WELDING HEALTH HAZARDS

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STATEMENT OF CANDIDATE

I, Salman Farhan, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for quail cation or assessment at any academic institution.

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ABSTRACT

Welding is one the most widely used processes for joining metal together. There is a diversity of welding methods that are used in different working conditions. Welding could be extremely harmful for a human health as it emits toxic gases and small respirable particulates that are also called welding fumes. The aim of this project is the assessment of welding fumes. Achieving this aim requires identifying the hazard, assessing the risk, and minimising the risk through proper control methods. To identify the hazard air sampling techniques will be used to capture gases and welding fumes. Four welding processes will be carried on for the fumes to be extracted and analysed TIG, MIG, SMAW, and OXY welding and data collection will be conducted through air sampling techniques. Based on the results a recommendation will be shown of the welding process and the welding rod material in terms of the least health hazards risk created. The effect of both the extraction distance and flow rate on particle size distribution and morphology was also covered.

Contents

List of Figures

List of Tables

Chapter 1

1 Introduction

Welding is one the most widely used processes for joining metal together. According to the international conference on health hazards and biological effects of welding fumes and gases “Welding is defined as a process where metals to be joined (parent metal) are melted by an electric arc of flame, in most cases using coated electrodes or wires (the consumables) as filler materials, which contribute metal to the joint area resulting in a weld with the proper metallurgical and mechanical properties” [19]. Welding is one of the main processes required in industries due to its cost-effectiveness, efficiency, and ease of operation. [10]

There are more than thirty different types of welding processes that operate differently. Mostly welding processes rely on high temperatures or the application of pressure to join metal together. Welding is used broadly in many industries it is used indoors, outdoors, and even underwater. Depending on the workplace condition and the required application a welding process could be chosen over another. Welding can be used for manufacturing, construction, and repair. [10]

Although it has countless benefits, welding effects on the health are high. Welding is a major source of gases emission and toxic fumes. According to studies, in Europe only there are approximately 5.5 million welding related jobs. Moreover, it has been stated that 5,000 tons of fumes are being produced yearly from welding, and 3 million persons are directly subjected to welding fumes and gas action. Several cases have shown the broad effects of welding. Welders are on a high health risk due to the exposure of welding fumes dissipated, that might lead to even death. As a result, it is essential to find methods for assessing the risk. [20, 21]

The risk on human health could be classified as a risk from the physical properties and the chemical properties. A human is exposed to gas mixtures, shielding gases, inert gases, composition of materials, respirable particles, and welding fumes which could lead to serious health effects and might lead to death. The main component of welding fumes are gases such as (carbon dioxide, carbon monoxide, oxygen, helium, hydrogen, argon, nitrogen monoxide, and nitrogen dioxide) and respirable particulates created from metal oxides. [17]

As a result the assessment of welding gases and fumes is of a great significance. Studying the welding processes is a key to achieving the aim of this project. Air monitoring could be one way to identify the risk through collecting welding fumes and gasses and analysing them. Knowing the gasses, chemical components, and physical properties is major component of the risk management process. With the use of several analysing techniques such as EDS (Energy dispersive X-ray spectroscopy), SEM (Scanning electron microscopy), GC (Gas chromatography), and Gravimetric analysis. Those techniques will allow us to identify the chemical composition, gas concentration, quantitative determination, and morphological analysis of welding pollutant.

1.1 Project Goal

The goal of this project is to create a control method to minimise the welding gases and pollutants emitted through welding. To achieve this goal, the project is divided into several components: understanding the welding processes, identifying the welding pollutants, studying the pollutants and their effects on health, which will allow us to assess the welding fumes through a proper control way. Understanding the welding process will allow us to know how the pollutant is formed. Studying the pollutant will allow us to detect and measure the health risk of each gas and material that contribute in the formation of the welding fumes, based on that a permissible exposure limit will be presented and compared to the PEL from other studies for each constituent of welding component. At last, the assessment of welding fumes via proper control ways will be achieved.

1.1.1 Scope

The projects initial scope is to be able to choose a technique to extract the welding fumes and gases when welding is carried on. It is more practicable if the extraction was directly from the filter in the local ventilation exhaust system, although the concern is not only the fumes themselves the operators distance from the fume source which is the welding gun is of high concern to determine the concentration of the pollutants, therefore extraction could not be from the filters in the ventilation system. Moreover, the extraction is meant to be as relative as possible to a human inhalation flow therefore employing the right equipment is a major point for this issue. Particulate size distribution is also a concern as sizes could be as small as 0.1um.Therefore the fume extraction technique should be considered clearly to allow us to successfully carry on the experiments and move on to the next stage of the project. Storage of the used equipment's is a key for an accurate results when analysing, hence equipment's will be stored properly, and transport will be as stable and shock free as possible. Choosing the right analysis equipment or software is significant and needs to be closely evaluated, the right choice will show the appropriate analysis on the required parameters or chemical and physical properties. Efficient training is also a key for efficient and reliable results. All the above factors contribute to the accuracy of the results, which allows us to assess the welding fumes properly.

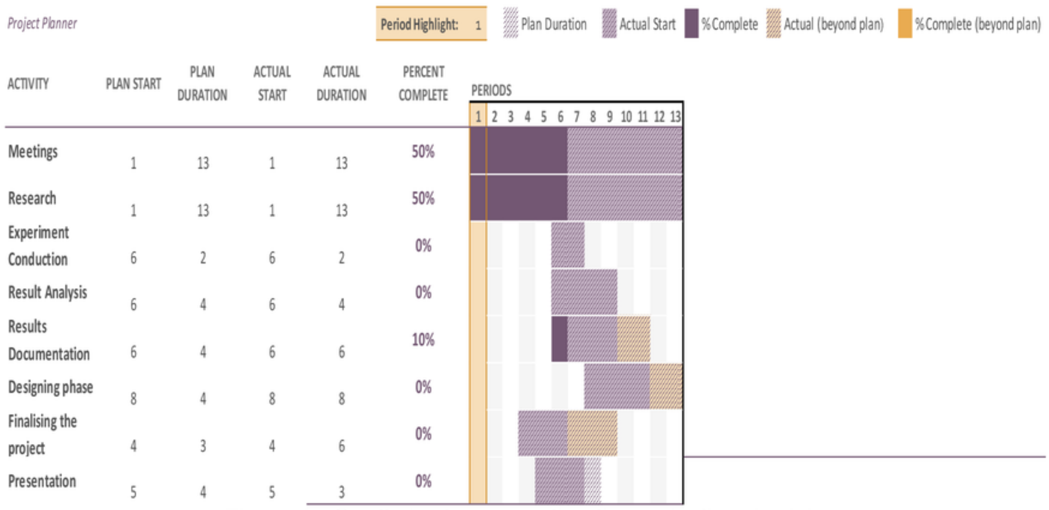

Figure 1: Gantt chart representing the project's schedule

1.1.2 Time

A project plan was set to ensure the completion of the project on time. The project plan timeframes was approved by the supervisor. Although Gantt chart was set up before starting the project to avoid delays it was not feasible to fulfil all the objectives on time therefore an updated Gantt chart was presented. Faults were present due to a lack of knowledge from me on analysing techniques and sample preparation, as no one from the chemical department was replying until week 4. At that time I was expected to start analysing my samples at least. Moreover the purchase order took more than expected as Australian supplier sites were not clear and show no prices therefore the order was purchased from the United stated , but still haven't been received and the personal sampling pumps could only be shipped in the US, therefore an alternative was provided for the Labs manager to purchase the order. As with any project schedule time slippage exists, all effort will be done to fulfil the aim of this project on time.

1.1.3 Cost

The project requires an initial budget of $991.50. This amount covers the first stage of the project which is experimenting or air monitoring. The labs are available for researching are available at no cost. Analysing equipment's are available as well for analysis at no cost. The following table shows the initial budget for the project:

Item NO	Item Description	Price per Unit (AUD)	Prices (AUD)
1	3 37mm PVC plastic cassettes	$84.00	
2	37mm PVC membrane filters 5um pore size (100pk)	$101.10	
3	Sample Gas bags Veriair	$55.35	
4	Luer Taper adapters (12pk)	$12.30	
5	personal sampling pump	$377.30	
6	Tubing 1/4 ID * 3/8 OD *100	$29.00	
		Sub Total Price	$659.05
		Shipping and Handling	$383.25
		Grand total	$991.50

Table 1: Projects initial budget

Chapter 2

2 Background and Related Work

In this section of the project a background information will be presented. The background information includes the welding processes that will be experimented through this project and a brief description of each of them. Furthermore, gases emitted via welding will be presented including their effects toward a human health. The chemical and physical properties of welding fumes. Existing solution used to control or minimise the welding fumes and gases will be presented.

2.1 Welding Process

2.1.1 Tungsten Inert Gas

Tungsten inert gas welding is also known as (GTAW) Gas Tungsten Arc Welding. In this welding process the electric arc is created between a tungsten electrode and the parent metal. This process requires high temperature to weld both metals together, the tungsten electrode heated to a temperature high enough for the production of the necessary electrons for the operation of the arc. An inert gas is required to protect the arc region, argon is the mostly used gas in this process. This process is performed when a high quality of the weld is required. The ability of welding thin materials and the wide range of alloys that can be welded makes TIG more efficient than other welding processes. In contrast, the high cost of the equipment, the high operator's skills that are required, the low deposition rates, and the complexity of the process are considered as disadvantages. Meanwhile it's typically used for piping systems and aerospace welding. [1, 2]

2.1.2 Metal Inert Gas Welding

Metal inert gas welding is also known as Gas metal arc welding (GMAW) , it uses a continuously fed solid wire electrode through a welding gun , pulling the trigger will feed the consumable electrode through. Through this process an electric arc is created between the electrode and the base material, which heats the base material allowing it to melt and join. This process of welding requires a shielding gas to prevent the molten weld metal from being effected from oxides and other atmospheric gases, which will reduce the quality of the weld. Argon is usually used as the shielding gas. The benefits of MIG it requires a lower heat input, minimal weld clean up, emits less welding fumes, and has a higher electrode efficiency. Despite those benefits, it limits the welder's position, the material should be clean free from dirt, the inability of welding thick materials, and the high cost of the equipment makes this process less efficient [1].

2.1.3 Shielded Metal Arc Welding

Shielded Metal arc welding also known as manual metal arc welding(MMAW) , it is a manual process which uses an electrode to carry the electric current in the form of direct or alternating current from a power supply is used to create an electric arc. The electric arc generates a high temperature that reaches 6500F which heats the base metal and the electrode causes them to melt and join. As the weld is placed the electrode coating forms a shielding gas of the emitted vapours. SMAW is usually used for construction and heavy equipment repairs. Although this welding process is portable, the equipment's cost is low, and is suitable for most of the workplace conditions, however the high level of skill required, the difficult to use on thin materials, and the great amount of wastes produced are the drawbacks of SMAW [1].

2.1.4 OXY welding

OXY welding is one of the welding process that requires a high flame rate to weld metals together. Oxy welding uses fuels, oxygen, and gases process the welding operation. This process relies on the combustion of oxygen and acetylene which will generate a flame with high temperatures which will allow the work piece material to reach its melting point. Temperatures generated through this process reaches 3500C. The equipment used in oxy welding is feasible, portable, and easy to use. The application requires a steel cylinder fitted with flexible hoses and regulators, which contains oxygen and acetylene stored under pressure. A welding torch is also needed which consists of a pipe or more to run the nozzle and allows the operator to adjust the oxygen and acetylene flows individually. Health risk associated with this application is high, as chemicals such as monoxide is produced in high quantities [3].

2.2 Welding Gases

2.2.1 Carbon Dioxide

Carbon dioxide is an odourless gas which has minor or no health effects at low concentration. It is supplied usually as an inert gas to protect the weld from oxidation and contamination. It is produced from the high heat in the flame and the arch. Carbon dioxide is considered non-toxic unless breathed in high concentrations. The exposure to this gas could lead to a variety of health effects. High level of exposure to CO2 might reduce the oxygen entering the body which will leads to several symptoms such as an increase in the heart rate, nausea, convulsion, coma, and even death. Moreover lack of oxygen could damage brain cells and heart organs. Eye contact to this gas could result in a permanent eye damage and blindness if the concentration increased. Direct contact to the skin might lead to infection, burning sensation, and skin tissue damage. CO2 exposure of 2000 – 5000 ppm causes headaches, increases heart rate, and a slight nausea. The exposure of 5000 ppm is the permissible exposure limit in workplace, other toxic gases might exist in the workplace due to reaction which could result in reduction of oxygen and air toxicity. Higher than 5000 ppm serious health hazards could be present which might result to brain damage, heart damage, or death [4].

2.2.2 Carbon monoxide

Carbon monoxide is one of the most highly poisonous gases present in welding. CO is formed from the breakdown of CO2 shielding gas in some welding processes. A report in the United States said that around 4000 people die annually from CO poisoning [5]. Headache, dizziness, weakness, nausea, vomiting, confusion, disorientation, and visual disturbances are some of the symptoms of CO poisoning. An increase in heart rate, syncope, and exertional dyspnoea are symptoms of a higher level exposure. With acute exposure coma, convulsion, and cardiorespiratory arrest may occur. Other health hazards that might occur of high levels of exposure are renal failure, skeletal muscle necrosis, hepatocellular injury, and pancreatitis [6]. The neurological system is at high risk of acute CO poisoning. Memory loss, neurological deficit, and neuronal death might be a result of this acute exposure [7], [8].

2.2.3 Hydrogen

Hydrogen is one of the toxic gases that exist in welding. It is formed from the radiation of the welding arc from the decomposition of the rod coating. Hydrogen has a very low exposure limit of 0.06 ppm on a short term and 0.02 on the long term. It has been stated in a report that the effect of hydrogen could be more severe if the gas contained fluoride, the formation of such a mixture forms from the hydrogen covered electrode containing large amount of calcium fluoride, the inhalation of this mixture may increase the risk of a lung disease [9]. Chronic exposure may result in chronic nose and throat irritation, and overexposure could lead to serious health issues in the respiratory system such as kidney and liver damage. [10]

2.2.4 Helium

Helium is a non-toxic gaseous element that does not form chemical compounds. It is commonly used as a shielding gas in welding processes. It is not considered as a risk on human health. Exposure to helium would cause minor short-term effects on health such as headache and dizziness. [11]

2.2.5 Argon

Argon is one of the gases that is used widely in industries due to its lack of reaction with other elements even in high temperatures. Argon is the most element that is used as a shielding gas in arc welding. Exposure to Argon might lead to serious health issues which might result in death. Acute exposure to this gas may result in lack of oxygen which causes rapid respiration, increases the heart rate, which leads to a loss of consciousness in first stages. In higher concentration serious headache, nausea, and vomiting may occur. With the continuous of the exposure the risk of deep coma, convulsion, and death increases. [12]

2.2.6 Nitrogen dioxide

Nitrogen dioxide is usually formed in welding processes from the oxidation of nitrogen at the arc. This gas in only generated at high temperatures greater than 1000C which is formed from the oxidation of nitrogen monoxide. The exposure of NO2 depends on several parameters such as the welding process, workplace condition, and material composition. The highest exposure rate of NO2 is reached as a result of oxy-acetylene welding as this process depends on flame heating which requires a temperature that might exceed 3450C to weld. In the first stages of NO2 exposure symptoms such as irritation, severe cough, a decrease in oxygen level, headaches, and dizziness might occur. High levels of exposure might result in a change of skin colour, anxiety, vomiting, shortness of breath, and chronic airway diseases such as asthma. [13, 14]

2.2.7 Nitrogen monoxide

Nitrogen monoxide is a nitrous gas that is generated at high temperatures from the oxygen and nitrogen in the atmosphere. Symptoms of low exposure rates are dizziness, irritation, and headaches. The increase of exposure rate could result in a high reduction in oxygen levels which leads to serious health risk. Several studies have shown the lung impairment that occurred of the chronic exposure to NO. [14]

2.3 Exposure Limits for welding fumes

Exposure varies in terms of several factors such as the welding process, workplace condition, and others. National Institute for Occupational Safety and Health (NIOSH), American Conference of Governmental Industrial Hygienists (ACGIH), and other organizations have published exposure limits for some materials and gases that produce welding fume. NIOSH also reported that due to welding fumes high complexity , it is not easy to establish an exposure limit for total welding emission , each welding constituent require its own exposure limit as additional toxic effects might be present when constituents interact. An acceptable exposure or breathing zone limit was measured to be from 1- 5 mg/m^3. (ACGIH) recommends a threshold limit value time weighted average of 5 mg/m^3 for total welding fume. The table below shows the exposure limit of each individual constituent of welding component. [15, 16, 17].

Substance	OSHA PEL-TWA (mg/m3)	NIOSH REL-TWA (mg/m3)	ACGIH TLV-TWA (mg/m3)	ACGIH BEI	Carcinogenicity
Aluminum Fume	15 (Total) 5 (res)	5	5		
Arsenic	0.01	0.002 (Ceiling)	0.01	35 µg As/L	A1
Barium	0.5	0.5	0.5		
Beryllium	0.002	0.5 (Ceiling)	0.002		A1
Cadmium Fume	0.005	LFC (Ca)	0.01 (Total) 0.002 (Res)	5 µg Cd/g creatinine	A2
Cobalt	0.1	0.05	0.02	15 µg Co/L	A3
Chromium(VI)	--	0.001	0.05	25 µg Cr/L	A1
Chromium metal	1	0.5	0.5		A4
Copper Fume	0.1	0.1	0.2		
Iron Oxide	10 (as Fe)	5	5		A4
Lithium	--	--	--		
Manganese	5 (Ceiling)	1	0.2	range 0.5 to 9.8 mg/L; up to 50 mg/L for occupational exposure	
Molybdenum	5(Soluble) 15 (Insoluble)	--	5 (Soluble) 10 (Insoluble)		
Lead	0.05	0.1	0.05	30 µg /dL (whole blood)	A3
Nickel	1	0.015 (Ca)	1	10µmol/mol creatinine	Elemental (A5) Insoluble inorganic (A1)
Platinum	0.002 (Soluble)	1(Metal) 0.002 (Soluble)	1		
Selenium	0.2	0.2	0.2		
Silver	0.01	0.01	0.1		
Tellurium	0.1	0.1	0.1		
Thallium	0.1	0.1(Soluble)	0.1	50 µg Th/g creatinine	
Titanium Dioxide	15	LFC (Ca)	10		
Vanadium Pentoxide	0.1 (Ceiling)	0.05(Ceiling)	0.05	50 µg V/g creatinine	
Zinc Oxide	5	5	5		
Zirconium	5	5	5		
Total fumes	--	LFC (Ca)	5		
Carbon monoxide	50 ppm	35 ppm	25 ppm	3.5% of (Hemoglobin) 20 ppm (end-exhaled air)	
Nitrogen dioxide	5 ppm (ceiling)	5 ppm (ceiling) 1ppm (STEL)	3 ppm		
Ozone	0.1 ppm	0.1 ppm	0.08 ppm		

Table 2: Exposure limit of each individual constituent of welding components [17]

2.4 Welding aerosol

Welding aerosols are produced from welding operations, they are a product of chemical and metallic oxides. The formation of welding aerosol depends on several factors the base metal, the filler material, and the welding electrode. These aerosols vary in sizes depending on the welding process, the welding material and several other parameters. Fume generation of these aerosol could be ranging from 100-400mgm^{-3}. Each metal has its own permissible exposure limit, it was reported to be from 1-5 mgm^{-3} by ACGIH and NIOSH. The toxicity of welding aerosol depends on factors such as size distribution, morphology, agglomeration state, chemical composition, surface area, porosity, and the surface chemistry. Several studies have reported the health effects associated such as decreases in pulmonary function, increased airway, hyper responsiveness, bronchitis, fibrosis, lung cancer, increased incidence of respiratory infections and metal fever.

2.5 Chemical Properties

A high level of chemical exposure to fumes and toxic gases could be a result of the pollutant created from welding. Therefore to evaluate the exposure rate of the worker, the toxicity of each element should be considered. Many elements can be found in welding fumes depending on the process and materials used. The toxicity of the metals might depend on the oxidation state. Some metals are considered as low toxic and some are classified as carcinogen and found to have a high level of toxicity such as hexavalent chromium (Cr^{6+}) . Shielding gases that are used to protect the weld might lead to a photochemical formation of toxic gases, such as ozone. Some gases such as trichloroethylene, are produced from decomposition of cleaning agents present on the metal to be welded. A study have shown that the elemental composition of particles depends completely on the used material. The previous study have also shown that particles relative abundance in the welding fumes depends on the heat input and electrode coating.[18] The concentration of elements can be determined by analysis methods such as EDX, SEM, and GC. [17, 19, 20]

2.6 Physical properties

The physical properties is an important factor in defining the health risk associated with welding fumes. Studies have presented that the size and aerodynamics of particles might be affected by the material and welding process used. All welding processes result in a release of a concentration of particles in lungs of exposed welder, FSW was reported to be the lowest deposition level followed by TIG and MIG. Particle aerodynamic sizes is not stable as it combines together in air to create a longer chain due to the turbulent conditions resulting from extreme heat generation. Electron microscopic study has shown that particles size range (0.01 – 0.10um) when first formed. Welding particles have been reported to be (0.5 – 2.0um) in size in the atmosphere of the welders breathing zone, which is easily inhalable and increases the risks on the respiratory system. [17, 18, 21]

2.6.1 Particulate Classification

There are several classifications to determine the welding particulate sizes. The size distribution could be helpful in determining the level of toxicity. Particles referred as coarse disperse particles are the particles that has an aerodynamic diameter greater than 1um. Particles with a diameter less than (0.1um) are classified as nanoparticles or ultrafine particles, studies have shown that nanoparticles are more harmful for human health than other particles, they can penetrate inside the respiratory system and enter the blood stream. Particles with a diameter ranging between 0.1-0.2um are called agglomerates they are usually formed from the coagulation of nanoparticles. Nanoparticle usually form through chemical reactions, gas to particle reaction or evaporation. Several reports have shown the severe effects nanoparticle have on a human system. Studies have shown that the exposure to nanoparticle could cause immune system impairment, cardiovascular diseases, and pulmonary diseases. [17, 18, 22]

2.7 Existing solution for assessment of welding fumes

2.7.1 Local Exhaust Ventilation System

Local exhaust ventilation as a primary engineering control, is used to eliminate pollutants before entering the breathing zone. Various parameters should be considered prior to designing an LEV. Type of welding, fume generation rate, arc to breathing zone distance, and workers exposure rate could be some parameter for an efficient local ventilation system. Its high cost and the requirement of a continuous maintenance are the limitations of a local ventilation system. [23, 24]

2.7.2 Fume Extracting Gun

Fume extracting gun could be another solution to assess the fumes. A fume extracting welding gun has a small exhaust hose around the circumference of the gun. Although it could be beneficial in terms of extracting larger amounts of fumes due to its very close distance to the arc, however its heaviness and its inability to control residual fume after completing the procedure could be viewed as a disadvantage. [25]

Figure 2: Fume extracting gun [26]

2.8 Experimental Studies

A study was carried on to determine the effects of the shielding gas temperature and flow rate on the welding fume particle size distribution. The theoretical reasons for the experiments have shown that the shielding gas temperature have an effect on welding fume particle disperse composition. Mainly as the temperature increases the density of the particle distribution or the fume formation rate decreases. The experimental result have also confirmed the theoretical reasons. Number of condensable atoms was shown to decrease as the shielding gas temperature increased. It have been concluded that as the temperature of shielding gas increase particle size range will decrease allowing more nanoparticles to be formed. An increase in the shielding gas temperature will allow both particles mode which are formed during the nucleation, nuclei growth, and coagulation to integrate and form into respirable or inhalable particles [37, 38, and 39].

A welding experiment was done to determine the evolution of welding fume aerosol with the time and distance from the source. Gas metal arc fumes were generated from mild steel plates. The distance of sampling was 30 cm form the welding arc which was considered the first hand exposure of the welding operator and 200 cm away representing the second hand exposure or the exposure of other workers in the workplace. The experimental results have shown a similar particle size distribution for the two sampling distances, however the major difference between the two measurements was in the presence of 15 and 50 nm particle size that only appeared in the 30 cm distance. The presence of the smaller particles at the shorter distance was possibly a result of the high concentration of metal vapour near the arc which quickly undergo condensation and coagulation upon being cooled to ambient temperature. The average mass concentration at the shorter distance was shown to be five times higher than that measured at 200cm form the welding arc. This might be a result of spatter particles that were only detected in the morphology samples at the shorter distance to the arc. The morphology of both samples were relatively similar particles were mostly formed in chainlike agglomerates, the only distinction was the spatter particles. Scanning electron microscopy images shown in the below figure: [40]

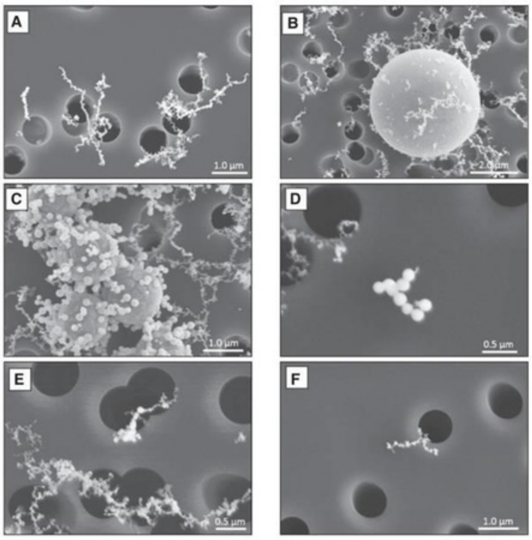

Figure 3: Scanning electron microscope images of the morphology samples collected at 30 cm frm the arc (Panels A, B, and C) and at 200 cm from the arc (Panels D, E, and F)[40]

Another welding experiment was carried out to develop the most efficient method to determine particle classification, mass concentration, chemical composition, and metal concentration of welding fumes using regular sampling equipment. A conductive plastic IOM sampler, a 37mm cassette, and a 47mm Teflon PFA filter holder, were the samplers that were tested. Samples were collected by employing a 5um PVC and a 0.4um polycarbonate membrane filter by a personal sampling pump operating at 2 l/min. GMAW and SMAW were the two welding processes that were conducted on carbon steel rods. The duration of the experiment was 2.5 hours and the samplers were mounted 20cm away from the welding zone. [43]

Several analysis were performed, but to determine the mass concentration a gravimetric analysis was done. Samples were weighed by a microbalance scale and for equilibration samples were left in the same room they were weighed in for 24 hours prior to being weighed. The results below show the mass concentration of the samples contained aerosol from carbon steel rods welded under SMAW and GMAW processes: [43]

Table 3: Results obtained at NAIT with total dust cassettes and PVC filters 5 μm [43]

Sample number	Mass concentration (mg/m^3)
1	0.438
2	0.478
3	0.487
4	0.510
5	0.528
6	0.438
7	0.487
8	0.535
9	0.494
10	0.540
Average	0.493
Standard deviation	0.036

Chapter 3

3 Experimental Procedure

3.1 Air Sampling Techniques

Air sampling methods is of great significance in determining the health hazards associated with welding. As the first stage of risk assessment states the importance of identifying the hazard. It is agreed upon that the welding fumes is the main source of health risk in welding. Therefore being able to extract the welding fumes for analysis and risk evaluation is highly recommended to fulfil the first stage of risk assessment successfully. Air sampling techniques is used to measure, identify, and quantify welding emission. Choosing the best strategy for sampling depends on several factors such as the welding process, workplace conditions, and weather conditions. In air sampling the process requires a method that is realistic to the real life conditions for example the flow should be relative to a human breathing in a normal condition. Therefore placing the sampling equipment in the breathing zone will provide with more accurate results. Determining the proper distance for sampling is extremely important for the optimum extraction, considering the distance will provide a more concentrated fume particles and gases for analysis. Moreover, the permissible exposure rate for each gas and metal should be well considered for the safety of the operator and the whole crew in the workplace. Collected samples should be stored properly to reduce the amount of data loss. Breaking down the welding fumes into particulates and gases will make the extracting and analysing process practicable. Therefore gases and particles will be extracted and analysed differently.

[27]

Sampling will be carried in several techniques to be able to cover the whole aspects of the experiment. Mild steel, Stainless steel, and Aluminium are the materials that were used for welding, cast iron was also used in one process due to limitations. The materials used are alloys therefore an analysis was carried on to determine the elemental composition and concentration of each metal prior to performing the experiment.

3.1.1 Particulate Extraction

Welding particulates are the fine particles that form during and before the welding procedure. Those particles formation rate depends on the welding process, the materials used, and the shielding gas. Welding fumes are considered a threat to the respiratory system as the particles are as small as 10um. Those ultrafine particles can easily enter the respiratory system and flow in the blood stream which might result in an acute or a chronic respiratory diseases such as asthma and lung cancer. The level of risk associated with those ultrafine particles depends on their shape and the penetration potential inside the respiratory system. Therefore being able to extract those particles might be an obstacle in this project as of their ultrafine sizes. Sampling of inhalable particles will be carried by employing a 37mm Millipore plastic cassette a PVC membrane filter with a pore size of 5um operating by a 3.0$Lmin^{-1}$ flow rate by a personal sampling pump. Due to the limitation two pumps were used operating at 15 $Lmin^{-1}$ which is considered relative to breathing flow rate and the other was a relatively high flow rate. This was considered as an advantage to be able to determine the effects that might be encountered with different flow rates. Although it is more recommended to follow NIOSH or OSHA methods for extracting welding particulate which uses a pump with a flow rate ranging from 1 - 3 $Lmin^{-1}$. The distance of extraction was 37cm which is roughly the distance from the operators shoulder to the welding pool and 20cm was done for results comparison. The duration of sampling was 2.5 and 5 minutes and welding was performed throughout this time [17, 18]

Figure 4: Particulate extraction technique [28]

3.1.2 Gases Extraction

Gases is another main source of air pollution in welding, it might have the same or higher concern on health in acute or chronic exposure levels. The level of formation of gases depends mainly on the welding process, some processes require high temperatures which will result in the formation of gases that react with oxygen in air, other process already use shielding gases to protect the weld from oxidation and vapours. Those oxides and vapours are considered as welding fumes. Shielding gases exposure is not a high concern on health it might lead to asphyxiants which are gases that reduce the oxygen concentration in breathing air. Several studies has shown that the exposure to certain gases might lead to serious health difficulties such as lung inflammation, neurological impairment, and cancer in some parts of the human systems. As a result, extracting those gases for analysis is of high concern.

More than an extraction method was used to determine the gases concentration efficiently. Gases were extracted by employing a gas bag operated at a constant high flow rate by a dual port pump. A tube was attached to the inlet of the pump sucking in the gases and transferring them through the outlet to the gas bag. The distance of sampling was as close to the welding operation as possible to ensure that the gas bag will contain a high concentration of gases. The following image shows the sampling procedure that will be used for gas extraction. [34, 35]

Figure 5: Gas extraction Techniques [29]

The other sampling method was by using a 20ml plastic syringe. The distance of extraction was relatively close to the welding operation, gases were sucked in slowly during and after the welding operation. The syringes head was covered by tape to prevent any leakage. Both samples were transferred to the labs for analysis.

3.2 Sampling conditions

It is significant for the sampling conditions to be documented clearly. The measurement of welding fumes and the risks associated could be important to provide a clear database of the health issues that might occur in future. Therefore, providing a consistent document is of high importance. The following types of information related to sampling conditions should be considered.

- Description of the working area
    - Description of the workspace :
      How organized is it?
      What type of activities are conducted in the workspace?
    - The location of the workspace
      Indoors / outdoors
      Windows or doors are opened or closed and the air conditioning system if there is one, if it's on or off as those factors might affect the airflow.
    - The area of the workspace, the height of the workspace.
- Types of machinery

    - The machinery conditions, types of machinery, machinery operation process, machinery year of production.
- The working procedure
    - The welding process, electrode type, current, voltage, wire speed, shielding gas if was used.
    - Operating time of each process, the air flow control, the distance of the samples to the welding power source.
    - Number of operators, the personal protective equipment's for safety, the local ventilation system if it is turned on or off.
- Sampling Procedure
    - If it was stationary for the whole work space or personal just on the operator.
    - Equipment's used for sampling (plastic cassettes, filters, pumps...etc.) [30]

3.3 Samples storage

For an increase in the analysis precision samples storage should be well considered. Filters should be as static as possible to prevent fume loss. Plastic cassettes were cleaned by acetone to clear out any contaminants. Filters were transported in cleaned cassettes by tweezers and sealed in a plastic bags. Prior to sampling cassettes were weighed then returned in plastic bags; filters in the cassette. After sampling, cassettes were returned to sealed plastic bags and carried carefully to the microscopy unit for analysis. Samples were stored at a room temperature environment and kept stable. Plastic bags were labelled according to the process and metal used.

For gas sampling, Tedlar gas bags and plastic syringes were used. Plastic syringes were covered with a plastic tape to prevent any gas leak after the sampling. Gas bags inlet was closed after a sample was taken. Both plastic syringes and gas bags were transported carefully and stored at a room temperature environment away from sunlight Samples will be labelled individually and analysed in proper analysing methods.

3.4 Welding Work Place

Welding was performed at Macquarie Engineering and technical services (METS) building. An operator from METS was responsible for doing the welding. TIG, MIG, SMAW, and OXY were the welding processes that were performed. Each one of the welding process has a different procedure in terms of several parameters. Following table will show the welding process and its parameters:

Table 4: The welding process parameters

Welding Process	Filler material	Shielding gas	Diameter -mm-	Current -amp-
TIG	Mild Steel	75Ar/25CO2	3.2	90 - 110
TIG	Stainless Steel	75Ar/25CO2	3.2	90 - 120
TIG	Aluminium	Argon	4	190 - 220
MIG	Mild Steel	75Ar/25CO2	0.8 (wire size)	60 - 180
OXY	Mild Steel	Acetylene + oxygen	3.2	90 - 110
OXY	Stainless Steel	Acetylene + oxygen	3.2	90 - 120
SMAW	Mild Steel	100Ar	3.2	90 - 140
SMAW	Stainless Steel	100Ar	3.25	75 - 110
SMAW	Cast Iron	100Ar	3.2	50 - 100

The working place was considered organized. Sampling was carried indoors, in terms of the flow one door and a window was open when the first sampling was taken, therefore to keep the consistency through the experiment a door and a window was opened deliberately when each sample was taken.

All personal protective equipment were available in the working place. The operator had the whole PPE on with the welding mask. For the safety of others in the workplace a welding mask must be worn when welding is carried on to protect the eye from ultraviolet and infrared rays.

Chapter 4

4 Data Analysis

4.1 Gravimetric Analysis

Gravimetric analysis is a techniques that quantifies the emission of welding fumes through the measurement of mass. It is usually the first step of analysis to be done to determine the amount of weld contained in a filter. This process is mostly used to determine the concentration of elements. The analysis will be carried to determine the amount of fumes generated or the amount of fumes carried in by a filter. Filters will be weighed in the plastic bag or in Petri dishes prior and after the experiment. The plastic bag, filters, cassettes, and filter holders will be cleaned before conducting the experiment for further precision in analysis. The analytical balance will be calibrated and equipped to reduce electrostatic charges with a readability of 0.01 mg. [30]

Calculation of Fume concentration [30]:

$$X = m_r - (m_p \times m_{rr}/m_{rp}) \quad (2)$$

where:

m_{rp} is the mean weight, in mg, of the three reference filters at the time the measurement filters are pre-weighed

m_{rr} is the mean weight, in mg, of the three reference filters at the time the measurement filters are re-weighed

m_p is the weight, in mg, of the measurement filter prior to sampling (measurement filter weight at pre-weighing)

m_r is the weight, in mg, of the measurement filter after sampling (measurement filter weight at re-weighing)

X is the dust weight on the filter, in mg.

4.2 EDX and SEM Analysis

Energy dispersive X-ray spectroscopy and scanning electron microscopy is an analytical technique to determine the chemical composition, particle dimension and shape. This analytical techniques shows the concentration of each element in a specific sample through x-rays. EDX data analysis could be generated on one point to determine the elemental composition in that specific point or by mapping where a specific area could be analysed. SEM will be used to determine particles dimensions and morphology by using the standard micrograph. The sampling plate for this analysis is 27mm and the filters used for the experiment is 37mm in size therefore the filters will be cut to the desired shape for sampling and all parts of the filter will be sampled. [31]

4.3 Gas chromatograph

Gas chromatography is widely used analytical technique for identifying and quantifying the compound in a mixture. The compound in the Tedlar gas bag will be transferred in a syringe and then injected onto the head of the chromatographic column for analysis. The compound inserted by a syringe will be transported through the column by the flow of the mobile phase. The mobile phase is also called the carrier gas it is usually an inert gas (helium, argon, hydrogen) that is specified depending on the type of the detector. The mobile phase containing the compound passes over a stationary phase. The amount of time it takes the sample in the carrier to pass the stationary phase is called the retention time. The solubility of the compound is factor that determines the retention time, the more soluble a mixture is the higher retention time it has. A stationary phase or the liquid phase is also required which separates the compound into its component, we can then determine which gases are present by the detector. To show the concentration of each gas a calibration curve is needed. An accurate calibration curve is created by running several dilutions of the compound of interest and then plotting the response time against concentration. Then, we can determine the concentration of the components by using the area under the peaks. [32, 33]

Chapter 5

5 Results

5.1 Welding Rods EDX Analysis

It is well known that welding fumes formation contains mainly of particulates and contaminants from the welding rods, due to high temperature applications on the rod which allows the rod to reach a high temperature above its melting point resulting in solid particle formation from vapour condensation. Therefore, analysing the welding rods prior to performing the experiment will be helpful in determining what will be expected in the result analysis. The following tables and graphs will show an EDX analysis on the three welding rods to determine the chemical composition. The following rods were the same rods that were used for TIG, OXY, and SMAW welding. In TIG and OXY welding the rods were the same, but in SMAW different rods were required and an analysis was done on all rods.

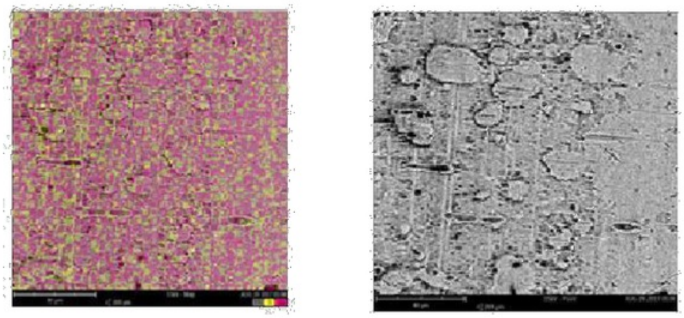

Figure 6: Aluminium Map EDX analysis and point EDX analysis

Table 5: Aluminium map elemental composition and point elemental composition

Map				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	92.36	83.26
14	Si	Silicon	4.04	3.79
47	Ag	Silver	3.59	12.95
Point				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	100.00	100.00

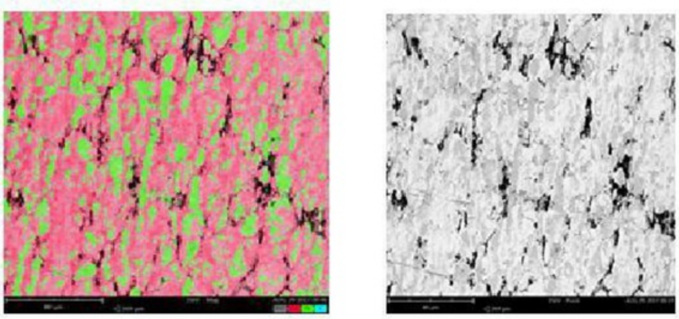

Figure 7: Mild steel Map EDX analysis and Mild steel Point EDX analysis

Table 6: Mild steel map elemental composition and Mild steel point elemental composition

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
29	Cu	Copper	44.17	55.69
26	Fe	Iron	35.65	39.50
6	C	Carbon	20.17	4.81

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	58.61	85.50
6	C	Carbon	39.41	12.37
14	Si	Silicon	1.02	0.75
25	Mn	Manganese	0.96	1.38

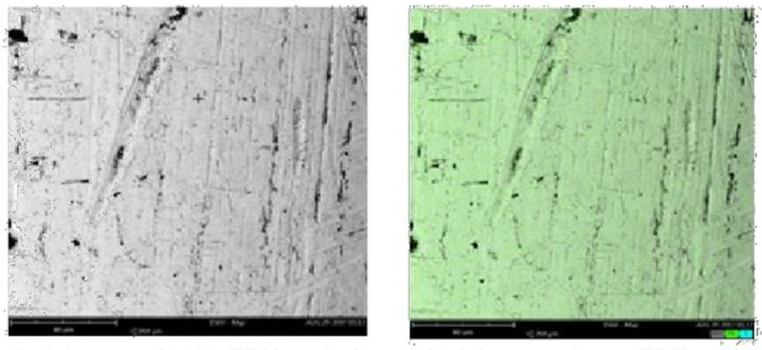

Figure 8: Stainless steel point EDX analysis and Stainless-steel map EDX analysis

Table 7: Stainless steel point elemental composition and Stainless-steel map elemental composition

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	51.52	62.97
24	Cr	Chromium	16.34	18.59
6	C	Carbon	16.18	4.25
28	Ni	Nickel	6.67	8.56
8	O	Oxygen	6.49	2.27
25	Mn	Manganese	1.77	2.13
14	Si	Silicon	0.63	0.39

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	53.86	62.63
24	Cr	Chromium	17.75	19.22
8	O	Oxygen	10.74	3.58
28	Ni	Nickel	6.86	8.38
6	C	Carbon	6.35	1.59
25	Mn	Manganese	2.26	2.58
14	Si	Silicon	1.06	0.62
13	Al	Aluminium	0.57	0.32
41	Nb	Niobium	0.56	1.08

The results above show the elemental composition of the welding rods that will be used as a filler material for the experiments. An EDX analyses was used to show the elemental composition on a specific point and a whole area by mapping. Welding rod samples were only cleaned by alcohol, for more accurate analysis rods should be polished to clear away any undesired contaminants form the storage and atmospheric pollutants. For the aluminium rod it is clearly shown that the rod is purely aluminium when a point analysis was done, when a map analysis was performed other metals such as silver and silicon were present in low percentages. For the mild steel rods as the rod was coated with copper for storage purposes, the percentage of copper was relatively higher than iron and carbon when a map analysis was done, when a random point was analysed iron was shown to have the highest concentration of 59%, silicon manganese were present with low values of 1.02% and 0.96% relatively, whereas copper was not shown and this might occur due to an unintentional removal of the coating while carrying the rods to the labs. For stainless steel both the map and point EDX analysis have shown relatively similar results with a slight difference in the concentrations.

The results below will show an EDX analysis on the welding rods that will be used for stick or SMAW welding. The rods that will be used are mild steel, stainless steel, and cast iron rods. Two random points on the rods were analysed to determine the elemental composition in a more accurate manner.

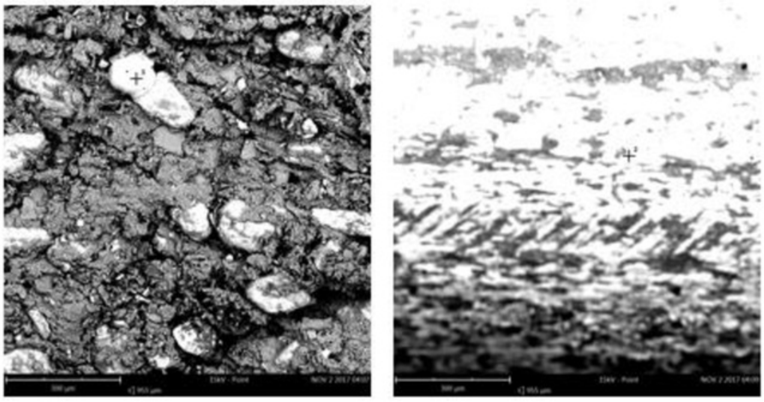

Figure 9: Mild steel rod EDX analysis on 2 random points

Table 8: Mild steel point 1 and 2 elemental composition

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	37.28	67.32
8	O	Oxygen	51.91	26.85
6	C	Carbon	7.86	3.05
14	Si	Silicon	2.68	2.44

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	41.99	70.48
8	O	Oxygen	33.58	16.15
6	C	Carbon	15.89	5.74
14	Si	Silicon	5.51	4.65
13	Al	Aluminum	1.59	1.29
19	K	Potassium	0.89	1.04
20	Ca	Calcium	0.54	0.66

An EDX analysis was performed on the same mild steel welding rod used for SMAW process. Two different points were analysed to be able to determine the elemental composition precisely. Results have shown a high value of oxygen and carbon in both points 51.21% and 37.28% in point 1 and 33.58% and 41.99% in point 2. Carbon and silicon was also present in both points 7.86% and 2.68% in point 1 and 15.89% and 5.51% in point 2. Whereas in point two more elements were detected in values lower than 2%.

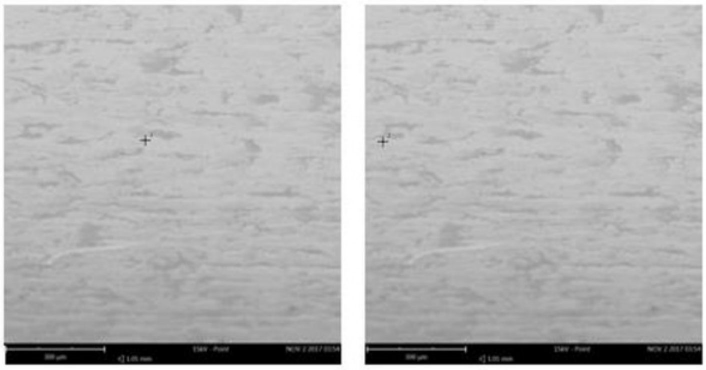

Figure 10: Stainless steel rod EDX analysis on 2 random points

Table 9: Stainless steel point 1 and 2 elemental composition

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	40.34	57.03
24	Cr	Chromium	11.48	15.11
8	O	Oxygen	36.45	14.76
28	Ni	Nickel	5.71	8.49
14	Si	Silicon	3.86	2.74
19	K	Potassium	0.72	0.71
13	Al	Aluminum	0.90	0.61
20	Ca	Calcium	0.55	0.55

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	46.81	60.99
24	Cr	Chromium	13.73	16.66
8	O	Oxygen	29.58	11.04
28	Ni	Nickel	6.56	8.98
14	Si	Silicon	2.77	1.82
20	Ca	Calcium	0.55	0.51

An EDX analysis was performed on the same stainless steel welding rod used for SMAW process. Two different points were analysed to be able to determine the elemental composition precisely. The results have shown high values of iron and oxygen were detected in both points 40.34% and 36.45% in point 1 and 46.81% and 29.58% in point 2. Chromium, nickel, and silicon were also present in both points, 11.48%, 5.71%, and 3.86% in point 1 and 13.73%, 6.56%, and 2.77% in point 2. Other elements were also present in both points in values less than 1%.

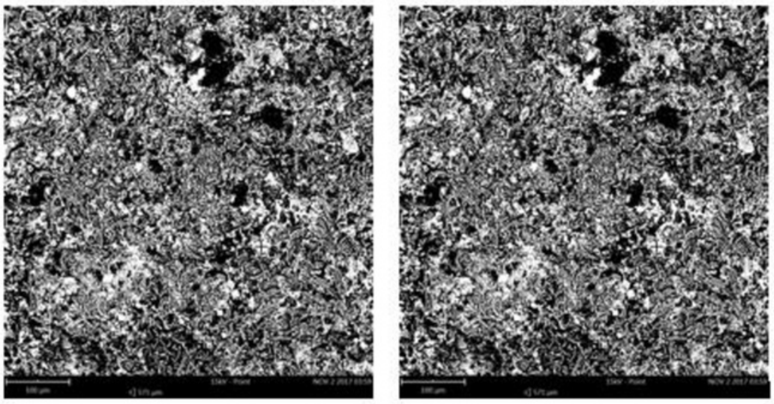

Figure 11: Stainless steel rod EDX analysis on 2 random points

Table 10: Stainless steel point 1 and 2 elemental composition

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	55.22	38.31
26	Fe	Iron	15.09	36.53
11	Na	Sodium	12.09	12.06
6	C	Carbon	13.53	7.05
14	Si	Silicon	2.42	2.94
49	In	Indium	0.27	1.33
12	Mg	Magnesium	1.09	1.15
22	Ti	Titanium	0.30	0.63

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	60.07	41.39
26	Fe	Iron	14.22	34.19
11	Na	Sodium	7.54	7.47
6	C	Carbon	12.30	6.36
14	Si	Silicon	3.78	4.57
49	In	Indium	0.82	4.06
24	Cr	Chromium	0.37	0.82
12	Mg	Magnesium	0.71	0.74

An EDX analysis was performed on the same cast iron welding rod used for SMAW process. Two different points were analysed to be able to determine the elemental composition accurately. Results have shown that oxygen, iron, carbon, sodium, and silicon were present in both points in values of 55.22%, 15.09%, 13.53%, 12.09%, and 2.42% in point 1 and 60.07%, 14.22%, 12.30%, 7.54%, and 3.78% in point 2. Other elements were also present in low values of 1% or less.

5.2 Aerosol Size Distribution and Morphology

The following figures will show an EDX analysis with a close focal length to determine the size distribution in different welding processes. The analysis was also performed to be able to determine the impact the flow rate and the distance range have on the particles size and morphology.

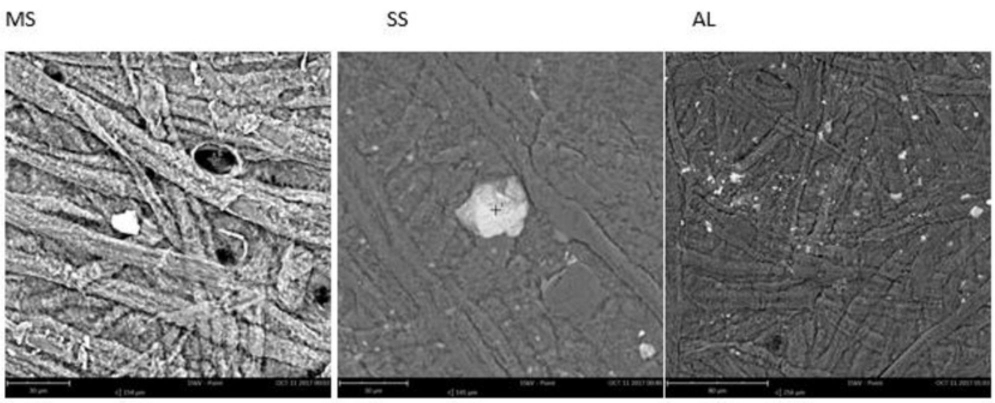

Figure 12: EDX analysis on filters containing aerosol from welded mild steel, stainless steel, and aluminium rods. TIG was the welding process, Distance range 1

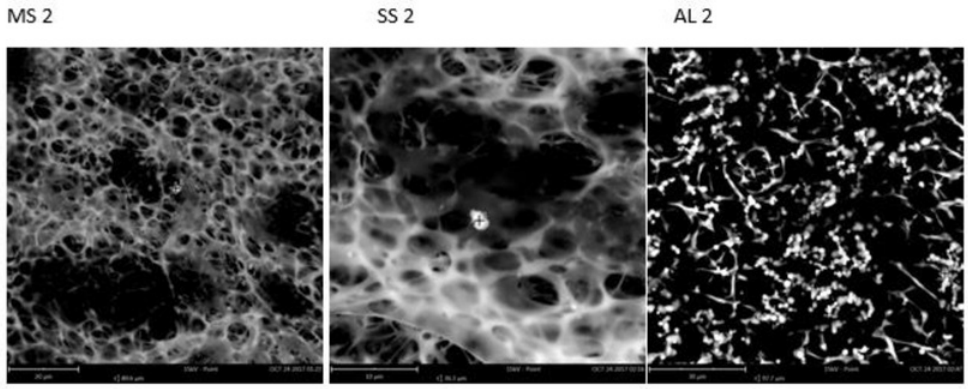

Figure 13: EDX analysis on filters containing aerosol from welded mild steel, stainless steel, and aluminium rods. TIG was the welding process, Distance range 2

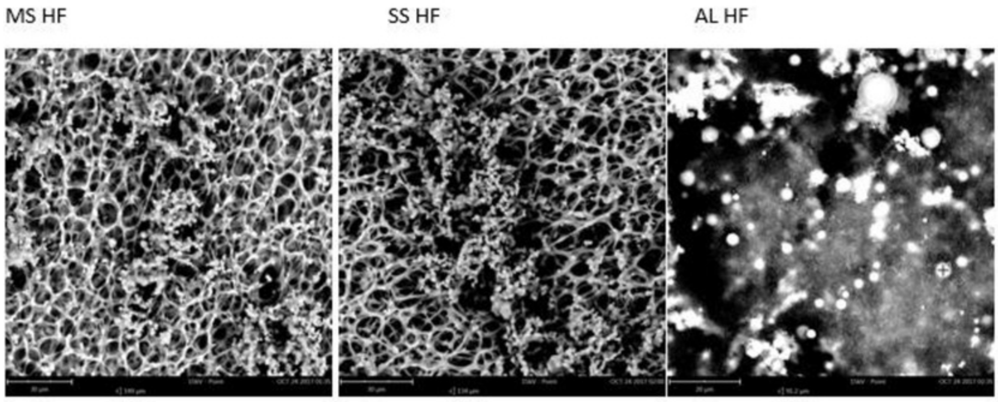

Figure 14: EDX analysis on filters containing aerosol from welded mild steel, stainless steel, and aluminium rods. TIG was the welding process, Distance range 2, and high flow

The above figures show an EDS analysis on a variety of filters where the welding process was TIG welding and mild steel, stainless steel, and aluminium were the materials used. The analysis was performed to determine the particles classification and morphology. The distance and flow rate were varied when particles were extracted. In figure 12 the distance was 37cm away from the welding pool with a flow rate of 15 l/min and a duration of 5 minutes. Figure 13 and 14 the distance was 20 cm away from the welding pool the duration was 2.5 min and flow rates were 15 l/min and an unknown high flow rate.

The results of the experimental study show differences in particle sizes and their morphology in figure 12. In all three materials particle sizes were as fine as 0.1um and as coarse as 40um. In AL particles were shown to be denser and more spread in the filter, it appears like they have been split apart, It can be seen from figure 13 the particle distribution between the three elements that aluminium consisted of more nanoparticles being produced whereas mild steel and stainless steel only ultrafine particles were detected.

Results that were shown in figure 14, where the filters were mounted 20cm away from the welding operation with the same flow rate, were quite similar to figure 13. Particle size distribution was similar, although less particles were detected for both mild steel and stainless steel. Aluminium accounted for the most particle distribution, nanoparticles were generated, and particles generated were mostly consisting of chainlike agglomerates.

In figure 14 where the flow rate was increased and the distance was 20 cm away from the welding pool, results were relatively different. Particle size distribution was the same particles sizes were ranging from 0.1um – 40um. All three filters contained particles that were formed in chainlike agglomerates. Larger chains were formed when aluminium was used with more coarse particles. Stainless steel and mild steel filters were comparable in size distribution and morphology, but stainless steel consisted of smaller particles. Nanoparticles were only generated during Aluminium and Stainless steel welding.

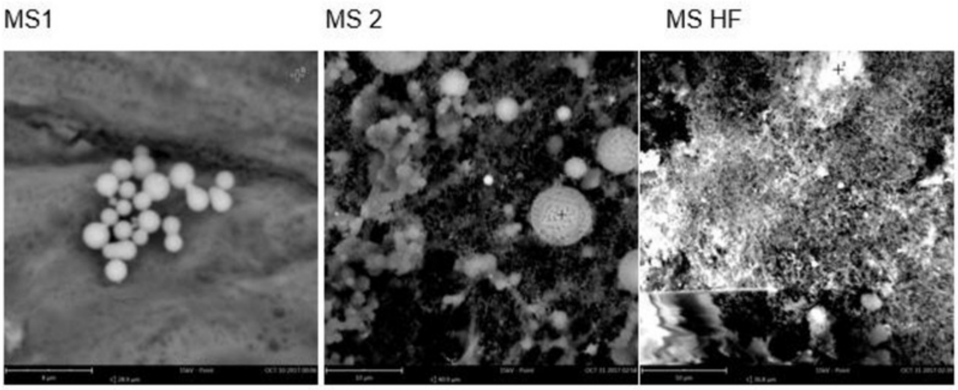

Figure 15: EDX analysis on filters containing aerosol from a welded mild steel rod. MIG was the welding process, Distance range 1 and 2, high flow

The above figure shows an EDS analysis of filters containing welding aerosol of MIG welding and mild steel was the material used. The figure shows a comparison in terms of the effect of flow rate and distance range on the morphology and size distribution of welding particles. MS 1 the distance was 37cm away from the welding operation and 15 l/min was the flow rate. MS 2 a similar flow rate was operating but the distance was 20 cm away from the welding operation. MS HF a higher flow rate was operating and the distance was 20cm away from the welding operation. The focal length of the images was 8um for MS 1, and 10um for both MS 2 and MS HF.

Aerosol size distribution and morphology was quite similar. All three filters when analysed contained nanoparticles and ultrafine particles. MS 1 particle size distribution range was from 75 nm - 10 um and particles were mostly formed in chainlike agglomerates. MS 2 aerosol size distribution was from 50 nm – 10um and particles were also detected to form in chainlike agglomerates. MS HF particle sizes were ranging from 25 nm – 5 um and chainlike agglomerates were also spotted. In the MS HF image the filter appears to contain more dust or aerosol in fine sizes covering the whole filter.

MS1 SS1

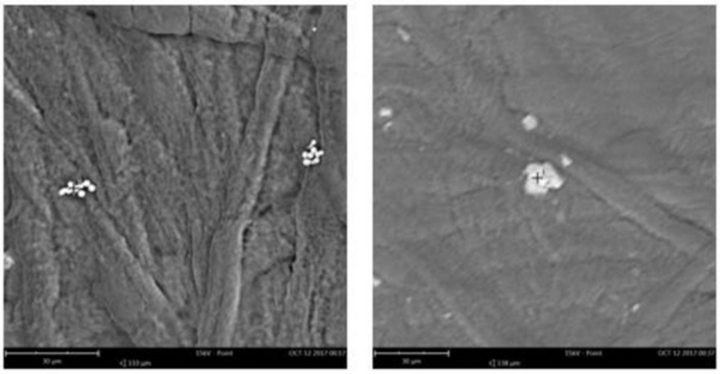

Figure 16: EDX analysis on filters containing aerosol from welded mild steel and stainless steel rods. OXY was the welding process, Distance range 1

MS2 SS2

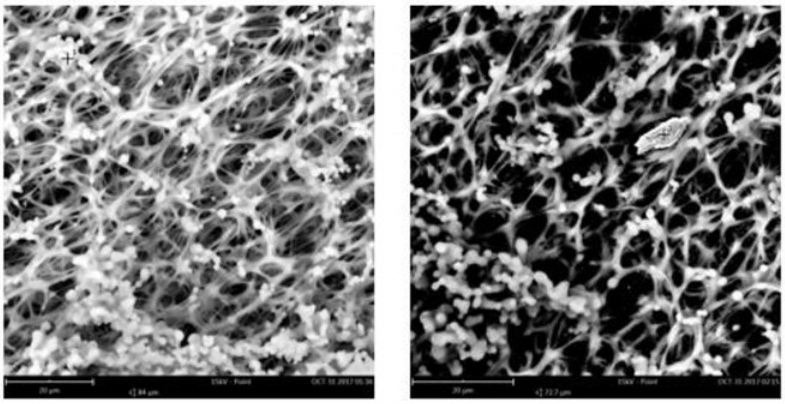

Figure 17: EDX analysis on filters containing aerosol from welded mild steel and stainless steel rods. OXY was the welding process, Distance range 2

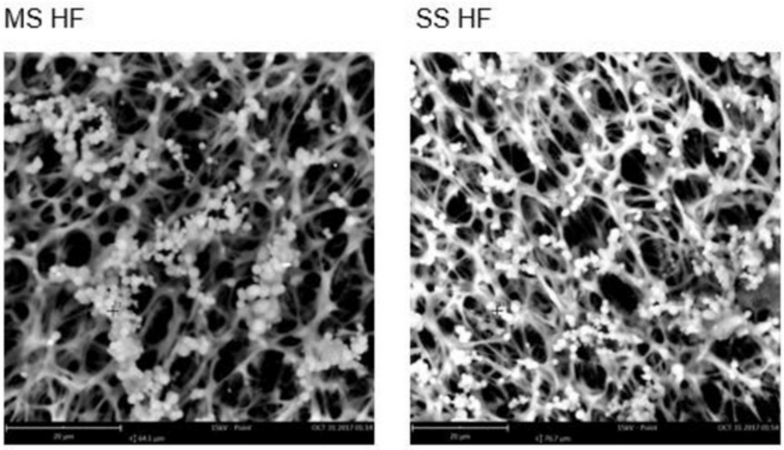

Figure 18: EDX analysis on filters containing aerosol from welded mild steel and stainless steel rods. OXY was the welding process, Distance range 2, high flow

The above figures show an EDX analysis on filters containing aerosol from OXY welding the material used was Mild steel and Stainless steel. The analysis was carried on to determine the impact of the airflow and the distance on the particle size distribution and morphology. In Figure 16 the filters were mounted 37cm away from the welding operation and the flow rate was 15 l/min. In figure 17 the distance was 20 cm and the flow rate was 15 l/min. In figure 18 the distance was 20 cm and a higher flow rate was operating. The focal length of the images Figure 16 30 um, Figure 17 and 18 20 um.

In Figure 16 particle size distribution was relatively the same ranging from 0.25um – 10um, and particles were formed in chainlike agglomerates when mild steel was used for welding. In figure 17 particle sizes was from 0.25um – 10um when mild steel was welded and 65 nm – 10 um when stainless steel was welded. Both filters contained particles forming in chainlike agglomerates, but filters containing aerosol from mild steel rods appear to form in larger chains. In Figure 18 particle size distribution was from 145 nm – 5 um for mild steel and 65nm – 5 um for stainless steel. Particles were mostly formed in chainlike agglomerates for both mild steel and stainless steel rods.

MS 1 SS 1 CS 1

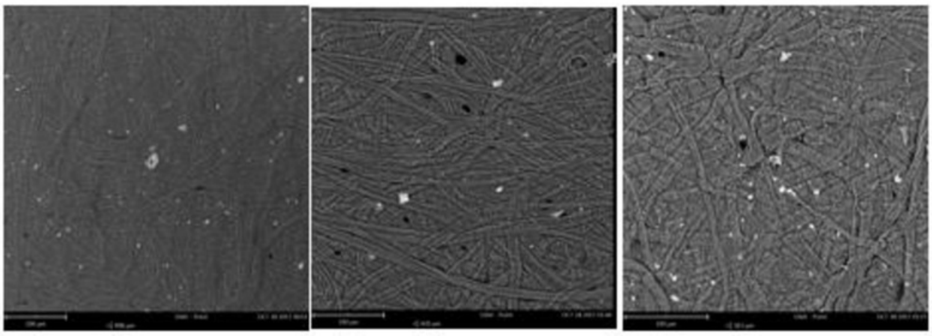

Figure 19: EDX analysis on filters containing aerosol from welded mild steel, stainless steel, and cast iron rods. SMAW was the welding process, Distance range 1

MS 2 SS 2 CS 2

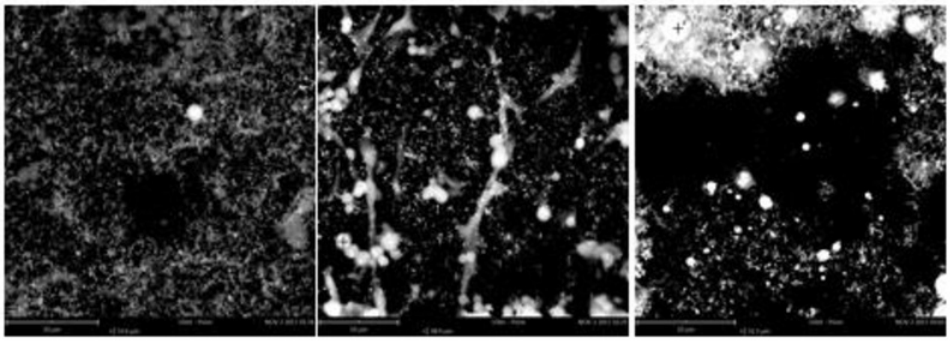

Figure 20: EDX analysis on filters containing aerosol from welded mild steel, stainless steel, and cast iron rods. SMAW was the welding process, Distance range 2

MS HF SS HF CS HF

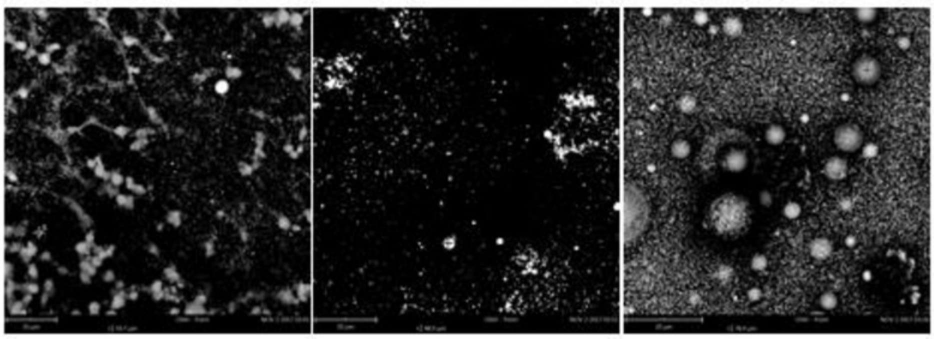

Figure 21: EDX analysis on filters containing aerosol from welded mild steel, stainless steel, and cast iron rods. SMAW was the welding process, Distance range 2, high flow

The above figures show an EDX analysis of filters containing welding aerosol form SMAW process using mild steel, stainless steel, and cast iron rods. The analysis was done to determine the impact the airflow and distance range on welding aerosol morphology and size distribution. Figure 19 the distance was 37 cm away from the welding operation, the flow rate was 15 l/min, and the duration of sampling was 5 minutes. In figure 20 the distance was 20cm, the flow rate was 15 l/min, and the duration of sampling was 2.5 minutes. In figure 21 the distance was 20 cm, the flow rate was relatively high, and the duration of sampling was for 2.5 minutes. The focal length of the images for Figure 19 was 100um, Figure 20 10um, and Figure 21 10um for both mild steel and stainless steel and 20um for cast iron.

In figure 19 particle sizes was comparable but MS 1 contained smaller particles. The particle size distribution for MS 1 and SS 1 filters was from 0.5 um – 15um and for CS 1 filter was 0.75 um – 25um. When stainless steel filter was analysed particles were spotted to be formed in chain like agglomerates, whereas filters contained aerosol from mild steel and cast iron rods particle were more spread not forming in chains.

In Figure 20 nanoparticles were spotted when analysing the filter containing mild steel rod aerosol, particle size distribution was 85 nm – 10 um, and chainlike agglomerates were detected in low percentages. The SS 2 filter contained particles that were mostly formed in chainlike agglomerates and particles size range was 0.25 um – 10um. Particles size distribution for CS 2 filters was 0.25um – 25um, coarse particles were detected, and a low percentage of particles were spotted to be formed into chainlike agglomerates.

In figure 21 nanoparticles were only detected when MS HF filters were analysed, with a size distribution of 60 nm – 5 um. SS HF filter consisted of particle size range of 0.25 um – 10 um and CS HF filter particle size range was 0.25 um – 25 um. Particles forming in chainlike agglomerates were spotted in all three filters, however SS HF consisted of particles forming in larger chains and particles were mostly formed in chains.

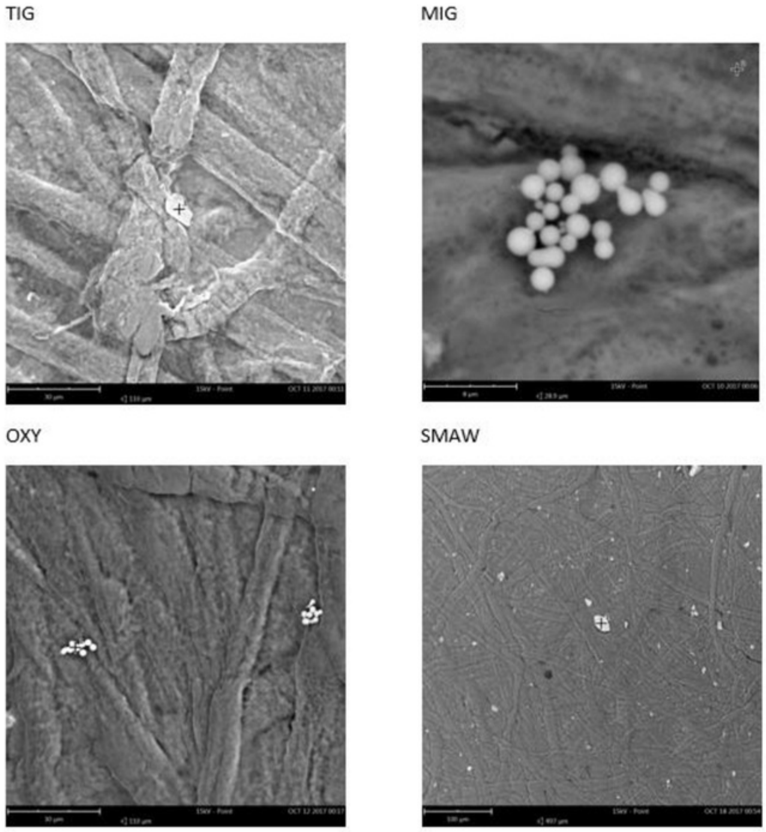

Figure 22: EDX analysis on filter containing welded mild steel. TIG, MIG, OXY, and SMAW were the welding processes used

The above figure shows an EDX analysis of filters containing aerosol from four different welding processes. TIG, MIG, OXY, and SMAW were the welding processes and mild steel was the material used. The distance of sampling was 37cm away from the welding operation. The focal length of the images for TIG was 30um, MIG was 8um, Oxy was 30um, and SMAW was 100um.

More fumes were created during MIG and SMAW compared to TIG and OXY. Particle sizes were significantly larger during the TIG welding ranging from 0.25 um – 43 um, nanoparticles were not detected and particles were not formed in chainlike agglomerates. Whereas MIG and OXY welding only ultrafine particles were spotted during OXY while filters containing aerosol from MIG contained both ultrafine and nanoparticles, particles were forming in chainlike agglomerates. Particle size distribution for MIG was 0.65nm – 10um and OXY 0.25um – 10um. When the filter containing particulates from SMAW was analysed nanoparticles were detected, more particles appeared to be spread into the filter not forming chainlike agglomerates.

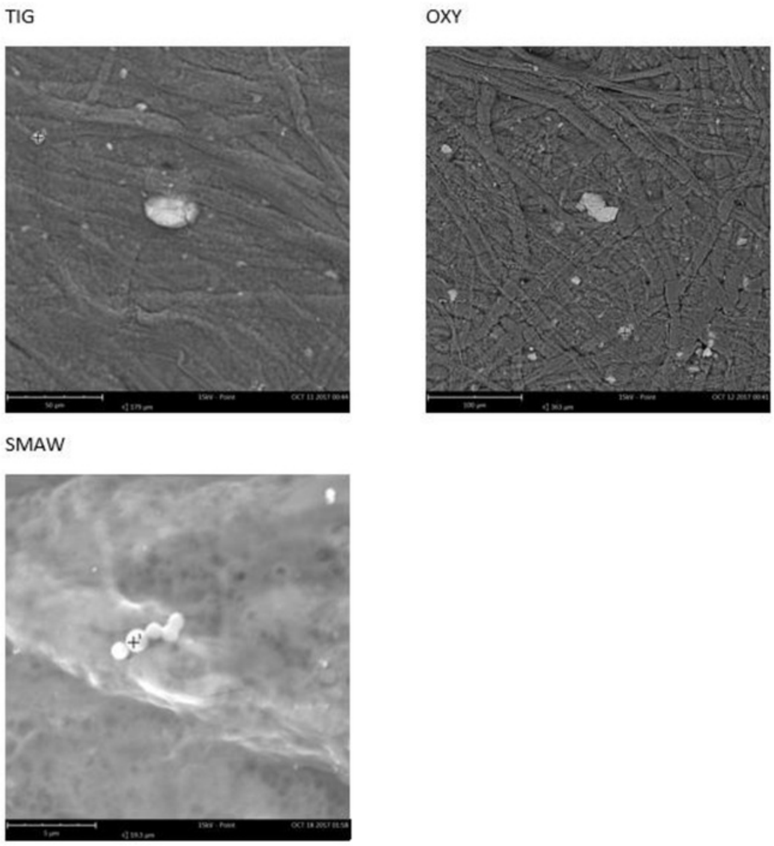

Figure 23: EDX analysis on filter containing welded stainless steel. TIG, OXY, and SMAW were the welding processes used

The above figure shows an EDX analysis of filters containing aerosol from three welding processes. TIG, OXY, and SMAW were the welding processes and stainless steel rods were used for welding. For TIG and OXY similar rods were used with a diameter 3.2 mm and SMAW rods were 3.25 mm in diameter. Welding was carried on for 5 minutes and the sampling filters were mounted on a 37cm distance away from the welding pool. The focal length of the images was 50um for TIG, 500um for OXY, and 5um for SMAW.

The particles size distribution for TIG was 0.5um – 35um for OXY was 0.25um – 25um and SMAW less than 0.1um – 10um. Filters containing aerosol form SMAW consisted of nanoparticles, ultrafine particles, and particles were mostly formed in chainlike agglomerates. In comparison, no nanoparticles were detected and particles formed in chainlike agglomerates were not spotted.

5.3 Mass Concentration

The following figures will show the mass concentration in the sampled filters. To be able to determine the mass concentration a gravimetric analysis was done. A comparison will be shown between the welding process and the different rods that were welded to determine the material that accounts for the most fume generation.

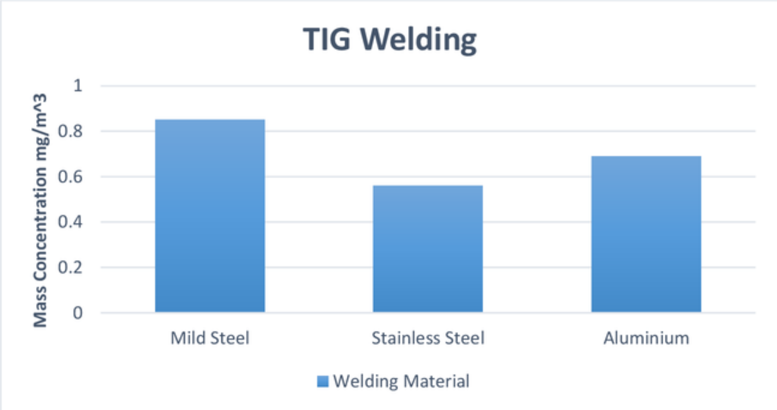

Figure 24: Mass concentration of filters containing aerosol from a welded mild steel, stainless steel, and an aluminium rod. TIG was the welding process

It could be clearly seen from the above chart that most fumes were generated when mild steel was the material used for welding. Aluminium and Stainless steel is shown to contain a relatively similar mass concentration value of 0.69 and 0.56 mg/m^3.

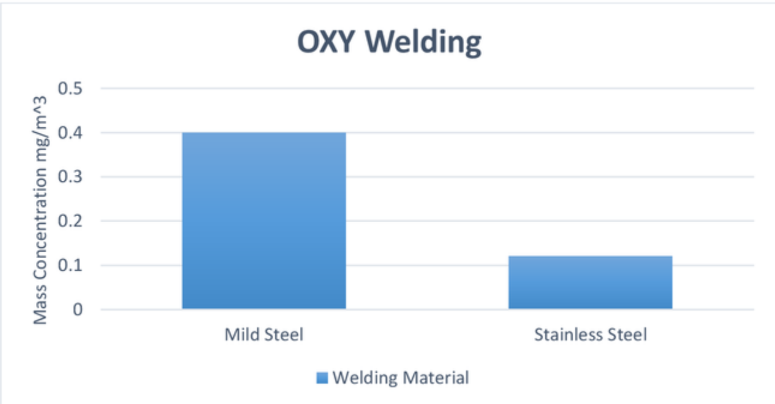

Figure 25: Mass concentration of filters containing aerosol from a welded mild steel and a stainless steel rod. OXY was the welding process

The above chart shows a comparison of a mild steel and a stainless steel rod in terms of fume generation during OXY welding. Mild steel rods is shown to generate more fumes than stainless steel rods. Roughly 0.4 mg/m^3 was the mass concentration on the filter when a mild steel rod was used for welding and 0.12 mg/m^3 was the mass concentration on the filter containing mild steel aerosol.

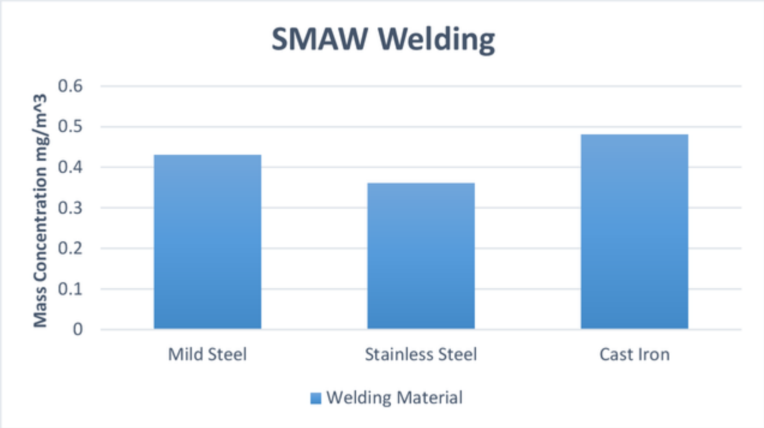

Figure 26: Mass concentration of filters containing aerosol from a welded mild steel, stainless steel, and a cast iron rod. SMAW was the welding process

The above charts shows the mass concentration of a mild steel, a stainless steel, and a cast iron to when SMAW was the welding process. The cast iron rod consisted of the most fume generated determined by the weight of the filter which was almost 0.5 mg/m^3. Whereas mild steel and stainless steel rod had a relatively similar value of 0.43 mg/m^3 and 0.36 mg/m^3 respectively.

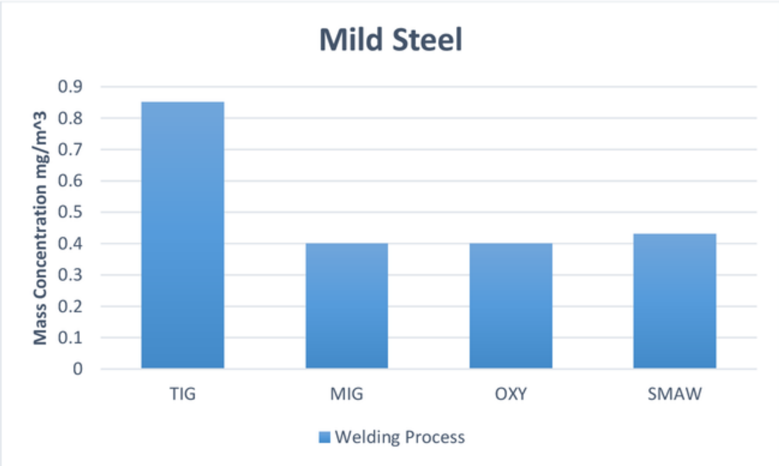

Figure 27: Mass concentration of a welded mild steel rod. TIG, MIG, OXY, and SMAW were the welding processes

The above figure shows the mass concentration of the aerosol of mild steel rods on four welding processes. Mild steel was the material welded and TIG, MIG, OXY, SMAW were the welding processes. TIG welding is shown to contain the most amount of mass in the filters which is 0.85 mg/m^3. However, MIG, OXY, and SMAW filters contained a similar mass concentration.

Figure 28: Mass concentration of a welded stainless steel aerosol. TIG, OXY, and SMAW were the welding processes

The above chart shows a comparison the mass concentration of stainless steel aerosol when TIG, SMAW, and OXY were the welding processes. The chart shows that TIG filters contains the most mass concentration in comparison to the other two which consisted of 0.56 mg/m^3. SMAW filters contained roughly 0.4 mg/m^3 and OXY contained the least mass concentration which was 0.12 mg/m^3.

5.4 Elemental composition

The following figures will show the elemental composition of the fumes contained in sampled filters. Sampled filters contained fumes from several welding processes and welded materials. The welding processes were TIG, MIG, OXY, and SMAW. The materials welded were mild steel, stainless steel, aluminium, and cast iron.

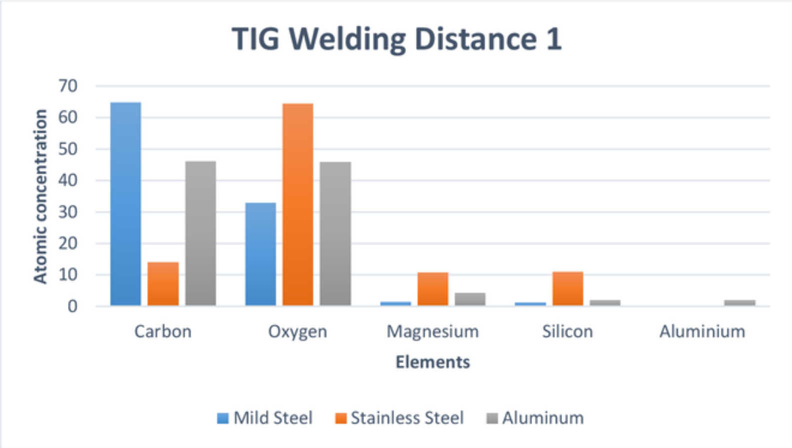

Figure 29: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel, stainless steel, and an aluminium rod. TIG was the welding process, Distance range 1

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel, stainless steel, and aluminium rods. TIG was the welding process that was used, sampling was carried on 37 cm away from the welding operation, and the 15 l/min was the flow rate operated by a personal sampling pump. In all three welding rods, the aerosol emitted contained carbon, oxygen, magnesium, and silicon. Mild steel is shown to have the highest atomic concentration of carbon which is 65% compared to the stainless steel and the aluminium rod. However stainless steel fumes emitted contained the highest elemental value of oxygen which was almost 65%. Aluminium was only found in aerosol emitted when an aluminium rod was welded with a value less than 5%. Magnesium and silicon were present in all three filters with a ratio of 1:1 in a relatively same percentage.

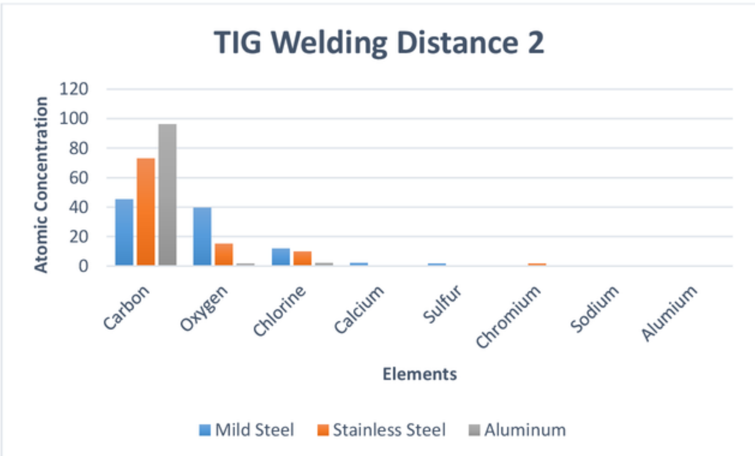

Figure 30: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel, stainless steel, and an aluminium rod. TIG was the welding process, Distance range 2

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel, stainless steel, and aluminium rods. TIG was the welding process that was used, sampling was carried on 20 cm away from the welding operation, and the 15 l/min was the flow rate operated by a personal sampling pump. All three filters contained carbon, oxygen, and chlorine in different percentages and carbon was present in the highest percentage in all three filters. The filter which contained aerosol emitted when an aluminium rod was welded contained almost 98% of carbon which was the highest percentage of carbon in all three and low values of chlorine and oxygen which are 2.19% and 1.47% relatively. Filters containing welding fumes generated when a stainless steel rod was welded contained 73% of carbon, 15% of oxygen, 9.85% of chlorine, less than 2% of chromium, and 0.37% sodium. Filters which contained welding fumes when a mild steel rod was welded consisted of 45% carbon, 39.5% oxygen, 11.88% chlorine, calcium and sulphur in values less than 2 %.

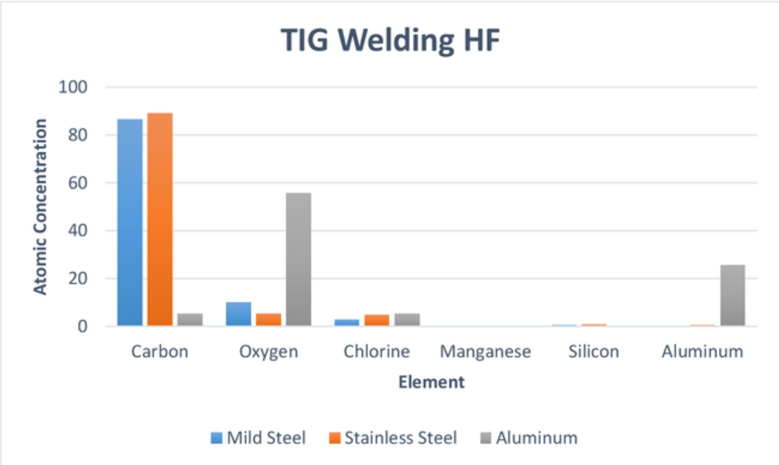

Figure 31: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel, stainless steel, and an aluminium rod. TIG was the welding process, Distance range 2, high flow

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel, stainless steel, and aluminium rods. TIG was the welding process that was used, sampling was carried on 20 cm away from the welding operation, and a high flow rate operated by a sampling pump. High percentages of carbon were present in filters contained aerosol from a welded mild steel rod and a stainless steel rod 86.1% and 89% relatively. Filters contained fumes from a welded mild steel rod also contained 10% oxygen, 2.73% chlorine, manganese and silicon in values less than 0.5%. Moreover, 5.21% of oxygen, 4.64% of chlorine, 0.65% of silicon, and 0.36% of aluminium was also detected when analysing the filter containing fumes from a welded stainless steel rod. A high percentage of oxygen 55.78%, 5.24% of both carbon and chlorine, and 25.67% of aluminium was found when a filter containing fumes of a welded aluminium rod was analysed.

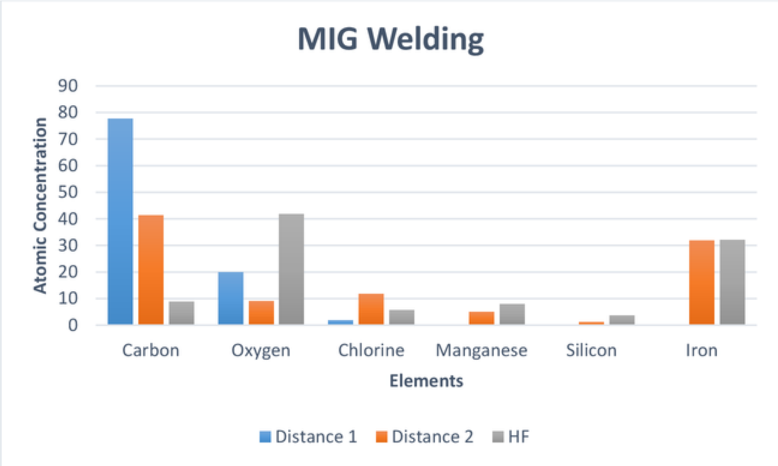

Figure 32: EDX analysis to determine the elemental composition in filters containing aerosol from welded mild steel rods. MIG was the welding process, Distance range 1, 2 and a high flow

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel rods. MIG was the welding process that was used, sampling was carried on 37cm in distance 1, 20 cm in distance 2, and 20 cm as well when the pump was operating on a high flow rate. In distance 1 and 2 the flow rate was 15 l/min and in HF the flow rate was high. In distance 1 the filters analysed was shown to contain 77.6% of carbon, 19.8% of oxygen, and 1.78% of chlorine. In distance 2 the filter analysed contained 41.27% of carbon, 8.94% oxygen, 11.68% chlorine, 5.05% manganese, 1.16% silicon, and 31.9% iron. The analysis has shown for the third filter where the flow rate was relatively high 8.8% of carbon, 41.75% of oxygen, 5.72% of chlorine, 7.94% chlorine, 3.71% silicon, and 32.08% of iron.

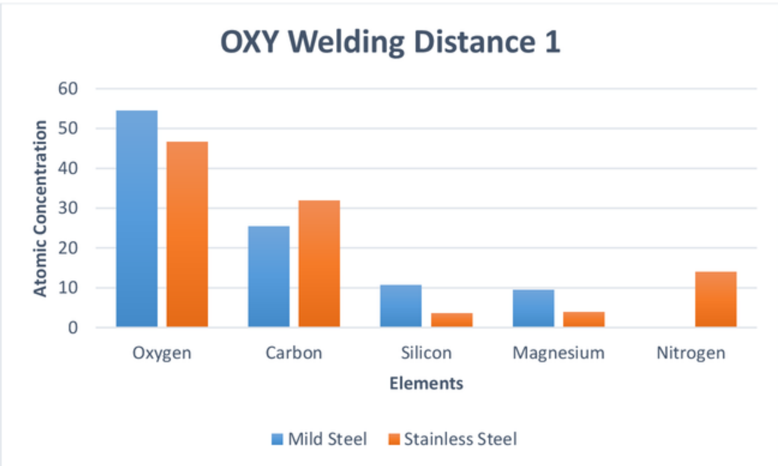

Figure 33: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel and a stainless steel, rod. OXY was the welding process, Distance range 1

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel and stainless steel rods. OXY was the welding process that was used, sampling was carried on 37cm away from the welding operation, and 15 l/min was the flow rate operated by a personal sampling pump. Results have shown a high concentration of oxygen in both filters. Filers containing aerosol from welded mild steel consisted of 54.48% of oxygen, 25.37% of carbon, 10.71% silicon, and 9.44% magnesium. However the other filter contained 46.68% of oxygen, 31.48% of carbon, 3.6% silicon, 3.93% magnesium, and 13.95% of nitrogen.

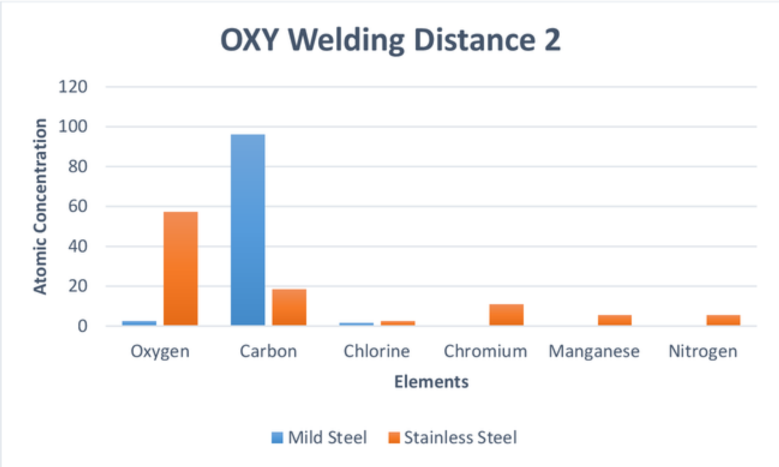

Figure 34: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel and a stainless steel, rod. OXY was the welding process, Distance range 2

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel and stainless steel rods. OXY was the welding process that was used, sampling was carried on 20 cm away from the welding operation, and 15 l/min was the flow rate operated by a personal sampling pump. The filter contained fumes of a welded mild steel rod consisted of 96.06% of carbon, 2.51% of oxygen, and 1.42% of chlorine. However, the other filter contained 57.19% of oxygen, 18.47% carbon, 2.35% chlorine, 10.87% chromium, 5.5% manganese, and 5.4% of nitrogen.

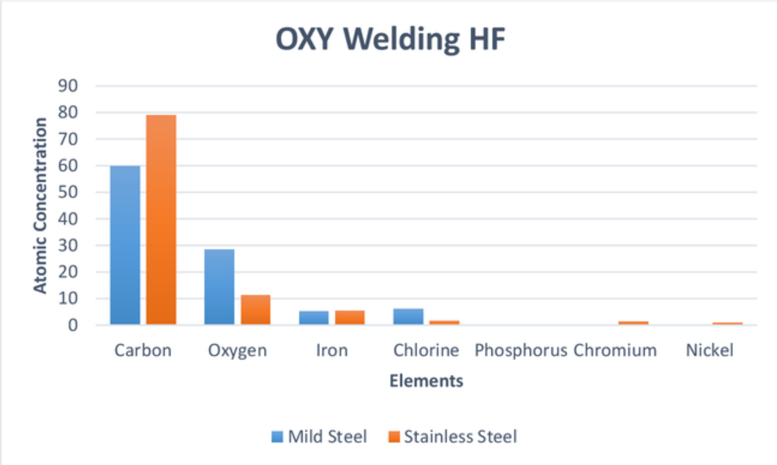

Figure 35: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel and a stainless steel, rod. OXY was the welding process, Distance range 2, high flow

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from a mild steel and a stainless steel rod. OXY was the welding process that was used, sampling was carried on 20 cm away from the welding operation, and the flow rate was relatively high operated by a sampling pump. The filter which contained fumes from welded mild steel rod consisted of 59.77% carbon, 28.36% oxygen, 5.24% iron, 6.14% chlorine, and 0.3% of phosphorous. The other filter contained 79.04% carbon, 11.35% oxygen, 5.44% iron, 1.56% chlorine, 1.32% chromium, and 1% nickel.

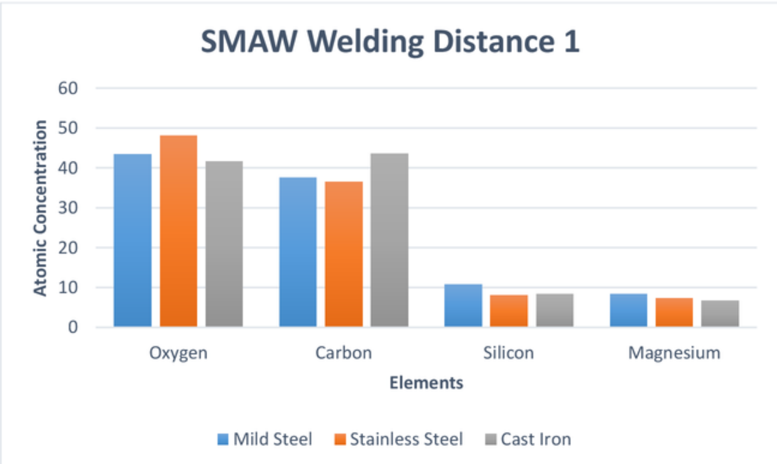

Figure 36: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel, stainless steel, and a cast iron rod. SMAW was the welding process, Distance range 1

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel, stainless steel, and a cast iron rod. SMAW was the welding process that was used, sampling was carried on 37cm away from the welding operation, and 15 l/min was the flow rate operated by a personal sampling pump. Results have shown that oxygen, carbon, magnesium, and silicon were the only elements that were detected in the filters. Filters containing fumes from a welded mild steel rod consisted of 43.37% oxygen, 37.53% carbon, 10.69% silicon, and 8.41% magnesium. Whereas filters containing aerosol from a welded stainless steel rod contains 48.02% oxygen, 36.52% carbon, 8.09% silicon, and 7.37% magnesium. The third filter which contained aerosol of a welded cast iron rod contained 41.5% oxygen, 43.49% carbon, 8.28% silicon, and 6.68% magnesium.

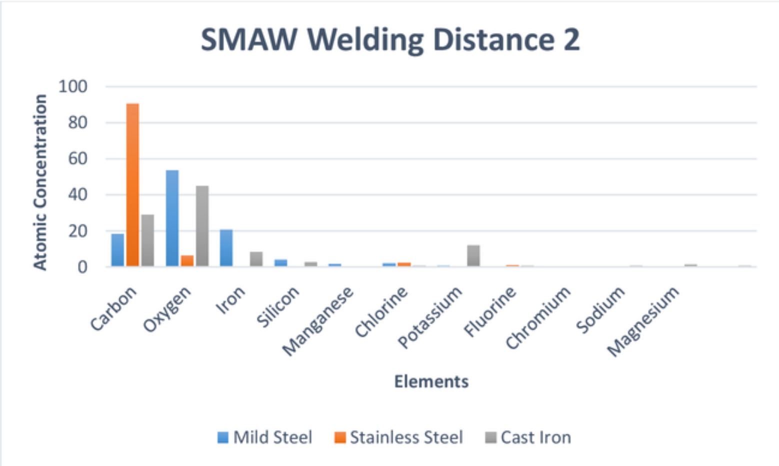

Figure 37: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel, stainless steel, and a cast iron rod. SMAW was the welding process, Distance range 2

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel, stainless steel, and a cast iron rod. SMAW was the welding process that was used, sampling was carried on 20 cm away from the welding operation, and 15 l/min was the flow rate operated by a personal sampling pump. The filter containing fumes from a welded mild steel rod consisted of 18.08% of carbon, 53.56% oxygen, 20.51% iron, 3.85% silicon, 1.54% manganese, 1.82% chlorine, and 0.64% potassium. The other filter which contained fumes from a welded stainless steel rod contained 90.33% carbon, 6.15% oxygen, 2.13% chlorine, 0.2% potassium, and 0.84% fluorine. However, the third filter contained 28.92% carbon, 44.8% oxygen, 8.41% iron, 2.6% silicon, 0.73% chromium, 11.98% chlorine, 0.55% potassium, 0.73% chromium, 128% sodium, and 0.72% magnesium.

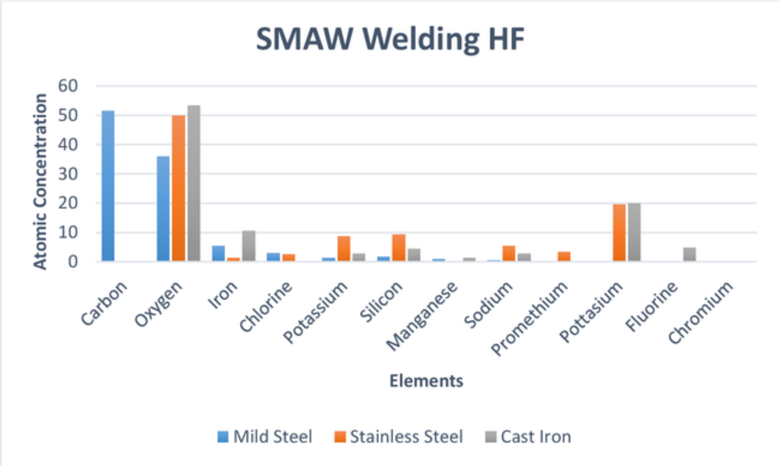

Figure 38: EDX analysis to determine the elemental composition in filters containing aerosol from a welded mild steel, stainless steel, and a cast iron rod. SMAW was the welding process, Distance range 2, high flow

The above chart shows an elemental composition that was determined by an EDX analysis. The analysis was performed on filters contained welding aerosol from mild steel, stainless steel, and a cast iron rod. SMAW was the welding process that was used, sampling was carried on 20 cm away from the welding operation, and the flow rate was relatively high operated by a sampling pump. The results have shown a high percentage of oxygen in all three filters. The filter containing aerosol from a welded mild steel rod consisted of 51.39% carbon, 35.92% oxygen, 5.43% iron, 2.97% chlorine, 1.28% potassium, 1.76% silicon, 0.83% manganese, and 0.42% sodium. Whereas the second filter which contained aerosol from a welded stainless steel rod consisted of 49.91% of carbon, 1.39% iron, 2.49% chlorine, 8.65% potassium, 9.19% silicon, 5.45% sodium, 3.43% promethium, and 19.48% fluorine. The third filter contained 53.27% of carbon, 10.61% iron, 2.79% potassium, 4.38% silicon, 1.31% manganese, 2.77% sodium, 20.02% fluorine, and 4.85% chromium.

Chapter 6

6 Discussion

6.1 Gas Chromatograph Result

According to the GC analysis it have been shown that no gases were detected through all the welding processes that were used. The gases were analysed by transferring the gases in the gas bag and plastic syringes into a GC syringe then injecting it in the GC. This process have been done in several studies and have been reported to be effective in determining gases and their concentration.

There are several possibilities that might be a reason why gases were not detected. Firstly, the GC process should be well known and considered. The way the GC works is by introducing a sample in the gas or liquid phase (which is called the mobile phase) through a tube that is lined with the stationary phase. In the mobile phase inert gases such as Argon and helium are used depending on the type of the detector. The stationary phase usually contains materials that are used to attract the molecules of interests. The mobile phase then transfers the sample through the column, and the stationary phase is exposed to a high temperature allowing molecules of interest to break down and move to the column and into the detector.

After knowing the process of a GC, it is well known that the gases detection is based on an increased temperatures for molecules to break loose and then gas detection will occur.CO2 is known to have the lowest temperature of gases therefore it is the first gas that should be detected in a GC. If carbon dioxide was not detected then no other gases will be shown in a GC analysis. Carbon dioxide is one of the gases that widely exist in welding either as a shielding gas or one of the gases that form from high temperatures of welding. In this experiment carbon dioxide was used as a shielding gas in two of the welding processes, which can ensure that CO2 at least will be detected.

One of the possibilities that did not allow the gases to be detected is the GC detection limit. Every department has its own values for the limit of detection (LOD) and method of detection (MDL). The limit of detection is the lowest concentration level or a quantity of a component that can be reliably detected with a given analytical method. The LOD would be the lowest concentration found from the measurement of a sample that we would be able to differentiate the concentration found from the measurement of a blank sample. For example, if we were to analyse some blank samples and we have an analytical procedure where the precision along the different concentration level is known and the results follow a normal distribution. Different values will be obtained when analysing the blank samples. The values obtained will be of a relatively low concentration distributed around the zero with a given standard deviation. Although we are analysing blank samples a non-zero concentration value was found. Therefore, based on the results a distribution limit could be set at a certain point, which is also called a critical level (LC). By having a critical point it will allow us to determine whether an analyte is present or not when measuring a sample. If the value detected was higher than LC that means a value have been detected and a component exists in the sample, otherwise samples are considered empty or blank [42].

In conclusion, the critical level is set depending an individual decision which depends highly on what kind of samples were measured and what kind of deviation was given to those samples. The method of detection limit is also a factor that has an impact on determining a consistent data. The method of detection limit is a relative measure of the performance of a particular lab, method or analyst. Data is usually obtained through many sources before evaluation and making the right choice. Ultimately, the GC limit of detection and method of detection is based upon individual analysis on what type of results will be expected later. A case where the GC analysis is used to measure samples with high analyte concentration for several years the detection limit will not be low unless set to be. Therefore, when samples were measured in the GC it have been shown that samples only contained air with no gases were detected, this could be a result of having a GC with a high limit of detection or relatively higher than the samples concentration. As no welding gases have ever been analysed in the GC that was used it could be clear that the GC was never been able to measure this low concentration of gases. Ultimately as the value obtained was not detected welding gases extracted through this experiment is considered below the permissible rate and are harmless.

The method used for gas extraction could be the other possibility of not being able to identify any of the gases. Gases were extracted by employing a high flow rate pump with an inlet and an outlet port, a tedlar gas bag attached to the outlet port and a tube attached to the inlet or the suction port. Gases were extracted through the suction port into the pump and transferred into the gas bag. Size of the tedlar gas bag was 1 l and the pump flow rate was relatively high therefore the gas bag will be filled in couples of seconds. When the welding operator begins welding the tube is held by his other hand to ensure that it's the maximum distance of extraction, as the fumes starts to emit in the atmosphere the tube attached to the outlet was slowly inserted in the gas bag allowing the gases to be transferred in the bag. A high flow rate pump was used due to limitations. Another extraction method was by using a 20ml plastic syringe being as close to the welding pool as possible roughly 10cm away and slowly sucking in the gases. Both methods are considered efficient and have been applied before in several experiments reported to be successful. Although if the flow rate was decreased to 0.01-0.05 $lmin^{-1}$ and the time rate was increased the experimental process could be more efficient and reliable, but this will not ensure that results will be obtained in the same GC will be different.

As a result, sampling and analytical method could be more efficient if following any reliable method such as OSHA which briefly explains the whole experimental and analytical procedure.

6.2 Welding Aerosol

Welding aerosol generation rate depends on several factors. The welding process is the main factor that determines the fume formation rate. The welded material could also have a great impact on determining amount of fumes generated. The health concern associated with welding particulates could increase depending on the particle size classification and the morphology. Our results have shown particle size distribution was as small as 25 nm and as fine as 45 um. Nanoparticles (<100 nm) was shown in several studies to have the highest concern on health as nanoparticles are easily respirable and can penetrate easily in the lungs. According to our results the distance and the flow rate of the sampling procedure had an influence on the type of metals being extracted, particle size distribution, and particles morphology.

6.2.1 Particle size distribution and morphology

6.2.1.1 Health concerns

The particle size distribution and morphology could be effected by several factors. The welding process and its parameters such as the amperage and the voltage could be one of those factors. The welding rod and its characteristics and parameters as well. The welding rod diameter or thickness could have an impact on particle sizes and morphology as the diameter increase more amperage is required to melt the welding rod. The welding material is as well considered one of the factors that determine the size and morphology of the particles, all materials have a melting point which varies depending on the alloys and the material itself. Materials with higher melting point requires an increased temperature to reach that melting point causing more nanoparticles to be produced. The effect of the welding fumes is known to be determined form the size distribution of the particles and the morphological state. As the particle size becomes less than 100 nm its toxicity increases.

According to several studies nanoparticles are more harmful and toxic to human health than larger particles. Nanoparticles are also named respirable particles they can deeply penetrate inside the respiratory system and easily enter the blood stream. According to a study it was shown that the higher amounts of nanoparticles are released by the process in which higher energy intensities are used. The level of intensity required for welding depends mainly on the welding application and the welding material. Another study was carried out to determine the effect of temperature on the particles size distribution, the results have shown that with an increase in the shielding gas temperature less welding fumes will be generated and more nanoparticles will be formed. The study also have shown that particles will be formed into chainlike agglomerates. What was concluded from the study is as the temperature increase particles will decrease in size and welding fume generation will be less.

In figure 19, 20, 21 where the filters contained aerosol from a welded mild steel, stainless steel, and a cast iron rod and the welding process was SMAW nanoparticles were only detected when mild steel rod was welded. Particles were shown to be formed mostly in chainlike agglomerates. Welded mild steel rod was shown to have more nanoparticles with smaller sizes in the sampled filters this could be a result of the increased temperature that have been applied on the welding rod. Although all three rods had the same diameter, nanoparticles were only formed when a mild steel rod was welded this is due to the characteristics of the welding rod. The mild steel rod requires the highest current among the other two therefore smaller particles were detected. Mild steel rod in the SMAW application is considered the most toxic due to the size of the particles being emitted.

Figure 12, 13, and 14 where the filters contained aerosol from welded mild steel, stainless steel, and aluminium rods and the welding process was TIG the effect of temperature in aerosol size was shown to be true. The figures have shown that only aluminium and stainless steel rods generated nanoparticles. However all three welding rods generated coarse particles ranging from 30 um – 45 um and the largest particle that was detected for stainless steel was 35 um. Stainless steel rods requires the highest temperature to reach its melting point, although aluminium requires the least melting point of the three materials nanoparticles were only generated due to the diameter of the rod which was the greatest of all three rods. Therefore aluminium was shown to contain more nanoparticles and form in larger chains which is considered the most harmful to human health. Whereas mild steel could be considered the least toxic of those three materials.

In figure 18 where the process was OXY welding the results could also confirm the impact of temperature on the sizes of the welding aerosol. As was stated before that stainless steel rods require the highest melting point the size distribution of the generated particles was from 65 nm – 5 um whereas mild steel consisted of particle size distribution of 145 nm – 5 um. Both are considered harmful due to the particle size distribution and the morphology but mild steel is considered less toxic.

In figure 22 and referring to other figures as well where mild steel rods were welded using the four welding processes several aerosol size range was detected. TIG welding no nanoparticles were detected and less particles were detected forming in chainlike agglomerates. Whereas during MIG welding particle size was relatively smaller ranging from 25 nm - 10 um and mostly forming in chainlike agglomerates. In OXY welding particle size distribution was ranging from 145 nm – 5 um and particles were detected to be formed in chains. Nanoparticles were also generated during SMAW process the particle size distribution was 60 nm – 10 um. In all processes the particle were spotted forming in chainlike agglomerates with a relatively smaller chains. In terms of the toxicity MIG welding was considered the most toxic due to the size distribution of the particles. SMAW is harmful as well due to the nanoparticles that were generated but not as harmful as MIG. TIG welding is also measured to be the least toxic of those four processes.

Figure 23 and referring to other figures where stainless steel rods were welded using TIG, OXY, and SMAW welding process nanoparticles were generated during TIG and OXY only. The particle size distribution was shown to be smaller sizes for OXY compared to TIG. As TIG and OXY welding rods were identical therefore the welding aerosol emission was relatively the same in size. In all three processes the particles were detected to be formed in chainlike agglomerates. However it has been determined that the most harmful process in terms of particle size distribution is OXY, and SMAW is the least harmful on health.

6.2.1.2 Effects of the Distance of extraction and the flow rate

The distance of extraction and the flow rate is of high significance to determine the aerosol size distribution and morphology precisely. Based on a study it was concluded that as the distance toward the welding arc decreases particles will be distributed in smaller sizes.

In our case the distance of sampling was 20 cm and 37 cm away from the welding arc. The results that were shown were relatively similar in both distances, however the samples mounted at the shorter distance consisted of smaller particles in some welding processes. In figure 20 and 21 the sampling results have shown that particle sizes were greater when the distance increased. Figure 19 where the distance was 37 cm away particle size range was 0.5 um – 15 um for welded mild steel and stainless steel and 0.75 um – 25 um for cast iron. Whereas In figure 20 where the distance was 20 cm away from the welding arc particle size range was 85 nm – 10 um for mild steel, 0.25 um – 10 um for stainless steel, and 0.25 um – 25 um for cast iron. In SMAW process particle size distribution in both distances was roughly similar, although as the sampling distance was decreased smaller particles were present and more particles were formed in chainlike agglomerates.

Figure 17 and 18 also present the same results as the sampling distance range was decreased smaller particles were present. In figure 16 mild steel and stainless steel consisted of particle size distribution of 0.25 um – 10 um. In figure 17 stainless steel also consisted of the same size distribution of 0.25 um – 10 um, however mild steel consisted of a size distribution of 65 nm – 10 um.

Figure 15 where mild steel was the welded rod and MIG was the welding process the particle size distribution was shown to be smaller as the sampling range was decreased. In distance 1 where the sampling was mounted 37 cm away from the welding arc the size distribution was 75 nm – 10 um. Whereas in distance 2 welding aerosol size was 50 nm – 10 um.

In figure 12 and 13 where TIG was the welding process the particle size distribution was the same in both distances. However nanoparticles were detected in distance 2 only when the aluminium rod was welded.

The level of extraction in terms of the flow rate have shown similar particle distribution range and morphology in most of the processes. The flow rate was 15 l/min and a relatively high flow rate operating by two different pumps. In most cases no change have been detected as the flow rate was varied the particle size distribution was the same, however fume generation rate was relatively higher more particles were detected in the filters when analysed. In figure 20 and 21 where SMAW was the welding process particle size distribution was the same , except when mild steel was welded nanoparticles were spotted during both flows in flow 1 particle size range was 85 nm – 10 um and flow 2 60 nm – 5 um.

In figure 17 and 18 when OXY was the welding process particle size range was similar for stainless steel and mild steel. However MIG welding consisted of smaller particles when sampling was operating at a higher flow, flow 1 50 nm – 10 um flow 2 25 nm – 10 um shown in figure 15. In figure 13 and 14 when TIG was the welding process nanoparticles were only detected when sampling was operating on a high flow for stainless steel, but nanoparticles were detected in both flow rates for aluminium. The morphology was not affected by the flow rate, except larger chains were created as the sampling was operating on a higher flow in mostly all processes.

6.2.2 Elemental Composition

The elemental composition should be clearly considered to understand the risk of the welding fumes. The welding fumes are mainly affected by the welding process and the material being welded. The properties of the emitted fumes in terms of the acidity or the chemical properties that might form through oxidation is also influenced by the metal itself. Some metals were shown to cause direct effects on the health such as skin irritation, and some were considered extremely severe when exceeding the permissible exposure limit.

6.2.2.1 Sampling Distance and Sampling Flow rate

The sampling distance and the flow rate was shown to contribute in the elemental composition of the extracted fumes in a sample. In all four processes as the distance was decreased and flow rate was increased more elements were detected. In distance 1 when the sampling was 37 cm away from the welding arc the only metals that were detected were carbon, oxygen, magnesium, and silicon shown in figure 29. However as the distance was decreased to 20 cm form the welding arc chromium and chlorine were present shown in figure 30. In figure 32 distance 1 carbon, oxygen, and less than 2% of chlorine were detected. Whereas more elements such as iron, manganese, silicon, and chlorine with a higher percentage were spotted when the distance to the arc was decreased. In the other two processes shown in figures 33, 34, 35, and 36 more elements were present when the distance was decreased and the only elements that were present at distance 1 were oxygen, carbon, silicon, and magnesium. The result of only having carbon, oxygen, silicon, and magnesium could be due to the distance of extraction and the atomic weight of the elements. As carbon and oxygen were present in all filters in high concentrations and considering the molar weight of carbon which is 12.0107 g/mol and oxygen 15.99 g/mol relative to silicon 28.0855 g/mol and magnesium 24.305 g/mol which were also present in a lower concentration which could be determined is that as the distance to the arc increase particles with a lower molar mass will be present. Moreover in distance 2 particles with a greater molar mass were present therefore which could be concluded is as the sampling distance decrease particles with a greater molar mass will be present in the sampling filters.

The flow rate effect on the elemental composition was not clearly shown in the results. In some processes as the flow rate was increased same elements were detected with higher concentrations, other cases have shown same elements and less concentrations, and in one process more elements were detected as the flow rate was increased. In figure 32 when

MIG welding was the welding process more manganese and oxygen were detected, less carbon and chlorine, and the same percentage of iron. However in figure 30 and 31 where TIG was the welding process aluminium, silicon, and manganese were only spotted when the flow rate was high. In OXY welding iron and nickel were present, chlorine concentration was higher, and manganese and nitrogen were not found when the flow was increased presented in figure 34 and 35. In SMAW welding new elements were spotted, some elements concentration was shown to be less, and other elements were shown to have a higher concentration when the sampling flow rate was increases. The effect of the flow rate could not be determined as the graphs have shown different results in each welding process and material used.

6.2.2.2 Elemental composition and mass concentration health concern

The health concern of elements can vary depending on the element itself, the overall permissible exposure limit was measured to be from 1 - 5 mg/m^3 of the total welding fumes. The elemental composition mainly depends on the welding process and material being welded. The risk of the welding fumes depends on both the elemental composition and the concentration of the fumes. The common chemical hazards of welding aerosol include particulates such as lead, nickel, zinc, iron oxide, copper, cadmium, fluorides, magnesium, and chromium. Those particles are considered extremely toxic in acute or chronic levels of exposure.

In figure 37 when SMAW was the welding process the elemental composition of particulates emitted when a mild steel rod was welded contained the highest amount of iron which might result in iron oxidation due to the high percentage of iron and oxygen relative to other elements. Whereas cast iron aerosol contained a low percentage of iron which was 8.41% and stainless steel aerosol was not detected to contain iron. Magnesium was also present in the highest percentage when mild steel aerosol was analysed. However chromium, magnesium, and fluorine were detected in values less than 1% when cast iron aerosol was analysed. Whereas only fluorine was present when stainless steel aerosol was analysed. Therefore, it could be stated that mild steel is the most harmful on human health with an increase in the exposure level.

In figure 34 and 35 when OXY was the welding process and mild steel and stainless were the materials welded stainless steel could be considered more toxic to human health in terms of the elemental composition. Both sampling filters contained iron in the same concentration, however the stainless steel rod only contained chromium and nickel which was shown to cause serious health issues with an increase in the exposure level.

In figure 30 and 31 when a mild steel, a stainless steel, and an aluminium rod were welded using TIG welding magnesium was present in all three sampling filters, however stainless steel was shown to contain the highest concentration of magnesium. Moreover chromium was only detected in stainless steel welding aerosol. Therefore stainless steel rods under TIG welding could be determined to be the most toxic.

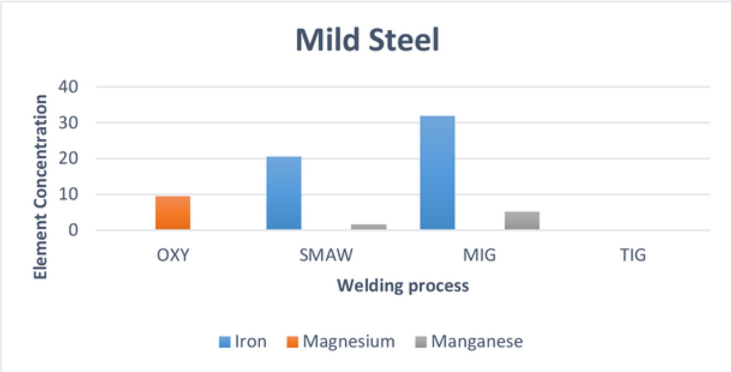

Figure 39: EDX analysis to determine the percentage of iron, magnesium, and manganese when a mild steel rod was welded using the four welding processes

The above figure shows the percentage of iron, magnesium, and manganese when mild steel rods were welded to determine the process which is less harmful in the elemental composition. Aerosol from MIG welding contained the highest amount of iron compared to SMAW process, however only aerosol from OXY welding contained magnesium. Therefore the level of harm could be determined from the high percentage of iron as the ratio of iron could determine the possibility of the formation of iron oxide. Therefore MIG welding could be considered the most harmful as it contained two of the elements shown in NIOSH and OSHA standard in a relatively high percentages. Ultimately, TIG welding is considered the least toxic when welding a mild steel rod as the welding fumes generated did not contain any of the chemical hazard elements that were mentioned earlier.

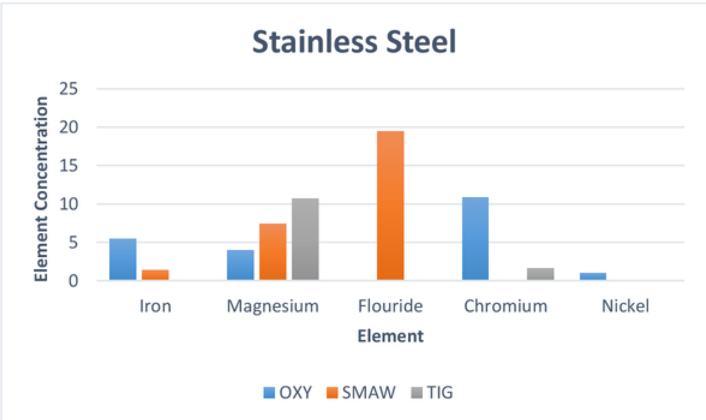

Figure 40: EDX analysis to determine the percentage of iron, magnesium, fluoride, chromium, and nickel when a Stainless steel rod was welded using the three welding processes

The above figure shows the percentage of iron, magnesium, fluoride, chromium, and nickel found in the welding aerosol of welded stainless steel rods using the three welding processes. The five elements shown in the graph are considered the most harmful elements when exceeding the permissible limit. According to the permissible exposure limit standard by NIOSH and OSHA elements such as nickel and chromium (VI) are considered A1 in the level of carcinogenicity (level A1 means definitely carcinogenic to humans). Chromium (VI) formation is a result of the exposure to high temperatures such as welding a stainless steel rod which already contains chromium. Therefore OXY welding could be considered the most harmful as it contained two level A1 carcinogenicity substances. Whereas SMAW was shown to be the least toxic although it contained a high percentage of fluoride and magnesium as those two elements were not shown in OSHA and NIOSH standard of permissible exposure limit table.

Due to the short term sampling the permissible exposure limit was not reached in any of the welding processes. The highest mass concentration value that was reached consisted of 0.85 mg/^3. Therefore the health concern could not be determined due to the short sampling duration, although based on other studies the effect of time on the aerosol generation rate will allow us to determine the most process in fume generation. Although the mass concentration rate measured in our experiment was shown to be high relative to the one shown in the literature review, this could possibly be due to the high flow rate that was operating in our sampling procedure. As the distance of sampling was decreased according to the study shown in the literature review the mass concentration will increase due to large particles which are also called spatter particles [40]. Faults were present when trying to calculate the mass concentration in the filters when the distance to the arc was decreased. To determine the mass concentration cassettes containing the filters are weighed before and after sampling. After sampling the cassettes were shown to contain less mass, a clear reason was not found for this fault.

Chapter 7

7 Conclusion

Welding is a highly required process in industries all around the globe. The health hazards associated with welding could lead to extremely adverse effects on humans. The welding process and the material being welded could be a major key to determine the level of harm. As the risk of welding could be effected by parameters such as the current, volt, and melting points of the welded materials. Analysing and sampling welding particles and gases in proper ways will allow us to determine the level of concern precisely. The physical and chemical properties of the welding particulates should be clearly understood to assess the risk properly. Following a permissible exposure limit standard such as NIOSH and OSHA is of high significance to measure the level of harm in terms of the elemental composition of the welding particles.

The aim of this project is the assessment of welding fumes and gases through proper control methods. Therefore welding fumes and gases were extracted and analysed through proper techniques. The analysed results were documented clearly and properly to allow us to determine the health concern associated with each welding process and welding material. The health risk for each process and material was also shown to measure the level of harm. The evolution of the extraction distance and flow rate on the particle size distribution and morphology was also covered and shown clearly in the results.

After analysing the fumes to determine the particle size distribution and elemental composition the level of harm could be determined. Welding a mild steel rod through TIG welding was shown to contain the least toxic effects on human. After analysing the filters contained aerosol form a welded mild steel rod the particle size range was above 0.1 um which is considered less toxic and the elemental composition have shown none of the elements that were shown in NIOSH and OSHA permissible exposure limit standard table. Whereas stainless steel rods under SMAW process was determined to be the least harmful among the other two processes. Under SMAW process no nanoparticles were spotted when analysing the filter containing stainless steel aerosol and the elemental composition contained none of the elements that were shown in NIOSH and OSHA table.

Gases were not detected in all the welding processes. GC was used to analyse the gases and determine their concentrations in a sample. A possible reason that gases were not detected was either the high detection limit of the GC or the sampling technique. The sampling was carried on following OSHA standard for welding gases extraction the only alteration was with the flow rate where it was significantly higher in our sampling process due to the limitations. Moreover another sampling technique was used to ensure the extraction of gases. However no gases were detected in the GC, therefore welding gases in our experiment could be considered safe as it have not exceeded or reached the lowest detection limit.

Ultimately, a recommendation of the least harmful process and material to use was given earlier. However the personal protective equipment must be worn at all times and a local exhaust system should also be turned on to reduce the harm of the welding fumes on the welder and workers in the workplace. All elements and gases exposure limits should be well considered prior to performing any welding operation. As the harms of the fumes could be as minor as metal fever or irritation and as high as cancer or death.

Chapter 8

8 Future Work

The data in this project could be used as a baseline for other experiments. In further experiments it is more recommended to follow OSHA methods and techniques for sampling precisely. OSHA methods were not followed due to the limitations as the pump that was used for particulate extraction operated on a constant flow rate of 15 l/min whereas OSHA recommends a flow rate below 3.5 l/min. Furthermore the limitations were also present in the gas extraction method where a dual pump was required to allow the gases to be sucked in from the inlet port and released to the gas bag from the outlet port. OSHA recommends for gas extraction a flow rate of 1 l/min whereas the pump that was used operated on a significantly higher flow rate. For the gas analysis it is more recommended to use a gas chromatograph mass spectrometry (GC/MS) it is simply an instrumental technique compromising a gas chromatograph coupled with a mass spectrometer which is more sensitive to gases than the GC.

It is of high significance to determine the exact value of each element in the samples collected for a more accurate measurement of the risk associated. Due to time limitation we were not able to fulfil this step in this project although it is of great concern. The elemental concentration could be determined by several analytical techniques that are shown in the following table:

Table 11: Frequently used analytical methods for workplace measurement of metals. [30]

Method	Analytical technique
Atomic absorption spectroscopy (AAS)	Flame and graphite furnace methods (electrothermal atomic absorption spectrometry, ET-AAS) Hydride technique Cold vapour technique
Atomic emission spectrometry (AES)	Inductively-coupled plasma optical emission spectrometry (ICP-OES) Inductively-coupled plasma mass spectrometry (ICP-MS)
Atomic fluorescence spectrometry (AFS)	
X-ray fluorescence analysis (XRF)	Energy dispersive Wavelength dispersive Total reflection
Spectrophotometry (UV/VIS)	
Liquid chromatography (LC)	Ion chromatography (IC) High Performance Liquid Chromatography (HPLC)

Some requirements should also be met prior to analysing the elemental concentration. The substance in the filters must be diluted and brought into a solution. One reaction vessel should be used to contain the solution through all working steps. Multi-stage digestion and combined methods must be avoided. To avoid interference during measurement concentration of contamination salts in the digestion solution should be kept low. Contamination should be reduced or avoided [30]

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Consultation meeting form

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	~~28~~ 4-08-17	• Clearing any doubts	salman	[illegible]
2	8-08-17	• methods of extracting fumes	salman	[illegible]
3	15-08-17	• Analysing equipments and strategies	salman	[illegible]
4	22-08-17	• Purchase order confirmation	salman	[illegible]
5	29-08-17	• Progress report	salman	[illegible]
6	05-09-17	•	salman	[illegible]
7	03-10-17	• Finalising experimental ~~Techniques~~ Methods	salman	[illegible]
8	10-10-17	• experimental results	salman	[illegible]
9	17-10-17	• experimental results	salman	[illegible]
10	24-10-17	• Experimental results	salman	[illegible]
11	31-10-17	• Finalising the Project	salman	[illegible]