Journal of Aerosol Science 114 (2017) 55–61

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Effects of shielding gas temperature and flow rate on the welding fume particle size distribution

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ARTICLE INFO

Keywords:
Arc welding
Shielding gas
Welding fumes
Particle size distribution

ABSTRACT

The disperse composition of welding fume from gas metal arc welding with various shielding gas temperatures and flow rates is studied. The dependencies of bimodal particle size distribution on the shielding gas temperature in range of 300–600 K and flow rate in range of 6–12 Lpm are demonstrated. It is shown that the shielding gas temperature increase leads to condensed material between modes redistribution and to total integration of inhalable particles.

1. Introduction

The gas metal arc welding (GMAW) is widely used as a semi-automatic or automatic arc welding process for joining metals and alloys in many applications. During arc welding, high-temperature metal vapors are generated by evaporation from molten welding wire tip, droplets that are transferred from the wire tip to the weld pool, and the surface of the weld pool itself. A fraction of generated metal vapors is transported by convection from the arc region and cools rapidly as it mixes with shielded gas and ambient air creating the vapor-gas mixture. Metal nanoparticles are formed by nucleation and nuclei growth from metal vapors, they are oxidized and solidified, and are called the primary particles. Subsequently, these particles collide, coagulate and form the inhalable particles (secondary particles) with size up to micrometer, which ascend from the arc, and released in the form of the welding fume.

Welding fumes inhalation is a great occupational health problem. Biological activity of the formed particles depends on physicochemical parameters, such as particle size distribution, morphology, specific surface area and chemical composition. The welding fume particles' size gives them a high probability of being deposited in the respiratory bronchioles and lungs alveoli where rapid clearance mechanisms are not effective (Antonini, 2003; Clap & Owner, 1977). Therefore, the particle size distribution of welding fumes is an important factor in determining the hazard potential of the fumes because it is an indication of depth to which the particles may penetrate into the lungs and the number of particles retained therein. As shown by Zimmer and Biswas (2001), the particle size distribution of welding fumes is multimodal and dynamically changed with respect to time. The different particle size distribution modes have different chemical composition (Berlinger et al., 2011; Jenkins & Eagar, 2005; Oprya et al., 2012; Sowards, Ramirez, Dickinson, & Lippold, 2008; Worobiec et al., 2007) and morphology (Carpenter, Monaghan, & Norrish, 2008; Sanibondi, 2015; Sowards, Ramirez, Dickinson, & Lippold, 2010; Tashiro, Zeniya, Murphy, & Tanaka, 2013).

Investigations of GMAW show that welding process depends on shielding gas properties (Kolarik, Kovanda, Kolarikova, Vondrous, & Kopriva, 2013; Murphy, Tanaka, Tashiro, Sato, & Lowke, 2009; Rao, Liao, & Tsai, 2010); in particular, Ojima (2006) and Topham et al. (2012) demonstrate dependency of particle size distribution on shielding gas flow rate.

The objective of this study is to investigate the effect of shielding gas (CO_2) temperature and flow rate on disperse composition of welding fume generated by GMAW.

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http://dx.doi.org/10.1016/j.jaerosci.2017.09.010
Received 5 September 2017; Accepted 7 September 2017
Available online 09 September 2017

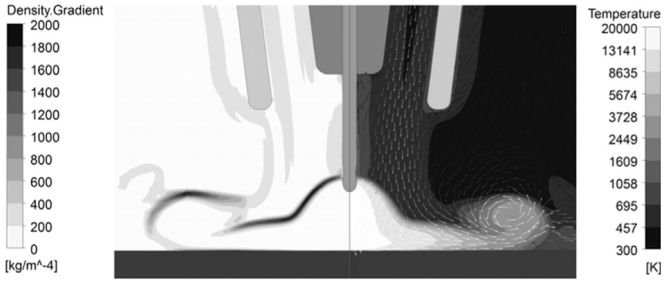

Fig. 1. Numerical simulation by Dreher et al. (2009).

2. Theoretical reasons for experiment

The high-temperature metal vapors from the weld materials mix up with shielding gas under the welding torch nozzle. As it follows from numerical simulation (Dreher, Füssel, & Schnick, 2009), which result is shown in Fig. 1, the gas average temperature in the boundary region at the torch outlet $T \sim 2500$ K. It means that nucleation occurs in the vapor-shielding gas mixture, before mixing with air.

The mass flow of vapor-gas mixture $J_{mix} = J_0 + J_{sg}$ is obtained by the turbulent mixing of the vapor mass flow J_0 with the shielding gas mass flow J_{sg}. The shielding gas flow rate can be approximately considered to be directly proportional to the mixture flow rate (Vishnyakov, Kiro, & Ennan, 2014b), i.e.

$$\frac{dJ_{sg}}{dt} = \frac{dJ_{mix}}{dt} = \alpha_T J_{mix},$$

where α_T is the factor, which is defined by the initial conditions of the vapors' efflux from the arc zone.

Hence, it follows,

$$J_{mix} = J_0 \exp(\alpha_T t), \quad J_{sg} = J_0[\exp(\alpha_T t) - 1]. \tag{1}$$

and the condensable components' mass fractions in the vapor-gas mixture are determined in the following form:

$$g_i(t) = \frac{g_{0i} J_0}{J_{mix}} = g_{0i} \exp(-\alpha_T t),$$

where g_{0i} is the initial component content in vapors.

Accordingly, the shielding gas mass fraction in mixture: $g_{sg} = 1 - \exp(-\alpha_T t)$, and the effective molecular mass of mixture is

$$\mu_{mix}(t) = \frac{1}{\sum g_i(t)/\mu_i + g_{sg}(t)/\mu_{sg}},$$

where μ_i is the components' molecular mass; μ_{sg} is the molecular mass of shielding gas (CO_2 in the case under consideration).

Thus, the current component partial pressure is described by equation:

$$P_i(t) = \frac{g_i(t)\mu_{mix}(t)}{\mu_i} P,$$

where P is the atmospheric pressure, and the number density of the component atoms is determined in the following form:

$$n_{Ai}(t) = \frac{g_i(t)\mu_{mix}(t)}{\mu_i} \frac{P}{k_B T(t)}. \tag{2}$$

Under assumption that a change in temperature of vapor-gas mixture occurs only by mixing with shielding gas, the current temperature can be described as:

$$T(t) = \frac{J_0 T_0 \sum (c_i g_{i0}) + J_{sg} T_{sg} c_{sg}}{J_0 \sum (c_i g_{i0}) + J_{sg} c_{sg}},$$

where T_0 is the initial vapor temperature; T_{sg} is the shielding gas temperature; c_i is the heat capacity of vapor component; c_{sg} is the heat capacity of shielding gas. Under assumption that $c_i = c_{sg}$, and with taken into account (1), the current temperature is determined in the following form:

$$T(t) = T_{sg} + (T_0 - T_{sg})\exp(-\alpha_T t). \tag{3}$$

From Eq. (3) follows:

$$\exp(-\alpha_T t) = \frac{T(t) - T_{sg}}{T_0 - T_{sg}},$$