ELECTROMAGNETIC CONTROL OF ELECTROPLATING

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Introduction. In many electrochemical processes, mass transfer is the rate-controlling mechanism for a high voltage between the electrodes. This is the case in e.g. continuous electroplating processes for mass production of various products. A well-known example is the reel-to-reel electroplating of gold on electrical connectors. In electroplating the near wall hydrodynamics is crucial as it controls the diffusive boundary layers transport of electro active species to the body to be coated. When plating individual work pieces like cylindrical connectors, forced convection usually distorts the distribution of the deposit and produces a significant difference between the thickness of the deposit layer between the upstream and downstream part of the cylinder [1, 2]. To compensate this disadvantage, turbulent lateral jets may improve the results [2]. Such jet may improve the rate of transfer but not satisfactory solve the non-uniform distribution of the deposit. An impose swirling motion around the cylinder should solve the problem but it is hard to envisage a circulation around each cylinder in an array being set up by some mechanical device. This paper presents a different strategy to reduce the level of inhomogeneity of the deposit by using an imposed low-frequency magnetic field.

The effect of magnetic field application in electrochemistry is well known now as essentially based on the acceleration of overall mass transfer process induced by the Laplace/Lorentz force that arises from the interaction between the electrolytic current and the magnetic field. The effect of an imposed magnetic field on electrolysis can somewhat crudely be subdivided into four classes: electrodes-process kinetics, thermodynamics properties, surface morphology and mass transfer. In the present work, the effect of magnetic field on mass transport and its coupling with a simple reaction mechanism at a cylindrical electrode are examined. These effects are caused by a modification of the Laplace/Lorenz forces that arise from the interaction of the magnetic field and the electric current. The possibility to use an alternate magnetic field to impose an alternate fluid flow around a cylindrical connector and thus to control the diffusive layer is examined here for the first time and could open the door to the use of the magnetic field in a large range of situations to solve some difficult problems of mass transfer, for example, by imposing a local predefined deposit.

1. Position of the problem. In classical elecro-deposition around cylindrical connectors, the deposit is operated in a channel of some centimetres in width and height and some meters long, the continuous moving of the cylindrical connectors of 1mm to 1 cm in diameter being very low, some cm/s, and characterised by a low Reynolds number. The two lateral parts of the channel constitute the two anodes when the cylindrical connectors are the cathodes on which a gold layer is deposited (Fig. 1).

Even if some turbulence is superimposed to the mean flow, the numerical calculation of mass transfer on a isolated cylinder in such situation characterised by

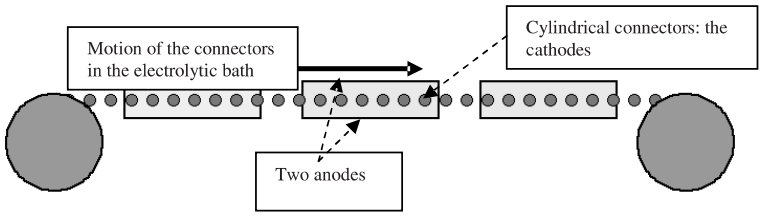

Fig. 1. Typical configuration of the gold electrodeposition on cylindrical connectors.

the well know von Karmann eddies street downstream the cylinder reveals a strong inhomogeneity (Fig. 2*a* and *b*) that is in good agreement with the measurement of the gold deposit operated by an industrial company [1].

This inhomogeneity results in the difference between the boundary layers thickness δ_ν (and in the diffusive layers thickness δ_D) from the upstream and downstream flow. At first these two layers are connected by the Schmidt number (Sc) [3]:

$$\frac{\delta_\nu}{\delta_\mathrm{D}} = \mathrm{Sc}^{\frac{1}{3}}$$

Consequently, the inhomogeneity of the hydrodynamics boundary layers produces an equivalent inhomogeneity of the mass transport and then of the thickness of the deposit. The objective of the present work is to determine the possibility given by the use of magnetic field to reduce this inhomogeneity and, if possible, to improve the rate of the mass transfer. A first solution is to superimpose a vertical homogeneous magnetic field (Fig. 3*a*) to create a tangential filed of force able to generate a rotating flow motion reducing the level of inhomogeneity [4]. Nevertheless, this solution does not give the expected results essentially due to the confinement effect of the channel walls generating a pressure distribution which acts on the flow distribution. The only result was characterised by an angular shift of the stagnation point and an angular displacement of the inhomogeneity. The main idea subtending the approach considered in this work consists in replacing the DC vertical magnetic field by a low-frequency AC magnetic field [4] (Fig. 3*b*).

Thus by choosing an appropriate frequency (characterised by period T) sufficiently low to permit the diffusion process and sufficiently high to induce several reversions of the magnetic field during the displacement inside the channel, it seems possible to reduce the level of inhomogeneity around the cylindrical connector.

2. Formulation of the problem. The mass transfer problem is governed by the following set of equation [4], in which the non dimensional variables are hereafter defined: typical length scale: D – the diameter of the connector; typical

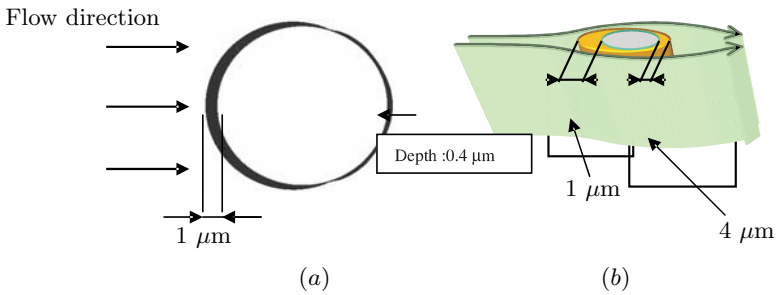

Fig. 2. (*a*) Calculation of the gold deposit thickness resulting from the numerical approach of P. Olivas [1] compared with (*b*) the measured thickness in a real industrial configuration operated by the Framatome Connectors society.

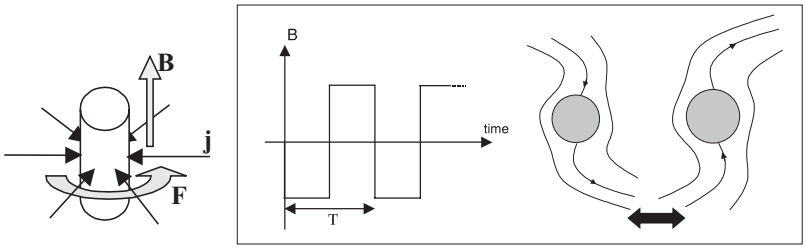

Fig. 3. (*a*) Configuration of the magnetic field giving tangential distribution of electromagnetic forces. (*b*) Principle used to induce the alternative flow motion from an AC low frequency magnetic field.

velocity U_0 – the travelling velocity of the connector inside the channel; typical concentration C_0 – the concentration at infinity of electroactive species, so the dimensionless form of the concentration write $c = C/C_0$ – typical pressure ρU_0^2, ρ being the volumic mass of the electrolyte; the intensity of the magnetic field is reported to B_0 the applied magnetic field intensity; the reference potential is chosen to be $f_0 = nFDC_0/\sigma$. Thus the set of equations writes:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2\mathbf{u} - \frac{M_\mathrm{D}}{\mathrm{Re}^2\mathrm{Sc}}\nabla f \times \mathbf{B}$$

$$\frac{\partial c}{\partial t} + \mathbf{u}\cdot\nabla c = \frac{1}{\mathrm{Pe}}\nabla^2 c\,, \quad \partial^2 f = 0\,.$$

These equations reveal three non-dimensional numbers that characterise the flow and mass transfer problem: the classical Reynolds number $\mathrm{Re} = \dfrac{\rho U_0 D}{\mu}$, the Peclet number: $\mathrm{Pe} = \dfrac{U_0 d}{D}$, the magneto diffusion parameter: $M_\mathrm{D} = \dfrac{nFC_0B_0D^2}{\mu}$ that characterises the magnetic field effect. With this definition the Schmidt number appears to be the ratio of the Peclet number to the Reynolds number. Its value in the electrochemical system is generally comprises between 1000 and 10 000 and thus the diffusive layer is more than 10 times lower than the hydrodynamics boundary layer. The function $f = f/f_0$, which appears in the expression of the Laplace/Lorentz force is the dimensionless form of the so call "effective potential" f and characterises the induced electric current calculated by the following Ohm law valid for the electrochemical system

$$\mathbf{j} = -\sigma\ \mathrm{grad}\left(\frac{nFD}{\sigma}C + \Phi\right) = -\sigma\,\mathrm{grad}\,f\,,$$

with Φ being the applied electric potential. Let us remark that the Navier–Stokes equation and the mass transport equation are completely coupled and must be

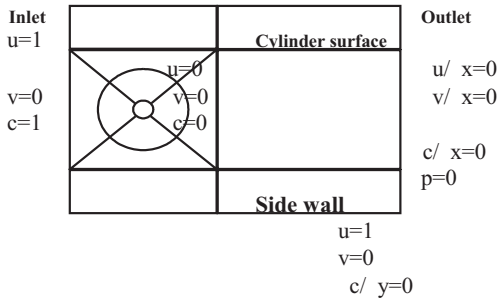

Fig. 4. Boundary conditions of the problem.

minimum value: (x 7)
total amount of deposited metal:
+ 36%

Fig. 5. Enlarged deposit layer thickness. Limiting current, Re = 10, alternative magnetic field with $T = 200$ and $\frac{M_{\mathrm{D}}}{\mathrm{Re}^2\mathrm{Sc}} = 0.05$.

solved simultaneously that is different from the classical mass transport problem, where the Navier-Stokes equation does not depend on the concentration and can be solved independently.

3. Boundary conditions. The boundary conditions are expressed in a frame linked to the cylindrical connector. This means that the connectors is supposed at rest when the fluid is moving with a velocity U_0 (it is contrary to reality). On the other hand, it is assumed that it is the gradient of electro active species that controls the current density in the vicinity of the connector (i.e., the cathode) that can be written in the form:

$$\left[\mathbf{n} \cdot \operatorname{grad} f = \mathbf{n} \cdot \operatorname{grad} c\right]_{\text{at the cathode wall}}$$

Other boundary conditions are represented in Fig. 4 hereafter. They suppose that far from the cylinder the concentration distribution is equal to Co and that the electric current at the two anodes is controlled by the electric field.

4. Results and discussion. The solution was found numerically by using the CFX 4.3 code [5]. The solution methodology is based on the finite-volume discretization of the transport equation and the continuity equation for an incompressible fluid, resulting in a discrete set of equations for velocity, pressure and concentration. By the chosen properly main parameter that controls the problem and by imposing a non dimensional time T characterising the period of oscillation of the imposed magnetic field greater than the diffusion time of the electro active species but lower than the travelling time of the connectors inside the channel, it is possible to reduce strongly the inhomogeneity of the gold deposition. One of the main results can be seen in Fig. 5, exhibiting a well homogeneous repartition in the thickness of the deposit as well as an improving of the rate of transfer.

It can be concluded [4] that by using a magnetic field it is possible to considerably improve the kind of industrial electroplating processes. One should also be aware of the fact that, as observed in many experiments, the use of the magnetic field improves the metallurgical structure of the deposit.

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