

การรับสัมผัสองค์ประกอบธาตุฟลูมโลหะจากการเชื่อมอาร์กโลหะฐานเหล็กกล้าคาร์บอนต่ำและ
เหล็กเคลือบสังกะสีด้วยกระบวนการเชื่อมอาร์กด้วยลวดหุ้มฟลักซ์และโลหะแก๊สคลุม
Exposure to Elemental Constituents of Metal Fumes Generated from
Flux-Cored Arc Welding and Gas Metal Arc Welding
of Low-Carbon Steel and Galvanized Steel

กัญญารัตน์ เทียมแก้ว¹ อัญมณี สร้างบุญ¹ รศิกานจน์ อินธนู¹ อภิญญา มณีรัตน์¹ ปิยฉัตร กลิ่นมาก¹
มนหาทิพย์ ธนาวิชิตฤกษ์¹ และ กฤษดา เพ็งอารีย์^{2*}

Kanyarat Tiamkaew¹, Unyamanee Sangboon¹, Rasikarn Inthanoo¹, Apinya Maneerat¹,
Piyachat Klinmak¹, Montatip Tanavichitlurk¹ and Kritsada Phengarree^{2*}

¹สาขาวิชาอาชีวอนามัยและความปลอดภัย สำนักวิชาสาธารณสุขศาสตร์ มหาวิทยาลัยเทคโนโลยีสุรนารี จังหวัดนครราชสีมา

²สาขาวิชาอาชีวอนามัยและความปลอดภัย ภาควิชาวิทยาศาสตร์ชีวภาพและสุขภาพ คณะวิทยาศาสตร์ มหาวิทยาลัยอุบลราชธานี จังหวัดอุบลราชธานี

¹School of Occupational Health and Safety, Institute of Public Health,

Suranaree University of Technology, Nakhon Ratchasima Province

²Occupational Health and Safety Program, Department of Biological Science,

Faculty of Science, Ubon Ratchathani University, Ubon Ratchathani Province

*Corresponding Author: kritsada.p@ubu.ac.th

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาปริมาณการรับสัมผัสฟลูมโลหะ ลักษณะของฟลูมโลหะ ธาตุและปริมาณธาตุองค์ประกอบของฟลูมโลหะที่เป็นอันตรายจากการเชื่อมโลหะฐานเหล็กกล้าคาร์บอนต่ำ และเหล็กเคลือบสังกะสี ด้วยกระบวนการเชื่อมอาร์กโลหะด้วยลวดหุ้มฟลักซ์ และการเชื่อมอาร์กโลหะแก๊สคลุม โดยการเก็บตัวอย่างฟลูมโลหะบริเวณหายใจติดตัวบุคคล และวิเคราะห์ปริมาณฟลูมโลหะด้วยการชั่งน้ำหนัก การวิเคราะห์คุณสมบัติลักษณะด้วยกล้องจุลทรรศน์แบบส่องกราด (SEM) การวิเคราะห์แยกองค์ประกอบธาตุด้วยเครื่องเอกซเรย์ฟลูออเรสเซนซ์ (XRF) และการวิเคราะห์ปริมาณองค์ประกอบธาตุด้วยเครื่องวิเคราะห์ปริมาณแร่ธาตุในระดับความเข้มข้นต่ำ (ICP-MS) ผลการวิจัยพบว่า การเชื่อมแบบกระบวนการเชื่อมอาร์กโลหะด้วยลวดหุ้มฟลักซ์ด้วยเหล็กเคลือบสังกะสีมีค่าความเข้มข้นฟลูมโลหะเฉลี่ยสูงสุด ($3.24 \pm 0.52 \text{ mg/m}^3$) รองลงมาคือการเชื่อมอาร์กโลหะแก๊สคลุมด้วยเหล็กเคลือบสังกะสี ($2.73 \pm 0.39 \text{ mg/m}^3$) มีขนาดสูงกว่าการเชื่อมที่ใช้เหล็กกล้าคาร์บอนเป็นโลหะฐาน ลักษณะฟลูมโลหะมีลักษณะทรงกลมมีขนาดอยู่ระหว่าง $1.027\text{--}1.474 \text{ }\mu\text{m}$ ซึ่งใกล้เคียงกัน ส่วนฟลูมจากเหล็กเคลือบสังกะสีมีทั้งอนุภาคขนาดไมครอน ($>1.0 \text{ }\mu\text{m}$) และนาโนเมตร ($<1.0 \text{ }\mu\text{m}$) ขนาดอยู่ระหว่าง $0.168\text{--}1.753 \text{ }\mu\text{m}$ องค์ประกอบฟลูมโลหะด้วย XRF พบว่า เหล็ก (Fe) เป็นองค์ประกอบหลัก รวมทั้งพบว่ามีปริมาณความเข้มข้นจากการวิเคราะห์ด้วย ICP-MS การเชื่อมอาร์กโลหะด้วยลวดหุ้มฟลักซ์ด้วยเหล็กเคลือบสังกะสีพบฟลูมโลหะรวมมากที่สุด (11.473 mg/m^3) และพบปริมาณองค์ประกอบหลัก 3 ลำดับ ได้แก่ เหล็ก (Fe) (7.968 mg/m^3) สังกะสี (Zn) (2.468 mg/m^3) และเงิน (Ag) (0.344 mg/m^3) ตามลำดับ ผลของงานวิจัยนี้ชี้ให้เห็นว่าปัจจัยที่มีผลต่อการเกิดองค์ประกอบธาตุและปริมาณของฟลูมโลหะคือชนิดของโลหะฐานและกระบวนการเชื่อม

คำสำคัญ: ฟลูมโลหะ, กระบวนการเชื่อมอาร์กด้วยลวดหุ้มไส้ฟลักซ์, การเชื่อมอาร์กโลหะแก๊สคลุม, การเชื่อมโลหะฐานเหล็กเคลือบสังกะสี, การเชื่อมโลหะฐานเหล็กกล้าคาร์บอนต่ำ

Abstract

This study aimed to investigate the level of metal fume exposure, the characteristics of metal fumes, and the elemental composition and concentrations of hazardous metal fumes generated from welding low-carbon steel and galvanized steel using Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW). Personal breathing zone samples were collected, and the total metal fume concentration was determined by gravimetric analysis. Fume morphology was examined using Scanning Electron Microscopy (SEM), elemental identification was performed using X-ray Fluorescence (XRF), and quantitative elemental analysis was conducted using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The results indicated that FCAW on galvanized steel produced the highest average metal fume concentration ($3.24 \pm 0.52 \text{ mg/m}^3$), followed by GMAW on zinc-coated steel ($2.73 \pm 0.39 \text{ mg/m}^3$), both of which were higher than those measured during the welding of carbon steel. The metal fumes exhibited predominantly spherical particles with sizes ranging from 1.027 to 1.474 μm . Fumes generated from zinc-coated steel consisted of both micron-sized ($>1.0 \mu\text{m}$) and nanoscale ($<1.0 \mu\text{m}$) particles, with sizes ranging from 0.168 to 1.753 μm . XRF analysis showed iron (Fe) to be the principal elemental component. ICP-MS results further revealed that FCAW on galvanized steel generated the highest total metal fume concentration (11.473 mg/m^3), with the three most abundant elements being iron (Fe) (7.968 mg/m^3), zinc (Zn) (2.468 mg/m^3), and silver (Ag) (0.344 mg/m^3), respectively. These findings highlight that both the type of base metal and the welding process significantly influence the elemental composition and concentration of metal fumes.

Keywords: Metal fumes, Flux-cored arc welding (FCAW), Gas metal arc welding (GMAW), Galvanized steel, Low-carbon steel

1. Introduction

In contemporary industrial sectors, manufacturing processes have continuously advanced through the integration of modern technologies aimed at enhancing efficiency, product quality, and operational safety. Among these technologies, welding serves a crucial role as a primary process for joining or fusing metal components to achieve strong and reliable bonds. This is particularly important in welding applications for furniture structures. Commonly, two major welding processes are employed: Flux-Cored Arc Welding (FCAW), which provides high-speed and durable welds, and Gas Metal Arc Welding (GMAW), which produces cleaner welded beads with reduced fume generation. Both techniques are widely used for welding carbon steel and galvanized steel in structural work, construction, and furniture manufacturing.

Welding processes typically generate metal fumes consisting of ultrafine particles (Quémerais et al., 2015; Stanislawska et al., 2017) formed through the condensation of vaporized metals from the weld pool. These particles can be directly inhaled into the respiratory system, posing both short-term and long-term health risks (Kulkarni, 2020). Numerous studies have reported health hazards associated with exposure to metal fumes and various metal oxides, influenced by factors such as welding current or base metal composition (Phengarree et al., 2025; Hedberg et al., 2021). Metal fumes may contain a range of hazardous elements. Silver (Ag) fumes can cause argyria following prolonged exposure, characterized by a gray or bluish discoloration of the skin due to the accumulation of silver particles in the body (Cohen et al. 2004; Kim et al., 2019). Cadmium (Cd) is highly toxic and classified as a carcinogen; chronic exposure is associated with an increased risk of lung cancer (Hartwig, 2012; García-Esquinas et al., 2014). Chromium (Cr), particularly in the hexavalent form (Cr^{6+}), is a potent carcinogen capable of inducing cellular mutations and DNA damage, which may lead to lung cancer and other malignancies (Pires et al., 2006). Although copper (Cu) is

less toxic than many other metals, inhalation of copper fumes can trigger metal fume fever, presenting flu-like symptoms such as fever, chills, and fatigue within hours of exposure. High or prolonged exposure to iron (Fe) fumes can cause siderosis, characterized by the accumulation of iron particles in the lungs, chronic inflammation, and impaired respiratory function (Nemery, 2022; Banerjee et al., 2006). Nickel (Ni) is another major carcinogenic metal associated with lung and nasal cancers due to its mutagenic properties and ability to promote carcinogenesis (Genchi et al., 2020; Duda-Chodak & Blaszczyk, 2008). Manganese (Mn) exposure over extended periods may lead to manganism, a neurodegenerative disorder resembling Parkinson's disease caused by manganese deposition in the brain (Guilarte, 2010; Aschner et al., 2009). Zinc (Zn) fumes may also cause fume fever, similar to copper, but generally less severe, with recovery typically occurring within 24 hours (Schoofs, Schmit, & Rink, 2024).

Given the health impacts and hazardous composition of metal fumes, many metals commonly encountered in welding processes, such as low-carbon steel and galvanized steel (Japanese Industrial Standards Committee, 2011) pose significant health risks to welding operators. Therefore, investigating metal fume exposure during welding is essential for risk assessment and the development of effective exposure control strategies in industrial workplaces. In addition to direct health risks, welding-related illnesses may also lead to indirect impacts in industrial settings, including increased medical expenses and compensation costs, prolonged work absences that affect workers' income, and disruptions to production processes, thereby resulting in broader economic and social consequences.

Based on a systematic review of the literature, a significant knowledge gap was identified in comparative studies on the characteristics of metal fumes and their elemental composition. Currently, limited research has been conducted in this area, and no studies have yet compared the Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW) processes for both low-carbon steel and galvanized steel. To address this gap, the present study aims to examine metal fume exposure generated during the welding of low-carbon steel and galvanized steel using Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW) processes.

The objectives are to quantify metal fume exposure levels, characterize the morphology and particle size of welding fumes, and analyze the chemical composition and elemental concentrations within the fumes. The resulting data can be utilized to improve occupational health and safety measures for welders in the industrial sector.

2. Materials and methods

This study employed quasi-experimental research and was approved by the Human Research Ethics Committee of Suranaree University of Technology, with the ethics approval certificate number COA No. 32/2564. The approval covered metal arc welding experiments, air sampling procedures, and all related analytical methods. The research methodology was described as follows:

2.1 Welding Techniques and Base Metals

In this study, commonly used welding processes for various types of furniture production were employed. Arc welding was selected as it utilizes an electric arc as a high-temperature heat source to melt and fuse metals. Two primary welding processes were used: (1) Flux-Cored Arc Welding (FCAW) employs flux to generate shielding gas and slag that protect the weld pool from atmospheric contamination. FCAW was performed using E71T-11 flux-cored electrodes with a diameter of 1.2 mm, and (2) Gas Metal Arc Welding (GMAW), which uses an inert shielding gas to protect the weld zone from reacting with oxygen and

other atmospheric gases. In this experiment, solid welding wire with a diameter of 1.2 mm was used, along with 100% pure argon (100% Ar) as the shielding gas.

Welding was carried out on carbon steel and galvanized steel plates measuring 200 × 100 mm with a thickness of 6 mm (plates with dimensions of 200 × 100 × 6 mm). For both welding processes, bead-on-plate welding in the flat position was performed for 10 minutes and repeated three times. All welding parameters were strictly controlled to ensure the accuracy and reliability of the experimental results. The experiments were carried out in an open-type industrial welding workshop using dilution or natural ventilation. Environmental conditions were monitored, with air velocity ranging from 0.00 to 0.12 m/s, relative humidity from 49% to 57%, atmospheric pressure between 755 and 757 mmHg, and ambient temperature from 31.1 to 32.6 °C.

2.2 Collection and Quantification of Total Metal Fumes

Metal fume sampling was conducted using a calibrated personal air sampling pump (Personal Air Sampler) with a constant airflow rate of 2.0 liters per minute (L/min). The air sampling procedure was adapted from NIOSH Method #0500 for total particulates, utilizing a filter cassette equipped with a 37-mm mixed-cellulose ester (MCE) membrane filter with a pore size of 0.8 µm, as further adapted from NIOSH Method #7200. The filter cassette was positioned within the welder's breathing zone to obtain samples representative of actual exposure.

Before sampling, all filters were conditioned in a desiccator for at least 24 hours and subsequently weighed using a six-digit analytical balance. After sampling, the filters were reweighed to determine the mass of collected metal fumes. The airborne metal fume concentration (mg/m³) was calculated using Equation (1). During sampling, environmental parameters, including temperature, relative humidity, atmospheric pressure, and air velocity, were recorded to support subsequent data analysis.

$$C = \frac{(W_2 - W_1) - (B_2 - B_1) \times 10^3}{V} \quad (1)$$

where: C is the concentration of total metal fumes (mg/m³); W₁ is the weight of the filter before sampling (mg); W₂ is the weight of the filter after sampling (mg); B₁ is the weight of the blank filter before sampling (mg); B₂ is the weight of the blank filter after sampling (mg); and V is the volume of sampled air (L).

2.3 Elemental Analysis by XRF

Elemental composition was examined using X-ray fluorescence spectrometry (XRF) (Horiba, XGT-5200WR, Japan). Filter samples containing collected metal fumes from both welding processes, Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW), were analyzed by performing X-ray measurements at nine points on each filter and comparing them with blank filters. This analysis provided qualitative information to identify elemental constituents in terms of weight percentage (Wt.%). The obtained values were then averaged and subsequently used to support quantitative analysis using an ICP-MS.

2.4 Quantitative Elemental Analysis by ICP-MS

After qualitative analysis using the XRF technique, the filter samples and filter blanks were digested using a microwave digestion system (Mars 6 Microwave Digestion). Digestion was performed with 2% nitric acid (HNO₃) at 180 °C and 1,000 W for 30 minutes. The resulting solutions were subsequently analyzed using inductively coupled plasma–mass spectrometry (ICP-MS) (Agilent Technologies, model 7700,

USA) to quantify the concentrations of metallic elements in the fumes, including Ag, Cd, Cr, Cu, Fe, Ni, Mn, and Zn.

A mixed standard solution was prepared from primary standard solutions at concentrations of 1, 5, 10, 20, 50, and 100 ppb to construct calibration curves, which demonstrated correlation coefficients (R) greater than 0.995. The ICP-MS results were initially obtained in units of $\mu\text{g/mL}$ (ppb) and subsequently converted to airborne concentrations (mg/m^3) using Equation (2) to allow comparison with occupational exposure limits.

$$C = \frac{C_s V_s - C_b V_b}{V} \quad (2)$$

where C is the concentration of metal fumes in air (mg/m^3 or $\mu\text{g/L}$); C_s is the concentration in the sample solution ($\mu\text{g/mL}$); C_b is the average concentration of the blank solution ($\mu\text{g/mL}$); V_s is the volume of the sample solution (mL); V_b is the volume of the blank solution (mL); and V is the total volume of sampled air (L).

2.5 Statistical Analysis

In this study, descriptive statistics, including mean, standard deviation (SD), maximum (Max), minimum (Min), and percentages (%), were used to present the quantitative results. The analysis measured metal fume concentrations in air (mg/m^3) and quantified the elemental composition of the fumes using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), also expressed in mg/m^3 .

3. Result

3.1 Metal Fume Concentration by Gravimetric Analysis

The results of metal fume concentration determined by gravimetric analysis are presented in Table 1. For Flux-Cored Arc Welding (FCAW), welding of low-carbon steel produced an average metal fume concentration of $2.22 \pm 0.36 \text{ mg/m}^3$, while galvanized steel exhibited a higher average concentration of $3.24 \pm 0.52 \text{ mg/m}^3$. For Gas Metal Arc Welding (GMAW), welding of low-carbon steel resulted in an average metal fume concentration of $1.56 \pm 0.49 \text{ mg/m}^3$, whereas galvanized steel showed an average concentration of $2.73 \pm 0.39 \text{ mg/m}^3$. Overall, both welding processes generated higher metal fume concentrations when working with galvanized steel compared to low-carbon steel. These results demonstrate that both the welding process and the type of base metal influence metal fume generation.

Table 1. The concentration of metal fumes as determined by gravimetric analysis

Welding Process	Type of Steel	Metal fume concentration (mg/m^3)				
		n	Max	Min	SD	Mean
FCAW	Low Carbon	3	2.61	1.73	0.36	2.22
	Galvanized	3	3.92	2.94	0.52	3.24
GMAW	Low Carbon	3	2.10	1.51	0.49	1.56
	Galvanized	3	3.24	2.32	0.39	2.73

3.2 Characteristics and Particle Size of Metal Fumes Observed by SEM

Scanning Electron Microscopy (SEM) (JEOL, model JCM-5000, Japan) was used to examine the characteristics of metal fumes generated during the welding of low-carbon steel and galvanized steel using two arc welding processes: Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW). The analysis showed that in both welding processes, the metal fumes were densely packed and similarly distributed on filter paper, exhibiting spherical shapes and granular, metal-like morphology with comparable particle sizes. For FCAW, the average particle size for low-carbon steel was $1.284 \pm 0.200 \mu\text{m}$, ranging from 1.027 to 1.565 μm , while for galvanized steel, the average particle size was smaller at $0.400 \pm 0.415 \mu\text{m}$, ranging from 0.168 to 1.228 μm , with a mean below 1 μm . Particle size analysis revealed two distinct ranges: particles smaller than 1 μm (submicron-sized particles) and particles larger than 1 μm . For GMAW, the average particle size for low-carbon steel was $1.313 \pm 0.133 \mu\text{m}$, ranging from 1.139 to 1.474 μm , and for galvanized steel, it was $1.358 \pm 0.212 \mu\text{m}$, ranging from 1.139 to 1.753 μm , indicating similar particle size characteristics. Among the two welding processes, FCAW of galvanized steel produced the smallest particle sizes compared with all other conditions. In summary, the results are presented in Table 2, and the morphological characteristics of the metal fumes are shown in Figure 1 for FCAW and Figure 2 for GMAW.

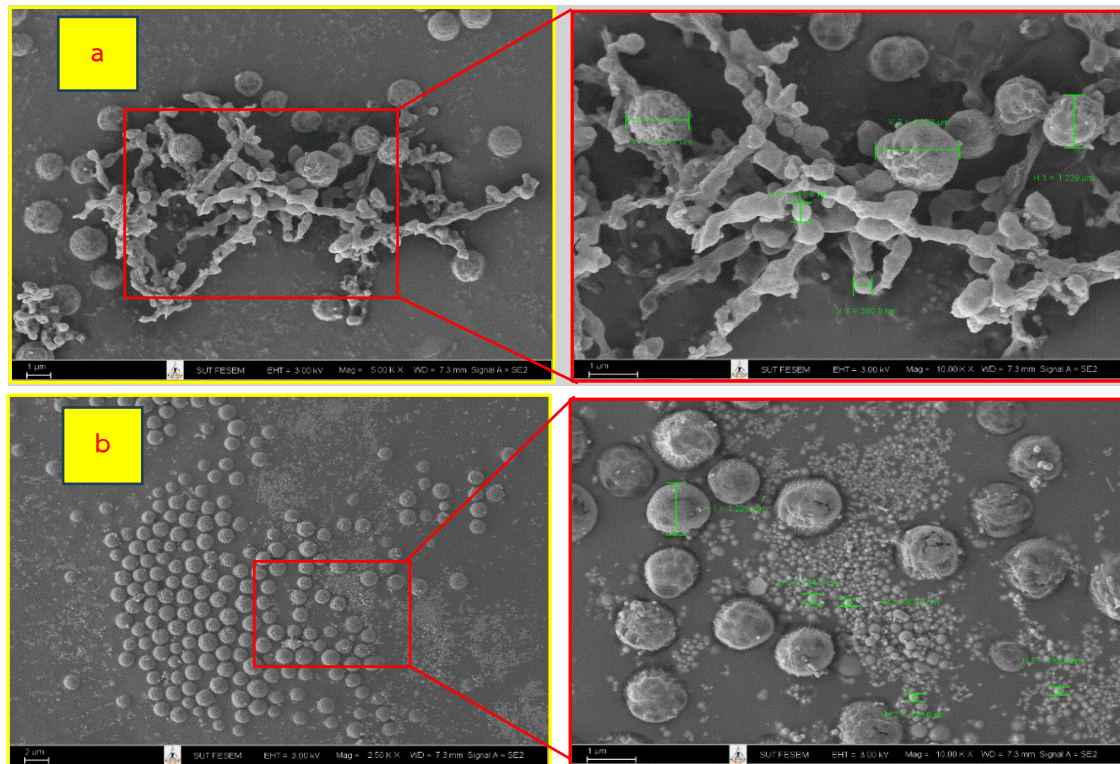


Figure 1. Morphology of metal fumes generated from Flux-Cored Arc Welding (FCAW)

(a) Low-carbon steel, and (b) Galvanized steel

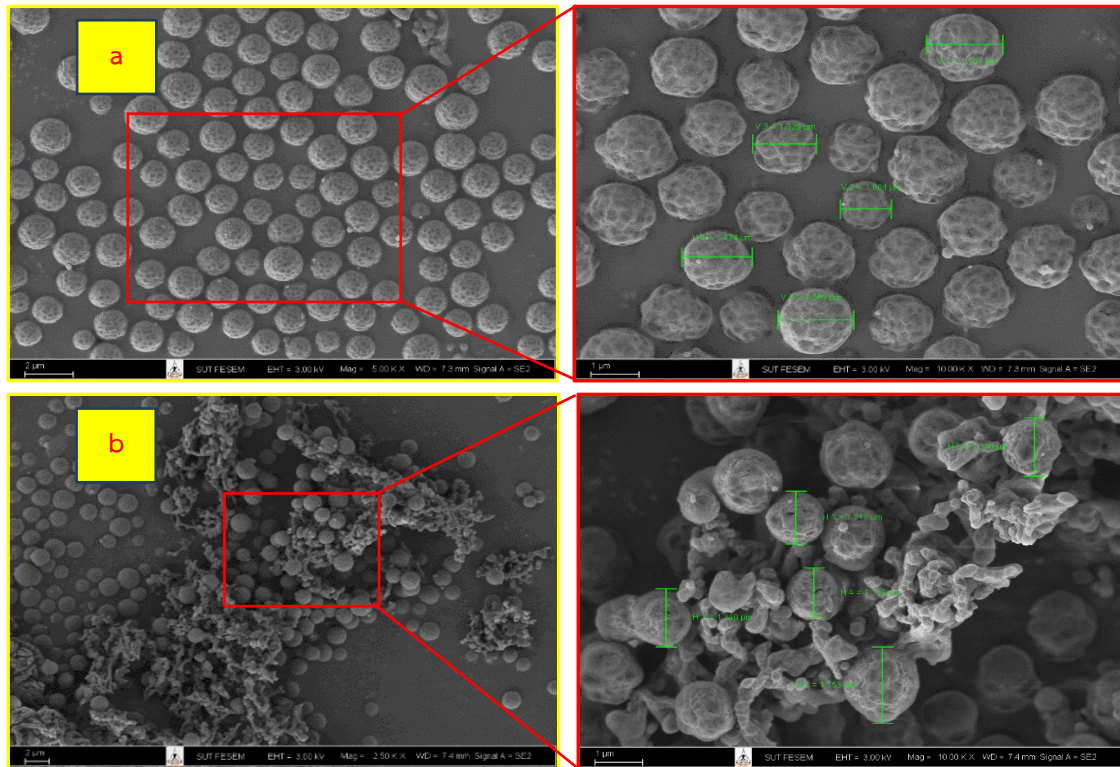


Figure 2. Morphology of metal fumes generated from Gas Metal Arc Welding (GMAW)

(a) Low-carbon steel, and (b) Galvanized steel

Table 2. Fume Particle Size from Scanning Electron Microscopy (SEM)

Welding Process	Fume particle size (μm)							
	Low Carbon Steel				Galvanized Steel			
	Min	Max	SD	Mean	Min	Max	SD	Mean
FCAW	1.027	1.565	0.200	1.284	0.168	1.228	0.415	0.400
GMAW	1.139	1.474	0.133	1.313	1.139	1.753	0.212	1.358

3.3 Elemental Composition of Metal Fumes by XRF

The elemental composition of metal fumes generated from welding varied depending on the welding process and the type of base metal. For Flux-Cored Arc Welding (FCAW) using low-carbon steel as the base metal, the five main elements in the fumes were iron (Fe, 44.37 ± 5.77 Wt.%), silver (Ag, 11.10 ± 1.64 Wt.%), manganese (Mn, 8.72 ± 0.056 Wt.%), zinc (Zn, 4.25 ± 2.24 Wt.%), and copper (Cu, 4.39 ± 3.23 Wt.%). In contrast, when galvanized steel was used as the base metal, zinc was the predominant element (Zn, 19.57 ± 13.07 Wt.%), followed by iron (Fe, 24.48 ± 16.50 Wt.%), silver (Ag, 5.51 ± 6.88 Wt.%), manganese (Mn, 4.36 ± 2.66 Wt.%), and copper (Cu, 0.31 ± 2.17 Wt.%).

For Gas Metal Arc Welding (GMAW) with low-carbon steel as the base metal, the top five elements were iron (Fe, 40.39 ± 5.06 Wt.%), silver (Ag, 17.83 ± 11.70 Wt.%), zinc (Zn, 6.65 ± 7.85 Wt.%), manganese (Mn, 6.37 ± 1.24 Wt.%), and copper (Cu, 4.38 ± 3.46 Wt.%). When galvanized steel was used as the base metal, zinc had the highest proportion, followed by iron (Fe, 35.60 ± 0.75 Wt.%), zinc (Zn,

28.77 ± 8.65 Wt.%), silver (Ag, 5.52 ± 7.27 Wt.%), manganese (Mn, 3.15 ± 0.76 Wt.%), and copper (Cu, 1.09 ± 1.39 Wt.%).

These XRF results provided qualitative information on the elemental composition of metal fumes, which served as preliminary data for subsequent quantitative analysis using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) to determine elemental concentrations at trace levels.

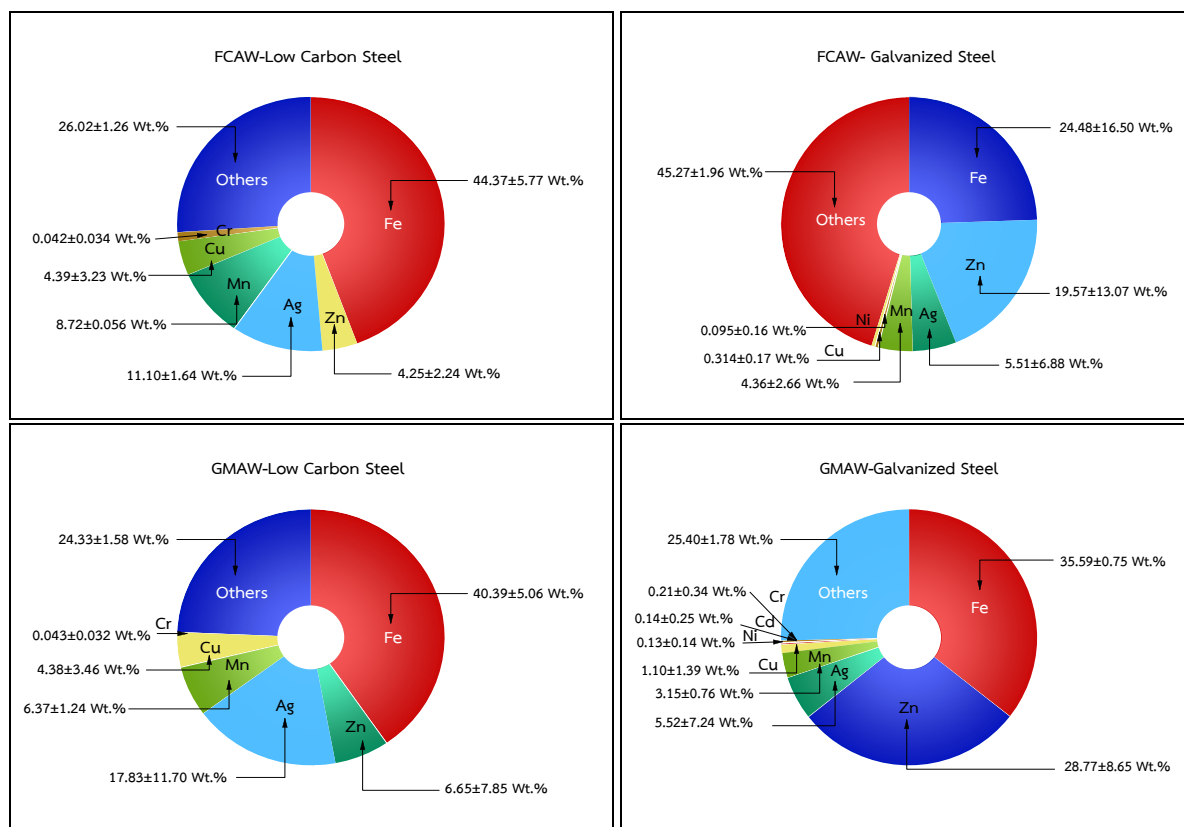


Figure 3. Weight percentage (Wt.%) of elemental composition from the welding processes

3.4 Concentrations of Elemental Components in Metal Fumes Determined by ICP-MS

When using low-carbon steel as the base metal in Flux-Cored Arc Welding (FCAW), the average concentrations of the elemental components in the metal fumes were as follows: iron (Fe) 1.235 mg/m³, zinc (Zn) 0.034 mg/m³, silver (Ag) 0.037 mg/m³, manganese (Mn) 0.130 mg/m³, copper (Cu) below 0.000 mg/m³ (below the detection limit), nickel (Ni) 0.006 mg/m³, cadmium (Cd) 0.014 mg/m³, and chromium (Cr) 0.017 mg/m³. For FCAW using galvanized steel as the base metal, the average concentrations were: Fe 7.968 mg/m³, Zn 2.468 mg/m³, Ag 0.344 mg/m³, Mn 0.677 mg/m³, Cu below 0.000 mg/m³, Ni 0.003 mg/m³, Cd 0.004 mg/m³, and Cr 0.006 mg/m³.

For Gas Metal Arc Welding (GMAW) using low-carbon steel as the base metal, the average concentrations were: Fe 0.644 mg/m³, Zn 0.017 mg/m³, Ag 0.041 mg/m³, Mn 0.059 mg/m³, Cu below 0.000 mg/m³ (below the detection limit), Ni 0.002 mg/m³, Cd 0.003 mg/m³, and Cr 0.298 mg/m³. For GMAW using galvanized steel as the base metal, the average concentrations were: Fe 1.760 mg/m³, Zn 0.641 mg/m³, Ag 0.118 mg/m³, Mn 1.185 mg/m³, Cu below 0.000 mg/m³, Ni 0.001 mg/m³, Cd 0.002 mg/m³, and Cr 0.003 mg/m³.

Figure 4 presents the results as the average concentrations of elemental components in metal fumes for each welding process using either low-carbon steel or galvanized steel as the base metal. The highest total metal fume concentration was observed in Flux-Cored Arc Welding (FCAW) with galvanized steel as the base metal (11.473 mg/m³), followed by Gas Metal Arc Welding (GMAW) with galvanized steel (2.743 mg/m³), FCAW with low-carbon steel (1.473 mg/m³), and GMAW with low-carbon steel (1.064 mg/m³), respectively.

Across both welding processes and base metals, the three most abundant elements on average were iron (Fe, 2.902 mg/m³), zinc (Zn, 0.790 mg/m³), and manganese (Mn, 0.263 mg/m³). These results indicate that FCAW using galvanized steel as the base metal produces the highest exposure to metal fumes.

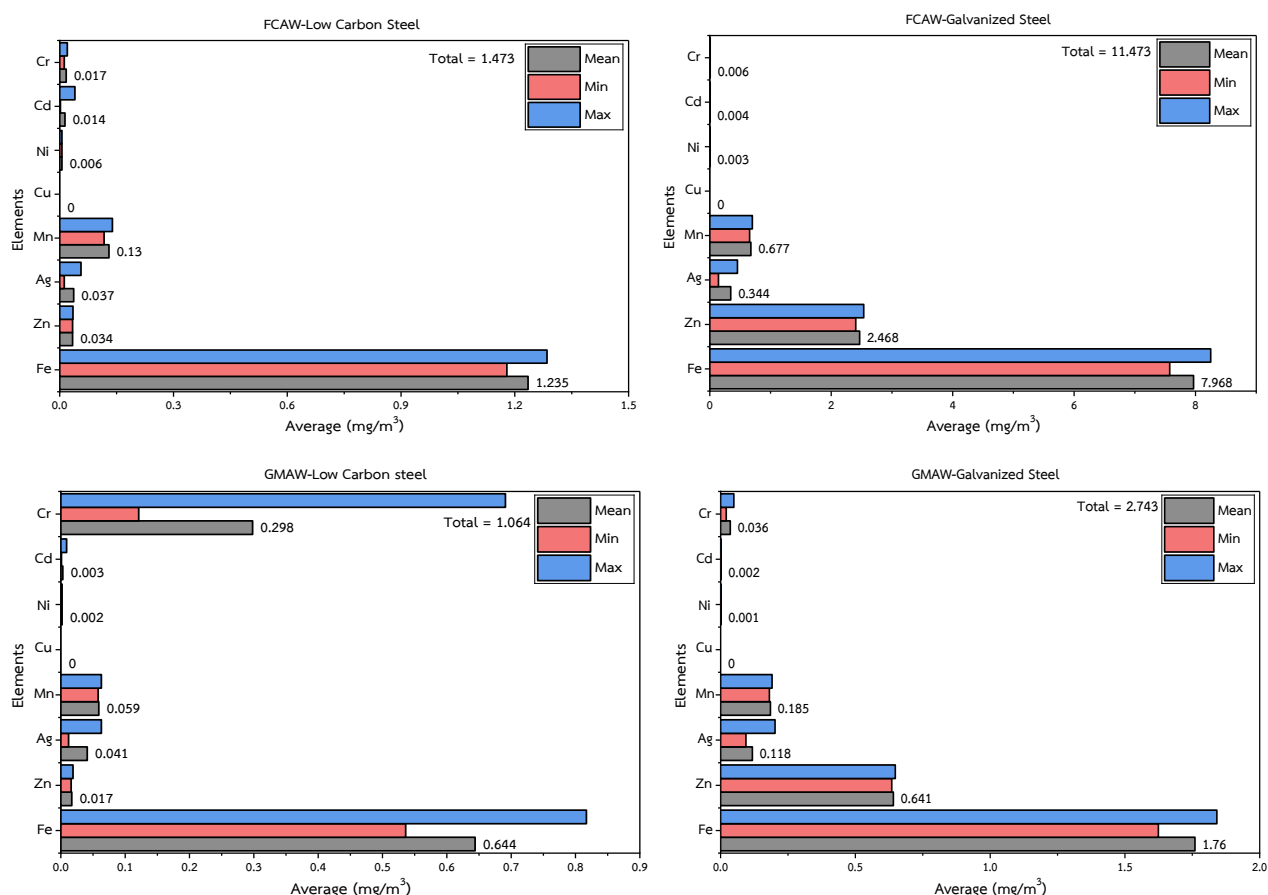


Figure 4. Concentration of elemental components in welding metal fumes (mg/m³)

4. Discussion

Analysis of Metal Fume Concentration by Gravimetric Method. The result of metal fume concentrations using the gravimetric method in the welding of low-carbon steel and galvanized steel through Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW) is shown in Table 1, FCAW with galvanized steel as the base metal produced the highest average concentration of metal fumes (3.24 ± 0.52 mg/m³), followed by GMAW with galvanized steel (2.73 ± 0.39 mg/m³). These concentrations were higher than those observed when low-carbon steel was used as the base metal. This finding is

consistent with previous studies by Cao et al. (2018) and Hartmann et al. (2019), which reported that welding galvanized steel leads to increased evaporation of metals and oxides under arc heating.

Morphology of Metal Fumes by Electron Microscopy. Scanning Electron Microscopy (SEM) analysis showed that metal fumes from low-carbon steel in both welding processes were densely packed and deposited on the filter in a similar pattern, exhibiting spherical shapes and metallic granules. This observation is consistent with Wycislik-Sosnierz et al. (2024), Sowards et al. (2008) and Phengarree et al. (2025), who reported that metal fumes from FCAW and GMAW form spherical particles that tend to agglomerate into micron-sized clusters. In the case of galvanized steel, metal fumes exhibited mixed particle sizes, including micron-sized particles ($>1.0\ \mu\text{m}$) and submicron-sized particles ($<1.0\ \mu\text{m}$), as shown in Figures 1A and 2B. Notably, welding with galvanized steel showed zinc volatilization, likely due to oxidation reactions in the arc atmosphere, leading to the formation of fine particles through condensation of evaporated metals (Lipton, 2025; Yang et al., 2018).

The elemental composition of metal fumes was analyzed by X-ray fluorescence (XRF), and the results are presented in Figure 3. The result showed that iron (Fe), the main component of both the welding wire and the base metal, was the predominant element in all welding processes. In FCAW using low-carbon steel, the major elements were Fe (44.37 Wt.%), Ag (11.10 Wt.%), and Mn (8.72 Wt.%). When galvanized steel was used as the base metal, Fe (24.48 Wt.%), Zn (19.57 Wt.%), and Ag (5.51 Wt.%) were the dominant elements. For GMAW, low-carbon steel exhibited Fe (40.39 Wt.%), Ag (17.83 Wt.%), and Zn (6.65 Wt.%), whereas galvanized steel showed Fe (35.59 Wt.%), Zn (28.77 Wt.%), and Ag (5.52 Wt.%). These findings are consistent with Guney (2021), confirming that Fe is the primary component of welding fumes. Other potentially hazardous elements, including Mn, Zn, and Ni, were also detected. The elemental composition varied depending on the base metal, welding process, and the presence or absence of ventilation. The results obtained from XRF analysis provided preliminary compositional information and were subsequently used for quantitative analysis using the ICP–MS technique.

ICP–MS analysis confirmed that Fe remained the predominant component of metal fumes. Welding of galvanized steel produced the highest total metal fume concentrations in both welding processes, with FCAW generating the highest levels (total metal fumes: $11.473\ \text{mg}/\text{m}^3$). In FCAW with galvanized steel, the average concentrations of elements were Fe $7.968\ \text{mg}/\text{m}^3$, Zn $2.468\ \text{mg}/\text{m}^3$, Ag $0.344\ \text{mg}/\text{m}^3$, Mn $0.677\ \text{mg}/\text{m}^3$, Ni $0.003\ \text{mg}/\text{m}^3$, Cd $0.004\ \text{mg}/\text{m}^3$, and Cr $0.006\ \text{mg}/\text{m}^3$, as shown in Figure 4. These metal fumes pose significant health risks. Hexavalent chromium (Cr^{6+}) is a potent carcinogen associated with lung and other cancers (Kouokam et al., 2022; DesMarias & Costa, 2019). Iron (Fe) exposure can lead to siderosis, resulting in chronic inflammation and impaired respiratory function (Nemery, 2022; Marques et al., 2022). Silver (Ag), identified as the third most abundant elemental component in zinc-coated, iron-based alloys, poses potential health risks following prolonged exposure. Chronic exposure to silver may result in argyria, a condition characterized by gray or bluish discoloration of the skin caused by the accumulation of silver particles within the body (Kim et al., 2019). Nickel (Ni) is a carcinogen linked to lung and nasal cancers (Genchi et al., 2020; Duda-Chodak & Blaszczyk, 2008). Manganese (Mn) exposure may induce neurotoxicity and Parkinson-like symptoms (Lu et al, 2023; Gonzalez-Alvarez et al., 2022; Khindri & Maj, 2025).

5. Conclusion and suggestions

The findings of this study indicate that Flux-Cored Arc Welding (FCAW) carries a higher risk of metal fume exposure compared to other welding processes, primarily due to the flux in the welding wire, which stabilizes the arc but also increases fume generation. Welding with galvanized steel further elevates

exposure because of zinc volatilization. Moreover, the smaller average particle sizes increase the likelihood of deep respiratory deposition and associated toxicity. Hazardous elements such as hexavalent chromium (Cr^{6+}), cadmium (Cd), silver (Ag), and iron (Fe) pose significant risks for respiratory diseases and cancer, emphasizing the need for effective exposure control measures. Overall, the factors influencing the generation and dispersion of metal fumes include the type of base metal, flux content in the welding wire, and arc intensity between the wire and base metal. For occupational safety, local exhaust ventilation (LEV) should be implemented, processes that minimize metal fume generation should be selected, and respiratory protective equipment in accordance with NIOSH 42 CFR Part 84 should be used.

5.1 Suggestions for Practical Application

The findings of this study can guide the enhancement of occupational safety standards in welding, particularly for tasks involving galvanized steel and Flux-Cored Arc Welding (FCAW), which were found to produce higher levels of metal fumes than Gas Metal Arc Welding (GMAW). Consequently, the results can inform the implementation of engineering controls, such as local exhaust ventilation systems, and the selection of welding processes that reduce metal evaporation. Moreover, knowledge of the composition of metal fumes can assist in choosing suitable respiratory protective equipment based on the level of risk. These findings can also support the development of safety manuals or best-practice guidelines for welders to ensure compliance with occupational health standards. Additionally, the data can be applied to improve training programs and workplace risk assessments, helping to minimize exposure to metal fumes and effectively safeguard workers' health.

5.2 Suggestions for future research

1) The study should be extended to examine metal fume generation from other types of metals, such as stainless steel or metal alloys, to compare the composition, particle size, and concentration of fumes under different welding conditions. In addition, long-term, systematic investigations on the health effects on workers are recommended.

2) Further research is needed to evaluate the influence of welding parameters and the effectiveness of ventilation systems in reducing metal fume concentrations. Real-time monitoring technology can be utilized to track changes in fume concentrations under actual working conditions and to develop control measures tailored to specific welding environments. In addition, welding activities should be investigated in real workplace settings, and the measured exposure levels should be compared with established occupational exposure limits, such as OEL–TLVs or other relevant standards, in order to identify hazards and assess health risks among welders.

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