Simulation and experimental research on nickel-based coating prepared by jet electrodeposition at different scanning speeds

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Abstract
In order to explore the deposition mechanism of the nickel-based coating prepared by jet electrodeposition, accurately control the thickness of the coating, and improve the coating performance, the deposition mechanism and process experiments of the nickel-based coating prepared by jet electrodeposition were carried out. Based on this deposition mechanism, a multi-physical field coupling model of the deposition process was established, and numerical solutions of the deposition processes at different scanning speeds were formulated. The numerical distribution of each physical field and the deposition thickness of nickel-based coating were obtained, a corresponding experiment for exploring preparation process was carried out, the cross-section thickness of the coating was measured, the wear resistance and corrosion resistance of the coating were characterised and the coating thickness obtained using the experiment results and numerical solution was analysed. Results show that the coating thickness obtained after the process test and that obtained using the numerical solution increase first and then decrease. The average engineering error $\delta$ is 19.43%, which verifies the accuracy of the numerical solution model. When the scanning speed is 200–1000 mm/min, the grain size of the coating decreases with increasing scanning speed, whereas microhardness, wear resistance and corrosion resistance increase first and then decrease. When the scanning speed is 600 mm/min, the nickel-based coating has good comprehensive properties, the maximum thickness is 26.65 ± 0.28 μm, the microhardness is 622.82 HV, the wear area is 2766.75 μm², the self-corrosion potential is $-0.33$ V, the self-corrosion current density is $5.16 \times 10^{-7}$ A cm² and the equivalent impedance is 4660 Ω.

Keywords Jet electrodeposition · Scanning speed · Numerical solution · Process experiment · Characterisation detection

1 Introduction
Nickel-based coatings have high chemical stability and excellent surface quality and are thus widely used in the surface protection and decoration of cast iron, steel, aluminium alloy and other materials [1–4]. Different metal coatings (such as nickel, copper, zinc and cadmium) can be prepared on the surfaces of substrates with the jet electrodeposition technology [5–9]. The principle is basically the same as that of traditional electroplating technology. A voltage is applied between the cathode and anode to produce a current, and metal ions in the electroplating solution are deposited on the surface of the cathode matrix to form a metal coating [10, 11]. At present, the processing method of jet electrodeposition is relatively mature, and the research mainly focuses on the preparation process, material parameters, coating properties, etc. [12–16]. Additionally, the research on the mechanism of electrochemical deposition and coating growth in the process of jet electrodeposition has become a hot topic [17–19], especially the numerical solution of deposition process under the coupling of multiple physical fields by utilising computer software.

Owing to the advancements in computer numerical solution research, researchers have used computer for numerical solution research of electrochemical machining process in recent years [20, 21]. Huang et al. [22] established a flow field model of friction-assisted jet electrodeposition to simulate and calculate the influence of cathode surface velocity on the coatings. They obtained...
smooth and compact coating through friction-assisted jet electrodeposition experiment at a high speed. Cui et al. [23] used the jet electrodeposition method to prepare Ni-sic composite coating, studied the relationship between jet rate and the kinetic energy of electroplating solution with ANSYS software, obtained the jet rate corresponding to the maximum kinetic energy and used it to explore the performance of the coating through experiments. Shourije and Bahrololoom [24] studied the interference of electric field generated by obstacles of different types and sizes on the electrodeposition process, using COMSOL software. The results showed that electric field interference reduces the thickness of the coatings, and the simulation results were consistent with the experimental results. Wang et al. [25] prepared Cu–Zn alloy microcolumns by constant potential water bath jet electrodeposition process and used COMSOL simulation data in describing the effects of field intensity on alloy composition, crystal phase, growth rate and diameter of microcolumns. The numerical solutions of electrodeposition machining technology mainly focus on single physical field and traditional electrodeposition technology, whereas the numerical solutions of jet electrodeposition under the coupling effect of multiple physical fields are few.

In this study, the deposition mechanism and process of jet electrodeposition on the surface of 45 steel substrate were explored. COMSOL software was used in establishing the coupling model of electric, flow, material transfer and temperature fields in the deposition process and numerically solving the deposition process at different scanning speeds. The numerical distribution of each physical field and the deposition thickness of nickel-based coating during the deposition process were obtained. Coating thickness values obtained with the experiment results and numerical solution were compared and analysed. The surface morphology, section thickness, microhardness, wear resistance and corrosion resistance of nickel-based coating prepared through jet electrodeposition at different scanning speeds were characterised with a scanning electron microscope, microhardness tester, material surface comprehensive performance tester and electrochemical workstation. The accuracy of the numerical solution model was verified, and the optimal scanning speed of the nickel-based coating was determined by comparing the experiment and simulation results.

2 Scanning jet electrodeposition experiment

2.1 Experimental scheme

The nozzle is connected with the motor system, under the control of the numerical control system, with a certain scanning speed over the workpiece reciprocating cycle movement. Thus, a coating is formed in the scanning area, and the platform for this jet electrodeposition experiment is shown in Fig. 1.

The composition of electroplating solution is shown in Table 1, in which nickel sulphate is the main salt of nickel-plating solution. Nickel chloride not only provides nickel ions but also ensure the normal dissolution of an anode metal as an anode activator. Sodium sulphate can improve the conductivity and dispersion ability of bath. As a buffer, boric acid can maintain pH at 4.5 ± 0.1, improve the binding force between the nickel-based coating and base metal, improve the cathodic polarisation and the conductivity of bath and increase current density; saccharin sodium is a brightener [26]. As a cathode surfactant, sodium dodecyl sulphate can reduce the interfacial tension between an electrode and plating solution, thus preventing hydrogen from attaching to cathode surfaces and pinholes and pitting [27].

The sample of 45 steel should be pretreated before the experiment. The operation process is shown in Fig. 2. The following procedures were performed: sandpaper grinding and metallographic polishing cloth polishing for 45 steel hair blank parts; oil removal with electric clean solution, weak activation of solution and strong activation of solution; washing with deionised water and drying after ultrasonic cleaning.

After pretreatment, a jet electrodeposition experiment was carried out, and the anode nozzle reciprocated at the speed of 200, 400, 600, 800 and 1000 mm/min in the motion and control systems. The specific experimental process parameters are shown in Table 2. By controlling the reciprocating velocity of a single variable nozzle, the influence of the velocity on the growth of electrodeposited nickel-based coatings was studied. After the experiment, rust formation was prevented by cleaning and drying the workpiece through ultrasonication. The coatings on the surface of the 45 steel workpiece were cut along the direction of the nozzle movement with a wire cutting technology. The obtained coating section was inlaid in a metallographic inlay machine (Fig. 2) to facilitate the measurement of coating thickness of the cross-section with the scanning electron microscope and reduce experimental error for the rule. Each group of parameters was subjected to three experiments, and the average thickness was obtained.

2.2 Experimental instruments

To investigate the effects of different scanning rates on the microstructure of the nickel-based coating prepared through jet electrodeposition, the surface morphology and section thickness of the coating were observed using a Quanta FEG250 scanning electron microscope produced by FEI Instrument Company in Oregon, USA. The scanning speed was 30 μs,
The microhardness of the samples was tested with a Duramin-40 microhardness tester produced by Strass Copenhagen, Denmark. Hardness was measured by holding 100 g of load for 15 s. The average hardness of each sample was measured at different points several times. A friction and wear experiment was carried out using a CFT-I material surface comprehensive performance tester. The GCr15 grinding ball with a diameter of 4 mm reciprocated linearly on the surface of the friction coating on the workpiece surface with a reciprocating distance of 4 mm and time of 20 min. The load was 320 g. The cross-section parameters (including cross-section width, cross-section height and cross-section area) of the wear marks were measured with a LEXT OLS4100 confocal laser microscope produced by OLYMPUS Instruments, Japan. A corrosion experiment of nickel-based coating was carried out using a three-electrode electrochemical testing method and CS350 electrochemical workstation produced by Wuhan Crest Instrument Co., Ltd., China. Before the corrosion experiment, epoxy resin was coated on the workpiece surface, and the exposed area of 1 cm² was retained as the working motor for corrosion. Saturated calomel electrode was used as the reference electrode, and Pt sheet was completely placed in 3.5wt% NaCl solution as the auxiliary electrode. After the corrosion experiment, the self-corrosion potential ($E_{corr}$) and self-corrosion current ($I_{corr}$) in the corrosion process were obtained and analysed using the CView module of CorrTest4 software. The equivalent circuit diagram of the corrosion process of composite coating was fitted using the ZView module, and the impedance curve after fitting was obtained.

**Table 1** Composition of electroplating solution

| Plating solution composition | Content g/L |
|-----------------------------|-------------|
| NiSO₄·6H₂O                  | 200 g/L     |
| NiCl₂·6H₂O                  | 30 g/L      |
| Na₂SO₄                      | 30 g/L      |
| H₃BO₃                       | 30 g/L      |
| Saccharin sodium            | 0.15 g/L    |
| C₁₂H₂₅SO₄Na                 | 0.06 g/L    |
3 COMSOL numerical solution

3.1 Geometric model

According to the actual processing process and deposition mechanism, the distribution of each field along the movement direction perpendicular to the nozzle basically remained unchanged, and a simplified two-dimensional model was adopted for numerical solution. Figure 3 shows the geometric model for numerical solution of scanning jet electrodeposition, in which the entire geometric region is filled with electroplating solution. As shown in Fig. 3b, the Γ1 boundary was the entry of the plating solution into the nozzle lumen, Γ2 indicated the side (marked in yellow) for the metal anode nozzle lumen borders, Γ3 and Γ4 were the outflows of the plating solution and Γ5 was the cathode substrate surface. The linear boundary set in Γ6 and Γ7 completely covered the actual machining area. The linear boundary was conducive to the calculation of the simulation model and ensured the accuracy of the calculation. The remaining boundary in Fig. 3b represented the flux free boundary. Figure 3c shows the geometric model distribution, and Fig. 3d–f show the moving grid interface distributions of the plating bath simulation model when the nozzle was at the left end, centre end or right end, respectively. The arbitrary Lagrange–Eulerian method was used in simulating dynamic grid reciprocating scanning movement. Considering the influence of the degree of motion on the convergence of calculation, auxiliary line segments were set where the mesh is prone to distortion (Fig. 3; local amplification figure). On the premise of keeping the continuity of physical fields, the meshes in the domain and at the boundaries are divided and refined. Thus, solve the problem of the non-convergence of calculation.

Table 2 Experimental process parameters

| The process parameters | The numerical |
|------------------------|--------------|
| The solution temperature | 60°C |
| Current density | 5A/dm² |
| Electroplating time | 10 min |
| Plating solution flow | 8L/min |
| Scanning speed | 200, 400, 600, 800, 1000 mm/min |
| workpiece size (length, width and height) | 25 × 10 × 8 mm |
| Nozzle outlet size | 12 × 1 mm |
| Distance between nozzle and matrix | 1.5 mm |

3.2 Mathematical model

The reaction rate and machining accuracy of jet electrodeposition are affected by many physical parameters, and the physical fields include flow field, electric field, material transfer fields and temperature fields. The mathematical model proposed in this paper is shown in Fig. 4. In this model, mass transfer is influenced through “convection” controlled by flow field and “electromigration”...
controlled by electric field. Meanwhile, mass transfer reacts on electric field through influencing “current density” in electrolyte. The temperature field is affected through the “heat transfer fluid” and “heat source of electrochemical reaction”, and the change of temperature acts on the flow field and electric field by affecting the “conductivity and “current efficiency”. The following equations are the specific analysis of the mathematical model:

During jet electrodeposition, the electrolyte had high pressure and flow rate, which ensured the continuity and stability of the process, supplemented ion consumption on the cathode surface and prevented concentration polarisation. The critical Reynolds number is the standard for evaluating the flow state of a liquid [28] and is defined as Eq. (1):

\[ Re = \frac{\rho v D}{\mu} \]  

where \( \rho \) is the density of electroplating solution, \( V \) is the average velocity of the tube section, \( D \) is the hydraulic diameter of flow section and \( \mu \) is the dynamic viscosity of the fluid. At the nozzle inlet, \( \rho = 1290.21 \text{ kg/m}^3, D = 0.006 \text{ m} \) and \( \mu = 0.001798 \text{ Pa s} \). The flow in the nozzle cavity was turbulent when \( V \) was greater than 0.53 m/s. To simplify the calculation, the following assumptions were made for the fluid during modelling: (1) the electrolyte is a continuous incompressible viscous fluid, and the electrolyte is in an ideal state and free of bubbles, solid particles and other impurities [29]; (2) material transfer is the result of diffusion,
diffusion is a constant at a given temperature, convection is determined by the flow field and migration driven by electric field and processing satisfies the mass conservation equation and momentum conservation equation [30]. According to the above analysis and reasonable assumptions, the plating bath flow field was controlled using the $k-\varepsilon$ equation of the Reynolds average type in the incompressible fluid turbulence model, as shown in Eq. (2):

$$
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p + \nabla \cdot \mathbf{u}] + F
$$

$$
K = (\mu + \mu_T)(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)
$$

where $F$ is the volume force (only gravity was used in this model; $F = \rho g$), $P$ is static pressure and $\nabla$ is the Laplace operator. The boundary conditions were set as follows: the inlet boundary condition of the flow field was set as applied constant normal inflow velocity ($u = u_{in}$), and the outlet boundary condition was set as pressure ($P_o = 0$ Pa). The inner and outer surfaces of the nozzle and the cathode surfaces were all set as “wall and no slip”.

In jet electrodeposition, material transfer and electrode reaction interact with each other and are affected by the flow field. The expression of material transfer was expressed as Eq. (3):

$$
R_i = \frac{\partial c_i}{\partial t} + \nabla \cdot (D_i \nabla c_i - z_i u_i F c_i \nabla \phi_i) + u \cdot \nabla c_i
$$

$$
\frac{\partial p}{\partial t} + \nabla \cdot [-p + \nabla \cdot \mathbf{u}] + F
$$

where $R_i$ represents the total molar flux of substance $i$, $D_i$ is the diffusion coefficient, $C_i$ is the concentration of ion $i$, $Z_i$ is the charge number, $u_i$ represents mobility (s mol/kg), $F$ represents the Faraday constant ($F = 9.65 \times 10,000$ C/mol) and $u$ is the velocity vector (m/s).

In the solution model, the potential and current density in the electrode and electrolyte must be solved, respectively, and the substance concentration and electrochemical reaction involved in the whole process should be considered. Electrodes in electrochemistry are usually metal conductors, and thus their current–current relationship follows Ohm’s law and the current conservation formula, which is expressed by Eq. (4):

$$
i_s = -\sigma_s \nabla \phi_s$$

$$\nabla \cdot i_s = Q_s$$

A similar set of equations exists in electrolytes and is expressed by Eq. (5):

$$
i_l = -\sigma_l \nabla \phi_l$$

$$\nabla \cdot i_l = Q_l$$
In the equation, \( i_s \) and \( i_t \) represent the current density vectors in the electrode and electrolyte (A/m²), respectively; \( \sigma_s \) and \( \sigma_l \) represent the conductivity of the metal electrode and electrolyte (S/m), respectively; \( \phi_s \) and \( \phi_l \) represent the electrode potential and electrolyte potential (V), respectively; and \( Q_s \) and \( Q_t \) represent the general current source term (A/m³, usually 0). Meanwhile, the electrolyte was an ionic conductor, and its current density was described by the flux sum of all ions and satisfied Eq. (6):

\[
i_t = F \sum z_i N_j
\]  

(6)

In addition to the conservation of current in the electrode and electrolyte, the current at the interface must be conserved. Electroplating solution with high concentrations of metal ions was sprayed to the cathode workpiece, and the concentrations of metal ions near the cathode did not decrease. Meanwhile, the heat generated by viscous dissipation in the fluid, which was set at 100% in the numerical solution.

The relationship between deposition speed and current density on the electrode surface is expressed by Eq. (8):

\[
v_c = \eta \frac{M_q}{nF \rho_t} I
\]

(8)

In the equation, \( \rho_t \) represents the density of precipitated metal, \( M_q \) represents the molar mass of material, \( n \) refers to the absolute value of the total number of positive or negative valences in a compound and \( \eta \) represents the machining efficiency, which was set at 100% in the numerical solution.

Finally, jet electrodeposition is always accompanied by heat transfer and temperature changes. Joule heat generated in the electrode and electrolyte and heat generated by electrochemical reaction are expressed in Eqs. (9) and (10), respectively:

\[
Q_{\text{HT}} = - (i_s \cdot \nabla \phi_s + i_t \cdot \nabla \phi_l)
\]

(9)

\[
Q_m = I \left[ Q_s + T \frac{\partial E_{\text{eq}}}{\partial T} \right]
\]

(10)

Equation (11) is the total theoretical equation of fluid heat transfer:

\[
\rho C_p \left( \frac{\partial T}{\partial t} + u \cdot \nabla T \right) + \nabla \cdot (q + q_r) = a_p \left( \frac{\partial p}{\partial t} + u \cdot \nabla p \right)
\]

\[
+ \tau : \nabla u + Q
\]

(11)

where \( C_p \) represents the specific heat capacity of the plating solution (J/kg K), \( q \) represents conducted heat flow (W/m²), \( q_r \) represents radiant heat flow (W/m²), \( a_p \) is thermal expansion coefficient (1/K), \( \tau \) stands for viscous stress tensor (Pa) and \( Q \) represents the heat source (W/m³) excluding viscous dissipation. The first term on the right of the equation is the work done by pressure change, which is the result of heating under adiabatic compression, and the second term represents the heat generated by viscous dissipation in the fluid, which were set as \( Q_p \) and \( Q_{\text{vis}} \), respectively.

In this model, \( q = -k \nabla T, q_r = 0 \) and \( Q = Q_{\text{HT}} + Q_m \) so Eq. (12) is the corresponding temperature field equation of this model.

\[
\rho C_p \left( \frac{\partial T}{\partial t} + u \cdot \nabla T \right) + \nabla \cdot (-k \nabla T) = Q_p + Q_{\text{vis}} + Q
\]

(12)

where \( k \) represents the heat transfer coefficient of the electroplating solution.

### 3.3 Numerical solution results

**3.3.1 Distribution results of multiple physical fields**

Physical fields distribution changes with nozzle axis coordinates \( X \), intercepting the flow field distribution at different positions of the nozzle in the last scanning period, as shown in Fig. 5. The flow field velocity increased with scanning speed, and nozzle about reciprocating scanning movement led to changes in the electrolyte flow direction and size in the cathode surface. This effect was conducive to the uniform diffusion of metal ions and heat during deposition, which in turn was conducive to the uniform growth of the coating. Driven by the nozzle, jet electrodeposition reduced the eddy current and stagnant water, thereby promoting heat and material transfer. Consequently, the conductivity of electrolyte and the concentration of metal ions in electrochemical reaction were evenly distributed.
and efficient [29]. The numerical solution of the flow field distribution showed that the flow lines did not interfere with each other during the flow of the electroplating solution, and the material transfer determined by the flow term occurred along the flow line direction only.

Figure 6 shows the distributions of electrolyte current density and electrode surface current density at different positions. Owing to geometric limitations, the electrolyte current density was the highest in the inner cavity near the nozzle mouth. As the nozzle moved from left to right, the value of current density increases and then decreases. When the nozzle was in the centre position, that is, $X = 0$, the current density on the electrode surface reaches the maximum, which leads to the highest central thickness of the deposit formed by deposition. Under the action of multi-physical field coupling, the peak current density...
decreased with increasing scanning speed, and the peak current densities of electrolyte at scanning speeds of 200, 400 and 600 mm/min were close to those at scanning speeds of 800 and 1000 mm/min.

Figure 7 shows the size and distribution of electrolyte concentration in the processing area at different positions. The size and distribution of electrolyte concentration in the electroplating solution were affected by the joint action of the flow and electric fields. The electrolytes moved to the cathode workpiece through the nozzle, and the lowest electrolyte concentration was detected on the electrode surface directly below the nozzle because the electrode reaction occurred at the position through which the nozzle passed. The electrolytes in the electroplating solution were consumed, and the unreacted electrolytes moved sideways because of the action of the jet fluid. When the scanning speed was 600 mm/min, the electrolyte concentration on both sides was high, and the concentration in the centre was the lowest, indicating that the fastest electrodeposition reaction had a speed of 600 mm/min.

3.3.2 Results of coating thickness distribution

Figure 8 shows that the growth thickness of the coating changed with the scanning speed of the nozzle. The maximum thickness of the coating increased first and then decreased with increasing scanning speed, and the maximum coating thickness was obtained when the scanning speed was 600 mm/min. The flatness of the coating gradually decreased because the rate of material diffusion to both ends increased with scanning speed. Thus, deposition was inadequate, and the rate of decrease in the thickness of the coating from the centre to both ends decreased.

Fig. 7 Electrolyte concentration and distribution at different locations

Fig. 8 Coating thickness of numerical solution
4 Comparison and analysis of the experimental results and simulation results

4.1 Surface morphology

The influence of scanning speed on jet electrodeposition mainly has two aspects. First, the scour effect due to movement affected the growth of the coating, and the speed of the scanning movement of the nozzle affected the deposition amount of each position of the coating. Scanning electron microscopy was used in observing the surface morphology of the coating centre at different scanning speeds, as shown in Fig. 9. When the scanning speed was 200 mm/min, the surface of the coatings showed obvious and large cellular structures with clear boundaries and uneven structures. When the scanning speed of the nozzle was increased to 400 mm/min, the grain size decreased obviously. When the scanning speed was 600 mm/min, the grain size of the sediment surface continued to decrease, and the cellular structure was uniform, smooth and compact. When the scanning speed of the nozzle continued to increase to 800 and 1000 mm/min, the grain size was basically the same as that at 600 mm/min, indicating that the effect of increase in scanning speed on the grain size of the coating was limited. However, cracks, holes and other defects appeared on the surface of the coatings.

The reason was that when the scanning speed decreased, the working time of the current in the area directly under the nozzle is longer, and the grain fully grew, with the increase of scanning speed, the electric field action time in the area directly under the nozzle is short, and the metal
ions are not sufficiently deposited on the surface of the substrate, so the crystal grains formed are relatively small. In addition, the increase in the number of scans in the same time period results in the formation of more grains in the area directly under the nozzle, so increasing the scanning speed has a role in grain refinement. However, when the scanning speed was extremely high, change in the flow field distribution force in the working area was

![Diagram showing section thickness of the coating at different scanning speeds](image_url)

Fig. 11 Section thickness of the coating at different scanning speeds

| Scanning speed |
|----------------|
| 200 mm/min |
| 400 mm/min |
| 600 mm/min |
| 800 mm/min |
| 1000 mm/min |

Table 3 Error between numerical solution and process experiment

| Scanning speed | −5 mm | −2 mm | 0 mm | 2 mm | 5 mm |
|----------------|-------|-------|------|------|------|
| 200 mm/min     | 23.89%| 14.89%| 12.69%| 13.91%| 24.48%|
| 400 mm/min     | 24.22%| 15.60%| 12.82%| 15.80%| 22.72%|
| 600 mm/min     | 25.42%| 12.94%| 11.99%| 13.07%| 25.51%|
| 800 mm/min     | 25.74%| 10.30%| 11.15%| 11.34%| 24.34%|
| 1000 mm/min    | 40.52%| 18.38%| 16.75%| 17.97%| 39.26%|
accelerated, resulting in the flow field disorder. The fluid stability of the substrate surface was reduced, and various defects formed on the surface of the coating. Therefore, appropriate scanning speed improves coating quality.

### 4.2 Thickness of the section

Three tests were performed at each scanning speed parameter, and the coating thickness was measured at five locations with the help of a scanning electron microscope. The collated data are shown in Fig. 10, and the section thickness of a group of coatings is shown in Fig. 11. The experimental results showed that the coating thickness increased and then decreased with increasing scanning speed, and the thickness growth law was consistent with the numerical solution results. Coating growth was uniform, and the thickness was symmetric at the centre. When the scanning speed was low, the coating thickness was uniform and smooth. When the scanning speed was fast, the coating thickness uniformity was low. However, owing to the limitation of machining efficiency, gaps between the actual thickness and the numerical results were obtained. The error between each point is calculated according to the formula \( \delta = 1 - \frac{T_n}{T_e} \), where \( T_n \) represents the coating thickness obtained by numerical solution and \( T_e \) represents the coating thickness measured by process experiment. The data sorted out are shown in Table 3. Therefore, the average error of this experiment is 19.43%.

### 4.3 Microhardness

Different points were randomly selected on the prepared samples for the measurement of the microhardness of the coating. Microhardness was measured 10 times for each parameter, and the average value was obtained. The microhardness of the coating at different scanning speeds is shown in Fig. 12. The hardness reflects the ability of the material to resist local plastic deformation. In this experiment, with the increase of scanning speed, the hardness first increases and then decreases [31]. When the scanning speed was 600 mm/min, maximum hardness of 622.82 HV, scanning speed of 200 mm/min and hardness of 528.68 HV were obtained. Figure 9 shows that the thickness of the coating on the surface of the grains increased, thus decreasing hardness at a low scanning speed. As scanning speed increased, coating grain size was refined, dense
surface levelled off, surface roughness was reduced and hardness increased. As scanning speed further increased, the coating surface cracks, holes and other defects increase and hardness decreases. Therefore, the factors affecting the microhardness of the coating are mainly grain size and surface quality of the coating.

### 4.4 Wear resistance

Figure 13 is the 3D section diagram of wear marks at different scanning speeds. Table 4 shows the specific parameter values. The cross-section parameters were inversely proportional to wear resistance. As indicated in Table 4, as scanning speed increased, the cross-section parameters decreased and then increased, indicating that the wear resistance of the coating improved first and then deteriorated. When the scanning speed was 200 mm/min, the highest values of the three cross-section parameters of the coating were obtained. The cross-section width was 498.61 ± 9.17 μm, the cross-section height was 16.86 ± 0.82 μm and the cross-section area was 4904.97 ± 57.57 μm². At a scanning speed of 600 m/min, the cross-section parameters of the coating were obviously smaller than those at other scanning speeds. The cross-section width was 389.88 ± 7.98 μm, the cross-section height was 10.61 ± 0.73 μm and the cross-section area was 2766.75 ± 58.80 μm². The wear resistance of the coating was mainly affected by the hardness and grain size of the coating. Surface quality increased with decreasing grain size, and the wear resistance of the coating increased with hardness.

### 4.5 Corrosion resistance

Figure 14a is the polarisation curve of nickel-based coating prepared at different scanning speeds. The values of self-corrosion potential ($E_{corr}$) and self-corrosion current density ($I_{corr}$) of the coating at different scanning speeds are shown in Table 5. The scanning speed showed considerable influence on the self-corrosion potential and self-corrosion current density. When the scanning speed increased from 200 mm/ min to 600 mm/min, the self-corrosion potential increased, and the self-corrosion current density decreased. As the scanning speed continued to increase, the self-corrosion potential decreased, and the self-corrosion current density increased. The impedance spectrum graph in Figure 14b shows the relationship between the impedance and frequency of the coating at different scanning speeds. The impedance increased with increasing frequency, indicating that the coating had good corrosion resistance at different scanning speeds.
potential of the coating decreased, and the self-corrosion current density increased. When the scanning speed was 600 mm/min, the coating had the highest self-corrosion potential (−0.33 V) and the lowest self-corrosion current density (5.16E-7 A cm²), indicating that the coating had good corrosion resistance. The reason was that the coating surface grains were small and compact. The coating had good quality and maximum thickness at this scanning speed. When the scanning speed was 1000 mm/min, the coating had the lowest self-corrosion potential (−0.77 V) and the highest self-corrosion current density (1.04E-5 A cm²), indicating that the corrosion resistance of the coating was poor. These reasons were the formation of fine chips, cracks, holes and other defects on the coating surface and poor quality of the coating surface, which greatly reduced the corrosion resistance of the coating. When the scanning speed was 200 mm/min, the corrosion performance of the coating was poor according to the self-corrosion potential (−0.65 V) and self-corrosion current density (1.36E-5 A cm²) because the surface grain of the coating was large despite that the coating had no obvious surface defect, and the hardness and wear resistance of the coating were poor. These characteristics increased the vulnerability of the coating to corrosion products.

Figure 14b shows impedance curves of the nickel-based coatings at different scanning speeds. The capacitive arc radius represents the impedance value of the coating. The strength of the corrosion resistance of the coating increased with the radius. The figure was attached with equivalent circuit, wherein \( R_s \) represents the equivalent resistance of the NaCl solution, \( R_p \) represents equivalent resistance of 45 steel matrix, constant phase angle \( CPE_1 \) is related to double electric layer capacitance of matrix, \( CPE_2 \) is related to double electric layer capacitance of the coating reaction and \( R_t \) represents equivalent resistance of coating, which is an important parameter of resistance of coating to electrolyte corrosion [32]. As scanning speed increased, the resistance of the coating increased and then decreased. When the scanning speed was 600 mm/min, the resistance of the coating reached 4660 Ω, which had the best corrosion protection effect on the workpiece. At 1000 mm/min, the coating had the lowest impedance value of 1882 Ω, which showed the worst corrosion resistance because obvious defects appeared on the surface of the coating and the surface quality was poor, which led to the insignificant corrosion protection effect of the coating.

### Table 5  Electrochemical corrosion parameters of nickel-based coatings at different scanning speeds

| Scanning speed | Self-corrosion potential (V) | Self-etching current density (A cm²) |
|----------------|-----------------------------|--------------------------------------|
| 200 mm/min     | −0.65                       | 1.36E-5                              |
| 400 mm/min     | −0.37                       | 7.99E-6                              |
| 600 mm/min     | −0.33                       | 5.16E-7                              |
| 800 mm/min     | −0.71                       | 1.58E-5                              |
| 1000 mm/min    | −0.77                       | 3.04E-5                              |

5 Conclusion

In this paper, an experiment for the jet electrodeposition of a nickel-based coating was carried out, and the multi-physical field coupling model of deposition process was established and numerically solved. The relationship between process experiment results and numerical solution was established by evaluating coating thickness. The coating was characterised and tested, and the influence of scanning speed on coating properties was examined. The results were as follows:

1. The numerical solution results of the jet electrodeposition COMSOL software showed that the coating thickness increased and then decreased with increasing scanning speed. When the scanning speed was 600 mm/min, the maximum thickness was 30.28 μm.

2. Scanning electron microscopy results showed that when the scanning speed was 200 mm/min, the surface grain size of the coating prepared through jet electrodeposition was large, and the boundary was clear. As scanning speed increased, grain size decreased. At scanning speed of 600 mm/min, the coating surface showed fine grains and a compact structure. When it reached 800 and 1000 mm/min, the coating surface showed obvious cracks and other defects, and the surface quality was poor. The thickness growth of the electrodeposited coating was consistent with the numerical solution, which verified the accuracy of the simulation.

3. The microhardness and wear resistance test showed that at 600 mm/min, the microhardness of the coating reached a maximum value of 622.82 HV, the cross-section area of the wear mark had a minimum value of 2766.75 ± 58.80 μm² and the best wear resistance was obtained. The grain size considerably affected the microhardness and wear resistance. The maximum grain size was obtained at 200 mm/min, the lowest microhardness was 528.68 HV and the worst wear resistance was achieved. The cross-section area of the wear marks was 4904.97 ± 57.57 μm².

4. Corrosion resistance analysis results show that at 600 mm/min, the coating had the highest self-corrosion potential, the lowest self-corrosion current density and the largest arc radius, showing the best corrosion resistance. At 1000 mm/min, the coating had the lowest self-corrosion potential, the highest current density and the lowest arc radius, showing the worst corrosion resistance. The surface quality of the coating greatly influenced the corrosion resistance of the coating.
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Availability of data and material All data and material are true and valid, available.

Declarations

Ethics approval Not applicable.

Consent to participate All authors agree to participate.

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