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A Field Study on the Respiratory Deposition of the Nano-Sized Fraction of Mild and Stainless Steel Welding Fume Metals

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Abstract

A field study was conducted to estimate the amount of Cr, Mn, and Ni deposited in the respiratory system of 44 welders in two facilities. Each worker wore a nanoparticle respiratory deposition (NRD) sampler during gas metal arc welding (GMAW) of mild and stainless steel and flux-cored arc welding (FCAW) of mild steel. Several welders also wore side-by-side NRD samplers and closed-face filter cassettes for total particulate samples. The NRD sampler estimates the aerosol's nano-fraction deposited in the respiratory system. Mn concentrations for both welding processes ranged 2.8–199 μg/m^3; Ni concentrations ranged 10–51 μg/m^3; and Cr concentrations ranged 40–105 μg/m^3. Cr(VI) concentrations ranged between 0.5–1.3 μg/m^3. For the FCAW process the largest concentrations were reported for welders working in pairs. As a consequence this often resulted in workers being exposed to their own welding fumes and to those generated from the welding partner. Overall no correlation was found between air velocity and exposure (R^2 = 0.002). The estimated percentage of the nano-fraction of Mn deposited in a mild-steel-welder's respiratory system ranged between 10 and 56%. For stainless steel welding, the NRD samplers collected 59% of the total Mn, 90% of the total Cr, and 64% of the total Ni. These results indicate that most of the Cr and more than half of the Ni and Mn in the fumes were in the fraction smaller than 300 nm.

Keywords

hexavalent chromium; manganese; nanoparticles; nickel; respiratory deposition; welding fumes

INTRODUCTION

Processes such as welding produce gaseous and aerosol byproducts composed of high concentrations of ultrafine particles. Welding byproducts are particularly known for their composition consisting of ultrafine metals, metal oxides and other chemical species with high fume formation.(1-3) The generated fumes place welders at high risk of exposure to nanoparticles.(4,5) Debia et al.(6) found that apprentice welders are exposed to high concentrations (up to 300,000 particles/cm^3) of particles with an aerodynamic diameter smaller than 100 nm. Elihn and Berg(7) showed that up to 60% of the particles emitted during welding processes were smaller than 100 nm. Chang et al.(8) investigated

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physicochemical and toxicological properties of welding fume particles generated in workplace settings; fine and ultrafine particle size ranges were found to generate the highest reactive oxygen species activities. Several studies have shown adverse health outcomes such as pulmonary fibrosis, mitochondrial damage, DNA damage, lung cancer, and asthma associated with exposure to high levels of fine and nano-sized particles.[9–13]

The consumables used during welding, the welding process, and the substrate affect the constituents of the fumes and the concentrations of each constituent.[14] Fumes generated during mild steel welding are primarily composed of iron (Fe) and manganese (Mn).[15] While particles containing Fe are considered a nuisance dust with little likelihood of causing chronic lung disease, Mn has been associated with neurological disease.[1,16,17] Stainless steel welding poses additional concerns as the fumes generated during this process also contain appreciable concentrations of hexavalent chromium (Cr(VI)) and nickel (Ni), two metals associated with asthma and cancer.[17–19] Additionally, exposure to welding fumes largely depends on work environment factors such as number of welders, welder's posture, and type and effectiveness of ventilation.[20]

As workers inhale welding fumes, a fraction of the particles comes in contact with the airways' surfaces and deposits there. Some of the inhaled particles remain airborne and are exhaled.[21] Recent work of laboratory-generated welding fumes from gas metal arc welding (GMAW) estimated that about 25% of Mn, Cr, Cr(VI), and Ni particles deposit throughout the respiratory system and that the sites of principal deposition are the head airways (7–10%) and the alveolar region (11–14%).[22] Most aerosol sampling conventions and devices are based on particle penetration rather than deposition. Discussion on these characteristics dates back to the development of unified size-selective sampling conventions which, based on the technology available at the time, favored the use of penetration.[23]

Samplers that mimic human-respiratory-system deposition have recently become available. An example is the nanoparticle respiratory deposition (NRD) sampler.[24] The NRD sampler was designed to follow a nanoparticulate matter (NPM) deposition curve based on deposition models developed by the International Commission on Radiological Protection.[25] Nonhygroscopic submicron particles such as welding fumes are well suited for deposition-based samplers.[26] In previous work we developed a method for recovery and chemical analysis of Mn, Cr, Cr(VI), and Ni nanoparticles collected by NRD samplers; the method's recovery rate (>95% for all metals tested) and limits of detection and quantitation were calculated on laboratory generated welding fumes and certified welding fume reference material.[27] The goal of the current study is to further test this method and characterize the exposure of welders to ultrafine metals in the workplace. In particular, the objective is to estimate, using an alternative method, the respiratory deposition of the nano-fraction of Mn, Cr, Cr(VI), and Ni in mild and stainless steel welders using NRD samplers.

METHODS

A field study was conducted to measure the nano-fraction amount of Cr, Mn, and Ni deposited in the respiratory system of welders. Exposure assessment surveys were conducted at two facilities located in the United States. Facility A consisted of an airplane manufacturer with two welding shops. Twelve welders were monitored at this facility while performing mild and stainless steel GMAW. The shield gas used during mild steel welding was primarily 75% Ar/25% CO_2 with the exception of three welders that used 100% CO_2. The mild steel welding wire was ER70S-6. For stainless steel, two welders were monitored, one welder used 100% Ar and one used 75% Ar/25% CO_2 as shield gas; the welding wire was ER308LSi. The weight-percent composition of the electrodes is reported in Table 1. No dedicated exhaust systems were in place and air movement, measured with a wind speed meter (Kestrel 4000; Nielsen-Kellerman, Boothwyn, PA) with sensitivity to 0.3 m/sec, was undetected. A plasma cutter was operating nearby some of the welders.

Facility B consisted of a truck/bus manufacturer with several welding stations. Thirty two welders were monitored at this facility performing flux-cored arc welding (FCAW) on mild steel (24 workers, 90 samples) and GMAW on stainless steel (8 workers, 18 samples). The welding wire for FCAW was E71T-14 while for stainless steel the wire was ER308/308L with 97% Ar, 3% CO_2 shield gas. Some welding stations were equipped with large fans activated at the welders' discretion; the fans were generally turned on during warm days and off during cold days. Two welders were located inside welding booths with dedicated exhaust systems while welding on small parts such as attaching washers to bolts or connecting parts shorter than 1 meter in length. Several welders worked in pairs on large parts (Figure 1); these parts consisted of bus/truck chassis or other components measuring 2 by 2 m or larger. A third group of workers assembled the steps used to board the buses. Air movement at this facility ranged from undetected to 7 m/sec. Air movements near the breathing zone of each worker were measured with a wind speed meter (Kestrel 4000; Nielsen-Kellerman, Boothwyn, PA) with sensitivity to 0.3 m/sec.

Sample Collection and Analysis

NRD samplers (Zefon NRD sampler, Zefon International Inc., Ocala, FL) were located on the welders' lapel at both facilities. The NRD sampler is shown in Figure 2 and it consists of a respirable cyclone (to remove particles >10 μm), an inertial impactor (to remove particles >300 nm), and a diffusion stage where particles smaller than 300 nm are collected similarly to their typical deposition in the respiratory tract.[24] Particles deposited on the diffusion stage of the NRD sampler represent the particles collected in the respiratory system according to the NPM deposition curve. Figure 2 shows the typical deposition of particles in the NRD sampler, the NPM deposition curve, and the ICRP total respiratory deposition curve. Each NRD sampler was operated at 2.5×10^{-3} m^3/min (2.5 Lpm) with a belt-mounted pump (Model 224-PCXR8; SKC Inc., Eighty Four, PA). A total of 118 samples were collected on 44 welders. At least triplicate samples were collected on most welders with the exception of 10 workers where only one sample per welder was collected. Sampling start and stop time were recorded along with measurements of air movement. Potential nearby sources of metal nanoparticles were noted and a condensation particle counter (CPC 3007; TSI Inc., Shoreview, MN) was used to measure background nanoparticle concentrations. These background measurements were used to establish other sources of nanoparticles nearby the welding stations. At facility B, nine FCAW workers and one stainless steel welder wore side-by-side NRD samplers and 37-mm closed face cassettes (CFCs) with SOLU-SERT inserts (CLCL-C3750; Air Sampling Devices, Milford, NH) operated at 2.0×10^{-3} m^3/min (2 Lpm). Three additional stainless steel welders at this facility wore side-by-side NRD samplers. No side-by-side comparisons were performed at facility A.

Samples were analyzed following procedures developed in previous laboratory work where the extraction and recovery methods were tested and limits of detection and quantitation, reported in Table 2, were established.[22, 27] All mild steel samples were microwave digested at 200°C in 10 mL ultrapure nitric acid and analyzed for Mn, Cr, and Ni content by inductively coupled plasma mass spectrometry. The stainless steel samples from facility A were immersed in 10 mL of extraction solution (2% sodium hydroxide, NaOH /3% Sodium carbonate, Na_2CO_3), placed in ultrasonic bath for 30 min, centrifuging for 15 min at 2400x g, and analyzed for Cr(VI) by ion chromatography. Of each side-by-side NRD stainless-steel sample from facility B one was analyzed for Mn, Cr, and Ni and one for Cr(VI). The side-by-side CFCs and NRD samplers were used to calculate for each metal what percentage of the total aerosol was collected by the NRD sampler. This percentage was calculated as NRD_{mass}/CFC_{mass}*100% and represents an estimation of the nano-fraction of each metal deposited in the welder's respiratory system. For multiple measurements on the same worker the percentages were averaged and the standard deviation of the percentages was calculated. Time-weighted-average mass concentrations for each metal were calculated as $M_m/(Q \times t)$, where M_m is the metal mass recovered from the sampler, Q is the sampling flow rate, and t is the sampling time. Multiple samples collected on the same worker were averaged.

Linear regression analysis was performed on air movements versus Mn mass concentrations and coefficients of determination (R^2) were calculated to establish the correlation between the two variables.

RESULTS AND DISCUSSION

The average mass concentration of Mn, Cr, Ni, and Cr(VI) nanoparticles collected by the NRD samplers is shown in Table 3. These concentrations represent an estimation of the deposited nano-sized metals throughout the workers' respiratory system. The analytical methods used for extraction of Mn, Cr, Cr(VI), and Ni from the NRD and CFC substrates have recoveries >95%.[22, 27] Most Cr and Ni concentrations in mild steel welding were between the limits of detection and quantitation and several Ni concentrations of FCAW were below the limit of detection (Table 3); these results were expected as these metals are present in extremely low concentrations in the consumables. The recorded concentrations above these limits may be from other nearby sources and not directly related to the welding fumes. In both facilities there was virtually no separation between work stations and nearby plasma and laser cutters. The highest Ni concentrations in Facility A (11.01 $\mu g/m^3$; Table 3) were recorded for a welder located less than 3 m (10 ft) from a plasma cutter. Background concentrations measured by the CPC near the plasma cutter ranged between 4×10^4 and 5×10^4 particles/cc when the cutter was not operational and jumped to above 1×10^5 particles/cc when it was actively operated. Near other welding stations at facility A, background concentrations ranged between 7×10^4 and 9×10^4 particles/cc. Measurements taken near the worker's breathing zone during welding were above 2×10^5 particles/cc. Concentrations above 1×10^5 particles/cc should, however, be treated with caution as they are above the maximum range of the instrument and subject to underestimation due to coincidence errors. At facility B, background measurements ranged between 6.6×10^4 and 9.5×10^4 particles/cc.

Concentrations of nano-sized Mn that are estimated to deposit in the respiratory system ranged from 2.8–199 $\mu g/m^3$ (Table 3). Cr and Ni concentrations in stainless steel fumes were substantially larger as the weight percentage of these metals in the stainless steel consumables is also larger (20% Cr and ~10% Ni, Table 1). NRD-measured Cr concentrations ranged from 40–105 $\mu g/m^3$ and Ni concentrations ranged from 10–51 $\mu g/m^3$. Cr(VI) concentrations ranged between 0.5 and 1.3 $\mu g/m^3$, these values indicate that 1–5% of the deposited nano-sized Cr was in the Cr(VI) valence state. NIOSH recommended exposure limits (RELs) exist for each of these metals. Unfortunately, these RELs are for concentration in total metal particles and are based on exposure, which is not directly comparable to the deposited metal concentrations measured by the NRD sampler. The REL for Mn is 1000 $\mu g/m^3$ while the REL for Cr is 500 $\mu g/m^3$ and 15 $\mu g/m^3$ for Ni. The Cr(VI) REL is 0.2 $\mu g/m^3$. The NRD sampler can help in the development of deposition-based RELs which in turn may better correlate with dose.

Figure 3 presents Mn concentrations by welding process, shield gas and task. This visual representation of the data shows that the smallest concentrations were reported for facility A mild steel GMAW welding with 100% CO_2 shield gas. In contrast, the largest concentrations were generated by mild steel GMAW with 25% CO_2, 75% Ar at the same facility. Mild Steel GMAW concentrations above 100 $\mu g/m^3$, however, were recorded for welders near a plasma cutter and may be a result of the combined exposure to fumes from both processes. For mild steel FCAW welders at facility B, the mass concentrations in Figure 3 were grouped by task. Within this group of welders the largest concentrations were reported for those working in pairs. This often resulted in one worker being exposed to his own welding fumes and to those generated from the welding partner that were pushed over by the fans. The lowest average concentrations were recorded for workers welding bus steps. Two of the workers welding small parts were inside welding booths with a built-in exhaust wall. Remarkably, these workers experienced the largest (52.9 $\mu g/m^3$) and the smallest (3.1 $\mu g/m^3$) concentrations within this group.

Ten workers at facility B (nine FCAW and one SS welder) wore side-by-side CFCs and NRD samplers. For each metal the mass collected by the NRD samplers was compared to that of the CFCs to obtain the percent of total metal concentrations that corresponds to an estimation of the nano-fraction deposited in the respiratory system; this data is presented in Table 4. Deposited Mn in mild steel ranged between 10 and 56%. Due to their low concentrations, deposited percentages of Cr and Ni were not calculated for mild steel.

For stainless steel welding, the NRD samplers collected 59% of the total Mn, 90% of the total Cr, and 64% of the total Ni. These results indicate that most of the Cr and more than half of the Ni and Mn in the fumes were in the size fraction smaller than 300 nm. The percentages of deposited Ni reported in Table 4 are comparable to those obtained in our previous laboratory work which reported 62% of deposited Ni collected by NRD samplers; however, Mn and Cr percentages are almost doubled (Mn = 34% and Cr = 48% in laboratory study). In the laboratory study, welding fumes were generated by a robotic arm equipped with 308LSi wire that welded virtually continuous lines on T304 stainless steel plates.[27] The welding cycles of the robotic welder and the laboratory ventilation system differed substantially from those of welders in the workplace and are likely the cause of the partial discrepancy.

Particle concentrations inside the welding helmets may differ from those measured on the workers' lapel. Depending on the helmet design, body position, and air movement conditions some helmets may attenuate exposure or fumes may accumulate inside the helmet. Liu et al.[28] investigated the relationship between metal particle concentrations inside and outside the welding helmet and found that these concentrations do not differ greatly (mean ratio inside:outside concentration = 0.9). For iron fume concentrations below 35 mg/m^3 they found virtually no difference between fume concentrations sampled inside and outside the welding helmet.[28] In our work, NRD samplers could not fit inside the welding helmets and were located on the worker's lapel; the results should be treated with this consideration in mind.

Air movement varied greatly between welding stations (Tables 3 and 4). Most stations at facility B were equipped with static fans operated at the discretion of the workers. When the fans were in operation, their effectiveness depended on the position of the worker. At times the workers were facing the fans and the fumes were pushed directly in their breathing zone, other times the workers were backing the fans or were positioned by the fans' side which resulted in more effective removal of the fumes from the breathing zone. Several welders worked in pairs. In these cases the fans would often effectively push the fumes away from one welder's breathing zone while immersing the adjacent welder in the plume as it can be observed in Figure 1. Linear regression was performed on air movements versus mass concentrations and no correlation was found between air movement and exposure (R^2 = 0.002). The lack of correlation may be due to the large variation in effectiveness of the fans in removing fumes from the breathing zone and the variability of the position of the workers with respect to the fans.

From the results reported in Table 3 it can be noted that faster air movement was not always associated with lower exposures. Fans and other general ventilation systems are not designed to control welding fumes which are toxic contaminants. Additionally, welders are close to the source and the generation of welding fumes is not uniform. Local exhaust ventilation systems designed to aspirate and capture the fumes at the source, before they reach the operator, would be more effective at lowering the workers' exposure in these facilities.[29, 30]

LIMITATIONS AND FUTURE WORK

Field studies have limitations because not all parameters can be controlled in the work environment. In this study our ability to control experimental variables was limited and it was not possible to determine the exact source of all exposures because of the presence of other nearby processes. Breathing-zone measurements for welders are typically taken inside the welding helmet; although NRD samplers are only about 10 cm tall, it was not possible to fit them inside the helmets. Exposures during welding may be highly variable depending on worker's posture, the position of the worker with respect to a fan, and the ratio of arc vs. set up time. Future studies should investigate in more detail the relationship between welding parameters, consumables, air movement and workers' exposure. Future work should also investigate other welding processes such as shielded metal arc welding and tungsten arc welding.

CONCLUSIONS

This study demonstrated that mild and stainless steel welders are exposed to large concentrations of Mn, Cr, and Ni nanoparticles that will have the ability to deposit in the respiratory system. Up to 56% of the total Mn from FCAW was collected by NRD samplers. For stainless steel GMAW, the NRD samplers collected 59% of the total Mn, 90% of the total Cr, and 64% of the total Ni, indicating that most of the Cr and more than half of the Ni and Mn in the fumes were in the nano-fraction. For stainless steel welding fumes, concentrations of nano-sized Ni and Cr(VI) that are estimated to deposit in the respiratory system generally exceeded the NIOSH RELs. The RELs for these metals are based on total particle concentrations while the nanoparticles that deposit in the respiratory system only represent a fraction of the total concentration. Up to 5% of the deposited nano-sized Cr was in the Cr(VI) valence state. Precautions, such as the use of local exhaust ventilation (LEV), should be applied to lower exposure to these toxic metals. This work found no correlation between air movement and exposure; however, the use of worker-controlled fans appeared to be ineffective when welders worked in pairs and highly variable when welders directly faced the fans and during cold weather when the fans were switched off. LEV systems that effectively aspirate the fumes, removing them from the worker's breathing zone, should be used instead.

The NRD sampler provides an estimation of the concentration of particles that deposit in the respiratory system. The methods for extraction and analysis of metals collected by the NRD samplers should be further expanded beyond Mn, Cr, and Ni. This information on respiratory deposition of metal nanoparticles can be used in future work to find links between welding fume exposure, dose, and adverse health effects.

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FIGURE 1.
Welders at facility B working in pairs.

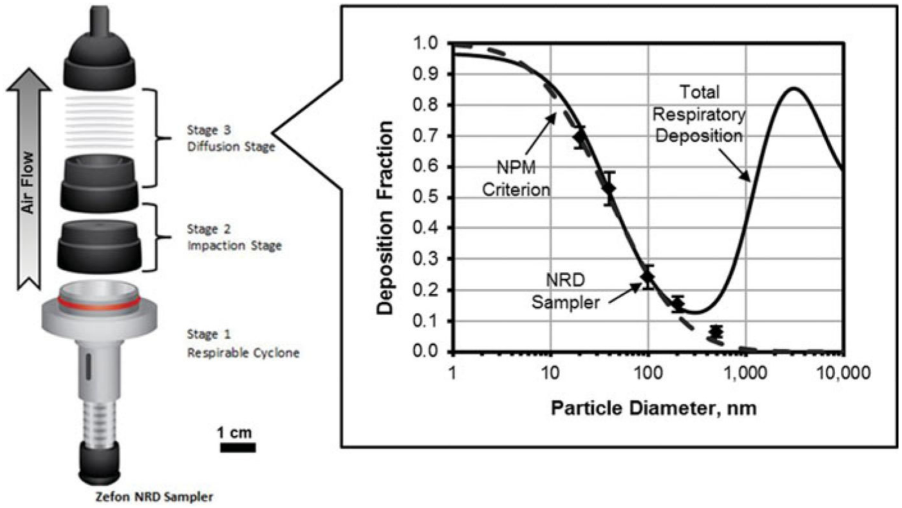

FIGURE 2.

Components of the NRD sampler, NPM sampling criterion, ICRP total respiratory deposition and effective deposition of the NRD diffusion stage. Reprinted with permission from Cena, L.G., T.R. Anthony, and T.M. Peters: A personal nanoparticle respiratory deposition (NRD) sampler. *Environ. Sci. Technol. 45(15)*:6483–6490 (2011). Copyright 2011, American Chemical Society.

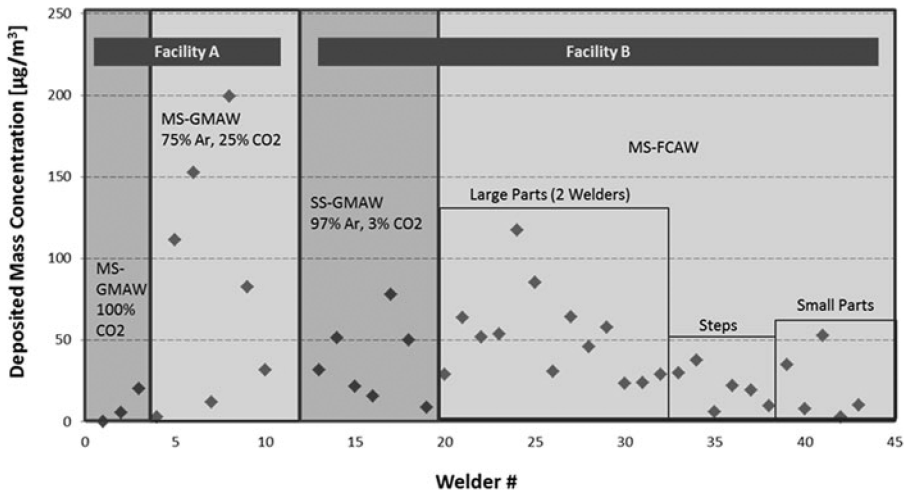

FIGURE 3.

Individual worker's deposition-associated Mn exposures by welding process and task.

TABLE I

Composition of GMAW and FCAW Wire (wt%)

	SS GMAW ER308LSi	SS GMAW ER308/308L	MS GMAW ER70S-6	MS FCAW E71T-14
Mn	2.1	1.6	1.63	1.0
Cr	20	20	0.05	0.0
Ni	10	9.0	0.04	0.0

SS = stainless steel; MS = mild Steel; GMAW = gas metal arc welding; FCAW = flux-cored arc welding

TABLE II

Limits of Detection (LOD) and Limits of Quantitation (LOQ) Expressed as Mass Collected in the Diffusion Stage of the NRD Sampler, and Average Percent Recovery

Metal	LOD [μg]	LOQ [μg]	Average% Recovery
Total Cr	1.1	3.33	102% ± 2%
Cr(VI)	0.4	1.42	97% ± 3%
Ni	0.4	1.14	103% ± 3%
Mn	1.3	4.43	100% ± 3%

TABLE III

Average Mass Concentrations of Mn, Cr, Ni, and Cr(VI) Nanoparticles Deposited in the Respiratory System as Collected by the NRD Sampler

Welding Method	Facility	Shield Gas	Wire Type (AWS)	Air Movement [m/s]	Mn [$\mu g/m^3$]	Cr [$\mu g/m^3$]	Ni [$\mu g/m^3$]	Cr(VI) [$\mu g/m^3$]
Mild Steel GMAW	A	CO_2	ER70S-6	n.d.	0.6[A]	0.2[A]	0.3[A]	—
	A	CO_2	ER70S-6	n.d.	5.6	1.2[A]	0.1[A]	—
	A	CO_2	ER70S-6	n.d.	20.4	1.1[A]	0.1[A]	—
	A	25%CO_2, Ar	ER70S-6	n.d.	2.8	1.0[A]	<0.1	—
	A	25%CO_2, Ar	ER70S-6	n.d.	112	3.1	11	—
	A	25%CO_2, Ar	ER70S-6	n.d.	153	3.7	0.8[A]	—
	A	25%CO_2, Ar	ER70S-6	n.d.	12.2	3.2	0.1[A]	—
	A	25%CO_2, Ar	ER70S-6	n.d.	199	1.5[A]	0.5[A]	—
	A	25%CO_2, Ar	ER70S-6	n.d.	82.5	4.4	0.4[A]	—
	A	25%CO_2, Ar	ER70S-6	n.d.	31.6	0.9[A]	0.2[A]	—
	A	Ar	ER308LSi	n.d.	—	—	—	0.9
	A	25%CO_2, Ar	ER308LSi	n.d.	—	—	—	<0.1
Stainless Steel GMAW	B	3%CO_2, Ar	ER308/308L	n.d.	—	—	—	1.4
	B[C]	3%CO_2, Ar	ER308/308L	n.d.	31.6	49.1	19.6	—
	B[B]	3%CO_2, Ar	ER308/308L	n.d.	51.6	91.2	50.8	1.1
	B[B]	3%CO_2, Ar	ER308/308L	n.d.	21.7	40.4	21.6	0.5
	B[B]	3%CO_2, Ar	ER308/308L	n.d.	15.7	24.9	10.4	1.3
	B	3%CO_2, Ar	ER308/308L	n.d.	77.9	106	41.2	—
	B	3%CO_2, Ar	ER308/308L	n.d.	50.1	59.8	23.2	—
	B	3%CO_2, Ar	ER308/308L	n.d.	8.8	0.9[A]	0.3[A]	—
Mild Steel FCAW	B	n.a.	E71T-14	2.0	29.0	9.1	4.2	—
	B	n.a.	E71T-14	2.0	64.0	10	2.3	—
	B	n.a.	E71T-14	7.0	52.0	2.4[A]	0.4[A]	—
	B	n.a.	E71T-14	7.0	53.7	2.0[A]	0.3[A]	—
	B	n.a.	E71T-14	3.4	118	1.2[A]	0.2[A]	—
	B	n.a.	E71T-14	4.0	85.3	17	8.3	—
	B	n.a.	E71T-14	4.0	31.0	0.5[A]	<0.1	—
	B	n.a.	E71T-14	4.0	64.1	2.5[A]	<0.1	—
	B	n.a.	E71T-14	4.0	45.9	0.8[A]	<0.1	—
	B	n.a.	E71T-14	4.0	58.0	0.6[A]	<0.1	—

Welding Method	Facility	Shield Gas	Wire Type (AWS)	Air Movement [m/s]	Mn [μg/m^3]	Cr [μg/m^3]	Ni [μg/m^3]	Cr(VI) [μg/m^3]
	B	n.a.	E71T-14	4.0	29.8	1.8[A]	0.3[A]	—
	B	n.a.	E71T-14	4.0	37.9	11	5.1	—
	B	n.a.	E71T-14	4.0	23.3	1.9[A]	<0.1	—
	B[C]	n.a.	E71T-14	2.0	6.0	2.7[A]	<0.1	—
	B[C]	n.a.	E71T-14	3.6	22.3	<0.2	<0.1	—
	B[C]	n.a.	E71T-14	1.8	35.1	0.5[A]	<0.1	—
	B[C]	n.a.	E71T-14	1.0	19.2	3.1[A]	<0.1	—
	B[C]	n.a.	E71T-14	0.0	10.0	0.3[A]	<0.1	—
	B[C]	n.a.	E71T-14	3.0	7.8	0.5[A]	<0.1	—
	B[C]	n.a.	E71T-14	2.0	52.9	0.8[A]	0.2[A]	—
	B[C]	n.a.	E71T-14	1.0	3.1	0.3[A]	<0.1	—
	B[C]	n.a.	E71T-14	4.0	10.2	0.5[A]	0.1[A]	—
	B	n.a.	E71T-14	4.0	24.1	3.6	15	—
	B	n.a.	E71T-14	4.0	28.8	2.0[A]	8.7	—

n.d. = not detected (<0.3 m/sec); n.a. = not applicable

- = not measured

[A]between LOD and LOQ

[B]side-by-side NRDs

[C]side-by-side CFC and NRD

TABLE IV

Estimation of the Nano-Fraction Deposited in the Respiratory System in Facility B. For Welders with Multiple Measurements the Average and Standard Deviation are Presented

Welding Method	Wire Type	Air Movement [m/s]	Deposited Mn [% ± StDev]	Deposited Cr [% ± StDev]	Deposited Ni [% ± StDev]
MS-FCAW	E71T-14	2.0	13% ± 2%	n.a.	n.a.
MS-FCAW	E71T-14	3.6	27%	n.a.	n.a.
MS-FCAW	E71T-14	1.8	34% ± 1%	n.a.	n.a.
MS-FCAW	E71T-14	1.0	54% ± 3%	n.a.	n.a.
MS-FCAW	E71T-14	n.d.	10% ± 0%	n.a.	n.a.
MS-FCAW	E71T-14	3.0	29% ± 4%	n.a.	n.a.
MS-FCAW	E71T-14	2.0	33% ± 12%	n.a.	n.a.
MS-FCAW	E71T-14	1.0	35% ± 3%	n.a.	n.a.
MS-FCAW	E71T-14	4.0	56%	n.a.	n.a.
SS- GMAW	ER308/308L	n.d.	59% ± 2%	90% ± 2%	64% ± 6%

n.d. = not detected; n.a. = not applicable (concentrations below LOD)