Prediction of fume formation in a pulse d gas metal arc welding process by means of a 2D time-dependent arc model coupled with nanoparticle tracking

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Abstract: Fume formation in a pulsed gas metal arc welding (GMAW) process has been investigated by coupling a time-dependent axi-symmetric 2-D model, which takes into account both droplet detachment and production of metal vapour, with a model for fume formation and transport based on the method of moments (MoM) for the solution of the aerosol general dynamic equation.

Keywords: Thermal plasmas, pulsed welding, nanoparticle synthesis, modelling, metal vapour

1. Introduction
Gas-metal arc welding (GMAW) [1,2] is a process in which a non-constricted plasma arc is ignited between a workpiece that works as the cathode and a metal wire that works as the anode; the latter is melted by the heat from the arc and a metal transfer occurs from the wire to the workpiece. Following recent studies on health effects for welding workers exposed to fume inhalation [3], a huge effort is currently being devoted to the investigation of fume formation during the welding process and to the development of processes with lower fume production rate. In the welding process, fumes are generated by nucleation and growth of nanoparticles from the metal vapour coming from evaporating weld pool, droplets and metal wire. Even if experimental try and fail approaches have been adopted to develop operating conditions that induce a lower formation of fumes, modelling is a valuable tool that provides insight on those physical processes occurring during the formation phase that cannot be easily monitored by diagnostics [5,6].

In this work, the simulation of fume formation in pulsed GMAW process is reported taking into account the metal transport and metal vapour formation in a self-consistent approach using the Volume-of-Fluid (VoF) method and modelling fume nanoparticles production using the method of moments (MoM) for the solution of the aerosol general dynamic equation. While this method has been widely used for the modelling of nanoparticle synthesis in thermal plasma reactors, this is the first attempt to implement the MoM approach in modelling fume formation in pulsed GMAW. This approach has allowed the investigation of fume formation mechanisms in different phases of the current pulse and the tracking of mass transport of fumes. We report simulative results of a pulsed process (peak current = 350 A, background current 30A, period = 9 ms) for a 1 mm diameter steel wire, with Ar shielding gas. Results showed that metal vapour production occurs mainly at the wire tip, whereas fume formation is concentrated in the fringes of the arc in the spatial region close to the workpiece, where metal vapours are transported by convection. The proposed modelling approach [4] allows a time-dependent tracking of fumes also in plasma processes where temperature time-variations occur faster than nanoparticle transport from the nucleation region to the surrounding atmosphere, as it is the case for most pulsed GMAW processes.

2. Process approach
Modelling of a pulsed GMAW process has been accomplished with reference to a Cebora Sound MIG 5040/TD Double Pulse source operated with a wire feed rate of 5 m/min and a mild steel wire of 1 mm diameter. The distance between the surface of the workpiece and the contact tip of the torch is set at 15 mm, with an average arc length of 4 mm and a stick out length of 11 mm. Ar was used as shielding gas, with a constant flow rate of 10 l/min. The pulsed current waveform used as a reference in this work is characterized by a period of 9 ms, a peak of current of nearly 350 A and a background current of 30 A (see figure 1).

Figure 1 Electric current waveform adopted in pulsed GMAW process modelling.
If the electric pulse is well tuned, after a transient start-up of some tens of pulses, the droplet detachment and metal transfer assumes a periodic behaviour. We reported results for a single droplet transfer in the periodic behaviour obtained after more than one hundred pulses. In figure 2 a schematic of the computational domain is displayed.

![Figure 2 Schematic of computational domain](image)

### 3. Modelling approach

The model [4] implies the solution of the mass continuity, momentum, energy, metal vapour conservation and volume of fluid transport equations:

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \tau + \rho \mathbf{F} + \nabla \cdot \mathbf{j} + \rho \mathbf{e} - \nabla T + \rho \mathbf{e} - \nabla T
\]

\[
\rho \frac{\partial e}{\partial t} + \nabla \cdot (\rho \mathbf{u} e) = \nabla \cdot \left( \kappa \nabla T \right) + \frac{\partial \left( \frac{\rho}{c_p} \right) \left( \frac{\partial T}{\partial t} \right)}{\partial T}
\]

\[
\rho \frac{\partial y_{\text{vap}}}{\partial t} + \nabla \cdot (\rho \mathbf{u} y_{\text{vap}}) = D_{\text{vap}} \nabla^2 y_{\text{vap}} + \frac{\partial}{\partial t} \left( \frac{\rho}{c_p} \frac{\partial T}{\partial t} \right)
\]

\[
\rho \frac{\partial \mathbf{u}_{\text{vap}}}{\partial t} + \nabla \cdot (\rho \mathbf{u}_{\text{vap}} \otimes \mathbf{u}_{\text{vap}}) = -\nabla p + \nabla \cdot \tau + \rho \mathbf{F} + \nabla \cdot \mathbf{j} + \rho \mathbf{e} - \nabla T + \rho \mathbf{e} - \nabla T
\]

\[
\rho \frac{\partial \mathbf{u}_{\text{vap}}}{\partial t} + \nabla \cdot (\rho \mathbf{u}_{\text{vap}} \otimes \mathbf{u}_{\text{vap}}) = -\nabla p + \nabla \cdot \tau + \rho \mathbf{F} + \nabla \cdot \mathbf{j} + \rho \mathbf{e} - \nabla T + \rho \mathbf{e} - \nabla T
\]

where \( \rho \) is the plasma density, \( t \) is the time, \( \mathbf{u} \) is the velocity vector, \( p \) is the pressure, \( \tau \) is the viscous stress tensor, \( c_p \) is the current density, \( B \) is the magnetic induction, \( g \) is the gravitational force, \( e \) is the specific energy, \( k \) is the thermal conductivity, \( T \) is the temperature, \( \mathbf{E} \) is the electric field, \( y_{\text{vap}} \) is the metal vapour concentration, \( D_{\text{vap}} \) is the metal vapour diffusivity, \( F \) is the production of metal vapour from liquid surfaces, \( \mathbf{F}_{\text{vap}} \) is the production of metal vapour due to evaporation of nanoparticles and \( \mathbf{F}_{\text{vap}} \) is the vapour consumption on behalf of nanoparticles formation.

The presence of both plasma and metal is taken into account by adding different source terms for momentum and energy equations. \( F \) represent the forces acting on the surface of the liquid, which are the surface tension force and the Marangoni force. \( K \) is function of metal temperature that represents the drag term during melting phase.

The energy source term for the surface of the metal includes electron heating due to the work function of metal and radiative cooling using Stefan Boltzmann law and an emission coefficient of 0.25. The latent heat of fusion is considered through variations of liquid fraction ratio. The source term for the plasma includes radiation losses and Thomson effect.

Diffusion of metal vapour from the molten metal has been taken in account using a simplified diffusion model, allowing the use of plasma properties weighted on the mass fraction of shielding gas and metal vapour. The production of metal vapour has been self-consistently calculated on the surface of the wire using Hertz-Knudsen-Langmuir equation, allowing to add the heat of vaporization cooling effect into the energy conservation equation; to grant a stable cathode arc attachment we impose on the workpiece a Gaussian temperature profile that allows us to add an imposed vapour mass flow. Turbulent effects on flow have been neglected; the electromagnetic field equations have been solved in their vector potential form using the extended field approach. The workpiece works as cathode with imposed current density on the wire inlet section.

For nanoparticle formation, the aerosol general dynamic equation is mathematically reformulated in order to obtain a system of equations that is easier to solve using the method of moments (MoM) [7,8] that relies on the following assumptions:

- spherical nanoparticles;
- negligible nanoparticles inertia;
- nanoparticles temperature and velocity identical to those of the plasma flow;
- nanoparticle size following a uni-modal log-normal distribution.

In the MoM approach, the equations for the first three moments of the PSDF are solved. The \( k \)-th moment is defined as:

\[
\langle \mathbf{r}^k \rangle = \int \mathbf{r}^k \rho(\mathbf{r}) d\mathbf{r}
\]
The moment steady state transport equations then take the form:

\[
\begin{align*}
\text{(6)}
\end{align*}
\]

\[
\begin{align*}
\text{(7)}
\end{align*}
\]

where the terms represent the net production rates due to nucleation, condensation, coagulation, diffusion and evaporation. These sources terms have been implemented according to \([9, 20]\).

The additional evaporation term has been implemented as follows:

\[
\begin{align*}
\text{(8)}
\end{align*}
\]

\[
\begin{align*}
\text{(9)}
\end{align*}
\]

where \(\rho_p\) is the particle density.

The system is then mathematically closed by the definitions of geometric standard deviation and of geometric mean volume and by the relation between moments:

\[
\begin{align*}
\text{(10)}
\end{align*}
\]

\[
\begin{align*}
\text{(11)}
\end{align*}
\]

\[
\begin{align*}
\text{(12)}
\end{align*}
\]

Finally, a source term has been added to the metal vapour conservation equation accounting for the metal vapour consumption on behalf of nucleation and condensation and for metal vapour production rate due to evaporation of nanoparticles, through the term

\[
\begin{align*}
\text{(13)}
\end{align*}
\]

4. Results

Results for plasma temperature, gas velocity, metal vapour concentration, vapour consumption and nanoparticle mass concentration are reported in figure 3 for time frame (a), where the current is set at the base level; consequently the temperature is generally lower than for the rest of the pulse. Maximum temperature is around 7000 K and the arc is diffuse. The wire is partially melted and the metal droplet has an almost spherical shape, mainly determined by surface tension forces. The metal vapours are mostly concentrated in the region close to the evaporating wire tip and in the vicinity of the workpiece surface, without inducing a significant cooling of the arc. Plasma maximum velocity in the arc is around 15 m/s and a recirculating pattern has been found close to the arc attachment at the workpiece.

At this time frame, some vapours produced during the previous pulse have been transported to the fringes of the arc by convection and diffusion and they are converted to nanoparticles; the vapour consumption field has a narrow distribution around the 2000 K temperature iso-contour, with two peaks with a value of about 0.05 and 0.5 \(\mu g/mm^3\) s close to the workpiece and to the wire tip, respectively.

Nanoparticles are formed mainly in the region with vapour consumption peaks: nanoparticles generated close to the workpiece are transported radially outward by the convective effect of the plasma gas, whereas those generated near the wire tip are dragged by the plasma flow to the high temperature region in the arc center where they are completely converted again to metal vapour. Nanoparticles formed during the previous pulse are transported away from the arc center by recirculating flow. A maximum mass concentration around \(5 \times 10^{-3} \mu g/mm^3\) is reached in the vicinity of the arc fringes before nanoparticles are dispersed in the surrounding atmosphere.

Another time frame (frame d) is reported in figure 3. About 2 ms after the pulse peak phase, the current has been reduced at 100 A and the droplet is already detached and it has been dragged by the plasma flow towards the workpiece. Results for plasma temperature, gas velocity, metal vapour concentration, vapour consumption and nanoparticle mass concentration are reported in figure 3 for this time frame. Plasma temperature has a peak value of 12500 K and the arc is less expanded in the radial direction, as the current is lower than for previous time frames. Gas velocity is about 40 m/s and thus convective transport is still the main contribution to metal vapour and nanoparticle transport phenomena. Vapour concentration is peaked on the torch axis as a consequence of the strong emission from the detached droplet and its satellite droplet during transition along the inter-electrode gap. Metal vapours are transported to the outer region of the arc where they are converted to nanoparticles, especially in the vicinity of the workpiece. In this region, the vapour consumption source has a maximum with a value of about 0.3 \(\mu g/mm^3\) s, whereas nanoparticles are nucleated and transported to the outer region and dispersed in the surrounding atmosphere with a mass concentration of about \(2 \times 10^2 \mu g/mm^3\).

Nanoparticle production rate predicted by this model at different time frames ranges between 1 and 11 mg/s; the
time-averaged mean value at 5.5 mg/s is in agreement with fume formation rate reported in many experimental works [2].

5. Conclusions
A pulsed gas metal arc welding (GMAW) process has been investigated using a novel modelling approach, which allows a time-dependent tracking of fumes also in plasma processes where temperature time-variations occurs faster than nanoparticle transport from the nucleation region to the surrounding atmosphere. This model offers insight on the pulsed GMAW process that could not be obtained with previous modelling approaches: the time distribution of fume sources with a time-varying current and their spatial localization and quantification along the fringes of the arc. This approach allows a time-dependent tracking of fumes also in plasma processes where temperature time-variations occur faster than nanoparticle transport from the nucleation region to the surrounding atmosphere, as it is the case for most pulsed GMAW processes.

The results reported in this work can be used as a basis for the optimization of pulsed GMAW process in order to reduce the production of harmful nanosized fumes.

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