Simulation of the multi-beam electron-beam wire-feed additive manufacturing process in a vacuum

R P Davlyatshin\textsuperscript{1,4}, R M Gerasimov\textsuperscript{1}, Y V Bayandin\textsuperscript{2}, F R Saucedo-Zendejo\textsuperscript{3} and D N Trushnikov\textsuperscript{1}

\textsuperscript{1}Perm National Research Polytechnic University, 29 Komsomolsky Ave., Perm, 614990, Russian Federation
\textsuperscript{2}Institute of Continuous Media Mechanics UB RAS, 1 Akadem. Koroleva St., Perm, 614013, Russian Federation
\textsuperscript{3}Autonomous University of Coahuila, Boulevard Venustiano Carranza, Saltillo, Coahuila, 25260, Mexico

E-mail: romadavly@gmail.com

Abstract. The paper considers modelling the wire deposition process with vertically fed wire by several symmetrically acting heat sources. We proposed the mathematical model to describe the above process, considering surface tension force, Marangoni force, vapor pressure force, and heat loss on evaporation. To solve the mathematical model, we use the smoothed particle hydrodynamics method. We carried out a series of numerical experiments for modelling the melting process of vertically fed wire with two symmetrically acting heat sources with different power and direction of action of heat sources. We found that vertical wire feeding provides uniform heating with the absence of shaded areas and flexible control of heat input into the metal. On the other hand, the weld bead geometry characteristics significantly depend on the heat sources' power and direction.

1. Introduction
Electron-beam deposition using metal wire materials is a productive solution for many promising materials, such as titanium and other chemically active metals and their alloys [1–3]. The filler wire has a much smaller specific surface area than powdered materials do and is less prone to oxidation and absorption of moisture or contaminants. The use of vertically fed wire with multiple symmetrically acting heat sources allows a significant improvement in the surfacing process and provides: 1) uniform heating with no shaded areas; 2) flexible control of the heat input to the metal; and 3) the ability to implement concurrent heating of the wire and substrate.

At the same time, this method of creating metal products has several drawbacks. The main disadvantage is the difficulty of setting parameters of the deposition process, namely the trajectory and speed of wire feeding, as well as the power and direction of the sources [4–5]. Incorrect setting of these parameters can lead to melting or even collapse of the walls of the future product, which leads to an increase in the number of rejects and, consequently, to higher costs and a slower production process.

Existing methods for optimizing the thermal effect parameters often do not consider real-time geometry changes, have low performance, and are mainly used for selective laser sintering [6–8]. Recently, researchers have been more likely to use meshless approaches to solve these problems, such as a smoothed particle hydrodynamics method (SPH). However, these studies aim to study the selective
laser sintering process or do not consider surface effects or solve the problem in a 2D formulation [9–11].

Thus, it is relevant to develop a mathematical model that would allow one to determine the volumetric distribution of temperatures, melt flow rates, shape, and deposited bead dimensions using more productive meshless methods to determine the geometry of the bead and adjust the parameters of the deposition process.

2. Materials and Methods

During electron-beam surfacing of wire (Figure 1), the geometry of a single bead depends significantly on many factors, namely material density, surface tension, and viscosity. These factors determine the nature of the metal flow in the molten bath, and in turn, depend on heat input, material, deposition method, interaction time with the energy source, etc.

The paper considers the interaction of solid and liquid metal. For this purpose, we consider two phases: \( \Omega_l \) – liquid and \( \Omega_s \) – solid, the union of which represents the whole investigated area – \( \Omega \). The solid phase, in turn, consists of a wire \( \Omega_{wire} \) and a substrate \( \Omega_{sub} \) (Figure 1). We describe the motion of metallic melt as the motion of a viscous incompressible fluid. In the general case, the system of equations will consist of differential equations describing the evolution of density \( \rho \), velocities \( u \), and temperature \( T \) in the form of balance laws (mass, momentum, and energy balance equations, respectively):

\[
\begin{align*}
\frac{d\rho}{dt} &= -\rho \nabla \cdot u, \quad R \in \Omega_{wire}, \\
\frac{d u}{dt} &= \frac{1}{\rho} (\nabla \rho f_s + f_s f_v + f_v + g), \quad R \in \Omega', \\
\frac{d\rho}{dt} &= 0, \quad \frac{d u}{dt} = 0, \quad R \in \Omega', \\
\rho c_p \frac{dT}{dt} &= -\nabla \cdot q + s_{src} - s_v - s_{env} - s_{rad}, \quad R \in \Omega
\end{align*}
\]

where \( u \) is velocity, \( \rho \) is density, \( f_v \) is viscous forces, \( f_s \) is surface tension force, \( f_v \) is vapor pressure force, \( g \) is an acceleration of gravity, \( c_p \) is specific heat capacity, \( \nabla \) is heat flow, \( k \) is thermal conductivity coefficient, \( s \) is heat loss by evaporation, \( s_{src} \) is a heat source.

Applying the discretization of the method of smoothed particles to the system (1), we obtain expressions for the i-th particle:
\[
\frac{d\rho_i}{dt} = -\sum_{j=1}^{N} m_j u_{ij} \cdot \nabla W_{ij},
\]
\[
\frac{du_i}{dt} = \frac{1}{m_i} \left[ F_{p,i} + F_{v,i} + F_{s,i} + F_{v,i} \right] + g_i,
\]
\[
\frac{dT_i}{dt} = -\frac{1}{c_i \rho_i} \left[ -\nabla \cdot q_i + s_{src,i} - s_{rad,i} - s_{env,i} \right]
\]

where \( F_{p,i} \) is the pressure force, \( F_{v,i} \) is the viscous force, \( F_{s,i} \) is the surface tension force, \( F_{v,i} \) is the vapor pressure force. The action on particle \( i \) is the result of summing up all contributions of interparticle interaction with neighboring particles \( j \). The viscous and pressure forces in the momentum equation (2) are discretized according to the formulation proposed by Adami et al. [12–13]. The application of surface tension forces in the SPH formulation is described in [14–15].

3. Results and Discussion
Using the developed mathematical model, we provided a series of numerical experiments. We studied the dependence of the geometric characteristics of the weld bead on the power of heat sources and the direction of the heat sources (along with the surfacing motion and perpendicular to the surfacing motion) for vertically fed wire with two symmetrically acting sources and inclined wire with one heat source [16]. We chose steel as the material for simulation.

For optimum performance, we selected the following geometry of the simulated system: the substrate size of 10 mm x 20 mm x 3.5 mm, the wire diameter of 1.2 mm, the wire–feed speed of 30 mm/s, the surfacing speed of 15 mm/s, the heat source diameter of 1.5 mm.

Below are the numerical simulation results of the melting process of obliquely fed wire at a heat source power of 1000 W (Figure 2).

![Figure 2](image_url)

**Figure 2.** Results of numerical modeling of the process of fusion of an inclined wire: visualization of the surfacing process (a), geometric characteristics of the melted zone (b), geometric characteristics of the weld bead (c).

We found that the deposition process of an inclined wire fed is accompanied by the formation of a melting channel under the action of the Marangoni force and vapor pressure. In some cases, this can lead to the erratic behavior of the molten metal, splashing, and its displacement outside the surfacing zone.

Below are the results of numerical simulation of the process of reflowing a vertically fed wire with an arc in a vacuum with two symmetrically operating sources located in the direction of the surfacing of different power: 300 W, 350 W, and perpendicular to the movement of the surfacing with a power of 350 W (Figure 3).
Figure 3. Visualization of rolls after surfacing with two symmetrically acting sources located along the direction of the substrate: 300 W (a), 350 W (b), and perpendicular to the surfacing direction 350 W (c).

Below we analyze the geometric characteristics of the welded beads (Figure 4).

Figure 4. Geometric characteristics of rolls after surfacing with two symmetrically acting sources located along the direction of the substrate motion: 300 W (a), 350 W (b), and perpendicular to the surfacing direction 350 W (c).

To analyze the melted zone when surfacing a vertical wire, we made a cross-sectional comparison at $x = 10$ mm and $t = 1$ sec (Figure 5).

Figure 5. Geometric characteristics of penetration zones after surfacing with two symmetrically acting sources located along the direction of the substrate motion: 300 W (a), 350 W (b), and perpendicular to the surfacing direction 350 W (c).

4. Conclusion
We found that vertical wire feeding with multiple hollow cathodes arranged radially around the filler wire axis and symmetrically around the filler wire axis provides uniform heating with no shaded areas and flexible control of metal heat input compared to a standard tilted wire feed and a single heat source. Furthermore, the vertical wire feed requires less heat input, which leads to improved geometry of the welded beads, prevents excessive metal melt spreading, and makes it possible to grow thin-walled products.
At the same time, the geometric characteristics of the weld beads qualitatively depend on the action direction of the heat sources. There is an asymmetric location of beads and melting zones relative to the surfacing direction when the heat sources are located in the direction of the surfacing.

Acknowledgments
The work is supported by the Ministry of Science and Higher Education of the Russian Federation (State Task No. FSNM-2020-0028), the Ministry of Education and Science of Perm Krai (Agreement C-26/512), and the Russian Foundation for Basic Research (RFBR Project No. 20-48-596006).

References
[1] Lorenz K A, Jones J B, Wimpenny D I and Jackson M R 2015 A review of hybrid manufacturing Solid Freeform Fabrication Conference Proceedings 53 96–108
[2] Stawowy M 2018 Comparison of LCAC and PM Mo deposited using Sciaky International Journal of Refractory Metals and Hard Materials 73 162–167
[3] Tarasov S, Filippov A, Savchenko N, Fortuna S, Rabtsov V, Kolubaev E and Psakhie S 2018 Effect of heat input on phase content, crystalline lattice parameter, and residual strain in wire-feed electron beam additive manufactured 304 stainless steel The International Journal of Advanced Manufacturing Technology 99 (9–12) 2353–2363
[4] Markl M and Körner C 2016 Multiscale Modeling of Powder Bed–Based Additive Manufacturing Annual Review of Materials Research 46 (1) 93–123
[5] Mladenov G, Koleva E and Trushnikov D 2018 Mathematical modelling for energy beam additive manufacturing Journal of Physics: Conference Series 1089 012001
[6] Jamshidinia M, Kong F and Kovacevic R 2013 Numerical modeling of heat distribution in the electron beam melting of Ti-6Al-4V Journal of Manufacturing Science and Engineering 135 (6) 061010
[7] Yuan P and Gu D 2015 Molten pool behaviour and its physical mechanism during selective laser melting of TiC/AlSi10Mg nanocomposites: simulation and experiments Journal of Physics D: Applied Physics 48 (3) 035303
[8] Hu R, Luo M, Liu T, Liang L, Huang A, Trushnikov D, Karunakaran K and Pang S 2019 Thermal fluid dynamics of liquid bridge transfer in laser wire deposition 3D printing Science and Technology of Welding and Joining 24 (5) 401–411
[9] Liu S, Liu J, Chen J and Liu X 2019 Influence of surface tension on the molten pool morphology in laser melting International Journal of Thermal Sciences 146 106075
[10] Shcherbakov A, Rodyakina R and Gaponova D 2018 Using of smoothed particle hydrodynamics method for constructing a mathematical model of electron-beam surfacing process Solid State Phenomena 284 523–529
[11] Trushnikov D N, Koleva E G, Davlyatshin R P, Gerasimov R M and Bayandin Y V 2019 Mathematical modeling of the electron-beam wire deposition additive manufacturing by the smoothed particle hydrodynamics method Mechanics of Advanced Materials and Modern Processes 5 (1) doi: 10.1186/s40759-019-0044-1
[12] Adami S, Hu X and Adams N 2012 A generalized wall boundary condition for smoothed particle hydrodynamics Journal of Computational Physics 231 (21) 7057–7075
[13] Adami S, Hu X and Adams N 2013 A transport-velocity formulation for smoothed particle hydrodynamics Journal of Computational Physics 241 292–307
[14] Brackbill J and Kothe D 1996 Dynamic modeling of the surface tension Proceedings of the 3rd Microgravity Fluid Physics Conference (Cleveland: NASA Lewis Research Center) pp 693–698
[15] He X, Wang H, Zhang F, Wang H, Wang G and Zhou K 2014 Robust simulation of sparsely sampled thin features in SPH-based free surface flows ACM Transactions on Graphics 34 (1) 1–9.
[16] Davlyatshin R, Gerasimov R, Bayandin Y, Permyakov G and Trushnikov D 2021 Mathematical modeling the process of wire surfacing by the smoothed particle hydrodynamics method Journal of Physics: Conference Series 1730 (1) 012003