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Electrocatalytic reduction of aldehydes and ketones on nickel(II) tetraazamacrocyclic complex-modified graphite felt electrode

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Abstract

Electrocatalytic reduction of aldehydes and ketones was studied using a nickel(II) tetraazamacrocyclic complex-modified graphite felt (GF) electrode. The nickel(II) tetraazamacrocyclic complex-modified GF electrode was prepared by attaching nickel(II) (6-(2′-hydroxyethyl)-1,4,8,11-tetraazacyclotetradecane)perchlorate chemically to the carboxyl groups of a thin poly(acrylic acid) (PAA) layer coated on the GF. The modified electrode gave a reversible electron transfer for the nickel(II)–nickel(I) redox couple in cyclic voltammetry at −0.95 V versus Ag/AgCl. A preparative electrocatalytic reduction of aldehydes and ketones to the corresponding alcohol and pinacol compounds was successfully achieved on the modified electrode with an adequate current efficiency (46.9–75.9%), conversion (48.1–84.6%) and turnover number of the nickel catalyst (1053–2267).

Keywords: Ni(II) tetraazamacrocyclic complexes; Mediator; Modified electrode; Electrocatalytic reduction

1. Introduction

The reduction of aldehydes and ketones to alcohols is one of the important subjects in organic synthesis. This kind of reactions are usually performed by using hydrides [1] dissolving metals [1], catalytic hydrogenation [1,2] and baker yeast [3]. However, use of even a catalytic amount of the hazardous metallic reagents or expensive enzymes is a matter of economic and environmental concern [4]. Organic synthesis using mediator-modified electrodes which attached a catalyst to the surface is a simple and clean process with easy isolation of product from electrolyte solution [5]. Recently, we have reported the electrocatalytic reduction of ketones to alcohols with multiple mediator-modified electrode system such as a poly(acrylic acid) (PAA)-coated graphite felt (GF) electrode immobilizing all the components of viologen, NAD^+, diaphorase, and alcohol dehydrogenase [6]. In the present paper, we describe a single mediator-modified electrode for the electrocatalytic reduction of aldehydes and ketones to alcohols. We used here nickel complex as a single mediator. Nickel complexes such as nickel(II) cyclam (1,4,8,11-tetraazacyclotetradecane) catalyze many electroorganic reactions such as carbon–carbon bond formation [7–9], dehalogenation of organohalides [10–12], reduction of CO_2 [13,14], and oxidation of H_2O_2 [15]. However, the use of nickel complexes in the electrocatalytic reduction of aldehydes and ketones has not been reported.

2. Results and discussion

2.1. *Catalysis of nickel(II) tetraazamacrocyclic complex-modified GF electrode for aldehydes and ketones*

The preparation method of the nickel(II) (6-(2′-hydroxyethyl)-1,4,8,11-tetraazacyclotetradecane)perchlorate (**1**)-modified GF electrode is shown in Scheme 1. The reduction potential of nickel(II) to nickel(I) was found at −0.95 V versus Ag/AgCl (Fig. 1) and the amount of electroactive **1** on the electrode surface was ca. 2.4×10^{-6} mol cm^{-3}. The details of characteristic and voltammetric behavior of the **1**-modified GF electrode was described in the previous report [12].

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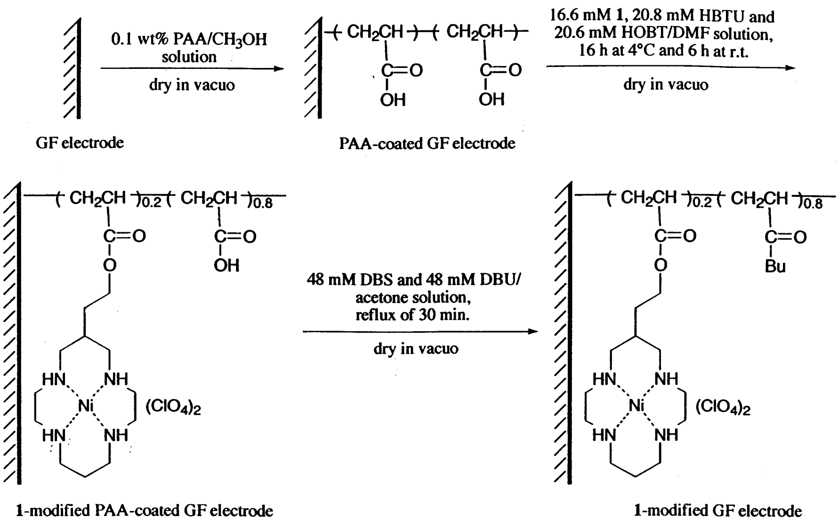


Scheme 1. Scheme for preparation of the **1**-modified GF electrode.

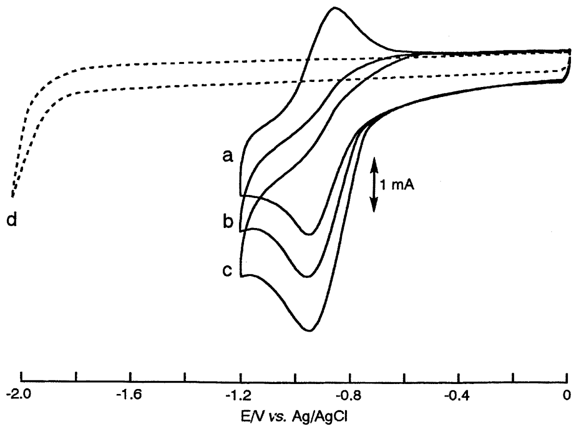


Fig. 1. Cyclic voltammograms of **1**-modified GF electrode (5 × 5 × 5 mm) at 100 mV s^{-1} in 0.1 M TEAP+CH_3CN with: (a) 0 M acetophenone, (b) 0.1 M acetophenone, and (c) 0.2 M acetophenone. (d) 0.1 M acetophenone on bare GF electrode (5 × 5 × 5 mm).

When acetophenone was added to electrolytic solution bathing the **1**-modified GF electrode, an increase of the nickel(II) reduction current was observed (Fig. 1). The nickel(I) oxidation current disappeared, and the new reduction peak current was proportional to the concentration of acetophenone. The ratio of this new reduction peak's height to the reversible nickel(II) reduction peak height decreased as scan rate increased. Acetophenone was reduced directly on a bare GF electrode in CH_3CN solution at about −1.85 V versus Ag/AgCl. All these results are characteristic [16,17] of electrochemical catalysis of the reduction of acetophenone to **1**-phenylethanol via the active (L)Ni(I) reductant. The 0.9 V positive shift in the peak potential represents a large decrease in the activation energy due to catalysis of the reduction of acetophenone. Similar results were seen with the other aldehydes and ketones used.

2.2. Macroelectrolysis of aldehydes and ketones using the nickel(II) tetraazamacrocyclic complex-modified GF electrode

Based on the cyclic voltammetry results, the preparative electrolysis reaction of acetophenone was performed at −1.0 V versus Ag/AgCl in CH_3CN solution. During electrolysis, the substrate and products were occasionally analyzed by high performance liquid chromatography (HLPC). A time course of the electrocatalytic reduction of acetophenone on a **1**-modified GF electrode is shown Fig. 2. A half millimole of acetophenone reacted about 85% in 15 h and was reduced to the corresponding alcohol and pinacol compounds. The current efficiency in the electrolysis was 75.9% during the course of electrolysis, and 1-phenylethanol and 2,3-diphenyl-2,3-butanediol were observed 39.2 (0.196) and 28.8% (0.144 mmol), respectively. The turnover number based on the amount of **1** on the electrode surface (given by the ratio of mol of products × 2 per mol of **1**) was calculated to be 2267 after 15 h of electrolysis. After electrolysis, the reduction peak current of nickel(II) to nickel(I) on the modified electrode was not decreased,

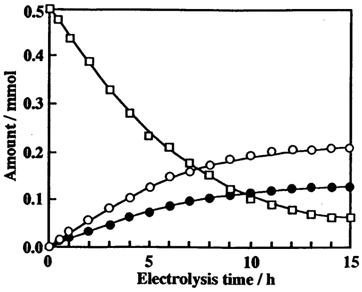
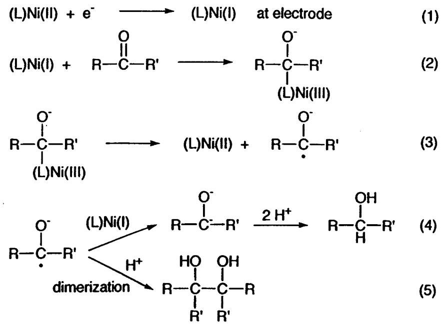


Fig. 2. Macroelectrolysis of acetophenone using a **1**-modified GF electrode in 0.1 M TEAP+CH_3CN. □, Acetophenone; ○, 1-phenylethanol; and ●, 2,3-diphenyl-2,3-butanediol.

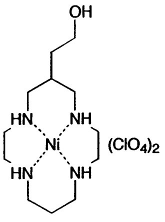
and the catalytic activity for acetophenone was also the same as for a fresh one. This means that the **1**-modified GF electrode can be used repeatedly for macroelectrolysis. In fact, the **1**-modified GF electrode has been used repeatedly more than ten times.

The results from the reduction reactions of a variety of carbonyl compounds are shown in Table 1. Preparative electrocatalytic reduction of the aldehydes and ketones was achieved successfully on a **1**-modified GF electrode with adequate current efficiency (46.9–80.1%), conversion (48.1–84.6%) and turnover number of Ni catalyst (1053–2267). Benzaldehyde and 4-methylbenzaldehyde as an aldehyde were obtained primary alchohol and pinacol compounds. On the other hand, ketones such as acetophenone, 4-methoxyacetophenone and 4-methylbenzophenone gave secondary alcohol and pinacol compounds.

On the basis of the observed products, the mechanism of electrocatalytic reduction of aldehydes and ketones with a **1**-modified GF electrode is proposed in Scheme 2. The metal complex undergoes one-electron reduction at electrode (Eq. (1)). The reduced form ((L)Ni(I)) interacts with the carbonyl compounds to yield an organometallic intermediate (Eq. (2)). The organometallic intermediate is subject to homolytic cleavage, and is led to (L)Ni(II) and anionic radical intermediate (Eq. (3)). This anionic radical intermediate can be consumed in such reactions to yield alcohols as reduction (Eq. (4)) and dimerization (Eq. (5)). In the formation of reduction product, the anionic radical intermediate again was reduced to dianionic intermediate by (L)Ni(I), and undergoes protonation to form alcohol. On the other hand, the anionic radical intermediate can dimerize and undergoes protonation to form the pinacol compound.



Scheme 2. Proposed mechanism for the electrocatalytic reduction of carbonyl compounds on the **1**-modified GF electrode.



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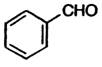
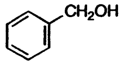
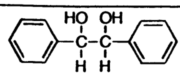
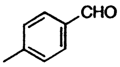
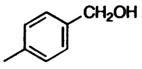
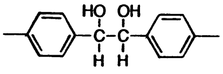
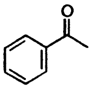
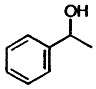
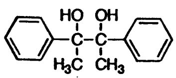
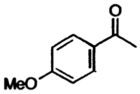
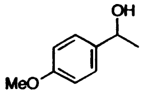
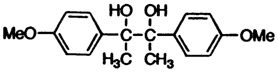
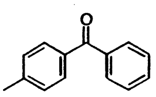
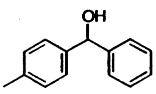
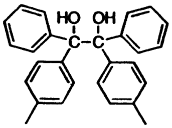
3. Experimental

3.1. Chemicals and solutions

Dry PAA (average molar mass (MW) 1 400 000) was prepared by freeze-drying a 25% w/v aqueous solution

Table 1

Electrocatalytic reduction of aldehydes and ketones using a **1**-modified GF electrode

Substrate	Products yield / %		Conversion / %	Current efficiency / %	Turnover number
	 18.8	 15.6	52.9	50.6	1147
	 17.4	 14.2	48.1	46.9	1053
	 39.2	 28.8	84.6	75.9	2267
	 36.2	 22.6	78.3	73.2	1960
	 54.2	 10.8	76.5	80.1	2166

obtained from Wako Pure Chemical Industries, Ltd. *O*-Benzotriazol-1-yl-*N,N,N′,N′*-tetramethyluronium hexafluorophosphate (HBTU) and 1-hydroxybenzotriazole hydrate (HOBT) were from Nakarai Tesque. Di-*n*-butyl sulfate (DBS) and 1,8-diazabicyclo[5.4.0]-7-undecene (DBU) were from Tokyo Chemical Industry. *N,N*-Dimethylformamide (DMF) and acetonitrile (CH_3CN) were purified by a method described in the literature [18]. Tetraethylammonium perchlorate (TEAP), ammonium perchlorate (NH_4ClO_4) and tetralin were from Tokyo Chemical Industry. All other reagents used were of commercially available reagent grade.

3.2. Synthesis of **1**

6-(2′-Hydroxyethyl)-1,4,8,11-tetraazacyclotetradecane was prepared by the procedure of Tabushi et al. [19]. Diethyl malonate (82.4 g, 0.51 mol) was added to 21 w/v% sodium ethoxide ethanol solution (100 ml). The mixture was then added to 2-bromoethanol (62.3 g, 0.5 mol), and was refluxed for 4 h. The reaction mixture was cooled and concentrated in vacuo. The residue was chromatographed on a silica gel column with 4:1 CH_3Cl–CH_3OH to give diethyl-2-ethylhydroxymalonate, as colorless oil (32.1 g, 31% yield). Then, condensation of this malonate (12.4 g, 60 mmol) with *N,N′*-bis(1-aminoethyl)-1,3-propanediamine (9.6 g, 60 mmol) in ethanol (80 ml) under reflux for 3 days gave 6-(2′-hydroxyethyl)-5,7-dioxo-1,4,8,11-tetraazacyclotetradecane (2.4 g, 15% yield), which was isolated through silica gel chromatography eluted with 3:2 CH_3Cl–CH_3OH. This cyclic diamide (1.4 g, 5 mmol) thus obtained was smoothly reduced with a large excess of diborane (0.6 g, 20 mmol) in refluxing tetrahydrofuran (50 ml) for 24 h. After treatment with 6 N HCl and KOH–CH_3OH, 6-(2′-hydroxyethyl)-1,4,8,11-tetraazacyclotetradecane was obtained in 78% yield (1.0 g) by recrystallization from benzene. This tetraazacyclotetradecane (0.4 g, 1.5 mmol) was dissolved in 10 ml of ethanol. A solution of Ni(II) perchlorate hexahydrate (1.0 g, 2.7 mmol) in 10 ml of H_2O was added dropwise with stirring. It was stirred for 3 h at room temperature (r.t.). The product crystallized from the reaction mixture and was filtered, washed with ethanol, and dried, giving 0.55 g (66% yield) of **1**.

3.3. Preparation of **1**-modified GF electrode

The preparation method of the **1**-modified GF electrode is shown in Scheme 1. A GF electrode (Nippon Kynol Inc., 50 × 20 × 5 mm) was coated with PAA by immersing it in a 0.1 w/v% methanol solution of PAA. The amount of coated PAA was 12.4×10^{-6} mol monomer units of acrylic acid (MW 72) per 1 cm^3 GF electrode. This coated electrode was then treated with 16.6 mM of **1** in DMF in the presence of 20.8 mM of HBTU and 20.6 mM of HOBT for 12 h at 4 °C and additional 6 h at r.t.. The **1**-modified GF electrode was then treated in acetone solution containing 48 mM of DBS and 48 mM of DBU at 80 °C for 30 min.

3.4. Cyclic voltammetry

The **1**-modified GF electrode (5 × 5 × 5 mm) and a platinum wire were employed as the working electrode and the counter electrode, respectively. The cathode potentials were referred to Ag/AgCl (saturated AgCl and $(CH_3)_3C_2H_5NCl$ in CH_3CN). Cyclic potential sweeps were generated by a Hokuto Denko Model HABF-501 potentiostat/galvanostat. Cyclic voltammograms were recorded on a Graphtec model WX1200 *X*–*Y* recorder. All electrochemical measurements were carried out at r.t. (ca. 20 °C) under nitrogen atmosphere.

3.5. Macroelectrolysis

Preparative potential-controlled electrolysis was performed in CH_3CN, using an ‘H’ type divided cell separated by a cationic exchange membrane (Nafion 117). The catholyte contained 0.5 mmol of substrate, 2 mmol of ammonium perchlorate (NH_4ClO_4) as a proton source, 0.5 mmol of tetralin as gas chromatographic standard and 0.5 mmol of tetraethylammonium perchlorate (TEAP) as a supporting electrolyte in a total volume of 5 ml. The anolyte was 5 ml of CH_3CN containing 0.5 mmol of TEAP. Controlled potential electrolysis was carried out at −1.0 V versus Ag/AgCl under nitrogen atmosphere. The **1**-modified GF electrode, the size of 5 × 5 × 5 mm, was used as working cathode electrode. During electrolysis, the substrate and product were arbitrarily analyzed by HLPC (Daisel CHIRALCELL-OD column, 46 mm $\phi \times 25$ cm, column temperature 40 °C, 2-propanol:*n*-hexane = 2:33, flow rate; 0.7 ml min^{-1}, detection; UV absorption at 254 nm).

4. Conclusion

The modified electrode made by linking **1** to PAA-coated GF gave reversible Ni(II)–Ni(I) voltammetry. The **1**-modified GF electrode was active for the reduction of several carbonyl compounds. A preparative electrocatalytic reduction of aldehydes and ketones to alcohols was successfully achieved on the modified electrode in adequate current efficiency, conversion and turnover number of Ni catalyst. The **1**-modified GF electrode exhibited no inactivation and thus can be used repeatedly for electrolysis.

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References

[1] M. Hudlick'y, Reduction in Organic Chemistry, Wiley, New York, 1984.

[2] N.P. Rylander, Hydrogenation Methods, Academic Press, New York, 1985.

[3] (a) B. Zhou, A.S. Gopalan, F. VanMiddlesworth, W.-R. Shieh, C.J. Sih, J. Am. Chem. Soc. 105 (1983) 5925;
(b) B. Zhou, A.S. Gopalan, F. VanMiddlesworth, W.-R. Shieh, C.J. Sih, J. Bioorg. Chem. 12 (1984) 98.

[4] J.M. Kauffman, J.R. Mckee, J. Chem. Educ. 59 (1982) 862.

[5] T. Osa, in: T. Osa (Ed.), New Challenges in Organic Electrochemistry, Gordon and Breach Science Publishers, Amsterdam, 1998, p. 183.

[6] Y. Kashiwagi, Y. Yanagisawa, N. Shibayama, K. Nakahara, F. Kurashima, J. Anzai, T. Osa, Electrochim. Acta 42 (1997) 2267.

[7] (a) S. Ozaki, T. Nakanishi, M. Sugiyama, C. Miyamoto, H. Ohmori, Chem. Pharm. Bull. 39 (1991) 31;
(b) S. Ozaki, H. Matsushita, H. Ohmori, J. Chem. Soc., Chem. Commun. (1992) 1120.;
(c) S. Ozaki, H. Matsushita, H. Ohmori, J. Chem. Soc., Perkin Trans. 1 (1993) 649;
(d) S. Ozaki, H. Matsushita, H. Ohmori, J. Chem. Soc., Perkin Trans. 1 (1993) 2339;
(e) S. Ozaki, I. Horiguchi, H. Matsushita, H. Ohmori, Tetrahedron Lett. 35 (1994) 725;
(f) S. Ozaki, H. Matsushita, M. Emoto, H. Ohmori, Chem. Pharm. Bull. 43 (1995) 32;
(g) S. Ozaki, S. Mitoh, H. Ohmori, Chem. Pharm. Bull. 45 (1995) 1435;
(h) S. Ozaki, E. Matsui, H. Ohmori, Chem. Pharm. Bull. 45 (1997) 198;
(i) S. Ozaki, E. Matsui, J. Waku, H. Ohmori, Tetrahedron Lett. 38 (1997) 2705;
(j) S. Ozaki, E. Matsui, H. Yoshinaga, H. Ohmori, Tetrahedron Lett. 39 (1998) 8121;
(k) S. Ozaki, E. Matsui, H. Yoshinaga, S. Kitagawa, Tetrahedron Lett. 41 (2000) 2621.

[8] (a) S. Olivero, J.P. Rolland, E. Duñach, Organometallics 17 (1998) 3747;
(b) S. Olivero, E. Duñach, Eur. J. Org. Chem. (1999) 185.

[9] (a) M. Ihara, F. Setsu, Y. Tokunaga, K. Fukumoto, Y. Kashiwagi, T. Osa, Chem. Pharm. Bull. 43 (1995) 362;
(b) M. Ihara, A. Katsumata, F. Setsu, Y. Tokunaga, K. Fukumoto, J. Org. Chem. 61 (1996) 677;
(c) K. Katsumata, K. Takasu, M. Ihara, Heterocycles 51 (1999) 733.

[10] K.M. Kadish, M.M. Franzen, B.C. Han, C. Araullo-McAdams, D. Saxon, Inorg. Chem. 31 (1992) 4399.

[11] G.K. Lahiri, L.J. Schussel, A.N. Stolzenberg, Inorg. Chem. 31 (1992) 4991.

[12] Y. Kashiwagi, C. Kikuchi, J. Anzai, J. Electroanal. Chem. 518 (2002) 51.

[13] (a) M. Beley, J.-P. Collin, R. Ruppert, J.-P. Sauvage, J. Chem. Soc., Chem. Commun. (1984) 1315;
(b) M. Beley, J.-P. Collin, R. Ruppert, J.-P. Sauvage, J. Am. Chem. Soc. 108 (1986) 7461.

[14] (a) M. Fujihira, Y. Hirata, K. Suga, J. Electroanal. Chem. 292 (1990) 199;
(b) M. Fujihira, Y. Nakamura, Y. Hirata, U. Akiba, K. Suga, Denki Kagaku (presently Electrochemistry) 59 (1991) 532;
(c) U. Akiba, Y. Nakamura, K. Suga, M. Fujihira, Thin Solid Films 210/211 (1992) 381.

[15] (a) K.V. Gobi, K. Tokuda, T. Ohsaka, Denki Kagaku (presently Electrochemistry) 67 (1999) 498;
(b) K.V. Gobi, K. Tokuda, T. Ohsaka, J. Electroanal. Chem. 444 (1998) 145.

[16] R.W. Murray, in: A.J. Bard (Ed.), Electroanalytical Chemistry, vol. 13, Marcel Dekker, New York, 1984, p. 191.

[17] R.W. Murray, in: R.W. Murray (Ed.), Molecular Design of Electrode Surfaces, Techniques of Chemistry Series 22, Wiley-Interscience, New York, 1992.

[18] J.A. Riddick, W.B. Bunger, Techniques of Chemistry Organic Solvents, vol. II, Wiley, New York, 1970.

[19] I. Tabushi, Y. Taniguchi H. Kato, Tetrahedron Lett. (1977) 1049.