



Influence of constant magnetic field on electrodeposition of metals, alloys, conductive polymers, and organic reactions

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Abstract

The paper presents and summarizes some research on constant magnetic field effects in chemistry. Metals and alloys electrodeposited under constant magnetic field have greater thickness and smoother surface with finest grains. Metallic materials deposited under the influence of uniform magnetic field may have stronger corrosion resistance, than those obtained without the presence of magnetic field. Constant magnetic field also causes an increase of the electropolymerization rate and yield of some organic reactions. Our research also shows that the presence of constant magnetic field affects the electrodeposition process of alloys and their morphology to a great extent. The effects of magnetic field on metals, alloys, composites, polymers and other materials are due to the Lorentz force and the magnetohydrodynamic effect. It is possible that the further development of magneto-electrodeposition will allow for using the constant magnetic field to improve the properties of metal coatings, alloys, polymers, and other materials in the industry.

Keywords Constant magnetic field (CMF) · Electrodeposition · Electropolymerization · Magnetohydrodynamic effect · Organic reactions

Introduction

Effects of constant magnetic field on electrolysis have been studied for 40 years [1] on such objects as metals, metal alloys, composites, and polymers.

A number of reviews of magnetic field effects have been published during the 40 years of research including very helpful reviews by Fahidy of 1973 [2] and 1983 [3]. The author explained and reviewed the effects of magnetic field on the properties of electrolyte, electrode kinetics, mass transport, and changes in electrodeposited metal properties. Almost 20 years later, Fahidy wrote another paper in which he reviewed constant magnetic field effects on metal surfaces. In 1995, Tacke and Janssen [4] published a review “Applications of magneto-electrolysis” in which they described practical applications of magnetic field in

electrochemistry. In 2014, Monzon and Coey [1] wrote a review paper about Lorentz force and its influence on electrodeposition. The aforementioned review works are invaluable for any scientist who works with constant magnetic field. However, in the recent years, scientists have carried out many new studies which are not included in the previous review papers. Analyses and summaries of this recent research may lead to a better understanding of magnetic field effects on chemical processes. The aim of this paper is to present and summarize the most important discoveries and research on the effects of constant magnetic field on the selected compounds and to verify how the magnetic field affects the properties of metals, alloys, polymers, and other materials, thus to describe these phenomena and establish the reasons for them. Our paper also aims to popularize magneto-electrochemistry, which is still a little known field of chemistry, in the scientific community.

Studies described in this paper prove that the application of constant magnetic field in electrodeposition processes offers many possibilities. Along with the development of science, we find that magneto-electrodeposition makes it possible to obtain improved properties of deposits or to reduce the electrodeposition time. The forces and phenomena arising during the electrodeposition under constant magnetic field are not yet

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fully understood and described, but researches still develop new explanations and equations and also look for new applications of magnetoelectrolysis. The subject of magnetic field effects is very wide. In addition to uniform magnetic field effects, researchers also study non-uniform magnetic fields and possibilities of their influence on chemical processes [5–7]. Inhomogeneous magnetic fields may cause changes in fluid flow, concentration, and convection [5]. Because of the wide scope of the subject, our paper focuses only on uniform magnetic field.

The effect of magnetic field on electrolysis may be due to its influence on mass transport, reaction kinetics, or metal deposition/dissolution. The first phenomenon which explains the effects of magnetic field, due to mass transport, is magnetohydrodynamic effect (MHD effect). In Moffatt's paper [8], we read that MHD phenomena are caused by the interaction of velocity fields with electromagnetic fields. MHD effect is connected with "effects that arise through the interaction of the motion of the fluid and any ambient magnetic field." The Lorentz force (F) is the total force, which acts on a charged molecule moving in an electromagnetic field and is expressed by the equation:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (1)$$

where q is charge on a particle, which velocity is v , E is electric field strength vector, and B is magnetic field flux density vector [4]. That force causes the increase of mass transport effect in the solution. The Lorentz force causes movement of the electrolyte which is near to the electrode surface due to the convective flow of the whole volume of the electrolyte. It causes a decrease in the thickness of the Nernst layer which is connected to the increase of the limiting current density.

Under the influence of constant magnetic field, Navier-Stokes hydrodynamic layer is formed. The Navier-Stokes layer has an impact on the flow velocity of electroactive species to the working electrode.

The effects of magnetic field may also be connected with electrokinetic-magnetohydrodynamic effect. It only concerns the diffuse double layer in the vicinity of the electrode. Under magnetic field, the charge moves across the diffuse double layer and this movement creates nonelectrostatic field. The force which acts in the double layer is an electrokinetic force (F_{EK}):

$$F_{EK} = \frac{\sigma_d E_{\parallel}}{\delta_0} \quad (2)$$

where σ_d is the charge density of the diffuse layer, E_{\parallel} is the induced nonelectrostatic field, and δ_0 is the boundary layer thickness [9, 10]. The electrokinetic force causes, like in the case of Lorentz force, the induction of convection in the solution [11].

Another force due to magnetic field is a paramagnetic gradient force (F_p):

$$F_p = \chi_m \frac{B^2}{2\mu_0} \vec{\nabla} c \quad (3)$$

where χ_m is the molar susceptibility of the ions, $\vec{\nabla} c$ is concentration gradient vector, and μ_0 is the permeability of free space. O'Reilly and Hinds [9, 10] predicate that the paramagnetic gradient force causes the movement of magnetic ions in the diffusion layer. The ions move in directions which are opposite to the applied magnetic field. However, the most important role in the diffusion layer is the concentration gradient force, which is a driving force for diffusion. The paramagnetic force, which is present only in the diffusion layer, acts in parallel to the driving force for diffusion. In aqueous electrolytes at the room temperature, the typical values of paramagnetic force and driving force for diffusion are 10^4 and 10^{10} N/m³ [11], respectively. Therefore, the ratio of these two forces may be negligible. Hinds and Coey [11, 12] published studies which show that the paramagnetic force does not cause any visible effects in electrochemistry.

In the paper about electrodeposition, it is necessary to write about the hydrogen evolution. This phenomenon accompanies each electrode reaction in the aqueous media and can change the properties of deposits. Hydrogen formed during the electrochemical reaction may deteriorate the properties of the electrodeposited metals or alloys. The atomic hydrogen, formed on the surface of the coatings, is adsorbed and evolves into molecular hydrogen. Recombination of atomic hydrogen to the molecular form generates pressure and causes fractures in the surface of the obtained metals or alloys. This phenomenon is called hydrogen embrittlement. Even small amounts of hydrogen in the coating spaces can increase the brittleness of metal or alloy. Constant magnetic field is a factor which increases the production of hydrogen [13]. The influence of hydrogen evolution on coating surface depends on orientation of the electrode and magnetic field. An electrode in downward horizontal facing orientation is more exposed to the attachment of hydrogen bubbles. A magnetic field which is perpendicular to the current density lines causes the surface of the electrode to be more susceptible to attachment of hydrogen bubbles [14].

Metals

Some of the electrolytically obtained materials are metal coatings. In order to deposit a metal on the surface of the electrode, it is necessary to apply such voltage that will generate the overpotential. The electrodeposition of metals can be divided into three steps:

- Providing ions to the diffusion layer
- Transition of electrons through electrolyte—electrode phase boundary and electrochemical reduction of ions and adsorption on the surface of the electrode
- Electrocrystallization—transfer of the species onto the electrode surface and growth of the coating structure

The rate of electrodeposition process is determined by the slowest step. Therefore, if the first step is the slowest one, the process is a mass transport-controlled reaction. If the charge transfer step is the slowest one, the reaction is controlled kinetically [15].

Metal coatings are commonly used for protection against corrosion and mechanical damage of various materials. Metal electrodeposition is useful in many industries: in the medical industry (manufacturing of surgical or dental instruments), in electroplating industry (strengthening of the working parts of machines), or in jewelry production (as decorative coatings). New applications of the metal electrodeposition emerge together with the technological development. Thin metal films, metal nanostructures, and alloys may be used in fabrication of thermoelectric devices, such as coolers and power generators [16]. Metal surface modification processes, such as titanium anodizing, are widely used in the medical industry [17]. Controlling the electrodeposition parameters can allow to obtain different properties of the metal coatings. Constant magnetic field applied during metal electrodeposition may cause changes in the electrolysis process and in the deposit properties; therefore, there are many possibilities for its usage in almost every area in which electrodeposition is used. In this section, the issue of how the application of constant magnetic field affects electrodeposition process and received coatings will be discussed.

Diamagnets

Copper

In 1998–2001, G. Hinds et al. [10, 18, 19] published works concerning magnetic field effects on copper electrolysis. The aim of those studies was to investigate the influence of constant magnetic fields on the electrochemical behavior of Cu^{2+}/Cu redox system in an aqueous medium. At LSV (linear sweep voltammetry) voltammograms recorded in $\text{pH}=0.5$ and 3.5 , the current density was observed to increase with the increase of magnetic field magnitude in the mass transport regime on the cathodic and anodic branch. Similar requests were obtained in 2007 by Matsushima and coworkers [20]. They investigated copper potentiostatic electrodeposition from $1.85 \text{ M H}_2\text{SO}_4$ and 0.6 M CuSO_4 with a sheet of copper as an anode. Electrodeposition of

copper was carried in the magnetic field up to 5 T . The authors divided the obtained polarization curve into three areas:

- *Activation area* at the cathodic potential ($-\eta \leq 130 \text{ mV}$)
- *Mass transport area* at the current plateau
- *Hydrogen evolution area* at hydrogen evolution ($-\eta > 500 \text{ mV}$).

In the first area, there are no effects of magnetic field on the current changes. In the second regime, in the applied magnetic field, plateau starts at more negative cathodic potential, and the limiting current density increases significantly. In the third area, if the magnetic field is applied, hydrogen starts to evolve at more anodic potential.

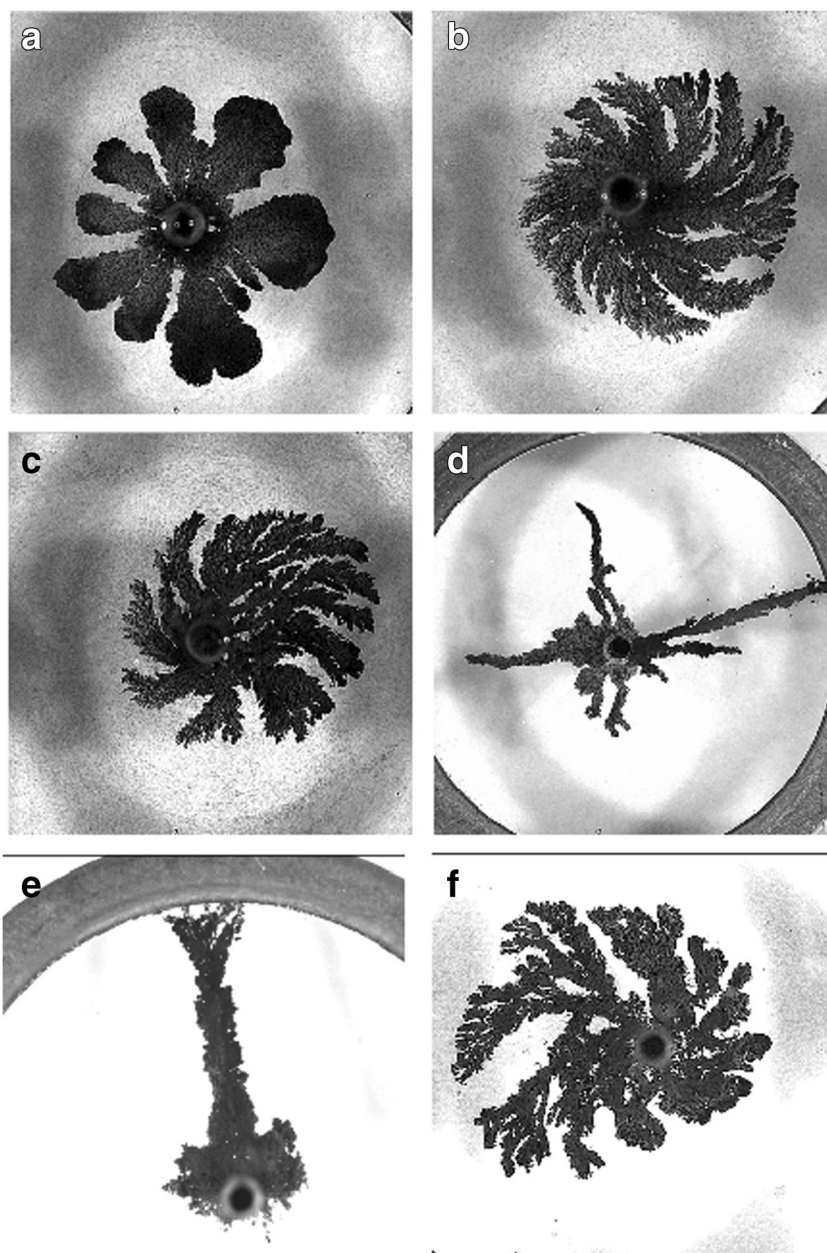
The effect of magnetic field on copper electrodeposition is noticeable in all papers described above [10, 18–20]. In order to investigate the effects of constant magnetic field on the surface morphology of the copper electrodeposited on glassy carbon electrode from CuSO_4 at $\text{pH}=0.5$ Hinds et al. [10] used SEM. It can be observed that copper films which are electrodeposited in the presence of a magnetic field have a rougher surface than those which were obtained in the absence of a magnetic field. XRD spectra showed that there is no appreciable effect of the field on the crystal structure and texture of the electrodeposited copper. Interesting results, shown in Fig. 1, were obtained by observation of fractal electrodeposits formed in the absence and presence of the magnetic field. Those studies were also published in 1999 [21] by the same scientists. To form the copper electrodeposits, 0.2 M CuSO_4 and the magnetic field in the range from 0.4 to 1 T were applied. Fractal electrodeposits that grew without magnetic field have dense radial shape. The shape of the electrodeposits formed in the presence of the field depends on the direction of fractal growth and the direction of the applied magnetic field.

In studies conducted by Matsushima and other scientists in 2007 [20], it was found that the size of copper grains decreases under magnetic field but the influence of intensity of the magnetic field depends on the cathode potential. The morphology of electrodeposits obtained at -60 mV potential differs from deposits obtained at -400 mV . As shown in Fig. 2, in the case of -60 mV potential, deposits are more dense and flatter than in -400 mV , where three-dimensional columns are formed.

Zinc

Similar effects as those observed for copper are described in Rhen's paper concerning zinc chronoamperometric electrodeposition [22]. The effects of 1.5-T magnetic field on zinc electrode in various solutions were studied. The electrode

Fig. 1 Electrodeposits of copper in various orientations of cell and magnetic field—in a horizontal flat circular cell: **a** without magnetic field, **b** under 0.4-T upward magnetic field, **c** under 0.8-T downward magnetic field, **d** under 1-T horizontal magnetic field, in the same cell oriented vertically: **e** without magnetic field and **f** in 1 T perpendicular to the plane of the cell magnetic field. Reprinted from [21], with permission of EDP Sciences



was investigated in ZnSO_4 —there was no effect of magnetic field, because of not sufficiently corroding properties of the solution. There was no effect of magnetic field also in the case of cathodic reaction in H_2SO_4 solution, which is not mass transport limited. Significant influence of the applied field on the increase of the limiting current and current density was observed in CuSO_4 and KNO_3 —in both solutions, cathodic reactions were mass transport limited.

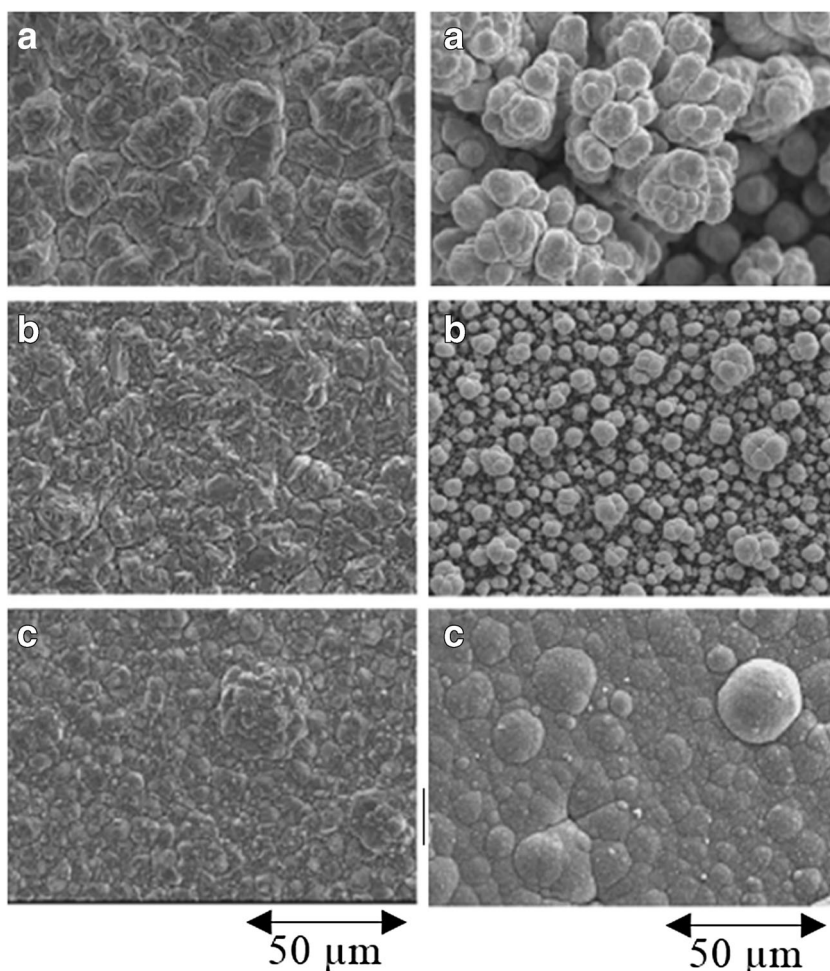
Heresanu and coworkers [23] investigated ramifying growth of zinc under 0.2-T magnetic field. When the magnetic field was directed in parallel to the plane of zinc growth, there were no changes. In perpendicular magnetic field, zinc electrodeposits had spiraling morphology.

Silver

In 2012, Aaboubi and Douglade [24] studied the chronopotentiometric process of silver cementation from AgNO_3 and KNO_3 solution on copper and zinc working electrodes under 1.2-T magnetic field. The results showed that the silver deposition time on copper electrode decreased in the case of electrodeposition under magnetic field, but there was no effect on the zinc electrode.

In the described studies, several effects of magnetic field on electrodeposition process were observed. There were effects of magnetic field on mass transport-controlled regimes and no effects on the reaction kinetics. Firstly, in cases of all diamagnetic metals under magnetic field, the current density

Fig. 2 Copper electrodeposits obtained at the potential -60 mV (left) and -400 mV (right) under 0 T (a), 3 T (b), and 5 T (c). Reprinted from [20], with permission from Elsevier



increased. The second effect that was discovered in the described studies is the change in morphology of the electrodeposits. The deposits of copper are less dendritic under the magnetic field [20], which can be caused the nature of electrochemical process. Dendritic structure is connected with full diffusion-control processes, which means that the structure obtained under magnetic field is due to mixed-control process [25]. An interesting effect of the magnetic field is the shape of obtained fractal deposits of diamagnets. Effects of magnetic field on growth of fractal electrodeposits depend on orientations of applied field. Patterns of fractal electrodeposits are the result of Lorentz force and natural convection acting [10]. Chirality of these patterns depends on the direction of the applied field. Fractal deposits are chiral when magnetic field is perpendicular to the area of their growth and when the magnetic field is in the plane; their patterns are asymmetrical [19]. Both electrochemical and morphological changes in electrodeposition of diamagnets are due to the increase of mass transport rate under the influence of magnetic field. The decrease in current density is caused by the convective flow of electrolyte near to the electrode surface and the decrease of the Nernst layer. The limiting current density (I_L)

depends on the strength of the magnetic field. For many years, scientists have been trying to find the comprehensive equation of limiting current density on magnetic field strength. It is obvious that the equation is influenced by different parameters of the applied system. Semi-empirical equations have different forms, depending on applied material system. The equation given by Leventis [26] for disc millielectrodes system is

$$I_L = (4.3 \times 10^3) n^{3/2} A^{3/4} D \nu^{-1/4} C^{*4/3} B^{1/3} \tag{4}$$

where n is the number of electrons involved in the Faradaic process, A is electrode area, D is diffusivity of the electrolyte, ν is kinematic viscosity, C is bulk concentration of the electroactive species, and B is the strength of the magnetic field [27]. Equations with $I_L \sim B^b$ dependence with different values of b were presented for example by Aogaki [28], and others with b values within the range of 0.25 to 1.6 [27]. Recent research on this subject, conducted by Sudibyo and Aziz in 2015 [29] for lead magneto electrodeposition, gave the following equation of limiting current density:

$$i_B = K' C^{1.271} A^{0.743} D \nu^{-0.673} B^{0.33} \tag{5}$$

where K' is a constant (and the Faraday constant F is included in K'), C is the concentration of the electroactive species, A is the electrode area, D is the diffusion coefficient of the electroactive species, ν is the kinematic viscosity of the electrolyte, B is the magnetic field strength, and n is the number of electrons of the oxidation-reduction reactions.

Paramagnetics

The case of electrodeposition of paramagnetics is unusual—most of these metals cannot be deposited alone from their aqueous solutions [30]. One of them is tungsten—direct reduction of its oxide is impossible because of low overvoltage for hydrogen evolution. The only way to obtain tungsten through electrodeposition would be by blocking the formation of hydrogen through changing the parameters of electrodeposition. However, this kind of blocking of hydrogen formation would cause changes in thermodynamic and kinetic properties, so this way is pointless [31]. It is possible to electrodeposit paramagnetic metals (such as zirconium, tungsten, molybdenum, germanium) by induced codeposition [31] as alloys with other metals [32]. The codeposition of paramagnetic metals, which cannot be deposited without other metals, will be described in the chapter concerning alloys.

There are paramagnetics, for example chromium, platinum or tin, which can be electrodeposited from their aqueous solutions. Unfortunately, there are hardly any publications, which describe the effects of constant magnetic field on electrodeposition of paramagnetics. The following example of tin is the only exception.

Tin

In 2015, Uzir et al. [33] investigated the influence of 0.3-T magnetic field on electrodeposition of tin dendrites using chronoamperometry. They used platinum plates as the working electrodes and they deposited tin from SnSO_4 and H_2SO_4 solution with additives (such as $\text{NaC}_6\text{H}_{11}\text{O}_7$, Na_2SO_4). They observed that the limiting current increased under the influence of magnetic field. The shape of fractal electrodeposits was wider in the case of electrodeposition with constant magnetic field. In SEM images, which are shown in Fig. 3, it is visible that crystals obtained with the presence of magnetic field create agglomerates. The surface of the tin film is denser and smoother than in the absence of magnetic field.

The case of tin shows that the effects of magnetic field on paramagnetic metals are similar to diamagnets. In both of them, it was observed that the limiting current increases, which can be explained by Nernst layer depletion, as in the case of diamagnets. The dendritic shape of paramagnetic tin crystals obtained under the influence of magnetic field was similar to the shape of copper electrodeposits. In both cases,

the deposits formed in the presence of constant magnetic field were denser and smoother. It is impossible to draw any conclusion based only on this single study, but it can be stated with caution, that the effects of constant magnetic field on paramagnets electrodeposition are similar to the effects it exerts on diamagnetic metals.

Because of the difficulties in obtaining paramagnetic metals, the metal anodizing process deserves attention. This process involves electrolytic formation of oxide film on the metal surface. One of the common applications of this process is titanium anodizing.

Titanium

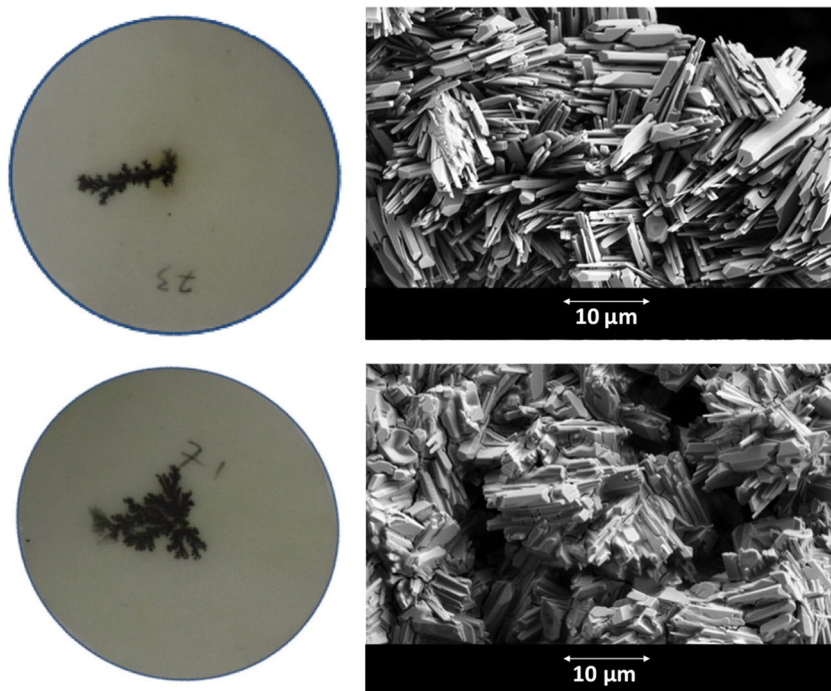
Titanium is a paramagnetic widely used in medicine. Because of its properties, this metal is commonly used as an implant material. To improve its properties, such as corrosion resistance, titanium anodizing is performed. In 2016, Kozuka et al. studied anodizing of titanium under the influence of 1-T constant magnetic field [17] in the potentiostatic mode. The results of that study show that magnetic field applied during titanium anodizing may cause various changes in surface morphology, depending on the direction of the magnetic field and the anodizing voltage. At low potential, the use of magnetic field creates a bumpy surface of the anodized material. At high potential, vertical magnetic field causes formation of a smooth surface with regular pore arrangement. At medium value potential, the surface obtained in the presence of magnetic field parallel to the anode surface has uniformly arranged pores, but on the surface created under vertical magnetic field, arrangement of pores is heterogenous.

Ferromagnets

Nickel

In 2004, Ganesh and other scientists published a paper concerning the effect of magnetic field on nickel electrodeposition [34]. Electrodeposition of nickel was carried out at the constant current density, using nickel sulfamate, nickel chloride, and boric acid solution with 1-T magnetic field. It was observed that the overpotential decreased during electrodeposition of nickel in the presence of magnetic field. The decrease of overpotential is due to the increase of the microroughness of deposit—current density increases in greater true surface. Another explanation of this phenomenon is connected with Lorentz force, which lowers the concentration gradient and, in consequence, increases the deposition rate and decreases the overpotential. The increase of the limiting current, which occurs during metal electrodeposition under magnetic field, causes growth of fine-grained nickel electrodeposits as opposed to laminar type structures in absence of the magnetic

Fig. 3 Fractal deposits (left) and SEM images (right) of tin films obtained without (top) and with (down) 0.3-T magnetic field. Reprinted from [33], with permission from Elsevier



field. STM, XRD, and SEM techniques show that spherical nanoparticles were formed in the magnetic field. As demonstrated by that research, in the presence of magnetic field, the overpotential decreases with time and rest potential shifts during electrolysis.

Similar studies were carried out later by Bund and co-workers [35]. Those scientists also deposited nickel at a constant potential from nickel sulfamate and applied the magnetic field up to 0.7 T with several orientations of the working electrode (anti-parallel to the natural convection—parallel to the surface of the working electrode, parallel to the natural convection—parallel to the surface of the working electrode and perpendicular to the gravity—perpendicular to the surface of the working electrode). In AFM micrographs, which are shown in Fig. 4, it is visible that the uniformity of the deposits increases under magnetic field both in anti-parallel and parallel orientation. In the case of parallel orientation of the working electrode, there are more nickel grains. In the magnetic field, the size of grains decreases.

Iron

Another examined ferromagnetic metal is iron [33, 34]. Matsushima and his coworkers [36] studied the potentiostatic electrodeposition of iron from FeSO_4 electrolyte in 0–5-T magnetic fields. AFM images of iron deposits were recorded in the absence of magnetic field and in 1–5-T constant magnetic fields as shown in Fig. 5. It is clearly visible that the grains of iron deposited under magnetic field are more roundish than those which were deposited without the field. The

same conclusions were drawn by Koza in 2008 [37]. He investigated the effects of magnetic fields up to 1 T, parallel and perpendicular (to the surface of working electrode) on parallel and perpendicular (to the surface of working electrode) electrodeposited potentiostatically from FeSO_4 electrolyte and found that limiting current densities and deposition rates increased. The deposited iron morphology also changed—the deposits were more homogenous in the presence of parallel magnetic field, but in perpendicular field, the grains were oriented in the direction of the magnetic field. In parallel magnetic field, the deposits were rougher than deposits obtained without magnetic field. The researchers did not find any changes in the crystallographic structure of the electrodeposited iron.

Cobalt

In 2004, Krause et al. [38] carried electrochemical studies of cobalt in the presence of up to 1-T constant magnetic fields parallel and perpendicular to the surface of working electrode. They observed that in the presence of parallel magnetic field, the total mass of cobalt deposits was greater than in the absence of the field. It is due to an increase of the limiting current density with the increase of field intensity. In the case of perpendicular magnetic field, they observed that the mass of the deposited cobalt decreased with the increase of magnetic field and that the limiting current also decreased. The deposits obtained under the influence of magnetic field have more homogenous morphology than those obtained without magnetic field.

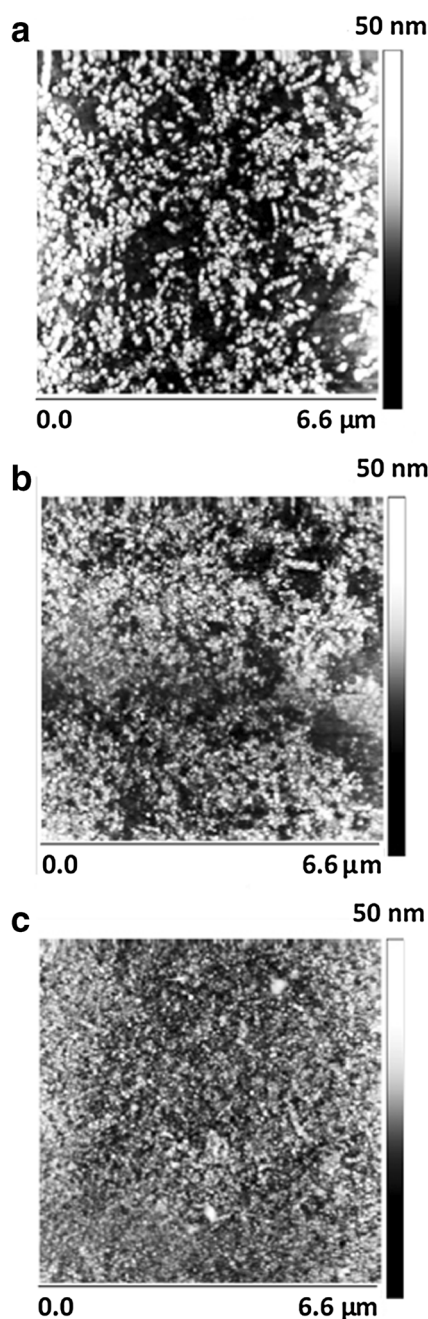


Fig. 4 Nickel electrodeposits obtained without (a), with anti-parallel (b), and parallel (c) 0.7-T magnetic field. Reprinted from [35]

In 2007, Matsushima studied the effects of 0–5-T magnetic fields on microstructural variation of electrodeposited cobalt films [39]. Cobalt films were deposited on a copper electrode at constant current density from CoSO_4 , H_3BO_3 , and CoCl_2 solution at $\text{pH} = 1.5$. It was observed that the cathode potential shifted during electrodeposition toward the anodic direction when the intensity of the magnetic field increased. Matsushima studied the morphology of the formed deposits. The SEM images of the cobalt films deposited in 0, 3, and 5-T magnetic field show that there were no significant changes in

the morphology of electrodeposits. The only change, which occurred in magnetic field above 3 T, was the elongation of deposit grains. The authors conclude that this phenomenon may be due to the incorporation of atomic hydrogen into the cobalt electrodeposits.

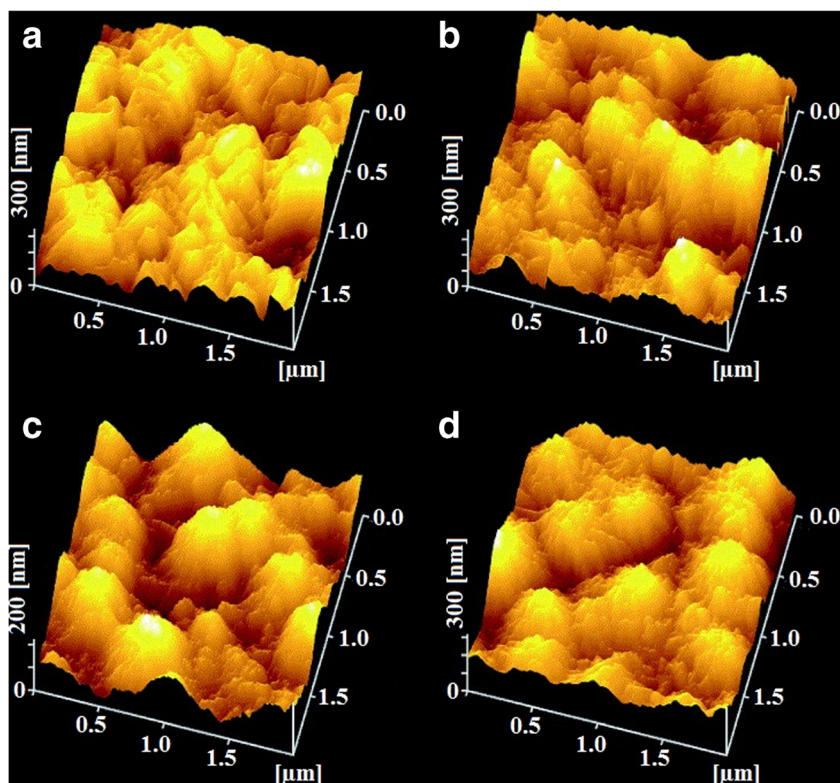
The studies described above show that the effects of magnetic field on ferromagnetic metals are similar to the ones related to diamagnetic metals. There is an increase of the limiting current, as well as changes in morphology of the deposits and the grain size. The explanations of these phenomena are the same in the case of ferromagnets and diamagnets, and they were described in this paper, in the part devoted to diamagnets.

There is also an effect of the magnetic field which is characteristic of ferromagnets. This effect is a significantly negative shift in the rest potential, which results from domain movements in the ferromagnetic metal. As suggested in Ganesh's paper [34], this change of the rest potential is due to the shift in chemical potential of the electrodes. In the case of ferromagnetic metals, electrons of opposite spins have different densities of states in the Fermi energy levels. This difference causes the shift of chemical potential in the electron system of ferromagnetic electrode. At the electrode-solution interface, the shift of the electrode potential occurs.

The smaller size of metal grains under magnetic field may be explained by the enhancement of the ions mass transfer. Due to magnetic convection, ions are provided to the vicinity of the electrode and therefore to each metal grain, which makes the obtained grains smaller and similar in size [36].

The authors of the papers cited above agree that magnetic field affects only the mass transport step of the reactions. All effects of the magnetic field are caused by a diffusion process. The magnetic field has no impact on the reaction kinetics [40]. It can be assumed that in electrodeposition of metals under the influence of magnetic field, the evolution of hydrogen is an important factor, which affects the electrochemical process and the morphology of electrodeposits. During metal electrodeposition, constant magnetic field may increase the mass transfer rate of hydrogen cations to the cathode surface [20, 34, 37]. The resulting hydrogen bubbles may cause the formation of holes in the obtained electrodeposits. The presence of magnetic field accelerates the desorption of hydrogen bubbles and thus, results in the formation of more homogenous deposits [38]. It is worth mentioning that more noble metals are more exposed to the hydrogen formation. Hydrogen is absorbed to a greater extent on the surface of those metals, which have low overpotential of hydrogen formation. In the case of more noble metals, hydrogen formation has a considerable influence on the morphology of surfaces.

Fig. 5 Iron electrodeposits obtained in 0-T (a), 1-T (b), 3-T (c), and 5-T (d) magnetic field. Reprinted from [36], with permission from Elsevier



Alloys

The mechanisms of electrodeposition of metals and alloys are similar, but in the case of alloys, there are two or even more simultaneously occurring reactions. Several reactions occurring at the same time make it possible to obtain an alloy with different electrode potentials. It is clear that the composition of the alloy will change depending on the electrode potential. In the case of two reactions that occur similarly, the change of the electrode potential will cause only a small change in the composition of the obtained alloy. In the case of reactions, which occur in different ways, a small potential change will make the composition of the alloy highly different. During the deposition of alloys, thermodynamic effects are present. The composition and properties of the alloy also depend on the solution composition or ions concentrations. The coating of various metals to improve their mechanical properties and corrosion resistance is not the only application of alloys. More advanced alloys obtained by electrodeposition are also used in new technologies. Cu-Sn nanowires have been used in nanoelectronics and nanodevices [41], Mn-Co coatings have been used in energy conversion devices [42]. Further application of magnetic field during the electrodeposition provides opportunities for preparing various metal alloys with diverse properties [15]. Our team has been engaged in the study of the influence of constant magnetic field on alloys for a long time. Our research [13, 43–45] shows that the presence of constant magnetic field significantly affects the electrodeposition of alloys and their

morphology. It is possible that further development of magneto-electrodeposition will allow for using the constant magnetic field to improve the properties of nanostructure alloys.

As already mentioned in this paper (in the section concerning metals), there are paramagnetic metals, which cannot be electrodeposited alone. These metals can however be obtained in the presence of the other metals.

Ni-Fe

In 2006, Ispas et al. [46] studied the effects of magnetic field up to 0.7 T on galvanostatic electrodeposition of Ni-Fe alloys. It was observed that electric field lines, which are perpendicular to the magnetic field, increase the rate of hydrogen evolution, but in the case of parallel (to the surface of the working electrode) magnetic field, there are no variations. Surfaces of Ni-Fe alloys obtained without magnetic field were porous. In alloys obtained in the presence of magnetic field, their surfaces were more homogenous. Roughness of the obtained surfaces decreased and grains became smaller under magnetic field.

Zn-Ni

In 2013, Rao and coworkers published the paper about magnetically induced electrodeposition at constant current density of Zn-Ni alloy coating [47]. They applied magnetic field

during electrodeposition from ZnCl_2 , NiCl_2 , NH_4Cl , boric acid, and additives (gelatin and glycerol) solution at $\text{pH} = 4.0$. It was observed that the thickness of Zn-Ni alloy decreases and hardness increases with the increase of the magnetic field. The corrosion rate of the alloy depends on magnetic field direction and magnitude. In parallel (to the surface of the working electrode), magnetic field corrosion rate increases whereas in perpendicular (to the surface of working electrode) magnetic field up to 0.8 T, the corrosion rate decreases and it is very high in 1-T magnetic field (but still lower than in the absence of magnetic field). The lowest corrosion rate of Zn-Ni alloy (which means the highest corrosion resistance) is obtained under 0.8-T perpendicular magnetic field. Under the influence of the magnetic field, the topography of the alloy has changed as well. In 0.8-T magnetic field the topography was smooth and compact, in contrast to 1-T field application which caused the formation of a more porous surface.

Ni-Cd

The same researchers in 2014 [48] investigated the effects of magnetic field on Ni-Cd alloys electrodeposited at the constant current density on mild steel. They found, as in the case of the Zn-Ni alloy, that perpendicular and parallel (to the surface of the working electrode) magnetic fields affect the character of the alloy to a greater extent. In the presence of perpendicular magnetic field, the thickness of alloy was observed to decrease and its microhardness to increase. The corrosion rate, in the case of both directions of the field, is lower than in the absence of the field and decreases up to 0.8 T. In 0.8-T perpendicular magnetic field, the corrosion resistance is about 35 times higher than without magnetic field. The topography of the alloy electrodeposited under 0.8 T is smooth and uniform in contrast to the alloy obtained in the presence of 1-T field, where the surface is more porous.

Ni-Mo

Aaboubi in 2014 studied the effect of magnetic field on nickel-molybdenum alloys electrodeposited on a platinum or titanium electrode, using potentiostatic polarization [14, 49]. The content of nickel and molybdenum in the obtained alloys was independent from the applied magnetic field. In 0-, 0.5-, and 1-T magnetic field, the percentage content of Ni:Mo was approximately 74:26. The roughness and porosity of the alloy were modified under magnetic field.

Sm-Fe

In 2015, Lou and his coworkers studied galvanostatic electrodeposition of Sm-Fe alloys under 2–4-T perpendicular and parallel (to the deposition current) magnetic fields [50]. The

alloys were deposited from the electrolyte consisting of SmCl_3 , FeCl_2 , C_2HNO_2 , H_3BO_3 , and $\text{H}_3\text{NO}_3\text{S}$ on a copper cathode. The morphology of the obtained films depended on the direction and density of magnetic field. In perpendicular magnetic field, the films were smoother than in the absence of magnetic field. In parallel orientation, the surface was rough, but that feature decreased together with the increase of magnetic field. Magnetic field affected the samarium content in the obtained alloy. In the perpendicular magnetic field, the amount of Se was smaller than in the parallel field. The thickness of the obtained films was also changed—without magnetic field, it was 24 μm , but in magnetic field, the thickness decreased with the increase of the field density.

Cobalt alloys

In 2007, Koza et al. [51] studied the potentiostatic electrodeposition of CoFe alloys in up to 1-T magnetic field. They deposited alloys from CoSO_4 , FeSO_4 , and Na_2SO_4 solutions on a platinum working electrode. In the case of magnetic field parallel to the surface of the electrode, the limiting current density and deposition rate increase and in a field perpendicular to the working electrode surface, there were no changes in limiting current density and deposition rate. At high potential ($-1600 \text{ mV}_{\text{MSE}}$), there was an effect of magnetic field on the alloy composition—the more noble metal was inhibited and the rate of this effect increased along with the increase of iron ions concentration in the solution.

In 2008–2014, our team investigated the effects of constant magnetic field on the electrodeposition of cobalt alloys at the constant potential [43–45, 52]. In every study, we used magnetic fields with values ranging from 0 to 1.2 T directed perpendicular or parallelly to the surface of the electrode. In these studies, we investigated the changes in morphology, topography, and ingredients content of the layer electrodeposited under constant magnetic field. Electrodeposition of alloys was carried out from solutions of cobalt sulfate (the main ingredient), sodium molybdate, and sodium tungstate with additives (sodium citrate, EDTA, and sulfuric acid). It was observed that Co-W, Co-Mo, Co-Mo-W, and Co-W-Cu alloys electrodeposited in the presence of the magnetic field were smoother than in the absence of field. The fractures on the layer deposited under magnetic field were reduced, as shown in Figs. 6 and 7. Changes in the morphology of alloys electrodeposited under CMF were also observed. The layers were denser and less porous in the case of all alloys. Grains formed in the presence of CMF were smaller. It had a significant effect on the ingredients content in the alloys deposited under CMF. In these studies [43, 45, 52], it was observed that the content of the main ingredient—cobalt—increases under CMF. The case of Co-Mo-W alloys [44] shows that changes in the alloy composition depend on the concentration of ingredients in the electrolyte, and it can be assumed that the presence of magnetic

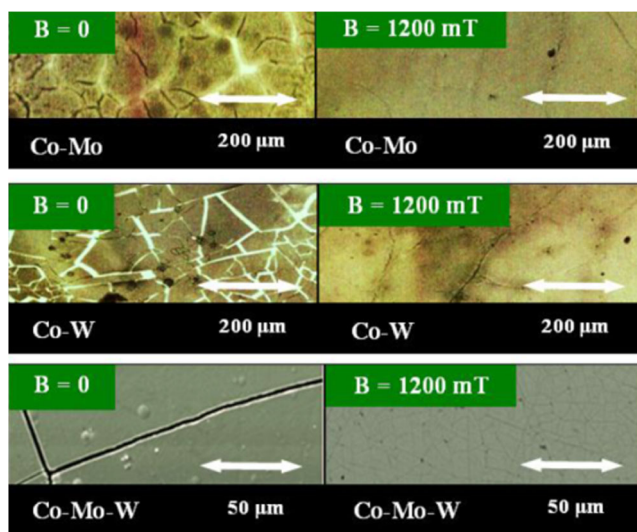


Fig. 6 Cobalt alloys obtained in various intensities of magnetic field. Reprinted from [44]

field has no influence of the content of ingredients in Co-Mo-W alloys. The ingredient content in the alloys obtained without and in the presence of constant magnetic field is shown in Table 1. In Co-W alloys [43] deposited under CMF, the deflection in some crystal planes was observed. The angle of deflection depends on the magnitude of the magnetic field and ranges between 15° and 20°.

In 2016, Aaboubi and others [53] studied the effects of magnetic field on the potentiostatic electrodeposition of CoNiMo alloys on a platinum disc electrode. They used different concentrations of Na₃C₆H₅O₄, Na₂MoO₄·6H₂O, CoSO₄·7H₂O, and NiSO₄·6H₂O in the studied solutions. It was observed that after depositing the alloy in magnetic field, which was parallel to the surface of the electrode, the content of cobalt increased and the content of nickel decreased. The current density increased in the presence of magnetic field. The SEM images shown in Fig. 8 show that the surface of the alloys was smoother and more compact, and the size of grains decreased.

As observed in all studies concerning alloys with cobalt as the main ingredient of the deposition solution, the amount of

Table 1 The chemical composition of alloys obtained in $B = 0$ T, $B = 200$ mT, $B = 600$ mT, and $B = 1200$ mT [43–45, 52], where % wt. is weight percentage of the elements in the alloy

Alloy	Component	% wt. in alloy obtained in 0 mT	% wt. in alloy obtained in 200 mT	% wt. in alloy obtained in 600 mT	% wt. in alloy obtained in 1200 mT
Co-W	Co	51.4	52.0	53.6	54.9
	W	25.4	23.1	17.7	13.5
	Other	23.2	24.9	28.7	31.6
Co-Mo	Co	57.9	60.6	64.2	68.7
	Mo	42.3	39.4	35.8	31.3
Co-Mo-W	Co	74.6	75.2	76.4	77.9
	Mo	16.9	16.5	15.5	14.2
	W	8.5	8.3	8.1	7.9

this ferromagnetic metal in the alloy electrodeposited under magnetic field was always larger than without the influence of magnetic field. The reason for this phenomena may be due to the cobalt mass transport rate, which increases because of magnetic convection. The deposition potential of less noble metals shifts through the interactions between components and the codeposition of cobalt and other metals becomes possible [53]. The situation is different in the case of an alloy with two ferromagnetic metals [51]. At a high potential, the amount of the more noble metal was lower in the alloy electrodeposited under magnetic field. It may be due to formation of metal hydroxides, which was described by Brenner [54]. The same phenomenon was visible in Zn-Ni alloys [47]—the amount of nickel was lower in the alloy than in the solution. Brenner’s theory about anomalous codeposition is also an explanation of these results.

In the deposition of metallic alloys, there are several characteristic effects of the applied magnetic field. Firstly, in the cited studies, the thickness of the alloy was smaller under magnetic field perpendicular to the applied current density. This phenomenon is caused by a decrease of the diffusion layer thickness. When the perpendicular magnetic field is

Fig. 7 Co-W-Cu alloy obtained without (left) and with (right) 1-T magnetic field. Reprinted from [52]

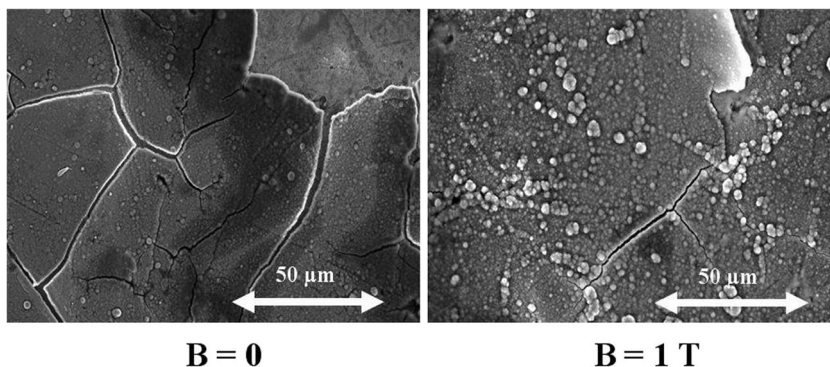
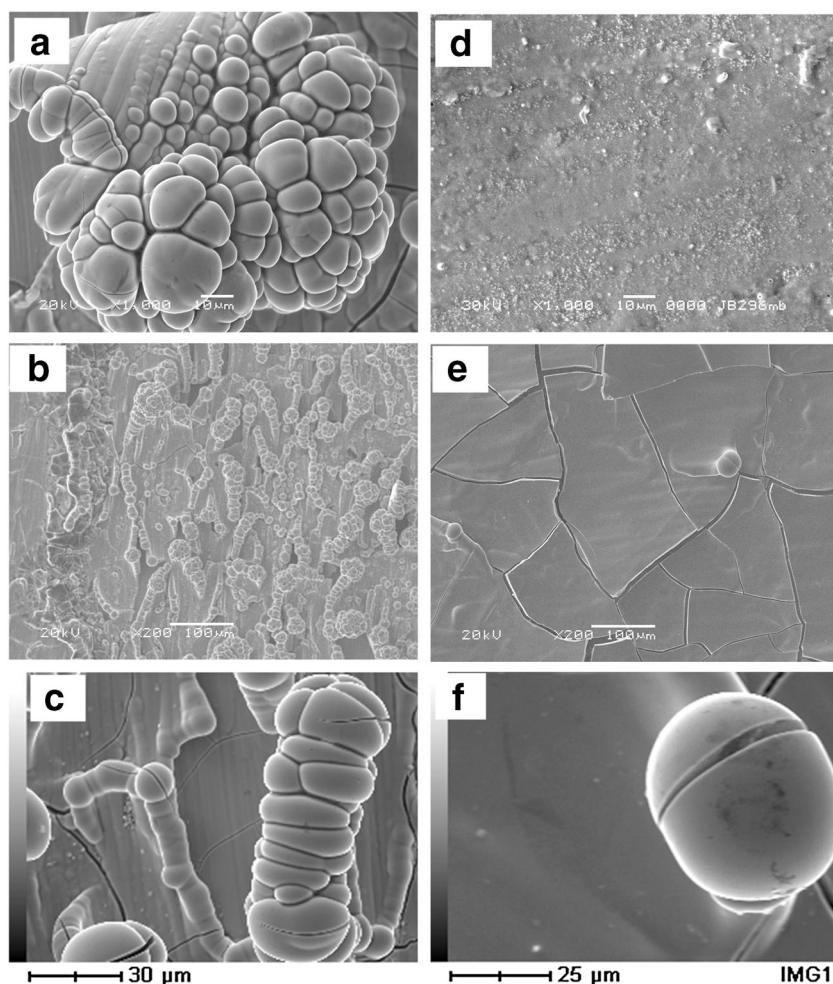


Fig. 8 CoNiMo alloys obtained without (a–c) and with (d–f) magnetic field. Reprinted from [53], with permission from Elsevier



applied, the Lorentz force acts on the ions and causes an increase of mass transport rate and hydrogen evolution. Enhanced hydrogen evolution tendency causes a decrease of the deposit thickness. This phenomenon is not pronounced in parallel magnetic field. The increase in the alloys hardness is caused by magnetohydrodynamic effect [47]—increased homogeneity of the surface causes the dislocation movement, which results in hardening of the coating. The increased roughness of coatings obtained at high magnetic field may also be caused by the enhanced hydrogen evolution.

Metal-nonmetal composites

In the section concerning alloys, the materials resulting from a combination of metals and non-metallic substances, generally referred to as composites, are also worth mentioning. Electrodeposition of composites is conducted carried from electrolytes containing suspended non-metallic particles. Composites can consist of two or more components, and their properties depend for example on the amount of components

or electrodeposition conditions [55]. The movement of nanoparticles suspended in the solution is due to the magnetophoretic force (f_{mp}), which is shown in the following equation:

$$f_{mp} = \frac{\Delta\chi}{\mu_0} (B \cdot \Delta) B \quad (6)$$

where $\Delta\chi$ is the susceptibility of the particles and μ_0 is the magnetic permeability of the free space and B is the magnetic flux density. Magnetophoretic force causes the movement of magnetic nanoparticles toward higher magnetic flux density regimes, which is connected to their susceptibility, and allows for their deposition. It is important that the magnetophoretic force acts only on the nanoparticles but not on the solution [56].

The surfaces coated with composites have different features than each, individual component. Composing metals with non-metals has been widely applied in various industries. Ni-SiC composites have been used in aerospace industry [57], Ni-Co alloys electrodeposited on graphene oxide films can be

used to fabricate supercapacitors [58] and CuSe/polypyrrole composite can be used in solar cells [59]. Further research into the influence of magnetic field on composites could, in the future, contribute to the use of constant magnetic field in nanoelectronics, energy engineering, or biotechnology.

Ni-SiC

In 2006, Hu investigated the effects of 0.3-T constant magnetic field on Ni-SiC composites [57]. The coating was deposited at the constant current density on the stainless steel cathode from nickel salt solution with boric acid, sodium dodecyl sulfate, and suspended SiC particles. LSV measurements showed that the magnetic field caused an increase of the current density. Under magnetic field, the morphology of the obtained surfaces changed as well. Nickel grains changed under the influence of magnetic field and the content of SiC increased significantly.

Ni-nanoAl₂O₃

Mohan and coworkers [56] investigated the influence of up to 0.5-T magnetic field, on the composite electrodeposited on copper working electrode. They used a solution which contained nickel salts and Al₂O₃ particles. It was observed that magnetic field applied during pulse current and direct current electrodeposition of Ni-nanoAl₂O₃ caused an increase of the current. The composite obtained under magnetic field was harder. The coating thickness also increased and the amount of deposited particles was greater. Under the influence of magnetic field, the size of nickel grains has decreased and their shape has changed. It was observed that corrosion rates of the obtained composites in NaCl solution decreased with the increase of magnetic field density. The SEM micrographs of the composites obtained with and without magnetic field are shown in Fig. 9.

Fe-Si

In 2014, Long et al. [60] investigated the effects of constant magnetic field on the Fe-Si composite, which was electrodeposited at the constant current density from iron salts solution

containing Fe-Si particles. They applied a silicon steel cathode, an iron anode, and up to 1-T magnetic field. Under magnetic field, the decrease of cathode current efficiency was observed. The amount of deposited Fe-Si particles was higher under magnetic field. A change in the morphology of the obtained composites was observed. The shape of the obtained structures was changed into needles under the influence of magnetic field, but when it increased, the shape appeared more dome-like.

Non-metals

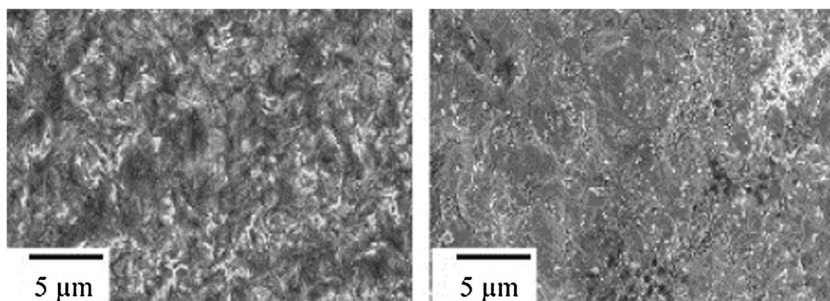
Effects of constant magnetic field on chemical reactions are not limited to electrolytic processes. The following studies prove that magnetic field can be used in electropolymerization or organic reactions. There are studies showing that the magnetic field can modify the pathways of various reactions or change the properties of their products [61, 62].

Alumina oxide structures

Anodization of aluminum in solutions of acids allows for obtain nanoporous anodic aluminum oxide. Various kinds of porous anodic aluminum structures are suitable for use in many industries. Porous anodic alumina films may be used in fabrication of batteries, fuel cells, or magnetic memories [63]. Those structures may be applicable in molecular separation, humidity sensors, or electronics [64–66].

In 2016, Prabowo et al. [65] studied the influence of vertical magnetic field on the anodizing process of aluminum. Aluminum anodizing was conducted in oxalic acid within 4 h under 50 V in the presence of up to 5-T magnetic field. Magnetic field vector was directed perpendicularly to the surface of the aluminum sheet. Prabowo et al. found that vertical magnetic field caused the reduction of the obtained alumina nanopores size and the decreasing of pore distance. Moreover, the nanopores became smaller with the increase of the magnetic field magnitude. Vertical magnetic field caused straight, vertical growth of AAO. The thickness of porous AAO increased under the influence of magnetic field, but there was no

Fig. 9 Ni-nanoAl₂O₃ composites obtained without (left) and with (right) 0.4-T magnetic field. Reprinted from [56], with permission from Elsevier



significant change in the thickness with increasing magnetic field intensity.

In 2016, Vrublevsky et al. [66] studied the effect of continuous magnetic field on nanoporous anodic alumina films fabrication. Anodization was carried out in 0.5- and 0.7-T magnetic field at 20 V in solutions of oxalic and sulfuric acids. The authors applied two substrates: SiO₂/Si and glass-ceramic substrate. The presence of 0.5- and 0.7-T magnetic field caused the reduction of pore and cell diameters and the decrease of interpore distances at both substrates in oxalic acid. In the case of anodization carried out at Si₂O/Si substrate in sulfuric acid, the decrease of pore and cell diameters and interpore distance occurred only in the presence of 0.7-T magnetic field.

In 2017, Esmaily, Mills, and Coey [64] investigated the fabrication of amorphous alumina nanotubes by magnetic hard anodization. They anodized an aluminum disc in H₂SO₄ solution at 25 V within 600 s and at 50 V thereafter without and with magnetic field present. The anodization process allowed to obtain alumina oxide pores—nanotubes. The average current flow of hard anodization decreased as a result of 1.5-T magnetic field application. The nanotubes obtained in 0.5-T magnetic field were more susceptible to separation than those obtained without magnetic field. In 1.5-T magnetic field, the nanotubes became completely separate.

Polymers

Electrochemical preparation and characterization of conducting polymers allow to control the synthesis of these materials and to obtain their suitable properties. There is a very large number of conducting polymer applications. Those materials may be used in electrocatalysis, organic chemistry, biochemistry, electroanalysis, and in many other areas. It is impossible to describe electropolymerization process by one scheme due to numerous types of these materials. Generally, it can be stated that the first step of polymer formation is the creation of cation radicals. Next, in the ideal case, dimerization and gradual chain growth occurs [67]. Generally, the effect of magnetic field on the obtained polymers and their properties is due to the alignment of the molecule bonds under the applied field. A material placed in magnetic field gains magnetization, which leads to the creation of magnetic energy. Magnetic energy may cause polymer structures to arrange in a specific direction depending on the applied magnetic field. This alignment is the source of changes in the polymerization process and in properties of the obtained materials [68].

Polypyrrole

In 1998, Mogi et al. studied the electropolymerization of PPy films [67, 69, 70] and published the paper about obtaining electrodes modified by those polymers [71].

PPy was deposited on platinum disc electrodes from 0.1 M aqueous solution of pyrrole in 0.1 M Na₂SO₄ under 5-T magnetic field. It was observed that electrodes with magnetoelectropolymerized films are more selective for the studied reaction. The authors suggest that this phenomenon is due to the orientation of pyrrole aromatic rings. Those rings line up in parallel to the applied magnetic field, and this configuration improves the selectivity of the electrode.

Poly(acrylamide)

In 1998, Chiriac et al. [72] studied the influence of up to 0.5-T magnetic field on the polymerization of acrylamide. Polymerization was carried out using acrylamide aqueous solutions with addition of potassium persulfate as an initiator. It was observed that molecular weights of the polymer obtained under magnetic field ranged from 900,000 to 1,400,000 depending on the monomer and initiator concentrations. For comparison, the same process carried out without magnetic field resulted in obtaining polymers with molecular weights ranging between 150,000 and 840,000. The increase in molecular weight of the polymer obtained with magnetic field depends on the field intensity. The polymer obtained under magnetic field was thermally more stable than the polymer obtained without magnetic field. In 2000, the same scientists [73] studied similar cases and they found that in 0.25-T magnetic field the properties of polymerization process and poly(-acrylamide) such as polymerization rate and conversion improved only slightly.

6-N,N-Dioctylamino-1,3,5-triazine-2,4-dithiol

In 2007, Wang [67] investigated the effects of 5-T magnetic field on the electropolymerization of 6-N,N-Dioctylamino-1,3,5-triazine-2,4-dithiol. It was observed that in magnetic field perpendicular and parallel to the direction of electrolytic current, the weight of the obtained polymer films is greater than in the absence of magnetic field. The effects of perpendicular magnetic field were greater than those of parallel field. The X-ray diffraction patterns show that in the perpendicular magnetic field, the formation rate was increased and the crystallinity of polymer was decreased. The parallel magnetic field caused the increase of polymer films crystallinity.

Polyaniline

Li et al. [74] studied the effects of up to 0.6-T magnetic field on polyaniline polymerized from the aqueous solution of aniline and additives. They observed that conductivities of the polymer obtained under magnetic fields of up to 0.4 T increased and in case of the polyaniline obtained in 0.6-T magnetic field, the conductivity was higher than without magnetic

field but lower than under 0.2-T field. The polymerization rate obtained under magnetic field increased up to 0.4-T field, but it was lower for 0.6-T field. The same dependence was observed in molecular weights and thermal stability of the polymer. Similar studies were carried out in 2008 by Zieliński [75], who deposited aniline from its aqueous solution on a platinum electrode with magnetic field up to 1.5 T. The results show that the orientation of magnetic field and other parameters influence the reaction rate and, under the best possible conditions, the reaction rate increases up to 20%. The obtained results suggest that aniline polymerization yields are higher in the presence of 1.5-T magnetic field.

EDOT

In 2008, Cho et al. [76] studied the effects of 1.17-T magnetic field on PEDOT—poly(3,4-ethylenedioxythiophene) which is a conductive, stable, and transparent (in the oxidized state) polymer. Thin films of PEDOT were polymerized from EDOT and tetrabutylammonium perchlorate solution on ITO glass as the working electrode under magnetic field. During polymerization, in the presence of magnetic field, they observed that the polymerization current was higher than during the same process conducted without the magnetic field. This value increased in time in contrast to the reaction carried out in the absence of magnetic field. It means that the magnetic field applied during electropolymerization causes an increase in the amount of the obtained polymer. The cyclic voltammograms show that the redox current was higher for PEDOT film polymerized with magnetic field—it can mean that magnetic field accelerates the rate of electropolymerization of PEDOT and increases the charge transfer rate. The Raman spectroscopy provided interesting results—it showed that in the presence of parallel (to the electrochemical cell) magnetic field, the conformation of the polymer became more linear or coil-expanded in shape. As it might be expected, these changes influenced the morphology of the polymer. As seen in SEM images in Fig. 10, the sharp crystalline structure of PEDOT is associated with the presence of magnetic field.

The discussed studies demonstrate several changes in the properties of polymers obtained in magnetic field. The increase of the polymerization rate may be explained with the

increase of species flow mobility near the electrode. The increase of the anion mobility accelerates the reaction. This increase of the reaction rate causes changes in the morphology of the obtained polymers. On the surface of the substrate, the number of nucleating centers increase, which causes more chain-like structure and easier growth of polymer [76]. In the case of parallel magnetic field, the polymer crystallinity increases because of MHD effect. This effect causes proper alignment of the polymer species. The increase in the polymer crystallinity is a result of the alignment of rings and chains of the polymer at the right angle [67]. The increase of polymers molecular weight is also due to the orientation of polymer chains and bonds [72].

Organic reactions

Zieliński et al. investigated the effects of magnetic field on the Kabachnik-Fields reaction [61] and the aza-Pudovik reaction [62]. The first reaction, which is shown in Fig. 11, was carried out in the refluxing acetonitrile in the absence and in the presence of 1-T magnetic field, and the reactions were monitored by ³¹P NMR spectra.

There were two types of magnetic field effects on Kabachnik-Fields reaction: improved yields of all the isolated aminophosphonates (3Aa-3Bf) and increased conversion rates as shown in Fig. 12. The reason for the accelerating effect of magnetic field may be due to the orientation of substrate molecules. Magnetic field forced the direction of molecules and reduced the distance between them.

The aza-Pudovik reaction, shown in Fig. 13, was carried out under 1-T magnetic field. The first step was the formation of imines IIa-IIf, but the magnetic field did not affect these reactions. Then, the formation of aminophosphonates IIIa-IIIf was carried out under and without magnetic field. The conversion rates of the reaction carried out under magnetic field were higher than those obtained without magnetic field, which proves that magnetic field has accelerating properties in aza-Pudovik reaction. Those results can be explained by the spin reversal due to energetic conditions, which consequently allows to transfer the molecule in its excited level.

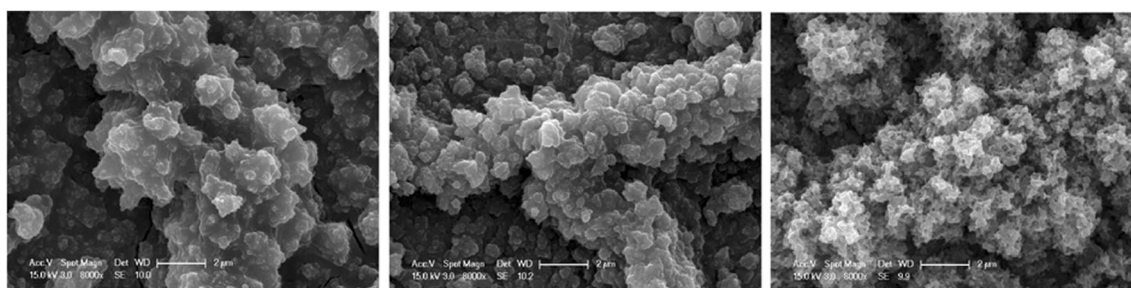
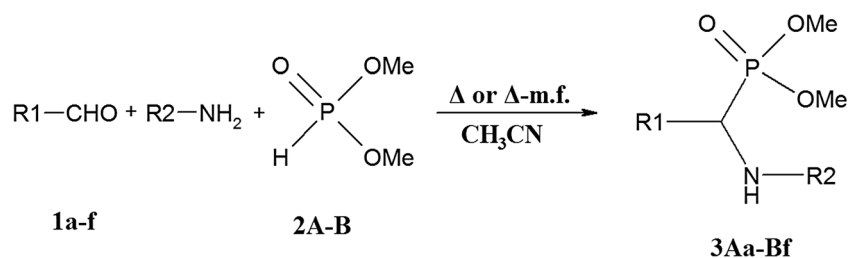


Fig. 10 PEDOT obtained in 0-T (left), perpendicular 1.17-T (center), and parallel 1.17-T magnetic field. Reprinted from [76], with permission from Elsevier

Fig. 11 Scheme of Kabachnik-Fields reaction [61]



R1 = **a**: Ph, **b**: ferrocenyl, **c**: 2-furyl, **d**: 2-thienyl, **e**: 2-phenylethenyl, **f**: c-Hex
 R2 = **A**: CH Ph, **B**: 4-methylphenyl

Cellulase

In 2009, Chinese scientists investigated the influence of 0.15-, 0.30-, and 0.45-T constant magnetic field on cellulase activity. The studies showed that constant magnetic field can improve the activity of cellulase at various temperatures and pH [77]. The authors explained that this phenomenon may be due to the availability of the substrate to the cellulase. Therefore, the enzyme subjected to the constant magnetic field has greater affinity to its substrate—it may be connected with the structural changes of cellulase.

Future applications of constant magnetic field

A multitude of applications of constant magnetic field gives prospects for its application in many branches of industry, science, or medicine. Magnetic field effects on increasing the corrosion resistance of metals or

acceleration of electrodeposition rate of metallic alloys provide many opportunities to improve the properties of metallic coatings in electroplating. The presence of magnetic field effects has also been confirmed in organic chemistry—acceleration of organic reactions rate and increase of their efficiency offers the possibility of carrying out organic reactions which take too long without magnetic field influence. Also, the chemistry of polymers may be developed using magnetic field, because of its influence on electropolymerization rate. Constant magnetic field is already used in clinical applications, for example in biomagnetic separation [78] of bacteria, cells or macromolecules for better detection and analysis. Strong magnetic fields seem to be a useful tool to improve properties of processed metals in materials engineering [79]. Magnetic field may prove useful in the wastewater treatment. There are some promising results for the use of magnetic field in the removal of volatile organic compounds [80]. There are also numerous papers describing the influence of constant magnetic field on living organisms [81].

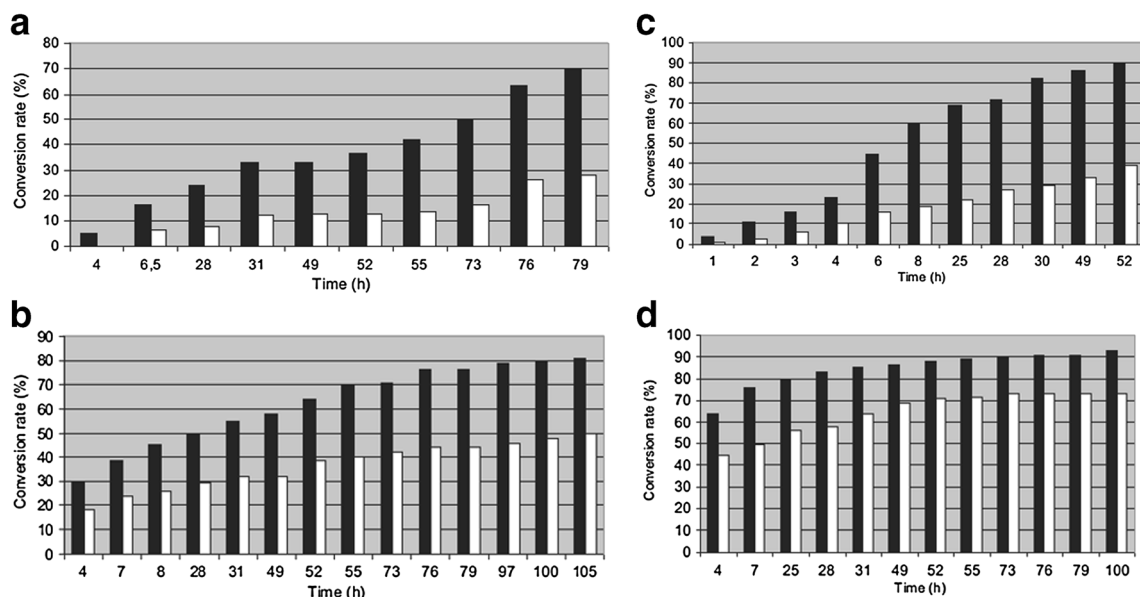


Fig. 12 Conversion rates of Kabachnik-Fields reaction without (white) and with (black) 1-T magnetic field **a** 2A + 1d, **b** 2B + 1c, **c** 2A + 1a, and **d** 2B + 1e reactions. Reprinted from [61]

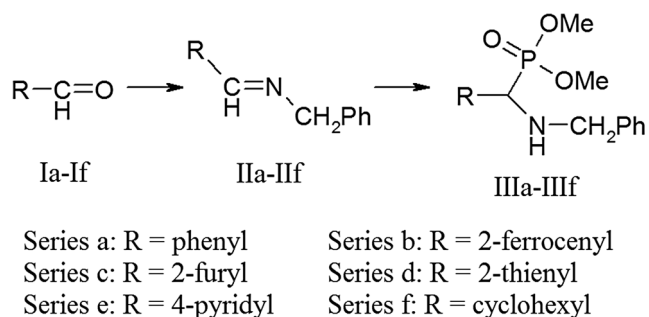


Fig. 13 Scheme of aza-Pudovik reaction [62]

The use of constant magnetic field in chemistry is interesting because of many possible applications. It creates opportunities to improve the well-known processes (such as electrodeposition or electropolymerization). However, constant magnetic field effects on more complex processes are still not fully understood. Finding a solution to this problem and new applications of constant magnetic field could be interesting for scientists in various subjects, in particular chemists or physicists.

Summary

Effects of constant magnetic field on chemical processes are a branch of science that is still developing. In the recent years, there have been many studies and numerous theories concerning magnetochemistry have been formulated. Analysis of the published studies investigating the influence of constant magnetic field on chemical reactions allowed to find several types of magnetic field effects. Firstly, electrodeposition, electropolymerization, and some organic reactions occur faster under constant magnetic field. The surface of metal and alloy coatings obtained in the presence of magnetic field is smoother, and their grains are finer. Uniform magnetic field, applied during electrodeposition, improves corrosion resistance of some coatings. Constant magnetic field also accelerates the transport of H^+ to the cathode surface and the desorption of hydrogen bubbles. Electrodeposition current of metals is shifted as a result of magnetic field presence, and in the case of ferromagnets, the rest potential is shifted as well.

The effects of constant magnetic field have not been fully investigated yet. There is no uniform model for controlling constant magnetic field in electrodeposition. Nevertheless, the studies described in this paper demonstrate that constant magnetic field can be widely used in electrochemistry and electrodeposition industries. This is the reason why it is useful to study those phenomena and work on further development of magnetochemistry.

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