practices. The same is true for applying previously derived emission rates to this group of welders. There was no difference in welding fume metals exposure concentrations observed in welders or non-welders over the 5 wk study duration.

Exposures to welding-related gases did not exceed the OSHA permissible exposure limits of 0.1 ppm TWA for O_3. The short term exposure limit (STEL) of 1 ppm and the ceiling limit of 5 ppm for NO_2 were not directly applicable to the 8 h TWA samples collected. There were higher exposure concentrations of NO_2 and O_3 for welders than non-welders, though this difference was not statistically significant. Welders in this study experienced exposures to NO_2 and O_3 that are in close agreement with those of the boilermakers in another study, who experienced exposure to NO_2 of 46.2 ppb and O_3 of 2.6 ppb[38]. The exposure for welders in this study compared to boilermakers was slightly higher for both gases but it seems reasonable to conclude that the types of work produce equal exposures. This study benefited from the ability to access an actual production-welding environment utilizing several types of welding. The study participants worked the same shift duration and manner as they would normally. Despite possible conservative estimates of welding fume metals exposures, this study provides more detailed exposure information in terms of the variety of metals analyzed by ICP-MS and in combination with the personal exposure assessment to welding-associated gasses.

The results of personal exposure to welding fume metals, as defined in this study are not readily comparable to occupational exposure limits and are likely lower concentrations than studies in which welding fume was collected and analyzed using gravimetric methods.

The facility in this study was reportedly in a low production mode at the time of this study. There were fewer workers than at normal production levels and the workers in the study welded for short times relative to their work shift. The absolute exposure concentrations may be lower than what could occur during full capacity production and should be considered a low estimate of possible exposures, when reviewing these exposure data.

Welders who were classified into specific groups by welding process also did other welding and tasks such as grinding or parts cleaning that may have affected their exposures. However, due to the consistencies in relative exposure concentrations by welding type between welders in our study and similar studies, it can be said with confidence that specific exposure profiles and average concentrations exist for certain welding types.

The methods of analysis only allowed for measurement of elemental forms of metals without being able to distinguish valance state. In addition, there was no way to account for the relative contributions of different oxides of metals that are often formed during welding. This method did not allow for the separation of certain metals such as chromium and nickel into separate forms that may have been in welding fume. This is important as the toxicity and bioavailability may differ with metal valence state.

Welding fume metals exposure was assessed with monitors located in the breathing zone of the welders. However, it was observed that as welders moved during the course of their work tasks and flipped their masks multiple times for visualization of their work, monitors were sometimes in and out of the welding helmet. One study showed that the inside to outside helmet ratio for welders was 0.9 but results were highly variable and another study showed the helmet did not reduce exposures in the welders breathing zone when welding in an enclosed space[43, 44]. The monitor placement may have affected certain exposure measures.

Conclusion

The results of this study were in agreement with similar exposure assessments of welders and are to some degree applicable to welders who perform the same welding types. This is true for the exposure concentrations and the proportions of metals measured for each welding process. The exceptions were the maintenance welder and welders who experienced relatively high exposures from short durations of welding.

Welders were exposed to significantly higher concentrations of welding fume metals, defined as the sum of metal mass for 30 individual metals, aluminum, chromium, copper, iron, manganese, and zinc. Welders were exposed to higher concentrations of ozone and nitrogen dioxide but the difference was not statistically significant. SMAW resulted in the highest average exposures, followed by GMAW, and GTAW. SMAW concentrations were significantly higher than GTAW.

Welders involved in maintenance or non-typical welding applications may experience much higher concentration exposures of more toxic metals for the same welding duration as those doing production SMAW, GMAW, or GTAW.

The welding process produces periods of high exposure which are not entirely accounted for by integrated sampling. These periods of high exposure and the type of metals involved may affect welders differently than the exposure that is characterized by their 8-hour time weighted average exposure. The sampling and analysis methods used in this study would be greatly complimented by real time or peak exposure measurements that characterized the maximum concentration and composition of welding fume metals exposure. This study would greatly benefit from a reassessment of exposures under higher production rates.

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