Polymeric 2,2⁻-biquinolyl-containing Ni^{II} complexes as catalysts for the Suzuki reaction

T. V. Magdesieva,^a* O. M. Nikitin,^{a,b} O. V. Polyakova,^a A. V. Yakimansky,^c M. Ya. Goikhman,^c and I. V. Podeshvo^c

 ^aM. V. Lomonosov Moscow State University, Department of Chemistry, Build. 3, 1 Leninskie Gory, 119991 Moscow, Russian Federation. E-mail: tvm@org.chem.msu.ru
^bA. N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, 28 ul. Vavilova, 119991 Moscow, Russian Federation
^cInstitute of Polimer Compounds, Russian Academy of Sciences, 31 Bol 'shoi prosp., 199004 Saint Petersburg, Russian Federation

The Suzuki reaction with polymeric Ni catalysts based on the biquinolyl-containing polyamic acids can be carried out under conditions close to the conditions used for the catalytic transformations in the presence of Pd^{II} complexes with the same polymeric ligands. However, the yields of the cross-coupling products on the Ni catalysts are somewhat lower than those obtained in the presence of palladium complexes. The yield of the cross-coupling product increases with the increase in the conformational mobility of the polymeric ligand. Unlike catalysis by palladium complexes, in catalytic transformations by nickel complexes activation of the catalyst is required. Such an activation can be carried out either by addition of chemical reducing agents or by applying the corresponding cathodic potential (-0.8 V relative to Ag/AgCl/KCI). The electrochemical activation was shown to lead to higher yields of the cross-coupling product than the use of chemical reducing agents.

Key words: electrocatalysis, biquinolyl, Ni polymeric complexes, cross-coupling reaction.

Nickel complexes with various O-, N-, P-, and S-containing ligands are widely used in catalysis.¹⁻⁹ In many cases, they can replace more expensive Pd- and Pt-containing catalysts and maintain high activity.^{1,2,9} However, to prepare complicated polyfunctional molecules, it is necessary to develop new catalysts. Requirements, which modern catalysts should meet, are becoming increasingly severe. One of the possible approaches allowing one to combine high catalytic activity and easy isolation of the catalyst from the reaction mixture is the use of coordination complexes with polymeric ligands as the catalysts. The presence of a macroligand makes the catalytic system very susceptible to the choice of a solvent, therefore, such catalysts, as a rule, can be easily separated from the reaction mixture by adding small amounts of the corresponding solvent. Polymeric macroligand serve to stabilize coordinatively unsaturated metal centers, which usually are the most active sites in catalysis. Variation in the structure of the polymeric chain gives virtually unlimited possibilities for the "fine tuning" of the system to the required parameters and properties.

The Suzuki reaction (cross-coupling of aryl halides with arylboronic acids or tetraarylborates¹⁰⁻¹²) belongs to the pool of the most important catalytic reactions. Complexes of Ni and Pd are widely used as catalysts of this

reaction.1-4,9-13 Application of Ni catalysts, as a rule, requires introduction of an additional reducing agent (for example, Zn dust) or electrochemical activation. The reason is that the formation of an active form of the catalyst (Ni⁰ complex) needs a stronger reducing agent than, for example, NaBPh₄. Electrocatalytic processes of cross-coupling with the use of nickel complexes are known and studied in sufficient detail.^{14,15} However, little attention so far was paid to the application of Ni complexes with polymeric ligands in catalysis and electrocatalysis. Among few examples are the catalytic oxidation processes of alkenes,^{16,17} phenol¹⁶ with participation of Ni^{II} complexes with Schiff bases or bipyridyl ligands covalently bonded to the polymeric chain, a number of cross-coupling processes,¹⁸ hydroesterification of styrene in the presence of bimetallic palladium-nickel catalyst based on polyvinylpyrrolidone,¹⁹ and polymerization of ethylene, which is catalyzed by Ni complexes with the diimine ligands bound to a polymeric support.^{20,21}

Recently, we have developed an approach to the synthesis of polymeric nickel complexes based on polyamic acids (PA).²² It was shown²² that polyamic acids containing biquinolyl (biQ) fragments in the main chain can become coordinated to the Ni^{II} ions to form coordination sites of two types: with one or two biQ-ligands in the

Published in Russian in Izvestiya Akademii Nauk. Seriya Khimicheskaya, No. 6, pp. 1181-1186, June, 2012.

^{1066-5285/12/6106-1193 © 2012} Springer Science+Business Media, Inc.

coordination sphere of the Ni^{II} ion. A relative amount of the coordination sites $[Ni(biQ)_2]^{2+}$ in the polymeric chain increases as the concentration of the biQ-units in the solution increases, as well as when conformation mobility of the polymer increases. The purpose of the present work is to investigate catalytic activity of new polymeric nickel complexes in the coupling reaction of various aryl bromides and sodium tetraphenylborate both under conditions of electrocatalysis and in the presence of chemical reducing agent, the Zn dust (Scheme 1).

Scheme 1

NaBPh₄ + Ar—Hal
$$\xrightarrow{i}$$
 Ar—Ph

i. Ni–PA, Zn or electrode, *N*-methylpyrrolidone (NMP), Na₂CO₃.

Experimental

N-Methylpyrrolidone (Aldrich) was dried over calcium hydride and distilled, the fraction with the b.p. of 80 $^{\circ}$ C (7 Torr) was collected.

Acetonitrile (pure grade) was stirred for 12 h over CaH_2 and distilled. Then, it was refluxed for 2 h over P_2O_5 , followed by distillation and collection of the fraction with the b.p. of 81-82 °C (760 Torr).

Electrolysis was performed using an P-5827 M potentiostat in a 10-mL undivided electrochemical cell. Nickel wire 2 mm in diameter was used as a reference electrode, platinum was used as an auxiliary electrode. Saturated silver chloride electrode was used as a reference electrode (the potential relative to Fc/Fc^+ was -0.48 V in NMP).

Reaction mixtures were analyzed on a Finnigan MAT SSQ 7000 GC-MS spectrometer (70 eV, a DV-5 quartz capillary column (30 m), the temperature regime: 70 °C (2 min) -20 °C min⁻¹ -280 °C (10 min)).

The equilibrium geometry of the oligomers was calculated using the AMBER molecular mechanics method in the Gaussian 09 program package. The equilibrium geometry of the complexes of low-molecular-weight ligand (biQ(COOEt)₂) with Ni^{II} was calculated by DFT method (PBE, L1)²³ in the PRIRODA 9 program.²⁴

Electrochemical synthesis of polymeric Ni^{II} complexes (general procedure). Polymeric Ni^{II} complexes were synthesized by the anodic dissolution of Ni in the presence of the polymer of choice in NMP containing 0.05 *M* Bu₄NBF₄ and H₂O (10 μ L, 5.5 \cdot 10⁻⁴ mol). Nickel wire (99.99%, *d* = 2 mm, *S* = 0.38 cm²) was used as the anode, platinum wire was the cathode (*d* = 1.5 mm). Oxygen was removed by passing dry argon through the cell for 10 min just before the electrolysis and during the experiment. The electrolysis was performed in the galvanostatic mode with $I = 1 \cdot 10^{-3}$ A. An electric current of 2.1 equivalent of electricity was passed through a cell containing 10 mL of the polymer solution in NMP (with the concentration of the biQ-fragments of 10⁻³ mM). The formation of the polymeric Ni^{II} complexes was indicated by the appearance in the voltammogram of peaks corresponding to the reduction Ni^{2+/0} at the potentials –390

and -650 mV (for polymer I) and -350 and -640 mV (for polymer II).²²

The Suzuki coupling. Chemical activation of the catalyst. Sodium tetraphenylborate (0.05 mmol), Na₂CO₃ (1 mmol) (fivefold excess with respect to the starting halide), and powdered Zn (1 mg, 0.015 mmol, for the activation of the catalyst) were added to a solution of aryl halide (0.2 mmol) in NMP (5 μ L). A flow of dry argon was passed through the reaction mixture for 15 min to remove the oxygen, a 1 m*M* solution of Ni^{II}-containing catalyst in NMP (200 μ L, 0.1 mol.% as calculated to the starting halide) was added. The reaction mixture was heated at 100 °C for 4 h under argon, followed by addition of water (30 mL) and saturated aqueous NaCl, and the reaction products were extracted with diethyl ether. The yields of arylphenyls were determined by GC-MS spectrometry, using anthracene as an internal standard.

Reaction of PhBr with NaBPh₄ in the presence of the complex Ni^{II}—polymer I as a catalyst. Sodium tetraphenylborate (17 mg, 0.05 mmol), Na₂CO₃ (105 mg, 1 mmol), and powdered Zn (1 mg) were added to a solution of PhBr (31 mg, 0.2 mmol) in NMP (5 mL). Then the reaction was carried out according to the general procedure. The yield of biphenyl was 65%. MS, m/z: 154 [M⁺], 77 [M⁺ – Ph].

Reaction of PhBr with NaBPh₄ in the presence of the complex Ni^{II}—polymer II as a catalyst. Sodium tetraphenylborate (17 mg, 0.05 mmol), Na₂CO₃ (105 mg, 1 mmol), and powdered Zn (1 mg) were added to a solution of PhBr (31 mg, 0.2 mmol) in NMP (5 mL). Then the reaction was carried out according to the general procedure. The yield of biphenyl was 21%. MS, m/z: 154 [M⁺], 77 [M⁺ – Ph].

Reaction of *p*-NO₂C₆H₄Br with NaBPh₄ in the presence of the complex Ni^{II}—polymer I as a catalyst. Sodium tetraphenylborate (17 mg, 0.05 mmol), Na₂CO₃ (105 mg, 1 mmol), and powdered Zn (1 mg) were added to *p*-NO₂C₆H₄Br (41 mg, 0.2 mmol). Then the reaction was carried out according to the general procedure. The yield of *p*-nitrobiphenyl was 82%. MS, m/z: 199 [M⁺], 153 [M⁺ – NO₂], 76 [M⁺ – NO₂ – Ph].

Reaction of p-NO₂C₆H₄Br with NaBPh₄ in the presence of the complex Ni^{II}—polymer II as a catalyst. Sodium tetraphenylborate (17 mg, 0.05 mmol), Na₂CO₃ (105 mg, 1 mmol), and powdered Zn (1 mg) were added to p-NO₂C₆H₄Br (41 mg, 0.2 mmol). Then the reaction was carried out according to the general procedure at 140 °C. The yield of p-nitrobiphenyl was 62%. MS, m/z: 199 [M⁺], 153 [M⁺ – NO₂], 76 (M⁺ – NO₂ – Ph].

Reaction of *p*-MeC₆H₄Br with NaBPh₄ in the presence of the complex Ni^{II}—polymer I as a catalyst. Sodium tetraphenylborate (17 mg, 0.05 mmol), Na₂CO₃ (105 mg, 1 mmol), and powdered Zn (1 mg) were added to *p*-MeC₆H₄Br (34 mg, 0.2 mmol). Then the reaction was carried out according to the general procedure. The yield of *p*-methylbiphenyl was 34%. MS, m/z: 168 [M⁺], 153 [M⁺ – Me], 76 [M⁺ – Me – Ph].

Electrochemical activation of the catalyst. Aryl halide (0.2 mmol) was dissolved in NMP (5 mL) in an electrochemical cell in the presence of Bu_4NBF_4 (0.25 mmol), followed by addition of NaBPh₄ (0.05 mmol) and Na₂CO₃ (1 mmol). A flow of dry argon was passed through the reaction mixture for 15 min to remove the oxygen, a 1 m*M* solution of Ni^{II}-containing catalyst in NMP (200 μ L, 0.1 mol.% as calculated to the starting halide) was added. Then, electric current (0.1 C) was passed through the reaction mixture (which allowed a complete reduction of the catalyst used) in the potentiostatic mode (at the potential of -0.8 V relative to Ag/AgCl/KCl). After this, the electrochemi-

cal cell was switched off, and the solution was heated at 100 °C for 4 h under argon, then, the reaction mixture was cooled, diluted with water (30 mL), saturated with aq. NaCl, and the reaction products were extracted with diethyl with ether. The yields of arylphenyls were determined by GC-MS spectrometry, using anthracene as an internal standard.

Reaction of PhBr with NaBPh₄ in the presence of the complex Ni^{II}—polymer I as a catalyst, electrochemical activation. Sodium tetraphenylborate (17 mg, 0.05 mmol) and Na₂CO₃ (105 mg, 1 mmol) were added to a solution of PhBr (31 mg, 0.2 mmol) in NMP (5 mL). Then the reaction was carried out according to the general procedure. The yield of biphenyl was 76%. MS, m/z: 154 [M⁺], 77 [M⁺ – Ph].

Reaction of p-NO₂C₆H₄Br with NaBPh₄ in the presence of the complex Ni^{II}—polymer I as a catalyst, electrochemical activation. Sodium tetraphenylborate (17 mg, 0.05 mmol) and Na₂CO₃ (105 mg, 1 mmol) were added to p-NO₂C₆H₄Br (41 mg, 0.2 mmol) in NMP (5 mL). Then the reaction was carried out according to the general procedure. The yield of p-nitrobiphenyl was 92%. MS, m/z: 199 [M⁺], 153 [M⁺ – NO₂], 76 [M⁺ – NO₂ – Ph].

Results and Discussion

The polymers I and II, with the main chain containing the biQ-fragments capable of coordinating to Ni^{II} ions, have been chosen for the study.

Both polymers belong to the polyamic acids, however, they have a number of essential differences. Polymer I contains a coordinating biQ-fragments in each monomeric unit. The model calculations by the AMBER method for the oligomer containing four monomeric units showed that it possesses sufficient conformational mobility (Fig. 1). Due to such a mobility, the energetically favorable contacts emerge: the π -stacking interactions in the absence of nickel ions and the coordination of Ni^{II} to one or two biQ-fragments of the same or neighboring polymeric chains in the presence of Ni^{II} ions. Polymer II is a blockcopolymer, in which the biO-fragments are present only in one of the monomeric units. By varying the structure of the comonomer it is possible to obtain polymers with the desired thermomechanical properties. The introduction of ether fragments in this case makes the polymer more thermally stable, which can be important in its further use in catalytic processes. In addition, polymer II is notable

for considerable conformational rigidity due to the presence of linear *N*-phenylenediamine fragments in the polymeric chain. These fragments decrease the conformational mobility of the polymer and can influence its coordinating ability. As it has been shown in our group earlier,²² an increase in the conformational rigidity of the polymer facilitated formation of the coordination sites $[Ni(biQ)L_n]$ (n = 2-4), in which the nickel ion contained only one biQ-fragment in its ligand sphere, whereas the rest of the coordination sites was occupied by readily eliminating solvent molecules. It could be expected that such metal centers would be the most active in catalysis, as we observed earlier in the studies of catalytic activity of Cu^I complexes with analogous ligands.^{25,26}

For the sake of comparison and to reveal the role of polymeric ligands in catalytic processes, we have also chosen a low-molecular-weight analog of the polymeric complexes, *viz.*, the nickel complex with dihexyl ester of 2,2'-biquinolyl-4,4'-dicarboxylic acid (biQ(COOHex)₂). The model calculations by the DFT method (PBE, L1) showed that for the nickel ions, the formation of two octahedral coordination sites Ni[biQ(COOEt)₂](NMP)₄ and Ni[(biQ(COOEt)₂)]₂(NMP)₂ with comparable equilibrium concentrations in the NMP solution was possible (see Fig. 1). The formation of tetrahedral structures was less probable in the case of the model compounds, however, it could be fairly acceptable in the complexes with polymeric ligands.

Earlier, we have synthesized²⁷ the Pd^{II} complexes with such polymeric ligands. It turned out^{27} that these complexes displayed high catalytic activity in the Suzuki reaction. The reaction could be carried out at moderate temperatures (40–80 °C) with the use of 0.05 mol.% of the catalyst both under conditions of the homogeneous catalysis and upon immobilization of the catalyst on a graphite felt with a high specific surface area. The reaction resulted in high yields of the cross-coupling products. The immobilization of the catalyst on the graphite felt increased its activity and facilitated separation of the catalyst from the reaction products and its reuse, the catalyst turnover number reached 10⁵. It was interesting to find out, whether the Ni^{II} complexes with analogous poly-





Fig. 1. An equilibrium geometry of the tetramer corresponding to the polymer I (*a*) (calculation by the AMBER method in the Gaussian 09 program package) and the low-molecular-weight model complexes Ni[($biQ(COOEt)_2$)]₂(NMP)₂ and Ni[$biQ(COOEt)_2$](NMP)₄(*b*) (calculation by the DFT method).

meric ligands would possess such a high catalytic activity in the Suzuki reaction.

Polymeric Ni complexes were obtained by the anodic dissolution of Ni in the galvanostatic mode in the presence of polymer I or II. The formation of polymeric Ni^{II} complexes was monitored by the appearance in the voltammogram of peaks corresponding to the Ni^{2+/0} reduction at the potentials -390 and -650 mV (for polymer I) or -350 and -640 mV (for polymer II).²²

Aryl bromides with both electron-donating and electron-withdrawing substituents have been chosen for the studies. First, we used Zn dust as the chemical reducing agent to obtain an active form of the catalyst, *i.e.*, Ni^0 complex. The catalyst was involved into the reaction in the concentration of 0.1 mol.% calculated based on the starting aryl bromide. The reaction was performed under conditions of the homogeneous catalysis, using NMP as a solvent, in which polymeric complexes are readily soluble. The composition of the reaction mixture was analyzed by GC-MS spectrometry in the presence of anthracene as the internal standard. Bromobenzene, treated with the Ni complex of polymeric ligand I, reacted with sodium tetraphenylborate in the presence of a base at 100 °C to form biphenyl (65%) within 4 h, with 32% of PhBr remained unreacted. When one-half of the amount (0.05 mol.%) of palladium complex with the same polymeric ligand I was used under similar conditions, the yield of biphenyl was 92%. This indicated the lower efficiency of the Ni-con-

ArBr	Polymer I		Polymer II	
	Ni (0.1 mol.%)	Pd (0.05 mol.%)	Ni (0.1 mol.%)	Pd (0.05 mol.%)
PhBr	65	92	21	12
$4-NO_2C_6H_4Br$	82	>99	—	—

Table 1. Yields (%) of biaryls in the Suzuki reaction for Ni- and Pd-containing catalysts*

* Conditions: 0.2 mmol of ArBr, 0.05 mmol of NaBPh₄, NMP, 100 °C, 4 h, 1 mmol of Na₂CO₃, 0.015 mmol of Zn in the case of nickel.

taining catalyst. The use of the Ni complex with more conformationally rigid polymeric ligand II gave even lower yield of biphenyl (21%). Polymeric ligand II in the case of Pd-catalyst showed lower catalytic activity than polymer I, as well.²⁷ Comparative data on the yields of biaryls for both catalysts are given in Table 1.

The lower yields of the cross-coupling product observed when the conformationally more rigid ligand II was used to prepare Pd-containing catalysts can be easily explained. As we have shown earlier,²⁷ the Pd^{II} ion, irrespective of the polymeric ligand (I or II), always forms coordination sites with only one biQ-fragment in the coordination sphere of the metal ion. Two biQ-fragments cannot be accomodated in the square planar Pd^{II} complex because of steric reasons.²⁸ The complexation of Pd^{II} ions with the conformationally more rigid ligand II proceeds slowly and less efficiently, therefore, the use of the conformationally more flexible ligand I is preferable. In the case of Ni^{II}, which prefers a tetrahedral geometry or at favorable steric condition octahedral surrounding), formation of coordination sites of two types is possible, with two or one biQ-fragment in the coordination sphere of the metal ion.²⁹ It could be expected that such sites are more active in catalysis, since the presence of the weakly bound solvent molecules instead of the strong biQ-ligand in the coordination sphere of the metal provides more possibilities for the coordination of Ni^{II} with the substrate molecule. However, the experimental data given above contradict this suggestion. It can be assumed that the catalytic activity is exhibited by the coordination sites of both types due to the ability of Ni to increase its coordination number to 5-6.29 In this case, an increase in the conformational rigidity of the polymeric ligand, which hinders complexation, should lead to a decrease in the catalytic activity, and this fact is observed experimentally.

The change in the ratio Ni : biQ (1 : 1, 1 : 2, and 2 : 1) in the synthesis of polymeric Ni catalysts has little effect on the catalytic activity of the complex (Table 2). Apparently, coordination sites of both types, $[NibiQL_n]^{2+}$ and $[Ni(biQ)_2]^{2+}$, are catalytically active, which agrees with the data on the comparative activity of Ni^{II} complexes with polymeric ligands I and II given above.

The reaction is applicable to aryl bromides with both electron-donating and electron-withdrawing substituents,

and as it is usually observed for this type of the reactions, electron-withdrawing substituents accelerate the catalytic process. When these conditions are applied to chlorobenzene, no reaction takes place.

The use of the Ni^{II} complex with the low-molecularweight ligand biQ(COOHex)₂ as the catalyst under such conditions does not lead to the formation of the crosscoupling product at all. This is an evidence that the polymeric ligand plays a key role.

Electrolysis at a controlled potential can serve as an alternative to the chemical reducing agents. In the polymeric complexes with ligands I and II, the redox transition Ni^{2+/0} occurs at the potentials from -350 to -390 mV and from -640 to -650 mV for the coordination sites [Ni(biQ)₂]²⁺ and [NibiQL_n]²⁺, respectively.²² Therefore, in order to activate both forms of the complex, the electrochemical activation of the catalyst was performed at the potential of -0.8 V, a somewhat higher cathodic potential than the reduction of the coordination site with one biQ-fragment.

The catalyst was activated in an electrochemical cell in the potentiostatic mode, passing the amount of elec-

Table 2. Yields of Ph—Ar in the cross-coupling reaction of aryl halides $(2 \cdot 10^{-4} \text{ mol})$ and NaBPh₄* $(0.5 \cdot 10^{-5} \text{ mol})$ in the presence of Ni catalysts

Entry	ArHal	Catalyst, conditions	Yield of Ph—Ar (%)
1	PhBr	Ni-I	65
2	PhBr	$Ni-I$, Ni^{II} : $biQ = 2 : 1$	58
3	PhBr	$Ni-I$, Ni^{II} : $biQ = 1:1$	62
4	PhBr	Ni-II	21
5	PhBr	Ni—I, -0.8 V**	76
6	PhBr	Ni-biQCOOR	_
7	4-MeC ₆ H ₄ Br	Ni—I	34
8	$4-NO_2C_6H_4Br$	Ni-I	82
9	PhCl	Ni—I	_
10	4-NO ₂ C ₆ H ₄ Br	Ni—I, -0.8 V**	92
11	$4-NO_2C_6H_4Br$	Ni-II***	62

* Conditions: 0.1 mol.%, the ratio Ni^{II} : biQ = 1 : 2 except if stated otherwise; NMP, 100 °C, 4 h, 10^{-3} mol of Na₂CO₃. ** For the preparation of the active form of the catalyst. *** T = 140 °C. tricity, which is necessary for the quantitative reduction of the Ni complexes. After the cell was switched off, the reaction mixture was kept at a required temperature for the required period of time.

It turned out that the electrocatalytic process was more efficient than the chemical reduction (*cf.* entries 1 and 5, as well as 8 and 10, in Table 2). In addition, the electrochemical activation does not require the introduction into the reaction mixture of additional reagents, *i.e.*, reducing agents, which have to be removed afterwards.

In conclusion, the Suzuki reaction with the polymeric Ni catalysts can be carried out under conditions close to the reaction conditions used to perform reactions in the presence of Pd^{II} complexes with the same polymeric ligands. However, the yields of the cross-coupling products are somewhat lower than those obtained with the Pd complexes. In addition, catalysis by nickel complexes requires activation of the catalyst either by addition of chemical reducing agents or by applying the corresponding cathodic potential. The electrochemical activation allows one to obtain the cross-coupling products with higher yields than in the case of chemical reducing agents. An increase in the conformational mobility of the polymeric ligand also leads to the increase in the yield of the cross-coupling product.

This work was financially supported by the Russian Foundation for Basic Research (Project No. 11-03-00220-a).

References

- 1. M. Tobisu, T. Shimasaki, N. Chatani, *Angew. Chem.*, *Int. Ed.*, 2008, **47**, 4866.
- 2. J. Terao, N. Kambe, Bull. Chem. Soc. Jpn, 2006, 79, 663.
- 3. B. Sarav, Dr. Jhaveri, R. Kenneth, Dr. Carter, *Chem. Eur. J.*, 2008, **14**, 6845.
- 4. Y. Tamaru, *Modern Organonickel Chemistry*, WILEY-VCH Verlag GmbH and Co, Weinheim, 2005, 327 pp.
- 5. I. N. Houpis, J. Lee, J. Organomet. Chem., 2002, 653, 23.
- 6. B. Marciniec, Coord. Chem. Rev., 2005, 249, 2374.
- 7. E. Shirakawa, T. Hiyama, J. Organomet. Chem., 2002, 653, 114.

- B. C. Enger, R. Lodeng, A. Holmen, *Appl. Catal. A*, 2008, 346, 1.
- 9. A. C. Frisch, M. Beller, Angew. Chem., Int. Ed. 2005, 44, 674.
- 10. N. Miyaura, A. Suzuki, Chem. Rev., 1995, 95, 2457.
- 11. F. Alonso, I. P. Beletskaya, M. Yus, *Tetrahedron*, 2008, **64**, 3047.
- 12. J. Corbet, G. Mignani, Chem. Rev., 2006, 106, 2651.
- M. A. Schade, A. Metzger, S. Hug, P. Knochel, *Chem. Commun.*, 2008, 3046.
- 14. J. Y. Nedelec, J. Perichon, M. Troupel, *Top. Curr. Chem.*, 1997, **185**, 141.
- 15. A. Jutand, Chem. Rev., 2008, 108, 2300.
- K. C. Gupta, A. K. Sutar, J. Macromol. Sci. Chem., 2007, 44, 1171.
- 17. X. Han, Z. Lei, J. Macromol. Sci. Chem., 1999, 36, 1337.
- 18. P. Styring, C. Grindon, C. M. Fisher, *Catal. Lett.*, 2001, 77, 219.
- B. S. Wan, S.-J. Liao, Y. Xu, D.-R. Yu, J. Mol. Catal., Chem., 1998, 136, 263.
- F. Alobaidi, Z. Ye, S. Zhu, *Macromol. Chem.*, 2003, 204, 1653.
- 21. D. Zhang, G.-X. Jin, Appl. Catal. A, 2004, 262, 13.
- T. V. Magdesieva, O. M. Nikitin, S. M. Masoud, A. V. Yakimanskii, M. Ya. Goikhman, I. V. Podeshvo, *Russ. Chem. Bull.*, *Int. Ed.*, 2011, **60**, 1601 [*Izv. Akad. Nauk, Ser. Khim.*, 2011, 1576].
- 23. D. N. Laikov, Yu. A. Ustynyuk, Russ. Chem. Bull., Int. Ed., 2005, 54, 820 [Izv. Akad. Nauk, Ser. Khim., 2005, 804].
- 24. D. N. Laikov, Chem. Phys. Lett., 2005, 416, 116.
- T. V. Magdesieva, A. V. Dolganov, A. V. Yakimansky, M. Ya. Goikhman, I. V. Podeshvo, V. V. Kudryavtsev, *Electrochim. Acta*, 2008, 53, 3960.
- T. V. Magdesieva, A. V. Dolganov, A. V. Yakimansky, M. Ya. Goikhman, I. V. Podeshvo, *Electrochim. Acta*, 2009, 54, 1444.
- 27. T. V. Magdesieva, O. M. Nikitin, R. M. Abdullin, O. V. Polyakova, A. V. Yakimanskii, M. Ya. Goikhman, I. V. Podeshvo, *Russ. Chem. Bull.*, *Int. Ed.*, 2009, **58**, 1423 [*Izv. Akad. Nauk, Ser. Khim.*, 2009, 1382].
- 28. E. D. McKenzie, Coord. Chem. Rev., 1971, 6, 187.
- 29. F. Meyer, H. Kozlowski, in *Comprehensive Coordination Chemistry II*, Eds J. A. McCleverty, T. J. Meyer, Elsevier Ltd., Amsterdam, 2004, Vol. 6, p. 52.

Received November 11, 2011; in revised form April 19, 2012