ARCHIVES
of
FOUNDRY ENGINEERING
10.24425/afe.2024.151317
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences
ISSN (2299-2944)
Volume 2024
Issue 4/2024
103 – 108
14/4

Morphology of Welding Fume Derived from Stainless Steels Arc Welding

J. Wyciślik-Sośnierz [a] *, **J. Matusiak** [a], **J. Adamiec** [b], **M. Lemanowicz** [c], **R. Kusiorowski** [d], **A. Gerle** [d]

[a] Łukasiewicz Research Network - Upper Silesian Institute of Technology, Gliwice, Poland
[b] Department of Metallurgy and Recycling, Faculty of Materials Science and Engineering, Silesian University of Technology, Katowice, Poland
[c] Department of Chemical Engineering and Process Design, Faculty of Chemistry, Silesian University of Technology, Gliwice, Poland
[d] Łukasiewicz Research Network – Institute of Ceramics and Building Materials, Cracow, Poland
* Corresponding author: E-mail address: joanna.wycislik-sosnierz@git.lukasiewicz.gov.pl

Received 20.08.2024; accepted in revised form 29.11.2024; available online 24.12.2024

Abstract

The article presents the research results of fume morphology derived from arc welding of stainless steels of 1.4301 and 1.4828 grade. The analysis was performed using laser diffraction and high-resolution scanning electron microscopy. Welding fume has been classified by the International Agency for Research on Cancer (IARC) as a group of agents with proven carcinogenic effects to human. The assessment of the risk related to exposure to welding fume emission depends on the amount of fume generated, its chemical composition and morphology. The combined analysis of these factors determines the toxicity of fume and its impact on the human body. The results of the fume particle size distribution and the analysis of the shape and chemical composition using SEM with EDS in connection with the determination of the fume emission rate enable to obtain an overall assessment of the health risk as-sociated with welding fume. Such assessment is particularly important during welding processes of corrosion-resistant steels, due to the presence of chromium and nickel compounds in the fume, which are classified as substances with proven carcinogenic effects to human (Group 1 according to IARC guidelines). It was found that 15-17% of particles deriving from arc welding belong to the respirable and tracheal fractions, which are the most harmful due to the penetration beyond the larynx.

Keywords: welding fume morphology, stainless steel, arc welding, laser diffraction, scanning electron microscopy

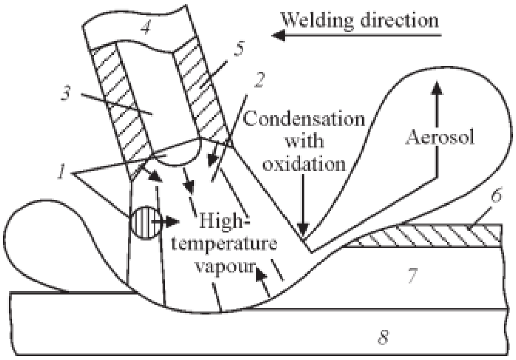
1. Introduction

Fume morphology is the science of the structure, forms, shapes, fractions and chemical composition of particles. It is a factor that determines their manner of inter-action with lung epithelial cells and, consequently, determines the effectiveness of deposition in various regions of the lung [1, 2].

During welding processes, similarly to foundry processes, dust is emitted into the work environment. Welding workstations, similarly to foundry workplaces, are associated with high concentrations of hazardous dust which contain also respirable fraction. Dust (two-phase condensing aerosol) is a mixture of solid particles (fume) and gases [3]. Solid particles are formed as a result of condensation and oxidation of metal vapor [4]. The mechanism of welding fume formation is presented in Figure 1.

Metallurgical processes occurring during welding have a significant impact on the formation of welding fume. These processes can be divided into three groups [5-9]:

1) physical phenomena and chemical reactions occurring in the area of the electric arc on the contact surface of molten metal drops and the gas atmosphere of the arc,
2) chemical reactions occurring in weld pool and between the pool and the protective atmosphere,
3) phenomena occurring in the heat affected zone.



Mechanism of welding aerosol formation [1]: *1* — drop; *2* — arc; *3* — electrode rod; *4* — electrode; *5* — coating; *6* — slag; *7* — weld metal; *8* — base metal

Fig. 1. The mechanism of welding fume formation [4]

Gas Metal Arc Welding (GMAW) is among the most widely used methods of joining steel structures. The process is also designated as MIG/MAG welding - MIG (Metal Inert Gas), which refers to welding in inert gas shields such as argon and helium, and MAG (Metal Active Gas), which in turn uses chemically active shielding gases such as CO_2, O_2 used most often as mixtures with helium or argon, containing admixtures of H_2, N_2, NO [10]. The source of the thermal energy required to melt the welded workpiece and the fusible electrode (wire) material is the heat of the electric arc creating between the electrode and the welded workpiece, in a shield of active or inert gas [10]. The molten metal of the electrode wire combines with the molten parent material to form a welding pool. The metal of the welding pool, as the arc moves in the direction of the weld, solidifies and forms a weld that permanently joins the edges of the welded piece [10].

The assessment of the risk related to exposure to welding fume emission depends on the amount of fume generated, its chemical composition and morphology. The combined analysis of these factors determines the toxicity of fume and its impact on the human body. An important factor influencing the toxicity of fume is particle size [11]. Welding fume particles have a near spherical shape and occur as very fine single particles, chains and agglomerates, and their absorption into the body depends on the form in which the fume is present [11].

The analysis of the MIG/MAG welding process of non-alloyed steel carried out by the specialists from the National Institute for Occupational Safety and Health in Morgantown (USA) assessed the particle size in the welder's breathing zone (distance of 30 cm from the welding arc) and in the neighboring work area (distance of 200 cm from the welding arc) [12].

The fume particles from the area 30 cm from the welding arc contained spherical particles (diameter 0.5 - 4.0 μm) and fine agglomerates. The results showed that the fume concentration in the area 30 cm from the welding arc was five times higher than in the area 200 cm from the arc [12].

On the other hand, a team of researchers led by J. M. Antonini characterized the fume generated during MIG/MAG welding of unalloyed and stainless steels [13]. Most of the fume particles formed consisted of fine grains with equivalent diameters in the range 0.1-1.0 μm. The magnitude of the aerodynamic diameter corresponding to the median mass distribution according to calculations was 0.3 μm for fume from welding unalloyed steel and 0.25 μm for fume from stainless steel [13].

Specialists from the Royal Institute of Technology in Stockholm carried out a size analysis of the fume generated during MAG welding with solid and powder wire of austenitic stainless steel 1.4307 and duplex steel 1.4162, divided into nano-scale (10-170 nm) and micro-scale (0.6-2.5 μm) fractions and determining the chemical composition of the fume [13]. The results showed that, despite the division into fractions directly in the air under study, each fraction predominantly consisted of nano-scale particles, which then formed larger agglomerates. Analysis of the results showed that the majority of particles had a near spherical shape, although irregularly shaped particles were also noted. The smallest fume particle determined was 6 nm in size [14].

Detailed research of welding fume are important due to the fact welding fume has been classified by the International Agency for Research on Cancer (IARC) as an agent with proven carcinogenic effects to human [15, 16, 17].

The research was carried out for samples generated during MIG welding of corrosion-resistant steels, grades 1.4301 and 1.4828. Grade 1.4301 (X5CrNi18-10) is austenitic stainless steel with good corrosion resistance and ductility. This grade is resistant to most oxidizing acids, foodstuffs, sterilizing solutions, most organic chemicals and dyes, and inorganic chemicals [18]. The steel is also characterized by good weldability. It is used, among others: in the food, processing, dyeing or construction industries [18, 19]. Steel grade 1.4828 (X15CrNiSi20-12) belongs to the group of austenitic heat-resistant steels and is widely used in industry. Its maximum operating temperature is 1000°C, it is characterized by good weldability, very good resistance to corrosion and oxidation, it can also be used in sulfates environment at temperature exceeding 850°C. This grade is mainly used in the production of industrial furnaces and heating elements, in the production of annealing equipment, aerospace engineering, automotive industry (exhaust systems) [20, 21].

It is worth mentioning that during welding of stainless steels nickel and chromium compounds are present in fume and they have carcinogenic effect on human [22].

2. Materials for research. Methodology

The fume morphology analysis was carried out for samples generated during MIG welding of corrosion-resistant steels, grades 1.4301 (X5CrNi18-10) and 1.4828 (X15CrNiSi20-12) [23]. For arc welding of selected corrosion-resistant steels, solid wire of 308L-Si grade with a diameter of 1.2 mm (classification G 19 9 L Si according to PN-EN ISO 14343) was used as filler metal. The shielding gas was 100% argon.

The analysis of the structure (shape, dimensions) of welding fume particles was carried out using the following analytical methods:

1. laser diffraction;
2. scanning electron microscopy (SEM).

Fume sampling for emission rate determination and fume characterization is based on gravimetric method. Fume was collected on filters during welding in a specially designed research station in the Centre of Welding of The Upper Silesian Institute of Technology (Fig. 2). The station consists of the chamber inside which welding process is conducted. The construction of chamber allows for protection against outside outflow of contamination. Suction port (in which filter is placed) is in side part of fume chamber. Position of chamber is stationary, only the welded item, which is placed on rotational welding table, turns. For the research filters in type of PTM-B with 150 mm diameter were used. Welding process was conducted using Phoenix 330 ColdArc + Phoenix drive 4L firmy EWM Hightec Welding company. Fume tested was generated during MIG welding of following technological parameters: welding current intensity 300 A, arc voltage 30 V, wire feed rate 10,5 m/min, welding speed 1,0 m/min.

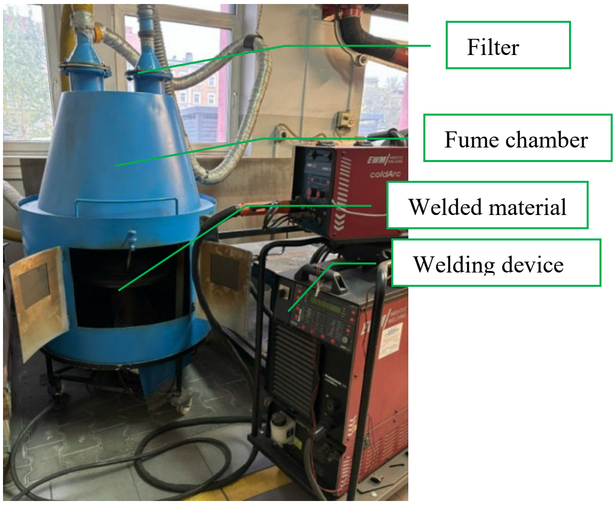


Fig. 2. Welding station for fume emission rate determination

3. Research results

To determine the particle size distribution, the laser diffraction technique is applied. It uses the phenomenon of light scattering on particles. Light hitting an object is scattered, and the angle of deflection of the wave is strictly dependent on the size of the particle (the smaller the particle, the larger the scattering angle) [24]. The spectrum of scattered light is analysed and the particle size distribution is obtained. Welding fume samples were examined using laser particle sizer Analysette 22 (Fritsch GmbH).

The size distribution of fume particles deriving from arc welding of 1.4828 steel is shown in Fig. 3.

In fume deriving from arc welding of the tested steel grades: 1.4301 and 1.4828, it was shown that the most numerous group included particles in the range of 10-20 µm. In fume samples, the volume share of this fraction was over 31%. In fume samples, the second highest volume fraction, ranging from 21.65 to 22.77%, was found in the range with particle sizes of 20-30 µm. In turn, the volume fraction of particles from the 0-10 µm fraction ranged from 15.70 to 17.72%.

Analysis of the results showed that fume particles smaller than 20 µm accounted for nearly 50% of the total sample, and particles smaller than 30 µm accounted for more than 2/3 of the sample.

In all tested fume samples, nearly 99% were particles whose size did not exceed 100 µm. The volume fraction of particles larger than 100 µm did not exceed 1%.

Results obtained showed no influence of the grade of the base material on the particle size distribution. The differences for individual fractions depending on the steel grade did not exceed 2%.

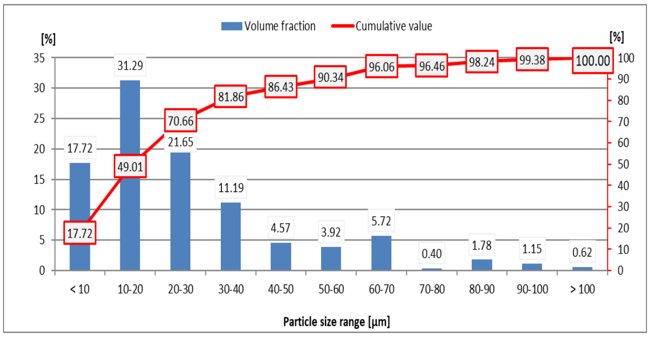


Fig. 3. The particle size distribution of fume deriving from arc welding of 1.4828 steel [23]

In order to evaluate the risk related to fume emission, the exact size distribution of particles belonging to the finest fraction (range below 10 µm) was determined and shown in Table 1.

Table 1.
Results of laser particle size analysis of fume derived from arc welding of 1.4301 and 1.4828 steel grades, including the respirable fraction of 0-3 µm and the tracheal fraction of 3-10 µm [23]

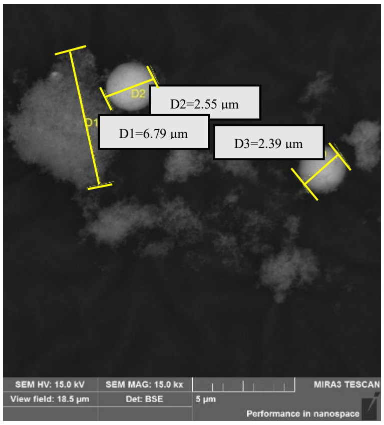
Size of particles [µm]	1.4301 steel grade		1.4828 steel grade	
	Volume fraction [%]	Cumulative value [%]	Volume fraction [%]	Cumulative value [%]
<1	0.61	0.61	0.79	0.79
1-2	1.23	1.84	1.48	2.27
2-3	1.29	3.13	1.44	3.71
3-4	1.21	4.35	1.35	5.06
4-5	1.62	5.96	1.85	6.91
5-6	1.05	7.02	1.23	8.13
6-7	1.33	8.35	1.54	9.67
7-8	1.76	10.11	1.99	11.67
8-9	2.38	12.48	2.62	14.28
9-10	3.22	15.70	3.43	17.72

Fume particles belonging to the respirable fraction, those whose size does not exceed 3 µm, and the tracheal fraction, whose size ranged from 3 to 10 µm, are specified. The analysis of the results showed that over 3% of the fume from arc welding of corrosion-resistant steels belongs to the respirable fraction, i.e. particles reaching and penetrating the ciliated respiratory tract, and 12-14% to the tracheal fraction - particles penetrating outside the larynx. The tests were carried out on fume samples collected on filters, where, as a result of increased mobility due to high temperature, the particles create larger clusters.

Microstructure analysis of welding fume samples was performed using a Mira 3 electron microscope from Tescan, equipped with an energy-dispersive spectrometer (EDS) system with AZtec Automated ver. 3.1 software. The analysis was performed at an accelerating voltage of 15 kV in the backscattered electron mode (BSE) or secondary electron mode (SE) for image formation. The measurements were carried out on the powder samples placed on a conductive carbon tape and additionally covered by a conductive layer of graphite by using a Quorum Q150R ES device.

The observations confirm the information obtained during the literature review [25] - fume occurs in the form of single particles with an elongated or spherical shape, or in the form of chains or agglomerates (Fig. 4). Measurements of the size of fume particles were carried out. The morphology of the particles and their chemical composition were analysed using the EDS method. The fume particles shown in Figure 4a have a diameter of 2.4-2.5 µm and contain mainly iron. At 25000x magnification, it was possible to determine fume particles with dimensions of 0.3-0.5 µm which tend to form agglomerates (Fig. 4 b).

a)



b)

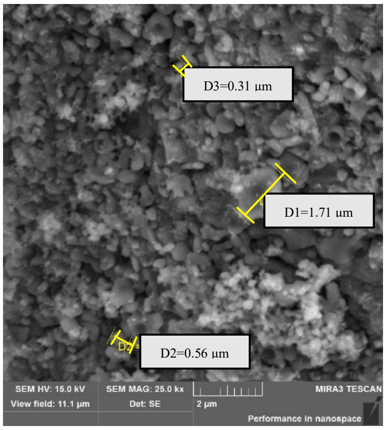
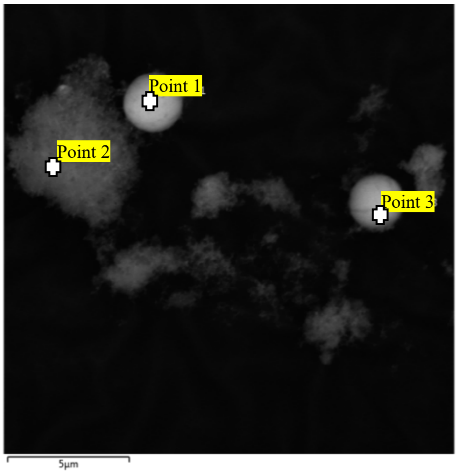


Fig. 4. Fume from MIG welding of steel 1.4301 a) fume structure at 15000x magnification, b) fume morphology at 25000x magnification [23]

Additionally, chemical composition analysis combined with particle size analysis was performed for selected fume samples from arc welding of corrosion-resistant steels of grades 1.4301 and 1.4828. Exemplary results for steel 1.4301 are shown in Figure 5. Spherical particles (measuring points 1 and 3) with a diameter of 2.5 µm consisted of over 70% of iron, nickel accounted for approx. 13.3-15.5%, and chromium approx. 9-11.5%. In turn, the irregular-shaped particle (measuring point 2) has a length of 6.81µm and consists of over 60% of iron, almost 19% of chromium, almost 9.5% of nickel, almost 1% of manganese and over 2% of silicon.



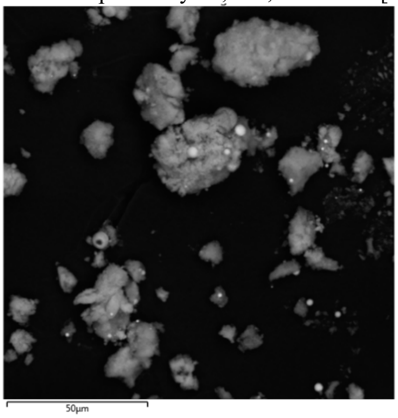
Chemical composition of fume where metals are expressed as oxides [%]			
	Point 1	Point 2	Point 3
Fe	72.8	61.3	74.6
Cr	11.6	18.9	8.9
Ni	15.6	9.5	13.4
Mn	-	6.0	0.9
Si	-	4.4	2.3

Fig. 5. Analysis of the chemical composition and morphology of fume derived from arc welding of 1.4301 austenitic steel

Figures 6 and 7 show a map of the elements distribution in fume samples from arc welding of 1.4301 and 1.4828 steels. The analysis of the obtained results showed in fume samples deriving from welding of 1.4301 and 1.4828 steel grades both single particles and larger clusters - chains or agglomerates. In case of 1.4828 fume sample more spherical particles were observed in comparison to 1.4301 fume sample.

The results of the chemical composition analysis for both steel grades were very similar. Fume from the welding of steel grade 1.4301 was characterized by a slightly higher content of iron. chromium and nickel (differences were 0.5% for Fe. 0.4% for Cr and 0.06% for Si). However. in the fume from arc welding of steel 1.4828, a higher content of manganese and silicon was revealed (differences were 0.4% for Mn and 0.5% for Si) - Fig. 6 and 7.

The results of the chemical composition analysis of fume derived from welding both steel grades revealed presence of oxygen (Fig. 6, 7). This suggests that the previously mentioned elements exist in the form of oxides. This is confirmed by the results of the phase identification, which showed the presence of iron, manganese, chromium and nickel compounds, which existed in the form of oxides - spinels with the general formula AB_2O_4 - where A and B are replaced by Cr, Mn, Ni and Fe [26].



Chemical composition of analyzed area where metals are expressed as oxides [%]				
Fe	Cr	Ni	Mn	Si
60.8	19.4	9.4	6.5	3.9

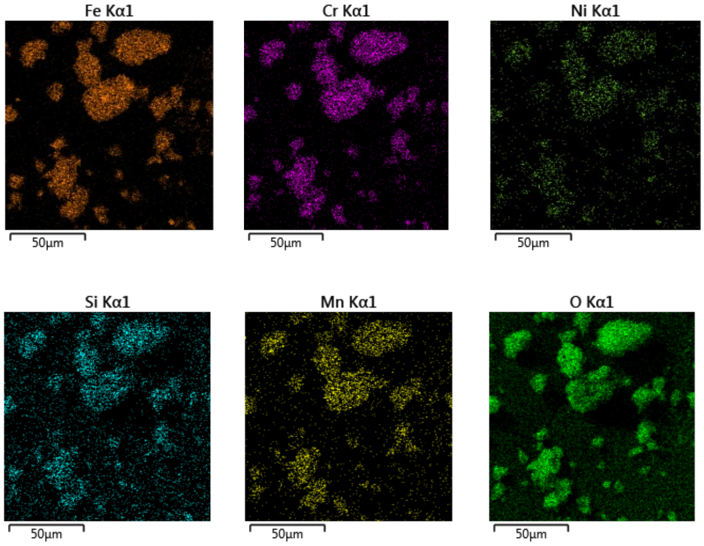
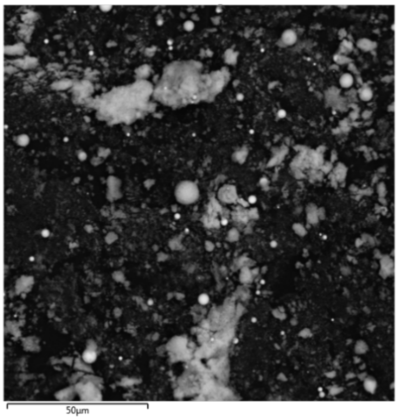


Fig. 6. Analysis of the chemical composition of the marked surface and a map of the elemental distribution of a fume sample from arc welding of corrosion-resistant steel grade 1.4301



Chemical composition of analyzed area where metals are expressed as oxides [%]				
Fe	Cr	Ni	Mn	Si
60.3	19.0	9.3	6.9	4.4

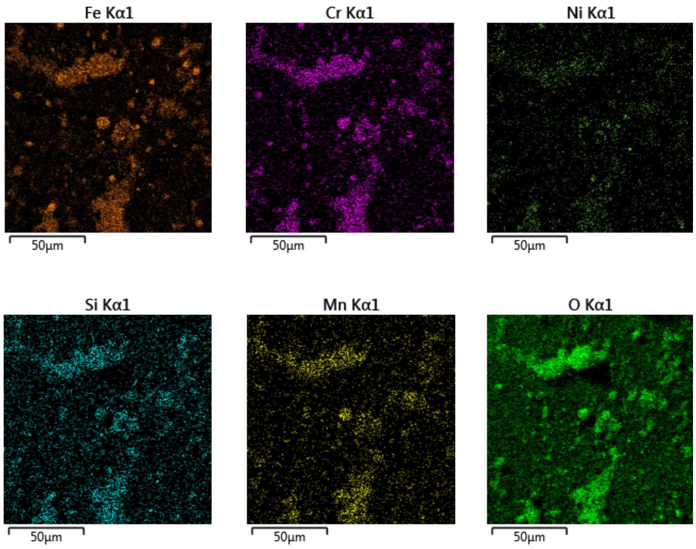


Fig. 7. Analysis of the chemical composition of the marked surface and a map of the elemental distribution of a fume sample from arc welding of corrosion-resistant steel grade 1.4828

4. Conclusions

The results of particle size distribution and SEM and EDS analysis in connection with the determination of fume emission rate and its chemical and phase composition allow for a complex assessment of the health risk associated with welding fume emission. This is particularly important during welding processes of corrosion-resistant steels due to the presence of chromium and nickel compounds in the fume. which constitute a significant threat to workers' health due to their proven carcinogenic effects (Group 1 according to IARC guidelines). The analysis of the obtained results allowed the following conclusions to be formulated:

- the main components of fume emitted during MIG arc welding of corrosion-resistant steels are iron. manganese. chromium. nickel and silicon;
- EDS X-ray microanalysis results showed the presence of oxygen. This is confirmed by the literature data which showed the presence of iron. manganese. chromium and nickel compounds. which existed in the form of oxides -

spinels with the general formula AB_2O_4 - where A and B are replaced by Cr. Mn. Ni and Fe;

- the results of the chemical composition analysis for both steel grades. i.e. 1.4301 and 1.4828. were very similar;
- 15-17% of particles originating from arc welding belong to the respirable and tracheal fraction. i.e. those that are among the most harmful because they penetrate beyond the larynx;
- these particles are characterized by a uniform distribution of elements and contain approximately 19% of chromium and nearly 10% of nickel. which was confirmed by the results of EDS microanalysis.

References

[1] Juda-Rezler, K., Toczko, B. (2016). *Fine dust in the atmosphere Compendium of knowledge about air pollution with suspended dust in Poland*. Warsaw: Environmental Monitoring Library. ISBN 978-83-61227-73-1. (in Polish).

[2] Antonini, J.M., Lewis, A.B., Roberts, J.R. & Whaley, D.A. (2003). Pulmonary effects of welding fumes: review of worker and experimental animal studies. *American Journal of Industrial Medicine*. 43(4), 350-360. https://doi.org/10.1002/ajim.10194.

[3] Matusiak, J. (2007). *The influence of technological conditions for stainless steel welding on fume toxicity.* PhD thesis. Gliwice: Politechnika Śląska. (in Polish).

[4] Gubenya, I.P. & Yavdoshchin, I.R. (2016). Mechanisms of formation of welding aerosol solid component and paths of its penetration into the living organism. *Paton Welding Journal*. No. 1. ISSN 0957-798X.

[5] Tasak, E. (2008). *Welding metallurgy*. Kraków. ISBN 978-83-923191-1-5. (in Polish).

[6] Lancaster, J.F. (1966). *Metallurgy of welding processes*. Warszawa: WNT. (in Polish).

[7] Linnert, G.E. (1965). *Welding metallurgy. vol. 1 Fundamentals*. New York: American Welding Society.

[8] Linnert, G.E. (1967). *Welding metallurgy. vol. 2 Technology*. New York: American Welding Society.

[9] Welding Metallurgy Module 3. (2024). Retrieved May 9, 2024, from https://www.nrc.gov/docs/ ML1215/ML12157A607.pdf.

[10] Ambroziak, A. (2010). *Manufacturing techniques. welding. laboratory.* Wrocław. ISBN 978-83-7493-592-0. (in Polish).

[11] Spiegel-Ciobanu, V.E., Costa, L., Zschiesche, W. (2020). *Hazardous substances in welding and allied processes*. International Institute of Welding. ISBN 978-3-030-36928-6.

[12] Cena, L.G., Chen, B.T. & Keane, M.J. (2016). Evolution of welding-fume aerosols with time and distance from the source. *Weld Journal*. 95(Suppl), 280-s–285-s.

[13] Antonini, J.M., Roberts, J.R., Stone, S., Chen, B.T., Schwegler-Berry, D., Chapman, R., Zeidler-Erdely, P.C., Andrews, R.N. & Frazer, D.G. (2011). Persistence of deposited metals in the lungs after stainless steel and mild steel welding fume inhalation in rats. *Archives of Toxicology*. 85, 487-498. https://doi.org/10.1007/s00204-010-0601-1.

[14] Mei, N., Belleville, L., Cha, Y., Olofsson, U., Odnevall, Wallinder, I., Persson, K.-A. & Hedberg Y.S. (2018). Size-separated particle fractions of stainless steel welding fume particles – A multi-analytical characterization focusing on surface oxide speciation and release of hexavalent chromium. *Journal of Hazardous Materials*. 342, 527-535. https://doi.org/10.1016/j.jhazmat.2017.08.070.

[15] Guha, N., Loomis, D., Guyton, K.Z., Grosse, Y., El Ghissassi, F., Bouvard, V., et al. (2017). Carcinogenicity of welding, molybdenum trioxide, and indium tin oxide. *The Lancet Oncology*. 18(5), 581-582. http://dx.doi.org/10.1016/S1470-2045(17)30255-3.

[16] Rahul, M., Sivapirakasam, S.P., Sreejith, M., Vishnu, B.R. & Gomes, J.F.P. (2022). Study on mass concentration and morphology of SMAW fume particles with a new covered electrode using nano-CaTiO3 as an arc stabilizer. *Journal of Manufacturing Processes*. 84, 230-239. https://doi.org/10.1016/j.jmapro.2022.10.015.

[17] Popović, O., Prokić-Cvetković, R., Burzić, M., Lukić, U. & Beljić, B. (2014). Fume and gas emission during arc welding: hazards and recommendation. *Renewable and Sustainable Energy Reviews*. 37, 509-516. https://doi.org/10.1016/j.rser.2014.05.076.

[18] Arpem Steel (2024). *Stainless steel AISI 304/ 1.4301 – useful information*. Retrieved May 9, 2024, from https://siatkitkane.com.pl/blog/13_stal-nierdzewna-aisi-304-14301-przydatne-informacje.html

[19] Arpem Steel. (2024). *Description of 1.4301 steel*. Retrieved May 9, 2024, from https://www.aperam.com/product/304-1-4301/

[20] Metalcor. (2024). *Datasheet of 1.4828 steel*. Retrieved May 9, 2024, from http://www.metalcor.de/en/datenblatt/56/

[21] Virgamet (2024). *X5CrNiSi20-12. 1.4828. AISI 309- Heat resistant steel*. Retrieved May 9, 2024, from https://virgamet.com/x15crnisi2012-1-4828-aisi-309-uns-s30900-heat-resistant-steel

[22] Newton, A., Serdar, B., Adams, K., Dickinson, L.M. & Koehler, K. (2021). Lung deposition versus inhalable sampling to estimate body burden of welding fume exposure: A pilot sampler study in stainless steel welders. *Journal of Aerosol Science*. 153, 105721, 1-11. https://doi.org/10.1016/j.jaerosci.2020.105721.

[23] Wyciślik-Sośnierz, J., Matusiak, J., Adamiec, J., Urbańczyk, M., Lemanowicz, M., Kusiorowski, R. & Gerle, A. (2024) Morphology of welding fume derived from stainless steel arc welding. *Proceedings*. 108(1), 8, 1-5. https://doi.org/10.3390/proceedings2024108008.

[24] A.P. Instruments. (2024). *Laser particle size analyser – Functional Principle*. Retrieved May 9, 2024, from https://apinstruments.pl/aparatura/malvern-panalytical/rodzina-mastersizer/mastersizer-3000/

[25] Norhidayah, Abdull, Nur Sarah Irina Muhammad, Khairiah Mohd Mokhtar & Zarifah Shahri (2024). Occurrence, characterization, and transport mechanism of welding fumes particles emitted during the welding process. *Journal of Physics: Conference Series*. 2688, 012010, 1-12. DOI 10.1088/1742-6596/2688/1/012010.

[26] Floros, N. (2018). Welding fume main compounds and structure. *Welding in the World*. 62, 311-316. https://doi.org/10.1007/s40194-018-0552-3.