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RESEARCH ARTICLE

Development and characterization of a resistance spot welding aerosol generator and inhalation exposure system

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Abstract

Limited information exists regarding the health risks associated with inhaling aerosols that are generated during resistance spot welding of metals treated with adhesives. Toxicology studies evaluating spot welding aerosols are non-existent. A resistance spot welding aerosol generator and inhalation exposure system was developed. The system was designed by directing strips of sheet metal that were treated with an adhesive to two electrodes of a spot welder. Spot welds were made at a specified distance from each other by a computer-controlled welding gun in a fume collection chamber. Different target aerosol concentrations were maintained within the exposure chamber during a 4-h exposure period. In addition, the exposure system was run in two modes, spark and no spark, which resulted in different chemical profiles and particle size distributions. Complex aerosols were produced that contained both metal particulates and volatile organic compounds (VOCs). Size distribution of the particles was multi-modal. The majority of particles were chain-like agglomerates of ultrafine primary particles. The submicron mode of agglomerated particles accounted for the largest portion of particles in terms of particle number. Metal expulsion during spot welding caused the formation of larger, more spherical particles (spatter). These spatter particles appeared in the micron size mode and accounted for the greatest amount of particles in terms of mass. With this system, it is possible to examine potential mechanisms by which spot welding aerosols can affect health, as well as assess which component of the aerosol may be responsible for adverse health outcomes.

Keywords

Aerosol generators, fumes, gases, inhalation, resistance spot welding

History

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Introduction

Resistance spot welding is a process that produces coalescence of metals at surfaces that are made to fit closely together for the purposes of making a joint (Stout, 1987). In a structure, a resistance spot weld has mechanical characteristics much like those of a rivet, although its soundness and strength are oftentimes many folds greater. Spot welding is used for light gauge metal parts up to 3 mm thickness that are superimposed on each other and is very effective for fabricating sheet metal articles where high rates of production are necessary. For this reason, spot welding has been particularly valuable in the automotive, aircraft, and appliance industries where high-speed, repetitive welds are needed and relatively thin section sizes are welded.

During spot welding, two copper electrodes are simultaneously used to clamp the metal sheets together and to pass very high levels of current, but at low voltage, through the metals. Extreme heat is generated due to the higher electrical resistance where the metal surfaces contact each other. The electrical resistance of the materials causes heat buildup in the work pieces and results in a molten pool contained between the copper electrodes. As the heat dissipates throughout the work piece, the molten area grows. When the current is stopped, the copper tips cool the spot weld, causing the metal to solidify under pressure. Because copper is an excellent conductor, the water-cooled electrodes remove the surface heat quickly, accelerating the solidification of the weld. Oftentimes during the spot welding process, different epoxy adhesives are applied as sealers to the seams and joints of the metals that are joined. Workers in areas where spot welding takes place may be exposed to complex aerosols that are composed of metal oxide particulates, volatile organic compounds (VOCs), and other gas vapors.

In a Health Hazard Evaluation performed by National Institute for Occupational Safety and Health (NIOSH) investigators at an automotive assembly plant, numerous workers in a body shop were determined to have developed respiratory illness (Kanwal & Boylstein, 2006). Numerous chemicals used in the body shop were detected in the air of the plant. Some of the substances (e.g., methyl methacrylate, acetic acid, phthalic anhydride, formaldehyde, styrene) can potentially cause respiratory irritation, asthma, bronchitis, and

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sinusitis. In addition, multiple studies have indicated that automotive assembly and manufacturing workers exposed to aerosols generated during resistance spot welding using adhesives develop respiratory symptoms and disease (Hammond et al., 2005; Loukzadeh et al., 2009; Luo et al., 2006). Importantly, each of these studies failed to identify which byproduct of the spot welding process was responsible for the respiratory effects that were observed. Hence, limited data exist about the composition and characterization of aerosols generated during resistance spot welding of metals treated with adhesives.

The goals of this project were two-fold: (1) to construct an automated, computer-controlled spot welding aerosol generator and inhalation exposure system that would simulate real workplace exposures and would allow for continuous spot welding for extended periods of time without interruption; (2) to expose laboratory animals and examine the potential effects of spot welding fumes on lung injury, inflammation, and function as well as the possible systemic effects on the vascular and central nervous system. This manuscript describes the development of a novel spot welding generator. Spot welding was performed on strips of mild steel sheet metal that were coated with an adhesive, and the chemical and physical characterization of the resulting aerosol were determined. The results of the animal inhalation toxicology studies are described in companion manuscripts (Zeidler-Erdely et al., 2014; Sriram et al., 2014).

Materials and methods

Description of resistance spot welding system

A novel resistance spot welder and inhalation exposure system has been designed and constructed by NIOSH investigators (Figures 1 and 2). A schematic diagram of the system design is depicted in Figure 1. A photograph of the completed system is shown in Figure 2. The system is divided into two separated areas: (A) enclosed control room that contains the welding computer controller, the sheet metal puller system controller, and the spot welding gun cooling system; (B) resistance spot welder, air-tight welding fume collection chamber, sheet metal pulling system (sheet metal rolls and assorted rollers), adhesive/sealant pump, adhesive dispenser system, and animal exposure chambers for control and spot welding fume-exposed animals with assorted aerosol characterization devices.

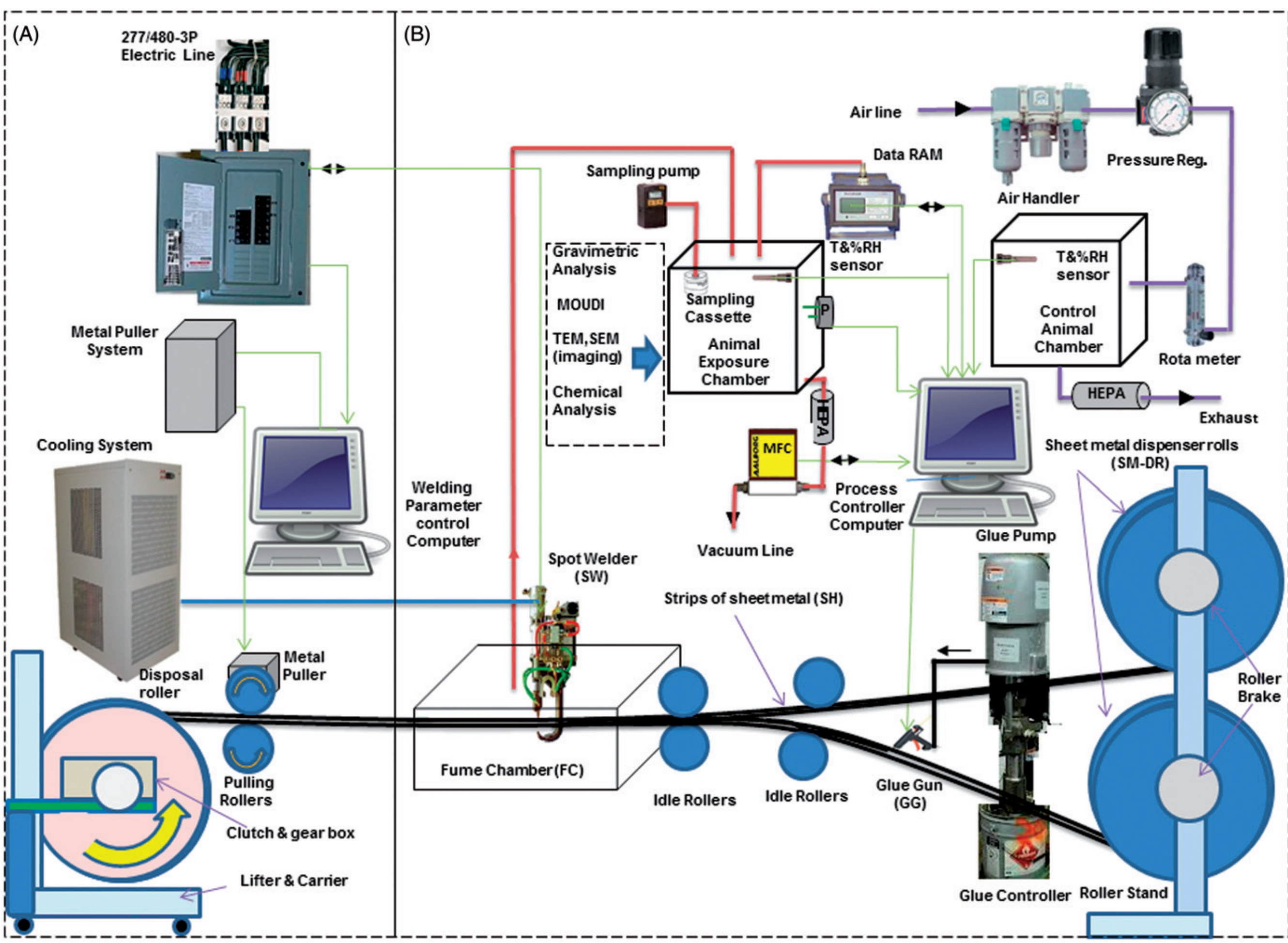


Figure 1. Schematic diagram of the resistance spot welding fume generation and exposure system. The system is divided into two separated areas: (A) enclosed control room that contains the welding computer controller, the sheet metal puller system controller, and the spot welding gun cooling system; (B) resistance spot welder, air-tight welding fume chamber, sheet metal pulling system (sheet metal rolls and assorted rollers), glue pump and gun dispenser system, and animal exposure chambers for control and spot welding fume-exposed animals with assorted aerosol characterization devices. DataRam, real-time aerosol monitor; MOUDI, Micro-Orifice Uniform Deposit Impactor; SEM, scanning electron microscopy; TEM, transmission electron microscopy; *T*, temperature; RH, relative humidity; SMPS, scanning mobility particle sizer; MFC, mass flow controller.

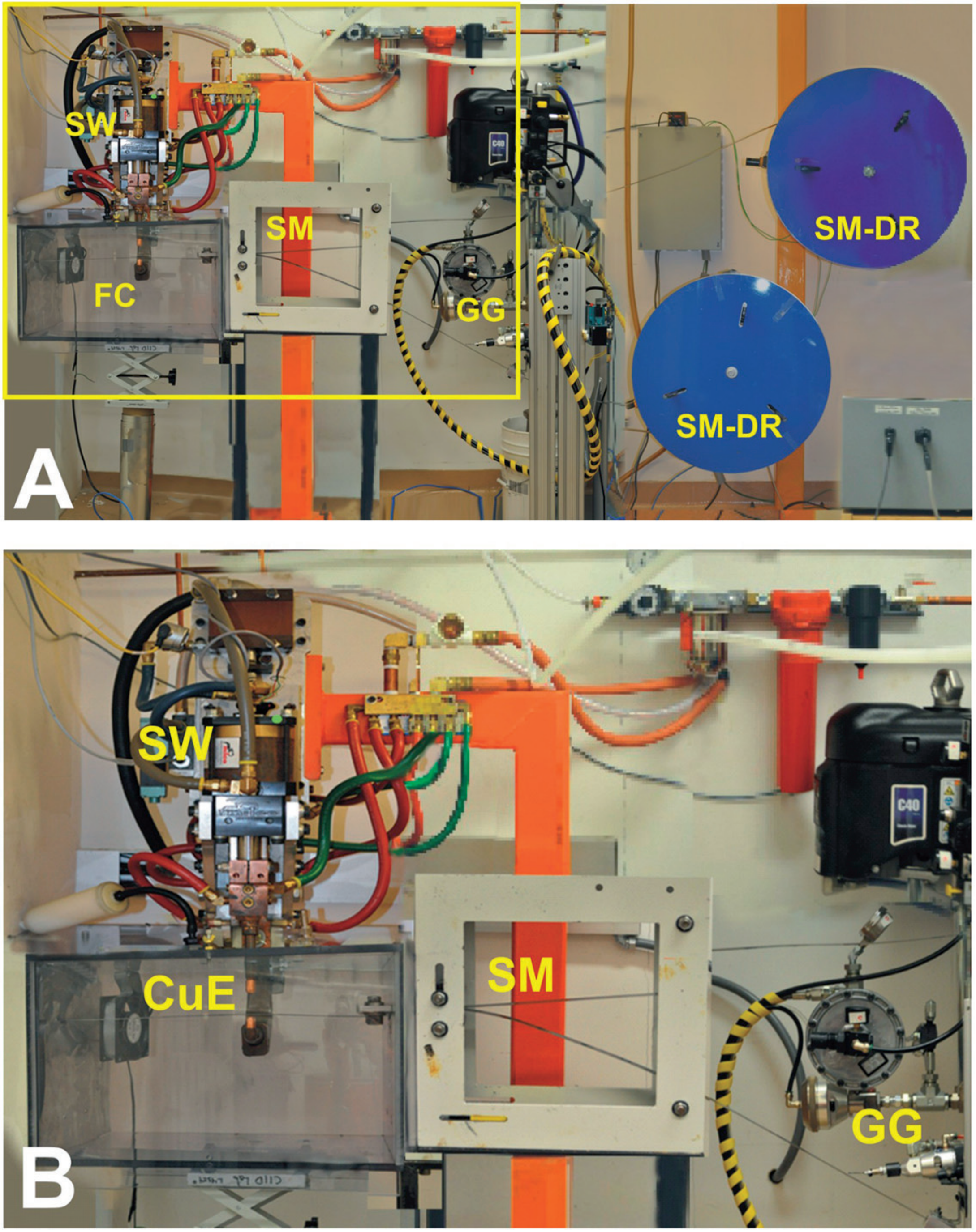


Figure 2. (A) Image of the resistance spot welder, air-tight welding fume chamber (FC), sheet metal (SM) and dispenser rolls (SM-DR), glue pump and gun (GG) dispenser system. The animal exposure chamber had been removed for this photograph in order to view the resistance spot welding fume generation system. (B) Enlarged image (boxed area of the system from (A)) of the resistance spot welder, the enclosed spot welding fume chamber that was designed to collect the generated welding aerosol prior to delivery to an animal exposure chamber. The chamber housed both copper electrodes of the spot welding gun (CuE). The strips of sheet metal to be welded were directed into the box through an opening after passing through a pair of superimposing rollers. An adhesive was injected between the two strips of metal by sealant pump system and glue gun before spot welding.

Resistance spot welding control system

The enclosed control room (Figure 1A) is used for programming and monitoring the operation and performance of the resistance spot welding aerosol and inhalation exposure system from a computer controller with built-in processor (Mutable Power Control Source 480 V AC 3 Phase Model SI6300.100L, Stegner Control Company, Auburn Hills, MI). The room is separated from the spot welding system by an airtight divider made of aluminum with protective glass doors to keep the investigators separated from the area where acting spot welding occurs. The spot welding process was continuously monitored from this room through the glass doors.

Resistance spot welding system and fume collection chamber

Two rolls that contained strips of low alloy, carbon steel sheet metal (thickness: 1/40 in. (0.64 mm), 24 gauge; width: 1 in.) were directed by a set of rollers to copper (class I)-tipped electrodes of the welder, and spot welded at a determined distance of 3/4 in. (20 mm) between each spot weld by an automated, computer-controlled resistance spot welding gun (small new modified ''C'' style Trans-gun 136 kva-AC; Milco Manufacturing Company, Warren, MI) (Figures 1B and 2). The desired aerosol concentration within the animal exposure chamber was dependent on the number of welds made per interval of time. The welding gun ''squeezes'' the sheet metal strips together by its built-in pneumatic actuator and welds them together by conducting a very high current through copper electrodes. The three-phase, 480 V gun, which is commonly used by the automotive industry, was activated by triggering the control box through a data acquisition and a program using LABVIEW software (National Instruments, Austin, TX). The welding gun parameters (e.g., current, squeezing time, welding, and holding time) were set with a computer through the software (BOS6000 version 1.35). Because of extreme heat that was generated during the spot welding process, a cooling system was included that became immediately operational once the system's control box was activated. A heat exchanger was used that continuously circulated antifreeze to the tips of welding electrodes and spot welding gun to protect them from heat buildup.

For most of the experiments, the spot welder was set at 7.5–10 kA with a welding time of 140 ms, a post-weld holding time of 50 ms, and a clamping force of 2.6 kN (600 lbs). These welding parameters were based on recommendations by numerous industry sources and standards [(Ruukki Co., Resistance Welding Manual (Helsinki, Finland); British Standards Institute, BS 1140:1993 Specification for Resistance Spot Welding of Uncoated and Coated Low Carbon Steel (London, England); Entron Controls, Low Carbon Steel Spot Welding Schedule (Greer, SC); and PW Resistance Welding Products, Ltd (Oxford, England)]. By controlling various combinations of parameters (the current and the time between spot welds), it was possible to generate aerosols with different characteristics. Aerosols were characterized when the weld current (7.5–9.0 kA) was reduced to levels that still produced quality spot welds, but without the generation of sparking or the expulsion of molten metal (low level metal sample). To achieve a chamber concentration of 25 mg/m^3, the average time between weld was 5 s when operating in this no spark mode. In another instance, aerosols were generated and characterized when sparking occurred during each weld at an average current of 10.5 kA (high metal sample). More aerosols were generated per weld in this mode resulting in a 20 s average time between welds to generate the same chamber concentration of 25 mg/m^3. The amount of current was gradually increased or decreased automatically through software or manually by the operator to control and maintain constant weld quality as the welding tips aged over a single day's exposure. A new pair of copper electrode tips was installed at the beginning of each exposure day.

The concentration of the aerosol within the animal chamber was automatically controlled by the exposure system software by making changes to the time between welds. The mass concentration in the exposure chamber was monitored in real time by a calibrated real-time aerosol monitor (DataRAM, MIE, Inc. DR-2000, Bedford, MA). At all times during this study, an adhesive (Tekoral 2300; Henkel Surface Technology, Madison Heights, MI) was injected between the two strips of metal before spot welding. The sealant pump system (Sealant Equipment and Engineering Adhesive Dispensing Equipment, Model S-5027, Plymouth, MI) used a pneumatic pump which collected sealant by pushing a plunger into a 5-gallon bucket of adhesive which pressurized the adhesive and sent it to the glue gun through a hydraulic hose. The glue gun conducted the pressurized sealant between the two metal strips to be welded with a determined rate through a data acquisition system. The flow of sealant is maintained constant with an air pressure line regulator.

Resistance spot welding occurred in an enclosed fume collection chamber that was designed to collect the generated spot welding fume prior to delivery to an animal exposure chamber (Figure 2). The chamber is a polycarbonate box (13–1/2 in. × 22–1/2 in. × 13.0 in.) which housed both electrodes of the welding gun. The whole chamber was internally covered with a thin sheet of stainless steel to prevent burning or damaging the chamber. The chamber also had a polycarbonate sliding door with an anti-fire glass window to observe the spot weld process. The strips of sheet metal to be welded were directed into the box through a 1–1/4 in. × 1–1/2 in. opening after passing through a pair of superimposing rollers. After the spot welding process, the welded strips of metal exited through an opening of the same size on the opposite side of the chamber. The chamber had ports for fresh air and an electric wire for a fan installed in the box that aided in the mixing of the air and generated spot welding fume.

Animal exposure chamber

Aerosols generated during welding were transported via tubing from the spot welding fume chamber to an animal exposure chamber that was designed for holding laboratory rodents and homogenously exposing them to the spot welding aerosol (Figure 1B). The animal exposure chamber was a custom built stainless steel box (22 in. × 22 in. × 20 in.) with multiple ports – five of the ports were inserted in the ceiling of the box, one was inserted in the middle, and one was placed in each of the four corners of the ceiling of the chamber with a distance of 3 in. from each side. The middle port was used for input air which carried the spot welding fume through 6 ft of Tygon tubing from the spot welding fume chamber to the top of the exposure chamber. The pressure inside the exposure chamber was monitored and maintained at a slightly negative pressure (2 in. of water column or less) to ensure that approximately 25 L/min of air was being delivered from the fume collection chamber into the exposure chamber. The other four were used for gravimetric sampling pumps to determine particle concentration by which cassettes with 37-mm filters were installed inside the chamber on ends of four stainless steel tubes which were inserted through a different port. Additional ports were located on the top of the chamber and used to measure chamber pressure and to collect additional particle samples to determine their size distribution, chemical composition, and for electron microscopy analysis. In addition, airborne emissions were collected onto desorption tubes in the enclosed exposure chamber for identification and measurement of VOCs. The temperature and relative humidity (Vaisala Temperature-Humidity Probe, model# HMP233; Woburn, MA) inside the exposure chamber were measured, continuously recorded, and observed to remain relatively constant during 4-h animal exposures. Chamber temperature ranged between 19 and 22 °C and relative humidity ranged from 35 to 40% during exposures. Additional ports were used to exhaust the fume by inserting three 5/16 in. perforated stainless steel tubes in the bottom of the animal exposure chamber. The tubes were connected together with a 4-way connector, and the exhaust fume was filtered using a HEPA filter before entering a mass flow controller connected to house vacuum and normally operating at 25 L/min.

The mass concentration in the chamber was monitored in real time by a real-time aerosol monitor (DataRAM, MIE, Inc. DR-2000, Bedford, MA). The DataRAM was calibrated by comparing its average readings over 3–6 h periods versus gravimetric filter samples taken from the same space within the exposure chamber. To maintain constant spot welding fume concentrations in the animal exposure chamber, the computer software would take reading from the DataRAM and make adjustments to the time between spot weld. The time between weld were typically 3 and 30 s, depending on the desired concentration.

Control animals were housed in an air-tight animal chamber that was located next to the spot welding exposure chamber and received conditioned, filtered air (Figure 1B). The control chamber had the same dimensions and was made from identical materials as the spot welding fume animal exposure chamber. Air flow into the chamber was manually set with a Rota meter to 25 L/min. The supplied air originated from a water-seal compressor, in-house air-line and was conditioned through a dryer, charcoal filter, and HEPA filter. The temperature and relative humidity of the animal control chamber were continuously monitored. A piece of wet cloth was placed in the air control chamber to maintain the same relative humidity in both animal exposure chambers. The exhaust air in the control chamber was vented, in a similar manner as the fume exposure chamber, through three perforated stainless steel tubes which were connected together with a 4-way connector and passed through a HEPA filter to the outside air.

Spot welding aerosol characterization

All aerosol collection was done in the breathing zone of the animals in the exposure chamber throughout a 4-h exposure period to ensure that the physical and chemical properties of the generated aerosols remained constant. Particle morphology, size distribution, and metal profile did not change during the 4-h exposure.

Particle metal analysis

Spot welding aerosols were collected inside the exposure chamber onto 5 μm polyvinyl chloride membrane filters in 37-mm cassettes during welding. The particle samples were digested and the metals analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) by Bureau Veritas North America, Inc. (Novi, MI), according to the NIOSH method 7303 modified for hot block/HCl/HNO_3 digestion (National Institute for Occupational Safety and Health, 1994). Metal content of blank filters also was analyzed for control purposes.

Scanning electron microscopy

Fume was collected during spot welding onto 47-mm Nuclepore polycarbonate filters (Whatman, Clinton, PA). The filters were cut into four equal sections and two sections were mounted onto aluminum stubs with silver paste. The collected welding particles were viewed using a Hitachi S4800 field emission scanning electron microscope (FESEM) and X-ray system (Bruker, Madison, WI). Elemental profiles of collected welding particles were determined by energy dispersive X-ray analysis (SEM-EDS) at 20 kV to map specific metal components of fume samples.

Particle size distribution

The size distribution of the spot welding aerosols inside the exposure chamber was determined by using a Micro-Orifice Uniform Deposit Impactor (MOUDI, MSP Model 110, MSP Corporation, Shoreview, MN) that is intended for general purpose aerosol sampling, and a Nano-MOUDI (MSP Model 115). Using the two MOUDI impactors in series or in tandem, particles were collected in the size range between 0.010 and 18 μm that were separated into 15 fractions. The 50% cutoff particle diameter for each stage is as follows: stage 1 (inlet): 18 μm; stage 2: 10 μm; stage 3: 5.6 μm; stage 4: 3.2 μm; stage 5: 1.8 μm; stage 6: 1.0 μm; stage 7: 0.56 μm; stage 8: 0.32 μm; stage 9: 0.18 μm; stage 10: 0.10 μm; stage 11: 0.056 μm; stage 12: 0.032 μm; stage 13: 0.018 μm; stage 14: 0.010 μm; stage 15 (back-up filter). The mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) of the welding fume were determined from gravimetric measurements.

VOCs identification

During the spot welding process, gas samples were collected on thermal desorption tubes during spot welding for qualitative identification of VOCs by thermal desorption gas chromatography/mass spectrometry (TD–GC–MS). The stainless steel desorption tubes contained three beads of sorbent material: the first section contained Carbopack Y (90 mg), the second section contained Carbopack B (115 mg), and the last section contained Carboxen 1003 (150 mg). Prior to sampling, the tubes were conditioned by heating at 350 °C for 90 min. In addition, a filter was placed upstream to separate the particulate phase from the volatile organic phase. Identification of VOCs was performed using a Markes Unity/Ultra automatic thermal desorption (ATD) system with an internal focusing trap packed with graphitized carbon sorbents (Model ATD 400; Perkin-Elmer, Waltham, MA). The thermal unit was interfaced directly to a Hewlett-Packard 6890A gas chromatograph with a Hewlett-Packard 5973 mass selective detector (International Equipment Trading Ltd., Vernon Hills, IL) which operated at EI conditions. A 30 m HP-1MS fused silica capillary column was used for analysis. Samples were purged with helium prior to analysis and desorbed in the ATD at 300 °C for 10 min.

Results

Aerosol generation

When a spot weld is made during resistance spot welding, sparks or the expulsion of molten metal are often generated (Figure 3A). After completion of the spot weld, the sparks subside and the resulting aerosol, a combination of metal fume derived from the welding of the strips of metal and VOCs from the heating of the adhesive applied between the metal strips, fills the sealed welding fume chamber (Figure 3B and C). By controlling the number of spot welds performed over time, different target aerosol concentrations could be maintained at fairly constant levels within the animal exposure chamber during the 4-h exposure period (Figure 4). The dips on the DataRAM readings indicate the time at which a spot weld is initiated and a spark is formed. The peaks on the DataRAM readings indicate the rise in aerosol concentration after the completion of a spot weld and the disappearance of the spark. In order to reach the desired concentration of 25 mg/m^3 (Figure 4A) in the chamber, significantly more spot welds (as indicated by a greater number of peaks and troughs) were performed per unit time when compared with the number of welds required to reach a concentration of 15 mg/m^3 (Figure 4B).

Aerosol composition

One goal of the project was to determine the contribution of each component (metal fume versus VOCs) of the spot welding aerosol that is capable of causing toxicological responses in the respiratory, vascular, immune, and central nervous systems.

Metal composition

To assess the potential differences in the metal profile of the generated spot welding fume using different process parameters, particle samples were collected on filters drawn from the exposure chamber during the spot welding process. When the spot welder parameters were selected to generate a significant amount of sparking (high metal sample), substantially more metal particles were generated during each weld when compared with spot welding conditions that generated little to no sparking (low metal sample). Nearly four times more metal was collected in the animal exposure chamber during spot welding with sparking (Figure 5). As expected when spot welding low carbon, mild steel (as was used in the current study), the particles formed were composed of 99% of iron, regardless of the welding parameter settings (Table 1). Less than 1% of the particles were manganese and copper. In addition, trace amounts of zinc, calcium, tin, chromium, and barium also were present in the particle samples.

VOCs identification

TD-GC-MS measurements were performed to identify VOCs that are generated due to the use of an adhesive during spot welding. In all situations examined in the current study, an adhesive was added between the two metal strips before spot welding. Independent of parameter setting, analysis indicated that most major peaks present were siloxanes and silicon-containing compounds, benzene, toluene, isopropanol, and 2-butoxyethanol (Table 2). Other compounds present included butanol and ethylene glycol. Most of the hydrocarbons identified were unsaturated hydrocarbons.

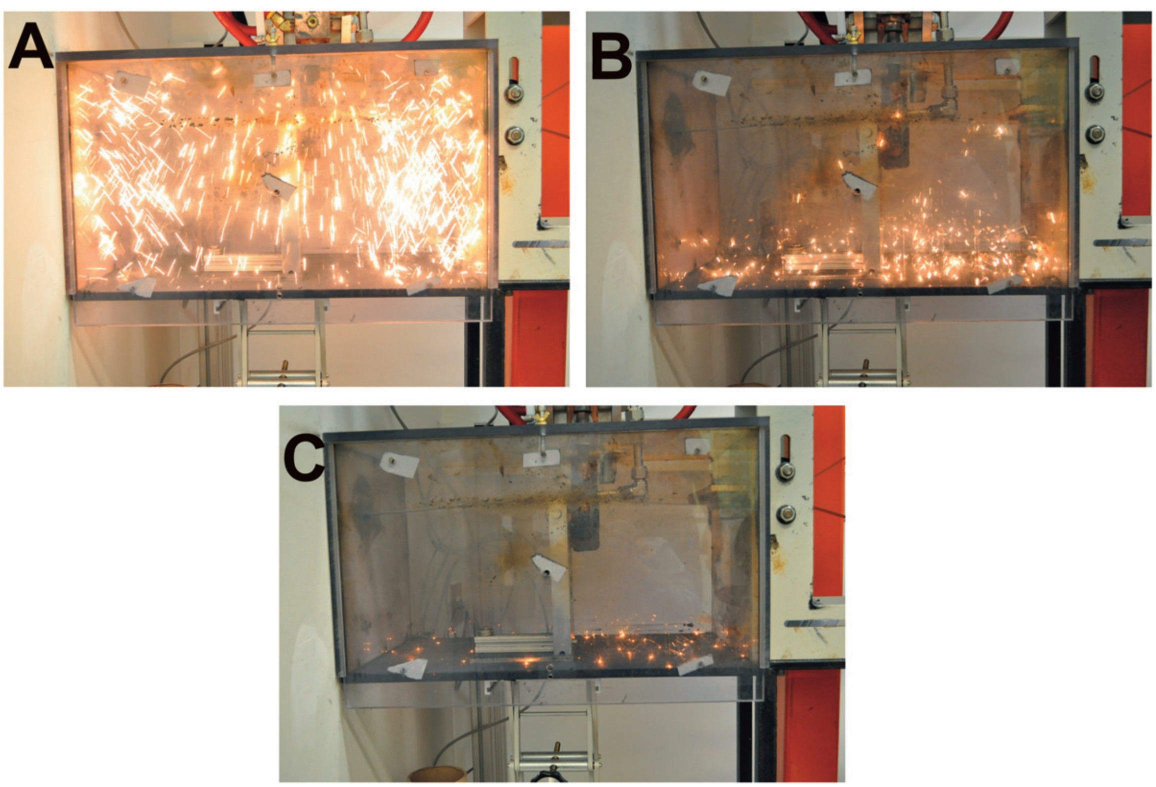


Figure 3. Time lapse images of an active spot weld from the formation of the weld and generation of sparks (A) through the completion of the spot weld as the sparks subside and the resulting aerosol fills the sealed welding fume chamber (B and C).

Figure 4. Representative exposure chamber aerosol concentration (mg/m^3) chartings during 4 h of welding on two different days as determined by a DataRAM light scattering instrument. The figure indicates that by controlling the number a spot welds performed over time different target aerosol concentrations could be maintained at fairly constant levels during the 4-h exposure period: (A) 25 mg/m^3 and (B) 15 mg/m^3.

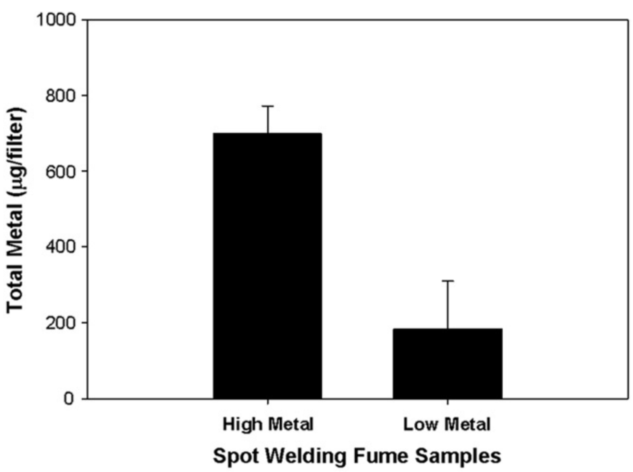


Figure 5. Total metal amount measured in spot welding fume that was generated to produce particles that contained either (A) a high level of metal or (B) a low level of metal.

Table 1. Metal composition of generated spot welding fumes.

Metals analyzed	High metal (weight % of metals[a])	Low metal (weight % of metals[a])
Iron (Fe)	99.2	99.0
Manganese (Mn)	0.539	0.534
Copper (Cu)	0.280	0.431

Trace amounts of zinc, calcium, tin, chromium, and barium also were present.
[a]Relative to all metals analyzed.

Table 2. Identification of volatile organic compounds by TD-GC-MS.

	Volatile organic compounds
Major peaks	Siloxanes
	Silicon-containing compounds
	Benzene
	Toluene
	Isopropanol
	2-Butoxyethanol
Minor peaks	Butanol
	Ethylene glycol

Particle size distribution/morphology

Some differences in particles size distribution were observed as assessed by a Moudi/Nano-Moudi particle impactor system when comparing spot welding fume that were generated at different process conditions (Figure 6). Three modes of particle sizes were measured when spot welding parameters were to set to generate aerosols that contained either high (sparking) or low (no sparking) levels of metal particles. The mass median aerodynamic diameter (MMAD) was determined for each particle size mode. For the aerosol that contained lower levels (no sparking) of metal particles, the MMAD was 1.66 µm for the micron-sized mode and accounted for 67% of the particle mass, 0.30 µm for the submicron-sized mode, and accounted for 33% of the particle mass, and ~0.01–0.05 µm for the nano-sized mode (ultrafine) and accounted for <1% of the particle mass (Figure 6A). For the aerosol that contained a high level (sparking) of metal particles, the MMAD was 3.04 µm for the micron-sized mode and accounted for 61% of the particle mass, 0.25 µm for the submicron-sized mode and accounted for 36% of the particle mass, and ~0.01–0.1 µm for the nano-sized mode (ultrafine) and accounted for <3% of the particle mass (Figure 6B).

Regardless of parameter settings for the spot welder, two distinct particle morphologies for each type of spot welding aerosol generated were observed (Figure 7A and B) – a reddish-brown metal particle that predominated in the smaller (nano-mode) particle size fractions (stages 7–11) and a darker, more black-colored particle that was observed in the larger (micron/submicron modes) particle size fractions (stages 4–6). As expected, significantly more particles deposited on each of the filters for the different size fractions when spot welder parameters were set to generate a significant amount of sparking and high amounts of metal (Figure 7B) as compared with spot welding at process parameters that generated little to no sparking (Figure 7A).

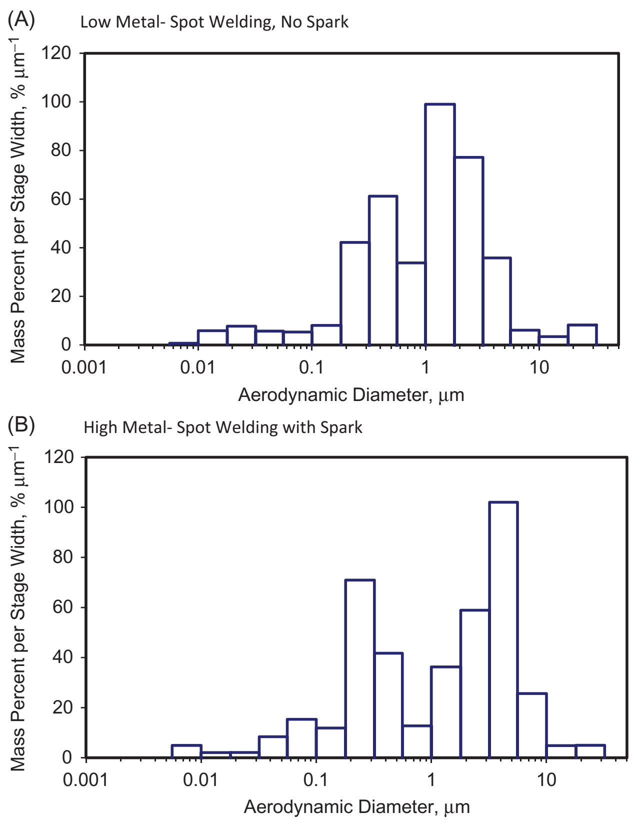


Figure 6. Particle size distribution of spot welding fume that contained either (A) a low level of metal or (B) a high level of metal comparing % mass concentration versus aerodynamic diameter as measured using a Moudi and Nano-Moudi impactor system.

Particle deposition appeared to be the greatest on stages 5–9 that covered a particle diameter size range of 0.18–1.8 µm.

In the assessment of particle morphology of the different size fractions of the generated fume during spot welding with an adhesive, the presence of more spherical particles was observed by SEM analysis in the larger (micron-sized mode) particle size fractions (Figure 8A and B). Chain-like, agglomerated particles that were similar in appearance to particles that are generated during other more standard arc welding processes were observed in the smaller (submicron/ultrafine) size fractions (Figure 8C–F). SEM-EDS analysis indicated that the metal composition of these spherical and agglomerated particle chains did not differ as the spectral peak for iron was the only element observed, regardless of the stage of the particle sampler (data not shown). It is important to note the appearance of multiple amorphous particles (arrows) on stages 8 (D) and 10 (E). The presence of chromium, and not iron, was detected when these amorphous particles were analyzed by SEM-EDS (Figure 9).

Discussion

Little is known about the health risks of inhaling aerosols that are generated during resistance spot welding of metals treated with adhesives, a common procedure used in the automotive industry where airborne concentrations of fine and ultrafine particles have been observed to be greater than 1 mg/m^3 (Buonanno et al., 2011; Liu & Hammond, 2010). Even less is known about the physical and chemical characteristics of aerosols generated during spot welding. Toxicology studies evaluating the health effects associated with the inhalation of aerosols generated during resistance spot welding are lacking. A resistance spot welding exposure system that produces aerosols that mimic what has been observed in the workplace is needed for animal toxicology studies. It then would be possible to determine the potential mechanisms by which inhaled spot welding aerosols may affect health, as well as to assess which component of the aerosol may be responsible for any adverse health outcomes that are be observed.

In the current study, a resistance spot welding aerosol generator and inhalation exposure system was developed.

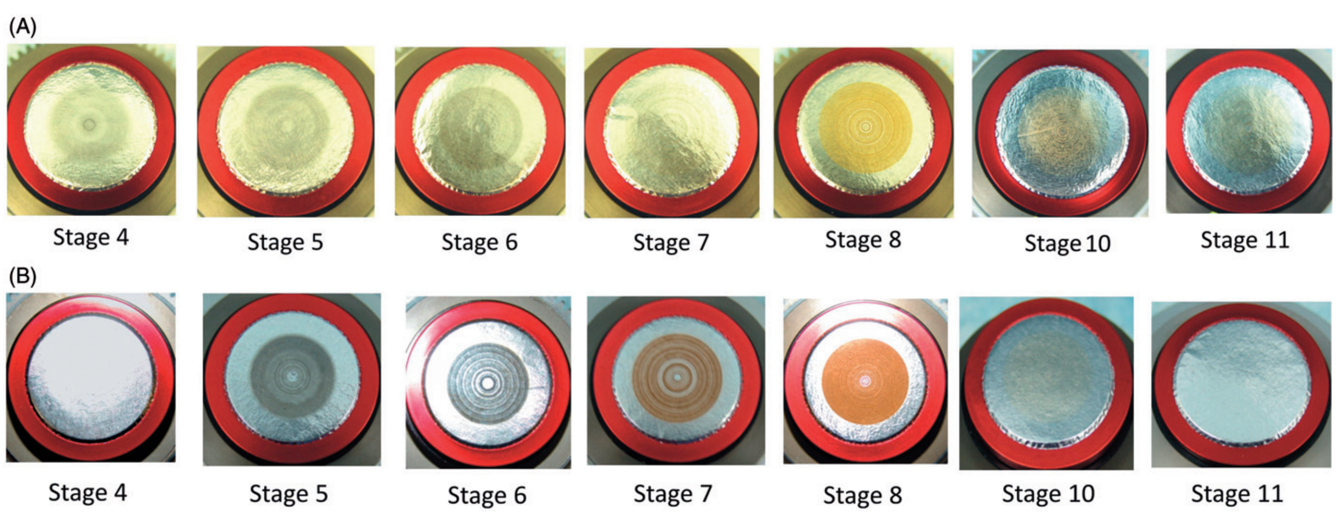


Figure 7. Images of particle deposition on different selected filters from the Moudi and Nano-Moudi impactor system after spot welding parameters were set to generate either (A) a low level of metal with no sparking or (B) a high level of metal with sparking.

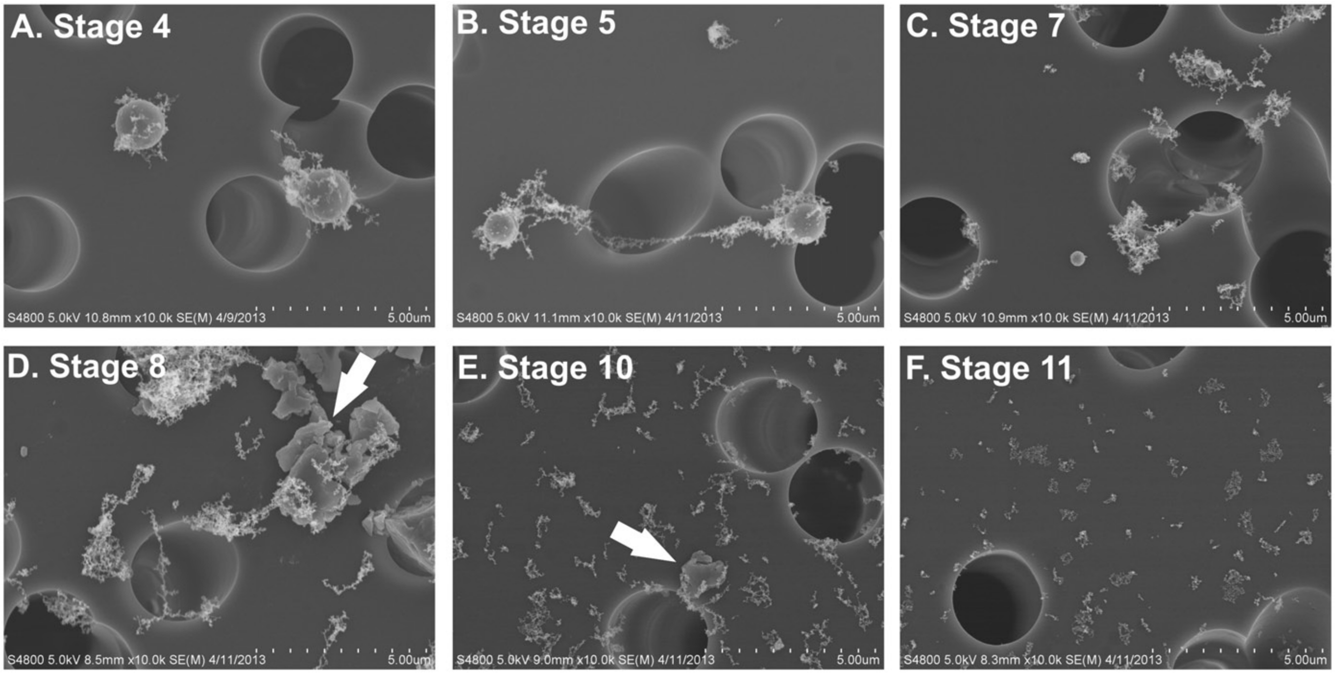
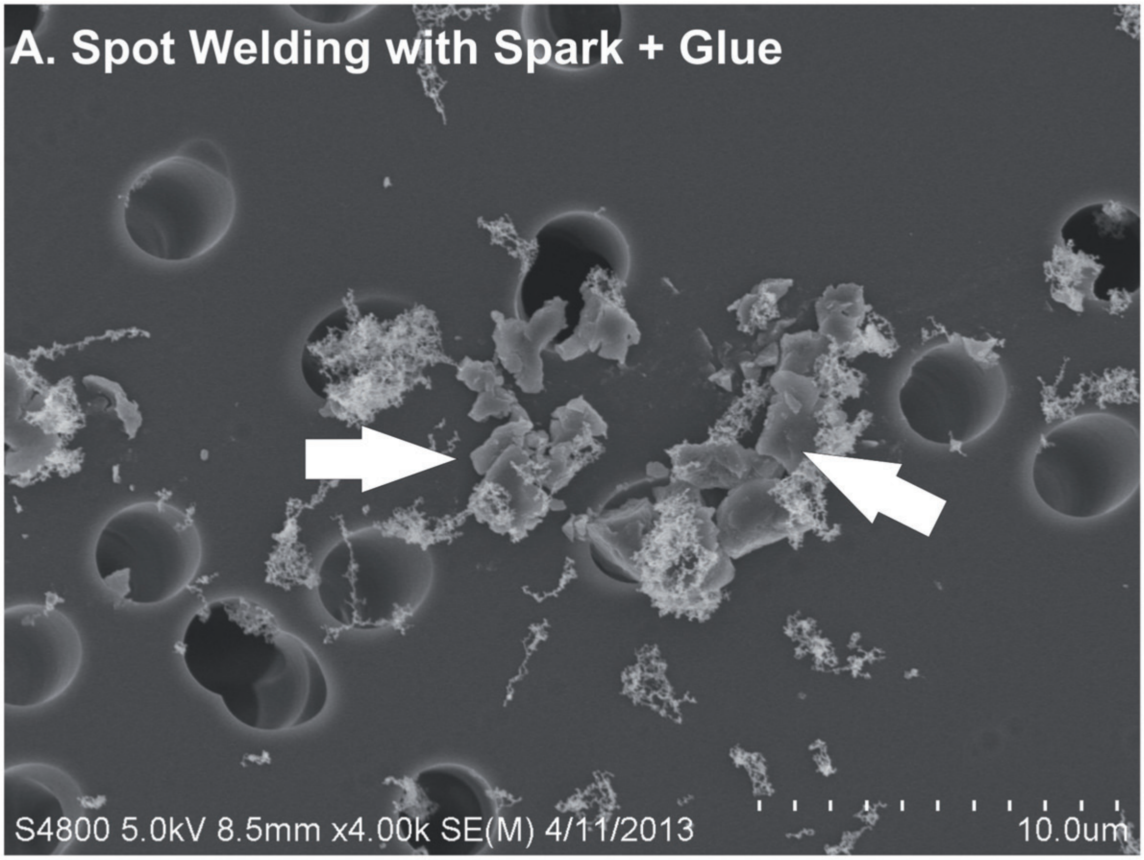


Figure 8. Representative scanning electron micrographs depicting collected particles on different stages of a MOUDI and Nano-MOUDI particle impactors after spot welding with sparking. The presence of more spherical particles was observed in the larger (micron mode) particle size fractions (A and B). In the smaller submicron and ultrafine size fractions (C–F), chain-like, agglomerated particles (typical for welding fume generated during arc welding) were present. Note the appearance of multiple amorphous particles (arrows) on stages 8 (D) and 10 (E). The 50% cutoff particle diameter for stage 4 is 3.2 µm, stage 5 is 1.8 µm, stage 7 is 0.56 µm, stage 8 is 0.32 µm, stage 10 is 0.10 µm, and stage 11 is 0.056 µm.

The system was designed in such a way that strips of sheet metal that had been treated with an adhesive were directed by a series of rollers to two electrodes of the spot welder. Spot welds then were made at a specified distance from each other by an automated, computer-controlled spot welding gun in air-tight fume chamber. The formed aerosols were transported to an animal exposure chamber and characterized by a number of particle sampling and analytical devices. By controlling the number of spot welds performed over time, different target aerosol concentrations could be maintained within the animal exposure chamber during a 4-h exposure period, thus allowing for possible dose–response and time-course toxicology studies. In addition, by controlling the spot welder current, aerosols were generated with different chemical and physical characteristics, possibly allowing for a determination of which component of the generated fume may induce adverse health outcomes.

Results showed that resistance spot welding performed with the system developed in this study produced complex aerosols that were composed of metal oxide particulates and VOCs. The metal particles were derived from the welding of the strips of mild steel sheet metal as the metal profile of the generated fume was identical to the composition of the metal strips with iron composing 99% of the metals present. Multiple animal studies have shown that the toxic potential of traditional arc welding particles is highly dependent on their metal composition (Antonini et al., 1996, 2011a; Erdely et al., 2011; Leonard et al., 2010; Taylor et al., 2003; Zeidler-Erdely et al., 2008, 2010). Particles generated when welding with mild steel materials were cleared from the lungs readily and caused minimal levels of lung toxicity in animal models compared with welding with stainless steel that contained other metals besides iron, such as chromium and nickel. Interestingly, the presence of small amounts of chromium was detected by SEM-EDS analysis in multiple amorphous particles that were observed on different impactor stages after spot welding. Because of their appearance, these particles do not appear to have formed by the typical vaporization–condensation mechanism that is most often observed for the complex metal particles generated during gas metal arc welding. Additional metal characterization analyses of the strips of sheet metal are ongoing to determine the possible source of the chromium.

By using an adhesive material during the spot welding process with the potential presence of VOCs in the resulting aerosol, the pulmonary and systemic toxicological responses may be quite different than what was observed after exposure to more standard gas metal arc welding fumes. Multiple VOCs were measured in the animal exposure chamber during spot welding when an adhesive was used between the metal strips that were identical to the adhesive used in the automotive processing plant where a Health Hazard Evaluation was performed by NIOSH (Kanwal & Boylstein, 2006). The health effects of VOCs can vary greatly according to the adhesive component, which can range from being highly toxic to having no known effects. Siloxanes, benzene, toluene, isopropanol, 2-butoxyethanol, butanol, and ethylene glycol were identified after spot welding using the adhesive in the current study. In general, short-term inhalation exposure to VOCs can cause eye and respiratory tract irritations, headaches, dizziness, visual disorders, fatigue, loss of coordination, nausea, and memory impairment (Environmental Protection Agency, 2012). Long-term inhalation may cause damage to the liver, kidney, and central nervous system. In addition, specific VOCs, including benzene, have been classified as human carcinogens. Toluene, like most VOCs, is



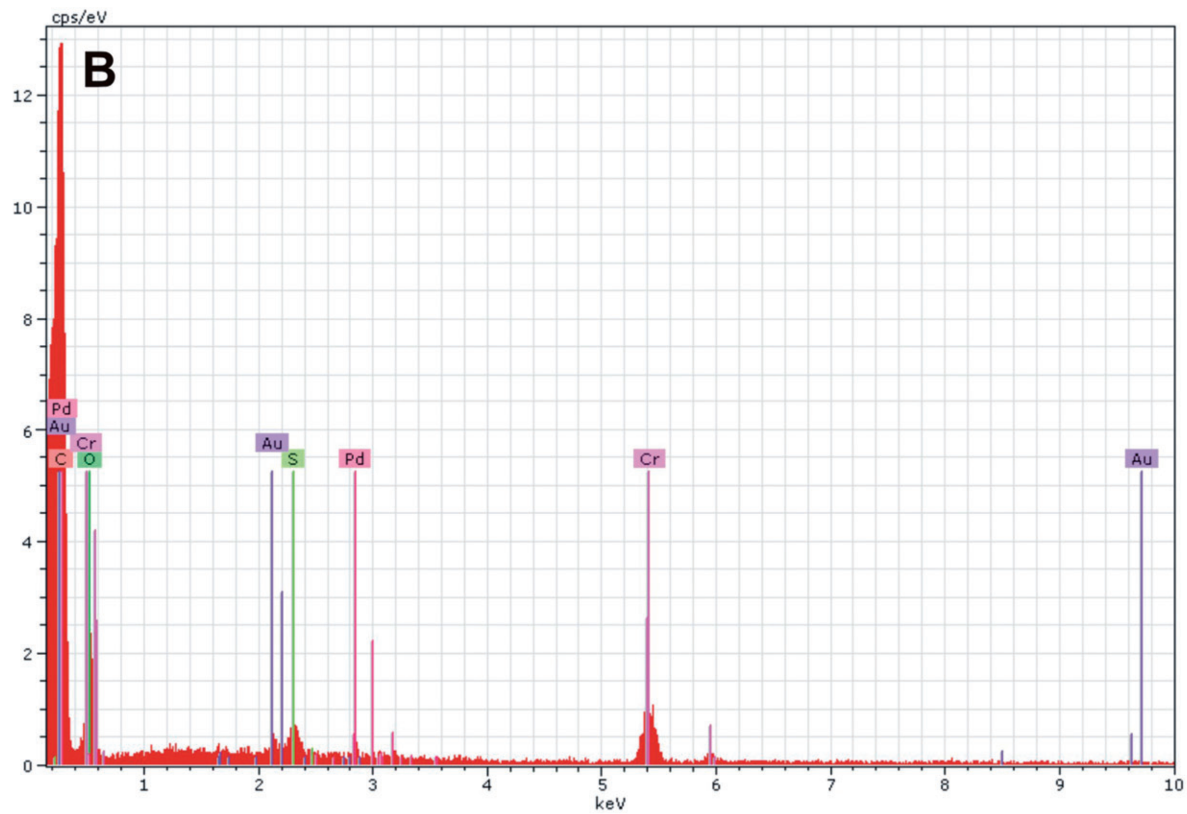


Figure 9. (A) Scanning electron micrographs depicting collected particles on stage 8 of a MOUDI and Nano-MOUDI particle impactors after spot welding with sparking using an adhesive. Note the presence of multiple amorphous particles (arrows). The 50% cutoff particle diameter for stage 8 is 0.32 µm. (B) SEM-EDS analysis detected the presence of chromium (Cr) in these amorphous structures. The signals for gold (Au) and palladium (Pd) were derived from the mounting medium used to process the tissue for SEM analysis. The labeled thin vertical lines are guidelines to the positions of the spectral peaks for the elements, and should not be confused with the spectra themselves.

highly lipophilic and easily crosses the blood–brain barrier, accounting for its primary effects on the central nervous system (McKeown, 2011). Chronic central nervous system effects after toluene exposure have included neuropsychosis, cerebral, and cerebellar degeneration with ataxia, seizures, optic, and peripheral neuropathies, and decreased cognitive ability. Toluene has been shown to interact with several key brain neurotransmitters, mainly g-aminobutyric acid (GABA) and possibly glycine and dopamine (Long, 2006). Pulmonary effects due to toluene inhalation have included bronchospasm, asphyxia, and acute lung injury. Due to genetic polymorphisms, some individuals may be more sensitive to the effects of inhaled toluene than others (Broberg et al., 2008). Occupational asthma has been found in workers exposed to toluene levels considered safe in the workplace.

Particle size and morphology of spot welding aerosols also may influence toxicological responses after inhalation. Size distribution of the generated particles was observed to be multi-modal. Aerosol formation appears to follow the same mechanisms in resistance spot welding as what is observed during standard arc welding processes (Jenkins et al., 2005; Zimmer & Biswas, 2001). High temperatures in the weld area caused metal vaporization followed by rapid condensation of the vapors to form ultrafine primary particles – a process called nucleation. The presence of free, non-agglomerated primary particles collected in the animal exposure chamber accounted for the small amount of particle measured in the nano-mode (ultrafine) size range. Less than 3% of the mass of particles formed were present as ultrafine particles. Most of the primary particles quickly coagulated and formed larger, agglomerated chains of the ultrafine primary particles. The submicron mode of agglomerated particles formed after spot welding had a MMAD of approximately 0.25–0.30 μm and accounted for the largest portion of particles of the three size modes in terms of particle number. Sparking or metal expulsion during spot welding caused the formation of larger, more spherical particles, referred to as spatter, which are formed due to the solidification of molten material after emission into the air. These spatter particles appeared in the micron size mode and accounted for the greatest amount of particles generated during spot welding in terms of mass. In comparison, a greater amount of the mass of particles was observed in the larger micron (spatter) mode during spot welding compared to what has been seen previously for arc welding processes (Antonini et al., 2006, 2011a,b; Jenkins et al., 2005).

In an analysis of airborne particles in the work area of resistance spot welding processes in three automotive processing plants, Dasch & D'Arcy (2008) found a bimodal particle size distribution consisting of supermicron spatter particles >20 μm in diameter and an agglomeration mode of smaller particles about 1 μm in diameter. Even though the morphology of the particles in the different size ranges that were collected in the automotive plants was identical to the morphology of the particles generated with our spot welding system, the presence of a significant amount of larger particles was not observed in the current study. Some possible reasons for this greater amount of larger particles measured in the automotive plant environment compared with our laboratory study may include more time for agglomeration, more metal expulsion in the plants, and additional airborne particles from other work processes. In addition, Dasch & D'Arcy (2008) observed about 7% of the particle mass measured in the automotive plants to be in the ultrafine size range compared with less than 3% of ultrafine particle mass in the current study. Additional filters also were analyzed for 68 individual VOCs collected in the automotive plant study to evaluate byproducts formed by the adhesives, but none of the 68 compounds was detected (Dasch & D'Arcy, 2008).

In summary, a resistance spot welding fume generator and inhalation exposure system was developed. The system produced complex aerosols that contained both metal particulates and VOCs. Different target aerosol concentrations and compositions could be maintained within an animal exposure chamber over an extended period of time. The size distribution of the generated particles was multi-modal. In addition, multiple VOCs were identified after spot welding using an adhesive, some of which have been shown to be toxic in humans and animal models. By controlling different spot welder process parameters, aerosols can be generated with different chemical and physical characteristics, which will be helpful in determining which components of spot welding fumes may cause adverse health effects. The development of this system makes it possible to expose laboratory animals by inhalation to spot welding aerosols and examine their effects on the lungs and other organ systems.

Declaration of interest

The authors of this manuscript have nothing to disclose.

The findings and conclusions of this paper have not been formally disseminated by NIOSH and should not be construed to represent any agency determination or policy.

References

Antonini JM, Krishna Murthy GG, Rogers RA, et al. (1996). Pneumotoxicity and pulmonary clearance of different welding fumes after intratracheal instillation in the rat. Toxicol Appl Pharmacol 140: 188–99.

Antonini JM, Afshari AA, Stone S, et al. (2006). Design, construction, and characterization of a novel robotic welding fume generator and inhalation exposure system for laboratory animals. J Occup Environ Hyg 3:194–203.

Antonini JM, Roberts JR, Stone S, et al. (2011a). Persistence of deposited metals in the lungs after stainless steel and mild steel welding fume inhalation in rats. Arch Toxicol 85:487–98.

Antonini JM, Keane M, Chen BT, et al. (2011b). Alterations in welding process voltage affect the generation of ultrafine particles, fume composition, and pulmonary toxicity. Nanotoxicology 5:700–10.

Broberg K, Tinnerberg H, Axmon A, et al. (2008). Influence of genetic factors on toluene diisocyanate-related symptoms: evidence from a cross-sectional study. Environ Health 7:15. doi: 10.1186/1476-069X-7-15.

Buonanno G, Morawska L, Stabile L. (2011). Exposure to welding particles in automotive plants. J Aerosol Sci 42:295–304.

Dasch J, D'Arcy J. (2008). Physical and chemical characterization of airborne particles from welding operations in automotive plants. J Occup Environ Hyg 5:444–54.

Environmental Protection Agency. (2012). An introduction to indoor air quality (IAQ). Volatile Organic Compounds (VOCs), US Environmental Protection Agency. Available from: http://www.epa.gov/iaq/voc.html.

Erdely A, Salmen-Muniz R, Liston A, et al. (2011). Relationship between pulmonary and systemic markers of exposure to multiple types of welding fume particulate matter. Toxicology 287:153–9.

Hammond SK, Gold E, Baker R, et al. (2005). Respiratory health effects related to occupational spray painting and welding. J Occup Med Environ Med 47:728–39.

Jenkins NT, Pierce WM-G, Eagar TW. (2005). Particle size distribution of gas metal and flux cored arc welding fumes. Welding J 84:156–63s.

Kanwal R, Boylstein RJ. (2006). NIOSH Health Hazard Evaluation Report: HETA# 2006-0059-3009, Daimler-Chrysler Jefferson North assembly Plant, Detroit, MI, July 2006; DHHS/Center for Disease Control and Prevention: Washington, DC.

Leonard SS, Chen BT, Stone SG, et al. (2010). Comparison of stainless and mild steel welding fumes in generation of reactive oxygen species. Particle Fibre Toxicol 7:32. doi: 10.1186/1743-8977-7-32.

Liu S, Hammond SK. (2010). Mapping particulate matter at the body weld department in an automotive assembly plant. J Occup Environ Hyg 7:593–604.

Long H. (2006). Inhalants. In: Flomenbaum NE, Goldfrank LR, Hoffman RS, et al. (eds.) Goldfranks' toxicologic emergencies. New York: McGraw-Hill, 1192–201.

Loukzadeh Z, Sharifian SA, Aminian O, et al. (2009). Pulmonary effects of spot welding in automobile assembly. Occup Med 59:267–9.

Luo JCJ, Hsu K-H, Shen W-S. (2006). Pulmonary function abnormalities and airway irritation symptoms of metal fumes exposure on automotive spot welders. Am J Ind Med 49:407–16.

McKeown NJ. (2011). Toluene toxicity, Medscape reference: drug diseases & procedures. Available from: http://emedicine.medscape.com/article/818939-overview. [Last accessed: 01 Jan 2013].

National Institute for Occupational Safety and Health. (1994). Elements by ICP (Hot Block/HCl/HNO_3 digestion): method 7303. In: NIOSH manual of analytical methods, 4th ed., Issue 2. Washington, DC: US Department of Health and Human Services, Publication No. 98–119.

Sriram K, Jefferson AM, Lin GX, et al. (2014). Neurotoxicity following acute inhalation of aerosols generated during resistance spot-weld bonding of carbon steel. Inhal Toxicol. doi: 10.3109/08958378.2014.954654.

Stout RD. (1987). The welding processes in relation to weldability. In: Welding Research Council (ed.) Weldability of steels, 4th ed. New York: Welding Research Council, 20–2.

Taylor MD, Roberts JR, Leonard SS, et al. (2003). Effects of welding fumes of differing composition and solubility on free radical production and acute lung injury and inflammation in rats. Toxicol Sci 75:181–91.

Zeidler-Erdely PC, Kashon ML, Battelli LA, et al. (2008). Lung inflammation and tumor induction in lung tumor susceptible A/J and resistant C57BL/6J mice exposed to welding fume. Particle Fibre Toxicol 5:12. doi: 10.1186/1743-8977-5-12.

Zeidler-Erdely PC, Li S, Kashon ML, Antonini JM. (2010). Response of the mouse lung transcriptome to welding fume: effects of stainless and mild steel fumes on lung gene expression in A/J and C57 BL/6J mice. Resp Res 11:70. doi: 10.1186/1465-9921-11-70.

Zimmer AT, Biswas P. (2001). Characterization of the aerosols resulting from arc welding processes. J Aerosol Sci 32:993–1008.

Zeidler-Erdely PC, Meighan TG, Erdely A, et al. (2014). Effects of acute inhalation of aerosols generated during resistance spot welding with mild steel on pulmonary, vascular, and immune responses in rats. Inhal Toxicol. doi: 10.3109/08958378.2014.944287.