Chapter

RISK ASSESSMENT OF WELDING OPERATIONS AND PROCESSES IN TERMS OF ULTRAFINE PARTICLES EMISSIONS

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ABSTRACT

Welding is extensively used in metallic construction worldwide, in spite of being able to produce dangerous fumes that may be hazardous to the welder's health. It is estimated that, presently, 1-2% of workers from different professional background (which accounts for more than 3 million persons) are subject to welding fume and gas action. Recently, studies have proved the existence of ultrafine particles emissions, from welding processes, thus increasing the health risks to exposed welders. In particular,

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it was found that the amount of emitted particles (measured by particle number and alveolar deposited surface area) are clearly dependent on the distance to the welding front, and also on the main welding parameters, namely the applied current intensity, heat input, nature of base metal, nature of addition metal, and nature of welding gases used. The emission of airborne ultrafine particles increases with the increase of current intensity as fume-formation rate does. In what regards welding gas mixtures, higher emissions are observed for more oxidant mixtures, that is, mixtures with a higher CO_2 content, which result in higher electric arc stability. These mixtures originate higher concentrations of ultrafine particles (as measured by number of particles per cm^3 of air) and higher values of alveolar deposited surface area of particles, thus resulting in more severe worker's exposure. Combining the obtained data, it is possible to compare different welding processes and operating conditions, in order to assess different levels of welder's exposure. Also, the graphical representation of measured concentrations of airborne ultrafine particles, with time and distance, allows to define "safe" and "critical" regions within a welding workshop in terms of welder's exposure. This information may be combined with the results of risk analysis derived by control banding and helps to categorize the sites where regulatory measures such as operation containment or dedicated exhaust ventilation need to be implemented.

Keywords: exposure, ultrafine particles, welding operations, risk assessment

INTRODUCTION

Nowadays, arc welding is extensively used in metallic construction worldwide, in spite of the fact that it can produce dangerous fumes that may be hazardous to the welder's health (Gomes, 1993). It is estimated that, presently, 1-2% of workers from different professional backgrounds (which accounts for more than 3 million persons) are subjected to welding fume (mainly composed of aerosol particulate) and gas action (Pires *et al.*, 2006). Several authors have shown that the emission of welding fume is dependent from a multitude of factors, the most important being related with specific processing parameters in metal active gas (MAG) which leads to energy transfer modes (Pires *et al*., 2006; Meneses *et al*., 2014; Gomes *et al*., 2014). Additionally, the nature of gas mixtures used in the welding process also have an influence on fumes (quantity and composition), since the higher the oxygen content of the gas, the higher the fume formation observed. With the advent of new types of welding procedures and consumables, the number of welders exposed to welding fumes is growing constantly, in spite of the mechanization and automation of the processes (Ascenço *et al.*, 2005). Simultaneously, the number of publications on epidemiologic studies (Gomes *et al.*, 2012) and the devices for welders' protection is also increasing.

Recently, the influence of very fine particulate, lying in the nano range, on human health has referred to be of much concern (Jenkins and Eager, 2005; Dasch and D'Arcy, 2008, Buonanno *et al*., 2011), as airborne fine particles can also result from macroscopic common industrial processes such as welding (Moroni and Viti, 2009; 2011; Elihn *et al*., 2011). The detrimental health effects of inhaling fine aerosols were recognised long ago and several attempts have been made to minimise exposure, such as the publication of specific regulations on emissions and objectives for air quality in working microenvironments.

When considering human exposure to airborne pollutants the exposure to airborne particles is of particular interest. Current workplace exposure limits, that have been established long ago, are based on particle mass, but this criteria is not adequate in what concerns nano sized particles as these materials are, in fact, characterized by very large surface areas (considering the same volume, nano sized particles have larger surface areas than micro sized particles, for instance), which has been identified to be the main distinctive characteristic that could even turn out an inert substance into a toxic one, but having the same chemical composition, and exhibiting very different interactions with biological fluids and cells (Oberdörster, 1995; Rickerby and Morrison, 2007). As a result, assessing workplace conditions and personal exposure based on measuring particle surface area is of increasing interest. It is well known that lung deposition is the most efficient way for airborne particles to enter the body and potentially cause adverse health effects (Shanbhag et al., 1994; Donaldson, et al., 1998; Sturm, 2013).

If fine particles can deposit in the lung and remain there, having an active surface chemistry and interacting with the body there is potential for exposure and dosing. It has been shown (Oberdörster, 2001) that surface area plays an important role in the toxicity of nanoparticles and thi is the measurement metric that best correlates with particle-induced adverse health effects. Thus, in order to be able to assess exposure, it is important to have an estimation of the surface area of emitted fine particles, as they are potentially able to deposit in the lower parts of the lung, such as the alveoli, or even being transferred to the blood circulation system with resulting distribution in several end organs (Kreyling *et al*., 2002).

In 1996, the International Commission of Radiological Protection (ICRP) developed a comprehensive model concerning lung deposition of radioactive aerosols. Several parameters are included in the construction of the model, such as breathing rate, lung volume, activity, nose/mouth breathing, etc., and the obtained deposition curves (for tracheobronchial and alveolar deposition) derived from the model can vary according to these parameters. For industrial hygiene applications, ACGIH (Phalen, 1999) developed a definition of a reference worker, in order to derive the corresponding deposition curves for tracheobronchial and alveolar lung deposition, based on the ICRP model: the tracheobronchial deposition curve represents the fraction of aerosol that deposits in the tracheobronchial region of the lung, while the alveolar deposition curve represents the fraction of the aerosol that deposits in the alveolar region of the lung. For exposure assessment applications it is common to sample aerosols relevant to their deposition in a specific region of the human lung thus depending on the aerosol being sampled. In what concerns ultrafine particles, due to its very fine dimensions, the health effects would be related to the deposition deep in the alveolar regions of the lung, so the respirable fraction of the aerosol is the metric of interest.

Recently some studies have been carried out regarding the characterization of nano size particles emitted during several welding processes (Berlinger *et al*., 2011, Gomes *et al*., 2012a; Gomes *et al*., 2012b, Zhang *et al*., 2013), which is now possible due to existence of reliable monitoring equipment (Fissan *et al*., 2007). It should be pointed out that these mentioned studies had the primary objective to demonstrate the emission of nano size particles from welding, but also aim to contribute to issuing future recommendations so that threshold limit values (TLV) concerning nanoparticles emissions could be produced considering also the results of toxicology tests currently being made (Wultsch *et al*., 2014). Meanwhile, the measured values could be of help in order to establish safety zones concerning exposed welders, that is, zones of certain levels of measured concentration of nanoparticles in a welding environment such as a workshop. This delimitation of zones is important to define specific zones where concentration of nanoparticles is expected to be high, whereas others have much lower concentrations, even ranging to zones where nanoparticles concentration is almost negligible. This constitutes an important information, that could be combined together with information on risk assessment coming from the application of Control Banding Tools, and will be effective in order to define specific area where containment of welding operations and/or the application of specific ventilation or exhaust measures have to be taken.

In fact, it is well known that the traditional industrial hygiene approach for controlling exposures to harmful particles in the workplace is to measure the air concentrations of the said particles in the worker's breathing zone and then compare those concentrations to existing exposure limits determined for those particles (Paik et al., 2008). From those comparisons, protection control measures can be derived in order to reduce concentrations below the exposure limits. This implies that: i) the sampled concentrations are representative of what the worker is actually breathing, ii) the adequate exposure limit is known, iii) appropriate analytical methods are available to quantify the exposure level, and iv) the exposure levels at which those particles can produce adverse health effects are also known (Maidment, 1998). If any of these factors is not well characterized, any measurements performed may have limited value as it would be difficult to obtain a valid risk assessment. Consequently, the derived protection measures are also questionable as they cannot be ascertained as effective. This situation tends to be rather complicated when addressing exposure to nanomaterials, both engineered nanoparticles and/or accidentally emitted nanoparticles (Maynard, 2007). In fact, when worker exposures to nanoparticles are concerned, it is not easy to observe the previously mentioned requirements. Traditionally, particles concentration in the worker breathing zone is measured by using a sampling pump, which uses forces such as particle inertia and gravity in order to force nanoparticles to follow the sampled air into the sampler line. However, the gravity field is somewhat weak for nanoparticles, which are defined as having two or three dimensions lower than 100 nm (ASTM, 2007). The second requirement has not yet been satisfied for nanoparticles, as an appropriate index of exposure has not yet reached scientific international consensus on what the relevant index of exposure is (NIOSH, 2006): for instance, some studies suggest that total surface area concentration may be a better exposure index than traditional mass concentration (Oberdorster et al, 1994; Tran et al., 2000). Of course, the inexistence of agreement on an appropriate index of exposure for nanoparticles results in the non-existence of a standard analytical method to quantify it, particularly when several methods and commercial equipment is becoming available in order to quantify some characteristics related with nanoparticles in gaseous media (Paik et al., 2008; Gomes et al., 2013). Furthermore, the fourth requirement is possibly the largest barrier in order to assess the risk of working with nanomaterials (Paik et al., 2008). In fact, very little toxicological data is already available for determining exposure limits: some limited studies concern in vitro or in vivo toxicity (Yongbin, et al., 2007; Chen et al., 2009), and virtually no human studies have been made so far (Maynard and Kuempel, 2005).

However, Control Banding (CB) strategies (Zalk and Nelson, 2008) seem to offer a simplified control of worker exposures when there is an absence of firm toxicological and exposure information. Control Banding was developed in the pharmaceutical industry as a pragmatic tool to manage the risk resulting from exposure to a wide variety of potentially hazardous substances in the absence of the said data. Basically, it is a risk assessment approach using the generally accepted risk paradigm, where risk can be measured as a function of the severity of impact (also known as hazard) and the anticipated probability of that impact (exposure). Both hazard and exposure are then classified into two to five different levels, usually referred to as bands. The two sets of bands are combined in a matrix, resulting into control or risk bands (Brouwer, 2012). CB principles have been widely used for the last decades to implement a risk management strategy, where R(isk) and S(afety) phrases are allocated to hazard bands (Brooke, 1998), and exposure bands are based on the statistical analysis of exposure data. Brouwer (2012) made an assessment of existing approaches, comprising the first CB approach for occupational "nano" exposure proposed by Maynard (2007), which was further on published by Zalk et al. (2009) and known as CB Nanotool 2.0 (available at: http://www.controlbanding.net); Precautionary Matrix for Synthetic Nanomaterials (Hock et al., 2008); the French approach ANSES (Ostiguy et al,., 2010); the Dutch Stoffenmanager Nano (Duuren-Stuurman et al., 2011) and the Danish NanoSafer (available at: http://nanosafer.i-bar.dk). These CB approaches represent a wide panel of methods to indicate or prioritize risks related to the use of nanomaterials, and it is expected that some modifications and adjustments on those approaches will arise in the next years as a result of experience with its application to real case studies (Brouwer, 2012).

Long ago, it has been recognized that welding results in the generation of potentially hazardous fumes: it is well known that welders are exposed to significant amounts of welding fumes produced, which depend on process parameters and shielding gas composition (Pires et al., 2007). Previous works (Pires et al., 2006) showed a correlation between processing parameters in metal active gas (MAG), that is, metal transfer modes, and the quantity of fumes formed expressed by the fume formation rate. With the advent of new types of welding procedures and consumables, the number of welders exposed to welding fumes is continuously growing, in spite of the mechanization and automation of the welding processes (Ascenço et al., 2005) and individual welders' protection equipment is improving. The number of epidemiologic studies (Gomes et al., 2012a) has increased in recent years due to the increasing concern on welding fumes and the emergence of more sophisticated equipment for detection and analysis of particles in the nano range scale. The influence of ultrafine particulate lying in the nano sized range, on human health has been pointed to be of much concern (Buonanno et al., 2011) as airborne ultrafine particles can also result from macroscopic common industrial processes such as welding (Moroni and Viti, 2011). The detrimental health effects of inhaling ultrafine aerosols were recognised long ago and various attempts have been made to minimise exposure, as the issuing of specific regulations on emissions and objectives for air quality in working microenvironments (Jenkins and Eager, 2005). More recently, studies were made regarding the emission of ultrafine and nanoparticles occurring in several welding processes (Pfefferkorn et al., 2010; Gomes et al., 2012a; Gomes et al., 2012b; Guerreiro et al., 2014; Meneses et al., 2014). The ultimate aim of these studies is to define safety measures in order to limit welder's exposure during operation. However, the obtention of this ultimate aim is compromised by the fact that, currently, there are no defined exposure limits for nanoparticles emitted in welding operations, neither the exposure levels at which those particles can produce adverse health effects are known. As pointed out previously, the lack of this information greatly compromises the effectiveness of any derived protection measures, which calls for the use of risk assessment techniques based on CB.

USE OF A CONTROL BANDING APPROACH

A study was performed consisting on the application of the CB Nanotool 2.0 (Zalk et al., 2009) in order to assess the welders' exposure to nanoscale particles emitted in common industry used welding processes, as follows:

a) Metal Active Gas (MAG) for mild steel, using three different shielding gas mixtures (Ar+10% CO_2; Ar+18% CO_2, and 100% CO_2);

b) MAG for austenitic stainless steel, using three different shielding gas mixtures (Ar+5% CO_2; 81% Ar+18% He+1% CO_2; 91% Ar+5% He+2% CO_2+ 2% N_2);

Regarding these conditions, monitoring tests were made in real welding situations described elsewhere (Guerreiro et al., 2014), which comprised the determination of Alveolar Deposited Surface Area (ADSA) of emitted particles in the nano scale range, using a Nanoparticle Surface Area Monitor (NSAM, TSI, model 3550), the determination of size distribution of those particles by means of a Scanning Mobility Particle Sizer (SMPS, TSI, model 3034), the collection of emitted particles using a Nanometer Aerosol Sampler (NAS, TSI, model 3089), and further morphology analysis by Transmission Electronic Microscopy (TEM, Hitachi, model H-8100 II), equipped with an Energy Dispersive X-ray Spectroscopy (EDS) probe for determination of elemental chemical composition, as described by Gomes et al. (2014). Table 1 shows the main characteristics of emitted particles, determined in MAG welding of mild steel, while table 2 shows the main characteristics of emitted particles determined in MAG welding of stainless steel (Pereira, 2013). It should be noted that the observed range of ADSA corresponds to the use of different welding transfer modes (short-circuit, globular and spray).

Table 1. Main characteristics of emitted nanoparticles during MAG welding of mild steel

Gas shielding mixture	Alveolar Deposited Surface Area ($\mu m^2/cm^3$)	Characteristics of emitted nanoparticles		
		Elements found	Morphology	Size (nm)
Ar+10%CO_2	8325-17574	Fe, Mn, Si	Amorphous Agglomerates	10-20
Ar+18%CO_2	22266-42896	Fe, Mn, Si	Amorphous Agglomerates	10-20
100%CO_2	12899-18292	Fe, Mn, Si	Amorphous Agglomerates	10-20

Figure 1 shows the RL matrix as a function of severity and probability (Paik et al., 2008).

Table 2. Main characteristics of emitted nanoparticles during MAG welding of stainless steel

Gas shielding mixture	Alveolar Deposited Surface Area ($\mu m^2/cm^3$)	Characteristics of emitted nanoparticles		
		Elements found	Morphology	Size (nm)
Ar+5%CO_2	23637-39376	Fe, Cr, Ni	Amorphous Agglomerates	10-20
Ar+18%He+1%CO_2	65829-94136	Fe, Cr, Ni	Amorphous Agglomerates	10-20
Ar+5%He+2%CO_2+2%N_2	33644-80861	Fe, Cr, Ni	Amorphous Agglomerates	10-20

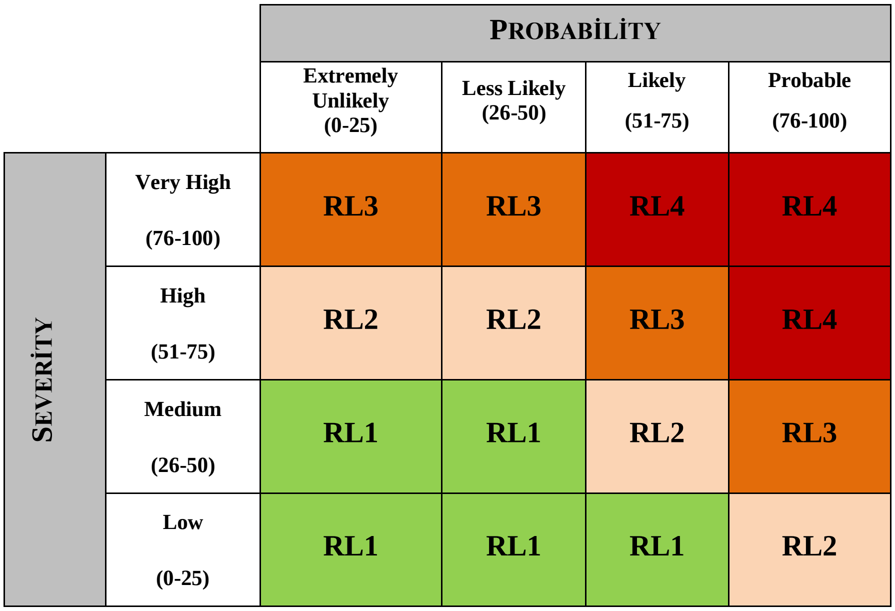
The full obtained results for the application of the CB matrix are presented elsewhere (Albuquerque et al., 2015). Here, only some examples are presented, as the resulting matrix was the same for all studied cases, which means that there are not enough distinct features among these situations. Therefore, the results are presented for each welding process. Risk assessment was mainly based of the following criteria:

i) chemical composition of the filler material;

ii) chemical composition of the shielding gas;

iii) chemical composition of the material to be welded (mild steel and stainless steel).

The characterization of each raw material used in each welding process was based on its safety data sheets, and is shown on Table 3. The consideration of these criteria formed the inputs to the CB tool as described elsewhere (Albuquerque et al., 2015). The output matrix, comprising severity and probability indexes, together with resulting control measures is depicted in Figure 2.



		PROBABİLİTY			
		Extremely Unlikely (0-25)	Less Likely (26-50)	Likely (51-75)	Probable (76-100)
SEVERİTY	Very High (76-100)	RL3	RL3	RL4	RL4
	High (51-75)	RL2	RL2	RL3	RL4
	Medium (26-50)	RL1	RL1	RL2	RL3
	Low (0-25)	RL1	RL1	RL1	RL2

Control bands: RL 1 – General ventilation; **RL 2** – Fume hoods or local exhaust ventilation; **RL 3** – Containment ; **RL4** – Seek specialist advice

Figure 1. RL matrix as a function of severity and probability

Activity	Severity	Probability	Total	Control Band
1	Medium (35)	Likely (57,5)	RL2 (125)	Fume hoods or local exhaust ventilation
2	Medium (30,5)	Likely (57,5)	RL2 (125)	Fume hoods or local exhaust ventilation
3	High (62,5)	Likely (55)	RL3 (150)	Containment

Figure 2 – Determination of the risk level for MAG welding of carbon steel, using a shielding gas of 100% CO_2

From this example it can be noticed that the chemical composition of the base material to be welded results in the highest risk level in what concerns the protection measures to be considered. In fact, the inclusion of other shielding gas mixtures does not have relevant impact on the risk level. Even the consideration of stainless steel, instead of mild steel, does not increases significantly the risk level. In fact, the main difference between these two situations resides, obviously in the presence of chromium and nickel which are present in stainless steel but not in mild steel. However, in spite of the carcinogenic character of these two metals, as they are present as alloyed to the steel, the matrix does not distinguish this particular situation so as to increase the level of risk. Nevertheless, the recommended protection measure is considered as adequate as it comprises the use of fume hoods of local ventilation devices for activities 1 and 2 and containment for activity 3, which is, of the course, the most potentially noxious one.

USE OF A SAFE/CRITICAL WORKING AREA APPROACH

As this is an experimental approach, in order to devise the identification of safe/critical working area zones, several determinations were done in a laboratory, reproducing as closely as possible, a welding workshop. Therefore, welding tests were performed in laboratory (8x10x5 m) using an experimental set-up consisting of an automatic welding machine Kemppi, model ProMig 501, controlled, which assured a stable electric arc, a constant welding speed and, therefore, repeatability of the welding process. Bead on plate welds were performed on 5 mm thick mild steel plates, and four different conditions were tested for MAG welding, varying the gas protection mixture and current intensity and voltage in order to produce globular and spray metal transfer modes. The welding voltage was adjusted automatically by the welding machine in accordance with the feeding wire speed. Each condition test was replicated four times, and between each test, time intervals were provided in order to allow for dissipation of the aerosol in the closed atmosphere of the sampling location.

In order to assess the emissions of ultrafine particles on the nearby welding environment, sampling (using NSAM) was performed in 5 different points at different distances from the welding front, as depicted in Figure 3.

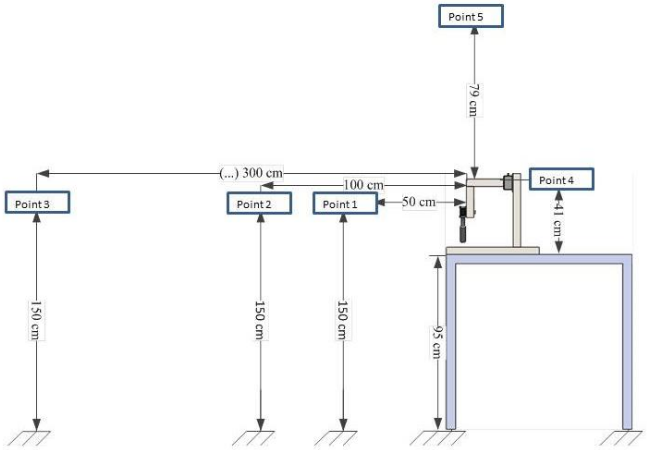


Figure 3. Sampling points locations. Point 4 is also the location of SMPS

Points 1 to 3 correspond to distances of 50, 100 and 300 cm, respectively, away from the welding front, in order to assess the contamination levels inside the welding workshop. Point 4 corresponds to the location inside the welder mask, near its breathing zone (as if the process was not automatic), 410 mm up from the welding front. Point 5 corresponds to an exhaustion duct, located 120 cm from the welding front. NAS was located in the same point during all tests, near the breathing zone of the welder, on point 4, where the SMPS analyzer was also located. During sampling, exhaustion was turned off, and doors and windows to the workshop were kept closed. For measuring ultrafine particle exposure, a Nanoparticle Surface Area Monitor (NSAM), TSI, Model 3550, was used. This equipment estimates the human lung-deposited surface area of particles expressed as square micrometers per cubic centimeter of air ($\mu m^2/cm^3$), being deposited in the alveolar region of the lungs. The operation of this equipment is based on diffusion charging of sampled particles (regardless of its size, shape and agglomeration, as discussed by Gomes *et al*., 2012a), followed by detection of the charged aerosol using an electrometer, as described elsewhere (Fissan, 2007). It estimates the surface area of ultrafine particles capable of being deposited in the alveolar region of the lung, using the deposition model of ACGIH (Phalen, 1999) previously mentioned. Due to the inexistence of an exposure limit value specific for fine particles, for each measurement task a baseline value was obtained for comparison purposes. Table 4 shows the main operating parameters for the welding machine, as well as specific conditions varying in terms of the nature of protection gas mixture and transfer modes tested.

Table 4: Operating parameters and test conditions for MAG welding

	Condition 1 Ar+18%CO_2	Condition 2 Ar+8%CO_2	Condition 3 Ar+18%CO_2	Condition 4 Ar+8%CO_2
Feeding speed of wire (m/min)	8	8	5	5
Voltage (V)	22.52	22.56	22.53	22.57
Current (A)	132.1	131.7	181.9	172.0
Transfer mode	Globular	Globular	Spray	Spray

Electrode used: AWS 5.18 ER70S-6
Electrode diameter (mm): 1
Width of base material (mm): 5
Gas mixture flux (l/min): 15
Welding speed (mm/min): 300
Length of welding seam (mm): 450
Welding time (S): 90

In order to confirm the existence of nanoparticles, other auxiliary measurements were also performed such as the determination of particle number concentration and size distribution of emitted particles, using a Scanning Mobility Particle Size Spectrometer (SMPS), TSI, Model 3034; and also the determination of the main chemical composition and morphology of emitted particles which were collected using a Nanometer Aerosol Sampler (NAS), TSI, Model 3089, on 3 mm diameter copper grids polymer coated for further observation by transmission electron microscopy (TEM), Hitachi, model H-8100 II, equipped with an energy dispersive X-ray spectroscopy (EDS) probe. A more precise description of these measurements can be found elsewhere (Guerreiro *et al*., 2014; Gomes and Miranda, 2017).

Figures 4 to 7 present the measured alveolar deposited surface area (ADSA) of emitted fine particles for sampling points 1 to 5 during tests for conditions 1 to 4, varying in time. These conditions correspond to globular transfer mode and a gas protection mixture consisting of Argon and 18% of carbon dioxide (condition 1) and another mixture consisting of Argon and 8% of carbon dioxide (condition 2). For spray transfer mode, the same gas mixtures were employed: Argon and 18% of carbon dioxide (condition 3) and Argon and 8% of carbon dioxide (condition 4). The maximum averaged values, between all sampling points as well as alveolar deposited surface areas, obtained for each condition, are shown in table 5. A full discussion on the relationship of the measured values with the tested operating welding parameters and respective conditions can be found elsewhere (Guerreiro *et al*., 2014; Gomes and Miranda, 2017).

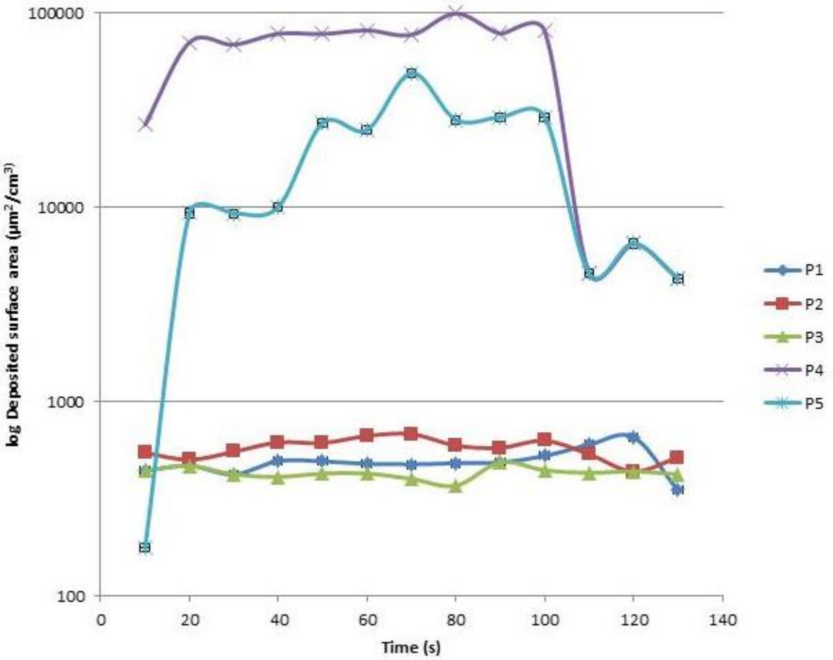


Figure 4. ADSA plot versus time, for points 1 to 5, in condition 1 (globular transfer mode and gas mixture: Ar+18%CO_2)

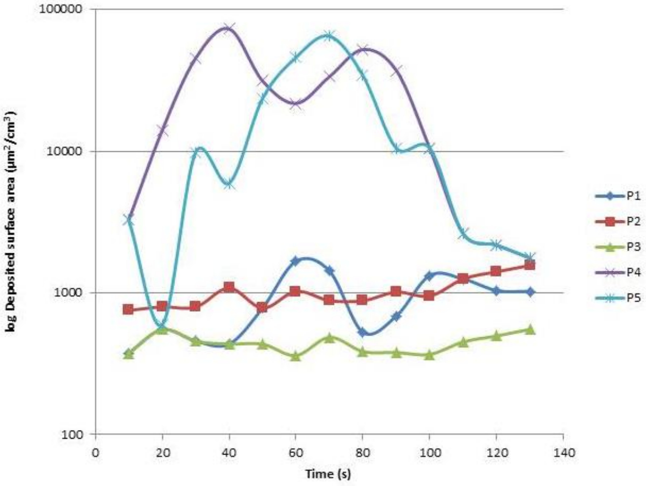


Figure 5. ADSA plot versus time, for points 1 to 5, in condition 2 (globular transfer mode and gas mixture: Ar+8%CO_2)

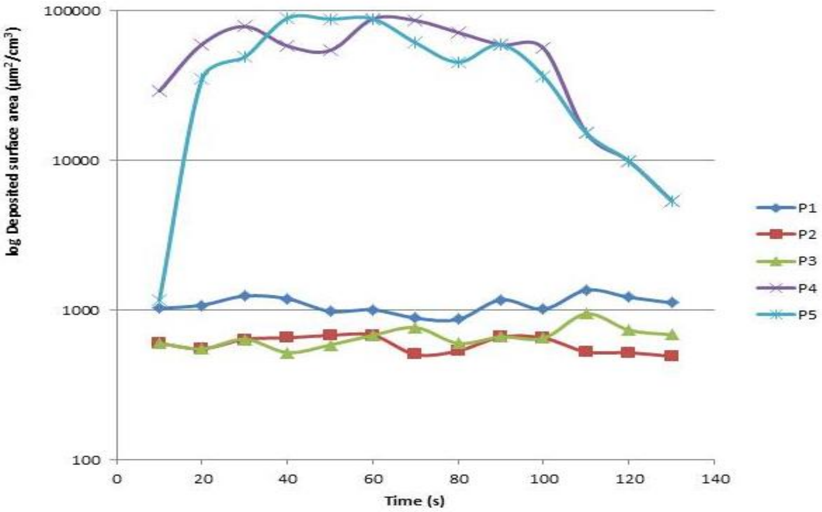


Figure 6. ADSA plot versus time, for points 1 to 5, in condition 3 (spray transfer mode and gas mixture: Ar+18%CO$_2$)

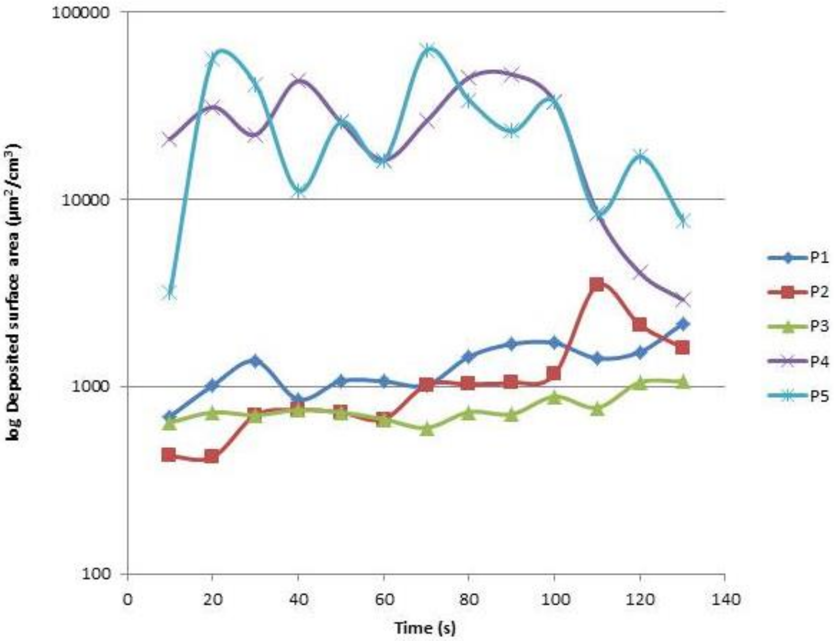


Figure 7. ADSA plot versus time, for points 1 to 5, in condition 4 (spray transfer mode and gas mixture: Ar+8%CO$_2$)

Table 5. Maximum averaged alveolar deposited surface areas for each experimental test condition

Condition	Location	Maximum alveolar deposited surface areas ($\mu m^2/cm^3$)	σ ($\mu m^2/cm^3$)	Minimum and maximum values ($\mu m^2/cm^3$)
1	P4	25878	44.4	25834-25922
2	P4	20291	42.4	20206-20376
3	P5	32946	22.6	32901-32991
4	P5	18314	14.6	18285-18343

Differences on the measured values were observed in relation with the sampling location. As expected, the highest values are obtained near the welding front (points 4 and 5), and as far as the sampling port is from the welding front, lower values are observed (points 1, 2 and 3). However, the nearest horizontal measurement point is sometimes lower, in concentration, than the two horizontal points, which is possibly related with local flow patterns with the welding from the heat creating a vortex so that the particles are looping at the top of the nearest measurement point. For sampling points 1 to 3, which are more distant from the welding front, after ultrafine particles are emitted deposition seems to start taking effect in a more stable atmosphere, while, for sampling points 4 and 5, closer to the welding front, emission and re-suspension seem to be continuously taking place until the welding test is over, and thus, emissions finally cease. The initial concentration peak detected by the equipment corresponds to the emission of fine particles, and further on, even after the welding operation is over, particles are still suspended in the atmosphere until they start to deposit.

The measured ADSA values, for each tested situation described earlier, are also depicted in figures 8 to 11 showing the evolution of ADSA per evolved time and for each sampling port location. This way, graphs show contour curves, corresponding to certain ADSA range of values, starting from the welding source (point 1) to crescent distances from this source. This representation forms a contour map of ADSA values thus allowing to:

i) understand the evolution of nanoparticles emissions from the source, with time;

ii) definition of both "safe" and "critical" zones, in the workshop where welding is taking place, regarding welder's exposure to nanoparticles;

iii) definition of zones, within a workshop where welding is taking place, where fume extraction or welding operation containment equipment should be installed in order to obtain a "safe" environment for exposed welders.

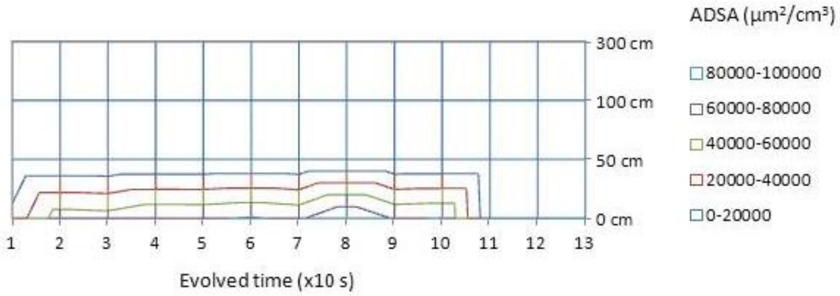


Figure 8. Contour plots of ADSA evolution with time, in condition 1 (globular transfer mode and gas mixture: Ar+18%CO$_2$)

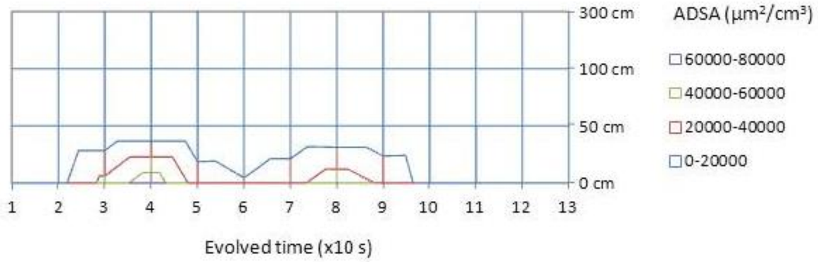


Figure 9. Contour plots of ADSA evolution with time, in condition 2 (globular transfer mode and gas mixture: Ar+8%CO$_2$)

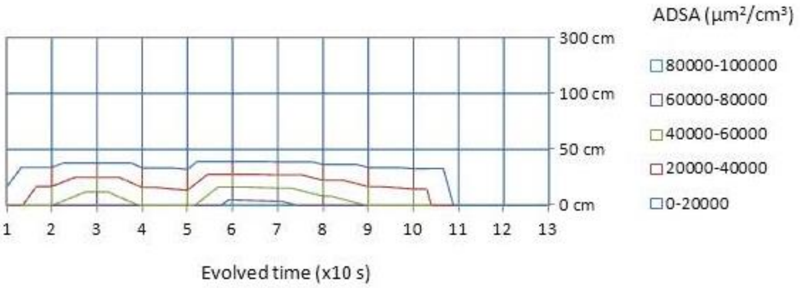


Figure 10. Contour plots of ADSA evolution with time, in condition 3 (spray transfer mode and gas mixture: Ar+18%CO_2)

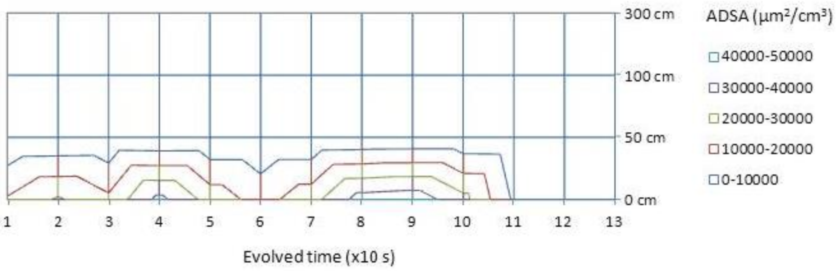


Figure 11. Contour plots of ADSA evolution with time, in condition 4 (spray transfer mode and gas mixture: Ar+8%CO_2)

CONCLUSIONS

a) The reduction of nanoparticles emissions during metal arc welding is necessary in order to improve working conditions in industry and to reduce the exposure risk level for welders. However, the obtention of such an improvement is a complex problem thus involving the development of newer and more efficient protective measures, as well as welding processes and even the use of only some more eco-friendly materials instead of potentially toxic ones. Generally, the adoption of good working practices should take into account the feasibility of changes to be considered in what concerns technological aspects, chemical composition of consumable materials and even shielding gases, thus related with an increased use of efficient ventilation systems and effective containment techniques. The use of risk assessment tools, such as the one described here this, consists of an easy to use method in order to protect the welder's health, reduce occupational diseases and, at the same time, develop eco-friendly welding techniques.

b) The experimental study performed confirms that the emission of nanoparticles in the MAG welding of carbon steel using mixtures of Ar+CO_2, is clearly dependent from the distance to the welding front and also from the main welding parameters, namely the current intensity and the heat input in the welding process.

The emission of airborne fine particles increase with the current intensity as fume formation rate does. A marked decay of ultrafine particles with the distance to the weld area is observed. When comparing the tested gas mixtures, higher emissions are observed for more oxidant mixtures, that is, mixtures with higher CO_2 content, which result in higher arc stability. The later mixtures originate higher concentrations of fine particles (as measured by number of particles by cm^3) and higher values of alveolar deposited surface area of particles, thus indicating a severe worker's exposure. However, size distribution of emitted particles does not seem to differ significantly, and morphology analysis shows that fine particles are lower than 10 nm, but form aggregates up to diameters as high as 100 nm or more. Its composition is mainly iron, resulting from projections of the molten material. During welding operations re-suspension and agglomeration of fine particles was also noticed as reflected in the evolution of alveolar deposited surface area of emitted particles, and its size distribution.

Representing measured ADSA values as contour curves, corresponding to certain ADSA range of values, starting from the welding source to crescent distances from this source, a contour map is obtained which allows to:

i) understand the evolution of nanoparticles emissions from the source, with time;

ii) definition of both “safe” and “critical” zones, in the workshop where welding is taking place, regarding welder’s exposure to nanoparticles;

iii) definition of zones, within a workshop where welding is taking place, where fume extraction or welding operation containment equipment should be installed in order to obtain a “safe” environment for exposed welders.

The need to install such an equipment described in iii) can result from the application of a Control Banding Tool for each particular welding operation, as described previously. Therefore, the use of ADSA measurements and its representation as contour curves is a complementary tool to the Control Banding Tool, thus contributing to achieving “safer” and “cleaner” welding processes.

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