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Particle size distribution of welding fume and its dependency on conditions of shielded metal arc welding

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ABSTRACT

The particle size distribution of the shielded metal arc welding fumes is studied. The laser aerosol spectrometer and optoelectronic aerosol counter with the total measurement range of 0.15–10 μm were used. It is demonstrated that the number-based size distribution is described by the three-modal lognormal distribution, where the first two modes are the result of the liquid-phase and solid-phase coagulation and the third mode is the coarse fume particles. The linear dependency of the average size of the particles on the product of welding parameters: the arc resistance, the wire feed rate and the electrode sectional area is revealed.

1. Introduction

The processes of arc welding are accompanied by formation of toxic aero-disperse particles in the size range of 0.005–20 μm, representing the danger for human health and environment, which are commonly referred to as ‘welding fume’. It is well known that the size and the shape of a particle is a predictor of the site of deposition in the respiratory tract (International Commission on Radiological Protection (ICRP), 1994; Hinds, 1999). In addition, the biological activity of the welding fume inhalable particles, like other slightly soluble substances, depends on their number density, size, shape and specific surface, i.e. is appropriately represented by the lower moments of the particle size distribution (PSD) (Hewett, 1995; Oberdorster et al., 2005). Therefore, the studies allowing to analyze the relationship between the welding fume PSD and the arc welding parameters are of large applied importance.

The welding fume particles are formed by the following processes: nucleation of the vapors of welding materials outside the high-temperature arc discharge zone and growth of the nuclei (the primary particles); coagulation of the primary particles (the agglomerates with different spatial structures and sizes over 0.1 μm); ejection and explosion of the liquid droplets of the electrode-material from the arc or the molten weld pool (coarse fume particles with sizes over 1 μm) (Berlinger et al., 2011; Jenkins et al., 2005; Sowards et al., 2008a; Voitkevich, 1995; Worobiec et al., 2007; Zimmer & Biswas, 2001). When the shielded metal arc welding (SMAW) is applied, the agglomerates of primary particles and coarse fume particles mostly prevail in the welder's breathing-zone. Therefore, while measurements of agglomerate and coarse PSD are determinants of the site of respiratory deposition and biological activity, measuring the chemical composition throughout

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the primary particle size distribution could be informative in understanding the resulting toxicity (Oberdorster, 1996; Richman et al., 2011). The size distribution of agglomerates and their spatial structure can essentially depend on the primary particles' electrical charge formed in the nucleation and growth processes (Onischuk et al., 2000).

The nucleation and growth of the nuclei occurs simultaneously with coagulation. If the colliding primary particles are in the liquid state, their association produces a spherical particle. If the collision happens between solid particles, they form agglomerates. It is difficult to define the agglomerates' real sizes experimentally, because their shape and spatial structure are very complex. Therefore, the existing methods of the welding fume PSD study are based on the measurement of the equivalent diameter instead of the real size (for example, aerodynamic, optical, electrical mobility), i.e. the diameter of the sphere that has the same value of a particular physical property as the real agglomerate.

For example, some authors (Berlinger et al., 2011; Breskey et al., 2012; Sowards et al., 2008b) measured the size distribution of the welding fume generated by SMAW in the size range of 0.05–10 μm with cascade impactors. The measured mass-based PSD obeys the bimodal lognormal distribution with parameters: $d_1 = 0.29$ μm, $\sigma_1 = 1.5$ and $d_2 = 2.6$ μm, $\sigma_2 = 3.29$ (Breskey et al., 2012). Sowards et al. (2008b) approximated the number-based PSD by an unimodal lognormal distribution with the geometric mean diameter $d = 0.1$–0.25 μm and the standard deviation $\sigma = 1.15$–1.25, while the mass-based PSD showed $d = 0.55$–0.75 μm and $\sigma = 1.11$–1.32, depending on the type of electrode coating and welding conditions. They noted also the tendency towards the increase of the geometric mean diameter as the welding heat input increases.

The essential disadvantage of the aerodynamic separation is the destruction of agglomerates when they pass through the impactor cascades and the collection of some coarse fume on the walls, but not on the impaction plates (Reist, 1984). In the present paper, a laser aerosol spectrometer was used for real-time monitoring of the inhalable particles' dispersion. The main aim of the study was to explore the dependence of PSD on the SMAW conditions.

2. Experimental technique and measurement procedure

The mild steel plates were used as a base material for the single-pass surface welding with a direct current of reverse polarity and the electrode travel angle of 45°. The SMAW commercial electrodes covered with rutile (TiO_2) Paton ANO-4 electrodes (American Welding Society (AWS) classification E6012) and the carbonate-fluorite ($CaCO_3$–CaF_2) Paton UONI 13/55 electrodes (AWS classification E6015) were used. The average welding parameters are presented in Table 1.

The welding fume plume was localized by extracting air at a distance of 40 cm from the welding arc with a flow of 75 l s^{-1} (Oprya et al., 2012) and redirected into the vertical pipe with the diameter of 19 cm and length of 120 cm. The air flow rate at the sampling spot was of 270 ± 20 cm s^{-1} (Fig. 1). A specially designed nozzle (2) for isokinetic sampling of the welding fume was used. The welding fume dispersion was measured using the laser aerosol spectrometer LAS-P (LAS-P, 2010). The LAS-P aerosol spectrometer allows determination of the size distribution of particles ranging from 0.15 to 1.5 μm in the media characterized by particle concentrations up to 2×10^3 cm^{-3}. The maximum relative errors in determining the volume of the air samples and the size of particles and their number density is $\pm 5\%$ and $\pm 10\%$ respectively. The multichannel size distribution had the following size ranges (μm): 0.15–0.2, 0.2–0.25, 0.25–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.7, 0.7–1.0, 1.0–1.5, >1.5. The standard optoelectronic aerosol counter OEAC-05 (with channels (μm): 0.5–0.7, 0.7–1.0, 1.0–1.5, 1.5–2, 2–3, 3–5, 5–7, 7–10, >10) was used in parallel.

The particle number density in the sample has the typical value of 10^5–10^6 cm^{-3} which is much more than needed for measurements using LAS-P number density ($\leq 2 \times 10^3$ cm^{-3}). Therefore, the dual-stage dilution system was used (Fig. 1). The first stage (4) has the fixed dilution ratio of 86 at a constant volumetric flow rate of 10 l min^{-1}. The dilution ratio of the second stage (5) depends on the volumetric flow rate of the pre-filtered air (7) and is 5 for the electrodes with the diameter of 3 mm and 4 mm, and 12.5 for the electrodes with the diameter of 5 mm. It provides the total dilution ratio of 430 and

Table 1
Welding parameters.

No.	Electrode type	Electrode diameter D (mm)	Arc voltage U (V)	Welding current I (A)	Wire feed rate v (mm s^{-1})
01	ANO-4	3	28	105	4.1
02	ANO-4	3	33	145	4.8
03	ANO-4	4	29	160	3.8
04	ANO-4	4	34	200	4.5
05	ANO-4	5	29	210	2.9
06	ANO-4	5	34	280	3.5
07	UONI 13/55	3	28	105	3.9
08	UONI 13/55	3	33	140	4.5
09	UONI 13/55	4	28	160	3.5
10	UONI 13/55	4	33	210	4.0
11	UONI 13/55	5	28	215	3.0
12	UONI 13/55	5	33	295	3.5