TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue II, June, 2026

NUMERICAL SIMULATION OF METAL COATING PROCESSES USING ELECTRICAL DISCHARGE DEPOSITION

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Abstract: *This study investigates the numerical simulation of microstructure deposition using three distinct electrode materials, utilizing COMSOL Multiphysics software. The electric discharge deposition (EDD) process serves as an advanced additive manufacturing technique for creating metal structures. This method relies on the high wear rate of the tool electrode, operating as the reverse of electrical discharge machining, to facilitate metal deposition onto a substrate. Additionally, the effect of tool electrode rotation was examined to determine its influence on material distribution and deposition uniformity. The research also examines the impact of a magnetic field on the EDD process for three electrode materials to enhance deposition quality. A finite element model was developed with parameterized working conditions to analyze their effect on the deposition process.*

Key words: *software, electric discharge deposition, modeling, simulation, electrodes, tool electrode rotation*

1. INTRODUCTION

In many advanced manufacturing technologies, layering is an important method of enhancing the surface of materials mechanically, physically, and biochemically [1]-[2]. It has played a fundamental role in the development of many advanced manufacturing technologies. Various coatings have been developed to enhance the resistance of materials to high temperatures, pressures, and hostile environments.

Recent studies have demonstrated that surface modification can significantly increase material strength, corrosion resistance, wear resistance, and biocompatibility, as well as generate new surface properties [3]-[4]. Surface coating methods are particularly important in enhancing abrasion resistance and electrochemical corrosion resistance by altering the composition of the deposited material [3]–[5].

By reviewing the latest literature in the field, a new technology has been developed: Electrical Discharge Deposition (EDD) [6]. EDD is an innovative technique derived from Electrical Discharge Machining (EDM), utilizing a reversal of the electrodes' polarity [7].

The technological configuration illustrated in Fig. 1 incorporates components derived from an electrical discharge (EDM) machining system. The work head facilitates the feed motion of the tool-electrode along the Z-axis in relation to the workpiece. An electromagnetic coil, strategically positioned on the worktable, governs particles' spatial distribution during pulsed voltage application. The tool-electrode is aligned within the frontal discharge gap (sF) relative to the surface of the workpiece. Additionally, the CNC control unit manages the positioning along the X and Y axes, enabling precise definition of the coating pattern and deposition geometry.

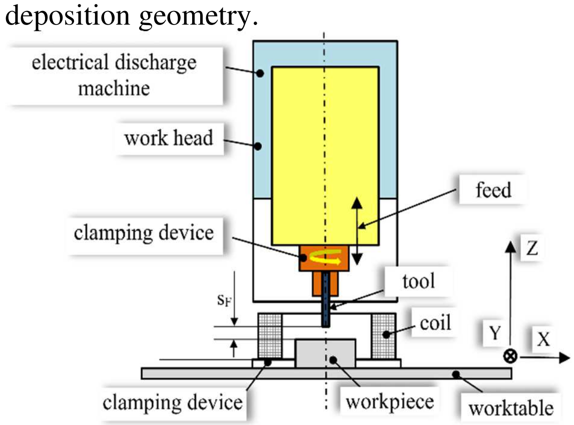


Fig. 1. Schematic representation of Electric Discharge Deposition technology [8]

Received: 28.04.26; **Similarities**: 07.05.26: **Reviewed**: 28.04. /28.04.26: **Accepted 1**5.06.26.

2. PHENOMENOLOGY

During the electrical discharge process, a significant potential difference is achieved within the two electrodes, specifically between the tool and the part. As these electrodes are brought into proximity, typically separated by a gap on the order of micrometers, intense physical phenomena are initiated. The combination of Joule heating and the strong electric field within the narrow gap induces thermionic and field emission processes at the cathode surface, resulting in the release of a substantial quantity of electrons. These emitted electrons, subjected to the force exerted by the electric field, are rapidly accelerated toward the anode.

As they traverse the dielectric medium, the high-energy electrons frequently collide with neutral atoms and molecules, leading to a cascade of ionization events that generate electropositive ions and secondary electrons. This ongoing collision and ionization phenomenon persists throughout the discharge, continuously supplying the system with charged particles and contributing to the self-sustaining nature of the plasma formation.

During successive ionizing collisions, the dielectric medium gradually transitions from an insulating state to a plasma state as the number of charged particles increases exponentially. Eventually, a highly conductive plasma channel is established between the electrodes, serving as the primary conduit for charge transfer.

During discharge, complex and interdependent physical events occur, emphasizing its inherently dynamic and nonlinear nature. Moreover, the intricate interaction between thermal, electrical, and particle transport phenomena fundamentally governs the stability, morphology, and efficiency of the discharge, thus defining the technological characteristics of the Electrical Discharge Deposition (EDD) process [9].

3. NUMERICAL SIMULATION OF THE COATING PROCESS

A dedicated modelling and simulation software was employed to gain a comprehensive understanding of particle dynamics during the electrical discharge process [10]-[11].

The simulation environment enables accurate reproduction of key physical phenomena. The cathode emits electrons, particles accelerate under electric fields, successive ionizing collisions occur within the dielectric medium, and plasma channels are formed [12]-[13]. The particle trajectory was modelled with a high spatial and temporal resolution, which allowed detailed analysis of the effects of various process parameters, such as the distance between electrodes, the voltage applied, and the dielectric properties of the particle [11]-[13]. The simulation results revealed complex interactions between charged particles and the surrounding medium, providing deeper insights into the mechanisms governing plasma channel initiation and development [13]. The integration of advanced computational modeling has proven essential for validating the theoretical hypothesis, optimizing process parameters, and improving the overall understanding of electrical discharge deposition (EDD) technology [10]-[13].

The discharge process and particle trajectory were accurately simulated using COMSOL Multiphysics by employing a parametric model.

The parameters relate to geometry, technological characteristics, particle characteristics, and the time allocated for numerical simulation, as shown in the capture in Fig. 2.

Parameters

Name	Expression	Value	Description
rc	0.5	0.5	electrode radius
hc	4	4	electrode height
rbe	8	8	outer radius coil
rbi	4	4	inner radius coil
hb	3	3	coil height
rcol	12.5	12.5	collimator radius
hcol	13	13	column height
E0	500[eV]	8.0109E-17 J	initial energy
mAl	4.480134e-26	4.4801E-26	Al ion mass
tpar	0.001*sF/vAl	5.0166E-9	target distance travel time
Jsz	10000	10000	surface current density
vAl	59801	59801	initial speed of ion Al
tps	5e-8	5E-8	Al ion study time
Np	1000	1000	number of particles
sF	0.3	0.3	distance cathode_workpiece
sB	1	1	coil vertical position
Ic	0.4[A]	0.4 A	current in the coil
Nc	3000	3000	number of turns

Fig. 2. EDD model parameters

COMSOL Multiphysics' drawing tools were used to create the geometry, which represents the coil, the tool electrode, and the collimator (workspace), according to Fig. 3.

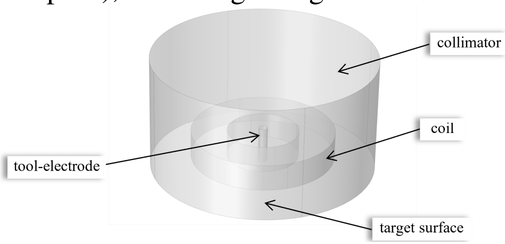
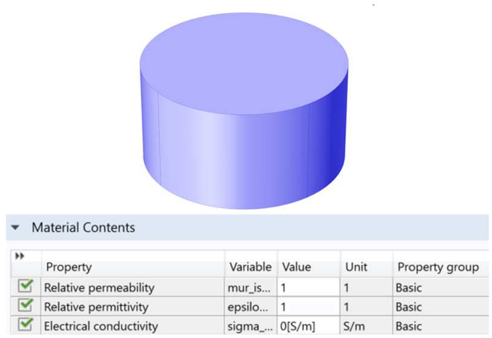


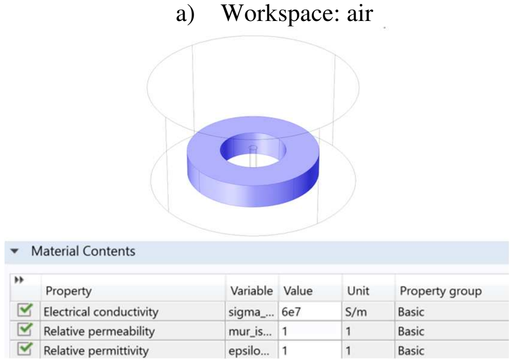
Fig. 3. Geometry of the EDD model

As shown in Fig. 4, for each component an assigned material with its physical properties is designated, which is used for future computations.



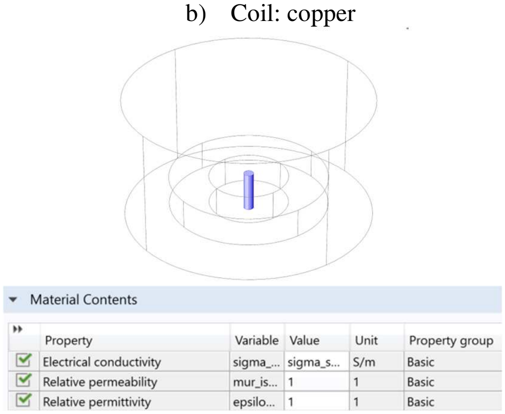
Property	Variable	Value	Unit	Property group
Relative permeability	mur_is...	1	1	Basic
Relative permittivity	epsilo...	1	1	Basic
Electrical conductivity	sigma_...	0[S/m]	S/m	Basic

a) Workspace: air



Property	Variable	Value	Unit	Property group
Electrical conductivity	sigma_...	6e7	S/m	Basic
Relative permeability	mur_is...	1	1	Basic
Relative permittivity	epsilo...	1	1	Basic

b) Coil: copper



Property	Variable	Value	Unit	Property group
Electrical conductivity	sigma_...	sigma_s...	S/m	Basic
Relative permeability	mur_is...	1	1	Basic
Relative permittivity	epsilo...	1	1	Basic

c) Tool – electrode: aluminum

Fig. 4. Materials allocated to the EDD technological system

Model meshing is an essential step in numerical simulation. It ensures that continuous geometry is transformed into discrete finite element networks that allow solution calculations to be performed. The analyzed model is modeled using free tetrahedral elements with Normal fineness, a standard option offered by COMSOL Multiphysics. Figure 5 presents this phase.

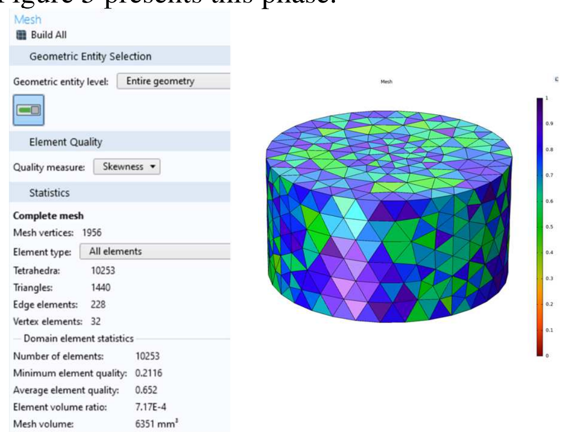
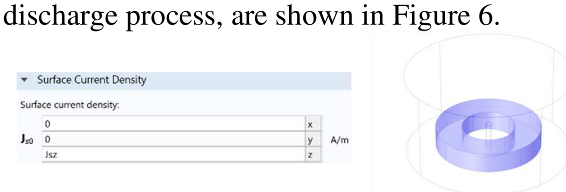
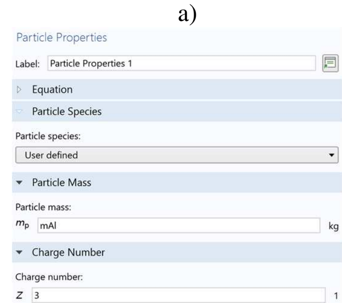


Fig. 5. Detailed model mesh

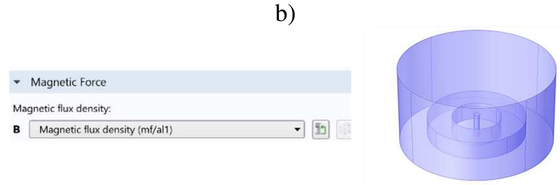
The boundary conditions assigned to the Magnetic Fields and Charged Particle Tracking modules, illustrating the simulation setup used to model the particle trajectories and the electromagnetic environment during the discharge process, are shown in Figure 6.



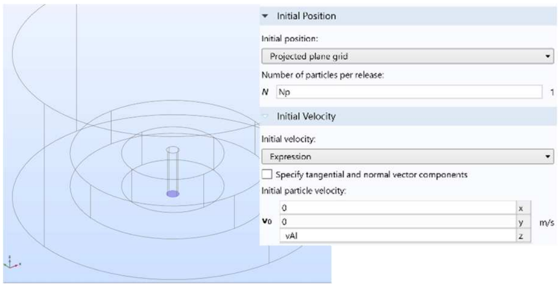
a)



b)



c)



d)

Fig. 6. Boundary conditions setup for magnetic and particle tracing modules

Within the Magnetic Fields module, an appropriate current density Jsz was assigned on the coil surfaces aligned with the z-axis (Fig. 6a). In the Charged Particle Tracing setup, aluminium ions were added for the particle characteristics (Fig. 5b). The magnetic force computed from the Magnetic Fields solution, was then applied across the surrounding air region (Fig. 5c). Finally, the emission surface was configured by setting the quantity of released particles (Np) and their initial speed (v0), as presented in Fig. 5d. This arrangement thus couples the field solution to particle dynamics, allowing the study to capture how the prescribed coil current influences emitted ions.

The formula for calculating velocity, v0 is [14]:

$$v_0 = \sqrt{\frac{2 \cdot E_0}{m_p}} \quad [m/s] \qquad (1)$$

In this case, E0 is the initial energy [J] and mp is the atomic mass of the particle [kg] - all parameters can be seen in Fig. 1.

4. CALCULATED RESULTS FROM NUMERICAL SIMULATIONS

As shown in Figure 7, the results of the first module of the simulation, Magnetic Fields, are shown in the section below. EDD in air is found to have a maximum result similar to the average of experimental data [15].

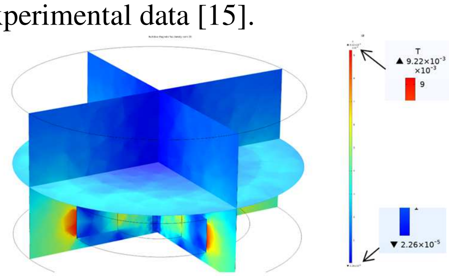
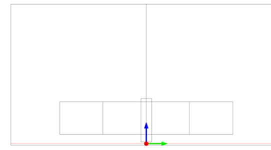


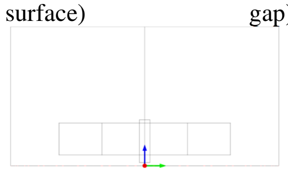
Fig. 7. Visualizing the magnetic field density [T] after running the model

Charged particle trajectories were analysed using the Charged Particle Tracing module. To facilitate the interpretation of particle behavior across the domain, three planes were established at specific Z-coordinate levels, as shown in Figure 8 (a–c).

a) z=sF (emission surface)



b) sF/2 (half of the gap)



c) z=0 (target surface)

Fig. 8. Cut planes

On the aluminum material, the trajectories and velocities of the studied positive ions are shown in Fig. 9.

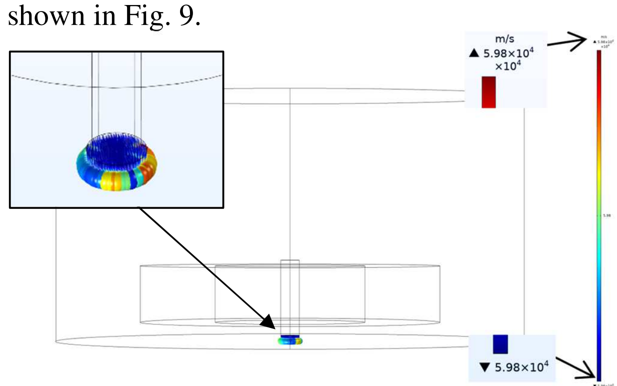


Fig. 9. The trajectory and velocity of Al ions

During the trajectory of the particles, the initial velocity (v0) remains unchanged because the Lorentz magnetic force (Fm) acts in the same direction as the particle velocity (vp), as shown in the following equation.

$$F_m = q\,(v_0 \cdot B) = q \cdot v_p \cdot B \cdot \sin\alpha \quad [N] \qquad (2)$$

where q denotes the electric charge [C], v_p represents the particle velocity [m/s], B is the magnetic flux density [T], and α is the angle between the directions of the velocity and magnetic field vectors.

A Poincaré map representing three distinct planes was used to analyze the spatial distribution of particles emitted (Np) during the interaction with the magnetic field. For this purpose, we used a three-color coding scheme: red for the source (electrode), blue for the midpoint of the working space, and green for the final product. As observed, all positively charged ions converge toward the middle of the target material, indicating a focusing effects indicated by the green dots.

Although the distinction among red and blue dots is not discernible at the current zoom level due to their proximity, it becomes visible at high magnification - see Fig. 10. Overall, the four Poincaré maps indicate minimal variation among the studied aluminum ions, even at this resolution. Greater differentiation emerges at an enlarged scale - again, refer to Fig. 9. The spatial distance (Δ) between the red and green points illustrates the focusing behavior of each ion species toward the center, as highlighted for each type of positive ion.

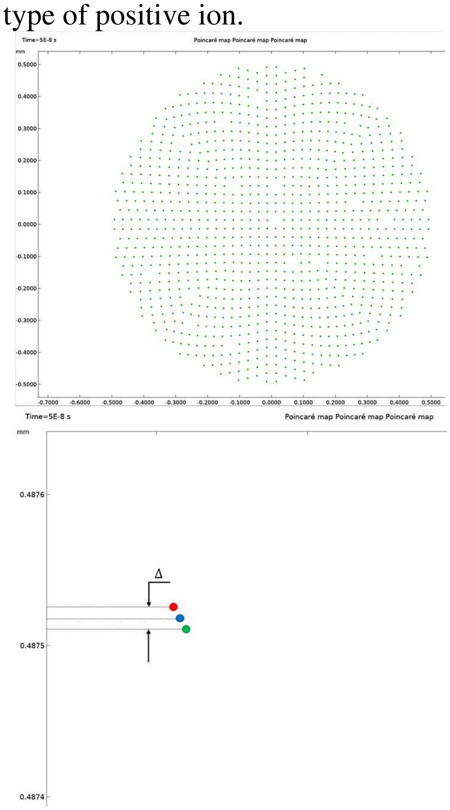


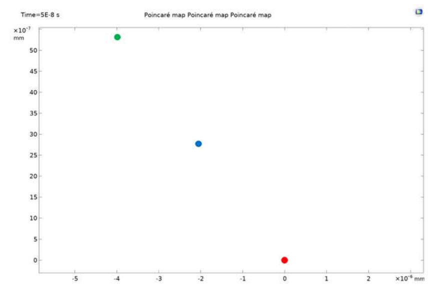
Fig. 10. Poincaré maps of aluminium ions deposition in three cut planes (less than 0.0001 mm focalization)

5. NUMERICAL SIMULATION OF DEPOSITED PARTICLE ADDING CATHODE ROTATION

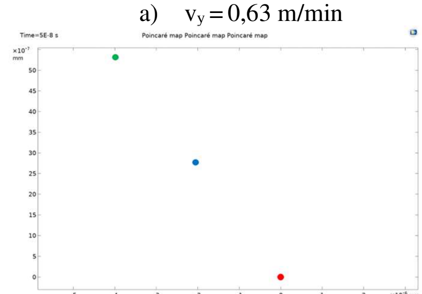
In order to extend the analysis, an additional peripheral velocity component will be introduced, in the y-direction perpendicular to the z-axis. Particle dynamics become more complex in this modification because it adds a lateral component of motion, which is capable of affecting trajectory, kinetic energy, and its interaction with electromagnetic fields.

Our modified boundary conditions are as follows: the number of particles emitted will be 1 since we are interested in understanding how a single particle deposition in a magnetic field changes over time, and the velocity on the y plane will be 0.63 m/min; 1.26 m/min; 1.88 m/min; 2.5 m/min; 3.77 m/min.

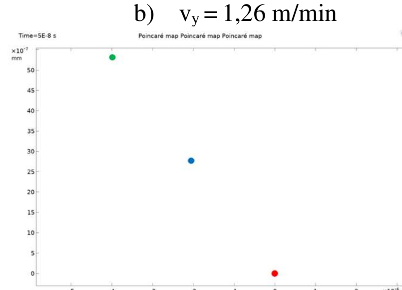
Based on the aluminum material used for the tool electrode, Poincaré maps were generated to analyze the system behavior. Fig. 10 illustrates the results systematically as follows:



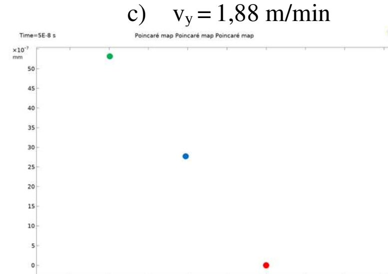
a) $v_y = 0{,}63$ m/min



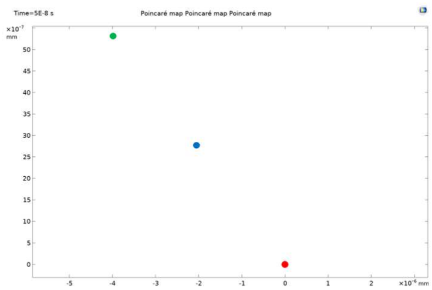
b) $v_y = 1{,}26$ m/min



c) $v_y = 1{,}88$ m/min



d) $v_{ee} = 2{,}5$ m/min



e) $v_y = 3{,}77$ m/min

Fig. 11. Poincaré maps for Al according to peripheral velocity

Based on the analysis of the resulting Poincaré map, the red point indicates the position of the tool electrode surface, representing the initial location of the deposition process under the influence of the magnetic field. In contrast, the green point denotes the final surface location where the particle is deposited.

The spatial distance between these two points reflects the particle's displacement throughout the process, governed by the combined effects of the magnetic field and the peripheral velocity component introduced in the simulation.

Initially (at the electrode surface), we have displacement in X and Y 0 mm. Subsequently, on the target surface, there is a deviation, and the displacement in X - 4·10-6 mm and Y 55·10-7 mm - values corresponding to the maximum peripheral velocity of 3.77 m/min (Fig. 11 e). The inclusion of a peripheral velocity component had a significant impact on the particle trajectory, resulting in its final position being shifted to a specific distance from the tool electrode.

This displacement is a key characteristic, highlighting how particle dynamics are affected by the complex interplay between the magnetic field and the initial simulation conditions. This behaviour confirms that peripheral velocity significantly modulates in-plane deposition precision, influencing both focalization and coverage uniformity in EDD applications.

The simulation results demonstrate that the modeling environment successfully captured these interactions, providing detailed insight into the mechanisms governing deposition accuracy and stability.

The distance between the initial emission point and the final deposition site emerges as a critical parameter, which may serve as a reference for validating and further optimizing the process.

Consequently, this simulation contributes to a deeper understanding of the physical phenomena involved and offers a robust foundation for parameter tuning in practical applications.

6. CONCLUSIONS

The present study has undertaken a comprehensive investigation into the dynamics of charged particles within the framework of Electrical Discharge Deposition (EDD) technology, employing high-fidelity numerical simulations to elucidate the complex interactions governing particle behavior under the influence of magnetic fields and initial velocity conditions.

By integrating advanced multiphysics modeling in COMSOL, including modules for Magnetic Fields and Charged Particle Tracing, the simulation environment enabled an in-depth analysis of the spatial evolution of positively charged ions from their emission at the tool electrode to their final deposition onto the substrate surface.

The Poincaré maps obtained under varying simulation configurations—with and without the inclusion of a peripheral velocity component—provided substantial insight into the mechanisms governing particle trajectory modulation. In scenarios lacking tangential motion, particle trajectories were predominantly aligned along the axial direction, exhibiting limited radial dispersion.

This behavior suggests that, in isolation, the magnetic Lorentz forces are insufficient to promote notable spatial deviation of the particles. However, when a peripheral velocity was introduced, a marked alteration in particle dynamics was observed, characterized by significant lateral deflection and a broader spatial distribution of the deposition zones. These findings underscore the pivotal influence of the particles' initial kinetic conditions on the efficiency of trajectory control, focalization, and the overall uniformity of the material deposition process.

Further research will focus on the experimental validation of the finite element analysis (FEA) results, aiming to correlate the simulated particle behavior and deposition patterns with physical observations under controlled conditions.

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Modelare numerică a proceselor de acoperire a metalelor prin depunere prin descărcare electrică

Acest studiu analizează simularea numerică a procesului de depunere a microstructurilor utilizând trei materiale distincte pentru electrozi, utilizând software-ul COMSOL Multiphysics. Procesul de depunere prin descărcare electrică (EDD) este o tehnică avansată de fabricație aditivă pentru fabricarea structurilor metalice. Metoda se bazează pe uzura ridicată a sculei electrodului, funcționând invers prelucrării prin descărcare electrică, pentru a permite depunerea metalului pe substrat. De asemenea, a fost analizat efectul rotației sculei electrodului pentru a determina influența acesteia asupra distribuției materialului și uniformității depunerii. Cercetarea a examinat, de asemenea, impactul câmpului magnetic asupra procesului EDD, aplicat celor trei materiale pentru electrozi, cu scopul de a îmbunătăți calitatea depunerii. A fost dezvoltat un model cu elemente finite cu condiții de operare parametrizate pentru a evalua efectul acestora asupra procesului de depunere.

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