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COMPOSITES THEORY AND PRACTICE

Milena Kurkowska[1*], Jerzy Bieliński[2], Anna Sałacińska[3], Rafał Kozera[4], Anna Boczkowska[5]

[1,3,4,5] Warsaw University of Technology, Faculty of Materials Science and Engineering, ul. Wołoska 141, 02-507 Warsaw, Poland
[2] Warsaw University of Technology, Faculty of Chemistry, ul. Noakowskiego 3, 00-664 Warsaw, Poland
**Corresponding author: E-mail: milenakurkowska88@gmail.com*

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ELECTROLESS DEPOSITION OF Ni-P/nano-SiO$_2$ COMPOSITE COATINGS ON PET AND CARBON FIBER SUBSTRATES

This paper presents the results of studies on the electroless deposition of Ni-P/nano-SiO$_2$ composite layers on pre-treated polymeric bases (PET polyester Mylar A type) and on carbon fibers (24k fibers with 7 µm Tenax rovings). The Ni-P matrix was deposited from a bath consisting of NiSO$_4$ 0.1 M; NaH$_2$PO$_2$ 0.2 M; glycine 0.21 M, with a pH = 7.5÷8.5 and thiourea added as a stabilizer, as well as cetyltrimethylammonium bromide as a surfactant. Silica powders (Sigma, grains 7 and 14 nm) were added in amounts of 10÷30 g/l, with ultrasonic homogenization of the suspension or by using a homogenizor. Under the applied experimental conditions, the deposition of composites with two types of silica on two types of substrate was carried out. The deposition was performed in the temperature range of 60÷70°C, during 5÷60 minutes, while the samples rotated at 1 rpm and the suspension was agitated with a stirrer. The composition of the deposited layers was determined by chemical methods and their surface morphology was investigated using SEM. Under the applied conditions, Ni-P/SiO$_2$ layers of a thickness within 120÷710 nm, an aluminium oxide content up to 17.3 wt.%, and 2÷3 wt.% phosphorus were obtained.

Keywords: **electroless composite deposition, Ni-P/SiO$_2$ composite layer, deposition rate and microstructure, PET and carbon fibers metallization**

BEZPRĄDOWE OSADZANIE WARSTW KOMPOZYTOWYCH Ni-P/nano-SiO$_2$ NA FOLII PET I WŁÓKNACH WĘGLOWYCH

Przedstawiono wyniki badań nad bezprądowym osadzaniem warstw kompozytowych Ni-P/SiO$_2$ na podłożach polimerowych typu Mylar (poliester PET) oraz na włóknach węglowych (wiązki 24k włókien o średnicy 7 µm Tenax). Osnowa Ni-P osadzana była z roztworu NiSO$_4$ 0,1 M; NaH$_2$PO$_2$ 0,2 M; glicyna 0,21 M, o pH = 7,5÷8,5 z dodatkiem tiomocznika jako stabilizatora oraz bromku cetylotrimetyloamoniowego jako surfaktanta. Dodawano proszków krzemu (Sigma, ziarna 7 i 14 nm) w ilości 10÷30 g/l z ultradźwiękową homogenizacją zawiesiny oraz z zastosowaniem homogenizatora. W zastosowanych warunkach doświadczeń prowadzono osadzanie na dwóch rozmiarach ziaren o nanometrycznej wielkości ziaren na dwóch rodzajach podłoża. Osadzanie prowadzono w zakresie temperatur 60÷70°C, w czasie od 5 do 60 minut, podłoża obracały się z szybkością 1 obr/min, a zawiesina mieszana była mieszadłem magnetycznym. Określano chemicznie skład osadzanych warstw oraz morfologię ich powierzchni za pomocą SEM. W zastosowanych warunkach osadzone bezprądowo warstwy kompozytowe Ni-P/SiO$_2$ o grubości 120÷710 nm zawierały do 17,3% mas tlenku krzemu oraz 2÷3% mas fosforu.

Słowa kluczowe: **bezprądowe osadzanie kompozytu Ni-P/SiO$_2$, szybkość osadzania i mikrostruktura, PET, metalizacja PET i włókien węglowych**

INTRODUCTION

The preparation of carbon fiber composites with a metallic aluminium matrix allows one to obtain material with high strength combined with low weight. However, on the interface between the carbon and aluminum, brittle Al$_4$C$_3$ material is formed by chemical reaction. The solution is a barrier coating which does not impair the mechanical properties of the final composite and at the same time ensures good adhesion to the fiber and aluminum alloy [1, 2]. In studies performed in the framework of the German-Polish project [3, 4], electroless deposition was used for a barrier layer such as Ni-P [4-7]. However, further experiments showed that with a longer time of infiltration, there is local contact of molten aluminum with the surface of the infiltrated carbon fibers. Increasing the thickness of the Ni-P coating was disadvantageous due to the introduction of a large amount of Ni and P to the aluminum alloy. However, it is possible to inhibit the dissolution of the barrier coating by co-depositing Ni-P along with more inert oxide particles. Previous experiments have shown that Ni-P/Al$_2$O$_3$ coatings contain only up to 8 wt.% oxide [7], whereas the metallization bath for the electroless deposition of an Ni-P/TiO_2 layer is highly unstable [8]. It was assumed that another oxide which could be applied in a barrier composite layer in an Ni-P matrix may be nano-SiO_2 [3].

Composite coatings consisting of a nickel matrix with an addition of SiO_2 were one of the first electrocomposites and at the beginning were used in a decorative coatings system [9]. Then, it was used as functional coatings on steel [9-11]. Electroless metallization was applied in the deposition of an Ni-P/SiO_2 composite layer on different types of substrates [10-12]. The objective was to improve the corrosion resistance [10, 13-19], to increase their hardness and wear resistance [12, 15, 16, 18, 20-25], and to obtain other functional properties [20, 22, 25]. It was found that the deposited composites exhibit better anti-corrosion or tribological properties than Ni-P coatings. Finally, a few works presented a more detailed study of the composite deposition process [15, 20, 24, 26]. Ni-P/SiO_2 coatings were deposited mostly on steel, less on copper or other metals and rarely on polymer [20, 22]. There is no information about the electroless metallization of the mentioned composite on carbon fibers or other samples with high surface area substrates. Conventional baths were used for Ni-P electroless deposition. The basic composition contained an Ni(II) salt, a hypophosphite as a reducing agent, buffering and complexing agent (hydroxyacid salts-citrates, hydroxyacetates and hydroxypropionate with the addition of acetate or propionate, sometimes some borate or ammonium salts). They were mostly acidic solutions (pH = 4.5÷5.0), less alkaline (pH = 9÷9.5 [20, 21, 26]. There is no information about other functional additives such as stabilizers (only in [13, 27] was a Pb(II) salt added) or a bath with commercial additives was used [17, 19, 24]. Additionally, there are no particular studies on the influence of the components in the solution on the deposition rate or the composition of the deposited coatings, except [20].

Ni-P/SiO_2 composite layer deposition takes place after the introducing SiO_2 powder to the Ni-P bath, usually in the form of nano-particles [13, 15-25] in amounts of 0.1 to 30 g/l. Micro-powders were used in previous studies or in selected experiments [10, 12, 26, 27]. The need for adequate mixing of the powder with the electroless bath before deposition was emphasized. Sometimes ultrasound was used as a mixing factor [13, 17, 18, 23]. The deposition was carried out with mixing the resulting suspension and the temperature range was relatively narrow (from 82 to 95°C). The basic characteristics of the deposition process of the composite coating is the relation of the content of second phase particles in the composite layers with respect to the concentration of particles in the suspension for the metallization [10, 28, 29]. Unfortunately, only a few works [20, 24, 25] contained data about the observed maximum of the SiO_2 content in the layer for the applied changes of powder concentrations in the bath. The huge variety of applied bath compositions and of electroless deposition conditions does not allow one to predict how this relationship for the deposition of Ni-P/SiO_2 from the glycine bath used in our studies might look like [7, 8, 30]. The objective of the present work was to determine the proper parameters for the electroless deposition of composite Ni-P/nano-SiO_2 layers for their use as barrier coatings in a carbon fiber-aluminum alloy system.

EXPERIMENTAL PROCEDURE

The parameters of the electroless deposition of Ni-P and Ni-P/SiO_2 layers from an alkaline glycine-buffered bath were similar to studies described earlier on the deposition of Ni-P/Al_2O_3 and of Ni-P/TiO_2 composite layers [7, 8]. They were proved initially on flat polymer foil then applied to carbon fibers roving metallization.

As the reference specimen, strips of PET foil (2.5 x 9 cm Mylar A 75 μm) were used. The way of preparing the specimen surface was precisely described in [7]. Activation of the surface with a Pd catalyst was accomplished in two steps: by immersion in $SnCl_2$ and $PdCl_2$ solutions. Immediately before metallization, the re-activation process of the catalyst was applied, involving immersion of the specimen in a reducer solution (NaH_2PO_2). The bath for Ni-P deposition was composed of 0.1 M nickel(II) sulfate, 0.2 M sodium hypophosphite (phosphate(I) sodium) and 0.21 M glycine. As a pH-regulating additive, H_2SO_4 and NaOH were used. Thiourea $SC(NH_2)_2$ was added as the stabilizer (TU, 0.02 mM), and cetyltrimethylammonium bromide - as the surfactant (CTAB, 0.1 mM).

Metallization proceeded within the 7.5÷8.5 pH range. Additionally, silicon dioxide SiO_2 powder with a 7 and 14 nm grain size (Sigma) was added as the composite nanofiller. Silicon dioxide powders in the amounts of 10 and 30 g/l were introduced at ambient temperature into the Ni-P bath. In order to obtain a stable suspension, a laboratory homogenizor and an ultrasonic disintegrator (Sonics&Materials VCX 750) were used. The main plating conditions for the electroless coatings were as follows: time - 60 minutes, temperature - 70°C and bath volume - 500 ml. The double mixing method was used; the suspension was agitated with a magnetic stirrer and the samples were rotated at 1 rpm with a mechanical stirrer. After deposition, the samples were carefully rinsed with distilled water, then dried, weighed and stored in a desiccator for further tests. Deposit composition analysis, performed just like in [7], allowed for calculation of the deposition rate and the content of Ni, P and SiO_2.

After the preliminary experiments, deposition was carried out on samples of Tenax HTA40 carbon fiber in the form of 11 cm long roving consisting of 24k fibers (7 μm in diameter). The fiber surface preparation process for their further metallization was performed in the same manner as in earlier described studies [6, 7] (in sequence: removal of epoxy resin, sizing, activation in two steps in $SnCl_2$ solution and next in a $PdCl_2$ solution, re-activation in an NaH_2PO_2+$NiSO_4$ bath, rinsing with distilled water after each individual step). The deposition time was shortened from 60 to 5÷15 minutes. The metallization process was performed in a thermostatic reactor and thermostatic ultrasonic washer (IS-20-Intersonic, 1200 W power). The deposit composition analysis was performed in the same manner as for the PET specimens. Observations of the composite coating surfaces were performed with the use of SEM (HRSEM Hitachi S5500, magnifications: 20k and 100k).

RESULTS AND DISCUSSION

Deposition of Ni-P/SiO_2 on PET substrate

The main problem in the electroless deposition of composite layers with nanofillers is to obtain a homogeneous bath with uniform dispersion of particles. Previous studies showed [7, 8] that ultrasonic deagglomeration ensures a homogenous suspension and prevents rapid sedimentation of the aluminium and titanium oxides powder in the reactor. The SiO_2 powders with a grain diameter of 7 and 14 nm had a tendency to form a colloidal solution when the disintegrator or homogenizer was used in the preparation of the powder and then ultrasonic vibration and mechanical agitation at the deposition step.

The experiment of metallization of the PET substrate (Table 1) allowed for initial visual control of the quality of the deposited coating and its adhesion to the polymer.

TABLE 1. **Ni-P/SiO_2 deposition on PET substrates from glycine buffered bath pH 8.5 - changes in process parameters**

TABELA 1. **Osadzanie powłok Ni-P/SiO_2 na folii PET z roztworu glicynowego o pH 8,5 - zmiany parametrów procesu**

SiO_2	Deposition time [min]	Deposition rate [mg/m^2*s]	P content [% mas]	SiO_2 content [% mas]	Grain size SiO_2 [nm]/ dispersion
10 g/l	60	15.8	1.9	3.6	7/hom
20 g/l	60	14.7	1.9	1.4	7/hom
30 g/l	60	15.6	2.1	4.9	7/hom
10 g/l	60	20.4	1.9	1.4	7/UD
20 g/l	60	20.4	2.1	4.3	7/UD
30 g/l	60	15.9	2.3	17.3	7/UD
10 g/l	60	21.9	1.8	2.2	14/UD
20 g/l	60	15.4	0.9	2.7	14/UD
30 g/l	60	14.7	1.0	2.9	14/UD

The deposition conditions (time 60 min; pH 7.5÷8.5; temp. 70°C) allowed us to obtain good quality coatings with a thickness within the 6÷10 μm range. Suspensions with three concentrations of SiO_2 powder - 10 g/l, 20 g/l and 30 g/l were applied. The content of nanopowder in the coatings depends mainly on the concentration of powder in the bath. The content of SiO_2 in the composite coating was 14 wt.% (7 nm grain size) and 2.2 wt.% (14 nm grain size) for 10 g/l of powder in the bath. A change to 30 g/l in the bath allowed for 17.3 wt.% (7 nm grain size) and 2.9 wt.% (14 nm grain size) content of SiO_2 in the coatings correspondingly.

Increasing the content of powder in the bath resulted in a distinct increase in the content of 7 nm grain size SiO_2 powder in the composite coating. A decrease in the rate of metallization with an increasing concentration of SiO_2 in the bath was observed. It is likely a result of covering the active Ni surface by grains of powder.

Deposition of Ni-P/SiO_2 on carbon fiber substrate

Coating of the carbon fiber substrate samples was conducted at three relatively reduced times of deposition 5, 10 and 15 minutes (Tables 2, 3).

These parameters were used because of the high load factor of the bath and rapid exhaustion of its components. That deposition time allowed us to obtain composite coatings with thicknesses up to 0.3 μm, which is demanded for the subsequent step of the aluminium infiltration process in the manufacture of an MMC [3, 4]. The other metallization parameters were the same as for the PET substrates. The glycine-buffered bath having a pH of 8.5 allowed us to obtain a coating with a phosphorus content of about 2÷3 wt.%. Increasing the content of the powder in the bath resulted in a decrease in the powder content in the composite coating. An increase in grain size did not have a significant influence on the content of the SiO_2 powder in the composite layer. The nanofiller content varied from 4 to 7 wt.%. Increasing the acidity of the solution from 8.5 to 7.5 resulted in an increase in the content of SiO_2 in the composite coating to a maximum of 13 wt.% (for smaller grain size 7 nm).

TABLE 2. **Ni-P/SiO_2 deposition on carbon fibers from glycine buffered bath pH 8.5 - changes in process parameters**

TABELA 2. **Osadzanie powłok Ni-P/SiO_2 na włóknach węglowych z roztworu glicynowego o pH 8,5 - zmiany parametrów procesu**

SiO_2	Deposition time [min]	Deposition rate [mg/cm*min]	P content [% mas]	SiO_2 content [% mas]	Grain size SiO_2 [nm]
10 g/l	5	3.8	2.7	6.3	7
	10	2.4	2.2	6.0	7
	15	2.9	2.7	4.7	7
30 g/l	5	1.5	2.9	4.8	7
	10	1.2	2.9	4.8	7
	15	0.9	2.9	7.3	7
10 g/l	5	1.3	2.3	5.9	14
	10	1.1	2.3	5.0	14
	15	1.1	2.4	7.1	14
30 g/l	5	0.5	2.4	4.2	14
	10	0.8	2.8	4.6	14
	15	0.4	2.8	3.7	14

TABLE 3. **Ni-P/SiO_2 deposition on carbon fibers from glycine buffered bath pH 7.5 - changes in process parameters**

TABELA 3. **Osadzanie powłok Ni-P/SiO_2 na włóknach węglowych z roztworu glicynowego o pH 7,5 - zmiany parametrów procesu**

SiO_2	**Deposition time [min]**	**Deposition rate [mg/cm*min]**	**P content [% mas]**	**SiO_2 content [% mas]**	**Grain size SiO_2 [nm]**
30 g/l	5	1.8	2.5	13.8	7
	10	2.9	2.6	11.1	7
	15	2.7	2.3	11.0	7
10 g/l	5	1.6	2.3	5.0	14
	10	1.6	2.4	5.8	14
	15	1.6	2.3	5.5	14
30 g/l	5	0.6	2.4	13.0	14
	10	0.9	2.3	12.1	14
	15	0.2	2.3	9.3	14

Generally, the SiO_2 powder content in the coatings on the carbon fiber was lower than on the PET foil samples. It is mainly connected with the less preferable hydrodynamic conditions of suspension flow between the fibers in the roving sample. Another cause of that relation is the considerably lower coating thickness (0.2÷0.5 μm) on the carbon fibers in comparison to over 10 μm for the PET samples. It is interesting that the codeposition of SiO_2 powder with Ni-P causes a distinct decrease in P content in the coatings (from 2÷3 wt.% to 1.5÷2 wt.%). It could decrease the amount of undesirable phosphorus introduced to the final Al/carbon fiber composite.

SEM micrographs (Fig. 1a,b,c) demonstrated that the observed surface morphology of the composite coatings are very similar to the Ni-P coatings. The micrographs proved good penetration of the bath ingredients into the substrate surface. The main problem of the deposition of the composite coating was the agglomeration of nanopowder particles in the solution and then in the coatings. The consequences of this is uneven distribution of the SiO_2 powder particles, visible on the Ni-P/SiO_2 layer (Fig. 1a,b). This effect has not been eliminated yet even in the bath containing the surfactant - CTAB. Further investigations on the inner structure of Ni-P/SiO_2 composites (cross sections and TEM microscopy), depending on the deposition process parameters are planned.

Control of the temperature at the step of preparation of the suspension and an additional dose of stabilizer introduced immediately after the start of deposition ensured the stability of the bath. Therefore, the bath could be used again after proper correction of its component concentrations and pH.

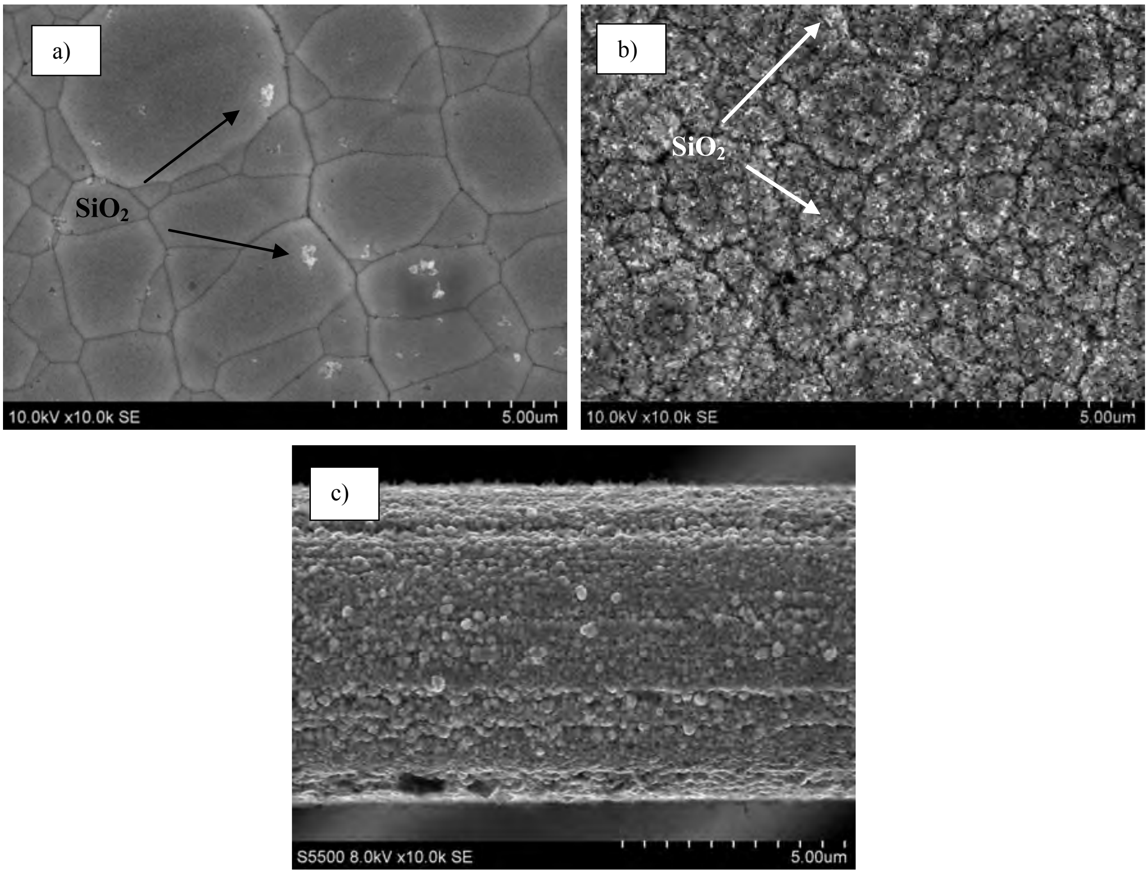

Fig. 1. Composite layer of Ni-P/SiO_2 on PET substrate obtained from glycine buffered bath with pH 8.5, deposition time 60 min: a) SiO_2 concentration 10 g/l; b) 30 g/l SiO_2; c) Ni-P/SiO_2 on carbon fibre

Rys. 1. Powłoka kompozytowa Ni-P/SiO_2 na PET otrzymana z roztworu glicynowego, pH 8,5, czas metalizacji 60 minut: a) 10 g/l SiO_2; b) 30 g/l SiO_2; c) powłoka Ni-P/SiO_2 na włóknie węglowym

CONCLUSIONS

The performed studies have led to the following conclusions:

- the addition of a stabilizer (TU) prevented spontaneous decomposition of the suspensions and an additional portion of stabilizer after deposition provides bath stability during storage,
- the results presented in Table 1 pointed out that a change in diameter of nano-SiO_2 (7 and 14 nm) additive caused an increase in the SiO_2 content in the composite up to approximately 17 wt.% (for 7 nm),
- transfer of the conditions for the deposition of composite layers developed for the PET bases is also possible for carbon fiber bases, after slight modification,
- to obtain an Ni-P/SiO_2 layer on carbon fibers, the deposition time has to be reduced to 5÷10 min, which allowed us to produce a thin average 500 nm composite layer (which is sufficient for the application as reinforcement in MMC), with a low phosphorus content (1.5÷3 wt.%),
- despite the usage of ultrasound and a homogenizer and the application of a surfactant, particle agglomeration was still observed.

Further investigations are planned to increase the stability of the metallization bath and content of nanopowder in the composite layer, as well as additional works on more effective degglomeration of silica particles in the applied bath.

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REFERENCES

[1] Morgan P., Carbon fibers in metal matrices, [In:] Carbon Fibers and their Composites, CRC Press, Boca Raton 2005.

[2] Rohatgi P.K., Tiwari V., Gupta N., Squeeze infiltration processing of nickel coated carbon fiber reinforced Al-2014 composite, J. Mater. Sci. 2006, 41, 7232 ()

[3] Sprawozdanie z realizacji polsko-niemieckiego projektu pt. „Kompozyty o osnowie aluminiowej ze wzmocnieniem tekstylnym typu 3-D (3D-CF/Al-MMC) dla elementów podlegających złożonym obciążeniom w przemyśle samochodowym i w budowie maszyn" (koord. Wydział Inżynierii Materiałowej PW; kier. prof. dr hab. inż. Krzysztof J. Kurzydłowski), Etap I. Warszawa 2008-2010. Etap II. Warszawa 2010-2012.

[4] Textile reinforced carbon fibre/aluminium matrix composites for lightweight applications, ed. A. Boczkowska, M. Gude, 2014, in press.

[5] Bieliński J., Broda A., Bielińska A., Boczkowska A., Bezprądowa metalizacja włókien węglowych dla wytwarzania kompozytów MMC, Kompozyty (Composites) 2008, 8(4), 332.

[6] Kozera R., Bieliński J., Broda A., Boczkowska A., Kurzydłowski K.J., Preparation of carbon fibres for aluminium composites, Advanced Materials Research 2011, 264-265, 1487-1491.

[7] Sałacińska A., Bieliński J., Zawadowska M., Kozera R., Boczkowska A., Kurzydłowski, Kompozyty K.J., Electroless deposition of Ni-P/nano-Al_2O_3 composite coatings, Composites Theory and Practice 2012, 12(2), 86-92.

[8] Sałacińska A., Zawadowska M., Bieliński J., Kozera R., Boczkowska A., Kurzydłowski K.J., Electroless deposition of Ni-P/nano-TiO_2 composite coatings on PET and carbon fibre substrates, Composites Theory and Practice 2013, 13(2), 86-91.

[9] Sajfullin R.S., Kombinirovannyje elektrochimiczeskije pokrytija i matieriały, Moskva, Chimija 1972.

[10] Sajfullin R.S., Nieorganiczeskije kompozicionnyje materiały, Chimija, Moskva 1983.

[11] Poradnik galwanotechnika, pr. zbiorowa; wyd. 1., red. T. Żak, WNT, Warszawa 1973; wyd. 2., red. T. Żak, Z. Kolanko, WNT, Warszawa 1985; wyd. 3, red. J. Olszewski, WNT, Warszawa 2002.

[12] Metzger W., Die Abscheidung von Nickeldispersionsschichten auf stromlosen Wege, Galvanotechnik 1972, 63(8), 722.

[13] Yu X., Wang H., Yang Z., Yin P., Xin X., XPS and AES investigation of two electroless composite coatings, Appl. Surf. Sci. 2000, 158, 335-339.

[14] Brooman E.W., Compliant electrodeposited and electroless nano-structured and nano-composite coatings to replace chromium coatings, Galvanotechnik 2005, 96(12), 2843.

[15] Petrova M., Noncheva Z., Dobreva E., Abscheidung von Nickel-Phosphor- und Nanodispersions-Nickel-Phosphor-Schichten auf Metallsubstraten, Galvanotechnik 2006, 97(9), 2115.

[16] Feng H., Hong X., Yu L., Zhi Y., Cao Y., Electroless Ni-P-SiO_2 composite coatings and their corrosion behaviors in simulated furnace flue gas, Advanced Materials Research 2010, 160-162, 1464.

[17] Rabizadeh T., Reza Allahkaram S., Corrosion resistance enhancement of Ni-P electroless coatings by incorporation of nano-SiO_2 particles, Mater. Design 2011, 32, 133-138.

[18] Hou J.Y., Research on crafts of Ni-P-Al_2O_3-SiO_2 electroless composite plating, Key Engineering Materials 2012, 501, 53.

[19] Allahkaram S.R., Zarebidaki A., Rabizadeh T., Evaluation of electroless Ni-P and Ni-P nano-composite coatings' properties, Int. J. Mod. Phys. Conf. Ser. 2012, 5, 817.

[20] Petrova M., Noncheva Z., Jakob C., Erler F., Stromlos abgeschiedene Nickel-Dispersionsschichten auf Kunstoffen. T. III. Nanoskaliger SiO_2-Dispersoid, Galvanotechnik 2002, 93(2), 370.

[21] Oberseider M., Jakob C., Petrova, M., Noncheva Z., Schawohl J., Untersuchung von chemisch abgeschiedenen nanoskaligen Nickeldispersionsschichten, Galvanotechnik 2005, 96(5), 1214.

[22] Zhang H., Liu R., Properties of Ni-P-SiO_2 (nanometer) electroless composite on PET fabrics, J. Soc. Fiber Sci. Technol. Japan 2008, 64 (12), 372.

[23] Dong D., Chen X.H., Xiao W.T., Yang G.B., Zhang P.Y., Preparation and properties of electroless Ni-P-SiO_2 composite coatings, Appl. Surf. Sci. 2009, 255, 7051.

[24] de Hazan Y., Zimmermann D., Z'graggen M., Roos S., Aneziris Ch., Bollier H., Fehr P., Graule Th., Homogeneous electroless Ni-P/SiO_2 nanocomposite coatings with improved wear resistance and modified wear behavior, Surf. Coat. Technol. 2010, 204, 3464-3470.

[25] Gutsev D., Antonov M., Hussainova I., Grigoriev A.Ya., Effect of SiO_2 and PTFE additives on dry sliding of NiP electroless coating, Tribology International 2013, 65, 295.

[26] Rudnik E., Incorporation of ceramic particles into nickel and cobalt electroless deposits, Adv. Mat. Sci. Appl. 2013, 2(1), 1.

[27] Xiong X., Xiao D., Choi M.M.F., Dissolved oxygen sensor based on fluorescence quenching of oxygen-sensitive ruthenium complex immobilized on silica-Ni-P composite coating, Sensors and Actuators B 2006, 117, 172.

[28] Balaraju J.N., Sankara Narayanan T.S.N., Seshadri S.K., Electroless Ni-P composite coatings, J. Appl. Electrochem. 2003, 33(9), 807.

[29] Sarret M., Müller C., Amell A., Electroless NiP micro- and nano-composite coatings, Surf. Coat. Technol. 2006, 201, 380.

[30] Bieliński J., Broda A., Kozera R., Bielińska A., Boczkowska A., Kurzydłowski K.J., Rola parametrów bezprądowej metalizacji w procesie wytwarzania pre-kompozytu Ni-P/włókno węglowe, Kompozyty (Composites) 2010, 10(3) 206-212.