INTERNATIONAL SCIENTIFIC AND PROFESSIONAL CONFERENCE
POLITEHNIKA 2023
Belgrade, 15th December 2023

ENVIRONMENT AND SUSTAINABLE DEVELOPMENT. MECHATRONICS. OCCUPATIONAL SAFETY AND HEALTH AND FIRE SAFETY. SMART MANAGEMENT SYSTEMS. GRAPHIC ENGINEERING. DESIGN. TRAFFIC ENGINEERING. BIOTECHNOLOGY AND HEALTHCARE. MECHANICAL ENGINEERING. ECOTOURISM AND RURAL DEVELOPMENT.

A STUDY ON THE ENVIRONMENTAL AND HEALTH IMPACT OF HAZARDOUS SUBSTANCES DURING WELDING

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Abstract: *Welding is a major joining process in modern manufacturing, primarily used for creating metal structures and components, as well as maintenance and repair operations. Welding, compared to other production processes, is regarded as a hazardous procedure that can have long-term detrimental consequences for persons and the environment. It's critical to be aware of these consequences and consider the possibility of employing environmentally friendly methods. Each welding process has distinct risks and pollutant exposures, thus choosing the proper technique for a given application with the lowest risk of hazards is critical. This article includes a technical and environmental overview of welding operations, as well as information on the major pollutants and their estimations. The effect of welding conditions, parameter optimization, operation, and materials on the formation of key contaminants is investigated and analyzed. The purpose of this study is to raise awareness of the dangers of welding contaminants to the environment and human health. It also suggests ways to mitigate these risks and promotes the development of green welding technology.*
Keywords: fumes, gases, health dangers, welding processes

1. AIMS AND BACKGROUND

Welding plays a significant role in manufacturing, particularly in industries that use complex metal components and structures. It is a metal-joining fabrication process that employs high heat, pressure, or a combination of the two, with or without filler material, to create a strong and permanent connection between the assembling metal parts. The solidification of the molten metal at the interface of the joining parts results in metallurgical bonding, which forms a solid welded joint with improved properties over the base metal [1]. Today, there are numerous welding processes available for a wide range of applications, which can be divided into two categories: fusion welding and pressure welding. Fusion welding processes use electric arc, gas, electrical resistance, and high energy to generate heat at the location of the joint. Pressure welding also known as solid-state welding uses mechanical pressure to achieve coalescence through friction or explosion. Welding technologies also differ in terms of their economic performance and environmental impact, because of this, selecting a technology for a specific application is crucial for welding costs and environmental burdens [2]. In the manufacturing sector, there is no clear preference for welding technologies; however, basic material properties and other conditions that arise from the specific case of application, such as the number of joints, shape, and dimensions, loading, connection purpose, and so on, are important considerations. Electricity, radiation, heat, flames, fire, explosion, noise, welding fumes, fuel gases,

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inert gases, gas mixtures, and solvents are the most dangerous aspects of welding. However, it is considered that the most dangerous welding byproducts are fumes and gases. Welding processes generate a complex mixture of fine and ultrafine aerosols and gaseous harmful substances that are due to the intensive heat that vaporizes the base metal, and the electrode coating condenses into small particles [3, 5]. These chemical agents are fumes and particulates with aerodynamic diameters of less than 1 μm and can be easily inhaled and attached to human lungs causing serious illness to the affected individual [4, 5]. The welding fume and particulate matter mainly consist of particles from the evaporated electrode and a little part of the basic material with chemical compositions that depend on the welding technique, parameters, electrode, basic metal, and flux composition [6]. Metal oxides with chemical particulates such as lead, nickel, zinc, iron, oxide, copper, cadmium, fluorides, manganese, chromium, and gases such as carbon monoxide, nitrogen oxides, and ozone are the main components of the emissions [6, 7]. A summary of all the chemical, physical, and radiation hazards are shown in Table 1[8]. The gaseous by-products originate from chemical reactions, ultraviolet irradiation of atmospheric elements, or shielding gases. Together with welding nanoparticles, they represent a significant source of air pollution, and their size and distribution should be monitored and evaluated. Several factors influence the volume of fumes and gases produced (welding parameters, arc length, electrode, shielding gas, welder experience, humidity, welding technique). As a result, there are compelling reasons to address the type and methodology used during these processes to ensure a working environment with the least amount of air pollution possible.

Table 1. Common hazardous byproducts during welding

Source: National Institute for Occupational Safety and Health, 2022 [8]

Fume	Aluminum, Cadmium, Chromium, Copper, Fluorides, Iron, Lead, Manganese, Magnesium, Molybdenum, Nickel, Silica, Titanium, Zink
Gases	Carbon Dioxide, Carbon Monoxide, Nitrogen oxide/dioxide, Ozone
Radiant energy	Ultraviolet, Visible, Infrared
Other Hazards	Heat, Noise, Vibration

The purpose of this article is to provide an overview of the major pollutants that affect worker health and the environment during welding. The results of several experimental studies on various welding processes are summarized to broaden knowledge and raise awareness of the potentially toxic effects of welding emissions.

2. RESULTS & DISCUSSION

2.1 Air pollution from welding

The hazardous air pollutants present at high temperatures during metal vaporization are the main source of concern in the welding process. As a result, electric arc welding is thought to emit these pollutants in substation quantities. Other welding processes, such as pressure welding, produce fewer fumes and are thus considered green welding technologies due to their lower operating temperatures Friction stir welding (FSW) and magnetic pulse welding (MPW) produce less pollution and emit no hazardous fumes because they do not require flux or fillers. Outgassing is also eliminated with diffusion welding. When compared to standard shielded metal arc welding (SMAW) and gas metal arc welding (GMAW), other techniques, such as laser arc hybrid welding (LAHW), have the lowest direct environmental impact. However, because the composition of the used wire is directly related to the composition of the fumes, gas tungsten arc welding (GTAW) emits fewer fumes than SMAW and GMAW. SMAW is considered a process that has negative health effects because there is a tendency to form hexavalent chromium [7]. Furthermore, high rates of toxic compound emissions are generated during SMAW stainless steel welding [7]. Plasma arc welding (PAW) is like the GTAW process and emits similar levels of air pollutants [7]. GMAW welding of aluminium produces more ozone than GTAW welding. Despite these environmental advantages, some of these techniques are impractical for specific applications or large jobs, so fusion welding processes remain the preferred method among manufacturers.

2.2 Polluting components

The chemical elements found in fumes are complex and highly dependent on the metal mixtures that evaporate at different rates and at different temperatures. Because most steels contain iron, silica, chromium, and nickel in varying amounts, the rates at which the alloying elements evaporate are also affected by element concentration. The fumes are primarily composed of manganese (Mn), nickel (Ni), chromium (Cr), cobalt (Co), and lead (Pb). Gaseous pollutants or greenhouse gases such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and ozone (O_3) are also present. The precise level of risk is determined by fume composition because each of these chemical elements and gases has a unique toxic effect that must be effectively controlled. Some of the chemical components in fumes and glass byproducts are discussed in the following paragraphs. When welding stainless steel or high alloy steel, chromium is measured in significant quantities. The concentration of hexavalent (Cr^{+6}) depends on the shielding gas, and it is a dangerous toxic compound with mutagenic potential that can cause lung cancer [8]. Nickel is commonly found when welding stainless steel and nickel alloys. It is a human carcinogen, and some studies show that the cancerogenic potency of different materials can vary significantly [8]. Dermatitis, pneumoconiosis, asthma-like lung disease, renal dysfunction, and respiratory tract irritation are also at increased risk [3, 4, 8]. Iron, in the form of iron oxide, can also be found in fumes. It is considered irritant dust with a low risk of causing chronic lung disease after inhalation, but these particles have been observed to accumulate in alveolar macrophages and the lung interstitium [8]. Welders develop pneumoconiosis known as siderosis because of long-term exposure to arc welding fumes [4]. Manganese can be found in most welding fumes, particularly when it is used as a flux agent in the coatings of SMAW electrodes, flux-cored electrodes, or as an alloying element, or when it is present in high concentrations in the base material [8]. As a symptom of chronic manganese poisoning, it affects the eyes and nose, and the central nervous system, and causes chemical pneumonitis and kidney damage [4]. The coatings of metal electrodes and flux-cored electrodes contain silica and fluorides. The silica is amorphous and non-cytotoxic, as opposed to the highly cytotoxic and crystalline form associated with silicosis [8]. Inhaling fluorine-containing gases has been shown to irritate the eyes, nose, and throat as well as harm the lungs, and occupational pulmonary exposure to particulate fluorides has been linked to occupational lung disease [3]. In addition, there is bone and joint damage, gastrointestinal symptoms, fluid in the lungs, and kidney dysfunction [3]. Long-term fluoride fume exposure can cause skeletal or dental fluorosis [4]. Exposure to zinc or zinc oxide in fumes is mostly caused by heated galvanized coatings on the base metal, which can cause acute respiratory illness [14]. Aluminum is found in fumes because it is used as an additive in many steels and nonferrous alloys, as well as welding electrodes, coatings, paint, electro-plated or sprayed elements, and filler wires [8]. Welding with aluminum encourages the formation of the pneumo-toxic gas Ozon, which can irritate the lungs. When welding copper and its alloys or using copper-coated GMAW electrodes, high concentrations of copper are possible. Vaporized copper and cadmium are metals known to cause metal fume fever [3]. Cadmium is an element that is used in the production of fluxes found in flux-cored electrodes on occasion [8]. Cadmium in welding fumes has been linked to acute chemical inhalation lung injury, and it is one of only a few welding-related exposures that can be fatal [8]. During arc welding processes, a large quantity of gases such as ozone, nitrogen oxides, carbon monoxide, and carbon dioxide are released. The airborne vapors around the arc undergo oxidation, which is aided by ultraviolet radiation from the welding arc, to produce phosgene, a pulmonary irritant gas [9]. Arc welding gases can be produced by shielding gases, decomposition of electrode coatings and cores, arc reaction with atmospheric constituents, ultraviolet light reaction with atmospheric gases, and decomposition of degreasing agents and organic coatings on the metal welded [9, 15]. Ozone is an allotropic form of oxygen produced by arc welding's UV radiation, which ionizes oxygen. The rate of ozone formation is determined by the wavelengths and intensity of ultraviolet light produced in the arc, which is influenced by the material being welded, the type of electrode used, the shielding gas, the welding process, and welding variables such as voltage, current, and arc length [9]. Ozone is a severe respiratory irritant that can cause extreme discomfort, nausea, coughing, and bronchitis at levels above 0.3 ppm, and pulmonary edema at levels above 10 ppm for several hours [8]. Nitrogen oxides are produced during welding processes because of direct oxidation of atmospheric nitrogen at high temperatures [8, 9]. When inhaled, nitrogen oxides have been shown to irritate the eyes, mucus membranes, and lungs [4]. Excessive pulmonary irritation and edema can result from exposure to extremely high concentrations [8]. Carbon monoxide is a toxic and dangerous gas produced during welding because of the action of UV radiation on carbon dioxide [8, 9]. Carbon dioxide and carbon monoxide are produced because of the decomposition of organic compounds in electrode coatings and cores, as well as the decomposition of inorganic carbonates in coatings [8]. It impairs the blood's ability to absorb oxygen, resulting in headaches, nausea, dizziness, confusion, death, cardiovascular symptoms, and carbon monoxide poisoning [4]. In a recent study, carbon monoxide, sulfur dioxide, and nitrogen gases were detected and measured in the air at the same time, resulting in significant negative effects, as shown in Table 2 [12].

Table 2. CO_2, SO_2, and NO_x emissions during welding
Source: G. Amza and D. Dobrotă in Metalurgija, 51, 2012[12]

Welding process	CO_2		SO_2	NO_x
	Min	max	SO_2/t seam	NO_x/t seam
SMAW	0.280	0.5	0.64	0.154
Submerged automatic arc welding (SAAW)	0.175	0.21		
GMAW and GTAW	0.205	0.24		
Oxyfuel welding	0.312	0.55		

According to the data presented, industrial activity for manufacturing welded constructions can be considered an environmental pollutant, particularly to the atmosphere, as evidenced by air quality monitoring results. The emissions are strongly influenced by the diameter and composition of the electrodes, the workpiece composition and coatings, travel speed, voltage, current, arc length, welding position, and deposition rates, so fumes can be reduced or increased depending on the choice [10]. The weight of fumes generated is a percentage of the weight of deposited metal or the length of the electrode used. It is found that 95 % of the welding fumes are generated from the additional material and only about 5 % from the base material [13]. Emission amount and variations in the fume formation rate (FFR) are heavily influenced by the type of welding and the operating conditions, as shown in Fig. 1 for various processes based on electrode type [10].

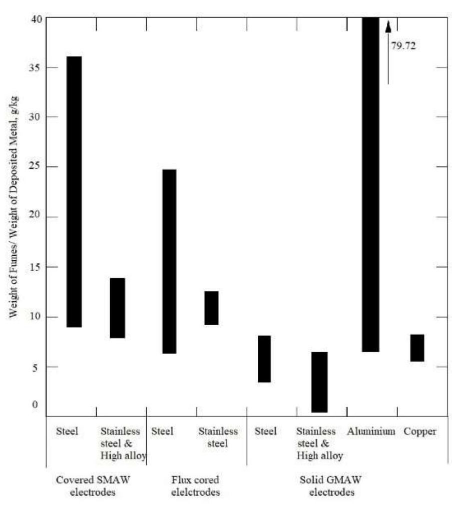

Figure 1. Particulate emissions from various arc welding processes
Source: Development of particulate and hazardous emission factors for electric arc welding, Final Report, 1994 [10]

Table 3 shows typical ratios of different welding processes and metals, the maximum rate of welding fume is achieved if the gas metal arc welding continuously welds on the carbon steel with 10lb/h or 0.09 lb/h (0.9%) [11]. The situation is different for stainless steel, the generation of fume with the same welding process is 0.7lb/h. If the welding processes last for half an hour, then the values of the fumes are going to be divided by two. The GMAW uses a shielding gas to protect the molten metal from the atmosphere to reduce oxidation and other reactions and provide a better quality of the weld. Usually, this gas is an inert gas mixture of argon, helium, or carbon dioxide and can intensify the production of toxins such as nitrogen oxides and ozone. Flux-cored arc welding uses flux with a high level of fluorides and silicates that vaporize and produce gases that protect the liquid melt from impurities.

Table 3. Welding fume ratios

Source: Source: *Welding fume control: regulations and processes, 2008 [11]*

Welding	Metal Type	Range Weight of Fumes/ Weight of Deposited Material
FCAW	Carbon Steel Stainless Steel	0.9-2.4% 0.9-2.4%
SMAW	Carbon Steel Stainless, High Alloy	1.1-5.4% 0.3-1.4%
GMAW	Carbon Steel Stainless Steel Copper/Aluminum	0.3-0.9% 0.6-7% 0.5-1.6%

2.3 Parameter considerations and operational conditions

The mechanisms that cause fume formation are complex, but changes in process parameters and operational conditions can help to reduce fume emissions and provide a healthier working environment. A recent investigation on fume emission when welding mild steel (MS) and stainless steel (SS) with the GMAW process at various current and voltage settings revealed that heat input and FFR are directly connected, meaning that with higher current or voltage there will be higher FFR so to lower the amount of fume generated welders should use the lowest current intensity as possible [16]. Also, it is concluded that the use of MS as base metal produces more fume when compared to SS, so there is a strong connection between fume rate generation and the chemical composition of the metal to be welded. Welding voltage and current both affect fume generation. The length of a welding arc can also influence fume generation. A longer arc gives the droplet more time to react and emit fumes. As the voltage increases, so does the amount of welding fume produced. The current levels in solid wire GMAW rise as current levels rise, depending on the shielding gas used. Metal transfer changes from short-circuiting to globular to fine droplet spray as the electrode current density increases. This change also has an impact on arc stability, which in turn has an impact on fume levels.

3. CONCLUSION

There is an urgent need to reduce air pollutants to protect the environment and workers' health. The composition of the consumable electrode alloy, the base metal being joined, and the presence of any surface materials or coatings on that base metal, all influence the substances found in the welding environment. When it comes to keeping fume exposures to very low levels, the challenges are significant. The only way to achieve and maintain low levels of exposure is to carefully select consumables and welding processes, as well as to use proper ventilation and personal protective equipment. Also, a study of various base materials revealed that stainless steel produces a greater quantity of nanosized particles than carbon steel, therefore the proper choice of base metal is crucial. When selecting a base metal, consider choosing the one that emits less fume and can be welded with a low fume emitting process, considering the type of electrode and, if necessary, the type of shielding gas for emission control. Fume levels in gas-shielded processes are influenced by the reactivity of the gas blend as well as its influence on the type of metal transfer required. When high percentages of argon are used, it is possible to achieve stable, finer droplet transfer at moderate current levels. When shielding gases contain more than 20 percent carbon dioxide, transfer remains globular within these same current ranges. Welding fume levels rise as the percentage of CO2 in the shielding increases. Prior to deciding on a specific welding process, the amount of fume must be considered; whenever specifications and conditions allow, the process generating the least amount of fume should be chosen. Overall, all welding processes can result in a significant concentration of nanosized particles being deposited in the lungs of exposed welders, but according to data from various studies, the lowest level of airborne particles transferred in the alveolar region of the lungs was associated with FSW, followed by TIG and metal active gas welding (MAG) [7]. While FCAW produces the most fumes, submerged arc welding (SAW) produces the least. To reduce fume emissions, the proper current, arc voltage, arc length, travel speed, and welding electrode angle should be chosen by the operator to ensure quality welds.).

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