ISSN 1070-4272, Russian Journal of Applied Chemistry, 2007, Vol. 80, No. 2, pp. 241–247. © Pleiades Publishing, Ltd., 2007. Original Russian Text © V.I. Varentsova, V.K. Varentsov, 2007, published in Zhurnal Prikladnoi Khimii, 2007, Vol. 80, No. 2, pp. 242–248.

> APPLIED ELECTROCHEMISTRY AND CORROSION PROTECTION OF METALS

## Recovery of Cadmium and Change in Properties of a Fibrous Carbon Electrode in Electrolytic Processing of Ammonia Washing Solutions Formed in Cadmium Plating

V. I. Varentsova and V. K. Varentsov

Institute of Solid-State Chemistry and Mechanochemistry, Siberian Division, Russian Academy of Sciences, Novosibirsk, Russia Novosibirsk State Technical University, Novosibirsk, Russia

Received May 29, 2006

**Abstract**—The possibility of recovering cadmium deposited on fibrous carbon electrodes from ammonium washing solutions formed in cadmium plating via operation of a short-circuited electrochemical system or anodic dissolution was examined. A polarization study of electrode processes that occur on a renewable graphite microelectrode in ammonium solutions of varied composition was carried out. The change in the properties of fibrous carbon electrodes in their cyclic use in electrodeposition–recovery of cadmium and the possibility of their repeated use were analyzed.

**DOI:** 10.1134/S1070427207020140

Owing to their specific properties, cadmium coatings are used for protection of articles in aggressive media (high humidity or tropic conditions) [1–3]. Cadmium(II) is to be removed from washing solutions formed in cadmium plating for detoxication of these solutions and recycling of cadmium into the electroplating process. Electrolysis is a way to simultaneously solve these two problems. With account of the low concentration of cadmium(II) in washing solutions, it is preferable to use electrolysis with 3D flow-through electrodes and, in particular, with electrodes made of fibrous carbon materials (FCM) [4].

In the recent decades, electrolysis with fibrous carbon electrodes (FCE) has been successfully used to recover noble and nonferrous metals in hydrometallurgy and electroplating [4, 5]. The use of FCM for electrolytic recovery of nonferrous metals from washing solutions formed in electroplating is due to the necessity for regeneration of carbon electrodes and recycling of the recovered metal into main process. An important issue is that of changes in the FCM properties during their cyclic use in electrodeposition– recovery and of the influence exerted by these changes on the parameters of both the processes. No systematic studies have been performed in this area. The results of previous studies [6-9] suggest that use of FCM in cyclic processes will strongly affect their properties. However, no unambiguous conclusion can be made about whether these changes exert positive or negative influence on the main process of metal electrodeposition because of the scarcity of the available data.

This study was undertaken in order to examine experimentally the possibility of recovery of cadmium deposited on FCE, changes in the FCE properties in an electrodeposition–regeneration cycle, and influence exerted by these changes on the main process for the example of electrolytic processing of washing ammonium solutions formed in cadmium plating.

## EXPERIMENTAL

Industrial cadmium-plating ammonium electrolytes of two compositions were chosen for study. Solution no. 1 contained (g l<sup>-1</sup>): CdSO<sub>4</sub> 50, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> 150, H<sub>3</sub>BO<sub>3</sub> 25 (pH 5); and solution no. 2: CdSO<sub>4</sub> 50, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> 250, urotropin 20, NF dispersant 75 ml l<sup>-1</sup> (pH 6) [2, 3]. Supporting electrolytes contained all the components listed above except cadmium. The electrode polarization was carried out using a TES-14 dc power supply in the galvanostatic mode, with the solution circulated by a pmp-304 peristaltic pump through the FCE volume and an intermediate tank at a rate of 0.2 ml cm<sup>-2</sup> s<sup>-1</sup> [9]. The solution was delivered to



**Fig. 1.** Kinetic curves of electrolytic recovery of cadmium(II) from electrolyte no. 1 in modeling of the electrolytic recovery of cadmium(II) from a catching bath. Initial cadmium(II) concentration 330 mg l<sup>-1</sup>, dilution factor n =20, interval between washings 15 min. (*c*) Cd(II) concentration, and ( $\tau$ ), time. Rise in the cadmium(II) concentration upon a single washing (mg l<sup>-1</sup>): (*I*) 27, (2) 54, and (*3*) 81.

an electrode with a back current lead from the back side with respect to the counter electrode. The FCE was made of NT-1 carbonized carbon graphite material, its geometric area was 2 cm<sup>2</sup>. A perforated titanium or platinum plate served as a current lead, and a platinum wire, as a counter electrode. To measure changes in the mass and electrical conductivity of the FCE electrode, it was washed with distilled water and dried at  $80-100^{\circ}$ C. The steady-state electrode potential of a cadmium plate and FCE in the electrolytes were measured relative to a saturated silver chloride reference electrode and recalculated to the hydrogen scale, without drying of the FCE.

The electrical conductivity of FCE was measured with a VM-509 ac bridge and the steady-state electrode potential, with an OR-265/1 pH-meter, using the procedure and setup described in [4]. Polarization curves were measured in the potentiodynamic mode with an RA-2 polarograph on a graphite microelectrode 2 mm in diameter with a surface freshened in the electrolyte solution [10], with a potential sweep rate of 50 mV s<sup>-1</sup>.

The efficiency of electrolytic recovery of cadmium was evaluated by the degree of recovery,  $\alpha = (c_0 - c_{\tau})/c_0$ ; current efficiency by cadmium,  $C_{\rm E} = [(c_0 - c_{\tau})VF]/I\tau M_{\rm eqiv}$ ; and electric power consumption  $W = IU\tau/(c_0 - c_{\tau})V$ . Here  $c_0$  and  $c_{\tau}$  are the initial and final cadmium concentrations in solution (g l<sup>-1</sup>); V, solution volume (l); F, Faraday constant (26.8 A hmol<sup>-1</sup>); *I*, current (A); *U*, cell voltage (V);  $\tau$ , experiment duration (h); and  $M_{\text{equiv}}$ , molar mass of the metal equivalent. The cadmium(II) concentration in solution was determined by the atomic-absorption method.

Figure 1 demonstrates the results of experiments on modeling of the electrolytic recovery of cadmium(II) from a catching bath for an automated cadmium-plating line. A portion of the cadmium-plating electrolyte was introduced at regular intervals of time (15 min) into a solution circulated between the electrolyzer and the intermediate tank, which models a catching bath. The Cd(II) concentration in the solution modeling a single washing of articles changed by 27 to 81 mg  $1^{-1}$ . The electrolytic recovery of cadmium(II) was carried out at a current density of 750 A  $m^{-2}$ . The kinetic curves presented in Fig. 1 reflect the change in the cadmium(II) concentration in a solution before introduction of a portion of the cadmium-plating electrolyte. It can be seen that the time in which a constant cadmium(II) concentration in solution is attained and the level of this constant concentration increase with the amount of the electrolyte introduced in a single washing. The fact that a constant cadmium(II) concentration in solution is reached shows that, under the chosen electrolysis conditions, the whole amount of cadmium(II) introduced in article washing is recovered by electrolysis between two successive washings. Depending on the introduced amount of electrolyte modeling washing of articles with different surface areas, this concentration is  $10-35 \text{ mg l}^{-1}$  before deposition of a certain amount of cadmium onto FCE. After that the efficiency of cadmium electrodeposition decreases, which is characterized by an increase in its concentration in solution. Evidently, the main reason for the decrease in the process efficiency is that the reaction surface area and the rate of electrolyte circulation decrease because of the plugging of the pore space in FCE by the deposited metal.

The amount of cadmium deposited per 1 g of FCE varies with the electrolyte composition and is determined by the deposit structure and by the localization of cadmium within the FCE volume, which are governed by specific features of cadmium electrodeposition from the electrolytes under consideration. In the case of metal electrodeposition onto FCM cathodes, the overvoltages of hydrogen evolution on FCM and on a metal being deposited are important for the metal distribution throughout the electrode volume [4]. The overvoltage of hydrogen evolution on cadmium is 1.1 V, and that on graphite, 0.8 V [1, 11]. Therefore, the overgrowth of the electrode with cadmium predominantly occurs on the metal deposited during

the initial stage of electrolysis. No less important is the solution pH, which is responsible for the stability of ammine complexes of cadmium; at pH > 5,  $Cd(NH_3)_2^{2+}$  complexes predominate in the solution  $(K_n = 1.8 \times 10^{-5})$  [2, 12]. In addition, electrolyte no. 2 contains cadmium(II) complexes with urotropin and a surfactant additive, and, therefore, the electrodeposition of cadmium from this electrolyte should be characterized by a higher polarizability [2, 3]. Thus, the varied content of components of the supporting electrolyte, inherent to washing solutions, should affect the polarization characteristics of the cathodic process in cadmium-plating electrolytes.

The polarization curves characterizing cadmium(II) discharge on a graphite microelectrode at different dilutions of the supporting electrolyte and a constant cadmium(II) concentration in the solution (300 mg  $l^{-1}$ ) are shown in Fig. 2. The polarization curves have four characteristic portions. The first of these (portion II) ranges from the steady-state potential to a sharp rise in current, which is associated with cadmium(II) reduction. This portion apparently corresponds to oxygen reduction, and the fourth portion, to intense hydrogen evolution. For both the electrolytes, the reduction of cadmium(II) is determined by a clearly pronounced plateau of the limiting current (third portion), whose length is about 500 mV for electrolyte no. 1 and 300 to 500 mV for electrolyte no. 2 and increases with the dilution of the solution. For both the electrolytes, the height of the plateau of the limiting current is proportional to the cadmium(II) concentration in a solution.

For electrolyte no. 1, the run of the polarization curve is little affected by dilution of the supporting electrolyte, with the potential of the onset of cadmium deposition only somewhat shifted in the positive direction. For electrolyte no. 2, a strong effect is observed. In this case, the potential of the onset of cadmium deposition is shifted in the positive direction, the length of the plateau characterizing cadmium deposition at the limiting current becomes longer, and the limiting current itself also increases. In addition, electrolyte no. 2 possesses a higher electrical conductivity (0.21 Cm cm<sup>-1</sup>), which is approximately 1.5–1.7 times that of electrolyte no. 1. Therefore, electrodeposition of cadmium from electrolyte no. 2 is characterized by a higher polarizability, which is clearly seen in curve 1 in Fig. 2b.

It was shown experimentally that, in the case of electrolytic recovery of cadmium(II) from electrolyte no. 1, cadmium is deposited on FCE on the front (closer to the counter electrode, anode) side of the elec-



**Fig. 2.** Polarization curves characterizing the electrode processes on graphite microelectrode in electrolyte nos. (a) 1 and (b) 2. (*i*) Current density, (*E*) potential; the same for Fig. 6. Cadmium(II) concentration (mg  $1^{-1}$ ): (1, 2) 300, (3) 150, and (4) 50. Supporting electrolyte dilution factor (times): (a) (1) 0, (2) 50, (3, 4) 20; (b) (1) 0, (2) 50, and (3, 4) 5. (I, II, III, IV) For explanation see text.

trolyte no. 2, it is localized on the back (closer to the current lead) side of the electrode. The electrolytic deposits of cadmium also differ in structure. In

RUSSIAN JOURNAL OF APPLIED CHEMISTRY Vol. 80 No. 2 2007

**Table 1.** Degree of anodic dissolution,  $\alpha$ , of cadmium deposited onto FCE in a supporting ammonium solution; current efficiency by cadmium,  $C_{\rm E}$ ; dissolution rate v; and energy expenditure W for dissolution of 1 g of cadmium at varied anode current density *i* (dissolution time 0.5 h, solution volume 100 ml, geometric surface area of the anode 2 cm<sup>2</sup>)

<i>i</i> , A m <sup>-2</sup>	α	C <sub>E</sub>	<i>v</i> , -2,-1	<i>W</i> ,			
	%		g m <sup>-2</sup> h <sup>-1</sup>	W h $g^{-1}$			
Electrolyte no. 1							
50	79.2	385	$400 (105)^*$	0.28 (1.00)			
100	96.0	230	480 (210)	0.50 (1.43)			
150	89.6	140	445 (315)	1.27 (1.80)			
200	99.5	120	500 (410)	1.60 (1.95)			
Electrolyte no. 2							
50	87.7	450	465 (105)	0.2 (0.86)			
100	90.8	215	450 (210)	0.60 (1.38)			
150	92.8	145	460 (315)	1.21 (1.80)			
200	99.9	120	500 (410)	1.60 (1.95)			

\* Values of the parameters at  $C_{\rm E}$  = 100%.

the case of electrodeposition from electrolyte no. 1, the deposit is porous, its adhesion to the surface of carbon fibers is weak, and deposit scales off. The cadmium deposit formed from electrolyte no. 2 is less porous and covers each fiber of the FCE. The amount of cadmium deposited on FCE from electrolyte no. 1 does not exceed 4.5 g per 1 g of FCE, the deposit grows on fibers in the direction of the electrolyte bulk



**Fig. 3.** Steady-state electrode potential (*V*) of (*1*–4) cadmium electrode ( $E_{Cd}$ ) and (5, 6) FCM electrode ( $E_{FCM}$ ) vs. the dilution factor *n* of the electrolyte for the supporting solution and cadmium(II). Composition of supporting solutions (g l<sup>-1</sup>): electrolyte no. 1 (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> 150 and H<sub>3</sub>BO<sub>3</sub> 25; electrolyte no. 2 (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> 250, urotropin 20, and NF dispersant 75 ml l<sup>-1</sup>. Electrolyte dilution (*I*) by supporting solution, cadmium(II) concentration 100 mg l<sup>-1</sup>, and (*II*) by cadmium(II). Electrolyte: (2, 3, 5) no. 1 and (1, 4, 6) no. 2.

and falls-off into the solution. In the case of cadmium(II) electrodeposition from electrolyte no. 2, cadmium is deposited on the back side of the electrode and then grows into the electrode, with the amount of deposited cadmium equal to 6.0-6.5 g per 1 g of FCE.

Cadmium deposited on FCE should be regenerated and recycled into the electroplating process. A promising way to achieve this objective is anodic dissolution.

The anodic polarization curves reflecting cadmium dissolution show that cadmium dissolves without any difficulties in both the electrolytes and the potentials corresponding to a steep rise in the anodic current are close (Fig. 2). The results obtained in studying the anodic dissolution of the cadmium deposit on FCE in the supporting solutions of electrolyte nos. 1 and 2 at different anode current densities are listed in Table 1. It can be seen that cadmium well dissolves in both the solutions and the degree of dissolution increases with the current density.

If anodic polarization of an FCE by a metal is performed without separation of the electrode spaces, dissolved cadmium is deposited on the cathode to give an electrolytic powder of cadmium.

If the electrode spaces are separated with an ionexchange membrane and the anodic dissolution is performed in the supporting solution of the corresponding electrolyte, a solution of the cadmium-plating electrolyte can be obtained. Such a procedure for recycling of cadmium deposited on the FCE can be performed in the same electrolyzer that is used for electrolytic recovery of cadmium. It follows from the data of Table 1 that, depending on the anode current density, the current efficiency by cadmium exceeds 100% by a factor of 1.2-4.5 for both the electrolytes. The rate of anodic dissolution depends on the current density only slightly. If, however, the rate of the anodic dissolution of cadmium is calculated for a 100% current efficiency the rate is 4-4.5 times lower at low current densities and increases as the current density becomes higher. The electric energy expenditure for dissolution of 1 g of cadmium is low; its values differ by a factor of 5-8 for current densities of 50 and 200 A  $m^{-2}$ . If the energy expenditure for dissolution of 1 g of cadmium is calculated for a current efficiency of 100%, the difference tends to zero. The aforesaid shows that there occurs a concurrent reaction accompanied by dissolution of cadmium. Such a reaction may be cadmium dissolution through operation of a short-circuited electrochemical system (SES) constituted by FCE, cadmium, and electrolyte solution.

Measurements of the steady-state electrode potentials of cadmium ( $E_{Cd}$ ) and FCE ( $E_{FCE}$ ) in solutions of electrolyte nos. 1 and 2 demonstrated (Fig. 3) that  $E_{FCE}$  is independent of the electrolyte dilution, whereas  $E_{Cd}$  depends on the electrolyte dilution for cadmium and components of a supporting solution. For electrolyte no. 2, this dependence is more pronounced (curves 1, 4). The difference between the steady-state potentials of cadmium and FCE for both the electrolytes remains considerable (850–950 mV). Therefore, cadmium deposited on FCE must dissolve in the supporting ammonium electrolyte via SES operation.

The process of cadmium dissolution via SES operation can be independently used for cadmium regeneration, because it is a simpler cadmium regeneration technique, which has been effectively used previously for regeneration of zinc and palladium deposited on FCE [13]. The studies performed demonstrated that cadmium deposited on FCE dissolves in the supporting solution of the corresponding electrolyte at a considerable rate (Fig. 4). Solutions containing 35– 40 g l<sup>-1</sup> CdSO<sub>4</sub> were obtained as a result of the cadmium dissolution through SES operation. These solutions can be used for preparation of cadmium-plating electrolytes.

In the course of cadmium regeneration, FCE undergoes cyclic cathodic and anodic polarizations. It has been shown previously [6–9] that the FCE properties can be considerably changed in the process. Therefore, it was necessary to study how the properties of fibrous carbon electrodes change after several cycles of cadmium electrodeposition–regeneration. The results obtained in measuring the mass and the electrical conductivity of FCE after several cycles of cadmium electrodeposition–dissolution are listed in Table 2.

It follows from the data of Table 2 that, when cadmium is dissolved in a cycle through operation of a short-circuited electrochemical system, the mass of FCE and its electrical conductivity decrease. This is due to electrode processes occurring in the cathodic and anodic periods of the polarization. The decrease in the FCE mass may also be due to mechanical disintegration of carbon fibers. The electrical conductivity decreases by a factor of 1.7-2. More significant changes in the FCE properties are observed after cadmium is regenerated via anodic dissolution. The FCE mass increases, whereas the electrical conductivity decreases by a factor of 6-12, depending on the electrolyte composition. This is due to the formation of oxide groups on the surface of carbon fibers during



**Fig. 4.** Kinetic curves of dissolution of cadmium deposited onto FCE through SES operation in the supporting solutions of electrolyte nos. (1) 2 and (2) 1. Solution volume 100 ml.  $m_{Cd}$  Mass of soluble Cd,  $\tau$  time.

the anodic cycle and also to the possible interaction of the electrolyte components with the FCM fibers [6, 7]. The less pronounced changes in the electrical conductivity and FCM mass in electrolyte no. 2 may be due to adsorption of the electrolyte components (urotropin and NF dispersant) on the FCE surface.

The change in the FCE properties can affect the process of cadmium electrodeposition. Figure 5 shows the results obtained in studying the cadmium electrodeposition on FCE samples on performing five cycles of cadmium electrodeposition–dissolution. It can be seen that the parameters of the electrolytic recovery of cadmium on fibrous carbon electrodes on their cycling in electrolyte no. 1 are not deteriorated significantly, with only a 10-15% decrease in  $\alpha_{Cd}$  observed during cadmium recovery via anodic dissolu-

**Table 2.** Change in mass,  $\Delta m$ , and electrical conductivity  $\chi$  of FCE after five cycles of cadmium electrodeposition–dissolution

Cycle	Electrolyte no.	$\Delta m, \ \%$	χ, Cm cm <sup>-1</sup>
Initial FCE Electrodeposition–dissolu- tion via SES operation Electrodeposition–anodic dissolution	1 2 1 2	-6.2 -3.0 +8.2 +7.0	0.024 0.012 0.014 0.002 0.004

RUSSIAN JOURNAL OF APPLIED CHEMISTRY Vol. 80 No. 2 2007



**Fig. 5.** Kinetic curves of electrolytic recovery of cadmium(II) during electrolysis on initial and regenerated FCE from electrolyte nos. (a) 1 and (b) 2. (a) Initial cadmium concentration 300 mg l<sup>-1</sup>, n = 20, current density 500 A m<sup>-2</sup>; (b) Initial cadmium concentration 250 mg l<sup>-1</sup>, n = 5, current density 750 A m<sup>-2</sup>. ( $\alpha$ ) Degree of Cd(II) recovery, ( $\tau$ ) time. (1) Initial FCM; FCM after five cycles of cadmium electrodeposition–dissolution (2) through SES operation, and (3) via anodic dissolution.



**Fig. 6.** Polarization curves of cadmium(II) recovery in cyclic cathodic–anodic polarization of a graphite microelectrode in electrolyte nos. (1) 1, cycles 1-5; and 2: (2) 1st cycle, (3) 2nd cycle, and (4) 3rd–5th cycles.

tion (Fig. 5a). The mass of cadmium deposited per unit FCE mass changed only slightly, compared with that of the starting material.

As for the results obtained in electrolyte no. 2, the parameters of cadmium electrodeposition on the electrodes used in five cadmium electrodeposition–dissolution cycles are improved (Fig. 5b). The adhesion of deposited cadmium to the surface of carbon fibers becomes considerably better, the deposit is more uniformly distributed across the electrode thickness, and the amount of cadmium deposited per 1 g of FCE increases to 7–7.5 g.

It is known that the efficiency of the electrochemical process in 3D flow-through electrodes is characterized by a distribution of the potential, polarization, and local current densities across the electrode thickness. The change in the distribution of the electrochemical process across the thickness of the FCM electrode, which is responsible for the change in the efficiency of cadmium electrodeposition in the cyclic deposition-dissolution, may be due to presence of such components as urotropin and NF dispersant in electrolyte no. 2. Presumably, the positive effect of urotropin and NF dispersant on the electrolytic recovery of cadmium from ammonium electrolytes is accounted for by the interaction of these components with the surface of carbon fibers of the electrode during its cyclic polarization. To verify this suggestion, special polarization studies were carried out. A graphite electrode was preliminarily subjected to up to five cycles of cathodic-anodic polarization in electrolyte nos. 1 and 2 containing 300 mg  $l^{-1}$  of cadmium(II).

It follows from Fig. 6 that cyclic treatment of FCE in a solution containing no urotropin and NF dispersant (electrolyte no. 1) has virtually no effect on the run of the polarization curve (Fig. 6, curve 1). In a solution containing urotropin, the polarization curve is shifted toward electronegative potentials already after the first cycle, the slope of the second portion of the polarization curve markedly increases (Fig. 6, curve 3), and, consequently, the polarizability is enhanced, too. Renewal of the electrode surface by cutting in a solution "returns" the polarization curve to the initial state, i.e., makes the run of the polarization curve similar to that measured in the initial solution without any cyclic treatment (curve 2). The most significant changes in the cathodic portion of the curve are observed during the first three cycles of polarization (curves 3, 4), which is probably due to adsorption of urotropin and NF dispersant on the surface of carbon fibers. Further increase in the number of polarization cycles has no effect on the cathodic polarization curve.

## CONCLUSIONS

(1) It was demonstrated that cadmium(II) can be electrolytically recovered from ammonium solutions formed in catching baths on a fibrous carbon electrode. The structure of the electrolytic deposit of cadmium and its distribution across the electrode thickness depend on the solution composition. The amount of cadmium deposited per 1 g of the fibrous carbon material is 4.5-6.5 g.

(2) The polarization study showed that the current of cadmium(II) reduction depends on the composition and dilution of the solution; presence of organic substances (urotropin, NF dispersant) shifts the potential of the onset of cathodic reduction of cadmium in the negative direction and leads to a decrease in the limiting current of reduction of cadmium(II) ions and in the length of the plateau of the limiting current. The anodic process proceeds without any hindrance.

(3) The possibility of regeneration of cadmium deposited on a fibrous carbon electrode through operation of a short-circuited electrochemical cell or via anodic dissolution was demonstrated. Solutions containing 35-40 g l<sup>-1</sup> CdSO<sub>4</sub> were obtained. In the case of cadmium regeneration via anodic dissolution, an electrolytic powder of cadmium can also be obtained.

(4) A change in the mass and electrical conductivity of fibrous carbon electrodes in their cycling in electrodeposition–dissolution of cadmium was found. The most pronounced changes were observed in cadmium recovery via anodic dissolution: the mass of the electrode subjected to five cycles increased by 7-8%, whereas its electrical conductivity decreased by a factor of 6–12, depending on the solution composition.

(5) It was found that the characteristics of cadmium(II) electroreduction on fibrous carbon electrodes are not deteriorated upon their cycling. The degree of electrolytic recovery of cadmium from solutions containing organic components is 20-30% higher, the structure of the deposit and its distribution across the electrode thickness of the electrode are better, with up to 7.5 g of cadmium deposited per 1 g of electrode.

## REFERENCES

- 1. Kudryavtsev, N.T., *Elektroliticheskie pokrytiya metallami* (Electroplated Metal Coatings), Moscow: Khimiya, 1979.
- Il'in, V.A., *Tsinkovanie, kadmirovanie, luzhenie i svintsevanie* (Zinc, Cadmium, Tin, and Lead Plating), Leningrad: Mashinostroenie, 1977.
- Azhogin, F.F., Belen'kii, M.A., Gal', I.E., et al., Gal'vanotekhnika: Spravochnik (Electroplating: Reference Book), Moscow: Metallurgiya, 1987.
- 4. Varentsov, V.K., Electrochemical Processes and Apparatus with Porous Flow-Through Electrodes for Recovery of Metals from Dilute Solutions, *Doctoral Dissertation*, Sverdlovsk, 1990.
- Varentsov, V.K., Zh. Prikl. Khim., 2003, vol. 76, no. 10, pp. 1635–1638.
- Varentsov, V.K. and Varentsova, V.I., *Elektrokhimiya*, 2001, vol. 37, no. 7, pp. 811–820.
- 7. Zonova, E.B., Bratskaya, S.Yu., Artem'yanov, A.P., et al., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, 2004, vol. 47, issue 2, pp. 7–11.
- Varentsova, V.I. and Varentsov, V.K., *Zh. Prikl. Khim.*, 2005, vol. 78, no. 3, pp. 433–437.
- 9. Varentsov, V.K. and Varentsova, V.I., *Zh. Prikl. Khim.*, 1999, vol. 72, no. 4, pp. 605–609.
- Kletenik, Yu.B., Bek, R.Yu., Polyakin, L.Yu., and Zamyatin, A.P., *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Khim. Nauk*, 1985, issue 1, no. 2, pp. 93–97.
- 11. Varypaev, V.N. and Krasikov, V.L., *Zh. Prikl. Khim.*, 1980, vol. 53, no. 3, pp. 586–590.
- 12. Yatsimirskii, K.B. and Vasil'ev, V.P., *Konstanty* nestoikosti kompleksnykh soedinenii (Instability Constants of Complex Compounds), Moscow: Akad. Nauk SSSR, 1959.
- 13. Varentsova, V.I. and Varentsov, V.K., *Zh. Prikl. Khim.*, 2003, vol. 76, no. 11, pp. 1788–1793.