Heliyon 10 (2024) e40815

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Exposure assessment to fine and ultrafine particulate matter during welding activity in the maintenance shop of a steelmaking factory

Sergio Pili [a], Luigi Isaia Lecca [a,*], Tatiana Pedrazzi [b], Roberta Ghitti [b], Alessandro Murru [a], Michele Uras [a], Daniele Fabbri [a], Marcello Campagna [a], Giuseppe De Palma [b]

[a] Department of Medical Sciences and Public Health, University of Cagliari, 09042, Monserrato, Italy
[b] Unit of Occupational Health and Industrial Hygiene, Department of Medical and Surgical Specialties, Radiological Sciences and Public Health, University of Brescia, 25121, Brescia, Italy

ARTICLE INFO

Keywords:
Welding fumes
Ultrafine particle
Particulate matter
Steelmaking factory
Inhalable fraction

ABSTRACT

Welding fumes are a main source of occupational exposure to particulate matter (PM), besides gases and ultraviolet radiations, that involves millions of operators worldwide and is related to several health effects, including lung cancer. Our study aims to evaluate the exposure to fine and ultrafine airborne particulate in welding operators working in a steel making factory.

In October 2019, air monitoring was performed for four days in five different welding scenarios and in the external area of a steelmaking factory to assess the exposure to airborne particles, ultrafine (UFP) particulate and inhalable fraction, during welding activities. The airborne particles distribution as particle number and mass concentration were measured using a low-pressure electric impactor, model ELPI™ (range of sampling 0.006 μm and 10 μm), whereas the airborne inhalable fraction was collected by filtration, using the IOM Sampler selector.

The particle concentration, i.e. the number of particles per cm^3 (part/cm^3) showed significantly higher exposure figures for nanoscale particles, especially for the fractions included in the last 4 stages sampled by ELPI (from 0.010 μm to 0.071 μm), the figure representing between 85 % and 91 % of the total, whereas for the last 7 stages (0.010 μm–0.314 μm), they represented from 98 % to 99 % of the total. The average figure was approximately 5.01×10^4 part/cm^3, while the maximum average was 1.95×10^5 part/cm^3 on TIG welding, with a peak of 1.52×10^7 parts/cm^3. In terms of mass concentration, the levels of PM inhalable fraction ranged between 0.1 mg/m^3 and 1.08 mg/m^3.

The results of the present study substantially confirm previous studies regarding the distributions in terms of number and mass of welding fumes for SMAW and TIG techniques on steel, the mass concentration levels resulting within the permissible exposure limits (PEL) indicated by OSHA regulations. The results highlighted the importance of the efficiency of localized aspiration systems and the need to apply prevention and protection measures despite the low levels of exposure measured in terms of mass.

Conclusion: Overall, The particle number concentrations showed an important contribution in the emission of UFP compared to background levels. The PM inhalable fraction was substantially

* Corresponding author. Department of Medical Sciences and Public Health, University of Cagliari, 09042, Monserrato, Italy.
E-mail address: luigii.lecca@unica.it (L.I. Lecca).

https://doi.org/10.1016/j.heliyon.2024.e40815
Received 28 June 2024; Received in revised form 31 October 2024; Accepted 28 November 2024
Available online 29 November 2024

contained within the PEL. Further studies are needed to better understand the chemical characterization of the particulate also considering further variables of the working process that could influence the levels of exposure to welding fumes.

1. Introduction

Atmospheric aerosol is defined as a suspension of solid or liquid particles, of different size and composition depending on their origin (natural or anthropic), relatively stable in the air [1].

Particulate matter (PM) of anthropic origin attributable to vehicular traffic and industrial activities is one of the causes of atmospheric pollution and is predominant with respect to that of natural origin. Industrial areas or near busy areas show the highest concentrations of fine and ultrafine particulate matter (UFP) have been shown to be. The subjects most exposed to UFP are therefore those who, due to residence or occupational exposure, are located near these areas or engaged in work activities such as transport, motorway toll booths, welding or combustion processes, heat treatments and so on [2].

The biological effects of the atmospheric particulate are attributable to the ability of the particles to penetrate the body, by inhalation, through the respiratory system. The size of the airborne particulate is decisive in the ability to penetrate the deepest airways, while the composition and the presence of chemical, organic or inorganic substances on the particles influence the type and severity of the effects. The type of biological response is also determined by the possible solubility of the particles, for the best ease of absorption [3].

As it concerns the occupational exposure to welding fumes, it is estimated that there are around 11 million operators directly involved in welding operations and that there are around 110 million workers exposed to the fumes generated during these processes worldwide [4,5].

The main emissions produced during the welding activity depend on the technology, the composition of the base metal, the composition of the "consumable elements", the amperage used in the welding process which dictates its speed, the composition of the shielding gas, and the presence of any surface impurity such as paints or coatings. Furthermore, it is also necessary to consider the oxidations, dissociations and other chemical reactions that can occur near the arc created for welding, the workers' experience, the position of welding, the environment in which the work is carried out (whether it is an open or a confined space). The persistence of the particulate in the environment depends on the presence or efficiency of the general and local aspiration [6] and the time elapsed since the last welding would also seem to be influential as it contributes to a phenomenon of accumulation of the particles, and a stratification of the level of exposure [5,7,8].

Although the effects of welding fume emissions on the health of exposed people and in particular the carcinogenic mechanisms are not yet fully understood [9], since the early 1990s a relationship has been highlighted between the inhalation of UFP and health effects [3].

In 1989, the IARC (International Agency for Research on Cancer, Lyon), classified welding fumes as possible carcinogens for humans, based on limited evidence of carcinogenicity (lung cancer) [5].

After almost thirty years of studies and evidence research, in 2018 the IARC came to publish with the monograph 118, entitled "welding, molybdenum trioxide, and indium tin oxide" the results of the work of 17 scientists on the carcinogenicity of welding, of molybdenum trioxide and indium-tin oxide arriving to classify welding fumes as belonging to group 1, i.e., certain carcinogens for humans. The monograph established that "there is sufficient evidence in humans for the carcinogenicity of welding fumes. Welding fumes cause lung cancer. Positive associations have been seen with kidney cancer. There is sufficient evidence in humans for the carcinogenicity of ultraviolet radiation from welding. Ultraviolet radiation from welding causes ocular melanoma" [10].

In the light of various evidence, although there are specific occupational exposure limits (OELs) for some of the components of welding fumes, no OEL has yet been established for undifferentiated welding fumes, intended as aggregate fumes or the various components and their possible additive or synergistic effects, but for their evaluation reference is made to the OEL established as PNOR (Particulates Not Otherwise Regulated) [11].

1.1. Objectives

Our study aims to evaluate the current occupational exposure levels to airborne particles, UFP and inhalable fraction particles in welding operators in the maintenance shop of an Italian steel making factory.

2. Materials and methods

2.1. Strategy of sampling

The monitoring campaign was carried out in a steel making factory in northern Italy which produces over two and a half million tons of steel and rolled products a year, specializing in the production of steel for construction, including bars, billets, spacers, electrowelded mesh, rewound rolls, shaped, drawn, wire rods.

In October 2019, environmental monitoring was performed for four consecutive days in a week to assess the exposure to airborne particulate, ultrafine particle fractions (UFP) and inhalable fraction (IF) particles, during SMAW (Shielded Metal Arc Welding) and

GTAW (Gas Tungsten Arc Welding) activities in a real working context. The welding activities were performed on mild steel as base materials, using different types of electrodes. In the last day, an environmental sampling was carried out outside, in the plant external environment.

The workplace was large, equipped with general aspiration and local aspiration (LEV, Local Exhaust Ventilation). The work was done on a workbench about 1 m high. The operators wore all personal protective equipment required by the UNI EN technical standards.

The airborne particulate, UFP and IF levels were determined using stationary samplers in the real working environment, considering the technology cycle and operational needs. The concentrations and distributions of the numbers and mass of the airborne particles and UFP fraction were monitored using an ELPI™ (Electrical Low-Pressure Impactor) sampler, whereas the collection of the IF took place using an IOM preselector according to the European standard method EN 481 [12]. The sampling times were the same and both ELPI™ and IOM were positioned approximately 1.5 m above the ground and at a linear distance between 1 and 1.5 m aside from the operator engaged in welding operations.

During welding, any event deemed as relevant for the correct data interpretation was noted.

2.2. Instruments

The airborne particles and UFP distribution and concentration were measured using a particle counter. The low-pressure electric impactor, model ELPI™ which allows the measurement of the particulate in a stationary position and, through the dimensional selection of the particulate in the air, detects the diameter of the particles in real time (dimensions between 0.01 μm and 7.298 μm), the concentration and, based on the data collected, provides an estimate of the concentration in the surface area/mass/volume of the particulate. The ELPI™ was connected to an air inlet pump with a flow rate of 0.6 m^3/h and a pressure of 40 mbar in the final stage of the impactor (absolute filter). The number of ultrafine particles (UFP) was calculated as the sum of particles having a central geometric mean diameter (Di) between 10 nm and 121 nm (D50 % range 6 nm–94 nm), assuming a density of 1 g/cm^3, corresponding to ELPI Stages 1–5. Data provided by ELPI™ were processed with ELPI™ VI 2.0 software (Dekati Ltd., Kangasala, Finland). Moreover, the fraction corresponding to the last 7 ELPI Stages (Stages 1–7, Di between 10 nm and 314 nm) was also calculated.

Detailed description about the considered stages of the ELPI with the geometric mean aerodynamic diameter is reported in Table 1.

Dust sampling of the inhalable fraction [12] was conducted using samplers with a constant flow rate of 2 L/min. The airborne material, i.e. the inhalable fraction, was collected by filtration, using the IOM Sampler selector (SKC Inc., Eighty-Four, PA, USA). IF was collected on cellulose ester membranes, with a diameter of 25 mm and a porosity of 0.8 μm, according to the NIOSH method [13]. The selector was connected to the pump (SKC Inc., Eighty-Four, PA, USA) set at a flow rate required. The dust analysis was carried out by the microgravimetric method on the membranes conditioned, before and after sampling, in a cabinet at controlled temperature and humidity for 24 h (Activa Climatic, Acquaria, Milan, Italy) and weighed on a scale to the fifth decimal scale. The difference in weight, in relation of the volume of air taken during the sampling, allowed the calculation of the dustiness in mg/m^3. The detection limit of the method is 0.03 mg and the coefficient of variation is 0.2 %. For air sampling, the filter holder was mounted on a support at a height of approximately 150–160 cm from the floor, away from obstacles or significant air flows.

2.3. Sampling programme

We sampled four SMAW (SMAW- 1–4) and one GTAW activities.

On the first day, the SMAW-1 was applied, using 26 chrome-coated electrodes (Cr 16 % - Ni>50 %) for 1 h, 13 min, 46 s (from 10:24:12 to 12:03:58). The ELPI™ sampler distance was approximately 1.5 m. The IF was evaluated on 200 L of sampled air.

On the second day, the SMAWs −2 and −3 were performed.

- SMAW-2 was performed using 25 chrome electrodes (Cr 10–50 % - Ni 0.1–50 %) for 1 h, 13 min and 26 s (from 10:05:47 to 11:19:13), in the presence of a Smoke Control aspirator (Teknoindustria Srl, Modena, Italy). The ELPI™ sampler was approximately 1.30 linear distance from the operator. The IF was evaluated on 168 L of sampled air.
- The SMAW-3 was performed using 50 nickel coated electrodes (Ni>50 %) for 1 h, 13 min, 51 s (from 14:01:30 to 15:15:21) The ELPI™ was located approximately 1.3 linear meters from the operator. The IF was evaluated on 144 L of sampled air.

On the third day, the SMAW-4 was performed using 45 chrome coated electrodes (Cr 16 % - Ni>50 %), for a total of 2 h, 15 min, 5 s (from 9:46 to 12:11:19). The distance of the ELPI ™ from the operator was about 1 m. From about 10:50 a.m. welding was carried out

Table 1
Description of ELPI stages. Di: geometric mean aerodynamic diameter; D50 %: cut-off diameter. Airborne particles: stages 1–14; UFP: stages 1–5.

Particle Fraction	Stage	D50 % (μm)	Di (μm)
Airborne Particles	14	5,3	7,3
Fraction ELPI Stages 1-7	7	0,25	0,31
Ultrafine particles (UFP)	5	0,094	0,12
	1	0,006	0,010

for about 1 min without aspirator. The IF was evaluated on 162 L of sampled air.

The GTAW was sampled on the fourth day, in the absence of aspiration, for 1 h, 17 min, 17 s. Welding was carried out using 7 filler rods (Cr 19,5 % - Ni>10 %) with Argon shielding gas. The distance of the ELPI sampler was approximately 1.3 m from the operator. The IF was evaluated on 148 L of sampled air. On the same day, external environment outside the workshop was sampled for 2 h, 30 min and 19 s (from 9:46:24 to 12:16:43). The IF was evaluated on 416 L of sampled air.

3. Results

3.1. Arborne particles number distribution

Fig. 1 shows the distribution of airborne particles number concentration (part/cm^3) measured by the ELPI during the five welding activities and in the steel foundry external environment.

In the SMAW and in the external samplings, the distribution of PM as particle number is generally more dominated by UFP, while the GTAW sampling shows a bimodal distribution where the most represented fractions are 0.05 μm and 0.1 μm.

In more detail, the SMAW-1 shows a concentration of 40.927part/cm^3 for the fraction size of 0.01 μm and the SMAW-2 of 21,061 part/cm^3 for particles of size 0.01 μm, 15,900 part/cm^3 for particles of 0.03 μm and 12,259 part/cm^3 particles of 0.121 μm. During

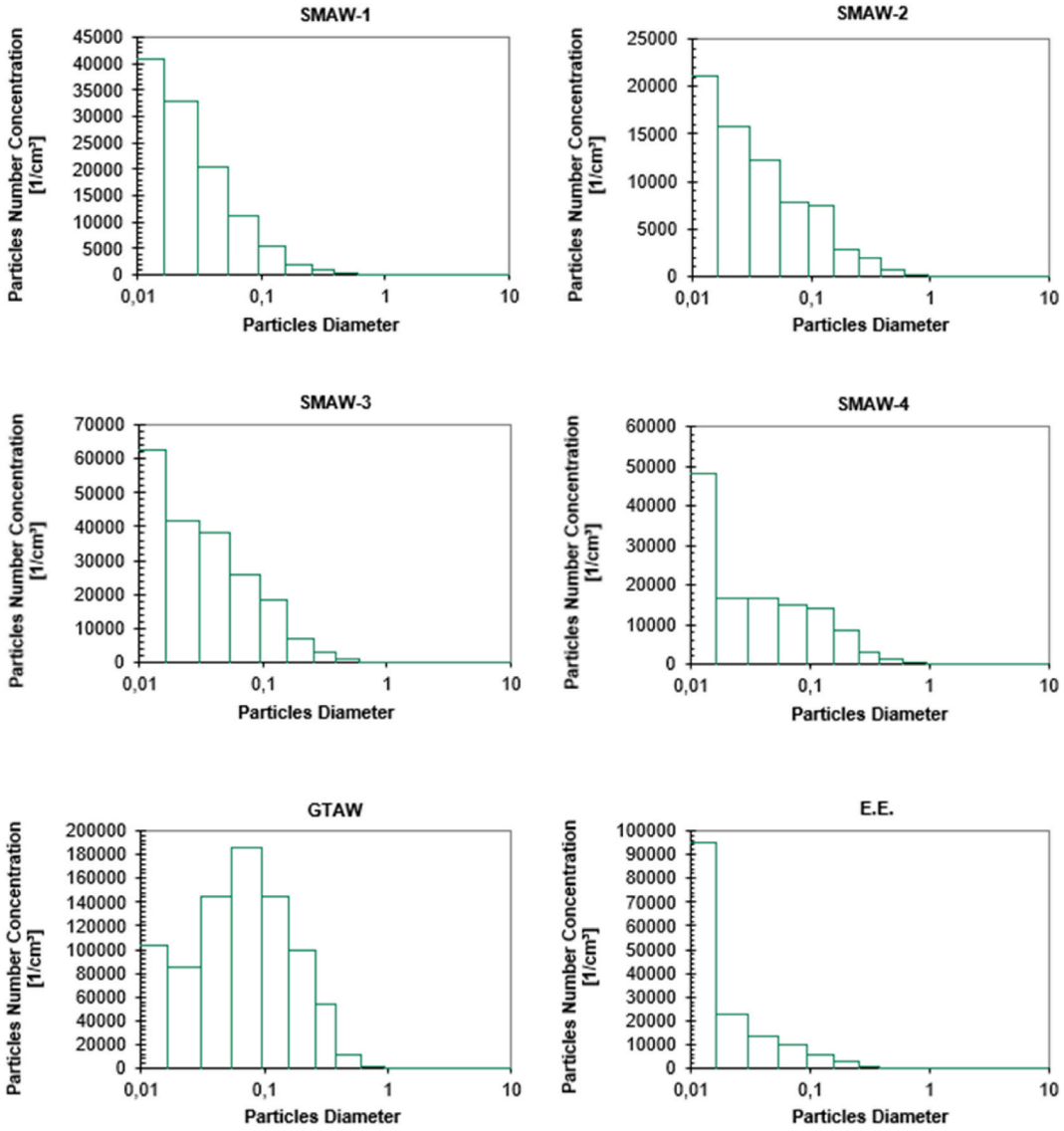

Fig. 1. *Distribution of* airborne particles *number concentration detected with ELPI during welding samplings. SMAW: Shielded Metal Arc Welding; GTAW: Gas Tungsten Arc Welding; E.E.: external environment.*

SMAW-3 higher values were recorded for 0.01 μm particles of 62676 part/cm^3, of 41574 part/cm^3 for particles of 0.03 μm and 38.308 part/cm^3 for particles of 0.05 μm. SMAW-4 revealed that the number distribution for 0.01 μm particles was 48,020 part/cm^3 and a bimodal distribution was highlighted for 0.03 μm and 0.05 μm particles with approximately 16,500 part/cm^3. During GTAW, values of the concentration in number of 104,182 part/cm^3 for the particles of 0.01 μm, of 84,600 part/cm^3 for the particles of 0.03 μm, the particles of 0.05 μm and 0.156 μm were approximately 145,400 and those of 0.094 μm accounted for the largest share with 185,800. In the steel foundry external environment there was a concentration of 95.035 part/cm^3 for the particles of 0.01 μm and of 22.366 part/cm^3 for those of 0.03 μm.

3.2. Arborne particles number concentration

Fig. 2 shows the summary descriptive statistics of airborne particulate number concentration; complete data are reported in Table 2. The fraction corresponding to the last 7 stages (10–314 nm) of ELPI samplings represents over 99 % of the total airborne particulate measured in terms of number (part/cm^3). So, the samples belonging to the fine fraction clearly influences the trend of the average of the whole sample.

Fig. 3 shows the concentration in number of particles belonging to the fraction corresponding to the last 7 ELPI stages (Stages 1–7, diameter between 0.010 μm and 0.314 μm) detected during environmental samplings in the welding workstations and in the external environment outside the workshop. An enlargement of Fig. 3A–F is provided in supplementary material (Fig. S1).

Fig. 3A shows the concentration in number of particles detected during the steel foundry external environment sampling, where it is possible to observe the sampling in detail with adjustment of the decimal scale to the peak recorded during the day. The maximum peak is 1.30×10^5 and is observed between 11:54 and 11:59. The most represented fraction is around 10 nm.

Fig. 3B shows the concentration in number detected in real time by ELPI during the SMAW-1. The procedure was performed by alternating short welding progress phases with subsequent short grinding cycles for the elimination of the slag. The highest peak was reached around 11:07 with a value of 7.76×10^6 during grinding activity. This is the second highest value that has been reached compared to the emissions recorded on other welding activities and lower only than the peak recorded during the GTAW activity.

Fig. 3C shows the concentrations in number (with the adjustment of the ordinate axis as a function of the maximum peak) detected during the sampling on SMAW-2, with no grinding and with the constant use of an aspirator (mod. Smoke Control Teknoindustria). The higher levels are represented by the lower particle size fractions.

Fig. 3D shows the concentration as number (with adjustment of the ordinate axis according to the maximum number of particles recorded equal to 1.34×10^5 part/cm^3) for particles with a diameter between 0.010 μm and 0.314 μm detected with the ELPI during SMAW-3 carried out through the total use of 50 coated electrodes on stainless steel and in the presence of forced suction.

Fig. 3E shows the number distribution (with adjustment of the ordinate axis) of the particles emitted during SMAW-4. The maximum peak was recorded around 10:55, when it was performed a weld procedure without aspiration system. It should be noted

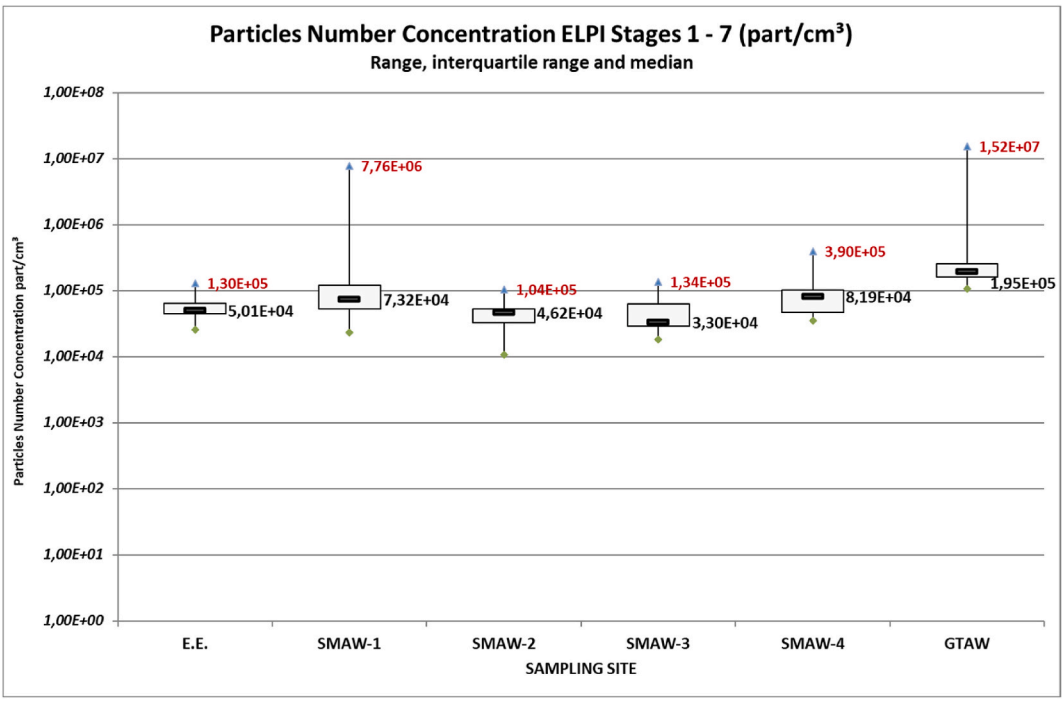

Fig. 2. Central tendency and dispersion of particles number concentrations as measured by the ELPI (Stages 1–7). SMAW: Shielded Metal Arc Welding; GTAW: Gas Tungsten Arc Welding; E.E.: external environment.

Table 2
Detailed data of airborne particles concentration by different fractions of particulate considering different ELPI stages. Stages 1–5 represent UFP fraction. E.E. External environment. TOT 1–5 range Di 0.010 μm–0.121 μm; TOT 1–7 range Di 0.010 μm–0.314 μm; TOT 1–14 range Di 0.010 μm–7.298 μm.

Number Concentration Part/cm^3																			
ELPI STAGE	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14
	E. E.			SMAW-1			SMAW-2			SMAW-3			SMAW-4			GTAW		
1Q	4,41E+04	4,47E+04	4,47E+04	5,06E+04	5,28E+04	5,36E+04	3,14E+04	3,24E+04	3,26E+04	2,72E+04	2,86E+04	2,88E+04	4,46E+04	4,72E+04	4,75E+04	1,44E+05	1,62E+05	1,63E+05
MIN	2,53E+04	2,58E+04	2,58E+04	2,24E+04	2,31E+04	2,32E+04	9,71E+03	1,06E+04	1,07E+04	1,69E+04	1,83E+04	1,85E+04	3,29E+04	3,53E+04	3,55E+04	9,17E+04	1,06E+05	1,07E+05
MEDIAN	**4,94E+04**	**5,01E+04**	**5,02E+04**	**6,80E+04**	**7,32E+04**	**7,61E+04**	**4,42E+04**	**4,62E+04**	**4,64E+04**	**3,13E+04**	**3,30E+04**	**3,32E+04**	**7,86E+04**	**8,19E+04**	**8,22E+04**	**1,76E+05**	**1,95E+05**	**1,96E+05**
MAX	1,29E+05	1,30E+05	1,30E+05	7,74E+06	7,76E+06	7,76E+06	1,02E+05	1,04E+05	1,05E+05	1,32E+05	1,34E+05	1,35E+05	3,83E+05	3,90E+05	3,90E+05	1,49E+07	1,52E+07	1,52E+07
3Q	6,26E+04	6,33E+04	6,33E+04	1,05E+05	1,19E+05	1,29E+05	5,20E+04	5,33E+04	5,36E+04	5,99E+04	6,22E+04	6,25E+04	9,77E+04	1,01E+05	1,02E+05	2,32E+05	2,53E+05	2,55E+05
MEAN	5,44E+04	5,50E+04	5,50E+04	1,72E+05	1,78E+05	1,81E+05	4,17E+04	4,30E+04	4,32E+04	4,67E+04	4,86E+04	4,89E+04	8,12E+04	8,44E+04	8,48E+04	4,02E+05	4,27E+05	4,29E+05
SD	1,53E+04	1,54E+04	1,54E+04	3,95E+05	3,96E+05	3,96E+05	1,33E+04	1,36E+04	1,37E+04	2,89E+04	2,94E+04	2,95E+04	4,04E+04	4,09E+04	4,09E+04	9,58E+05	9,78E+05	9,79E+05

that at around 11:11 a grinding was performed on an external station about 50 m from the sampling station, and at around 11:47 the entrance door of the workshop was opened, generating a strong current.

Fig. 3F shows the concentration in number recorded during the GTAW, in the absence of a local aspirator. It should to be noted that the graph was adjusted to the maximum peak recorded, by an order of magnitude higher than the previous ones. At 14:40, 5 min before the start of the impactor, which took place at 14:45, the operator used an emery wheel to cut a stainless-steel plate, at the same time as the sampling began, the operator smoked a cigarette in the vicinity of the ELPI and at 14:52 he started welding activities. The peak concentration in number is reached around 15:01.

3.3. Airborne particles mass distribution

Fig. 4 summarizes the mass distribution of the particles, expressed in mg/m^3. An overall analysis shows that the mass of the coarse particle size fraction is represented during the sampling of the five welds, while they are not present in the sampling of the steel foundry general environment. For the GTAW, a bimodal distribution is shown for the 50 nm and 150 nm particles.

Fig. 5 shows the summary description of the quantitative statistical *airborne particles mass* concentration (ELPI Stages 1–14) recorded during all the sampling days, allowing for an overview of the main dispersion indices. Detailed data are reported in Table 3.

Fig. 6 shows the trends of particles mass concentrations expressed in mg/m^3, detected during sampling in the steel foundry external environment and during the welding processes. An enlargement of Fig. 6A–F is provided in supplementary material (Fig. S2).

In the external environment, it is noted that the maximum concentrations are recorded during the first phase of sampling (Fig. 6A).

During SMAW-1, as reported in Fig. 6B, the most relevant mass fractions were those from 3.007 μm to 7.298 μm. As previously indicated, welding alternated with short grinding cycles.

Also, during SMAW-2, as indicated in Fig. 6C, the most represented fractions were those of bigger size approximatively 3–7 μm.

Fig. 6D shows the mass concentrations detected during SMAW-3 and during which higher concentrations were recorded on the total for the size 4.437 and 7.298 μm.

Fig. 6E related to SMAW-4 reported higher mass concentrations for the fractions from 2.007 μm to 7.298 μm. Around 11:11 a grinding was performed outside the workshop about 50 m away from the welding station. There was a peak around 11:47 in conjunction with the opening of the entrance door of the workshop, which generated a strong air current.

Fig. 6F reported mass concentration detected in the GTAW sampling.

3.4. Inhalable fraction results

Table 4 shows the mass concentration (mg/m^3) of the inhalable fraction (IF) measured during the sampling of the five welds and the using the IOM preselector. The highest level was sampled during GTAW.

Table 4. Synthetic summary of the sampling of the inhalable fraction on the welding workstations. IF: inhalable fraction; SMAW: Shielded Metal Arc Welding; GTAW: Gas Tungsten Arc Welding.

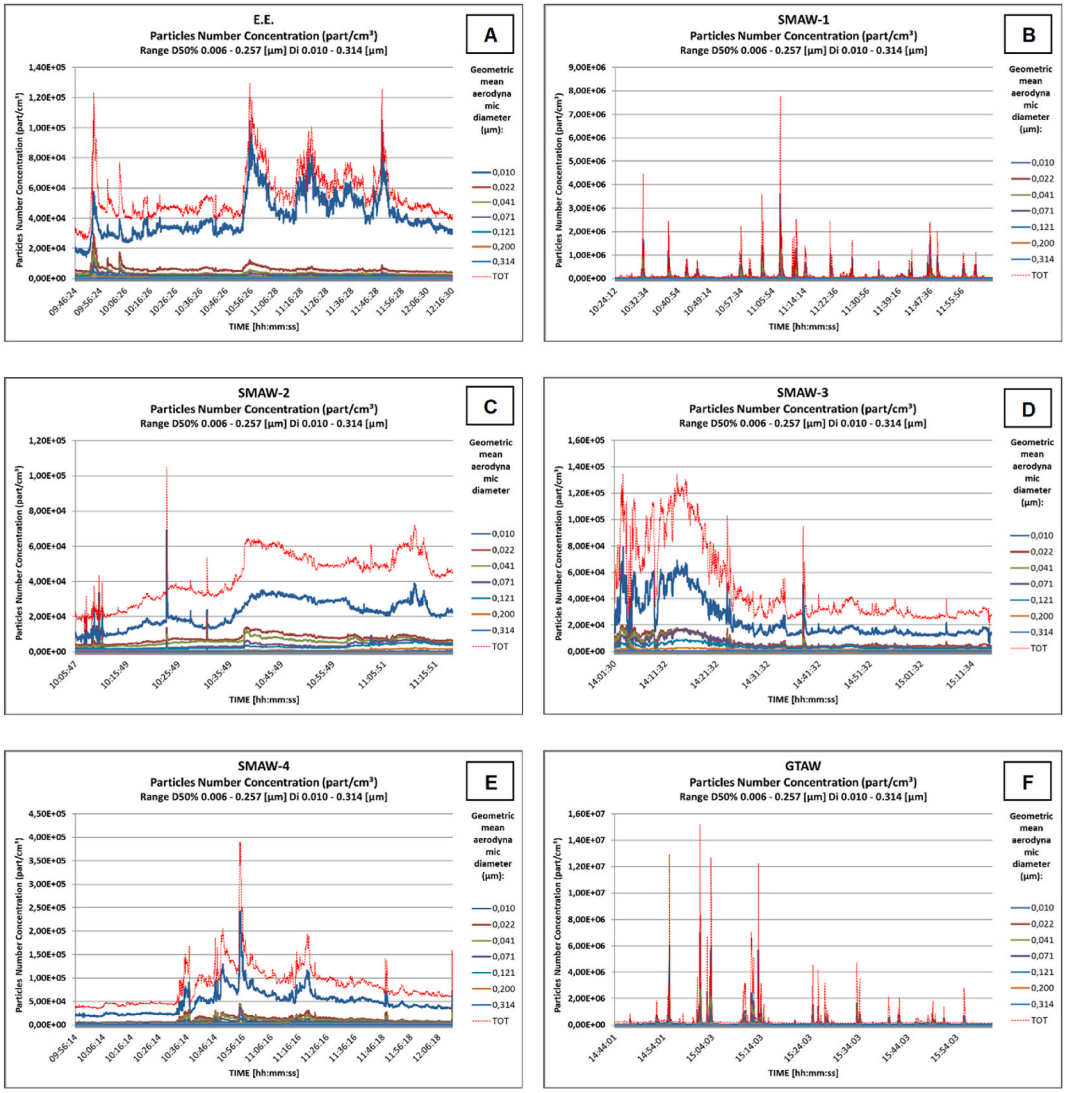

Fig. 3. Concentration in number of particles with a diameter between 0.010 µm and 0.314 µm with D50 % 0,257 µm (ELPI stages 1–7) with axis adjustment of the concentration detected during samplings. SMAW: Shielded Metal Arc Welding; GTAW: Gas Tungsten Arc Welding; E.E.: external environment.

4. Discussion

The airborne particles exposure assessment performed in five different welding workstations showed that the distribution of concentrations in number for all samplings was significantly higher for nanoscale particles. Specifically, the fractions included in the last 7 ELPI stages (Stages 1–7, 0.010 µm–0.314 µm) represented for each weld from 98 % to 99 % of the total, and for the last 4 ELPI stages (Stages 1–4, 0.010 µm–0.071 µm) concentrations between 85 % and 91 %.

A previous study by Debia et al. [8] noted that the fraction of fine and ultrafine particles with a diameter <100 nm was about 65 % of the total. Other studies have observed that for the median particle size distributions, only 10–16 % of the particles sampled in the MMAW (Manual metal arc welding), MAG (Metal-arc Active Gas), MIG (Metal-arc Inert Gas) methods (at 60 cm from the weld site) had aerodynamic diameters smaller than 50 nm, while the modal distribution for these welding operations was around 110–140 nm. As confirmation of the different tendency to form agglomerates depending on the type of weld, the particle size distributions produced by GTAW welding have a completely different structure. The particles produced with this technique (at 60 cm from the welding site) are almost all smaller than 100 nm and at least 90 % are smaller than 50 nm. These particles are almost exclusively UFP, indicating that the agglomeration of the primary particles is much slower [14].

During the first welding carried out with the SMAW technique on stainless steel, alternated to short grinding cycles in the presence of a local aspirator, some maximum peaks of 7.76×10^6 part/cm^3 were recorded. Albeit the peaks in the graph would seem to correspond to the grinding actions, it is not possible to attribute this relationship univocally, accordingly with other studies in which

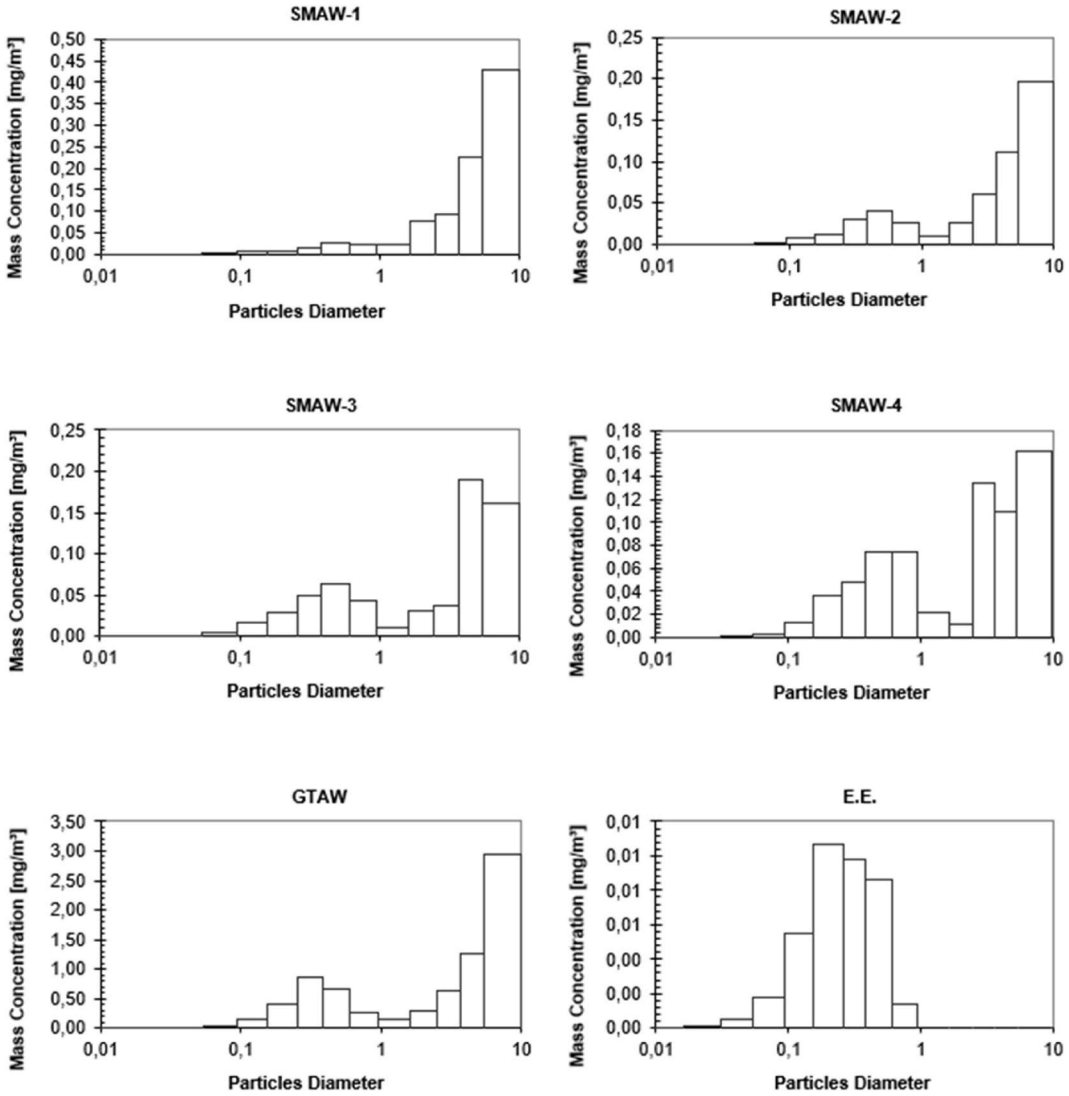

Fig. 4. Mass concentrations of the particles. SMAW: Shielded Metal Arc Welding; GTAW: Gas Tungsten Arc Welding; E.E.: external environment.

welding and grinding activities were carried out at the same time and it was not possible to evaluate the influence of each individually [5].

The sampling of the GTAW weld, performed in the total absence of aspiration, showed a maximum concentration of approximately 186,000 parts/cm^3 recorded for the 94 nm particles. The dimension of the particles is similar to that observed in studies carried out on two schools of welding during the monitoring of a GTAW weld, but on aluminium-based material. The data of the distribution in number in that case probably differed due to the presence of forced aspiration, which allows to record lower concentrations than our sample, between 30,000 part/cm^3 and 100,000 part/cm^3 [8].

GTAW welding showed a bimodal distribution for the 50 nm and 150 nm modes. Other studies have observed similar results [8,14]. Some authors have shown that the bimodal distribution may be due to the ability of particles of smaller diameters to agglomerate. The particles generated mechanically by the fusion of the material and those produced by condensation would be represented in the aerosol [15].

The formation of the multimodal number size distribution in some cases observed near the breathing zone, for some authors it would seem to be attributable to complex dynamics including nucleation, condensation, coalescence, coagulation and deposition [14].

The concentrations detected on the steel foundry external environment revealed that the ultrafine fraction was very limited and the coarse fraction completely absent. Fine particulate was detected in suspension, probably the accumulation fraction, i.e. particles too large to escape the Brownian motion but too fine to precipitate due to the force of gravity and therefore manage to remain suspended in the atmosphere for up to a month.

As it concerns the average concentration monitored in the workshop it was approximately 5.01×10^4 part/cm^3, while the

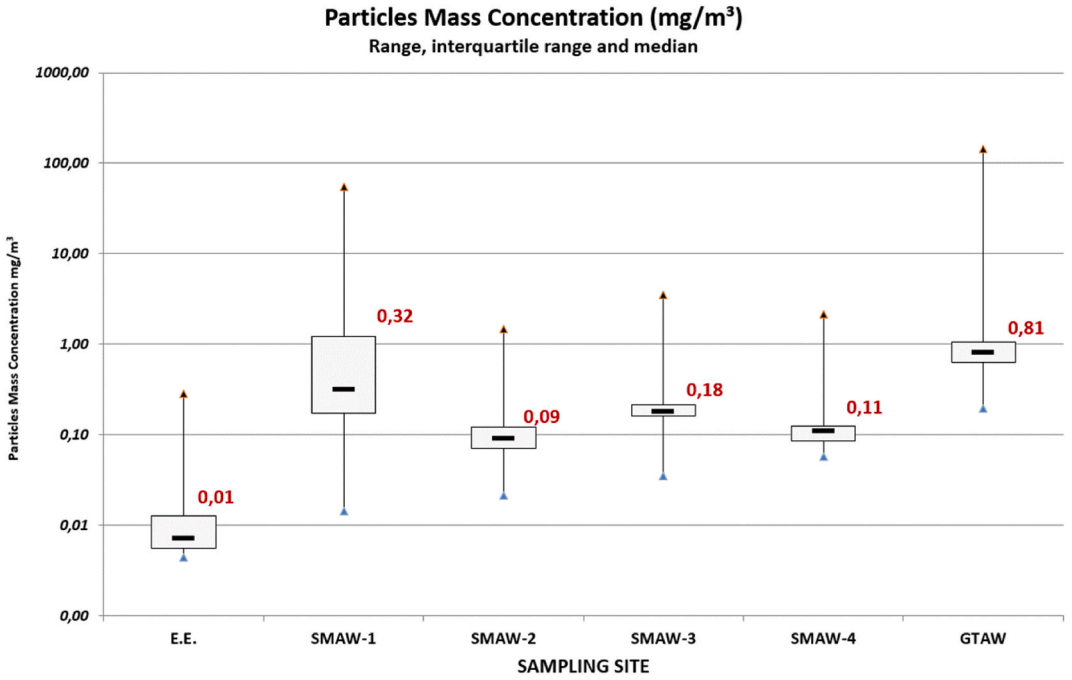

Fig. 5. Central tendency and dispersion of mass airborne particles measured by ELPI (Stages 1–14). SMAW: Shielded Metal Arc Welding; GTAW: Gas Tungsten Arc Welding; E.E.: external environment.

Table 3
Detailed data of airborne particles mass concentration by different fractions of particulate considering different ELPI stages. Stages 1–5 represent UFP fraction. E.E. External environment. TOT 1–5: 0.010 μm–0.121 μm; TOT 1–7: 0.010 μm–0.314 μm; TOT 1–14: 0.010 μm–7.298 μm.

Mass Concentration mg/m³																		
ELPI STAGE	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7		TOT 1-5	TOT 1-7	TOT 1-14	TOT 1-5	TOT 1-7	TOT 1-14
	E. E.			SMAW-1			SMAW-2			SMAW-3			SMAW-4			GTAW		
1Q	1,52E-03	4,52E-03	5,62E-03	2,65E-03	1,04E-02	1,74E-01	2,31E-03	1,02E-02	7,04E-02	2,88E-03	1,37E-02	1,60E-01	4,59E-03	2,27E-02	8,55E-02	2,46E-02	1,37E-01	6,28E-01
MIN	1,24E-03	3,63E-03	4,43E-03	1,24E-03	6,50E-03	1,44E-02	1,24E-03	7,81E-03	2,12E-02	2,31E-03	1,08E-02	3,51E-02	3,49E-03	1,76E-02	5,73E-02	1,63E-02	1,12E-01	1,92E-01
MEDIAN	**1,65E-03**	**5,27E-03**	**7,21E-03**	**4,52E-03**	**2,64E-02**	**3,16E-01**	**2,95E-03**	**1,27E-02**	**9,17E-02**	**3,62E-03**	**1,65E-02**	**1,82E-01**	**5,46E-03**	**2,91E-02**	**1,11E-01**	**2,87E-02**	**1,55E-01**	**8,07E-01**
MAX	7,92E-02	2,81E-02	2,82E-01	2,57E-01	7,91E-01	5,52E+01	8,46E-03	2,85E-02	1,45E+00	1,28E-02	1,01E-01	3,51E+00	2,36E-02	8,87E-02	2,16E+00	9,00E+01	2,29E+00	1,44E+02
3Q	1,92E-03	6,13E-03	1,25E-02	9,50E-03	8,81E-02	1,20E+00	4,63E-03	1,65E-02	1,22E-01	5,73E-03	2,21E-02	2,13E-01	6,42E-03	3,23E-02	1,23E-01	3,62E-02	1,86E-01	1,05E+00
MEAN	1,81E-03	5,81E-03	1,41E-02	8,63E-03	6,72E-02	1,34E+00	3,48E-03	1,38E-02	1,06E-01	4,81E-03	1,87E-02	2,00E-01	5,73E-03	2,92E-02	1,25E-01	5,11E-02	2,10E-01	2,08E+00
SD	6,06E-04	2,49E-03	1,80E-02	1,38E-02	8,91E-02	2,93E+00	1,46E-03	4,40E-03	6,89E-02	2,66E-03	6,79E-03	1,19E-01	1,79E-03	7,99E-03	9,84E-02	7,81E-02	1,94E-01	7,81E+00

maximum average concentration recorded on all samplings was 1.95×10^5 part/cm^3 on GTAW welding, with a peak of 1.52×10^7 parts/cm^3. Gomes et al. (2012) found an average concentration of 9.75×10^3 part/cm^3 detected during MAG welding when sampling at different distances from the process (30–60 cm) [16]. This average level is substantially lower than detected during our measurements, that is very similar to that detected from Bonanno et al., 2011 of 1×10^5 part/cm^3 [7]. Different results on average concentrations could be due to different welding process and different sampling distance with respect to those performed in our study. For instance, Gomes et al. sampled a MAG welding on carbon steel at 30–60 cm from the welding process, while Buonanno et al. sampled in several body shops of an automotive plant at 3 m from the source.

This finding is similar to that observed during a review of measurements in different environments by Morawska et al., in 2008, according to which the average environmental background levels vary from 2610 parts/cm^3 in rural areas to 48,180 parts/cm^3 along

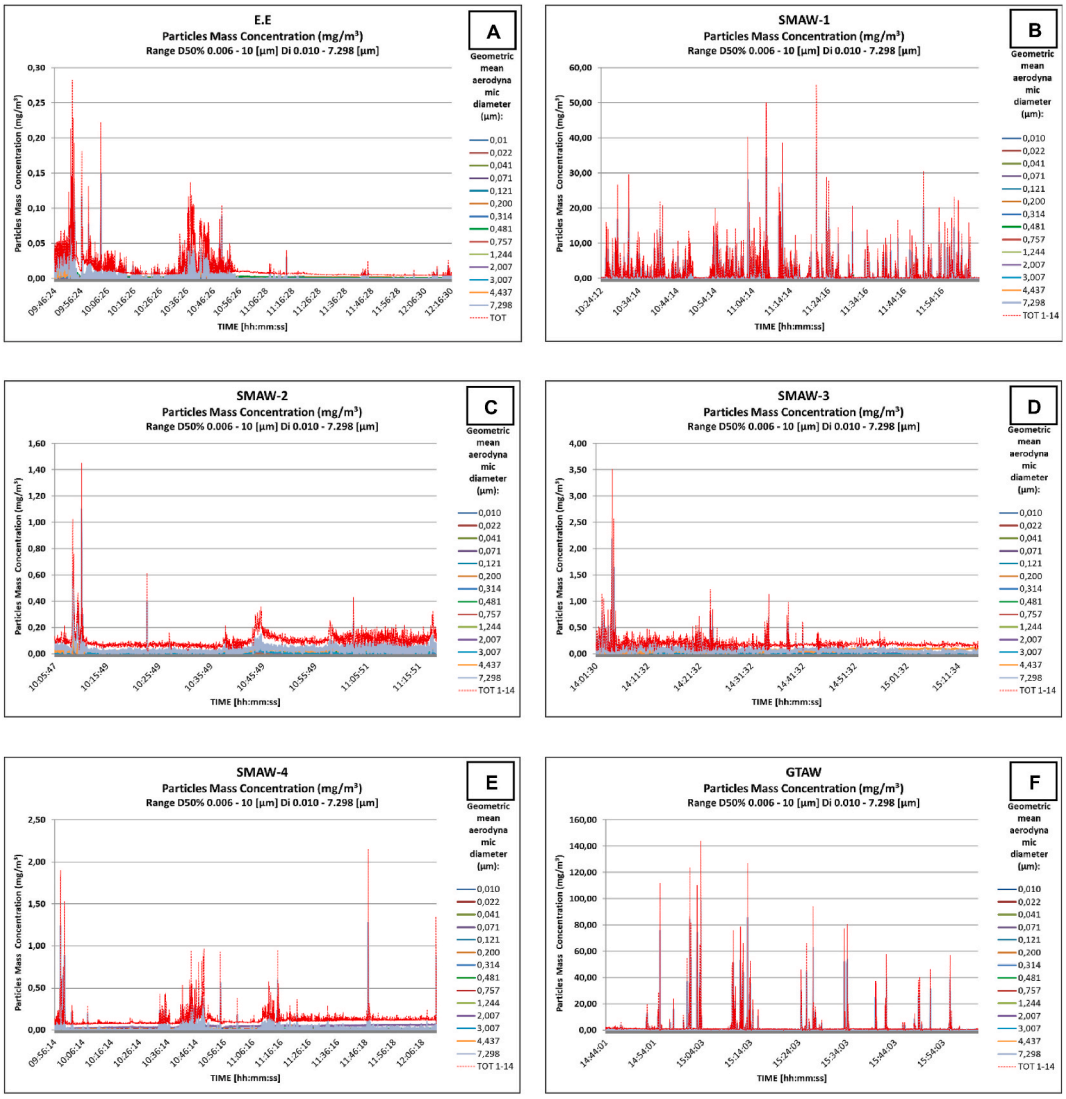

Fig. 6. Trends of mass concentration of particles with a diameter between 0.01 µm and 7.298 µm (stages 1–14) detected by ELPI samplings. SMAW: Shielded Metal Arc Welding; GTAW: Gas Tungsten Arc Welding; E.E.: external environment.

Table 4
Summary of IF samplings.

Welding	Litres	IF, mg/m^3	Electrode composition
SMAW-1	200	0.1	Cr16 %; Ni>50 %
SMAW-2	168	0.18	Cr10-50 %; Ni > 0,1–50 %
SMAW-3	144	0.69	Ni>50 %
SMAW-4	162	0.12	Cr16 %; Ni>50 %
GTAW	148	1.08	Cr = 19,50 %; Ni = 10 %

roadsides. Further studies attribute exposure values up to 100 times the urban background and peaks that can reach 1000 times the background levels, considered as exposure of the general population [17,18].

The IF detected for the five different welding showed levels between 0.1 mg/m^3 and 1.08 mg/m^3. Previous studies published similar levels, confirming ranges between 0.16 mg/m^3 and 1.1 mg/m^3 [5].

The highest level of IF again was observed on the GTAW welding procedure, but overall, these results are much lower than the exposure levels indicated by OSHA regulations, of 15 mg/m^3 for total dust and of 10 mg/m^3 for inhalable fraction as recommended limit proposed by ACGIH (No TLV TWA established) [19].

Some limitations affect the present study. Previous studies have observed that the amperage used in the different welding processes can have importance in determining different emissions [20,21]. In our assessment, the impact of the variation of current intensity was not observed and could have been implemented in further evaluations. The current intensity, despite it determine deeper welds, could affect fume emissions as the filler material fusion process could happen more or less quickly. Moreover, a chemical characterization of the ultrafine particle could be useful to understand the exact composition of the fumes generated in several welding activities as reported in similar studies [22,23].

Despite those limitations, the results of the present study substantially confirm what was observed in previous studies regarding the distributions in terms of number and mass of welding fumes for SMAW and GTAW techniques on steel and the relevant influence of local aspiration on the emissions. In line with previous studies, the results highlighted the importance of the efficiency of localized aspiration systems and the need to apply prevention and protection measures despite the low levels of exposure measured in terms of mass [6,24].

5. Conclusion

Through a multimetric and multi-instrumental approach, our study assessed the exposure to airborne particulates during various welding activities. Airborne particles distribution and concentration highlighted a relevant variability in relation to the different working conditions including the efficiency of the aspirator, the composition of the base metals, the composition of electrode used and the technology employed. Moreover, number concentration showed an important contribution in the emission of UFP compared to background levels. When comparing IF levels with the appropriate regulatory references, they were substantially contained and below the OELs.

There is a need for further studies aimed at the chemical characterization of the particulate and at the analysis of further variables of the working process which could influence the exposure levels to welding fumes.

Fundings

This research did not receive a specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Sergio Pili: Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Luigi Isaia Lecca:** Writing – review & editing, Writing – original draft, Visualization. **Tatiana Pedrazzi:** Writing – review & editing, Visualization, Investigation. **Roberta Ghitti:** Writing – review & editing, Visualization, Investigation. **Alessandro Murru:** Visualization, Investigation. **Michele Uras:** Visualization, Investigation, Formal analysis. **Daniele Fabbri:** Visualization, Investigation. **Marcello Campagna:** Visualization, Validation, Supervision, Resources, Conceptualization. **Giuseppe De Palma:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

No acknowledgements.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e40815.

References

[1] A. Marconi, Materiale particellare aerodisperso: Definizioni, effetti sanitari, misura e sintesi delle indagini ambientali effettuate a Roma, Ann. Ist. Super Sanita 39 (2003) 329–342.
[2] INAIL. Protocolli di acquisizione delle informazioni e metodi di caratterizzazione dell'esposizione a nanomateriali, in: Libro Bianco. Esposizione a nanomateriali ingegnerizzati ed effetti sulla salute e sicurezza nei luoghi di lavoro, 2002, pp. 95–124.
[3] A. Marconi, Particelle fini, ultrafini e nanoparticelle in ambiente di vita e di lavoro: possibile effetti sanitari e misura dell'esposizione inalatoria, 2007.
[4] M.K. Honaryar, R.M. Lunn, D. Luce, et al., Welding fumes and lung cancer: a meta-analysis of case-control and cohort studies, Occup. Environ. Med. 76 (2019) 422–431, https://doi.org/10.1136/oemed-2018-105447.
[5] I. Iavicoli, V. Leso, L. Fontana, et al., Characterization of inhalable, thoracic, and respirable fractions and ultrafine particle exposure during grinding, brazing, and welding activities in a mechanical engineering factory, J. Occup. Environ. Med. 55 (2013) 430–445, https://doi.org/10.1097/JOM.0b013e31827cbabe.

[6] M. Lehnert, A. Goebel, W. Zschiesche, et al., How to reduce the exposure of welders to an acceptable level: results of the InterWeld study, Ann Work Expo Heal 66 (2022) 192–202, https://doi.org/10.1093/annweh/wxab082.
[7] G. Buonanno, L. Morawska, L. Stabile, Exposure to welding particles in automotive plants, J. Aerosol Sci. 42 (2011) 295–304, https://doi.org/10.1016/j.jaerosci.2011.02.003.
[8] M. Debia, S. Weichenthal, A. Dufresne, Case study: ultrafine particles exposure in apprentice welders, J. Occup. Environ. Hyg. 11 (2014) D1–D9, https://doi.org/10.1080/15459624.2013.836280.
[9] Z. Soltanpour, Y. Rasoulzadeh, Y. Mohammadian, Occupational exposure to metal fumes among Iranian welders: systematic review and simulation-based health risk assessment, Biol. Trace Elem. Res. 201 (2023) 1090–1100, https://doi.org/10.1007/s12011-022-03246-y.
[10] IARC, Welding, Molybdenum Trioxide, and Indium Tin Oxide, 2017.
[11] M. Harris, Welding fume is a Group 1 carcinogen with no OEL and no method-Suggestions for a path forward, J. Occup. Environ. Hyg. 16 (2019) 367–371, https://doi.org/10.1080/15459624.2019.1600703.
[12] European Committee for Standardization, EN 481:1993-09, Workplace Atmospheres: Size Fraction Definitions for Measurement of Airborne Particles, European Committee for Standardization, Brussels, 1994.
[13] NIOSH. Manual of Analytical Methods (NMAM), in: fourth ed.PARTICULATES NOT OTHERWISE REGULATED, TOTAL: METHOD, 1994 0500, 1–3.
[14] P. Brand, K. Lenz, U. Reisgen, et al., Number size distribution of fine and ultrafine fume particles from various welding processes, Ann. Occup. Hyg. 57 (2013) 305–313, https://doi.org/10.1093/annhyg/mes070.
[15] F.E. Pfefferkorn, D. Bello, G. Haddad, et al., Characterization of exposures to airborne nanoscale particles during friction stir welding of aluminum, Ann. Occup. Hyg. 54 (2010) 486–503, https://doi.org/10.1093/annhyg/meq037.
[16] J.F. Gomes, P.C. Albuquerque, R.M. Miranda, et al., Comparison of deposited surface area of airborne ultrafine particles generated from two welding processes, Inhal. Toxicol. 24 (2012) 774–781, https://doi.org/10.3109/08958378.2012.717648.
[17] A.-K. Viitanen, S. Uuksulainen, A.J. Koivisto, et al., Workplace measurements of ultrafine particles—a literature review, Ann Work Expo Heal 61 (2017) 749–758, https://doi.org/10.1093/annweh/wxx049.
[18] L. Morawska, Z. Ristovski, E.R. Jayaratne, et al., Ambient nano and ultrafine particles from motor vehicle emissions: characteristics, ambient processing and implications on human exposure, Atmos. Environ. 42 (2008) 8113–8138, https://doi.org/10.1016/j.atmosenv.2008.07.050.
[19] Occupational Chemical Database, Particulates Not Otherwise Regulated, Total and Respirable Dust (PNOR). https://www.osha.gov/chemicaldata/801.
[20] J. Sajedifar, A.H. Kokabi, S.F. Dehghan, et al., Evaluation of operational parameters role on the emission of fumes, Ind. Health 56 (2018) 198–206, https://doi.org/10.2486/indhealth.2017-0155.
[21] K. Kirichenko, A. Zakharenko, K. Pikula, et al., Dependence of welding fume particle toxicity on electrode type and current intensity assessed by microalgae growth inhibition test, Environ. Res. 179 (2019) 108818, https://doi.org/10.1016/j.envres.2019.108818.
[22] V. Adamec, K. Köbölová, M. Urbánek, et al., The presence of fine and ultrafine particulate matter in the work environment, Cent Eur J Public Health 28 (Suppl) (2020) S31–S36, https://doi.org/10.21101/cejph.a6174.
[23] N. Kato, M. Yamada, J. Ojima, et al., Analytical method using SEM-EDS for metal elements present in particulate matter generated from stainless steel flux-cored arc welding process, J. Hazard Mater. 424 (2022) 127412, https://doi.org/10.1016/j.jhazmat.2021.127412.
[24] M.R. Flynn, P. Susi, Local exhaust ventilation for the control of welding fumes in the construction industry–a literature review, Ann. Occup. Hyg. 56 (2012) 764–776, https://doi.org/10.1093/annhyg/mes018.