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Total Fume Emissions and Emission Factors Applicable to Gas Metal Arc Welding

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This thesis is dedicated to my dear parents, Mr. Carlos Oliveira de Souza and Mrs. Maria Alice Regina de Souza who has always loved me unconditionally and whose good examples have guided me to work hard for the things that I desire to achieve. I also dedicate this thesis to my brother Lucas de Souza and my fiancé Victor Hugo Bezerra Gomes, for the constant support and encouragement. I am very thankful for having you all in my life.

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Abstract

Welding is a common industrial practice that has the potential to emit air pollutants. Emission factors are useful indicators to help in the understanding of the extent of pollution from a process and managing them to reduce or minimize health impacts. The objective of this thesis is to determine emission factors applicable to the gas metal arc welding (GMAW), under varying current and voltage conditions. The most used base metals and an electrode for the shipbuilding industry were considered. A weld fume chamber was used to achieve the project goals along with standard sampling and analytical procedures. Three test runs were performed for each sampling scenario to ensure repeatability. The EPA EF average for MS experiments with the ER70S-6 electrode is 5.2 g/kg, and for SS experiments with the ER316L-Si electrode is 3.2 g/kg, while the average results for this study were 6.81 g/kg and 3.28 g/kg respectively.

Keywords: Gas metal arc welding, fume emissions, emission factors, shipbuilding industry.

1. Introduction

Welding is an essential component in many industrial processes, requiring trained and specialized labor (American Welding Society, 2018). In the United States, an employment survey indicated that about 382,730 people employed as welders, solderers, and brazers in 2016 (United States department labor, 2017). Welding applications include the manufacture of machines, construction, shipbuilding, offshore platforms, pipelines, pressure vessels, the automotive industry, defense industry, railway industry, and aviation and aeronautical industry.

The concept of welding emerged as "forge welding" during the Bronze Age, consisting of a rudimentary way to joining metals with a flame to heat metal to extremely high temperatures and hammering each piece together until they became one. However, only in the 19th century, the modern welding was invented, and with the second industrial revolution, more sophisticated welding techniques started to be used in different industries sectors (AWS, 2018). In the shipbuilding industry, where shipping represents over 90% of total trade in the world, activities for joining metals and create vessels are essential to the economy (IMO, 2017). Before the 19th century, the construction of ships used to be made by clinch joint. However, nowadays the welding process is more utilized because it has better water resistant than the clinch technique (Turan and Koçal, 2011).

The welding was also essential for the economy in the 1940s during World War II. After the Pearl Harbor attack, thousands of men left their welding jobs to fight for the United States across the sea. However, ships, vehicles and other factory items still needed to be built, and those jobs were filled by the women that learned all those construction techniques to support their country (American Welding Society, 2018). The shipbuilding industry was very productive during the war were 2710 Liberty ships, 531 Victory ships, and 525 T-2 tankers were built.

Although welding is a significant economic activity, it can emit toxic fumes that can contaminate the workspace environment, creating a hazardous ambient to the workplace. Welding fumes can also pollute the surrounding air quality, resulting in a public health concern as well. In Figure 1, a welder is working, and it is possible to see the fumes created by this activity.

Figure 1: Welder and emission fumes

Source: U.S. Navy photo, 2009

In the shipbuilding industry, welding is pointed out to be one of the most important emission sources during the manufacturing process. Moreover, welding activity was also classified as a possible carcinogenic and has gained increasing attention as a high priority risk assessment nowadays (Krishnaraj et al., 2017). Welders may work in confined spaces with poor ventilation inside the shipyards, exposed to many hazardous airborne contaminants (Mert and Ekinci 2017), as presented in Table 1.

Table 1: Welding hazardous

Metal fumes	Toxic gases	Radiation
Chromium (Cr)	Carbon monoxide (CO)	Ultraviolet
Hexavalent chromium (Cr (VI))	Ozone (O_3)	Infrared radiation
Manganese (Mn)		
Nickel (Ni)		
Lead (Pb)		

Any material is a potential source of fume when heated to high temperatures. The process of heating the base metal with the electrode above its boiling point can evaporate part of those components to the atmosphere. The welding fume is a result of the condensation of the gases and vapor mixture created during the welding (Voitkevich, 1995). Those fumes are composed by a complex micron and sub-micron size mixture of fine solid metal particles that may contain metallic oxides, silicates, and fluorides. Those particles will be suspended in the air until some eventual force (air movement, gravity, or some electrical fields) will settle them down.

The suspended particles in the atmosphere can be easily inhaled and can penetrate deeply into the respiratory tract, being carried inside to inner parts of the lungs, causing severe damage to the body (Krishnaraj et al., 2017). If the welders have been exposed to those particles over time, it can be extremely harmful to their health, causing severe respiratory, neurological, and reproductive damage to their organism. Knowing how to decrease and control the emission levels of welding fumes by selecting the right process parameters and operating conditions can be very useful for the workers at workplace. For this reason, accurate fume formation data is necessary to understand better the welding mechanisms that can reduce the fume emissions, to create a more sophisticated fume control strategy.

This research intends to measure and quantify the welding emissions for GMAW utilizing the two most widely used base metals in the shipbuilding industry viz., mild steel (AH36), and stainless steel (316L), playing with the most significant process parameters and operating conditions in the fume formation. A weld fume chamber following the AWS F1.2:2013 standard was used to achieve the project goals, and several tests runs were performed for each test scenario to check the repeatability of the results. The findings of this work can be used by:

- The maritime industry and other industries in their environmental decision-making and emission inventories.
- The EPA to update the AP42 emission factors inventory.
- The public health experts to develop more sophisticated techniques for emission control strategies, and health risk assessment.
- Further researches.

2. Objectives

The primary objective of this study is to understand the particulate EFs applicable to GMAW, which is a commonly used welding process in maritime and other heavy industries under various process conditions.

The specific objectives of the research are to compute the following variables applicable to GMAW on mild steel as well as stainless steel using different process parameters and operational conditions in an adapted weld fume chamber appropriate for this study. Combinations to be studied included:

(a) Fume formation rate (g/min)

(b) Total fume emission factor (g/kg of electrode consumed)

3. Literature Review

3.1 Welding Process

Metals have excellent mechanical properties when compared to other materials; they are hard tough, strong and durable (Shackelford et al., 2016). Therefore, techniques like welding are immensely used in industries to join metal pieces. To create a weld, it is necessary a base metal and a source of heat. The filler metal and the use of pressure are implemented sometimes to reinforce the join; however, they are optional (Turan and Koçal, 2011). The fusion technique is what makes welding different from brazing or soldering, as shown in Figure 2. In the brazing and soldering process, the heat can only melt the filler metal, and in the fusion process, the heat and pressure are enough to melt the filler metal and the base metal, making them become a single piece.

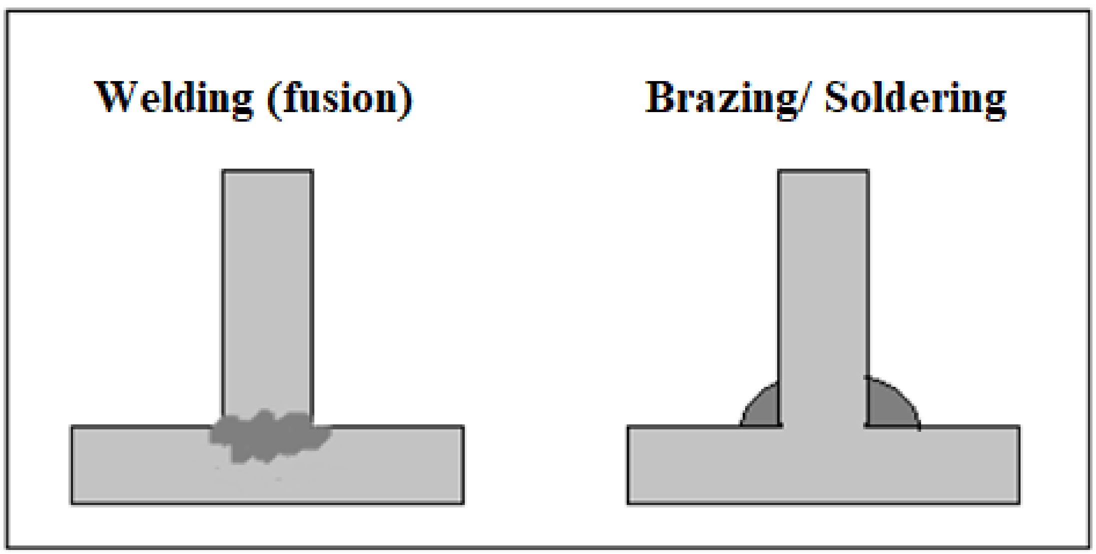

Figure 2: Welding and soldering/brazing technique

For an adequate welding fusion, it is essential to have heat and atmosphere protection (Phillips, 2016). The heat melts the welded metal pieces, and the shielding gas works as a shelter to protect the metals from atmosphere contamination, as shown in Figure 3. The principal atmosphere contaminations are:

- Nitrogen: In solidified steel, the nitrogen can reduce the ductility and cause an impact in the strength of the weld. It can also cause cracking and porosity in the weld.
- Oxygen: The oxygen combines with carbon in steel to form carbon monoxide (CO). This

gas can be trapped in the metal, causing porosity.

- Hydrogen: When hydrogen, present in water vapor and oil, combines with either iron or aluminum, it can cause porosity and cracking may occur in the weld.

The shielding gas is not mandatory; however, it will guarantee a better quality of the weld since the impurities present in the air can oxidize the metals and compromise the weld fusion (Phillips, 2016). For this reason, it is recommended to use shielding gas in welding activities.

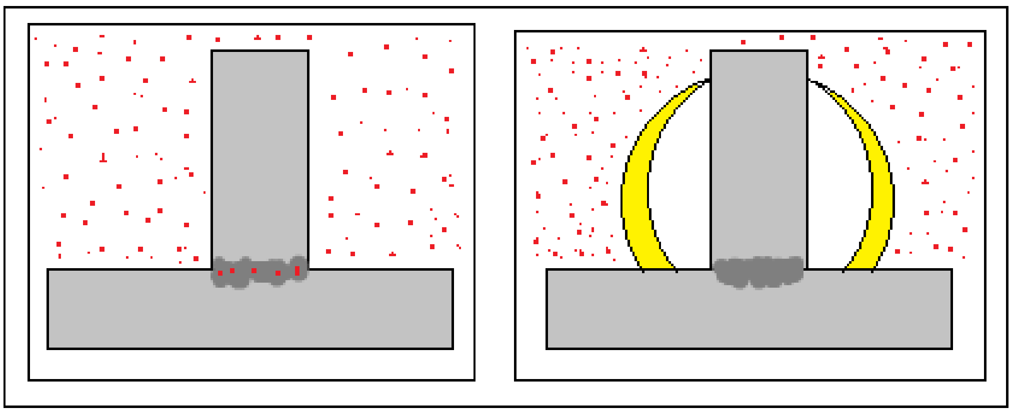

Figure 3: Shielding gas weld protection from atmospheric contaminants

Welding is a unique tool that can work in different locations, including underwater. The welding techniques mostly differ from each other by the type of equipment, heat performance, the pressure applied, and the filler metal used (Turan and Koçal, 2011). According to AWS, there are 80 welding techniques registered in the world, and there is more than one factor that can influence in the decision of which one to choose for specific work (Villaume et al., 1979). In the shipbuilding industry, for example, electric arc welding is the most widely used type of welding technique (OSHA, 2018).

3.2 Gas Metal Arc Welding

Arc welding is a popular welding method due to the high electrode efficiencies, high deposition rate, low cost, and high versatility. According to AWS (2018), the most popular welding process today are*:*

- 45% shielded metal arc welding (SMAW)
- 34% GMAW
- 17% flux core arc welding (FCAW)

In the shipbuilding industry, the most common arc welding methods used currently are the SMAW, GMAW, submerged arc welding, and plasma arc welding (Mert and Ekinci, 2017). They are classified as "arc welding" because an electrical current is used to melt and join the metals. It can create an arc plasma between the feed wire and a workpiece, which gives an arch-like appearance (Dos Santos et al., 2017). The welding arc area is very complex and has many physical and chemical reactions that can influence the metal transfer and the quality of the weld (Armao, 2014).

The GMAW, also known as MIG (Metal Inert Gas) welding, is typically used for most types of metal and it is a popular arc welding technique used in the shipbuilding industry (Kou, 2003). Due to the importance of this technique for this industry sector, this thesis designed all the experiments using the GMAW process. Figure 4 shows the GMAW equipment and Table 2 demonstrated its advantages and limitations.

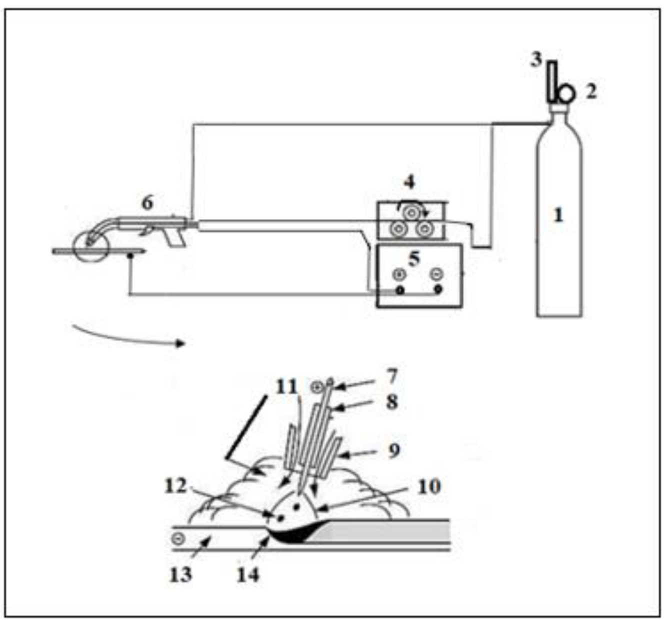

Figure 4: Schematic presentation of GMAW

Source: Adapted from Kou, 2003.

Where: (1) cylinder, (2) regulator, (3) flow meter, (4) wire control, (5) power source, (6) welding gun, (7) wire electrode, (8) contact tube, (9) shielding gas nozzle, (10) welding arc, (11) shielding gas, (12) metal droplet, (13) base metal, (14) weld pool.

In the GMAW process, there is a creation of an electric arc between the base metal and the consumable electrode. The consumable electrode is continually fed into the arc, and it is responsible for conducting the current through the workpiece. The arc melts the electrode and the base metal, allowing them to fuse into a weld. A reel supplies the wire by the drive rollers, pushing the wire through a flexible conduit in the hose package to the gun. The electrical energy necessary for the arc passes to the electrode through the contact tube in the welding gun. The electricity only passes in the wire when the operator squeezes the trigger on the top of the gun, and it is de-energized when the trigger is released, for safety purpose. Furthermore, the gas nozzle that surrounds the contact tube supplies shielding gas to protect the arc and the weld pool from the atmosphere contaminants (Weman, 2011). For GMAW, the shielding comes from an inert gas, usually a mixture of argon and carbon dioxide, that surrounds the arc during the welding (Pires et. al., 2007).

Table 2: GMAW advantages and limitations

Advantages	Limitations
Low cost	Sensitive to atmosphere contaminants
High electrode efficiencies and deposition rates	Low portability
Easy to clean and use	Wind sensitive
Less welding fumes emission	Ultraviolet (UV) rays exposure

3.3 Principle of Operation

In the GMAW operation process, the feed wire deposit into the weld pool in the form of liquid droplets. The mode of droplet transport depends on welding conditions, especially the welding current and the arc voltage (Weman, 2011; Kou, 2003; Pires at. all, 2007). The three significant modes that exist in GMAW are the short-circuit transfer, globular transfer, and spray transfer (Figure 5).

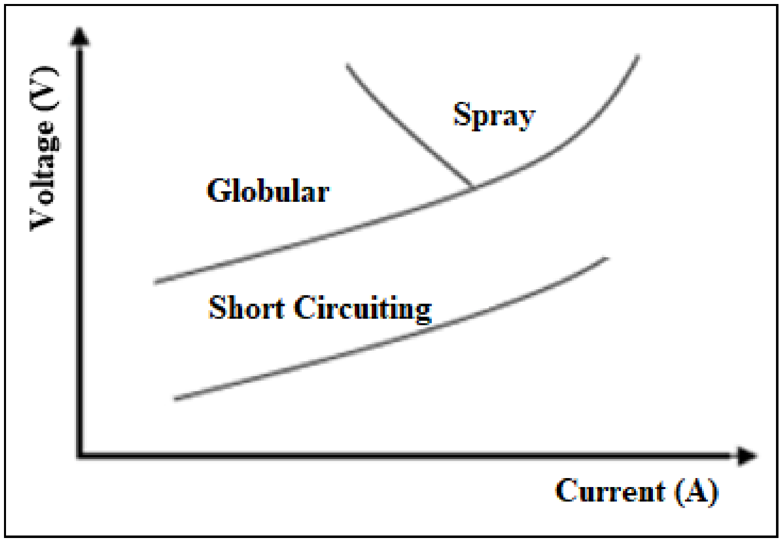

Figure 5: Welding modes

Source: Adapted from Weman, K., 2011.

When a low welding current and low arc voltage are selected in the welding process, the short-circuit transfer occurs at rates of 50 per second (Kou, 2003). This type of metal transfer has the lowest cost when compared to the other modes; it can weld thin materials and operate in any position. The negative point of this mode is that it can produce a lot of spatters and, due to the low current, incomplete fusion might occur.

In the globular transfer mode, where a large liquid droplet appears at the tip of the electrode, the current should be above 200A to indicate a globular arc or spray arc mode (Jones, Eagar, and Lang, 1998). The droplet size is approximately three times the wire diameter, and it uses gravity to do the metal transfer. This mode has higher deposition rates. However, professional welders usually avoid this mode because it can create some spatters, uses more material than necessary, and it can only operate in a horizontal or flat position.

In the spray mode, the small discrete droplets are present, an argon-rich shielding gas is typically used, and the current travel across the arc at a much higher frequency than in the other modes (Jones, Eagar, and Lang, 1998). This transfer mode is stable, and the welding current and the arc voltage are at such a high level that the heat input is relatively high. Furthermore, with high current, it is possible to achieve better penetration in the base metal. In the spray mode, there is no spatters,

and the beads appearance are excellent. However, it can only operate in a horizontal or flat position, and because of the high current, it is not appropriate for thin metals. It is common to use of argon or argon-helium gas mixture for this mode, and base metals like aluminum, titanium, or magnesium.

Different components can influence the metal transfer modes, droplet size, spatter and fume formation (Gomes et al., 2014). According to Pires et al. (2007), the fume formation rate is low for short circuit transfer mode and increase for globular and spray transfer modes, due to increment in the arc temperature and instability. However, this relationship is not entirely clear because this increase is not wholly linear (Castles and French, 1995). There are still some debates in the literature about fume formation mechanisms, and a more in-depth debate about it is present in this thesis discussion.

3.3.1 Weld Bead

A good welding activity produces less spatters, and the top of the bead is not overly high, which suggests a good penetration. Figure 6 and Figure 7 summaries the observations below about welding variables.

- Welding feed speed (WFS): WFS controls penetration and current range. When a very high wire feed speed occurs, it tends to produce high current, some spatter, and a high-crowned bead. When a lower wire feed speed happens, it tends to produce low current, small beads, a lot of spatters, and sometimes inadequate fusion. Inside any welding machine, there is a recommended chart with the WFS and the corresponded voltage for the most used base metals. It is suggested to follow the machine instructions for not waste material and get the right penetration with the proper bead profile.
- Contact to the work distance (CTWD): If the CTWD increase at a constant voltage level, there will be more resistance to the flow of electricity through the electrode, which can increase the resistance, decrease the current and consequently the penetration level. If the CTWD decrease, the resistance will also decrease, and the current and penetration will increase.

- Travel Speed: How fast the electrode travels to the joint can affects how much time the arc energy is transfer into the base metal to a specific point along the joint. With an increase in the travel speed, less material is deposit to the join, resulting in a low penetration level. As travel speed decreases, the penetration increases.
- Voltage: Voltage has a considerable influence in the bead shape (with a higher voltage, the bead will be flatter) and some impact in the heat input (an increase in the voltage can increase the heat input). As shown in Figure 7, high voltage produces excessive spatter, and the bead is irregular, much wider and flatter. A low voltage shows some spatters, very poor penetration and the bead is thinner and elevated. Voltage can change the shape of the weld bead from narrow to wider.
- Shielding gas: The shielding gas is not mandatory; however, it will guarantee a better quality of the weld since the impurities present in the air can oxidize the metals and compromise the weld fusion.

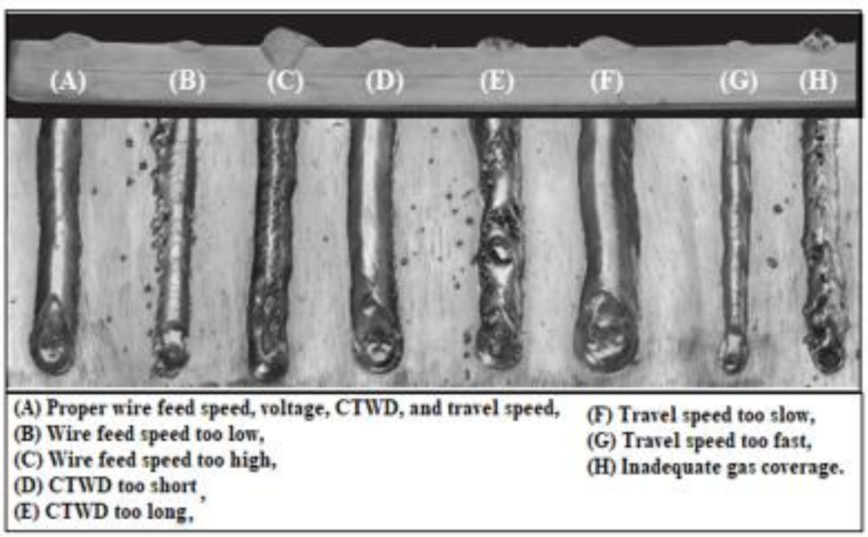

Figure 6: Effects on welding variables

Source: adapted from Lincoln electric, 2018

Figure 7: Effects on voltage variations

3.4 The Influence in the Process Parameters and Operating Conditions in the Welding Fumes

The fume formation in the welding activity can change with variations in the process parameters and operating conditions. The reduction of fume emissions at the source is essential for fume control, and the magnitude of the hazard depends on the composition and concentration of the fumes and gases during the exposure time.

3.4.1 Process Parameters

3.4.1.1 Electrode

In the GMAW, a consumable electrode wire is used to conduct current through a workpiece to fuse the two pieces.

- The electrode used in the welding can mostly determine the fume composition, due to the high temperatures that it can reach the arc (Jacobs, 1995).
- The wire diameter can have a modest effect on FFR due to differences in voltage, current and possibly in the welding mode. A wire diameter of 1.2 mm (0.045 in.) is specified in the AWS standard (Pires at. all, 2007).

3.4.1.2 Base Metal

As presented in the CCOHS (2017) document, the different metal composition in the base material can also have some influence in the structure of the welding fume, for example:

- Mild steel base metal can emit fumes that contain iron in their formula.
- Stainless steels base metal can create fumes with a higher concentration of chromium and nickel and present lower amounts of iron.
- The base metal contributes less than 10% to the total fumes (Hilton, 1991).

3.4.2 Operating Conditions

3.4.2.1 Current and Wire Feed Speed

The WFS and the electrode type can determine the quantity of material being deposited in the weld pool. Moreover, an increase (or decrease) in the WFS will cause an increase (or decrease) in the current (Kou, 2003). When the electrode receives a lower current, the short-circuit mode will occur, and if a high current is applied, higher energy modes transfer like the globular and spray will happen, creating a deeper welding penetration. Current is defined as charges/ electrons released per unit area and as welding current increases (i.e., more amperage), the temperature will also increase, melting the metals and increasing the weld penetration.

- Current is pointed out by the literature to be one of the most significant operational condition that can influence the welding fume formation (Weman, 2011; Kou, 2003; Pires at. all, 2007).
- An increase in current tends to increase the FFR, as the high current produces an increment in the heat, generating more fumes (Kou, 2003). High current can also increase the ultraviolet radiation from the arc and the ozone fume formation as well.
- The welder should select the lowest current and voltage level as possible, without compromise the quality of the weld beads, to avoid extra emissions (U.S. EPA AP-42, 1994)

3.4.2.2 Voltage and Polarity

The voltage is responsible for moving the electrons from point to point and control the power source (Jenney and Brien, 2011). If the voltage is too high, the electrons will move at greater speed throw the filler metal to the base metal. Voltage can influence the amount of power input in the internal welding circuitry by supplying the appropriate amount of welding current necessary to maintain a stable arc (Lancaster, 1984). If there is no control over the current, a very high amperage rate can occur, far beyond the design parameters of the power source, which could explode the wire electrode. A "constant voltage'' supply is possible to be set in the GMAW machine to supply the necessary welding current due to the welding machine polarity (Figure 8). The polarity is the electrical connection between the electrode and the terminal of a power source that controls the electrode at the required rate (Jenney and Brien, 2011). In the GMAW it is typically used the direct current electrode positive (DCEP), which means that the positive (+) lead is connected to the torch while the negative (–) lead is connected to the workpiece. The DCEP can create a stable arc, smooth metal transfer, generated less spatters, it has an excellent weld bead characteristic and can create a deep penetration for a wide range of welding currents, producing a good weld (Wilford I Summers, 1987).

- The polarity has a directed influence in the power source which is responsible for controlling the voltage supply.
- A small change in voltage can have a substantial change in current (i.e., 2V = 100A) and can also influence the fume formation rate (Hughes, 2009).

3.4.2.3 Drag Angle and Work Angle

The working angle is the angle between the electrode and the weld joint, and the drag angle is the angle created when the top of the wire or torch follows the travel direction. In Figure 8, it is possible to visualize the drag angle and the work angle.

- The inclination of the welding torch has some influence in the weld bead (Jenney, and Brien, 2011).
- Welding close to a perpendicular angle can reduce the fume emission (U.S. EPA AP-42, 1994).

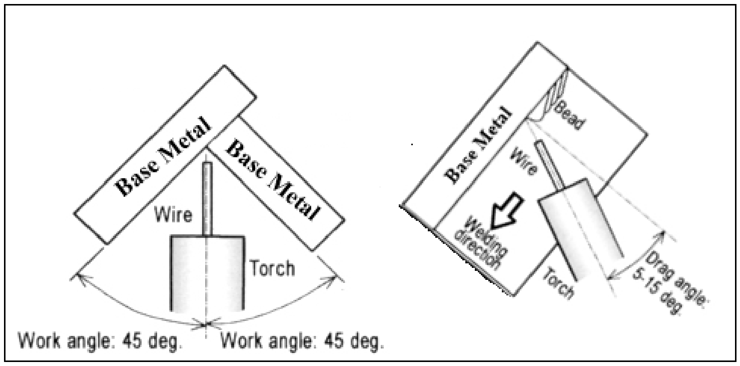

Figure 8: Drag angle and work angle

Source: Kobelco, 2019

3.4.2.4 Welding Speed and Arc Time

The welding speed, also known as travel speed, is the linear velocity at which the welding arc moves along the base metal and the arc time can determine the duration of the welding activity (Hermans, 1997). As the travel speed decreases, the amount of time that the arc is over a particular point along the joint increases and as a result, the penetration level increase (Gery, and Maropoulos, 2005).

- Changing the torch travel speed by a factor of two can decrease the fume rate by about 5% (Heile and Hill, 1975).
- Studies have shown that the arc time and severity of the exposure influences the quantity of FFR (Jenney, and Brien, 2011; Gery, and Maropoulos, 2005).

3.4.2.5 Contact tip to the Work Distance

It is essential to maintain the electrode that is coming out of the welding gun always constant, as the current can vary with an increase or decrease of the electrode extension. The electrode extension is the part of the electrode that is visible to the welder and the contact tip to the work distance (CTWD) is the distance between the end of the contact tip to the base metal, as presented in Figure 9.

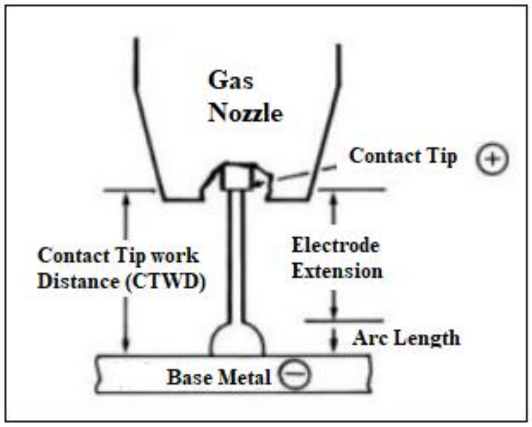

Figure 9: Electrical Extension and Contact Tip to Work Distance (CTWD)

Source: adapted from Armo et al., 2014

It is essential to maintain the electrode extension consistency for a smooth penetration profile along the arc length to guarantee a good weld bead.

- An increment in the electrode extension will increase the resistance to the current flow in the electrode, decrease the current in the arc and consequently emit fewer fumes (Armo et al., 2014).

3.4.2.6 Shielding gas and Shielding gas flow rate

The correct shielding gas selection for a given GMAW application is critical to the quality of the weld. The shielding gases can react in different ways under the heat of the arc, affecting the current flow (Williams, 1996).

Argon (Ar) and helium (He) are the two shielding gases most used to protect the molten weld pool (Armao et al., 2014). They are inertness, which means they do not have a chemical reaction with metals, is the primary gas in the shielding gas mixture. However, to become a conductive gas (plasma), it must be ionized by being mixed with some reactive gas, usually CO_2 or O_2. Those reactive gases are inert at room temperature although, in the presence of high temperature, during the welding activity they become reactive to the atmosphere, generating more fumes (Kou, 2003).

- Higher concentrations of CO_2 or O_2 can produce more fumes. However, higher

concentrations of CO_2 can cause more welding fume emissions (Pires, Quintino, and Miranda, 2007).

One percent of our atmosphere is composed of Ar, which is colorless, odorless and nontoxic (Lide, 1996). Argon is the most common inert gas used in welding procedures because it requires less ionization energy than He. For this reason, Ar gas can create a better arc starting them. He, increasing the molten droplet transfer rate (Armao et al., 2014). In other words, Ar requires less energy to give up an electron (ionization energy), resulting in a finger-like penetration profile and can also support spray transfer better them He. Nickel, copper, aluminum, titanium, and magnesium base metals use 100% Ar gas to perform welding. Ar is also the main component gas used in binary (two-part), or ternary (three-part) mixes for GMAW welding (Tanaka et al., 2003).

Even though Ar is the most used inert shielding gas in the GMAW process, it has some disadvantage when used alone (100% Ar), due to the low heat input (Tanaka et al., 2003). The thermal conductivity, or the ability of the gas to transfer thermal energy, is the most important consideration when selecting the shielding gas for the work or experiment. The conduction of the thermal heat into the workpiece can affect the shape of the arc and the temperature distribution in the region. Higher thermal conductivity input can be achieved using a mixture of Ar with CO_2 or O_2.

- Argon 2% O_2: This mixture is frequently used for stainless steels base metals, it provides some wetting action for a better bead penetration profile and increase the corrosion resistance of weld.
- Argon 25% CO_2 (C-25): This range is universally known as the gas used for GMAW with short-circuiting transfer on mild steel. This combination is popular due to the weld quality, the simple installation process, and low cost.
- The composition of the shielding gas can interfere in the fume formation process; emission rate tends to grow with the increase in the active components concentrations (i.e., oxygen and carbon dioxide).
- The shielding gases can also react in the heat of the arc, affecting the current flow, the heat transfer, and consequently the fume formation (Williams, 1996; Murphy et al., 2009).

3.5 Emission Factor

According to EPA (2018), EFs are fundamental parameters to develop emission control strategies for air quality management, measuring how polluting an activity could be. Furthermore, EFs are used nationally for about 80 percent of emissions reporting. The EF can calculate the released amount of pollutant into the atmosphere from a specific process or activity. In other words, EF calculates the quantity of pollutant emitted per unit amount of work done (U.S. EPA, 2018). Generally, the EF measures the weight of contaminant emitted per unit weight, duration, volume or distance of the activity that emits the pollutant. The EFs for welding activity is expressed as:

- g/kg of electrode consumed

Since 1972, EPA is publishing EFs data from more them 200 air pollution source categories from different source test, material balance studies, and engineering estimates to produce the Air Pollutant Emission Factors (AP-42) compilation document, which is continually being updated with new data (U.S. EPA, 2018). In the AP-42 the collected data is presented in a table format (candidate emission factors), and they are generally rated, depending on the quality of the individual data sets used. The AP-42 documents provide EF ratings to indicate the robustness, or appropriateness of EFs based on source operation, sampling, process data, analysis, and calculations. These ratings variates from A through U (US Environmental Protection Agency, 1994):

- A = Excellent. The EF came from A, and B rated source test data taken from many random facilities in the industry.
- B = Above average. The EF came from A, and B rated source test data taken from a moderate number of facilities in the industry.
- C = Average. The EF came from A, B, and C rated test data from a reasonable number of facilities. However, it is not clear if those facilities tested represent a random sample of the industry.
- D = Below average. The EF came from A, B and C rated test data from a small number of facilities, and probably these facilities do not represent a random sample of the industry.

- E = Poor. The EF came from C, and D rated test data from a very few numbers of facilities, and probably those results do not represent a random sample of the industry.
- U = Unrated. The EF results from source tests which have not been evaluated yet. The data are not necessarily "poor," but more information and supporting documentation are needed.

Table 3 presents the average EFs for GMAW and some of the most common electrode types used for this process, with their respective EF ratings. An upgrade in this table can bring a significant contribution to the AP-42 document.

Table 3: Average EFs for GMAW activity

Welding Process	Electrode Type	Average EF (g/kg of electrode consumed)	EF Rating
GMAW	E70S-6	5.2	A
	ER316L-Si	3.2	C
	E308L	5.4	C
	ERNiCu-7	2.0	C

Current = 160 to 460 A; voltage = 19 to 32 V.

Source: U.S. EPA AP-42, (1994)

All the fumes generated in Table 3 are considered to be PM-10 (particles ≤ 10 μm in aerodynamic diameter), the mass of pollutant per mass of electrode consumed is the average weighted of all data sets, and the shielding gas can influence the emissions generated. Since EF represent the average emission rate for an entire process or source category, emissions may vary widely from one source to another. Besides, the welder skill can also impact the emissions, because there is a voltage/ current range that can produce an acceptable weld, emitting different quantities of fumes. The demand for EF is increasing since companies started to use the AP-42 to measure and report their environmental progress, developing their greenhouse gas (GHG) emission inventories, air permit applications, environmental impact assessment, and health risk assessments (U.S. EPA, 2018). Moreover, stakeholders and the public are also demanding from the companies to give them more accurate information about their emissions.

The actual AP-42 document contains data with a conservative assumption; the report needs to be improved with more realistic data. The last AP-42 update was in 2011; however, the AP-42 chapter 12: metallurgical industry category, where welding is inserted, has not been updated yet. In 1994 EPA released the document "Development of Particulate and Hazardous Emission Factors for Electric Arc Welding (AP-42, Section 12.19) Revised Final Report" where 52 test reports and other information were provided to support preparation of a new AP-42 section for electric arc welding. In 1995 the AP-42, section 12.19 for electric arc welding was created, and the updates until now for this section are presented below:

- Errata – June 2009
- Table 12.19-2 was corrected to add 'lb' to the HAP emission factor column heading
- The final chapter – January 1995
- Background document - May 1994

The present AP-42 data does not represent the EFs generated from actual shipyard conditions and variables (Kura et al., 2009). According to the same source, the national shipbuilding research program (NSRP) considered the EF database as a priority necessity to understand the emissions for this industry sector better and create a realistic environmental impact assessment. If EPA improves the quality of the EFs, there will be a significant improvement in environmental decision-making to reduce air pollution. In the other hand, if EPA uses poor EFs data quality, it can result in millions of tons of uncontrolled emissions per years, increasing the risk of adverse health effects and environmental impact. The EFs database can also be used to create new impositions for manufactures of both equipment and consumables, demanding them to take severe measures to decrease pollutant emissions, as a way to reduce the incidence of professional diseases in welders.

3.5.1 UNO Previous Research on Emission Factors

Since 2006, the University of New Orleans (UNO) is conducting researches in a controlled environment, to simulate the emissions from industrial process and measure (a) amount of work, raw materials and product used, and (b) quantify the pollutants generated in different process conditions. The UNO researches about EFs (Kambham, 2006; Kura, Jackens, Keay, 2009; Jackens

et al., 2009; Jilla, 2017) had estimated the EFs from many different processes such as abrasive blasting, welding, and metal cutting. Below a summer of the principal findings from UNO researches about this topic.

- Total Particulate Matter (TPM) EFs from Abrasive Blasting

The Kalpalatha (2006) research, determine the total fume particulate matter EFs for expendable abrasives. Industries like shipbuilding, automobile, and aerospace use abrasive machine compressed air to force the abrasive material into high velocities to clean the steel or other metal surfaces. However, this procedure can emit particulate matter that can be harmful to human health. In this emission tests work the author used a test chamber, blasting equipment, test plates, exhaust duct, stack sampling system, and a particulate collection system. Three different expendable abrasives (coal slag, copper slag, and specialty sand) were tested to clean base plates in an enclosed test chamber, using different blast pressure and abrasive feed rate to determine EFs under different conditions. The author developed EFs for the various process conditions for the three-different abrasive materials, as shown in the equations below.

a) kg total productive manganese (TPM) per unit area cleaned = $\frac{Mass\ of\ total\ TPM\ emmited\ (kg)}{Area\ cleaned\ m^2}$

b) kg TPM per unit mass of abrasive = $\frac{Mass\ of\ TPM\ emitted\ (kg)}{Quanntity\ of\ abrasive\ used\ (kg)}$

Kalpalatha (2006) work in EFs made a significant contribution to estimate the TPM emissions for dry abrasive blasting process and to develop emission control strategies to minimize pollutants. The finds of this research indicated that the TPM from Copper Slag emits fewer EFs than Coal Slag and Coal Slag emits fewer EFs than Specialty Sand.

- Heavy metal (Cr (VI) and total metals) Emission Factor from welding processes

The researchers conducted at UNO (Kura, Jackens and Keay, 2009) on the heavy metal EFs in welding processes had the objective to capture and analyze 100% of the fume generated from different electrodes in the SMAW and FCAW welding processes. The AWS designed the weld fume chamber for those experiments, as shown in Figure 10. This thesis used the same fume

chamber and filter handling procedure for the tests, due to the high capacity of this machine to capture the fumes. This research also estimated the emissions of Cr (VI) and total heavy metals per 1g of weld rods (electrodes) consumed using the OSHA ID-215 and the National Institute for Occupational Safety and Health (NIOSH) 7300 methods in the analyses.

Figure 10: Weld fume chamber and filter handling

Source: Kura et al., 2009

- <u>Particulate Matter and Carbon Monoxide Emission Factors from Incense Burning</u>

Jilla (2017) research brought a contribution to the indoor air quality area by determining the particulate matter and carbon monoxide EFs from incense stick burning. To make it possible, the author built a test chamber and installed some pollutant sensors to achieve the project goals. Several experiments with different scenarios were performed to estimate EFs accurately, and test runs were made for each case scenario to test the repeatability of the results. The findings of this work show that the (CO), PM2.5 (mass), PM2.5 (number), PM10 (mass), PM10 (number) EFs analyzed in this research are measured between 110-120 mg/g of incense, 2.5-3 mg/g of incense, 800-1100 particles/µg of incense, 32-33 mg/g of incense, 1200-1400 particles/µg of incense respectively.

3.6 Reducing Welding Fumes Exposure

Welders and other workers must avoid hazardous fumes and gases produced during welding, brazing, soldering, and cutting activity. To reduce the fume exposure, OSHA established a time-weighted average (TWA) 8-hour TWA of 5 mg/m³ for some types of welding fumes (CDC, 2018). OSHA concludes that a permissible exposure limit (PEL) for welding fumes is crucial to protect welders from the risk of metal fume fever and respiratory irritation associated with the generation of welding fumes. Adequate ventilation can protect workers from fume exposure, and if the exposure exceeds the permissive levels, even with proper ventilation, then respiratory protection should be used for every worker in the area.

Some public agencies are demanding, even more, stricter PELs for welding. Those opposed to this idea argue that much capital will need to be invested in maintenance and ventilation equipment that might not bring significant gains in worker health. In the other hand, proponents of standards argue that medical fees, liability suits and lifestyle limitations related to welding fume are likely to cost even more. Presently, about 2% (3 million people) of workers from different backgrounds are subjected to welding fume exposure. In confined spaces, welding can be deadly. Without proper ventilation, the intensity of the toxic fumes can be higher, and possibly over the respective limits for toxic substances (Pires et al., 2007).

The inhalation of the welding fumes can produce an immune reaction in the body, alternating the proteins in the lung function (Antonini et al., 2004). The modified proteins enter the bloodstream and create an allergy reaction. As a result, workers can feel symptoms like fever, chills, nausea, headache, fatigue, metallic taste in the month, muscle joints and joint pain. The metal fume fever typically subsides within 24 to 48 hours after exposure and a full recovery can occur after four days. Although, continuous exposure to welding fumes can cause severe damage to the organism. Welders need to know how to protect themselves to avoid breathing the welding fume and gases, as this exposure is a potential occupational carcinogenic that can threaten public health (OSHA, 2018). To guarantee more safety to the welders, employers must provide more information and training on hazardous materials in the workplace.

Welders should always stay upwind when performing welding in open or outdoor environments. The general ventilation can reduce fume exposure and gas levels in the work area, removing them from the welder's breathing zone. Weld in confined spaces without ventilation is not appropriate, and additional protection may be required if the work practices and ventilation do not reduce exposures to safe levels. The gases generated during the welding activities should be discharged safely, according to the government rules and regulations.

Whenever possible, welders should consider adopting a lower fume-generating or a less toxic welding type. For example, in arc welding, the GMAW and the GTAW are the ones that release fewer emissions when comparing to the other arc welding techniques. To reduce the exposure to welding fumes, the OSHA (2018) provided a list of standards applicable to welding, the most important ones for the shipyards are:

- Welding, Cutting & Brazing—29 CFR 1910 Subpart Q
- Welding, Cutting & Heating—29 CFR 1915 Subpart D
- Permit-required confined spaces—29 CFR 1910.146
- Confined & Enclosed Spaces & Other Dangerous Atmospheres in Shipyard Employment—29 CFR 1915 Subpart B
- Respiratory Protection—29 CFR 1910.134
- Air Contaminants—29 CFR 1910.1000 (general industry), 29 CFR 1915.1000 (shipyards), 29 CFR 1926.55 (construction)

3.7 Toxicity of Welding Fumes

The PEL for some material consumables, base metals or the atmosphere during the welding operations is 1.0 mg/m³ or less due to the toxicity of this component for the human health (OSHA, 2018). Nowadays, there is a higher concern from the environmental and health agencies about the welding fume formation from chromium, hexavalent chromium, manganese, lead, cadmium, manganese, and nickel. Manufacture's manual should be consulted to determine the filler metals toxicity.

Epidemiological studies have shown a correlation between welding activity and some respiratory illness such as bronchitis, asthma, and a possible increase in the incidence of lung cancer (Antonini

et al., 2004). According to the Occupational Safety and Health Administration (OSHA, 2018) some factors that can contribute to the worker exposure to welding fume are:

- The type of welding process
- The base metal and filler metals composition
- The location (open space or confined space)
- The kind of ventilation controls (mechanical or local)
- Welder work practices.

The toxicity of the welding fumes can variate due to differences in the materials used and methods employed. Most welding materials are alloy mixtures of metals characterized by different steels that may contain iron, manganese, chromium, and nickel.

- Studies with animals indicated that stainless steel (SS) welding fumes, which contain higher levels of nickel and chromium, are very toxic and can cause more lung injury than the mild steel (MS) welding fumes, which mostly contain iron in their composition (Antonini et al., 2004).
- The SS fumes contain elevated levels of soluble metals, which can be very toxic to the respiratory system.

3.7.1 Toxicity of Welding Fume at the Shipbuilding Industry

Since 1990, the toxicity of welding fume emissions in the shipyards has become very strict under the environmental legislation of the clean air act amendments title V permitting and title III hazardous air pollutants (HAP's), demanding emissions from welding and cutting operations to be addressed (Jacobs, 1995). This legislation established a national policy for managing waste through source reduction, which means preventing the generation of waste. Similarly, OSHA regulations also become more restricted with indoor air quality and employee toxic exposure, as discussed before.

Most of the welding activities in the shipbuilding industry happen in indoor areas, and it is becoming an important topic to be discussed in recent years, due to the adverse health effects related to it (OSHA, 2018). In the indoor environment, the exposure to particulate dust, various

gaseous pollutants, and Volatile Organic Compound (VOCs) can increase the health risks probability for the workers. According to the U.S. EPA (2018), the concentration of the pollutants in an indoor environment can be 2-5 times higher than ambient levels.

3.8 Welding Health Effects

The air particulates are generally categorized by how deep they can penetrate in the human respiratory system and cause an adverse health effect. Welding can emit fumes that contain different particulate matter with different gaseous pollutants. It is known that the most respirable particles are in the size of 0.1 to 5 microns (μm).

- If the particle is less than 0.1 μm in size, it can be easily removed from the body by exhalation (Pires et al., 2010).

- 0.1 μm in size, it can be easily removed from the body by exhalation (Pires et al., 2010).

- The fine particle that has 2.5 μm ($PM_{2.5}$) in size can penetrate deeply into the human respiratory system, being the most prejudicial ones to the human body.

    - The health effects of inhalable $PM_{2.5}$ due to short-term exposure include metal fume fever (i.e., flu-like symptoms), respiratory and cardiovascular morbidity, such as asthma aggravation, and an increase in hospital admissions (WHO, 2018).

    - Long-term exposure risks may include mortality from cardiovascular or respiratory diseases, lung damage, neurological disorders, and lung cancer and Parkinson's disease (WHO, 2018).

- Particles that are greater than 2.5 μm and less than 10 μm (PM_{10}) in size are known as coarse particles.

    - These particles can be too large to enter the human respiratory system, but prolonged exposures to PM_{10} can lead to respiratory illness.

        - Particles with more than 5 μm in size can be deposited in the upper respiratory tract with long term exposure.

- Short-term exposure to PM_{10} has a vast effect on respiratory health, but for mortality, $PM_{2.5}$ is a significant risk factor than PM_{10} for prolonged exposures.

Furthermore, the duration, frequency, and concentration of the exposure can also define the risk of injury and disease. Table 4 presents the two categories division of the exposure classification according to OSHA.

Table 4: Exposure indication comparison (OSHA)

Exposure	Indication
Acute	Irritation (eye, nose, and throat), fever, headache, nausea, shortness of breath, muscle pain, and a metallic taste in the mouth.
Chronic	Respiratory effects (coughing and decreased pulmonary function).

Source: OSHA, 2018

Gases are also generated during the welding, which may include carbon monoxide, ozone and nitrogen oxides.

- The use of carbon dioxide (CO_2) as a shielding gas can produce carbon monoxide (CO) which is an odorless, colorless.
    - Overexposure to CO can result in asphyxiation since the body's red blood cells cannot carry the oxygen efficiently to other tissues in the body. The CO generation in the welding activities can only be a concern when welding performed in a confined space (Pires, 1996).
- Ozone and nitrogen oxides are produced in the welding arc by the interaction of ultraviolet light with the surrounding air.
    - These gases can cause eyes, nose and throat irritation. High exposures can also cause fluid in the lungs and pulmonary illnesses (Pires, 1996).

The welding fumes can be very harmful to human health. Therefore, it is essential to follow the manufacturer's instructions, standards, material safety data sheets (MSDSs), and safety protocols to minimize the hazards of welding fumes. While respiratory symptoms can appear in the welders, there is not enough prove if those symptoms are caused by weld fume alone or for a combination of exposure to other toxicants in the work environment (CDC, 2018). However, some notable health effects on the welders that ingested weld fumes are indicating a possible association between the welding fumes and the adverse health effects from this activity.

3.9 Welding Safety

Arc welding can be very safe with the proper precautions. However, if welders ignore some secure proceedings, they can be exposed to many dangers such as electric shock, eye injuries, skin burn, fumes, and gases, that can compromise their health and security (CCOHS, 2017). For the welder's safety, Table 5 summarizes the types of personal protective equipment (PPE) necessary to use when performing welding activity.

Table 5: Welding personal protective equipment (PPE)

Equipment	Reason
Welding helmet	Protects the eyes and the face from radiation (infrared wavelengths), flying particles, sparks, intense light, irritation, and chemical burns
Mask	Protects the lungs from the welding fumes
Earplugs	Protects the ears from the noise
Leather jacket	Protects the skin from the heat, fires, burns, radiation
Leather boots	Protects the feet from electric shock, heat, burns, fires
Leather gloves	Protects the hands from electric shock, heat, burns, fires

3.10 Previous Studies

Few previous studies in the literature analyze the process parameters and operating conditions in the GMAW process, to evaluate the fume formation rate (FFR) and EFs in a controlled environment. Some of them are summarized below:

In the Melton (2012) work, a study about the metal transfer modes in GMAW using high-speed video (5000 fps) and high sampling rate parameter monitoring was performed. Welding FFR has been measured over a range of welding process parameters and operating conditions. The tests used a mild steel base metal, copper coated, welding wire (G3Si1, 1.2 mm diameter), with argon shielding gas mixtures containing between 5 and 18% CO_2. The results have shown that a reduction in FFR is possible by selecting the right combination of shielding gas and welding parameters. The fume emissions are always associated in the literature with variations in current; however, in Melton work, it was possible to see that the correct voltage is as essential as the current to ensure stable metal transfer and low fume emission. The instrument used in this experiment (high-speed video) is expensive, there was no repeatability in the tests, and the EFs results are missing. The research had all the necessary data for EFs calculations which could have brought a significant contribution to the EPA AP42 emission factors inventory if they were calculated.

Pires and Gomes (2006) developed a study about how the shielding gas composition (Ar + 2%CO_2, Ar + 8%CO_2, Ar + 18%CO_2, Ar + 5% O_2, Ar + 8% O_2, Ar + 3%C O_2 + 1% O_2 and Ar + 5%CO2 + 4%O_2) can influence the FFR. They utilized the GMAW technique, the stainless-steel base metal, the welding current intensity variating between 150 - 280 A and the voltage variates between 15 - 35 V. The research followed the standard described in AWS F1.2:2013 manual, they used the same glass fiber filets and the same fume chamber as used in this thesis. In the findings of this work, it was clear that the FFR increases with the increase in the concentrations of CO_2 and O_2 in the gas mixture, and the number of fumes released during welding can be higher for mixtures with CO_2 than the ones that use O_2 with the same oxidizing potential. The authors did a great job showing the variations in the fume formation with different shielding gas mixtures, and they also made a nice graphic showing the huge influence that the current has in the fume formation process. However, there is no graphics, tables or descriptions showing the influence in the voltage in the FFR. The shielding gas composition is one of the operating conditions that can have some

influence in the FFR. However, it was shown by the literature that the current and voltage are the ones that most contribute for FFR (Weman, 2011; Kou, 2003; Pires at. all, 2007). In the presented thesis the correlation between current, voltage and FFR are better demonstrated, and there HI and EFs calculations are also included.

In Tandon et al. (1984), the Australian automatic welding and fume collection system were used for five different electrodes for SMAW, performing the welding with both an AC and DC power supply and the recommended power setting. The voltage was constant for all the experiments, the welding was performed horizontally at 150 mm/min, and the authors used glass fiber filters to collect the fume samples. FFR graphs were created for the electrodes at various power levels for DC and AC current. The results showed that AC and DC welding generated approximately the same fume rates when operated at the same power level. However, the Australian method varied substantially from the AWS welding chamber technique, and it would have been interesting if the authors had also performed GMAW and played with the voltage ranges to see if there is any difference in the FFR as well. The EFs results of this study are presented below in Table 6.

Table 6: Summary data from Tandon et al. (1984)

Welding Process	Electrode Type^{a}	Total Fume Emission Factor (g/kg of electrode consumed)
SMAW	(E01) 1855A4	26-55
	E9018 G	15-25
	E9015 B3	10-22
	(E11) 1215A4	35-70
	(E12) 2355A1	40-75

a: Australian classification of electrodes.

A study conducted by EPA (1991), tested the fumes of the ten most used electrodes, according to the ANSI/AWS F1.2-85 standard method. The voltage was constant for all the test and the current variates (130 A - 180 A). The fume was collected utilizing glass-fiber filters and weighed to determine the EFs. A summary of the results for the electrodes tested is shown in Table 7 below. It would have been interesting if the authors had played with voltage ranges as well to see if there

is any difference in the FFR with those variations.

Table 7: Summary of data EPA (1991)

Welding Process	Electrode Type	Total Fume Emission Factor (g/kg of electrode consumed)
SMAW	E6010	22.7
	E6011	38.4
	E6013	13.6
	E308-16	6.4
	E7018	15.7
GMAW	E308L-Si	8.6
	E70S-3	7.9
	E70S-6	5.2
FCAW	E70T-1	8.7
	E71T-1	12.0

4. Methods and Materials

4.1 Methodology

In this section will be discussed the experimental design, filter specification, the necessary care needed with the experiments (weight, handling, storage), calibration procedure, and the sample calculation formulas.

Welding activity can generate a different amount of fume emissions. As the shipbuilding industry uses large quantities of MS and SS in their production, calculations for the HI, FFR, and EFs were made for those two base metals by changing some process and operating conditions:

- Process Parameters:
    - Base metal (AH36 mild steel, 316L stainless steel)
    - Electrode (ER 70S-6, ER 316LSi)
- Operating Conditions:
    - Current
    - Voltage
    - CTWD
    - Welding Speed
    - Shielding Gas
    - Shielding Gas Flow Rate
    - Work Angle
    - Drag Angle
    - Polarity
    - Arc Time

In this thesis proposal, the work angle, drag angle, shielding gas, shielding gas flow rate, CTWD, welding speed, and polarity were kept constant for all the test runs. However, the current and voltage were varied with the experiments as they are the ones that can most influence the fume formation process (Weman, 2011; Kou, 2003; Pires at. all, 2007). For this reason, the tests were designed with a low, medium, and high conditions for voltage and current values, keeping all the other variables constant for each base metal. The objective is to play with those combinations, to see the variation in the fume formation for each base metal.

4.1.1 Calculations

The calculations for the HI, FFR, and total fume EFs were developed in an excel spreadsheet, using the equations below, according to the AWS pacifications (AWS, 2013).

$$\text{Heat input (KJ/min)} = \frac{A\ x\ V\ x\ 0.06}{S} \quad (1)$$

$$\text{Fume Formation Rate (g/min)} = \frac{F.W - I.W}{arc\ time} \quad (2)$$

$$\text{Total Fume Emission Factor (g/kg)} = \frac{F.W - I.W}{g\ of\ electrode\ consumed} \quad (3)$$

Where: I.W = Initial Weight (filters), F.W = Final Weight (filters)' Arc Time = 30 seconds for Mild, Steel and 1 minute for Stainless Steel. (A) welding current, (V) voltage, (S) welding speed (cm/min), (0.06) standardizes the units.

In the equations (2) and (3), it is necessary to measure the difference between the filters before and after sampling. In equation (3) the welding wire consumed needs to be presented in grams of electrode consumed. More information about the electrode consumption calculations is given in the appendix A of this thesis.

In the SS experiments, the arc time selected was 30 seconds more than the MS one, because the SS base metal emits fewer fumes them the MS ones. However, the SS fumes are more hazardous to human health, due to the hexavalent chromium (Cr (VI)) emissions.

> "There is sufficient evidence in humans for the carcinogenicity of chromium (VI) compounds as encountered in the chromate production, chromate pigment production, and chromium plating industries " (IARC, 1999).

4.1.2 Calibration

For accurate results, the calibration tests should follow the AWS standard specifications. The calibration has the purpose of bringing consistent and reliable fume measurement for similar fume test chambers. In this process, it is possible to collect and compare the fume generation rate data from different sources, by using the same calibration methods.

The calibration experiments used the base metal A36 and the electrode ER70S-3. Table 8 presents the calibration results, and according to the AWS, the results of the calibration experiments can vary no more than ± 20% from the values given in AWS manual to be considered valid (AWS, 2013). If the wire feeder settings and voltage are accurate, and if the CTWD has been measured correctly and remained the same during the welding activity, the results should be close to the AWS recommended values. It is also primordial to check if no significant amount of fume escapes from the test chamber during the welding activity to avoid wrong results.

Table 8: Calibration results

Voltage (V)	Wire Feed Speed (in/min)	Shielding Gas	Shielding Gas Flow Rate	Welding Speed (mm/sec)	CTWD (mm)	FFR AWS (g/min)	FFR UNO Fume Chamber Results (g/min)
24	300	CO_2	35	6	19	0.32	0.28
26	300	CO_2	35	6	19	0.46	0.42
28	300	CO_2	35	6	19	0.61	0.56

4.2 Experimental Design

The experiments were designed for the two most used base metals in the shipbuilding industry AH36 mild steel and 316L stainless steel with their respective electrodes ER 70S-6 and ER 316LSi and appropriate shielding gases. Table 9 and Table 10 presents the experimental design for each base metal, composed by 9 different scenarios, in which each scenario was repeated 3 times to see the repeatability of the results, resulting in 54 experiments in total. The experimental design follows the specifications in the American Welding Society (AWS) manual.

Table 9: Experimental design mild steel

S.NO	Desired Current (A)	Voltage (V)	Welding Speed (cm/min)	Shielding Gas	Flow Rate (ft^3/h)	CTWD (mm)	Base Metal	Electrode
1	180	22	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
2	220	22	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
3	260	22	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
4	180	26	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
5	220	26	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
6	260	26	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
7	180	29	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
8	220	29	50	Ar+25 CO_2	35	19	AH36	ER 70S-6
9	260	29	50	Ar+25 CO_2	35	19	AH36	ER 70S-6

Table 10: Experimental design stainless steel

S.NO	Desired Current (A)	Voltage (V)	Welding Speed (cm/min)	Shielding Gas	Flow Rate (ft^3/hr.)	CTWD (mm)	Base Metal	Electrode
1	180	22	50	Ar+2 O_2	35	19	316L	ER 316LSi
2	220	22	50	Ar+2 O_2	35	19	316L	ER 316LSi
3	260	22	50	Ar+2 O_2	35	19	316L	ER 316LSi
4	180	26	50	Ar+2 O_2	35	19	316L	ER 316LSi
5	220	26	50	Ar+2 O_2	35	19	316L	ER 316LSi
6	260	26	50	Ar+2 O_2	35	19	316L	ER 316LSi
7	180	29	50	Ar+2 O_2	35	19	316L	ER 316LSi
8	220	29	50	Ar+2 O_2	35	19	316L	ER 316LSi
9	260	29	50	Ar+2 O_2	35	19	316L	ER 316LSi

Some observations:

- Welding currents from 50 amperes to 600 amperes are commonly used at welding voltages of 15V to 32V. However, the welding machine used in this thesis, the Millermatic 252, has a voltage limit that goes until 29.9 V and for this reason, the experiments were limit until 29 V range.
- As a precaution, after all, test, the bead length was measured using a rope and a ruler to check if the welding speed was correct. The measured range is then divided by the arc time, and the result should be close to the one adjusted in the turning table.
- The CTWD was kept constant for all runs, using semi-automatic welding support, capable of ensuring the same 19 mm CTWD for all experiments, making it possible to compare the

emission results.

- The work angle was determined to be zero degrees for all the experiments and the drag angle 10 degrees, as specified by the American Welding Society (AWS) manual.
- The correct current for the a) ER316LSi and (b) ER70S-6 wires was determined according to the AWS manual for 0.045” (1.2 mm) diameter.

4.2.1 Determining the Welding Current

As explained before, the WFS has a directed influence in the current. Figure 12 shows how this relationship, known as “burn-off,” work for (a) ER316LSi and (b) ER70S-6 wires. Different wire electrode diameter at determining wire-feed speed has different current and each type of wire (steel, aluminum) has a different burn-off characteristic. In the graphic it is possible to see the burn-off curve for each wire diameter, in the lower current range, the curve is nearly linear (proportional and constant increase in the melt-off). However, at higher welding currents, mostly for small diameter wires, the burn-off curve becomes non-linear and higher currents cause larger increases in the burn-off in this region, due to resistance heating of the wire extension beyond the guide tube. When the current for a given GMAW electrode reach the maximum level, no additional current pass through the wire (Armo et al., 2014). In Figure 8 for example, it is possible to observe this phenomenon for the 0.045” (1.2 mm) diameter stainless steel solid wire, when the current reaches approximately 360 A. Figure 11 was used to determine the wire feed speed for each ER316LSi and ER70S-6 experiments, according to the desired current. Moreover, some welding tests were made outside the fume chamber to double check if the WFS and the desired current were right before starting the experiments.

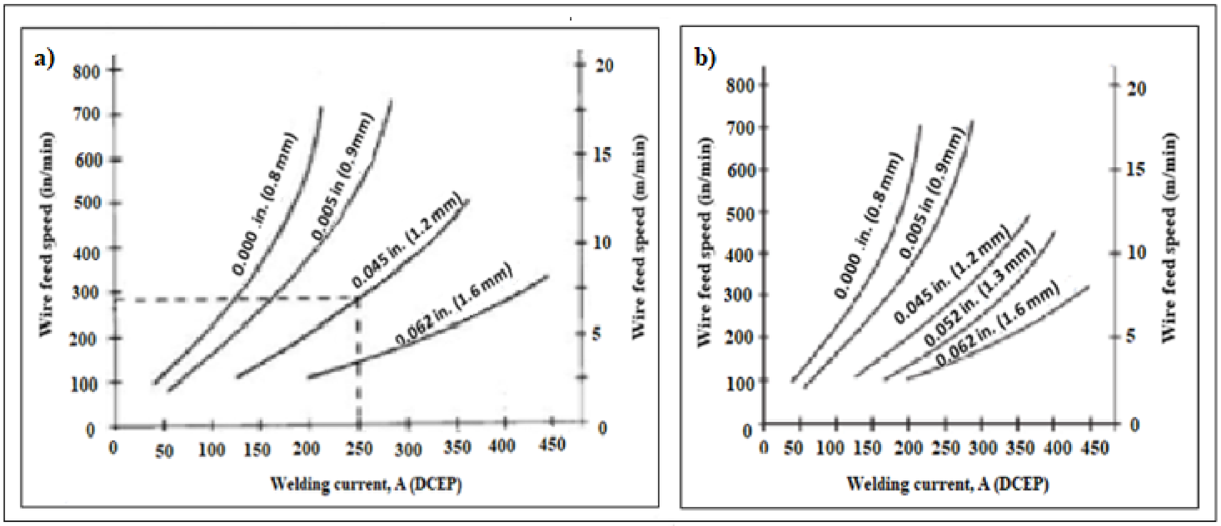

Figure 11: Welding current and wire feed speed for (a) ER70S-6 and (b) ER316LSi wire

Source: AWS, 2018

According to Figure 11, the WFS to achieve the same current is different for each electrode used with their correspondent diameter, as presented below:

- ER70S-6 (MS experiments):
  - 200 in/min = 180A,
  - 280 in/min = 220 A,
  - 365 in/min = 260 A.
- ER316LSi (SS experiments):
  - 235 in/min = 180 A,
  - 350 in/min = 220 A,
  - 435 in/min = 260 A.

4.3 Experimental Procedure

All the experiments in this research were conducted at the University of New Orleans. The first step to start the experiments is to put the filters in the oven for 1 hour at 200 °F to 225 °F (93 °C to 107 °C) to take out the possible air humidity that could influence the filter weight. The use of gloves is mandatory to avoid the contamination of the filters and guarantee safety in the laboratory. When the filters are about to get ready, it is time to clean the fume chamber using wipes; it is

essential to clean inside and outside of the equipment to remove any dust on the walls of the chamber. It is also necessary to clean the base metal properly before placing it inside the chamber. When the fume chamber is clean, it is time to turn on the blower and fix the turntable speed. When the filter time is up, the initial weight of the filter is measured and noted. After that, the filter is fixed properly in the filter support and then placed in the top of the fume chamber.

Before starting the experiment, it is necessary to take some steps to guarantee the quality and safety of the procedure. First, it is essential to check if no source of fire is around while opening the cylinder. If the workspace is safe, it is time to open the gas cylinder valve to guarantee a proper shelter for the welding bead. The connections between the GMAW machine, gas cylinder, the power source, and the fume chamber should also be checked to certify if they are working correctly. Furthermore, it is necessary to verify the wire tension by shooting the gun in hand using leather gloves. If the wire makes a curl, it is working correctly. Finally, clean the nozzle and the contact tip, and check if there is any damage to their structure otherwise, replace them.

When the GMAW is turned on, it is necessary to fix the voltage and wire feed speed. It is also important to shoot a little bit the gun to the wire electrode comes out and, with the machine turned off, the electrode extension should be cut in 19 cm to proceed with the experiment. The excel spreadsheet with all experimental variants (base metal & thickness, filler metal & thickness, shielding gas, shielding gas flow rate, wire feed speed, weld speed, CTWD) should be kept closed all the time to check for the experiments steps. Moreover, a clamp meter should be attached to the welding wire to capture the current readings, and a cell phone device should be used to record the clamp meter readings. With the equipment turned off, the welding torch is placed inside the fume chamber and fixed in the adequate height for the semi-automatic (hand-held torch operations) procedure. It is essential to seal the chamber properly after each experiment, to avoid the fumes to escape.

Before the experiment starts, the use of personal protective equipment (PPE) like gloves, jacket, helmet, and mask are mandatory. The test should proceed for 30 seconds for MS and 1 minute for SS. At the end of the experimental time, the filter should be left inside the chamber for an additional 10 minutes to capture all the fumes created during the welding activity. After that, the filter goes again to the oven and stay there for more 1 hour at 200 °F to 225 °F (93 °C to 107 °C). When the

filter time is over, then it is time to retake the weight of the filter, put the result in the excel spreadsheet, and do the procedure for the fume calculation. The Ziplocs were used to set the filters before and after each experiment to avoid any moisture contact or any contamination of the filter for the environment. When the operations are over, it is recommended to disconnect all the cables, clean the equipment, turn off the gas cylinder, the blower, and the welding machine to let the space ready for others to use.

4.4 Materials

4.4.1 Electrode

The electrode, also known as filler metal, was determined to be 1.2 mm (0.045 in) diameter for all the experiments, following the specifications for the base metals thickness. The electrodes and the respective base metals used:

- ER70S-3 electrode with the A36 base metal (calibration procedure),
- ER70S-6 electrode with the AH36 mild steel base metal,
- ER316LSi electrode with the 316L stainless-steel base metal.

All the electrodes used in the experiments are from the ESAB company. The chemical composition for the wires and their respective base metal are presented in the appendix B section of this thesis.

4.4.2 Base Metal

The base metal can respond to thermal and mechanical treatment, and they are the primary alloying element added to the joint. All the base metals used were bought from Phoenix Metals company and cut in the exact dimensions for the thesis experiments. For this study, the A36 mild steel base metal was used for the calibration experiments, as recommended by AWS F1.2:2013. After calibration, the equipment was ready to measure the total fume emissions and the EFs for the two base metals used in this research, with an 8 mm thickness and 300 mm diameter each piece:

- The AH36 mild steel
- The 316L stainless-steel

The AH36 and 316L base metals are used mainly in the shipbuilding industry due to their low density, high strength, excellent formability, and weldability, making them a preferred metal for alloys. Figure 12 presents the base metals used in this thesis, and it is also possible to see the beads created during the welding. The SS experiments have a longer arc time (1 minute) than the MS experiments (30 seconds), as observed in the beads below.

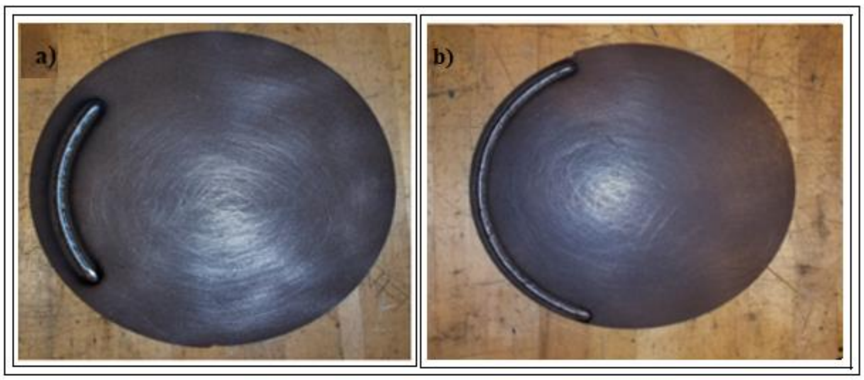

Figure 12: a) AH36 mild steel and b) 316L stainless-steel base metals

4.4.3 Gas Shielding

The gas cylinder used is from the Industrial Gas and Supply Inc. and the pressure regulator HRF 1425-580 is from the Victor CutSkill company. Moreover, the flow rate was 35 ft^3/h (989 L/min) for all experiments, as presented in Figure 13.

- The base metal AH36 used the shielding gas $Ar+25CO_2$,
- The base metal 316L used the shielding gas $Ar+2O_2$.

Figure 13: Flow rate equipment

4.4.4 Gas Nozzle and Contact Tip

The contact tip used was 0.045 inches from the Miller brand, and the orifice nozzle was ½ in (12 mm) diameter from the same brand, as shown in Figure 14. The material composition of those pieces is copper, which is an excellent electrical conductor among metals, with a very competitive price comparing to the other options. The contact tip has the function to transfer the current to the consumable wire until it makes contact to the base metal surface. The GMAW process stability is very sensitive to small changes in the contact tip condition. For this reason, it was necessary to change the contact tip during some experiments, when some imperfection was detected, to avoid poor weld deposition and problems in the wire feed.

Figure 14: Gas nozzle and contact tip

4.4.5 Clamp Multimeter

The current readings for the research used the MS2108A auto range digital clamp multimeter from the AIMO meter company, as shown in Figure 15. This instrument can measure the current up to 400 amps. The clamp multimeter was adjusted to do the measurements in a direct current (DC) mode (electrons flow in one same direction) because the GMAW machine was working in a DCEP polarity.

Figure 15: Clamp multimeter

A cell phone camera with a support device was used to record a video of the current readings on the clamp multimeter during the welding. The VLC video program in the computer was used to modify the video into two screenshots per second, as the current fluctuates twice per second, to be easier to read the values. The current values were transferred to an excel spreadsheet, and the average of them was taken to have one reading for each experimental run and make all the necessary calculations.

The current readings are crucial for accurate results. If the current reads are too low, the contact tip may be damaged, or the wire diameter may be undersized. If the current readings are too high, the wire diameter may be oversized. It is recommended to check the current reading before considering the results.

4.4.6 Filter

The filter for all experiment was the TFAGF205 Glass Fiber Filter from Staplex Inc. with an 8.07 in (204.978mm) diameter, a pore size of 4 μm, and a capacity to capture fumes of 99.9%. Figure 16 shows the a) filter, b) filter support to the chamber and c) the filter with fumes after the experiment. The filter pads needed to be uniform in appearance and the fiber distribution, cuts, tears, holes, and voids are not acceptable. The Ziplocs were used to put the filters before and after each experiment to avoid any moisture contact or filter contamination.

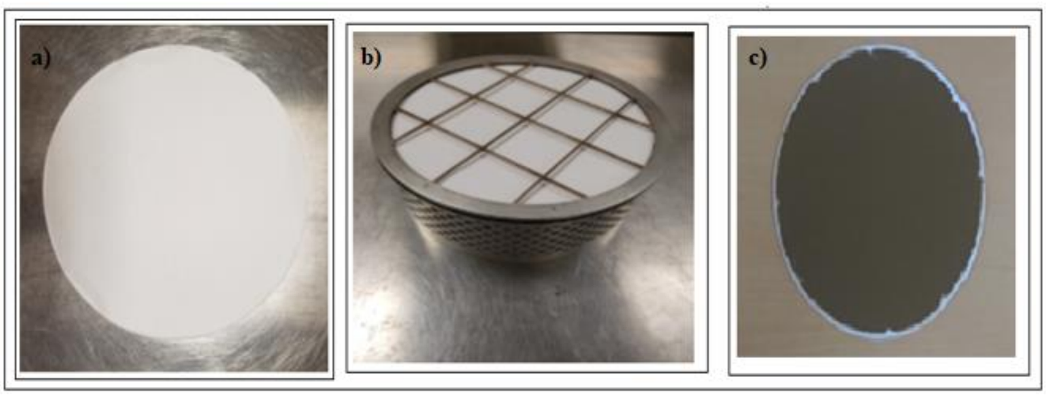

Figure 16: Glass fiber filter procedure

4.4.7 Test Chamber

All the experiments occur in a conical test chamber, designed by Delweld Industries Corporation. This machine can capture the welding fumes generated during the welding activities on an eight-inches diameter filter in a controlled environment. The device was built using AWS standards. However, there was a reduction in the support screen cross-sectional. Figure 17 shows the weld fume chamber used in this research.

Figure 17: Fume chamber UNO

As presented in Figure 17, a window is placed in the center of the chamber to provide visibility for setting up and observing the welding activity. It is also possible to see the four leaving bolts responsible for maintaining an air gap of about ½ to ¾ in (13mm to 19mm) between the base of the chamber and the surface on which it rests. The filter assembly used to collect the fumes consist of:

- The filter
- Filter support

The chamber is designed to maintain an air gap between the turntable and the conically shaped part so that ambient air can be drawn into the weld fume chamber and directing the fumes towards the filter. Furthermore, the UNO fume chamber is composed of four wheels, making the chamber transportation very easy. The experiments occurred in a semi-automatic machine with a rotated turntable that rotates a plate inside the fume chamber. In this semi-automatic process, a torch can be positioned inside the chamber through one of the hand holes and held at the appropriate CTWD distance. The operator needs to insert an arm through the holes to press the weld gun and do the experiment. For accurate results, careful attention is necessary for setting up the process parameters and operational conditions.

In the weld fume, chamber control panel (Figure 18) an "on/off" switch control the blower flow

rate, another on/off switch control the turntable. Furthermore, there is a volumetric air flow gauge in cubic feet per minute (CFM) that can make the flow reading and measure the quantity of air flow drawn inside the chamber. The pressure drop gauge is also presented in the control panel, and it is used to measure the differential pressure across the filter to indicate the degree to which the filter is loaded. To avoid overloading, the pressure drop should not exceed 40 inches of water. As more fumes are deposited in the filter pad, more the pressure drop across the filter will increase, until a possible clogging occurs. The filter pad capacity is about 2 g according to AWS (AWS, 2013). That is why it is essential to check the pressure drop during the experiments.

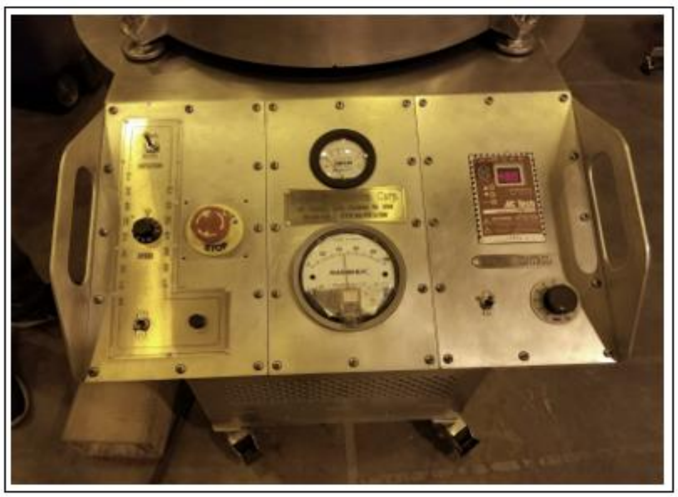

Figure 18: Weld fume chamber panel of control

4.4.8 Welding Machine

The Millermatic 252 welding machine manufactured by Miller Inc., was used in this research, as shown in Figure 19. In this machine, it is possible to set the voltage and the wire feed speed for the welding activity. Furthermore, an external cylinder gas is attached to the machine during welding, to guarantee a better bead by using the shielding gas to protect the weld from the atmosphere contaminants.

Figure 19: Welding machine

4.4.9 Oven

The oven from the Despatch brand, as shown in Figure 20, was used to take the possible filter humidity before and after each experimental run, to assure correct results. The temperature inside the oven was set up to be in between 200 °F to 225 °F (93 °C to 107 °C) for all the experiments.

Figure 20: Despatch oven

4.4.10 Balance

After taken the filters from the oven, the initial weight of the filters is measured in grams, using the AD50 Torbal sensitive balance (Figure 21). The final weight of the filters is also measured after each experiment run, using the same scale. However, in the final weight measurements, the

filters are folded to secure the welding fumes. The initial and final weight is entered manually in an excel spreadsheet for further calculations on FFR and total fume EFs. The AWS recommends a minimum weight of fume collected to be 0.2 g or more for consistent results (AWS, 2013).

Figure 21: AD50 Torbal sensitive balance

4.4.11 Welding Personal Protective Equipment (PPE)

For safety propose, during the welding activity, all the equipment described in Table 5 were used. In Figure 22 the welding helmet, leather jacket and leather gloves used are from Lincoln Electric company.

Figure 22: Welding personal protective equipment

5. Results and Discussion

According to the literature, the current and the voltage are the variables that can cause the most impact on the fume formation process (Weman, 2011; Kou, 2003; Pires at. all, 2007). For this reason, the experiments were designed with a low (22), medium (26) and high voltage (29) and with a low (180), medium (220) and high (260) current, keeping all the other variables constant for each base metal and their respective electrodes and shielding gas mixtures. Below, the considered variables in this thesis study.

- Process Parameters:
  - Base metal (AH36 mild steel, 316L stainless steel),
  - Electrode (ER 70S-6, ER 316LSi).
- Operating Conditions:
  - Current (low (180), medium (220) and high (260)),
  - Voltage (low (22), medium (26) and high (29)),
  - Shielding Gas (Ar+25%CO_2 for mild steel, Ar +2% O_2 for stainless steel).

The objective of this thesis is to play with the combination of those process parameters and operational conditions to see the variations in the welding fume formation. This thesis is composed of nine different scenarios, in which each scenario was repeated three times to examine the repeatability of the experiments, and the results presented are the average of these measurements. The total experimental runs for each base metal was 27, resulting in 54 experiments in total. This section shows the average results for the HI, FFR, and total fume EFs calculations for each base metal. It is important to highlight that:

- The calibration results (Table 8) of this thesis varies no more than ± 20% from the values given in AWS manual, indicating that the fume chamber was in compliance with the standards.
- The EFs computed in this research correspond to a controlled environment since the samples were collected in a special emission chamber with the proper design for this kind of procedure. Also, the emissions presented in this research corresponds to uncontrolled emissions since the samples were collected without applying any emission controls.
- All the experiments were performed at the University of New Orleans in October,

November, and December 2018. The data from each trial was noted in an Excel spreadsheet and then analyzed to compute the results.

5.1 Current Analysis

For quality purpose, there should be no more than 10% difference between the desired current and the recorded current for the experiment to be considered, according to the AWS F1.2:2013 (AWS, 2013). All the calculations were made with the average recorded current.

Table 11 and Table 12 present the average of MS recorded current experiments and the average SS recorded current experiments variate less them 10%, demonstrating that those values are very close to the desired ones and the results can be considered.

5.1.1 Average Current Results for Mild Steel Experiments

Table 11: Average recorded current results for mild steel experiments

S.NO	Desired Current (A)	Average Recorded Current (A)	Percentage Difference %
1	180	163.89	8.95
2	220	215.35	2.11
3	260	251.84	3.14
4	180	167.34	7.03
5	220	213.10	3.14
6	260	243.14	6.48
7	180	169.52	5.82
8	220	217.82	0.99
9	260	252.80	2.77

5.1.2 Average Current Results for Stainless Steel Experiments

Table 12: Average recorded current results for stainless steel experiments

S.NO	Desired Current (A)	Average Recorded Current (A)	Percentage Difference %
1	180	167.62	6.88
2	220	212.82	3.26
3	260	244.03	6.14
4	180	168.95	6.14
5	220	212.49	3.41
6	260	240.47	7.51
7	180	164.43	8.65
8	220	198.26	9.88
9	260	239.19	8

5.2 Fume Formation Rate and Heat Input Average Results

In the welding activity, the FFR (g/min), as described before, is the difference between the final weight and the initial weight of a filter divided by the arc time. For this reason, special care in the filter weight process was taken to guarantee precise results. According to Heile and Hill (1975), the factors that can cause higher FFR are the increase in the droplet temperature, lower metal transfer stability, and especially higher HI. The HI corresponds to electrical energy supplied by the welding arc to the workpiece. Table 13 and 14 present the average HI for the experiments.

Table 13: Average heat input for mild steel experiments

S.NO	Voltage (V)	Desired Current (A)	Record Current (A)	Average HI (KJ/min)
1	22	180	163.89	0.43
2	22	220	215.35	0.57
3	22	260	251.84	0.66
4	26	180	167.34	0.52
5	26	220	213.10	0.66
6	26	260	243.14	0.76
7	29	180	169.52	0.59
8	29	220	217.82	0.76
9	29	260	252.80	0.88

Table 14: Average heat input for stainless steel experiments

S.NO	Voltage (V)	Desired Current (A)	Recorded Current (A)	Average HI (KJ/min)
1	22	180	167.62	0.44
2	22	220	212.82	0.56
3	22	260	244.03	0.64
4	26	180	168.95	0.53
5	26	220	212.49	0.66
6	26	260	240.47	0.75
7	29	180	164.43	0.57
8	29	220	198.26	0.69
9	29	260	239.19	0.83

- Comparing Table 13 and Table 15; Table 14 with and Table 16, it is possible to see that current and voltage have some influence in the HI.
- HI, and FFR are directly related; an increase in HI can increase the FFR.
- As observed in Table 13 / Table 15 and Table 14/ Table 16, at low current (180A), with a low HI, the FFR is low, and fewer fumes are created.
- As shown in Table 13 / Table 15 and Table 14 / Table 16, high current (220A/ 260 A) have higher HI and high FFR, creating more fumes.

It is generally accepted that FFR increases with welding current, due to increment in the arc temperature and instability (Pires et al., 2007). However, this relationship is not entirely linear, due to the different metal transfer modes that are influenced by the variations in the current, the type of electrode, wire diameter, and shielding gas used (Castles and French, 1995). Some authors have noticed a decrease in FFR at the transition point between globular and spray transfer (Yastes at. Al, 1992), and others found little correlation between current and FFR (Gray, 1992), even when using the appropriate voltage for the corresponded current. Furthermore, the voltage effect on FFR is not so well defined yet (Melton, 2012). However, some studies have reported that changes in the voltage can have a significant influence on the FFR (Carter, 1998 and Willingham 1986). According to Melton (2012), there are still some debates about fume formation mechanism in the literature, and further studies are required.

- If the welding machine used in this thesis could range higher voltages values (32-34V), the visualization of the FFR drops and rises would be more apparent. According to the literature, if it was possible to do more experiments with even higher voltage levels, the fume emissions would rise again due to the arc instability (Castles and French, 1995).
- The FFR decreases with arc stability and produces less spatters (material that is projected for regions outside the influence of shielding gas, which normally oxidize and vaporized to the atmosphere as a fume emission).
- Considering the dimension of the parameters analyzed, the experiment that has highest FFR for the MS was the Table 15 experiment 8 (220A, 29V, 0.5 g/min) and for the SS was the Table 16 experiment 9 (260 A, 29 V, 0.38 g/min). As expected, high current and high voltage can emit more fumes.
- The FFR for the MS experiments is higher than the FFR from the SS experiments.
- The experiment with lowest FFR for the MS was the Table 15 experiment 1 (180A, 22 V, 0.23 g/min) and for the SS was the Table 16 experiment 4 (180 A, 26 V, 0.03 g/min).
- In Table 15 it is possible to see that the fume emissions increase with the increase in voltage. Hoverer, in Table 16, for the SS experiments 4 and 7 with low current and medium and high voltage, lower fumes were observed. In appendix D, additional experiments were made to see the use of different shielding gas mixtures with the voltage variations. Moreover, a smooth arc sound was heard during those experiments, without generating significant spatter and creating the lowest fume emission scenario. The use of high-speed camera could help us to understand the reasons why fume generation is that low at these combinations for the SS base metal using the Ar +2% O_2 shielding gas. These results are inconclusive and need to be investigated by further researchers.

5.2.1 Average Fume Formation Rate for Mild Steel Experiments

Table 15: Average fume formation rate for mild steel experiments

S.NO	Voltage (V)	Desired Current (A)	Record Current (A)	Average FFR (g/min)
1	22	180	163.89	0.23
2	22	220	215.35	0.25
3	22	260	251.84	0.36
4	26	180	167.34	0.34
5	26	220	213.1	0.44
6	26	260	243.14	0.38
7	29	180	169.52	0.45
8	29	220	217.82	0.5
9	29	260	252.8	0.41
			Average	0.37

5.2.2 Average Fume Formation Rate for Stainless Steel Experiments

Table 16: Average fume formation rate for stainless steel experiments

S.NO	Voltage (V)	Desired Current (A)	Recorded Current (A)	Average FFR (g/min)
1	22	180	167.62	0.21
2	22	220	212.82	0.23
3	22	260	244.03	0.26
4	26	180	168.95	0.03
5	26	220	212.49	0.31
6	26	260	240.47	0.37
7	29	180	164.43	0.05
8	29	220	198.26	0.33
9	29	260	239.19	0.38
			Average	0.24

5.3 Total Fume Emission Factor Average Results

The total fume emission factor (g-weld fume/kg-weld wire) is the difference between the final weight and the initial weight of a filter divided by the electrode consumed.

- The highest EF for the MS experiments (ER70S-6 electrode) is the experiment 7 in Table 17 (EF = 11.05 g/kg) and for the SS experiments (ER 316L-Si electrode) is the experiment 8 in Table 18 (EF = 4.54 g /kg).
- The lowest EF for the MS experiments (ER70S-6 electrode) is the experiment 2 in Table 17 (EF = 4.45 g/kg) and for the SS experiments (ER 316L-Si electrode) is the experiment 4 in Table 18 (EF = 0.67 g/kg).
- The EPA (1994) GMAW average EF for the ER70S-6 electrode is 5.2 g/kg (emission factor rating A), while the average results for this study were 6.81 g/kg and for the Keane et all (2014) was 6.4g/kg. The EPA average EF for the ER 316L-Si electrode (emission factor rating C) is 3.2 g/kg, while the results for this study was 3.28 g/kg.
- Since the EFs results for this study was conducted using sound methodology with proper documentation; the generated data can be used by EPA to update the AP42 emission factors inventory.

5.3.1 Average Total Fume Emission Factor for Mild Steel Experiments

Table 17 presents the GMAW results for the MS experiments utilizing the ER70S-6 electrode.

Table 17: Average total fume emission factor for mild steel experiments

S.NO	Voltage (V)	Desired Current (A)	Record Current (A)	Emission Factor (g/kg of electrode consumed)
1	22	180	163.89	5.61
2	22	220	215.35	4.45
3	22	260	251.84	4.88
4	26	180	167.34	8.28
5	26	220	213.1	7.65
6	26	260	243.14	5.05
7	29	180	169.52	11.05
8	29	220	217.82	8.7
9	29	260	252.8	5.59
			Average	6.81

5.3.2 Average Total Fume Emission Factor for Stainless Steel Experiments

Table 18 presents the GMAW results for the SS experiments utilizing the ER 316L-Si electrode.

Table 18: Average total fume emission factor for stainless steel experiments

S.NO	Voltage (V)	Desired Current (A)	Recorded Current (A)	Emission Factor (g/kg of electrode consumed)
1	22	180	167.62	4.47
2	22	220	212.82	3.44
3	22	260	244.03	2.94
4	26	180	168.95	0.67
5	26	220	212.49	4.35
6	26	260	240.47	4.13
7	29	180	164.43	0.93
8	29	220	198.26	4.54
9	29	260	239.19	4.08
			Average	3.28

6. Conclusion

The mechanisms responsible for the fume formation are complex. However, the control of welding fumes at the source by modification of process parameter and operational conditions can be used to complement existing control strategies, contributing to reduce the fume emission and provide a healthier environment for the workers. The objective of this thesis was to determine total fume emission factors for GMAW under various current and voltage settings. EFs were determined for both, mild steel (MS – AH36) and stainless steel (SS – 316L). The methodology used in this work complies with AWS recommended quality requirements and allowed in the determination of new emissions data. Some of the main highlights of this thesis are:

- Current and voltage have some influence in the HI.
- HI, and FFR are directly related; an increase in HI can increase the FFR.
- By selecting the right welding current intensity and voltage, the FFR can be reduced. Whenever it is possible, welders should use the lowest current intensity as possible to perform welding. However, thicker base metals may need higher voltage and current to accomplish ideal penetration which may result in higher emissions. In those situations, welders should be protected against excessive exposures.
- The MS base metal can produce more fumes than the SS base metal.
- The EPA (1994) GMAW average EF for the ER70S-6 electrode is 5.2 g/kg (emission factor rating A), while the average results for this study were 6.81 g/kg and for the Keane et all (2014) was 6.4g/kg. The EPA average EF for the ER 316L-Si electrode (emission factor rating C) is 3.2 g/kg, while the results for this study was 3.28 g/kg.
- According to the EPA databased (Table 3), the electrodes ER316L-Si, largely used in the shipbuilding industry, have a very low emission factor rating (EF rating C), indicating the need for more research using this electrode. Since the EFs results for this study was conducted using sound methodology with proper documentation and they are consistent with the literature; the generated data could be used by EPA to update the AP42 emission factors inventory for the ER70S-6 and ER 316L-Si electrodes.
- The EFs results in this research can also be used for assessing public health risks, and the presented methodology can inspire other researches to measure other EFs for different pollutants.

- Federal agencies like EPA, OSHA, NIOSH, can use this thesis information in their database to protect public health.
- Entities like the American Conference of Governmental Industrial Hygienists (ACGIH) can also use this work to provide information for the scientific community to protect the workers' health.
- Private entities and industries can use this thesis to reduce worker exposure and reduce the work risks of welding in a confined space. This research can also be used as a guide for the industries to stay in compliance with OSHA and USEPA regulations.

7. Limitations and Future Recommendations

7.1 Limitations

- Only a limited number of samples could be obtained for this welding process due to lack of funding.
- The welding machine Millermatic 252 used for in this thesis, has the voltage range until 29.5 V, limiting the experiments.
- Additional equipment such as a high-speed camera to evaluate metal transfer modes in GMAW would have improved this thesis work for better understanding the fume formation mechanisms.

7.2 Recommendations

- It is recommended for future researchers to compute the FFR with higher voltages (>29 V) to see the effect on the fume formation process.
- Future studies could also do the heavy metal analyses and particle size distribution in complement to this thesis work.
- A high-speed camera can be used for further researches to have a better understanding of the welding fume formation mechanism.
- A study with different shielding gas mixtures to analyze the FFR is recommended for future researchers.
- There is still considerable debate in the literature about the fume formation mechanisms, and further studies are required to gain a better understanding

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9. Appendix

9.1 Appendix A – Calculations for the Electrode Consumption

10 inches of electrode weighted is (2.038 g) for MS and SS experiments and, according to Figure 12, the WFS to achieve the same desired current is different for each electrode used with their correspondent diameter (ER70S-6 for the MS experiments, ER316LSi for the SS experiments). Below in Table 15 and Table 16 the desired current, the corresponded WFS, and electrode consumption for each electrode used:

Table 19: Desired Current, the Corresponded WFS, and Electrode Consumption for ER70S-6

Desired Current (A)	WFS (in/min)	Electrode Consumption (g)
180	200	20.38
220	280	28.53
260	365	37.19

Table 20: Desired Current, the Corresponded WFS, and Electrode Consumption for ER316LSi

Desired Current (A)	WFS (in/min)	Electrode Consumption (g)
180	235	47.89
220	250	71.33
260	435	88.65

- Observation: The electrode consumption for the SS experiments is higher than the MS experiments because the arc time for the SS experiments is higher (SS experiments = 1 minute, MS experiments = 30 seconds).

Calculations:

- Experiment 1-1 MS (180 A, 22 V): ER70S-6 for 30 sec. arc time (10 in wire = 2.038g):
  - 200 in/min: $\frac{2.038g}{10\ in}\ x\ \frac{200\ in}{1\ min}$ = 40.76 g/min = 20.38 g (in 30 seconds)
    - Ex. EF calculation = $\frac{(2.721\ g\ F.W.)-(2.614\ g\ I.W.)}{20.38\ g\ of\ electrode\ consuption}$ = 0.005250 g/g = 5.25 mg/g or 5.25 g/kg of electrode consumed
    - 5.25 g/kg x 20.38 g = 106.99 g of fumes emitted from 200 inches of ER70S-6 wire in 30 seconds.
  - 280 in/min = $\frac{2.038g}{10\ in}\ x\ \frac{280\ in}{1\ min}$ = 57.064 g/min = 28.53 g (in 30 seconds)
  - 365 in/min = $\frac{2.038g}{10\ in}\ x\ \frac{365\ in}{1\ min}$ = 74.387 g/min = 37.19 g (in 30 seconds)

- Experiment 1-1 SS (180 A, 22 V): ER316LSi for 1-min. arc time (10 in wire = 2.038g):
  - 235 in/min = $\frac{2.038g}{10\ in}\ x\ \frac{235\ in}{1\ min}$ = 47.89 g/min
    - Ex. EF calculation = $\frac{(2.9131\ g\ F.W.)-(2.641\ g\ I.W.)}{47.89\ g\ of\ electrode\ consuption}$ = 0.005681 g/g = 5.68 mg/g or 5.68 g/kg of electrode consumed
    - 5.68g/kg x 47.89 g/min = 272.015 kg of fumes emitted from 235 inches of ER316LSi wire in a minute.
  - 350 in/min = $\frac{2.038g}{10\ in}\ x\ \frac{350\ in}{1\ min}$ = 71.33 g/min
  - 435 in/min = $\frac{2.038g}{10\ in}\ x\ \frac{435\ in}{1\ min}$ = 88.65 g/min

9.2 Appendix B - Base Metal and Electrode Composition

The electrode ER70S-6 was used for the MS base metal AH36, and the electrode ER316LSi was used in the 316L SS base metal experiments. Below, Table 17 with the base metals and electrodes composition used in this thesis.

Table 21: Base Metal and Electrode Composition

Element (Weight %)	Base Metal		Electrode	
	AH36	316L	ER70S-6	ER316LSi
Carbon	0.18	0.030 max	0.06 – 0.15	0.03 max
Chromium	0.20	16.00 - 18.00	0.15 max	18.0 – 20.0
Copper	0.35	-	0.50 max	0.75 max
Columbium	0.02/0.05	-	-	-
Iron	-	Balance	-	-
Manganese	0.90/1.60	2.00 max	1.40 – 1.85	2/0 – 3.0
Molybdenum	0.08	2.00 - 3.00	0.15 max	-
Nickel	0.40	10.00 - 14.00	0.15 max	11.0 – 14.0
Nitrogen	-	0.10 max		-
Phosphorus	0.035	0.045 max	0.025 max	0.03 max
Silicon	0.10/0.50	0.75 max	0.80 – 1.15	0.65 – 1.00
Silver	-	-		-
Sulfur	0.035	0.030 max	0.035 max	0.03 max
Titanium	-	-	-	-
Vanadium	0.05/0.10	-	0.03 max	-

Some of the elements present in the base metal in Table 15 have been identified by the Environmental Protection Agency (EPA) as harmful if chronic exposure to these pollutants occurs. Source: AWS Chemical Composition Requirements (2018).

9.3 Appendix C - Experimental Results for all Scenarios

9. 3.1 Mild Steel Experiments

Table 22: Mild Steel Experiments Recorded Current

S.NO	Voltage (V)	Desired Current (A)	Run 1 (A)	Run 2 (A)	Run 3 (A)	Average (A)	Percentage Difference %
1	22	180	156.87	166.87	167.92	163.89	8.95
2	22	220	220.01	210.58	215.46	215.35	2.11
3	22	260	255.45	251.48	248.58	251.84	3.14
4	26	180	163.93	167.71	170.39	167.34	7.03
5	26	220	213.25	208.49	217.57	213.10	3.14
6	26	260	241.54	245.99	241.89	243.14	6.48
7	29	180	175.05	168.96	164.54	169.52	5.82
8	29	220	220.31	217.18	215.98	217.82	0.99
9	29	260	246.07	259.15	253.18	252.80	2.77

Table 23: Mild Steel Experiments Heat Input

S.NO	Voltage (V)	Desired Current (A)	Record Current (A)	Average HI (KJ/min)
1	22	180	163.89	0.43
2	22	220	215.35	0.57
3	22	260	251.84	0.66
4	26	180	167.34	0.52
5	26	220	213.10	0.66
6	26	260	243.14	0.76
7	29	180	169.52	0.59
8	29	220	217.82	0.76
9	29	260	252.80	0.88

Table 24: Mild Steel Experiments Weld Fume Formation Rate

S.NO	Voltage (V)	Desired Current (A)	Record Current (A)	Run 1 (g/min)	Run 2 (g/min)	Run 3 (g/min)	Average (g/min)
1	22	180	163.89	0.22	0.24	0.22	0.23
2	22	220	215.35	0.25	0.25	0.24	0.25
3	22	260	251.84	0.37	0.35	0.37	0.36
4	26	180	167.34	0.32	0.36	0.33	0.34
5	26	220	213.10	0.46	0.42	0.45	0.44
6	26	260	243.14	0.41	0.31	0.40	0.38
7	29	180	169.52	0.51	0.44	0.39	0.45
8	29	220	217.82	0.51	0.48	0.50	0.50
9	29	260	252.80	0.40	0.42	0.42	0.41

Table 25: Mild Steel Experiments Total Fume Emission Factor

S.NO	Voltage (V)	Desired Current (A)	Record Current (A)	Run 1 (g/kg)	Run 2 (g/kg)	Run 3 (g/kg)	Average (g/kg)
1	22	180	163.89	5.28	5.87	5.67	5.61
2	22	220	215.35	4.44	4.51	4.41	4.45
3	22	260	251.84	4.92	4.86	4.85	4.88
4	26	180	167.34	7.81	8.78	8.26	8.28
5	26	220	213.10	7.98	7.31	7.66	7.65
6	26	260	243.14	5.57	4.13	5.44	5.05
7	29	180	169.52	12.60	10.84	9.70	11.05
8	29	220	217.82	9.01	8.33	8.76	8.70
9	29	260	252.80	5.40	5.64	5.72	5.59

9.3.2 Stainless Steel Experiments

Table 26: Stainless Steel Experiments Recorded Current

S.NO	Voltage (V)	Desired Current (A)	Recorded Current (A)	Run 1 (A)	Run 2 (A)	Run 3 (A)	Average (A)	Percentage Difference %
1	22	180	167.62	174.81	164.93	163.12	167.62	6.88
2	22	220	212.82	211.69	208.95	217.82	212.82	3.26
3	22	260	244.03	246.01	247.83	238.25	244.03	6.14
4	26	180	168.95	166.34	176.40	164.11	168.95	6.14
5	26	220	212.49	212.82	208.93	215.73	212.49	3.41
6	26	260	240.47	246.86	236.73	237.82	240.47	7.51
7	29	180	164.43	155.87	167.93	169.48	164.43	8.65
8	29	220	198.26	188.41	201.66	204.72	198.26	9.88
9	29	260	239.19	238.03	243.17	236.36	239.19	8

Table 27: Stainless Steel Experiments Heat Input

S.NO	Voltage (V)	Desired Current (A)	Recorded Current (A)	Average HI (KJ/min)
1	22	180	167.62	0.44
2	22	220	212.82	0.56
3	22	260	244.03	0.64
4	26	180	168.95	0.53
5	26	220	212.49	0.66
6	26	260	240.47	0.75
7	29	180	164.43	0.57
8	29	220	198.26	0.69
9	29	260	239.19	0.83

Table 28: Stainless Steel Experiments Weld Fume Formation Rate

S.NO	Voltage (V)	Desired Current (A)	Recorded Current (A)	Run 1 (g/min)	Run 2 (g/min)	Run3 (g/min)	Average (g/min)
1	22	180	167.62	0.27	0.15	0.21	0.21
2	22	220	212.82	0.24	0.23	0.23	0.23
3	22	260	244.03	0.27	0.25	0.26	0.26
4	26	180	168.95	0.030	0.031	0.030	0.030
5	26	220	212.49	0.30	0.31	0.31	0.31
6	26	260	240.47	0.36	0.38	0.37	0.37
7	29	180	164.43	0.05	0.04	0.05	0.05
8	29	220	198.26	0.30	0.35	0.35	0.33
9	29	260	239.19	0.35	0.37	0.41	0.38

Table 29: Stainless Steel Experiments Total Fume Emission Factor

S.NO	Voltage (V)	Desired Current (A)	Recorded Current (A)	Run 1 (g/kg)	Run 2 (g/kg)	Run 3 (g/kg)	Average (g/kg)
1	22	180	167.62	5.68	3.20	4.53	4.47
2	22	220	212.82	3.35	3.35	3.37	3.44
3	22	260	244.03	3.06	2.80	2.95	2.94
4	26	180	168.95	0.63	0.68	0.71	0.67
5	26	220	212.49	4.27	4.29	4.50	4.35
6	26	260	240.47	4.05	4.28	4.05	4.13
7	29	180	164.43	1.02	0.86	0.91	0.93
8	29	220	198.26	4.15	4.92	4.56	4.54
9	29	260	239.19	3.99	4.21	4.04	4.08

9.3.3 Mild Steel and Stainless-Steel Experiments Graphics

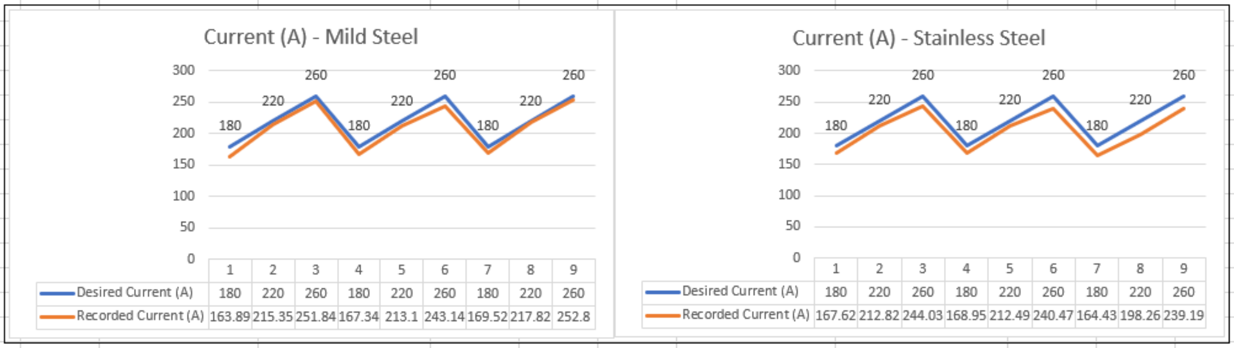

Figure 23: Mild Steel and Stainless-Steel Experiments for Recorded Current

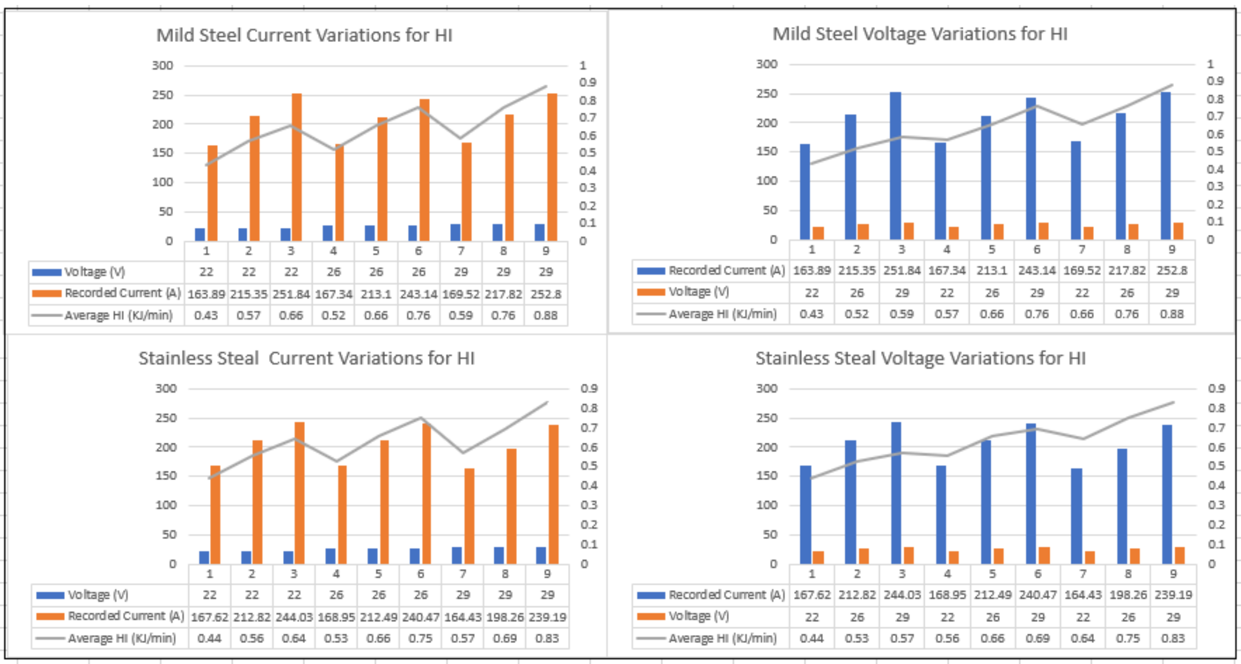

Figure 24: Mild Steel and Stainless-Steel Experiments for Heat Input

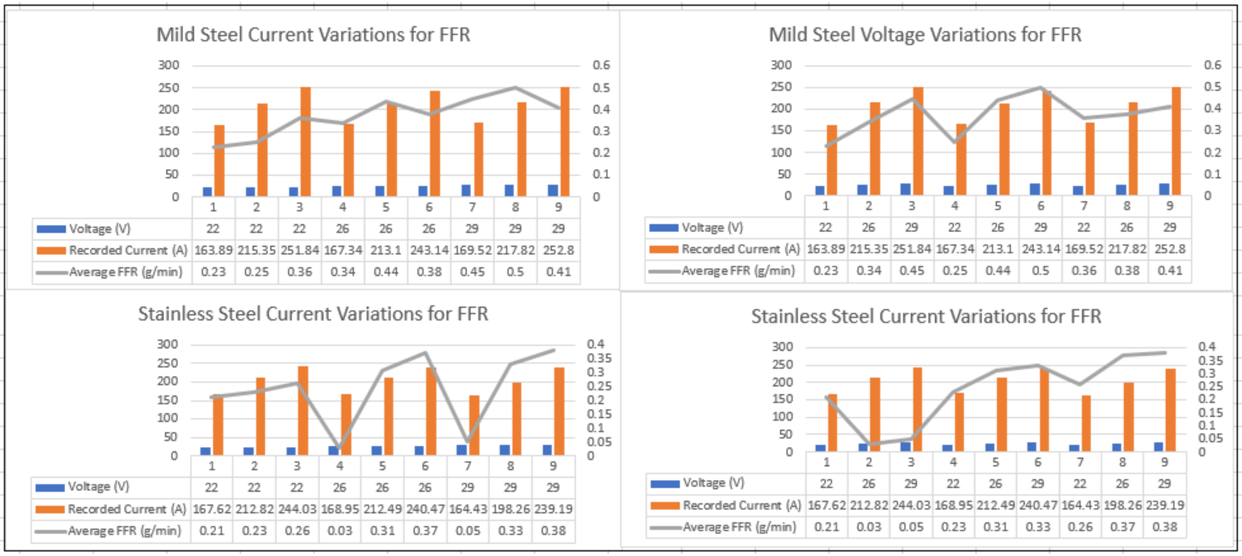

Figure 25: Mild Steel and Stainless-Steel Experiments for Weld Fume Formation Rate

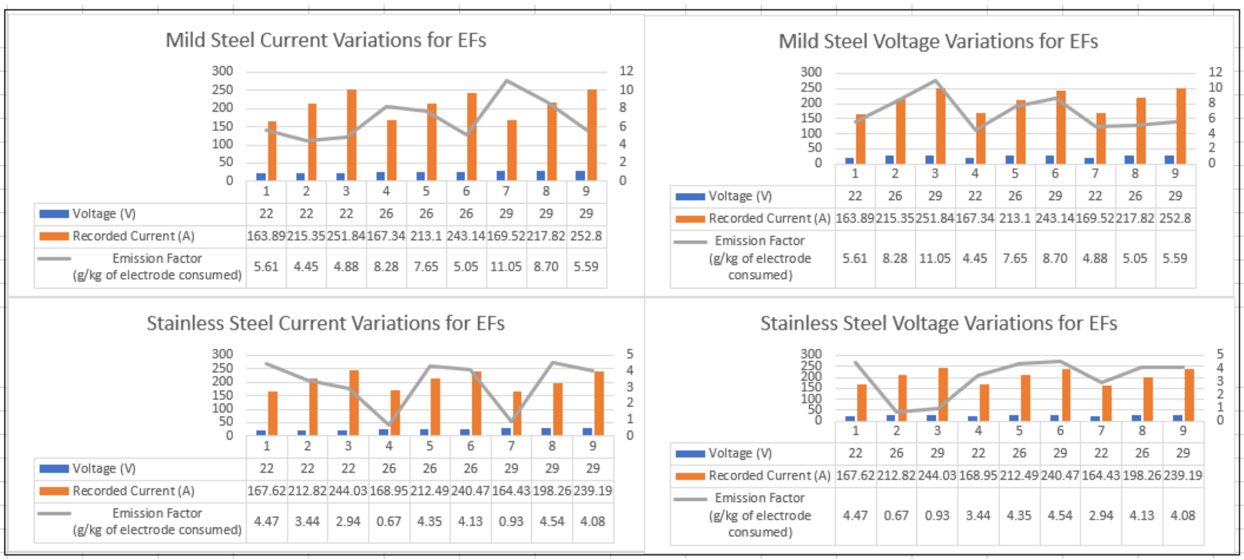

Figure 26: Mild Steel and Stainless-Steel Experiments for Emission Factors

9.4 Appendix D – Shielding Gas Experiment with Voltage Variations

The composition of the shielding gas can interfere in the FFR. The emission rate can increase with higher concentrations of active components (i.e., oxygen and carbon dioxide). For mixtures with argon and oxygen, there is a shorter range of welding current and voltages to obtain a stable spray transfer mode when comparing to a mixture with argon and CO_2 (Helie and Hill, 1975). According to the same authors, the argon arc length is much more sensitive to voltage changes than the CO_2 arc length. This reduction in the fume emission can be related to a metal transfer mode (globular to spray) wherein a uniform droplet is transferred to the wire electrode at a smooth arc sound, being wholly enveloped in the arc and without generating significant spatter. However, according to the Table 30 and Figure 27, it is possible to observe this phenomenon for low current and high voltage values when using the Ar +2% O2 shielding gas

- Performing welding w/o gas produce higher levels of fumes
- Low current 180 A with midium and high voltages level 24 -29 V is responsible for the lowest EFs when Ar +2% O2 shielding gas is used.
- For low current 180 A with midium and high voltages level 24 -29 V when using the Ar+ 25%CO2, the emissions values are consistent with the ones presented in the literature.

Table 30: Shielding Gas Experiment with Voltage Variations

S.NO	Voltage (V)	WFS (in/min)	Desired Current (A)	Shielding Gas	Average FFR (g/min)	Emission Factor (g/kg of electrode consumed)
1	23	200	180	Ar +2% O2	0.18	4.46
2	24	200	180	Ar +2% O2	0.03	0.74
3	25	200	180	Ar +2% O2	0.03	0.74
4	26	200	180	Ar +2% O2	0.03	0.67
5	29	200	180	Ar +2% O2	0.05	0.91
6	26	200	180	Ar+25%CO2	0.34	8.28
7	29	200	180	Ar+25%CO2	0.45	11.05
8	24	200	180	W/O	0.79	19.33
9	25	200	180	W/O	0.91	22.3

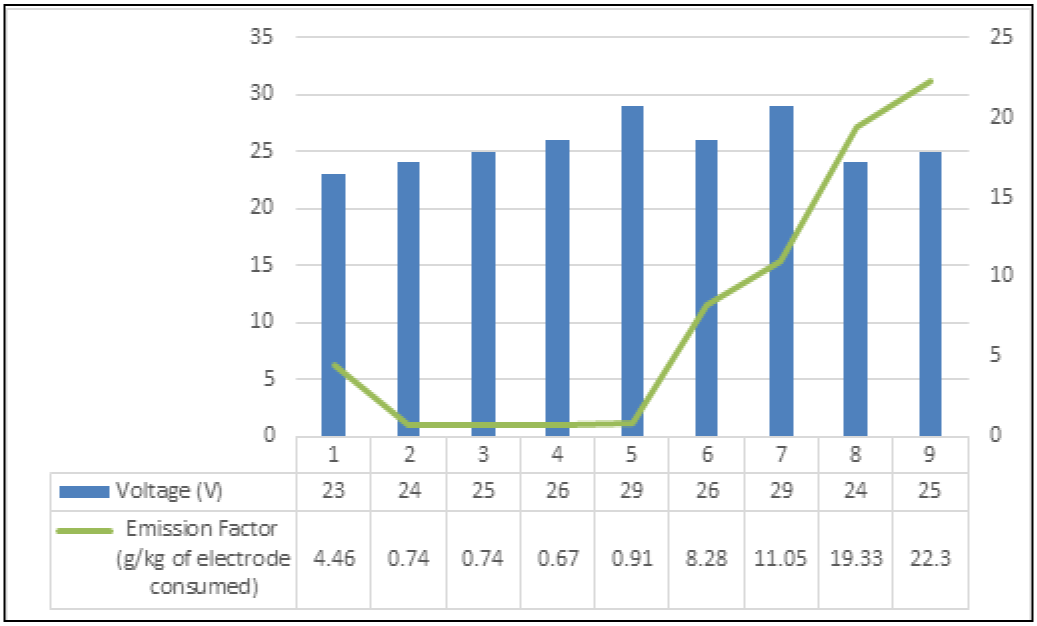

Figure 27: Shielding Gas Experiment with Voltage Variations

Vita

Nayara de Souza was born in Botucatu, Brazil on June 20, 1991. She graduated from the University of Sorocaba in 2015 and received a fully funded scholarship from the Brazilian Government (Brazil Scientific Mobility Program 2014 - 2015), to study four terms at Portland State University. Later she joined University of New Orleans (UNO), Louisiana to obtain master's degree in Civil and Environmental Engineering, working as a Graduate Research Assistant in Civil & Environmental Engineering under Dr. Bhaskar Kura supervision. Nayara served as President of "Brazilian Student Association" (2014 - 2015) at Portland State University and worked as a volunteer in the Oregon Food Bank (November 2014). In June 2012 Nayara joined the Brazilian Association of Lifecycle (ABCV), in 2015 she was invited to make part of the IIE Alumni Community (August 2015 – present), Omicron Delta Kappa Honor Society (March 2018-present), Air & Waste Management Association (April – present) and Tau Beta Pi Honor Society (May–present). She participated in the International Conference on Life Cycle Assessment (CILCA) in Mendoza, Argentina 2012 and presented a paper in the XIX International Encounter on Business Management and Environment 2016. In 2018 she submitted an article in the third international symposium on naval architecture and maritime in Turkey. As honors, Nayara received the PROBIC Scholarship in 2013, the Brazil Scientific Mobility Program scholarship in 2014, was nominated Inspirational Student by Portland State University 2015, was considered a Featured Student by Brazil Scientific Mobility Program 2015, and in 2018 received the Louisiana Section of Air & Waste Management Association (A&WMA) Tuition Scholarship Award.