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Particles in Welding Fumes

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Particles in Welding Fumes

by

Rebecca T. Williams

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Public Health
Department of Environmental and Occupational Health
College of Public Health
University of South Florida

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List of Abbreviations

AWS	American Welding Society
BG	Background (6ft from welding arc)
BLS	Bureau of Labor Statistics
BZ	Breathing Zone
CDNP	Combustion-Derived Nanoparticles
CPC	Condensation Particle Counter
Cr6	Hexavalent Chromium
CS	Carbon Steel
EDS	Energy Dispersive Spectroscopy
IN	Inconel
MIG	Metal Inert Gas Welding Procedure
NIOSH	National Institute of Occupational Safety and Health
NP	Nanoparticles
ORNL	Oak Ridge National Lab
OSHA	Occupational Safety and Health Administration
PBMCs	Peripheral Blood Mononuclear
SMPS	Scanning Mobility Particle Sizer
SS	Stainelss Steel

TEM	Transmission Electron Microscopy
UFP	Ultrafine Particles
WBGT	Wet Bulb Globe Temperature
WDNP	Welding Derived Nanoparticles

Abstract

The purpose of this study was to investigate whether or not differing base metals and filler wires used during welding processes contributed to differing amounts of ultrafine particles (UFP) and nanoparticles being emitted during the welding procedure in order to determine if UFP and NP exposures differed with base metal and filler wire, all welding processes utilized the same welding machine for metal inert gas (MIG), the same wire speed, and the same voltages during each welding process. The only variation in welding procedures were cover gases used, base metals, and filler wires.

Measurements gathered during welding procedures were conducted in the breathing zone of the welder and pipefitters consisted of UFP measurements taken by two different condensation particle counters (CPC), which operated in synchrony at the start and cessation of the welding process. NP measurements were taken by a NanoScan Scanning Mobility Particle Sizer (SMPS) and were also placed in the breathing zone of the welder

According to the results, base metal and filler wire do emit differing amounts of NP and UFP during the welding processes. Carbon steel emits the highest amount of nanoparticles, while stainless steel emits the second highest amount, and Inconel emits the least. The results also concluded that welders are exposed to a greater concentration of nanoparticles and UFPs than those experienced by pipefitters who stand 6ft from the welding arc.

Introduction

Background

According to the Bureau of Labor Statistics (BLS), in 2012 there were over 370,000 welders in the United States. The BLS anticipates that as the rate of industrialization increases the corresponding need for welding professionals will also increase.

The occupation of welding can be dated as far back as the Bronze Age, where pressure welded golden boxes were a popular commodity. The huge technological advancements in welding came in the 1800's following the discovery of acetylene in 1836 and the creation of an arc generated by a battery between two carbon electrodes. Fast forward to 1919 and the American Welding Society (AWS) was born. The primary objective of this society was to advance the welding field with technology and knowledge.

Welding processes present a myriad of health hazards, including airborne exposures to hexavalent chromium, lead, and iron. The risks associated with these exposures are well documented; however, adequate prevention of exposure might be impeded by the belief that only visible welding fumes pose health hazards. Determining and understanding the impact that ultrafine particles play in hazardous exposures will be critical to ensuring that safe work is being conducted. Unfortunately, there are no established regulatory thresholds or limits for ultrafine particulate.

Current day welding techniques, such as metal inert gas welding (MIG), was developed in the 1940's. MIG welding is a semi-automatic process that allows the welder to control the wire speed of their welding procedure. This type of welding is typically found in fabrication industries where the demand for production is high and time is of the essence. MIG is considered one of the most popular forms of welding techniques as it is highly versatile with base metals options and is able to accommodate a wide array of welding proficiency levels.

In order to conduct a MIG weld, three things are required; electricity, an electrode, and a cover (shield) gas. MIG uses a D/C current and electrode that is positive. Welding machines used in this type of welding process, utilize a constant power voltage supply, meaning that the voltage is able to be manipulated, controlled, and adjusted per the needs of the particular weld and filler rod. MIG welding essentially uses high-voltage to melt metal, which is then used to fuse two pieces of metal together. In order to protect the newly formed weld from oxidizing and setting improperly, a cover gas is used to shield the weld. After the weld has cooled, the two pieces of metal are fused together.

Although MIG welding is a very in-demand form of welding, it has several inherent hazards that can lead to occupational health injuries. Fire, skin burns, eye burns, UV light exposure, radiation, electrocution, and respiratory hazards are all occupational dangers that could lead to adverse health effects from MIG welding exposure.

Welding fumes can contain a wide spectrum of metals and chemicals that can cause systemic and respiratory issues in welders. Among these components are, hexavalent chromium (Cr6), iron oxides, beryllium, cadmium, lead, cobalt, copper, carbon monoxide, ozone, nitrogen oxides, barium, fluoride, manganese, nickel, silica, zinc, and a myriad of other hazardous materials. Particular base metals used also pose particular hazards both in regards to their

coatings and chemical makeup. Stainless steel welds, for example, create welding fumes comprised of high levels of oxides of iron, silicon, and manganese. Inconel welds usually create fumes comprised of high levels of nickel and chromium. When chromium reacts with the oxygen in the air after being released in the weld fume, it reacts and forms hexavalent chromium, which is a known carcinogen. Carbon steel is yet another base metal that poses a significant health risk to welders, as its fumes often are comprised of high iron oxides, and chromium levels. Not only are these components hazardous on their own, but the particle sizes of these welding fumes cause a myriad of health complications. Although OSHA regulates permissible exposure levels to these toxic fumes, they do not regulate an exposure limit in regards to particle sizes found in welding fumes. As seen in Figure 1, the size of particles in the pulmonary system play a critical role in their potential toxicity and ultimately determine where they settle.

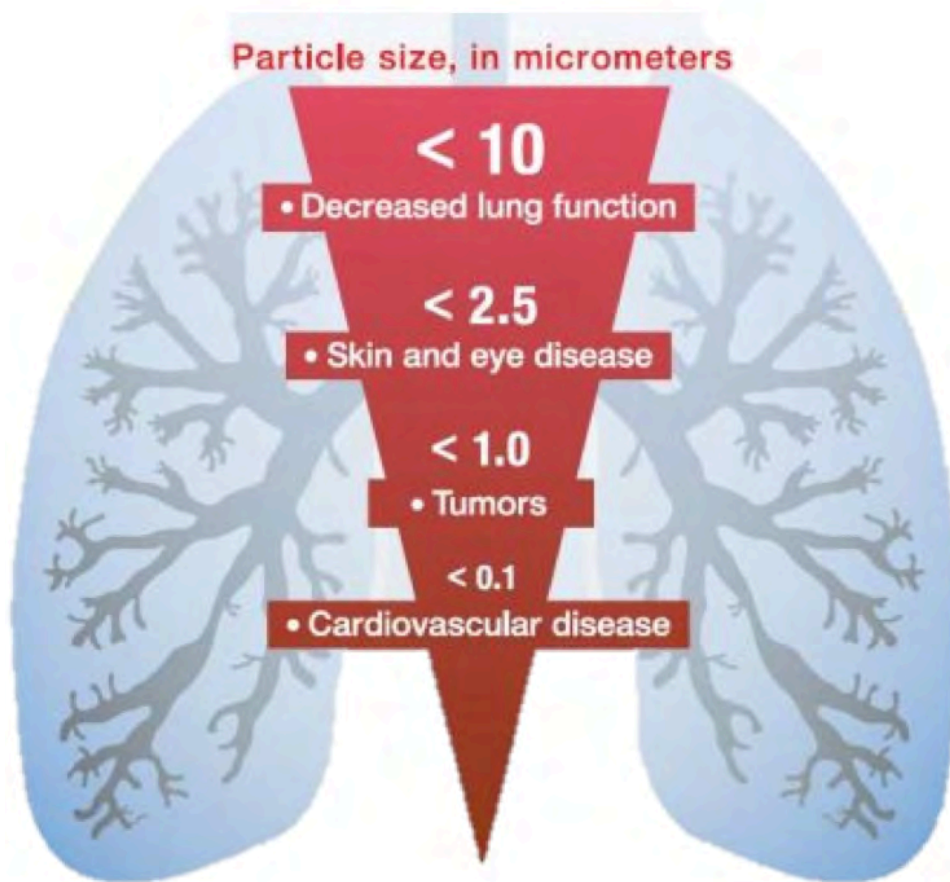


Figure 1: Particle Size Pulmonary Deposition

A particle size of particular concern is that of the ultrafine particle ($<100\text{nm}$) and nanoparticle range ($1\text{nm} - 100\text{nm}$). The reason for concern regarding these particles is that their toxicity in humans is relatively unknown and the ability to control exposure to them, is not an easy undertaking. It is believed that nanoparticles cause the greatest toxic effects at the cellular levels, when compared to that of larger particles. This is because nanoparticles tend to generate a greater amount of reactive oxidative species activity. Although people are regularly exposed to nanoparticles daily via car engines, computers, hair dryers and a myriad of other mechanical mechanisms, welders are exposed to a much higher concentration of these particles. Not only is their concentration exposure much greater than that of a normal populations' exposure, but the

chemical makeup of these welding derived nanoparticles can be comprised of extremely hazardous substances such as hexavalent chromium, nickel, and manganese.

The concentration emission of WDNP depends of a wide spectrum of circumstances, such as the type of welding taking place, the melting point of the base metals / filler wires, the voltages used, and the wire speed of the welding process. It is a very arduous process to protect a welder from nanoparticles and ultra-fine particles when there is such a large number of factors that play a key role in the fume particle concentration variances. With such a vast array of new metals used in welding each year and the projected increase of industrialization rates requiring hot work procedures, the necessity of welding safety knowledge is rapidly reaching a tipping point. Due to this demand, it is important to have scientific studies completed in which an industrial hygienist can refer to in an attempt to gain a deeper understanding of a welder's potential exposure to these particles in regards to the specific welding type, base metal, and voltages they intend to use for a given welding project.

Purpose

The purpose of this project was to characterize ultrafine and nanoparticle exposures of welders by collecting personal samples within their breathing zones (BZ) and background (BG) area samples from a 6ft distance from the welding arc. This data was used to determine if UFP and nanoparticle welding fume concentrations varied between three different base metals that utilized the same wire speeds, voltages, welding type, and welding machine.

Literature Review

In order to ascertain a deeper understanding of the emission of ultrafine particles in welding procedures, the following scientific studies were reviewed. Donaldson et al, highlighted the inhalation toxicity of combustion-derived nanoparticles in his review entitled, “Combustion-derived nanoparticles: A Review of Their Toxicity Following Inhalation Exposure.” Welding fumes were a critical component within his review, in which he links systemic pulmonary decreases to nanoparticles derived from welding fume exposure. Brouwer et al (2004), investigated various sampling techniques for the characterization of ultrafine particles in, “Personal Exposure to Ultrafine Particles in the Workplace: Exploring Sampling Techniques and Strategies.” A study conducted in 2017 by Shoeb et al, examined the oxidative stress and DNA mutation in cells post lung exposure to welding derived nanoparticles in a research paper titled “Oxidative Stress DNA Methylation, and Telomere Length Changes in Peripheral Blood Mononuclear Cells After Pulmonary Exposure to Metal-Rich Welding Nanoparticles.” The results of these studies and reviews are summarized below:

Combustion-derived nanoparticles: A Review of Their Toxicity Following Inhalation Exposure – Donaldson et al

The purpose of Donaldson's article was to "review the toxicity of combustion-derived nanoparticles (CDNP) following inhalation exposure." Donaldson showed that CDNP pose a significant health risk to pulmonary functions and states that oxidative stress of the compounds is indicative of their potential toxicity. Although Donaldson investigates the toxicity potential of several CDNP mechanisms, one of particular interest are particles derived from welding fumes. Welding fume exposures have been shown to cause bronchitis, fibrosis, and lung cancer. Donaldson also notes that metal fume fever, a systemic condition derived from exposure to zinc oxide particles and metals that undergo redox-cycling, cause pro-inflammatory responses in cells in culture and animals. Donaldson's review highlights a key fact in that, exposure to CDNP via welding fumes, is associated with increase of inflammation of the cytokine within the bronchoalveolar region of the respiratory system as well as an increase in the systemic oxidative stress potential. Additionally, rats exposed to welding fumes in a study had shown a significant increase in inflammatory responses and lipid peroxide formations in their pulmonary systems, all of which are indicative of oxidative stress. Donaldson concluded by explaining that, in regards to CDNP from welding fumes, the soluble transition metals are the key mechanisms of inflammatory responses and oxidative stress reactions in the pulmonary systems of those exposed.

Personal Exposure to Ultrafine Particles in the Workplace: Exploring Sampling Techniques and Strategies.

Brouwer et al (2003) evaluated various sampling strategies and techniques for the collection of ultrafine particles and nanoparticles in an occupational setting. Brouwer et al, noted that these particles are typically defined as having an aerodynamic diameter of $<100\text{nm}$ and can be generated in a variety of ways in workplaces including, welding, soldering, laser ablations, and vehicle emissions. His investigation compared readily available techniques and instrumentation for the characterization of ultrafine particles and nanoparticles in the workplace. Among these instruments / techniques were, a condensation particle counter (CPC), scanning mobility particle sizer (SMPS), SEM and TEM. The study took place over the course of three consecutive work days and the premise of the study was to determine personal exposure to UFPs in the work place with the respective instruments / sampling techniques. Day one consisted characterizing particles during the welding of cheese racks. Days two and three consisted of characterizing particles near a robotic welding machine with no local exhaust ventilation (LEV) in use. All welding procedures utilized gas metal arc welding on stainless steel with an argon/ CO_2 cover gas.

The study noted that the CPCs performed very well in occupational settings and were instrumental in identifying, in real time, emission sources. The CPCs were very portable and easy to maneuver. The CPCs can detect particles in the range of 3-300 nm and are utilized to determine a concentration per cm^3 of particles for that given size range. Brouwer et al determined that the CPC is best used when multisource emission scenarios need to be detected. A limitation of the CPC is that the movement of air sources or cross winds, can significantly impact the reading of the CPC.

Brouwer et al, evaluated the use of a SMPS and found it to be a reliable instrument for the measurement of aerosol surface area. The SMPS gives the user real time analysis of mobility diameter through the detection of particle concentration number. An advantage of the SMPS was that it was relatively portable and reliable. Additionally, the SMPS can be selected to determine a particular particle size in either the UFP or nano particle size range.

TEM and SEM analyses were also evaluated in this small scale study. SEM was used to identify the morphology of the particles, surface area, and chemical identification. The SEM analysis indicated that the particles were not spherical in the study, and that the density of the particles were significant in the region in which they would settle/ deposit. The SEM in conjunction with the TEM analysis was also used to understand the agglomeration of the welding fumes, which is critical in determining their potential pulmonary toxicity.

Oxidative Stress DNA Methylation, and Telomere Length Changes in Peripheral Blood Mononuclear Cells After Pulmonary Exposure to Metal-Rich Welding Nanoparticles

Shoeb et al (2017), found that the components in welding fumes such as, chromium (Cr), manganese (Mn), nickel (Ni), and Iron (Fe), have various adverse health effects in people exposed to these particular types of welding fumes. The study's objective was to identify biomarkers indicating telomere length and DNA methylation in rats, following exposure to welding fumes derived from gas metal arc welding on mild steel and manual metal arc welding on stainless steel.

After a 24-hour period, the study showed that oxidative stress markers in the peripheral blood mononuclear cells (PBMCs) had significantly increased after exposure to the stainless steel welding fumes.

Methods

These measurements were taken every day that sampling occurred in order to determine a starting UFP concentrations and baseline environmental conditions. Additionally, before any welding occurred, but after the welding machine was turned on, a background UFP measurement was taken to determine UFPs emitted from the machinery itself. During the welding procedures, the only mechanical pieces of equipment that were operating were the MIG welding machine, the snorkel ventilation, and the pieces of equipment used specifically in this characterization of particles study. To determine an ongoing background UFP concentration, a CPC was placed 6ft away from the welding arc and behind a welding curtain while welding procedures took place.

Personal samples were taken from the breathing zones of the welders while the welding operations took place and their results were used to characterize particle welding fumes. The samples were taken with a dedicated breathing zone CPC, Nanoscan SMPS, and filter apparatus attached to a high flow pump for TEM and SEM analyses. These samples were critical in the characterization of welding fumes emitted and determining the concentration of ultrafine particles welders were being exposed to. This study was also important in determining the concentration of welding fumes that pipefitters or firewatchers were being exposed to in the background vicinity during the welding processes.

A Miller Field Pro Smart Feeder 300935 MIG welding machine was used for all welding procedures. A standard wire speed of 205 inches per minute (ipm) was used for all welding

processes. Voltages of the machine varied slightly on all three base metals, depending on the heat and filler metal splatter of the weld, from 24.5 volts – 26.5 volts (see Figure 8). Carbon Steel (A 36/ UNS K02600), stainless steel (316 /UNS S21600), and Inconel (incoloy-800 / UNS N08800) were used as the base metals for the welding operations (see Figure 9). The filler metals ER70S (UNS K11022), ER 316L (W31643), and ERNiCr-3 (UNS N06082) were used respectively with the previously mentioned base metals. The cover gas used for welding on carbon steel and stainless steel was a mix of 98% argon and 2% oxygen. The cover gas used for MIG welding on inconel was a mix of 75% argon and 25% helium.

Welding Room Layout

The fumes for this study were collected in a welding laboratory at Oak Ridge National Laboratory. The room in which this welding research took place, contained only one welding station and no additional hot work or separate work practices took place in this room except for those conducted for the purposes of this study. The dimensions of room are as follows: 24ft x 18ft x 22ft (see Figures 2-4). A snorkel ventilation system was used in close proximity to the welding operations. An appropriate capture velocity distance was determined by ORNL's laboratory ventilation space manager, Marwan Bader, prior to the initiation of this research. Using a hot wire anemometer, he determined the appropriate capture distance for the snorkel ventilation was 6in from the source of the arc (see Figures 5-6). An adjacent slot hood ventilation system was in place to the left of the welding booth and remained off until the welding operations ceased (see Figure 3). A 20ft tall yellow welding curtain divided the welding booth from the remainder of the room and hung 2 feet below the surface of the ceiling (see Figure 2). A metal door separated the welding lab from the main hallway and remained closed

while welding operations took place. Metal inert gas (MIG) welding was conducted on three base metals, carbon Steel (A 36), stainless steel (316), and inconel (800 Inconel).



Figure 2: Entry to Welding Laboratory Room



Figure 3: Measuring Welding Laboratory & Slot Hood Ventilation



Figure 4: Sectioning Sample Area with Blue Tape



Figure 5: Snorkel Capture Velocity

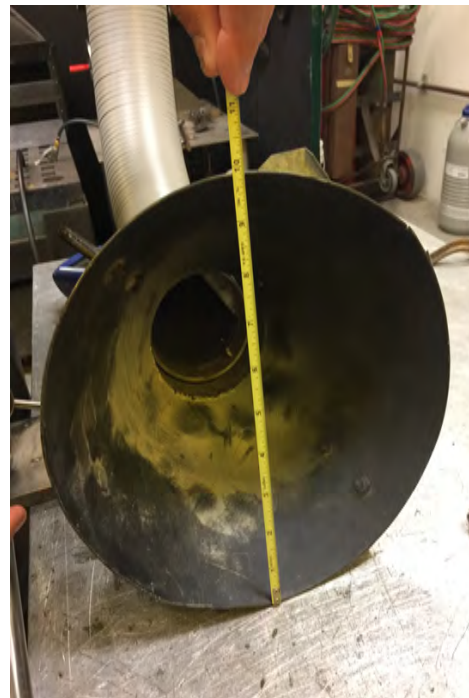


Figure 6: Snorkel Measurement

Sampling Strategy

All direct-read measurements were taken with three TSI Condensation Particle Counters (CPC), one Nanoscan (SMPS), and a WBGT meter (see Figure 7).



Figure 7: Characterization Equipment

One CPC (#939) was exclusively used for measurements in the welder's breathing zone. Another CPC (#637) was used exclusively to measure the 6ft background UFP exposure behind the welding curtain while the welding procedures took place. A third CPC (#200), was used to determine the pre-welding operations "normal" environmental UFP concentrations before each sampling operation took place and UFPs from the welding machine after once turned on, but before physical welding occurred. CPC #200 was also used in between each welding sample to determine when the background UFP concentration had returned to the pre-weld concentration, so that a next welding sample could begin. A WBGT meter was used pre-welding operations to determine the temperature and humidity within the room, pre-weld (see Figure 6).

A three-piece cassette filter was attached to a high flow pump via Tygon tubing. It hung in the breathing zone of the welder during the welding procedures. Each base metal had one cassette filter used for TEM and SEM analysis.



Figure 8: Welding Machine



Figure 9: Three Base Metals

Area Samples

UFP Measurements: Pre-weld

The welding laboratory area samples were taken in the breathing zone of the welder prior to any welding procedures taking place, but after the welding machine was turned on. This was used to determine the concentration of UFP's emitted from the welding machine to be subsequently subtracted from the final UFP results emitted during the welding processes. The UFP concentrations were taken 2 minutes prior to each welding sample on July 13th, August 3rd, and August 10th. These measurements were taken with a TSI CPC that was “zeroed” directly before each use, with a carbon filter, per the manufacturer’s instructions (see Figure 10). Manufacturer’s instructions on proper use were followed and no deviations were made.



Figure 10: Zero Filter for CPCs

Environmental Background Conditions: Pre-weld

Environmental conditions of the welding laboratory were measured 2 minutes prior to each welding sample on July 13th, August 3rd, and August 10th. These measurements were taken in the breathing zone of the welder with a QuestTemp36 WBGT meter. Manufacturer’s instructions were followed and no deviations were made (see Figure 7).

UFP Measurements: During Welding Operations

Background UFP concentrations were measured using a TSI CPC during each welding procedure. The background CPC was placed at the same sitting height of the welder, but positioned to be 6ft behind the welder (see Figure 11). This was done to obtain a background UFP concentration understanding, representative of pipefitters or firewatcher that are commonly found in welding booths. The background CPC was initiated and ceased in synchrony with CPC #939 that was placed in the breathing zone of the welder during welding operations and was “zeroed” within the welding laboratory prior to each sampling process, using an appropriate carbon filter (see Figure 10). The background CPC was used in accordance with manufacturer’s guidelines and no deviations were made.

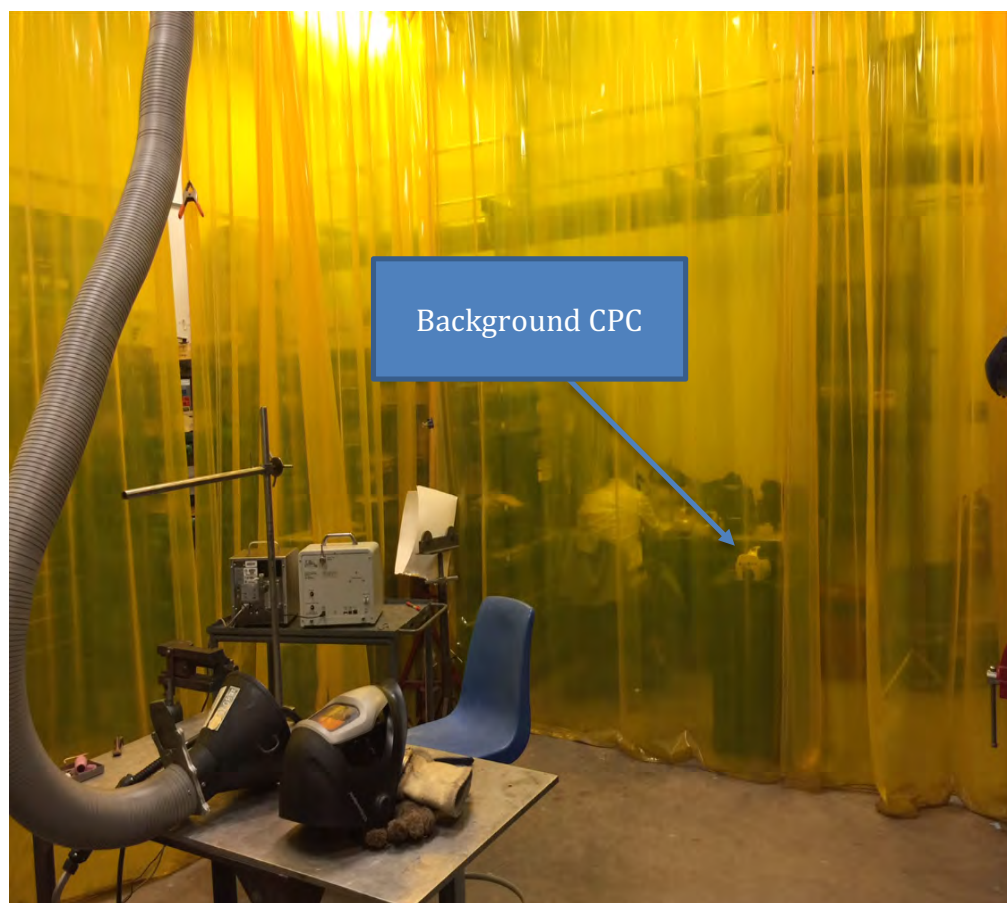


Figure 11: Background CPC Behind Welding Curtain

Personal Samples

Personal samples were taken from the breathing zone of the welder during welding procedures. One sample was obtained from each of the five-minute minimum welding procedures. There were three base metals used in this study and each of those metals were analyzed for a minimum of three welding samples each, that lasted for a minimum of five minutes per sample. The personal samples of the welder's exposure to welding fumes were taken on July 13th, 2017, August 3rd, 2017, and August 10th, 2017. Each personal welding fume sample was taken with one CPC, one Nanoscan SMPS, and one .08 micrometer cellulose ester membrane filter for TEM analysis. Multiple samples for various welding techniques were obtained in a same day. Before the start of each new sample / welding operation, the adjacent hood vent was turned on, the doors were opened, and a minimum of 15 minutes elapsed before the initiation of each new welding procedure. Additionally, a CPC was used to determine the adequate removal of subsequent UFP welding fumes by comparing the reading to that of the pre-weld UFP measurement. The next welding operation did not occur until current UFP measurements matched within 10% of the pre-weld UFP measurements.

Condensation Particle Counter

A CPC was placed on a stand in the breathing zone of the welder during the welding operations (see Figure 12). It began at the same time of the background CPC. The CPC was "zeroed" before each sample took place and ran for a minimum of 5 minutes per sample. Caution was taken to ensure the CPC's inlet faced the welding fume and was not tilted during any of the samplings. The distance of the CPC to the welding fumes were constant during each welding

procedure for continuity purposes. All manufacturers guidelines were adhered to and no deviations were made.



Figure 12: Breathing Zone CPC # 939

Nanoscan Scanning Mobility Particle Sizer (SMPS)

A Nanoscan SMPS was placed on a stand in the breathing zone of the welder during the welding operations. The SMPS was utilized in two different modes of operation. One mode was to measure all particles below 10nm at 1 second intervals during the welding operations (SINGLE mode) (see Figure 13). The second mode utilized, analyzed particles of size ranges between 11nm – 365nm every 1 minute (SCAN mode) during the welding procedures (see Figure 14). The alcohol wick used in the SMPS was cleaned and reinserted before each welding sample. Manufacturer's instructions were followed and no deviations were made.



Figure 13: SMPS SINGLE Mode

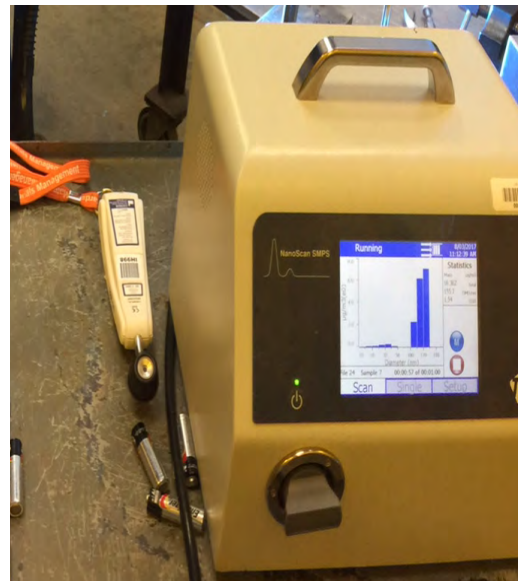


Figure 13: SMPS SCAN Mode

Transmission Electron Microscopy (TEM) Analysis & STEM Analysis

A 0.08 micrometer cellulosic ester filter, housed within a three stage cassette, was placed in the breathing zone of the welder during the welding operations (see Figure 15). The filter was attached to a high flow pump using Tygon tubing. The high flow pump was calibrated five times prior to each sampling day. The flow rate used for each welding sample was 25 liters/ min.

On August 3rd, 2017, inconel welding was conducted and the procedure was sampled for 16 minutes with the BZ cassette for TEM and STEM analysis. The total volume sampled during this particular weld was 400 liters and lasted for 16 min.

On August 10th, 2017, stainless steel welding was conducted and the procedure was sampled for 10 min with the BZ cassette for TEM and STEM analysis. The total volume sampled during this particular weld was 250 liters and lasted for 10 min.

On August 10th, 2017 carbon steel welding was conducted and the procedure sampling lasted for 10 min. The BZ cassette for TEM and STEM analysis passed a volume of air totaling 250 liters.

All samples were packaged according to ORNL chain of custody IH sample guidelines and mailed over night to the RJ Lee Group for TEM and SEM analysis.



Figure 14: Filter Breathing Zone Samples

Results

Area Samples

UFP Measurements: Pre-Weld & Environmental Background Conditions: Pre-weld

Representative values of pre-work UFPs, indoor environmental conditions, and welding machine UFPs collected during all three research sampling days are shown in Table I below.

Table I - Pre-Welding Area Samples

Pre-Welding Area Samples				
Sampling Dates	Indoor Environment Temperature and Humidity		Pre-work UFP (Concentration n/ cm ³)	Welding Machine UFP (Concentration n/ cm ³)
July 13 th , 2017	75 F	40%	473	810
August 3 rd , 2017	77 F	42%	510	780
August 10 th , 2017	75 F	41%	482	758

UFP Measurements: During Welding Operations

Representative values of background UFP welding fume samples taken from all carbon steel MIG welding procedures are shown in Table II below.

Table II- MIG Carbon Steel Background CPC

MIG Carbon Steel Background CPC				
	07/13	07/13	07/13	08/10
	#1	#2	#3	#4
Mean(#/cm³)	6370	75900	32900	37400
Min. (#/cm³)	4390	21300	5230	1030
Max. (#/cm³)	10100	187000	108000	130000
Std. Dev. (#/cm³)	954	45880	25502	46600
Sample Time (secs)	389	388	390	397

Representative values of background UFP welding fume samples taken from all Inconel MIG welding procedures are shown in Table III below, with exception to sample #3 as the BG CPC died during welding procedures.

Table III– MIG Inconel Background CPC

MIG Inconel Background CPC			
	08/03 #1	08/03 #2	08/03 #3
Mean (#/cm ³)	3140	20300	No Data
Min. (#/cm ³)	2250	3720	No Data
Max. (#/cm ³)	11100	178000	No Data
Sample Time (secs)	419	536	No Data

Representative values of background UFP welding fume samples taken from all stainless steel MIG welding procedures are shown in Table IV below, with exception to sample #3 as the BG CPC died during welding procedures.

Table IV - MIG Stainless Steel Background CPC

MIG Stainless Steel Background CPC				
	07/13 #1	07/13 #2	07/13 #3	08/10 #4
Mean (#/cm ³)	10300	24500	No Data	4260
Sample Time (secs)	376	394	No Data	439

Results of personal samples from all three welding procedures and their respective welding samples are shown below.

MIG Carbon Steel

Sample #1 Taken on July 13th, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC and results of background ultrafine particle samples taken with a separate synchronized CPC are shown below in Figure 16.

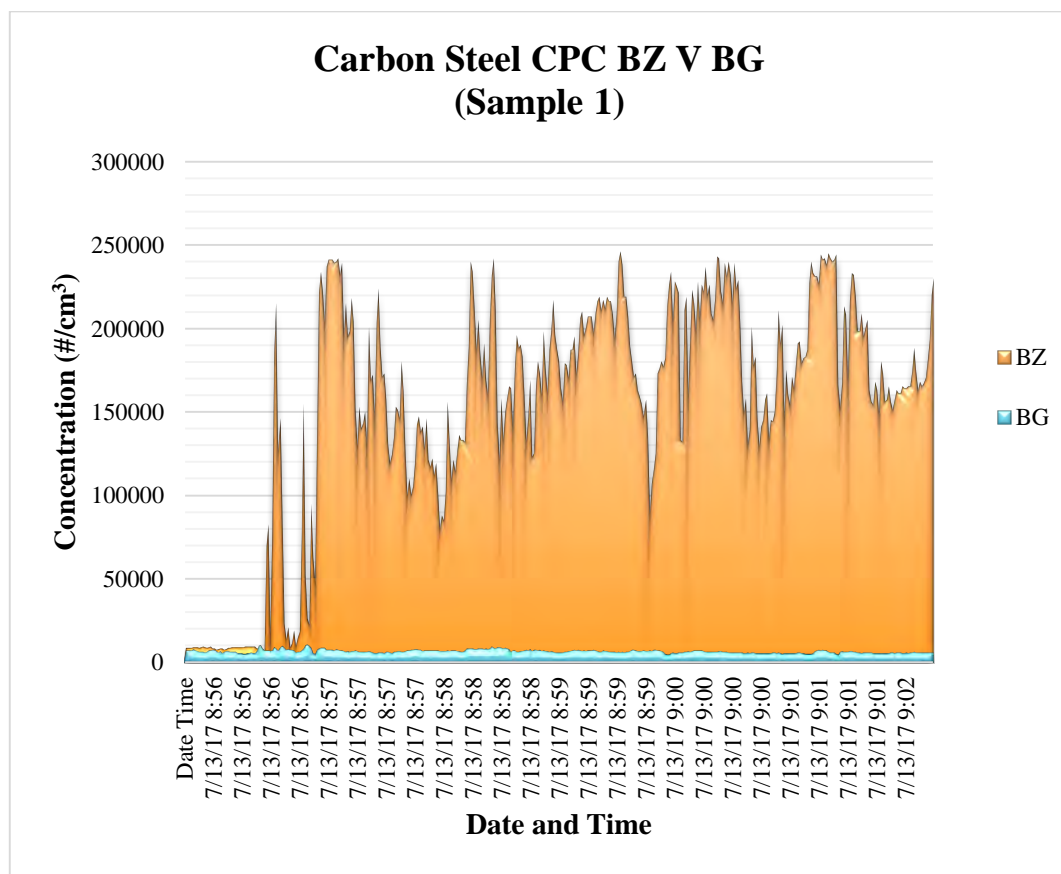


Figure 15: Carbon Steel BZ V BG (Sample 1)

Results of nanoparticle samples (particles below 10nm in diameter) taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the duration first carbon steel MIG welding sample, is shown below in Figure 17 and Table V.

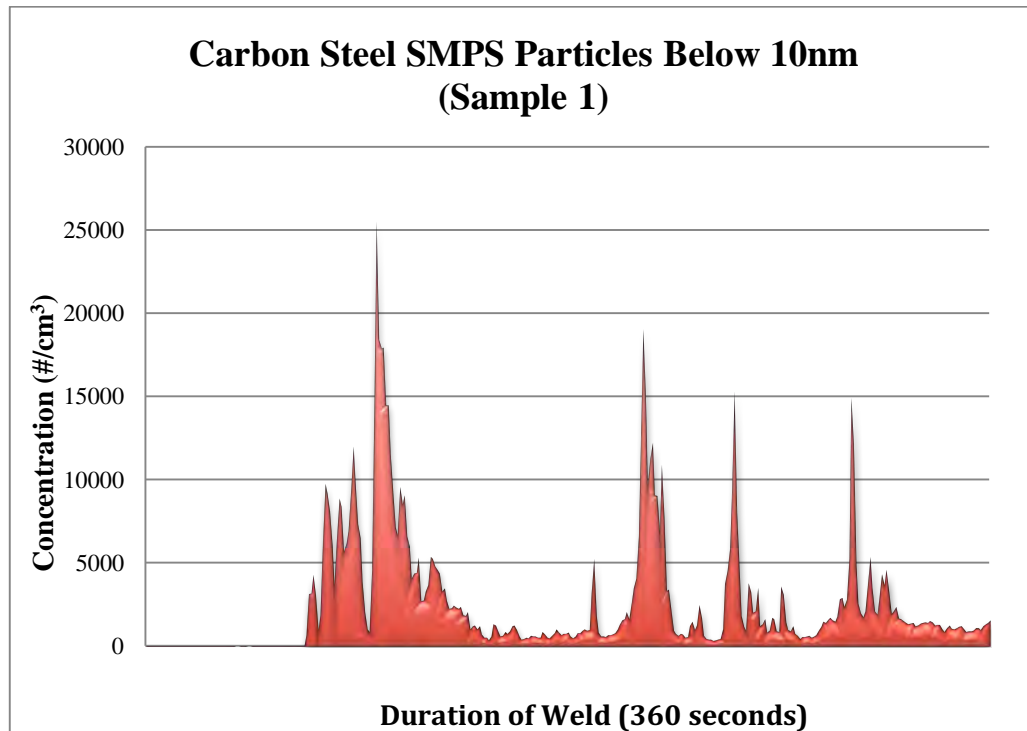


Figure 16: Carbon Steel SMPS (<10nm)

Table V- Carbon Steel SMPS Particles Below 10nm (Sample 1)

Carbon Steel SMPS Particles Below 10nm (Sample 1)				
	# (#/cm³)	Surface (nm²/cm³)	Volume (nm³/cm³)	Mass (ug/m³)
Mean	2629	826000	1380000	0.001
Min	30	9424	15700	0
Max	2550 0	8020000	13400000	0.016
Time (s)	360			

MIG Carbon Steel

Sample #2 Taken on July 13th, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC and results of background ultrafine particle samples taken with a separate synchronized CPC are shown below in Figure 18.

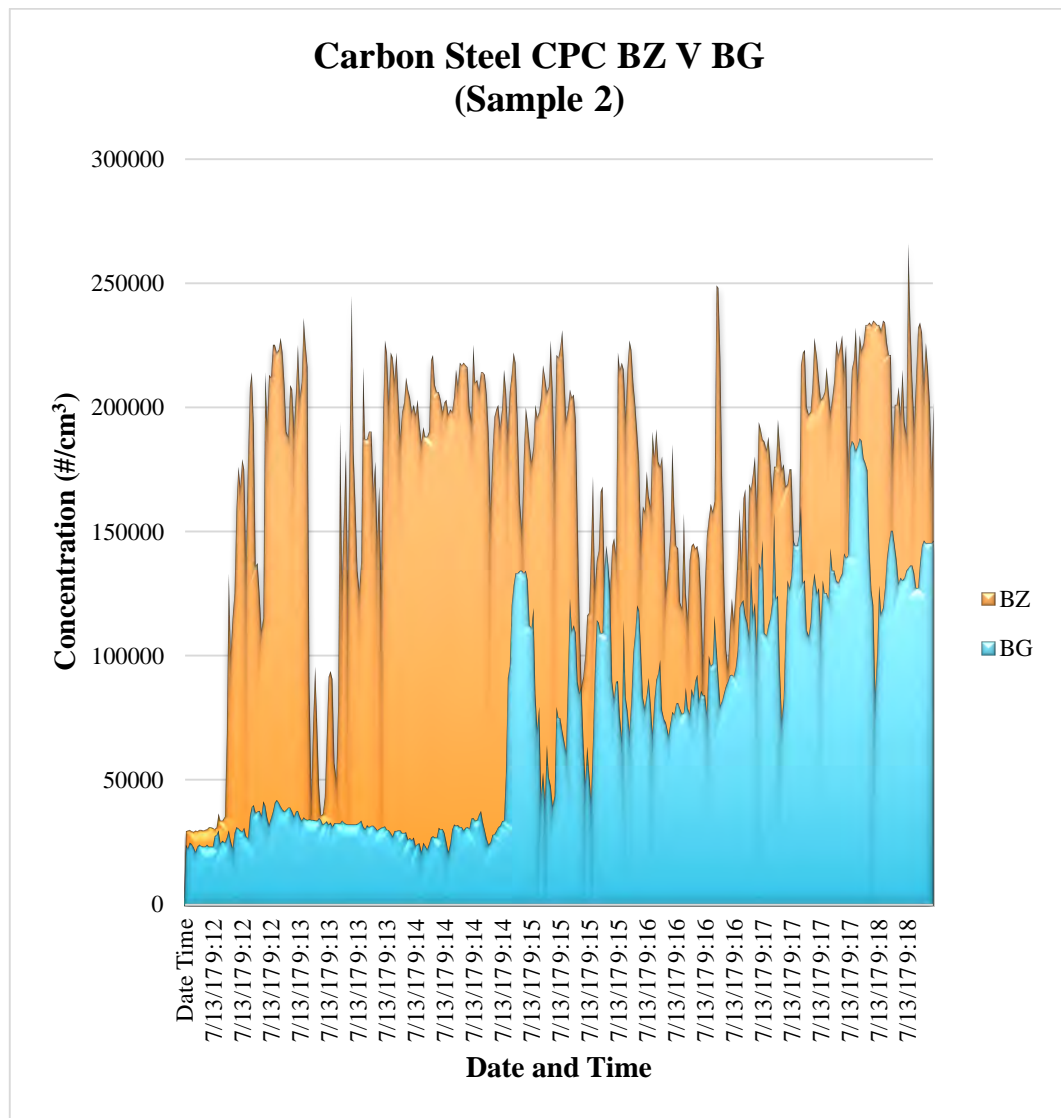


Figure 17: Carbon Steel CPC BZ V BG (Sample 2)

Results of nanoparticle samples (particles below 10nm in diameter) taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the duration second carbon steel MIG welding sample, is shown below in Figure 19 and Table VI.

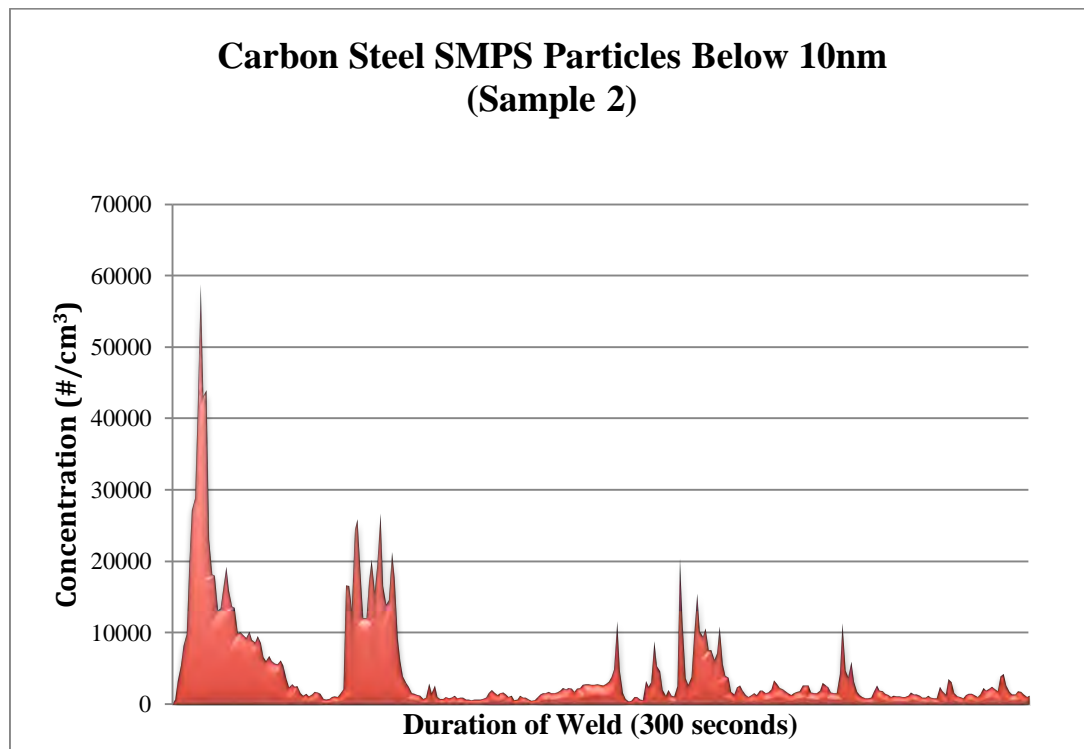


Figure 18: Carbon Steel SMPS Particles Below 10nm (Sample 2)

Table VI- Carbon Steel SMPS Particles Below 10nm (Sample 2)

Carbon Steel SMPS Particles Below 10nm (Sample 2)				
	Number (#/cm³)	Surface (nm²/cm³)	Volume (nm²/cm³)	Mass (ug/m³)
Mean	5050	1590000	2640000	0.0032
Min	481	151000	252000	0.0003
Max	58700	18400000	30700000	0.0369
Sample Time (s)	300			

MIG Carbon Steel

Sample #3 Taken on July 13th, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC and results of background ultrafine particle samples taken with a separate synchronized CPC are shown below in Figure 20.

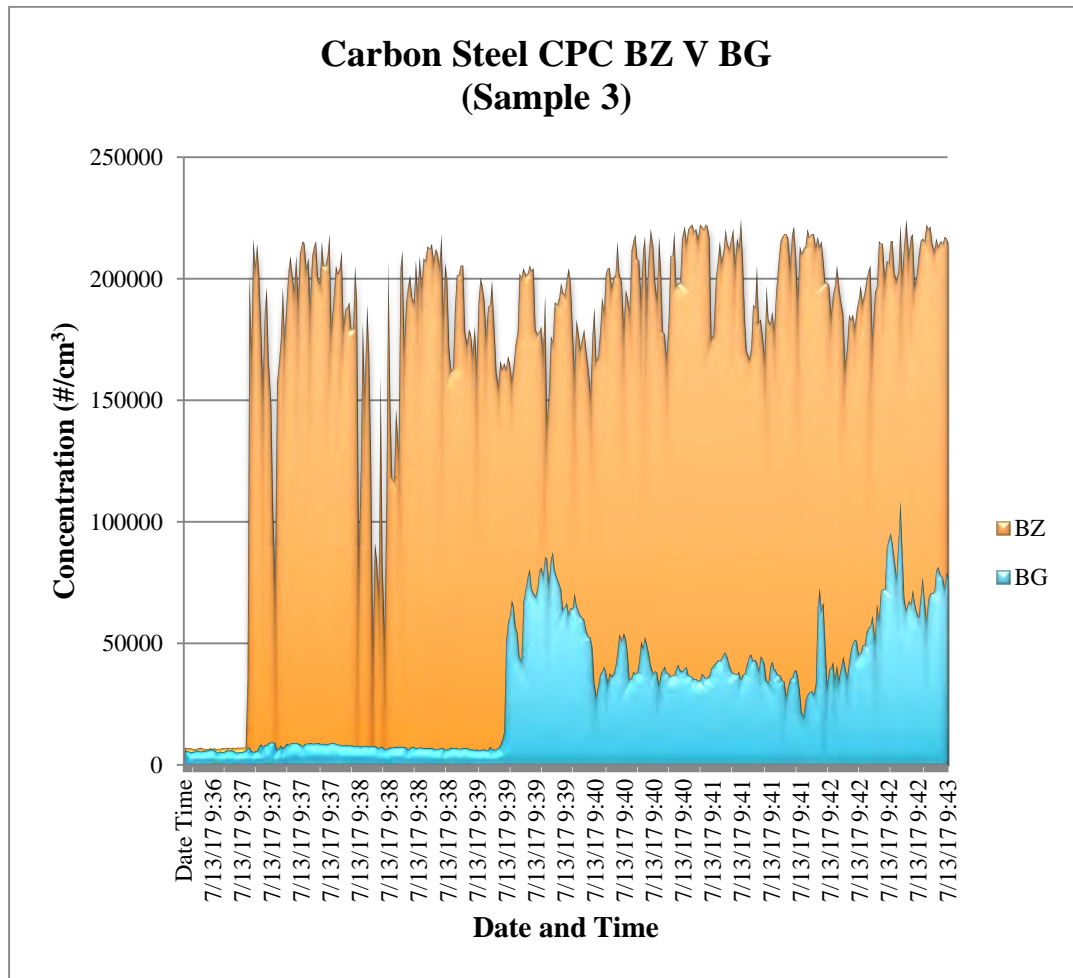


Figure 19: Carbon Steel CPC BZ V BG (Sample 3)

Results of nanoparticle samples (particles below 10nm in diameter) taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the third carbon steel MIG welding sample, is shown below in Figure 21 and Table VII.

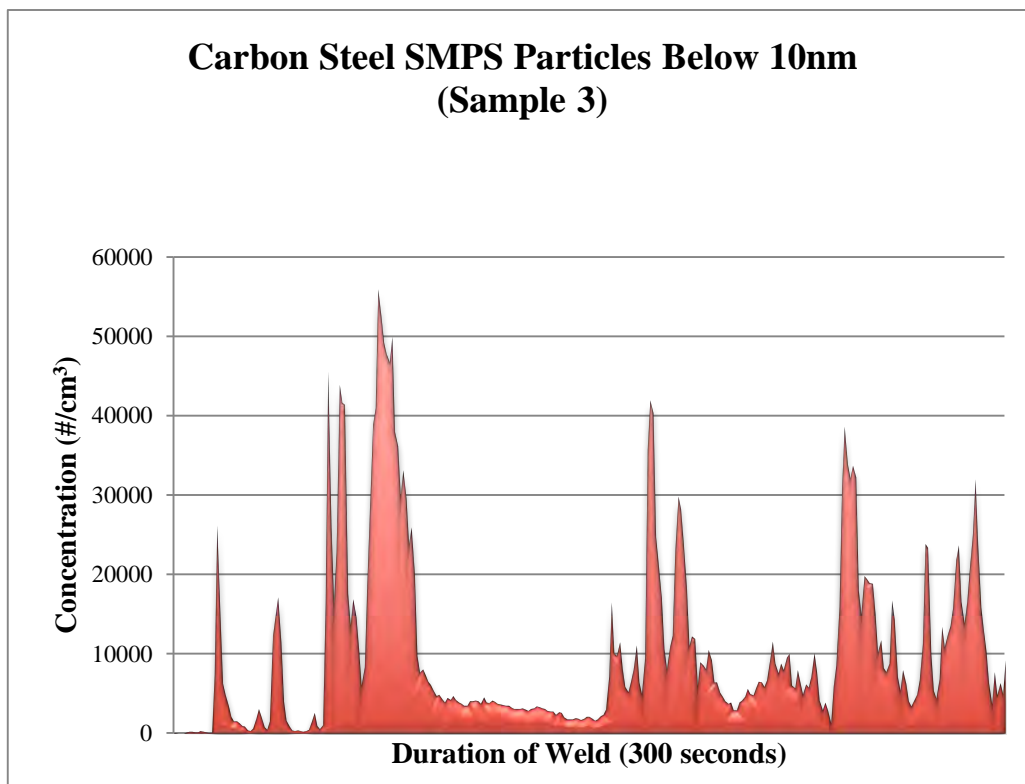


Figure 20: Carbon Steel SMPS Particles Below 10nm (Sample 3)

Table VII - Carbon Steel SMPS (Sample 3)

Carbon Steel SMPS (Sample 3)				
	Number (#/cm³)	Surface (nm²/cm³)	Volume (nm²/cm³)	Mass (ug/m³)
Mean	10400	3270000	5440000	0.0
Min	19	6031	10100	0
Max	55800	17500000	29200000	0.03
Sample Time (s)	300			

MIG Carbon Steel

Sample #4 Taken On August 10th, 2018

Results of personal ultrafine particle samples taken with a breathing zone CPC and results of background ultrafine particle samples taken with a separate synchronized CPC are shown below in Figure 22.

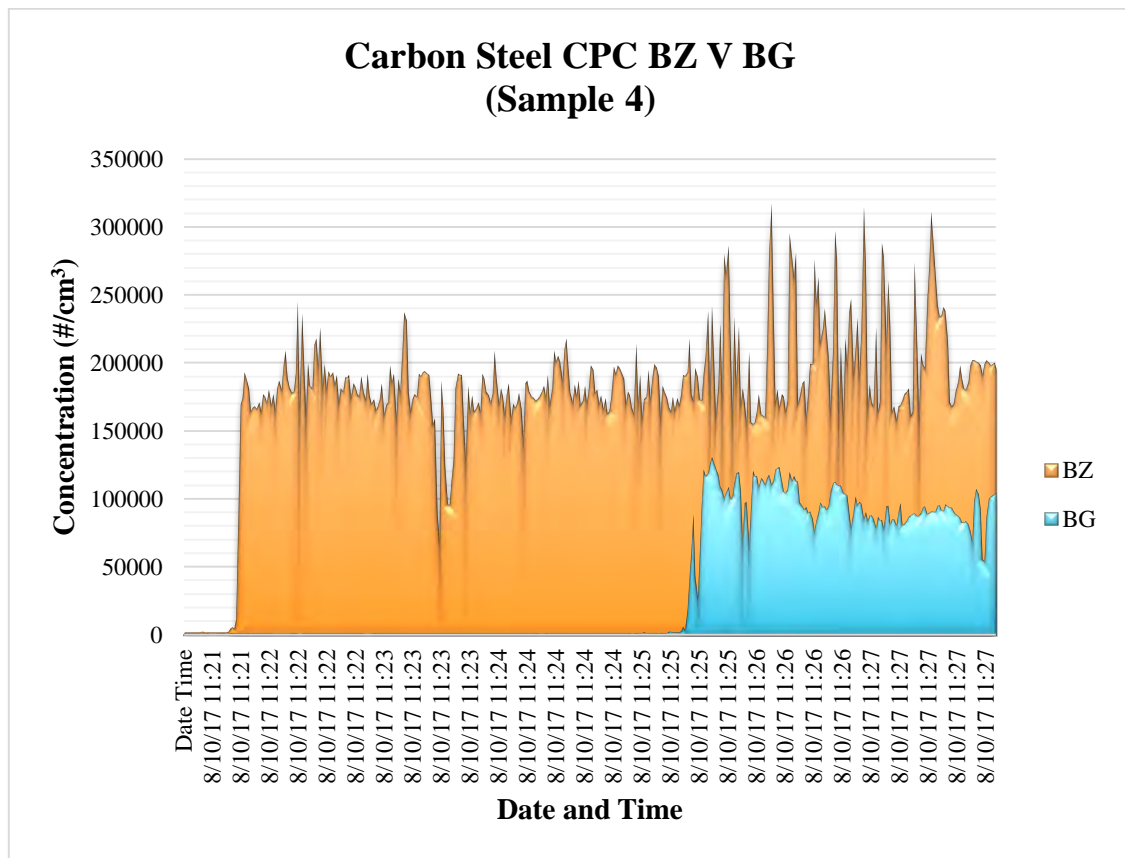


Figure 21: Carbon Steel CPC BZ V BG (Sample 4)

Results of particle diameter size during the span of each minute of the welding sample time taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the duration fourth carbon steel MIG welding sample, is shown below in Figure 23.

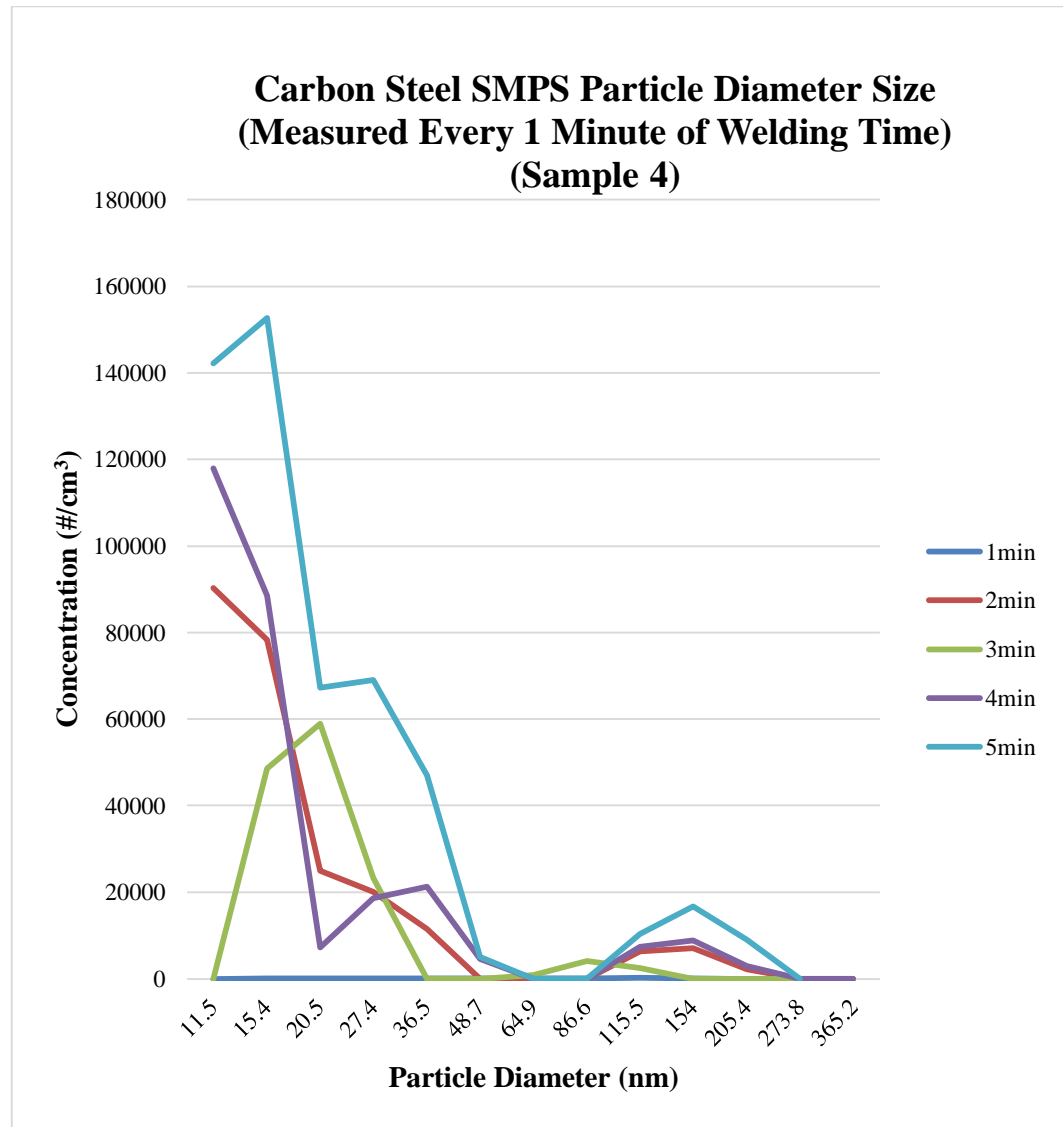


Figure 22: Carbon Steel Particle Diameter Size During Every 1 Minute of Welding Time (Sample 4) Taken with SMPS

SEM analysis results of MIG welding on carbon steel during August 10th, 2017, taken in the breathing zone of the welder, can be seen in Figure 24.

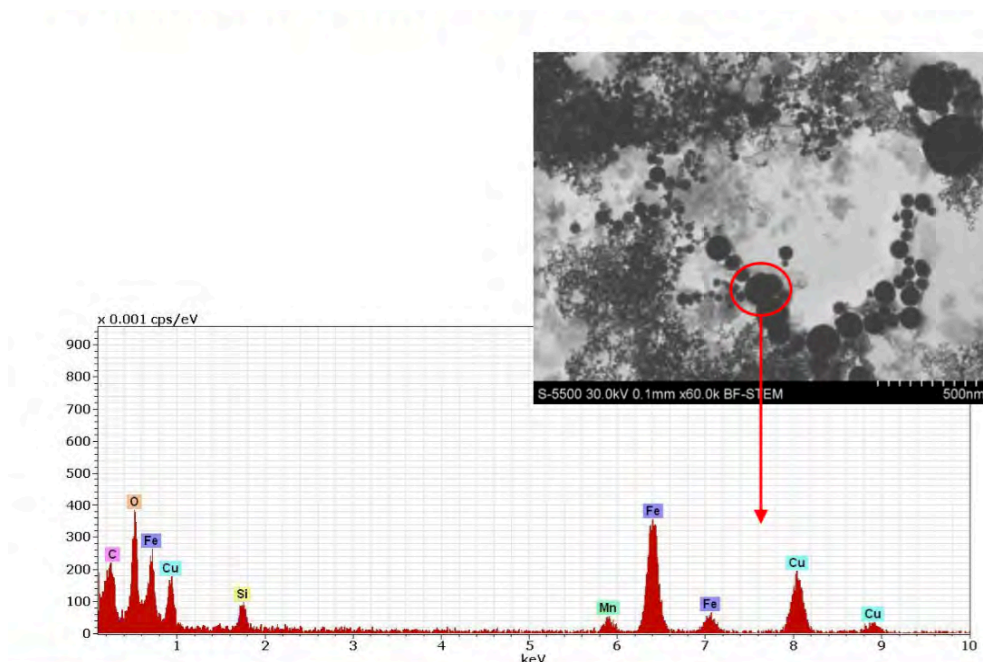


Figure 23: SEM Analysis of MIG Carbon Steel Welding Fumes in BZ

TEM analysis (field view) results of MIG welding on carbon steel during August 10th, 2017, taken in the breathing zone of the welder, can be seen in Figure 25.

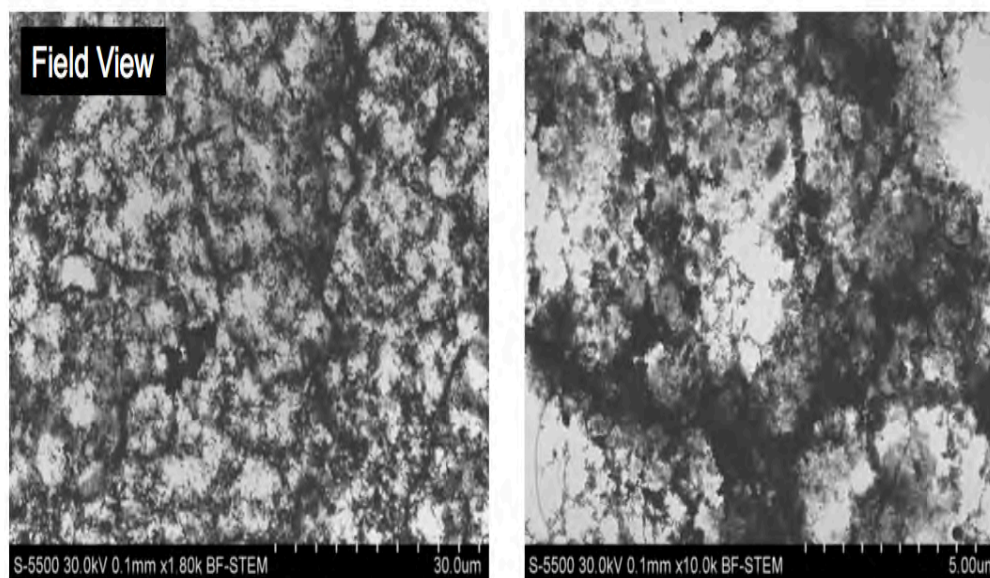


Figure 24: TEM Analysis of MIG Carbon Steel Welding Fumes BZ

Results of ultrafine particle concentrations in all four CPC breathing zone and background samples taken from MIG welding fumes on carbon steel base metals can be seen below in Table VIII.

Table VIII - Carbon Steel CPC UFPs BZ V BG (All Four Welding Samples)

Carbon Steel CPC UFPs BZ V BG (All Four Welding Fume Samples)								
UFPConc. (#/cm ³)	7/13 #1 BZ	7/13 #1 BG	7/13 #2 BZ	7/13 #2 BG	7/13 #3 BZ	7/13 #3 BG	8/10 #4 BZ	8/10 #4 BG
Mean	1. 54E+05	6 .37E+03	1 .73E+05	7 .59E+04	1 .76E+05	3 .29E+04	1 .77E+05	3 .74E+04
Min.	7. 34E+03	4 .39E+03	2 .90E+04	2 .13E+04	6 .79E+03	5 .23E+03	2 .30E+03	1 .03E+03
Max.	2. 46E+05	1 .01E+04	2 .66E+05	1 .87E+05	2 .24E+05	1 .08E+05	3 .17E+05	1 .30E+05
Total Sample Time (secs)	3 89	3 89	3 88	3 88	3 95	3 95	4 03	4 03

MIG Inconel

Sample #1 Taken on August 3rd, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC and results of background ultrafine particle samples taken with a separate synchronized CPC are shown below in Figure 26.

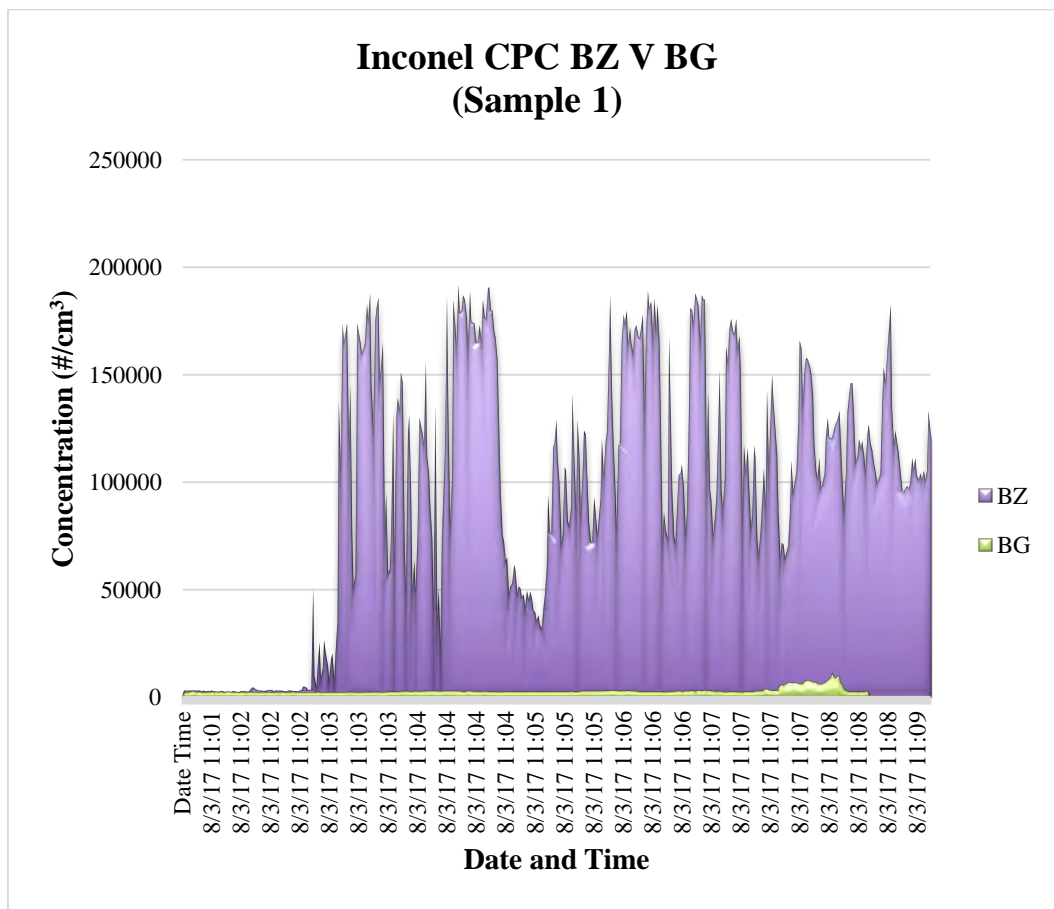


Figure 25: Inconel CPC BZ V BG (Sample 1)

Results of particle diameter size during the span of each minute of the welding sample time taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the duration first inconel MIG welding sample, is shown below in Figure 27.

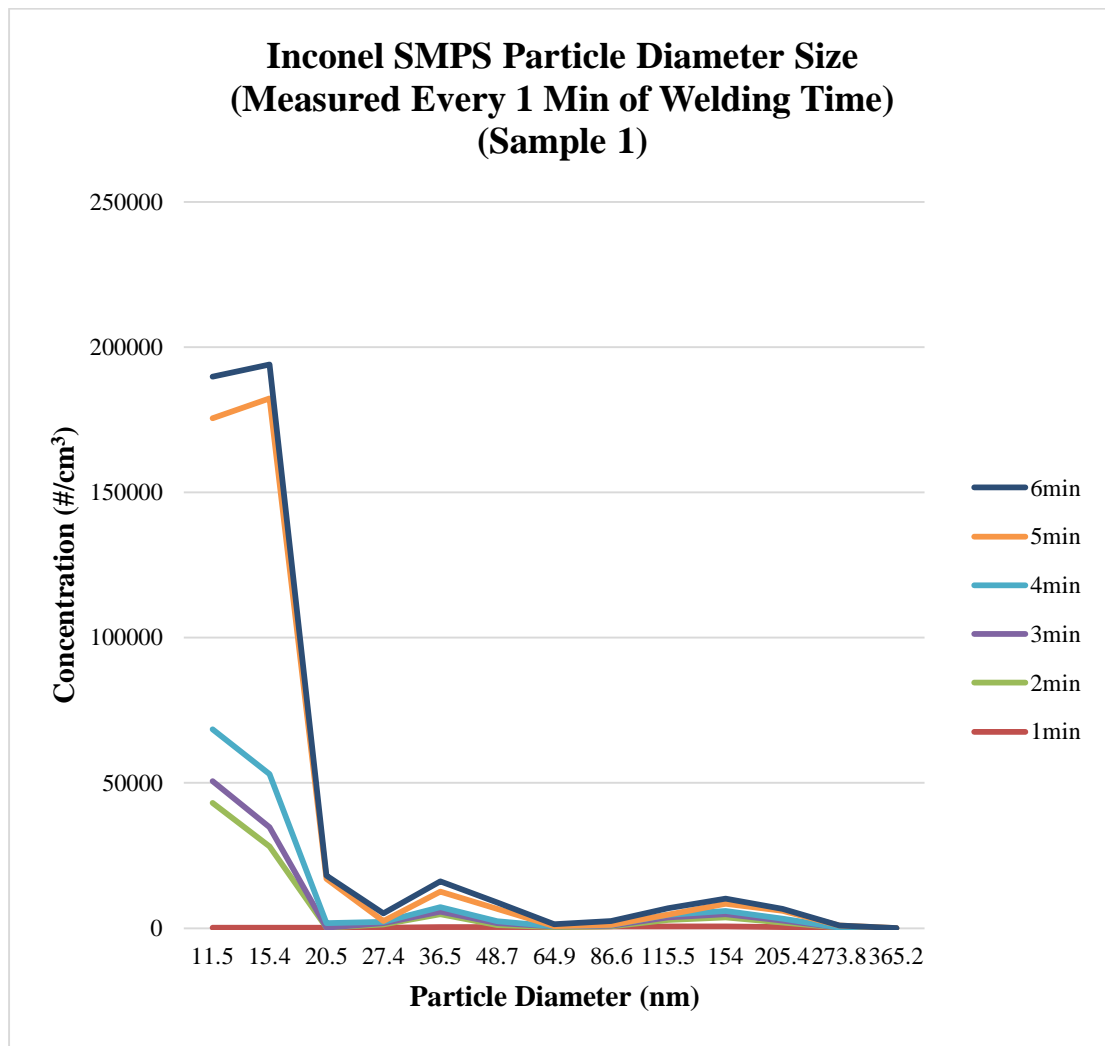


Figure 26: Inconel SMPS Particle Diameter Size (Measured Every 1 Minute of Welding Time) (Sample 1)

MIG Inconel

Sample #2 Taken on August 3rd, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC and results of background ultrafine particle samples taken with a separate synchronized CPC are shown below in Figure 28.

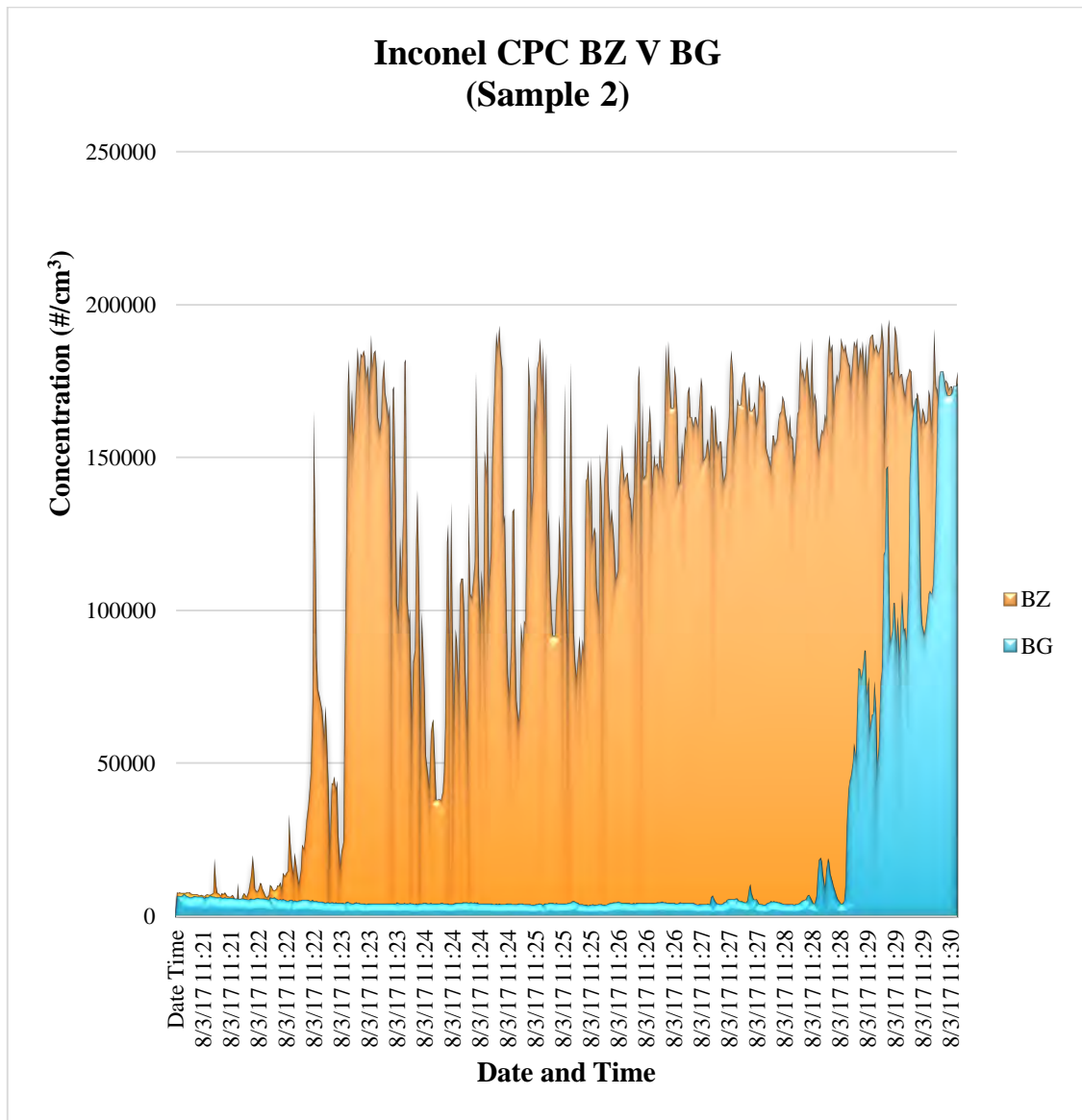


Figure 27: Inconel CPC BZ V BG (Sample 2)

Results of particle diameter size during the span of each minute of the welding sample time taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the second inconel MIG welding sample, is shown below in Figure 29.

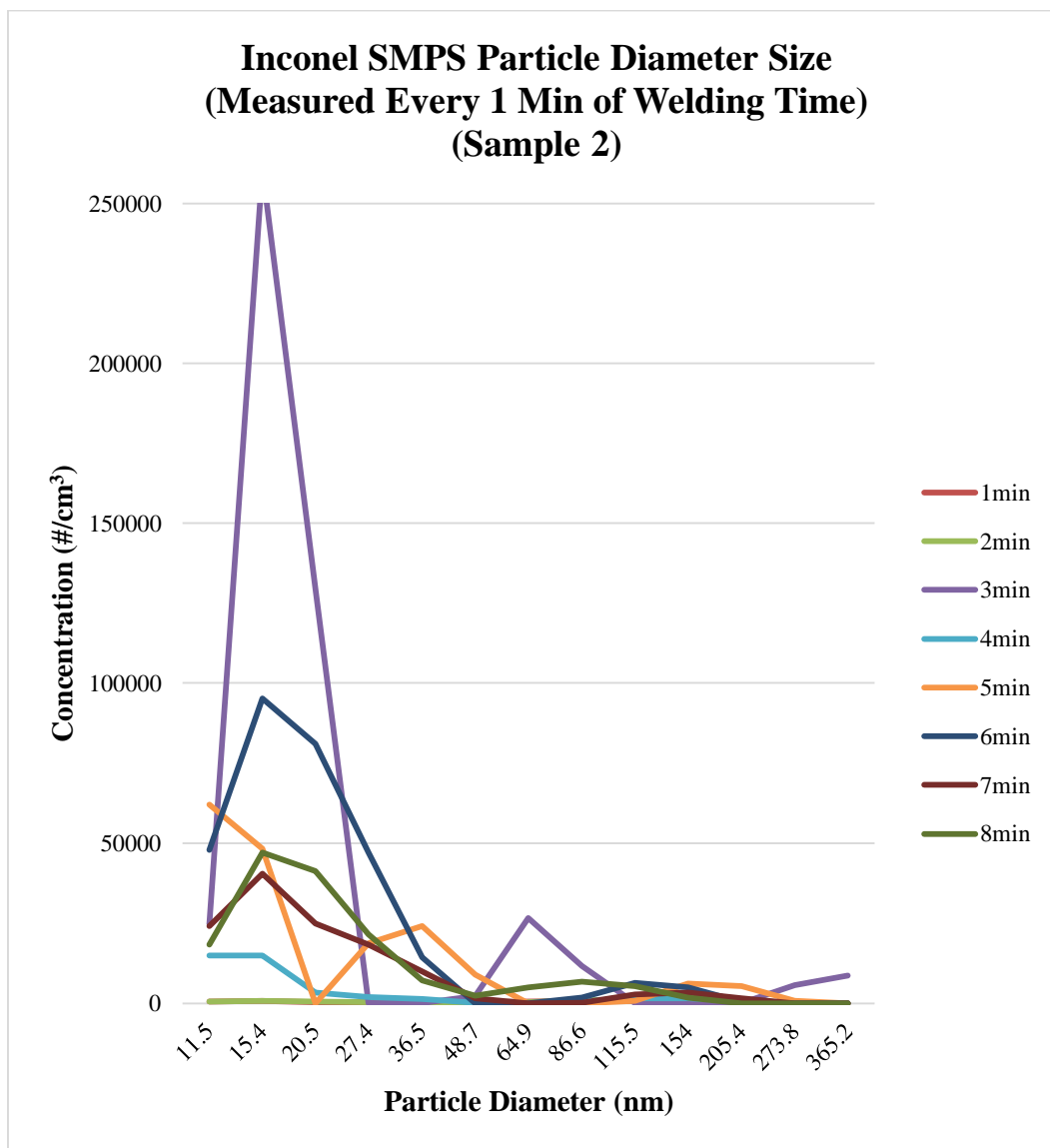


Figure 28: Inconel SMPS Particle Diameter Size (Measured Every 1 Minute of Welding Time)

MIG Inconel

Sample #3 Taken on August 3rd, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC are shown below in Figure 30.

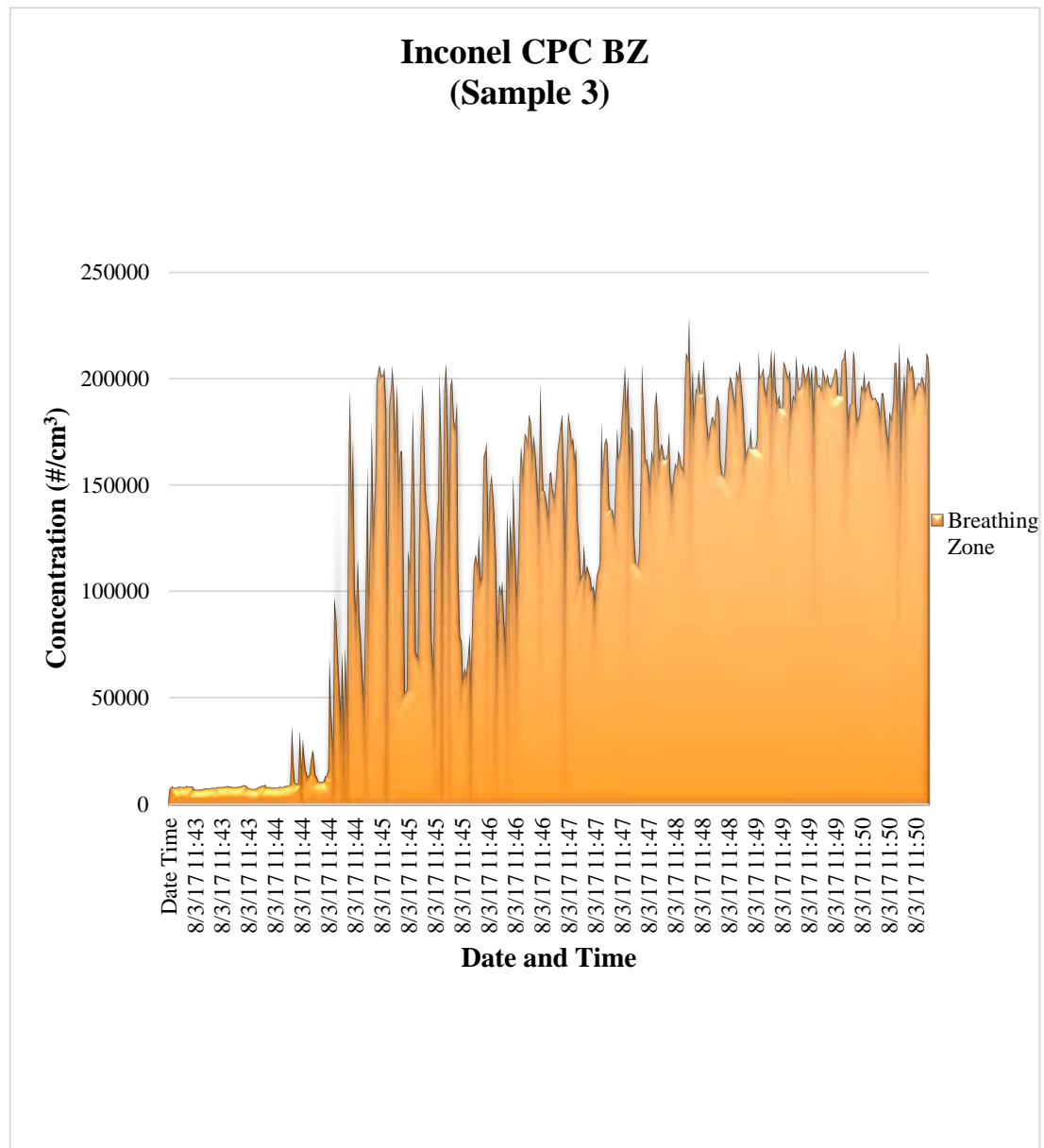


Figure 29: Inconel CPC BZ (Sample 3)

Results of particle diameter size during the span of each minute of the welding sample time taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the third inconel MIG welding sample, is shown below in Figure 31.

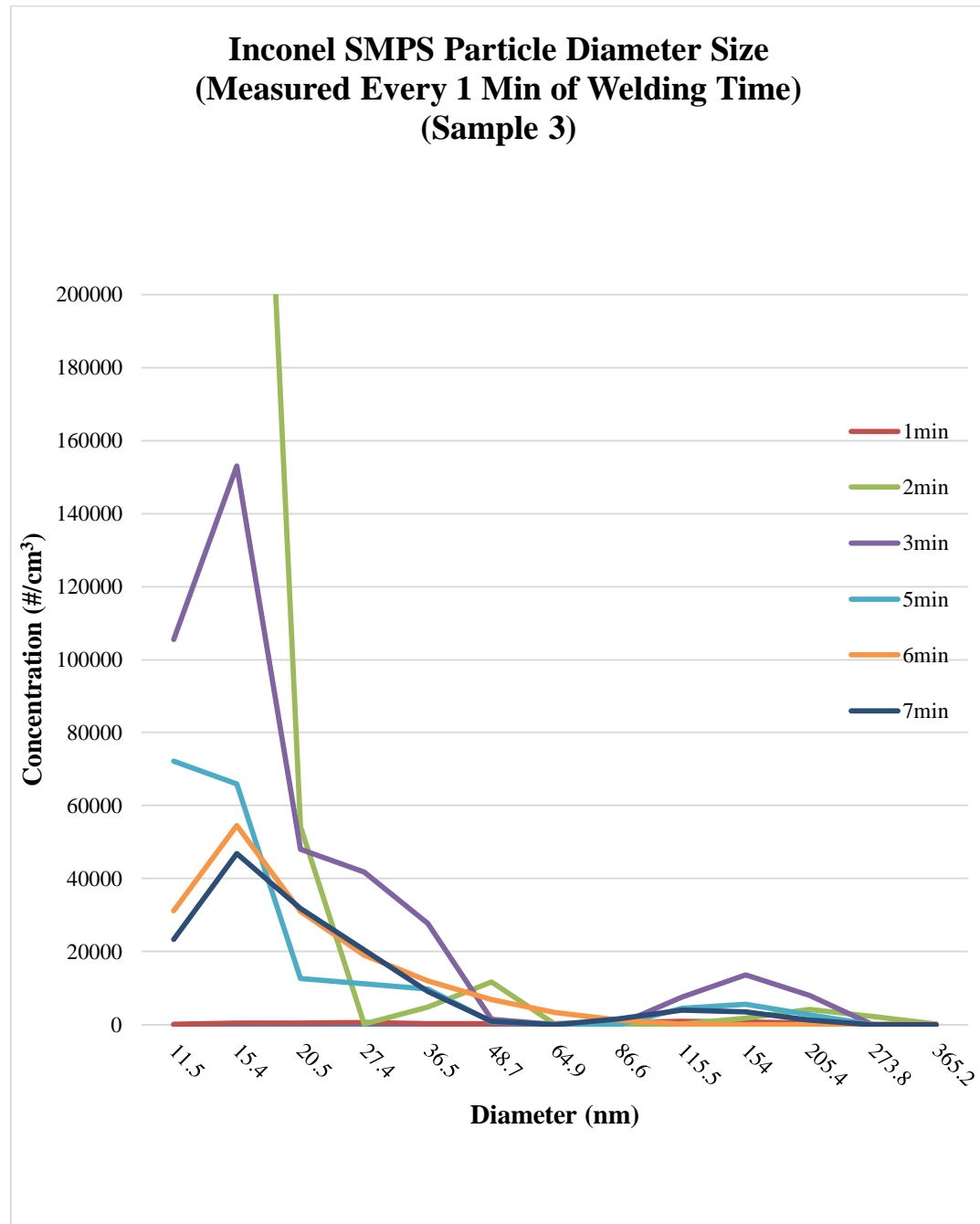


Figure 30: Inconel SMPS Particle Diameter Size (Measured Every 1 Min of Welding Time) (Sample 3)

SEM analysis results of MIG welding on inconel during August 3rd, 2017, taken in the breathing zone of the welder, can be seen in Figure 32.

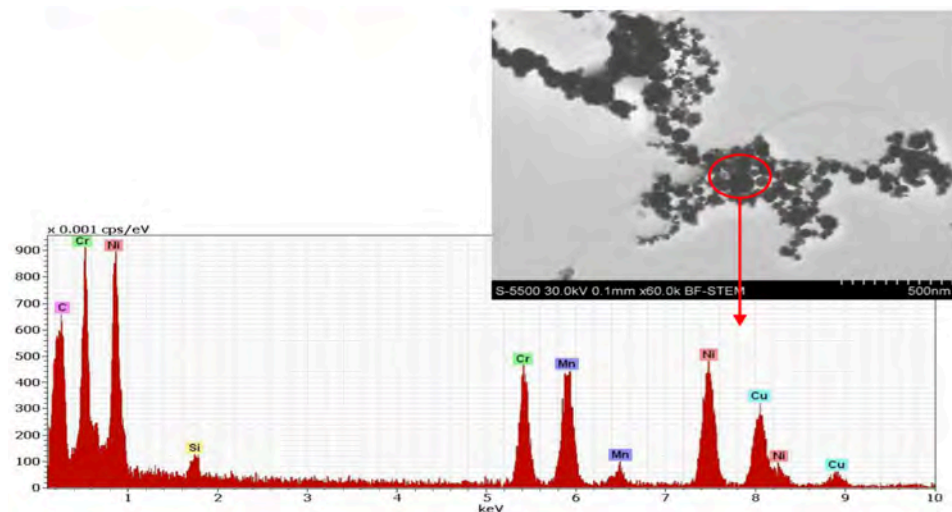


Figure 31: SEM Analysis of MIG Welding Fumes in BZ

TEM analysis (field view) results of MIG welding on inconel during August 10th, 2017, taken in the breathing zone of the welder, can be seen in Figure 33.

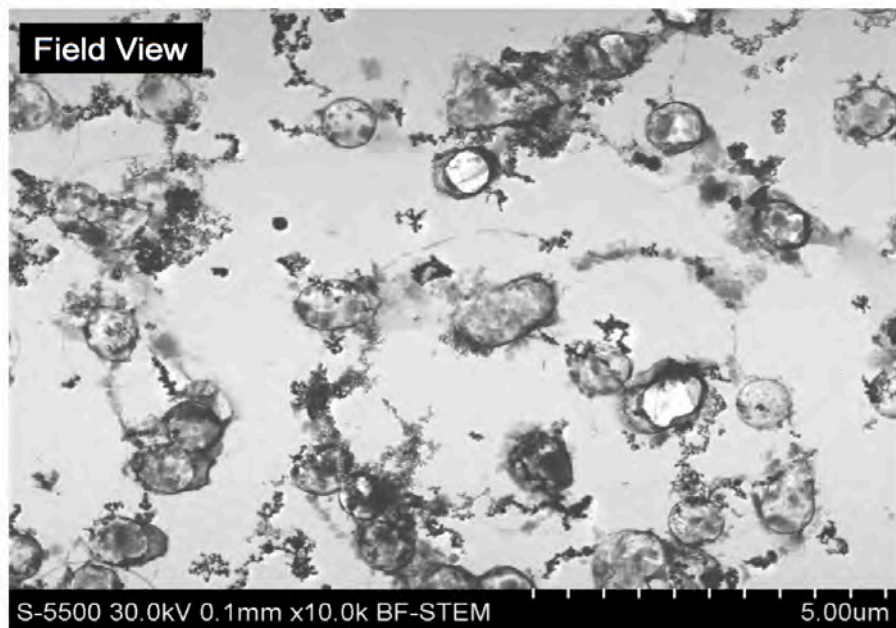


Figure 32: TEM Analysis of MIG Inconel Welding Fumes BZ

Results of ultrafine particle concentrations in all four CPC breathing zone and background samples taken from MIG welding fumes on inconel base metals can be seen below in Table IX. Sample #1 BG was limited to a 419 second sample, as the batteries in the CPC died towards the end of the sampling measurement and Sample #3 BG was not recorded as the batteries failed.

Table IX - Inconel CPC UFPs BZ V BG (All Four Welding Samples)

Inconel CPC UFPs BZ V BG (All Four Welding Fume Samples)						
	7/13 #1 BZ	7/13 #1BG	7/13 #2 BZ	7/13 #2 BG	7/13 #3 BZ	7/13 #3 BG
Mean	96100	140	121000	20300	130000	No Data
Sample Time (secs)	458	19	536	536	484	No Data

MIG Stainless Steel

Sample #1 Taken on July 13th, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC and results of background ultrafine particle samples taken with a separate synchronized CPC are shown below in Figure 34.

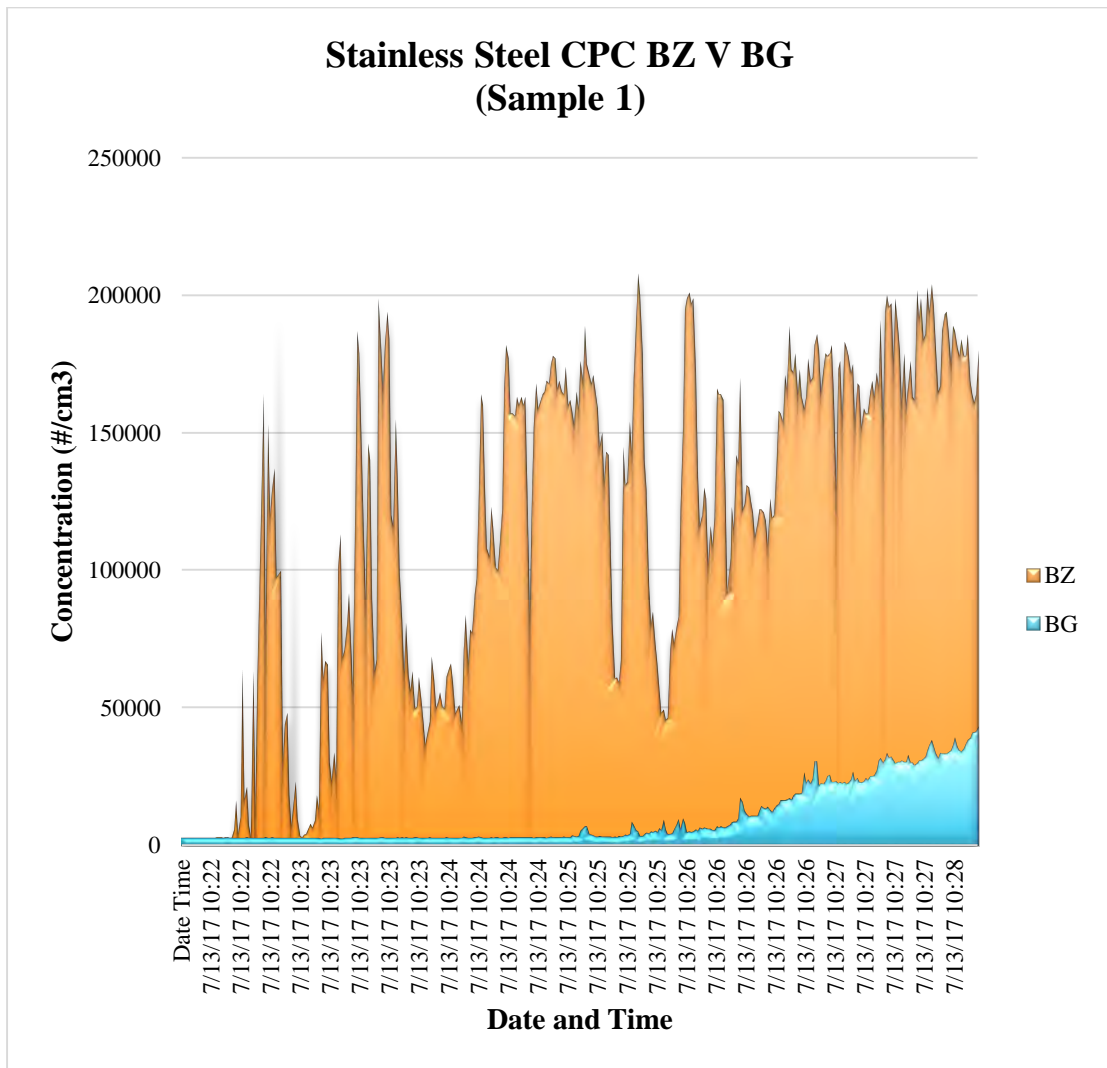


Figure 33: Stainless Steel CPC BZ V BG (Sample 1)

Results of nanoparticle samples (particles below 10nm in diameter) taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the first stainless steel MIG welding sample, is shown below in Figure 35 and Table X.

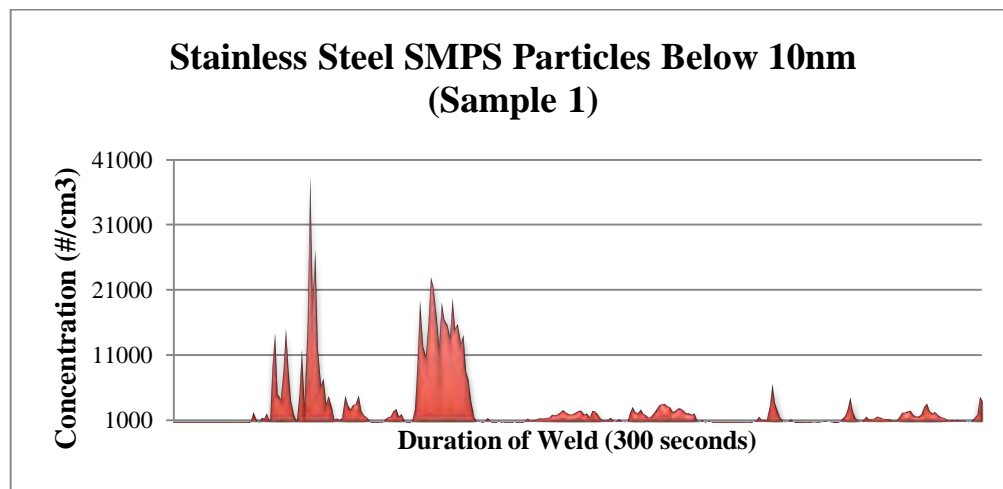


Figure 34: Stainless Steel SMPS Particles Below 10nm (Sample 1)

Table X - Stainless Steel SMPS (Sample 1)

Stainless Steel SMPS (Sample 1)			
	Number (#/cm ³)	Surface (nm ² /cm ³)	Volume (nm ³ /cm ³)
Mean	3044	956000	1590000
Min	2	527	879
Max	38500	12100000	20200000
Sample Time (s)	300		

Sample #2 Taken on July 13th, 2017

Stainless Steel CPC BZ V BG (Sample 2)

The chart displays the concentration of two components, BZ and BG, over time. The Y-axis represents Concentration (#/cm³) from 0 to 250,000. The X-axis represents Date and Time from 7/13/17 10:42 to 7/13/17 10:48. The BZ component (orange) shows high concentration peaks, while the BG component (blue) shows lower concentration peaks.

Date and Time	BZ Concentration (#/cm³)	BG Concentration (#/cm³)
7/13/17 10:42	~10,000	~10,000
7/13/17 10:42:30	~170,000	~10,000
7/13/17 10:43	~10,000	~10,000
7/13/17 10:43:30	~90,000	~10,000
7/13/17 10:44	~190,000	~10,000
7/13/17 10:44:30	~10,000	~10,000
7/13/17 10:45	~140,000	~40,000
7/13/17 10:45:30	~180,000	~40,000
7/13/17 10:46	~160,000	~30,000
7/13/17 10:46:30	~170,000	~30,000
7/13/17 10:47	~100,000	~30,000
7/13/17 10:47:30	~80,000	~40,000
7/13/17 10:48	~100,000	~50,000

Figure 35: Stainless Steel CPC BZ V BG (Sample 2)

Results of nanoparticle samples (particles below 10nm in diameter) taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the first stainless steel MIG welding sample, is shown below in Figure 37 and Table XI.

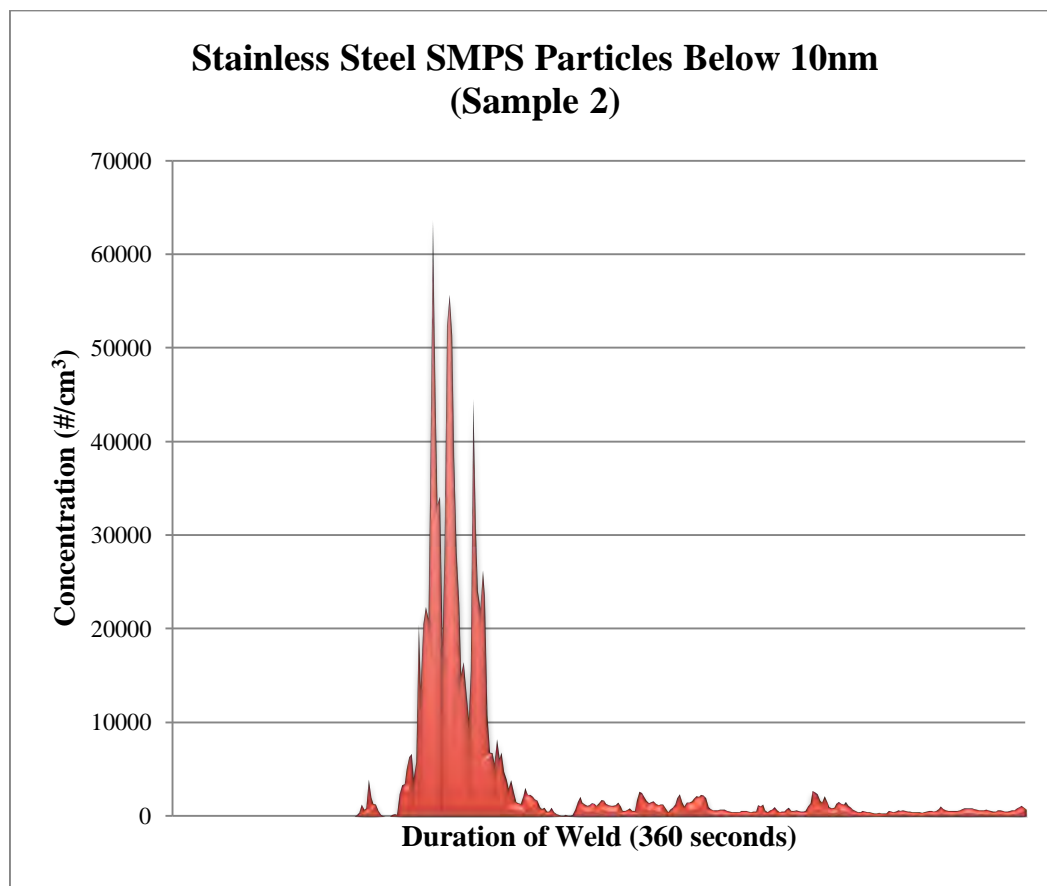


Figure 36: Stainless Steel SMPS Particles Below 10nm (Sample 2)

Table XI - Stainless Steel SMPS (Sample 2)

Stainless Steel SMPS (Sample 2)				
	Number (#/cm ³)	Surface (nm ² /cm ³)	Volume (nm ³ /cm ³)	Mass (ug/m ³)
Mean	3306	1040000	1730000	0.0021
Max	63600	20000000	33300000	0.04
Sample Time (s)	360			

MIG Stainless Steel

Sample #3 Taken on July 13th, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC are shown below in Figure 38.

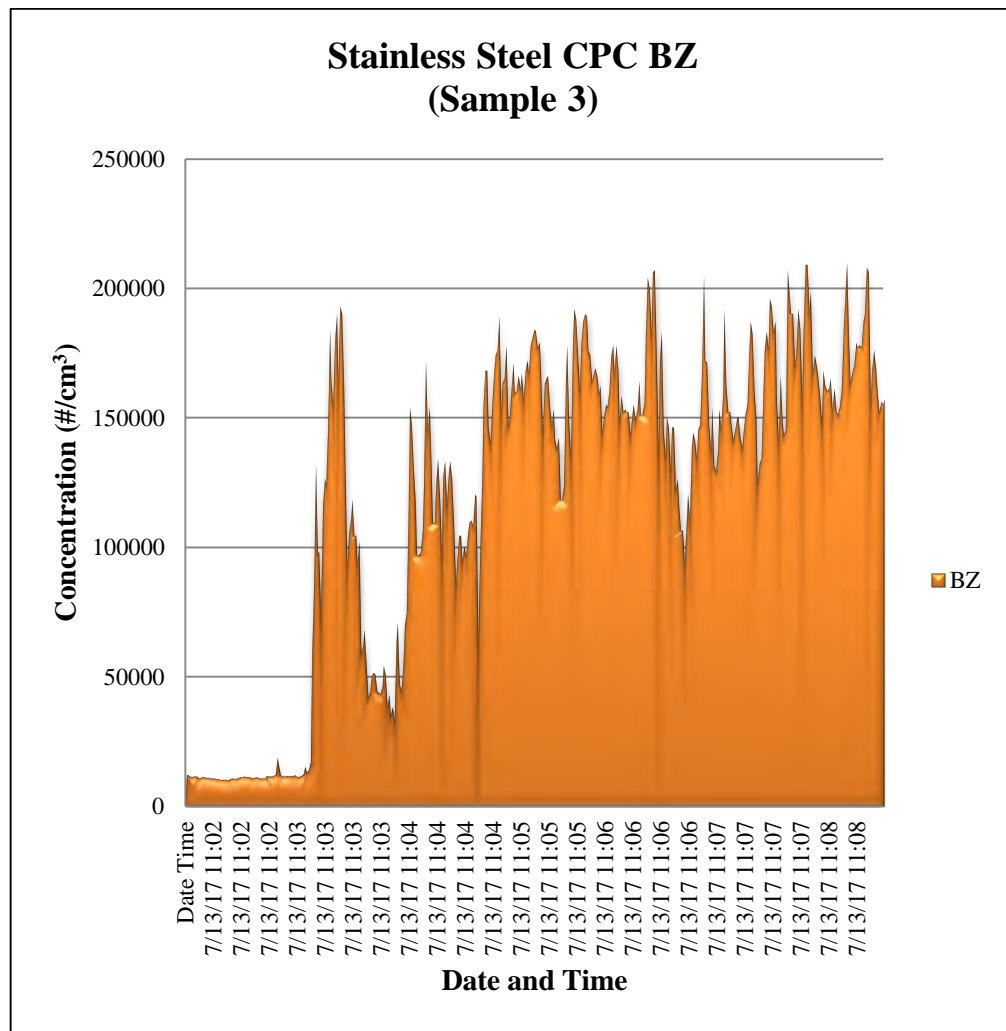


Figure 37: Stainless Steel CPC BZ (Sample 3)

Results of nanoparticle samples (particles below 10nm in diameter) taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the first stainless steel MIG welding sample, is shown below in Figure 39 and Table XII.

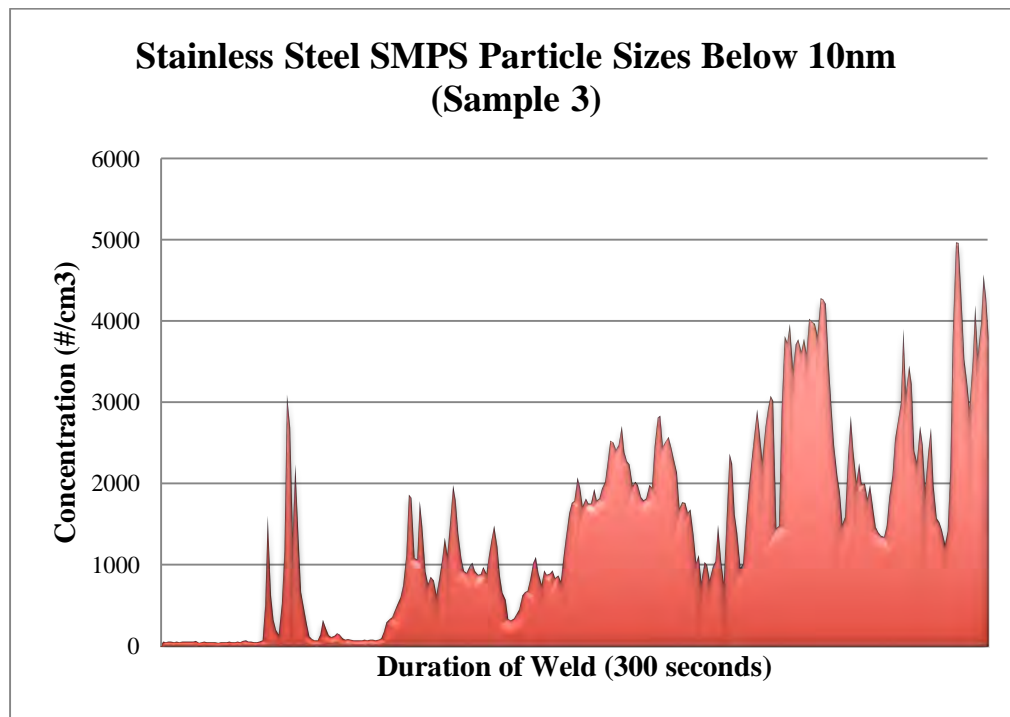


Figure 38: Stainless Steel SMPS Particle Sizes Below 10nm (Sample 3)

Table XII - Stainless Steel SMPS (Sample 3)

Stainless Steel SMPS (Sample 3)				
	Number (#/cm ³)	Surface (nm ² /cm ³)	Volume (nm ² /cm ³)	Mass (ug/m ³)
Mean	1513	475000	792000	0.001
Max	4964	1560000	2600000	0.0031
Sample Time (s)	300			

MIG Stainless Steel

Sample #4 Taken on August 10th, 2017

Results of personal ultrafine particle samples taken with a breathing zone CPC are shown below in Figure 40.

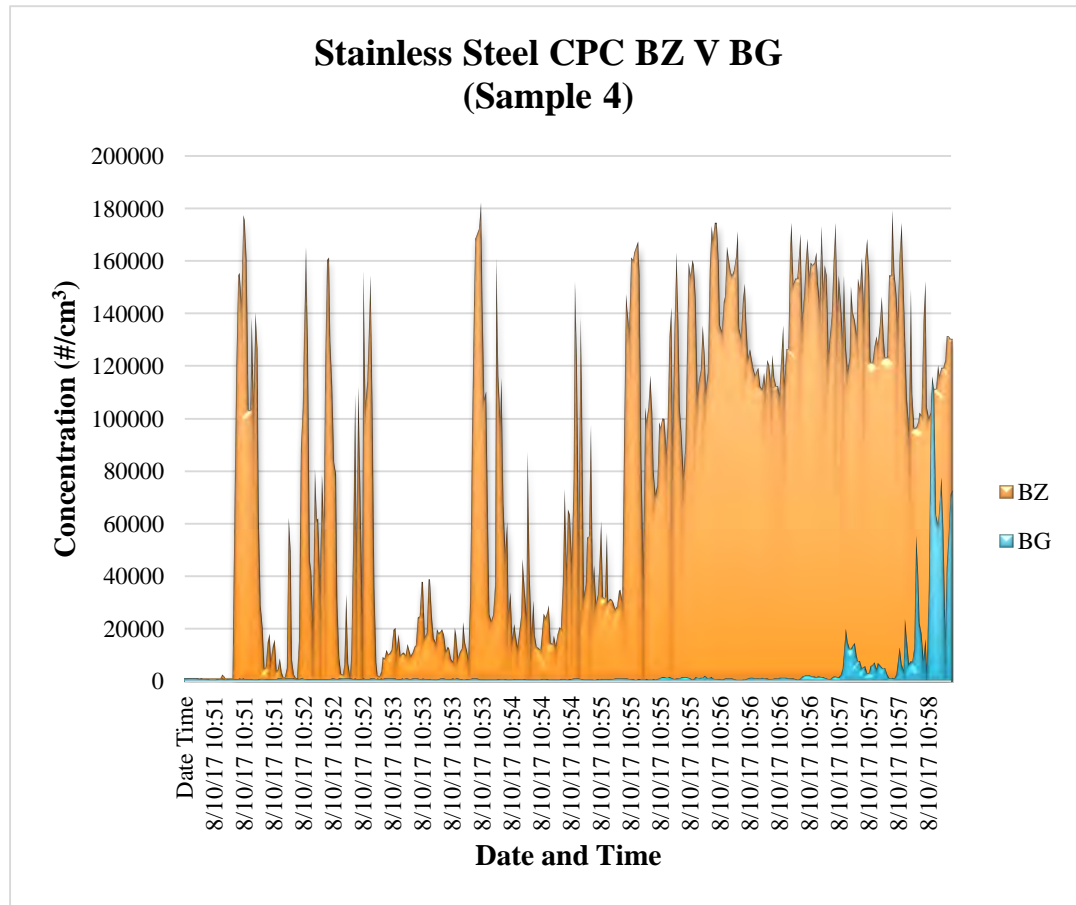


Figure 39: Stainless Steel CPC BZ V BG (Sample 4)

Results of particle diameter size during the span of each minute of the welding sample time taken with a NanoScan Scanning Mobility Particle Sizer (SMPS) placed in the breathing zone of the welder during the fourth stainless steel MIG welding sample, is shown below in Figure 41.

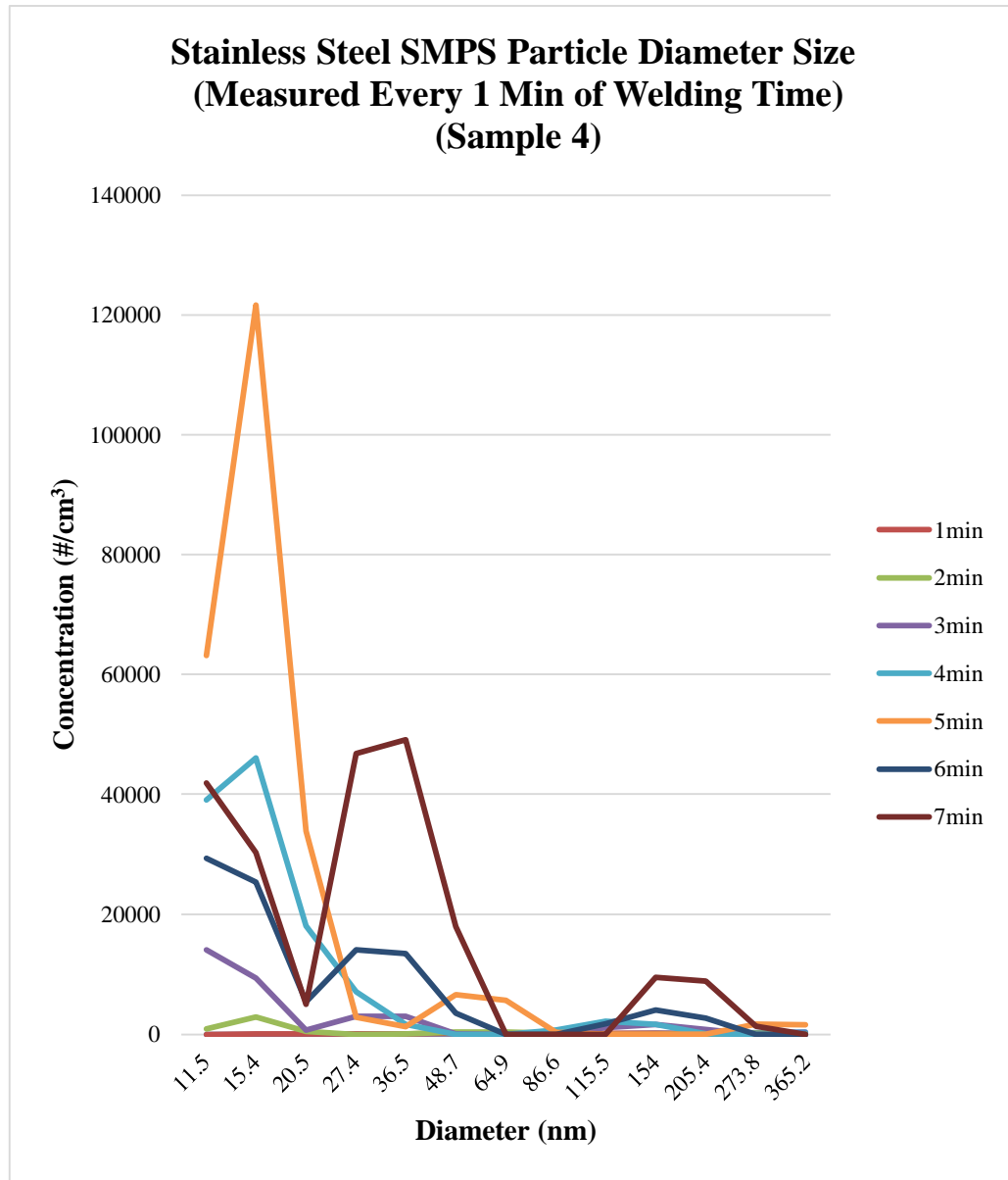


Figure 40: Stainless Steel SMPS Particle Diameter Size (Measured Every 1 min of Welding Time) (Sample 4)

SEM analysis results of MIG welding on stainless steel during August 10th, 2017, taken in the breathing zone of the welder, can be seen in Figure 42.

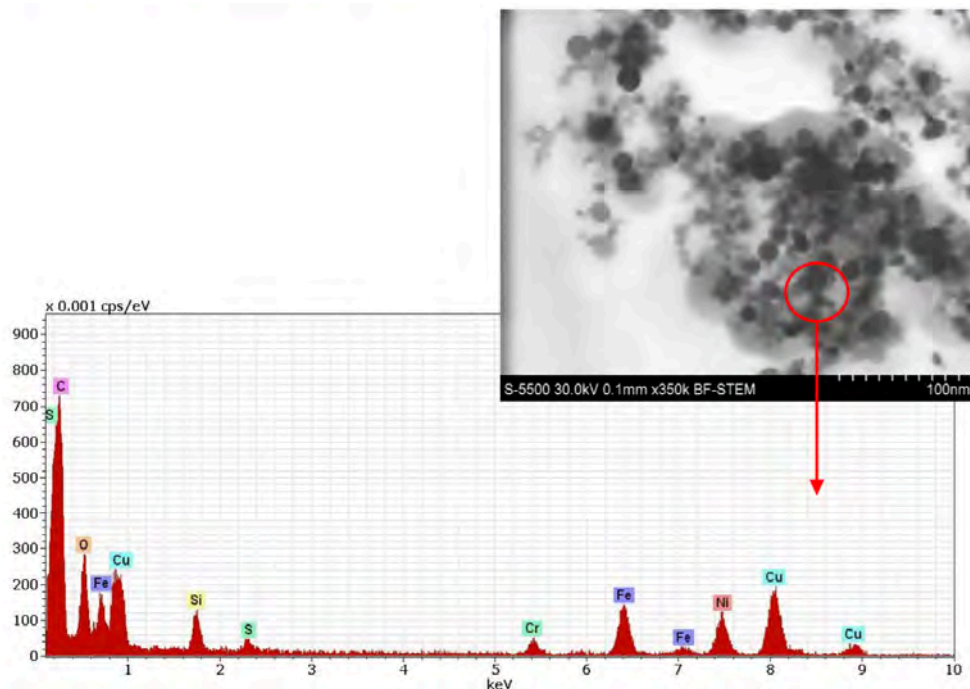


Figure 41: SEM Analysis of MIG Welding On Stainless Steel

TEM analysis (field view) results of MIG welding on stainless steel during August 10th, 2017, taken in the breathing zone of the welder, can be seen in Figure 43.

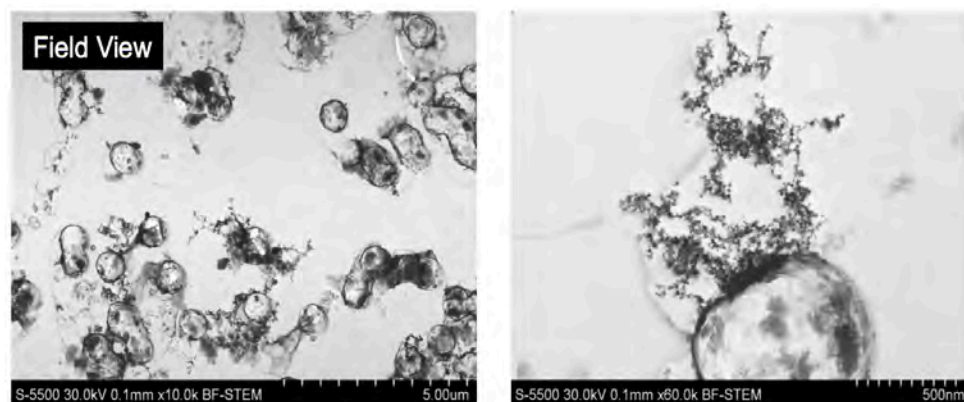


Figure 42: TEM Analysis of MIG Welding on Stainless Steel

Results of ultrafine particle concentrations in all four CPC breathing zone and background samples taken from MIG welding fumes on stainless steel base metals can be seen below in Table XIII.

Table XIII - Stainless Steel CPC UFPs BZ V BG (All Four Welding Fume Samples)

Stainless Steel CPC UFPs BZ V BG (All Four Welding Fume Samples)								
UFP Concentration (#/cm ³)	7/13 #1 BZ	7/13 #1 BG	7/13 #2 BZ	7/13 #2 BG	7/13 #3 BZ	7/13 #3 BG	8/10 #4 BZ	8/10 #4 BG
Mean	118000	10287	91219	4500	20000	no Data	2100	264
Max.	208000	42900	206000	3000	10000	no Data	82000	16000
Total Sample Time (secs)	376	376	394	94	99	NO Data	39	39

All Base Metals

Results of mean ultrafine particle concentrations among all four base metal fumes and their respective samples can be seen below in Figure 44.

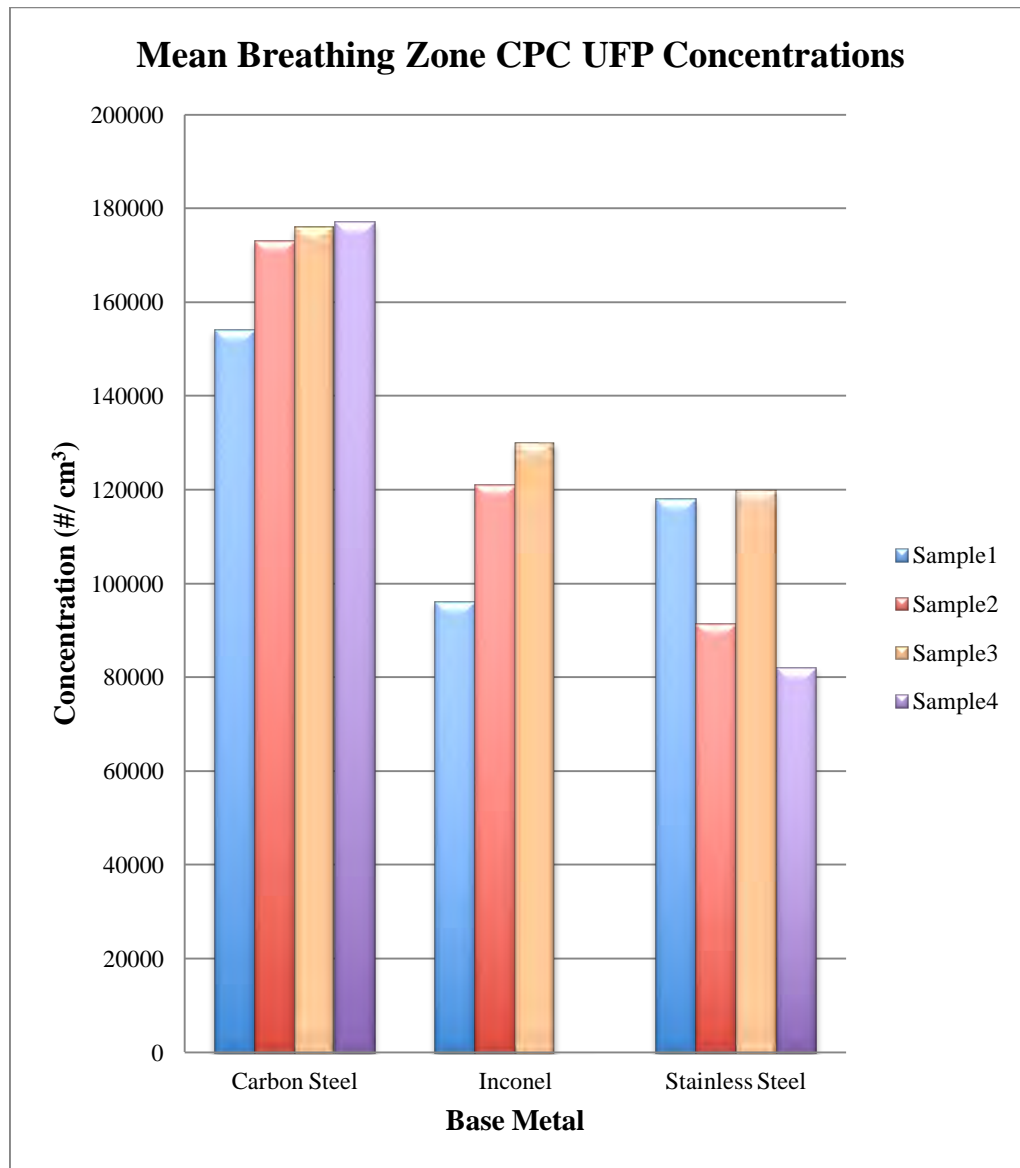


Figure 43: Mean BZ CPC UFP Concentrations

Results of mean SMPS particle diameter size and concentrations among all four base metal fume samples can be seen in Figure 45.

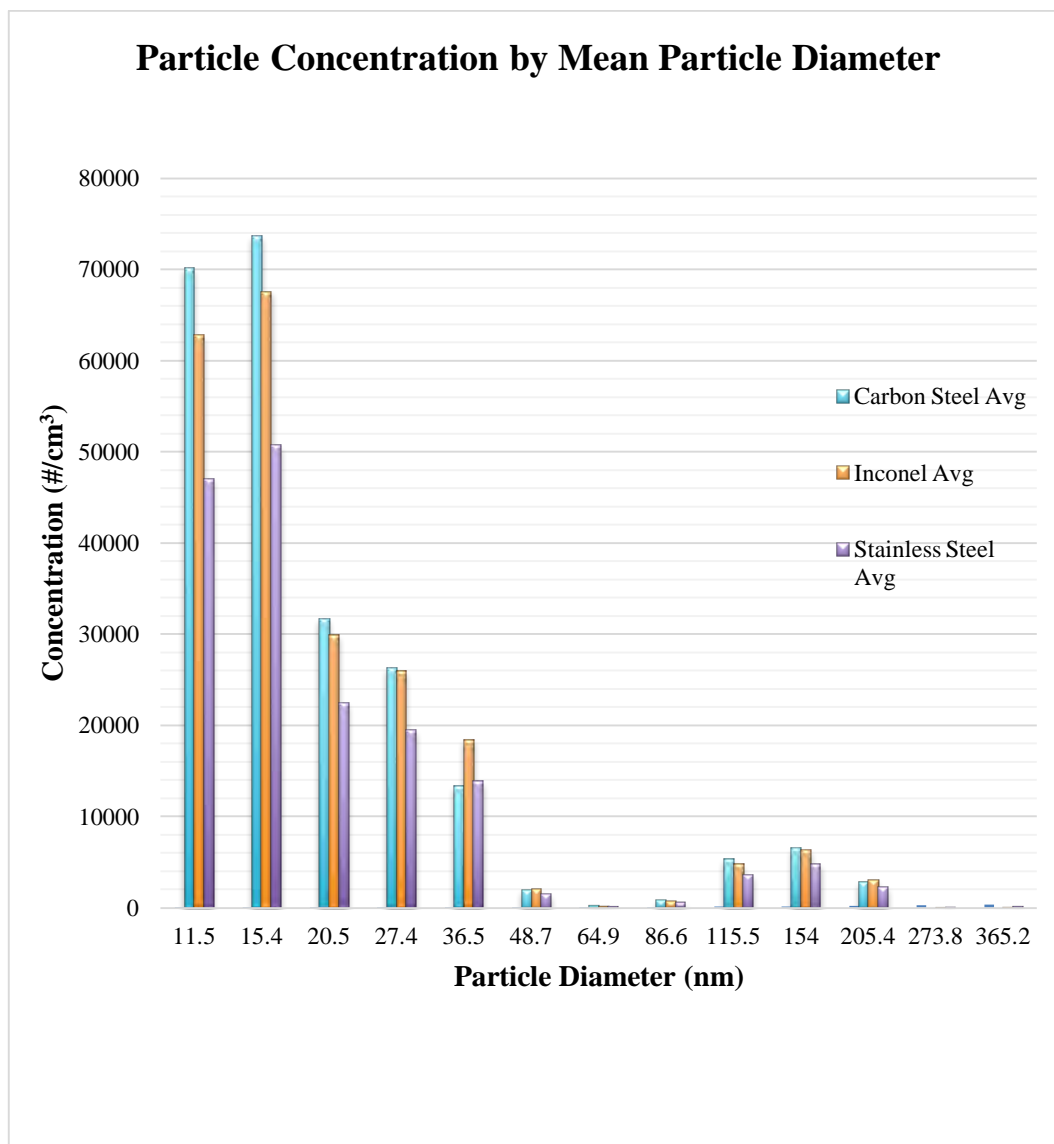


Figure 44: Particle Concentration by Mean Particle Diameter Size According to Base Metal

Discussion and Conclusions

The results gathered from this study appear to be on par with those results conducted in similar studies. The results also indicate a need for further studies to investigate different base metals and welding procedures and their respective relationships to UFP and NP welding fume emissions.

Area Samples

Before a welding procedure began, area samples of pre-weld environmental conditions were measured with a WBGT monitor and CPC.

A WBGT monitor was utilized to obtain daily working environmental conditions within the welding lab. CPCs and SMPSs are highly susceptible to have invalid results if they are utilized in areas with high humidity. The results gathered from the WBGT involved relative humidity and temperature, to ensure that the welding processes took place in environmental conditions that were conducive to reliable results from all particle characterization equipment.

Measurements were taken with a CPC to understand the background normal UFP concentrations before any welding samples took place. The same CPC was used to determine UFP concentrations that were emitted from the welding machine simply being turned on, but not

operational. These results were taken into account during the analysis of the UFP welding fume results.

Since the results of the pre-weld UFP measurements were so low, pre-weld nanoparticle measurements were not taken with the SMPS, as their results would have been fairly insignificant.

Sources of error may have occurred from the door to the welding lab being ajar during the pre-weld area sample measurements, allowing trace amounts of UFPs to percolate into the lab from outside sources.

Personal Samples

General

Due to the lack of OSHA regulations regarding nanoparticle and UFP concentration exposure limits, there were no guidelines or regulations to compare the results of this study to. Since no regulations exist, the results of this study were compared to the determined “normal” UFP concentrations obtained by the pre-weld CPC. To extend the UFP comparison, the CPC placed in the welder’s breathing zone was compared to the CPC placed in the breathing zone of the pipefitter, approximately 6ft from the welding arc.

In order to determine the welder’s nanoparticle welding fume exposure, a SMPS was placed in the vicinity of their breathing zone. The SMPS was used in a variation of two different modes, SINGLE and SCAN.

The SINGLE mode isolated particles within a select size range and analyzed the concentration every 1 second. For the purpose of this study, the SINGLE mode size range

selected was 10nm. An example of the SINGLE mode SMPS operation can be seen in Figure 17: Carbon Steel SMPS (<10NM).

The SCAN mode provided real time particle size distributions ever 1min of analysis and ranged in particle diameter sizes from 11.5nm – 365.2 nm. This mode was used to determine particle agglomeration over time (if there was a decrease in nanoparticle concentrations and an increase in larger particle concentrations) and also helped to understand at what time intervals during the welding process, that welders were most susceptible to NP exposure. An example of the SMPS operating in SCAN mode can be seen in Figure 23: Carbon Steel Particle Diameter Size During Every 1 Minute of Welding Time (Sample 4) Taken with The SMPS.

Sources of error during all personal sampling of UFP and NP welding fume exposures may have occurred as a result of contaminated alcohol wicks used in the CPC and SMSP. Although the wicks were cleaned after each welding sample, the alcohol was not replaced in-between each sample per the manufacturer's instructions. This may have results in slight contamination of the wick. Additionally, it was impossible for the welder to weld while simultaneously measuring the exact distance of the welding arc from the snorkel ventilation, therefore certain time frames may have skewed results as in that moment, the snorkel could have been closer or further from the arc source.

MIG Carbon Steel

Three separate carbon steel welding procedures took place on July 13th, 2017(samples 1-3). Each sample lasted for a minimum of 5min. An additional CS welding procedure took place on August 10th, 2017(sample 4) and lasted for a total of 6min.

Samples 1-3, (seen in Figures 16, 18, and 20) indicate a significant increase in a welder's exposure to UFP concentrations when compared to those of background UFP measurements indicative of a pipefitter's exposure. A numerical comparison of all four samples regarding the BZ V BG UFP exposure for carbon steel welding can be seen in Table VII. In sample 1, the BZ mean UFP concentration was $1.54 \text{ E}+05$ whereas the mean BG UFP concentration for sample 1 was $6.37\text{E}+03$. The remaining 3 samples follow a similar trend and their results also show a profound discrepancy between a welder's exposure to UFPs and a background UFP concentration that would typically be indicative of a pipefitter's or fire watcher's exposure.

Samples 1-3 were taken with the SMPS operating in SINGLE mode, to isolate welding fume particles below 10nm. These particles were analyzed every 1 second of operation as seen in Figures 17, 19, and 21. Sample 3 had the highest concentration of particles below 10nm with results of a mean concentration of $10,400 \text{ \#/cm}^3$. Sample 2 had a mean concentration of $5,050 \text{ \#/cm}^3$ and sample 1 had a mean concentration of $2,629 \text{ \#/cm}^3$.

Sample 4, taken on August 10th, 2017, utilized the SMPS operating in SCAN mode. The results of the SCAN mode were recorded every 1 min of operation. The SCAN mode results, as seen in Figure 23, show an increased concentration of nanoparticles with 11.5 nm particle diameter, occurring at the 5min mark. The second highest concentration with an 11.5nm particle diameter size occurred during the 4min mark. Subsequently, the 5min mark also saw the highest concentration of 273.8nm particle diameter size fumes, with the 4min mark falling behind in second highest exposure.

TEM analysis and ED analysis were taken on August 10th, 2017 with the use of a filter attached to a high flow pump, which was placed in the breathing zone of the welder during the welding operations. As seen in Figure 24, the welding fumes from carbon steel resulted in high

concentrations of iron, silica, oxygen, and copper. Figure 25 shows the TEM analysis results, which indicate particle agglomeration.

MIG Inconel

Three separate inconel welding procedures took place on August 3rd, 2017(samples 1-3). Each sample lasted for a minimum of 5min.

Samples 1-3, (seen in Figures 25, 27, and 29) indicate a significant increase in a welder's exposure to UFP concentrations when compared to those of background UFP measurements indicative of a pipefitter's exposure. A numerical comparison of all four samples regarding the BZ V BG UFP exposure for carbon steel welding can be seen in Table VIII. In sample 1, the BZ mean UFP concentration ($\#/cm^3$) was 96,100 whereas the mean BG UFP concentration for sample 1 was 3,140. The remaining 2 samples follow a similar trend and their results also show a profound discrepancy between a welder's exposure to UFPs and a background UFP concentration that would typically be indicative of a pipefitter's or fire watcher's exposure.

Sample 1-3 utilized the SMPS operating in SCAN mode. The results of the SCAN mode were recorded every 1 min of operation.

The SCAN mode results for sample 1 can be seen in Figure 26. Figure 26 show an increased concentration of nanoparticles with 11.5 nm particle diameter, occurring at the 6min mark. The second highest concentration with an 11.5nm particle diameter size occurred during the 5min mark. Subsequently, the 6min mark also saw the highest concentration of 273.8nm and 365.2nm particle diameter size fumes.

The SCAN mode results for sample 2 can be seen in Figure 28. Figure 28 show an increased concentration of nanoparticles with 11.5 nm particle diameter, occurring at the 3min

mark. The second highest concentration with an 11.5nm particle diameter size occurred during the 6min mark. Subsequently, the 3min mark also saw the highest concentration of 365.2nm particle diameter size fumes.

The SCAN mode results for sample 3 can be seen in Figure 30. Figure 30 show an increased concentration of nanoparticles with 11.5 nm particle diameter, occurring at the 2min mark. The second highest concentration with an 11.5nm particle diameter size occurred during the 3min mark. Subsequently, the 2min mark also saw the highest concentration of 273.8nm and 365.2nm particle diameter size fumes.

TEM analysis and ED analysis were taken on August 3rd, 2017 with the use of a filter attached to a high flow pump, which was placed in the breathing zone of the welder during the welding operations. As seen in Figure 31, the welding fumes from inconel resulted in high concentrations of chromium, nickel, manganese, copper, and carbon. Figure 32 shows the TEM analysis results, which indicate particle agglomeration and shape.

MIG Stainless Steel

Three separate carbon steel welding procedures took place on July 13th, 2017(samples 1-3). Each sample lasted for a minimum of 5min. An additional SS welding procedure took place on August 10th, 2017(sample 4) and lasted for a total of 7min.

Samples 1-3, (seen in Figures 33, 35, and 37) indicate a significant increase in a welder's exposure to UFP concentrations when compared to those of background UFP measurements indicative of a pipefitter's exposure. A numerical comparison of all four samples regarding the BZ V BG UFP exposure for carbon steel welding can be seen in Table XXII. In sample 1, the BZ mean UFP concentration ($\#/cm^3$) was 118000 whereas the mean BG UFP concentration for

sample 1 was 10287. The remaining 3 samples follow a similar trend and their results also show a profound discrepancy between a welder's exposure to UFPs and a background UFP concentration that would typically be indicative of a pipefitter's or fire watcher's exposure.

Samples 1-3 were taken with the SMPS operating in SINGLE mode, to isolate welding fume particles below 10nm. These particles were analyzed every 1 second of operation as seen in Figures 34,36, and 38. Sample 2 had the highest concentration of particles below 10nm with results of a mean concentration of 3306 #/cm³. Sample 1 had a mean concentration of 3044#/cm³ and sample 3 had a mean concentration of 1513 #/cm³.

Sample 4, taken on August 10th, 2017, utilized the SMPS operating in SCAN mode. The results of the SCAN mode were recorded every 1 min of operation. The SCAN mode results, as seen in Figure 39, show an increased concentration of nanoparticles with 11.5 nm particle diameter, occurring at the 5min mark. The second highest concentration with an 11.5nm particle diameter size occurred during the 4min mark. Subsequently, the 5min mark also saw the highest concentration of 365.2 particle diameter size fumes, with the 7min mark falling behind in second highest exposure.

TEM analysis and ED analysis were taken on August 10th, 2017 with the use of a filter attached to a high flow pump, which was placed in the breathing zone of the welder during the welding operations. As seen in Figure 40, the welding fumes from stainless steel resulted in high concentrations of carbon, oxygen, copper, silica, and iron. Figure 41 shows the TEM analysis results, which indicate particle agglomeration and shape.

All Base Metals

Mean Welder's Breathing Zone UFP Concentrations

In order to determine which base metal emitted the greatest concentration of UFP welding fumes, the mean concentrations from each base metal welding sample can be seen in Figure 42.

Carbon steel had the greatest concentration of breathing zone UFP welding fumes amongst all four of its samples. Among the four CS samples, the fourth sample had a slightly higher concentration 177,000 The third sample emitted a mean concentration of 176,000. The second sample emitted 173,000 and the first sample emitted 154,000.

Inconel had the second highest mean breathing zone UFP concentrations among the three base metals. The third inconel sample had a mean concentration of 130,000. The second sample had a mean concentration of 121,000 while the first sample had a mean concentration of 96,100.

Stainless steel had the least amount of breathing zone UFP welding fumes among the three differing base metals. The third sample of SS welding emitted the highest mean concentration of 120,000. The first sample emitted 118,000, the second sample emitted 91,219, and the fourth sample emitted 82,100.

All Base Metals

Particle Concentration by Mean Particle Diameter (SMPS SCAN mode)

In order to determine which base metal emitted the greatest concentration of particles based on an array of particle diameter sizes, the mean results of all samples from each base metal were averaged respectively and combined into Figure 43. This figure represents mean particle diameter sizes from 11.5nm – 365.2nm.

The results for the 11.5nm particle diameter category indicated that carbon steel had an overwhelmingly higher concentration than the other two base metals. Inconel had the second highest which was followed by stainless steel.

The results for the 15.4nm -27.4nm particle diameter categories indicated that carbon steel had an overwhelmingly higher concentration than the other two base metals. Inconel had the second highest which was followed by stainless steel.

The results for the 36.5nm particle diameter category indicated that inconel had an overwhelmingly higher concentration than the other two base metals. Stainless steel had the second highest which was followed by carbon steel.

The results for the 48.7nm-365.2nm particle diameter categories resulted in insignificant measurements as all fell well below 10,000 #/cm³ concentrations.

A combination of these results indicate that MIG welding on all three base metals to indeed vary based upon the base metal and filler wire used during the welding procedures. The results also show that MIG welding generates larger amounts of very small nanoparticles as opposed to the larger particle diameter sizes. This is an interesting concept in that it is often thought that welding fumes agglomerate before they reach the breathing zone of the welder, but the results obtained from this study indicate otherwise.

Recommendations

Although there are no OSHA regulations in place to shield welders and pipefitters from ultrafine particles and nanoparticles derived from welding fumes, there are things employers can do to limit exposure. Understanding that differing types of base metals and filler wire can emit larger or smaller amounts of UFP/ NP is the first step in being able to take action to thwart exposure. It would be of great interest of welding facilities to utilize stronger snorkel ventilation, robotic welding, and PPE when welders are working with base metals that emit higher concentrations of UFPs and NP, particularly those comprised of hexavalent chromium and other hazardous substances.

Reducing the continuous welding time would also seem to reduce the concentration of nanoparticle and UFP welding fume exposure. According to the data gathered from the SCAN mode on the SMPS with all three base metals, minute 1 and minute 2 had the least amount of nanoparticles, UFPs, and larger particle diameters. This can be extrapolated to mean that capture velocity of the snorkel, or vicinity of the welding arc to the snorkel, was most efficient between the first 120 seconds of welding time. Taking breaks after 120 seconds of continuous welding could help ensure effective ventilation is being utilized and a welder's exposure to UFPs and NPs are significantly reduced.

It would also be beneficial to understand what type of welding process emits the most UFPs and NPs, such as tungsten inert gas, metal inert gas, stick welding, or robotic welding. All

welding procedures utilize different pieces of equipment, differing cover gases, differing wire speeds/ wire consumption rates, and voltages. If a large welding procedure is to take place over an extended amount of time, consideration of UFP and NP fume emissions should be taken into account when choosing a particular welding procedure to utilize.

Another aspect to consider would be to utilize ventilation that pulls air downward, instead of upwards. Placing the base metal on a grid that allowed air flow to move downward would be beneficial in hindering the movement of fumes towards the breathing zone of the welder while simultaneously protecting the welding integrity provided by the protection of the undisturbed cover gas. Additionally, an increase in capture velocity may help protect the welder from exposure to UFP and NP fumes.

Recommendations for Future Research

Based on the results of this study, continual improvement and future research could be conducted in the following areas of inquiry:

- Due to the fact that many professional welders operate various types of welding machinery and utilize different welding techniques, further studies should be conducted utilizing similar wire consumption rates and voltages to determine if there is any variation of UFP and NP exposure occurring due to exclusive the use of base metals and filler wire.
- Further studies of pipefitters' and fire watchers' exposures to nanoparticles could be investigated. Due to a lack of additional SMPS equipment, we were not able to conclusively study the 6ft background nanoparticle welding fume exposure.
- Although the alcohol wicks were cleaned after every welding sample, the alcohol within the container they were placed in was not. Future studies may have more reliable results if the alcohol is replaced after every sample to thwart particle contamination, although this practice is not directly recommended by the manufacturer of the equipment.

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Appendices

Appendix I

Equipment List

#1 Gillian- AirCon2 High Volume Air Pump
Model 520
Serial # A5920R
St Petersburg, FL USA
Calibrated 05/04/2017

#2 Quest Technologies- QuestTemp 34
Model 34
Serial # T69021433
St Medley, FL USA
Calibrated 02/08/2017

#3 TSI -Condensation Particle Counter
Model 3007
Serial #70556203
St Paul, MN USA
Calibrated Date 03/01/2017
Calibration Due 03/02/2019

#4 TSI -Condensation Particle Counter
Model 3007
Serial #70556204
St Paul, MN USA
Calibrated Date 03/01/2017
Calibration Due 03/02/2019

#5 TSI -Condensation Particle Counter
Model 3007
Serial #70556958
St Paul, MN USA
Calibrated Date 01/20/2017
Calibration Due 01/21/2019

#6 TSI –NanoScan SMPS Nanoparticle Sizer
Model 3910
Serial#NP8052L9
St Paul, MN USA
Calibrated Date 03/01/2017
Calibration Due 03/02/2019

Appendix II

IRB Approval



June 22, 2017

Oak Ridge Site-wide IRB (FWA #00005031)

Title of Study:	Particles in welding continued
Investigator:	Rebecca Williams
Type of Review:	Non-Committee Review
Expedited Category	(7)(a) Behavioral research
IRB Submission ID:	ORAU000408
Documents Reviewed:	• 2017_informed_consent.doc, Category: Consent Form; • 06_22IRB.pdf, Category: IRB Protocol;
Action:	Approved
Approval Date:	6/22/2017
Expiration Date:	6/21/2018
Consent Waiver:	Waiver of consent documentation

Before the expiration date or within 30 days of study closure, whichever is earlier, you must submit a continuing review application/ progress report. To submit a continuing review, navigate to the active study and click "Create Modification / CR."

This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

Any changes in the approved research activity or to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All unanticipated problems or adverse events must be reported to this office (see [DOE Order 443.1B Chg 1](#)). Please use the appropriate form for this procedure. All FDA and sponsor reporting requirements should also be followed.

Report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office (see [DOE Order 443.1B Chg 1](#)).

Please note that all research records must be retained for a minimum of three years after the completion of the study.

If continuing review approval is not granted before the expiration date of 6/21/2018, approval of this study expires on that date and all study activity that involves human subjects must cease.

Sincerely,
The Oak Ridge Site-wide IRB ORSIRB@ornl.gov 865-574-4359