# Electrodeposition of Layered Fe/Ni Nanowires in the External Magnetic Field — Morphological and Mössbauer Studies

U. KLEKOTKA<sup>a,\*</sup>, M. BIELICKA<sup>b</sup>, D. SATUŁA<sup>c</sup> AND B. KALSKA-SZOSTKO<sup>a</sup>

<sup>a</sup> Faculty of Chemistry, University of Bialystok, Ciołkowskiego 1K, 15-245 Białystok, Poland <sup>b</sup>Doctoral School, University of Bialystok, Ciołkowskiego 1K, 15-245 Białystok, Poland <sup>c</sup> Faculty of Physics, University of Bialystok, Ciołkowskiego 1L, 15-245 Białystok, Poland

Received: 12.08.2024 & Accepted: 24.02.2025

Doi: 10.12693/APhysPolA.147.343

\*e-mail: kalska@uwb.edu.pl

The presented paper shows a successful attempt to obtain layered Fe/Ni nanowires by electrochemical deposition in the anodized alumina matrix in the presence of an external magnetic field oriented parallel or perpendicular to the plane of the electrodes. In the experiment, various numbers and thicknesses of layers were obtained by sequential deposition. For physicochemical characterization, the obtained nanowires were imaged by scanning electron microscopy, and the amount of Fe or Ni was monitored by energy-dispersive X-ray spectroscopy. The crystal structure of the nanowires was characterized by X-ray diffraction. The magnetic properties of these materials were determined by Mössbauer spectroscopy. Analysis of the obtained data allows us to conclude that the presence of the external magnetic field changes the amount of deposited elements in favor of Fe.

topics: magnetic materials, multilayered nanowires, electrochemical deposition, Mössbauer spectroscopy

# 1. Introduction

The production of various layered nanomaterials is one of the main interests among scientists and technologists due to the possibility of merging a few unique chemical, magnetic, catalytic, mechanical, electrical, and optical properties [1] in one object. Because of the progressive miniaturization of electronics, nanowires have been investigated, especially for the application in magnetic recording media for long-term stage and easy data recovery, as well as in a few miniaturized magnetic devices [2-4]. In addition, nanowires can be used to produce biomedical materials, sound, gas sensors, and diodes or transistors in electronic circuits [5–8]. Fe–Ni alloys have become an auspicious material in recent years. Due to the possibilities of modifying the structure and regulating the magnetic properties, they are used as, e.g., electrocatalysts for renewable energy installations, batteries, etc. [9]. In general, nanomaterials can be obtained in many different ways: by wet synthesis, electrochemistry, solgel reactions, condensation, and many others [10]. One of the electrochemical methods used to obtain and modify nanomaterials into the wire or tube shape is electrodeposition in the structured matrix, which gives access to the synthesis of wire alloys. Template-based methods are often used due to their simplicity, low cost, and good controllability and scalability. Production of functional nanoparticles in a matrix allows for control of the resulting nanowires' diameter, length, and densities. There are several types of well-established matrices for this process: alumina in nanochannels (NCA) [11], polycarbonate (PC) [12], and anodized alumina (AAO) [13]. AAO matrix is one of the most commonly used due to its thermal stability, mechanical strength, and the possibility to arrange high-density nanowires. Additionally, changes in voltage or temperature during matrix preparation affect pore diameter growth and thus the nanowires [10, 11].

Fe–Ni materials can be produced by electrodeposition in many different forms: multilayers, alloys, nanowires, or core-shell objects [14, 15]. Depending on the amount of a given element in the alloy, they have different, interesting magnetic properties, which change during heat treatment, e.g., high permeability in small magnetic fields [16]. The resulting nanowire's properties largely depend on the galvanization process, pH variation, temperature, chemical conditions, cathode, current, and electrical conditions [10]. It is interesting how magnetic structures can be affected by environmental changes, for example by the application of magnetic fields during electrodeposition. The use of a uniform external magnetic field (EMF) during electroplating improves the catalytic activity and quality (e.g.,

grain size and surface roughness, which is related to the magnetohydrodynamic effect (MHD)) [17–19]. Also, the use of the EMF may cause interactions between electric and magnetic currents, leading to possible morphological changes in the nanowires, as observed for thin films [17, 20]. Additionally, if the same deposition conditions of Fe and Ni can run with different efficiency, and especially if codeposition can be influenced by an anomalous effect, the less noble metal, here Fe, is deposited preferentially [21]. Few models can explain the mechanism of anomalous deposition of the Fe–Ni alloys, e.g., kinetic characteristic, hydrogen evolution, mono hydroxide-discharge-controlled mechanism, and hydroxide suppression [19, 21, 22]. Studies show that the reason for the preferential deposition of Fe is connected with the suppression of Ni deposition because of the presence of  $Fe(OH)_2$ . This hydroxide forms preferentially on the cathode, and the deposition of Ni is strongly connected with the solution's pH and current density [23]. Therefore, it was observed that the percentage of iron content in layers was higher than the amount of nickel [24].

This paper aims to investigate the impact of an external magnetic field on the morphology and composition of electrochemically deposited nanowires, as well as to explore the mechanism behind possible Fe and Ni deposition taking place within AAO templates, and in particular to examine the selected deposition on the prestructured substrates. This type of electrodeposition of layered Fe/Ni nanowires has not been discussed to a large extent, although similar investigations were carried out for Fe [25] and CoFe nanowires [26].

## 2. Experimental details

## 2.1. Material and apparatus

To obtain multilayered nanowires, the following chemicals from Avantor were used:  $FeSO_4 \cdot 7H_2O$ ,  $NiSO_4 \cdot 7H_2O$ ,  $H_3BO_3$ ,  $C_6H_8O_6$  (ascorbic acid), acetone, and NdFeB permanent magnets (IBS Magnet).

For AAO matrix preparation, aluminum foil was used, and the following chemicals were purchased from the same supplier:  $H_3PO_4$ ,  $CrO_3$ ,  $HClO_4$ , and  $HNO_3$ . The morphology of the nanowires was observed with the use of the scanning electron microscope (SEM, Inspec S60 from FEI). The chemical composition of the nanomaterials was analyzed by energy dispersive X-ray spectroscopy (EDX) present in SEM. The crystal structure was characterized using an X-ray diffractometer SuperNova from Agilent Technologies with a Mo microfocused source with wavelength  $K_{\alpha 2} = 0.713067$  Å. Mössbauer spectra were measured using a standard spectrometer working in a constant acceleration mode with a <sup>57</sup>Co<u>Cr</u> radioactive source.

# 2.2. Anodic aluminum oxide template preparation

AAO templates for the nanowire deposition were fabricated in a 3-stage anodization procedure. Before this process, templates were cleaned with acetone and degreased in the mixture of  $HClO_4$ ,  $HNO_3$ , and distilled water in a volume ratio of 70:20:10. Finally, the dried templates were heated at  $60^{\circ}$ C for 3 h. Then, the electrochemical polishing process was performed in an ethanol and HClO<sub>4</sub> mixture in a volume ratio of 75:25. The polishing conditions were 1°C and 15 mA. A Pt electrode was used as a counter. The anodization process, in which pores in AAO were obtained, was conducted in 10% H<sub>3</sub>PO<sub>4</sub> solution at 1°C and 80 V in a three-step manner (1st -10 min, 2nd -3 h, 3rd -5 min). After every anodization step, alumina templates were dissolved for 5 min in the mixture of  $H_2CrO_4$  and  $H_3PO_4$  in a molar ratio of 0.2:0.4 heated to 60°C. After 3rd anodization, the amorphous oxide layer remained on the Al foil. Before the electrodeposition process, AAO matrixes were again placed in the same mixture of  $H_2CrO_4$  and  $H_3PO_4$  for 5 min to remove the barrier layer. More technical information about AAO matrix preparation can be found in our previous papers [13, 27]. The resulting pore diameter after the procedure was estimated to be  $170\pm20$  nm. An example SEM image of an AAO matrix is depicted in Fig. 1.

## 2.3. Preparation of nanowires

In the experiment, nanowires deposited in various sequences result in different amounts of layers. During every electrodeposition process, the magnetic field was generated by a set of two 1T magnets, placed parallel ( $\parallel$ ) or perpendicular ( $\perp$ ) to the AAO matrix plane. The schematic



Fig. 1. SEM image of AAO template.



Fig. 2. Schematic presentation of electrodeposition set-up in the presence of external magnetic field oriented (a) parallel and (b) perpendicularly to the sample plane. Abbreviations in the scheme stand for A — anode, C — cathode, DC — direct current source.

presentation of the deposition set-up is depicted in Fig. 2. Obtained magnetic field strength varied in the deposition volume according to the distance from the magnet and ranged from  $80 \times 10^{-3}$ to  $20 \times 10^{-2}$  T (with an accuracy of  $\pm 2\%$ ) [17]. The electrodeposition process was conducted in DC mode at room temperature (RT) and a current of 0.1 mA. The AAO matrix was a working electrode, and the Pt wire was a counter. The solutions used for deposition have the following compositions:  $FeSO_4 \cdot 7H_2O: H_3BO_3: C_6H_8O_6$ or  $NiSO_4 \cdot 7H_2O:H_3BO_3:C_6H_8O_6$  in molar ratio (0.12:0.48:0.02). In the last step, nanowires were released from the matrix by dissolving AAO in 1 M NaOH. Finally, the nanowires were washed with distilled water and acetone to remove unreacted residues.

As a result, 10 types of nanowires, with different layer sequences and various magnetic field arrangements, were obtained. The summary of types of nanowires is presented in Table I.

## 3. Results and discussion

## 3.1. SEM studies

The morphology of obtained nanowires released from the matrix was observed by SEM. Example images of each type of nanowires are presented in Fig. 3 (respectively parallel or perpendicular orientation of the external magnetic field, as marked).

SEM images in Fig. 3 show that elongated structures were obtained regardless of external magnetic field orientation. That proves the undisturbed growth of nanowires in the AAO matrix. Wires are organized in bunches due to their significant magnetic interaction when released from the matrix. Some residues of AAO are also seen. It is clear from the pictures that nanowires deposited

Summary of the types of nanowires (by columns): first — notation of samples with magnetic field orientation relative to the surface plane during deposition, second — time ratio, third — total time of electrodeposition process, fourth — total number of layers (Fe, Ni). For example, a time ratio of 2:3 means that the sample was prepared as follows: 2 min (Fe deposition), 3 min (Ni deposition), 2 min (Fe deposition), 3 min (Ni deposition), in a total of 10 min of the deposition.

Sample	Time ratio	Total time	Total number
Sample	(Fe:Ni)	$[\min]$	of layers Fe:Ni
$1_{\parallel}/1_{\perp}$	1:0	10	1:0
$2_{\parallel}/2_{\perp}$	5:5	10	1:1
$3_{\parallel}/3_{\perp}$	2:3	10	2:2
$4_{\parallel}/4_{\perp}$	1:3	12	3:3
$5_{\parallel}/5_{\perp}$	1:1	10	5:5
$6_{\parallel}/6_{\perp}$	0:1	10	0:1

in the presence of an external magnetic field (perpendicular or parallel) do not show any noticeable difference in morphology in comparison to undistributed growth (without external magnetic field presence) [27]. Regardless of the magnetic field orientation, obtained nanowires have similar diameters of around 190–200 nm, which is in good agreement with matrix characterization (Fig. 1). Length of the wires exceeds 5  $\mu$ m, which is especially well visible in Fig. 3a, b, and d. Shorter parts are present due to the fragmentation of larger wires due to matrix dissolution and mechanical treatment (Fig. 3d, for example).

#### 3.2. EDX studies

Multilayered nanowires were also examined by EDX to monitor if any difference in the metal ratio was caused by the variation of external magnetic field orientation. An example quantitative spectrum is depicted in Fig. 4. The obtained quantitative data analysis is presented in Table II, as a summary of all methods.

As can be seen from Table II values, in every case, Fe deposits easier than Ni, which results in a higher concentration of Fe than Ni regardless of the orientation of the external magnetic field, the number of layers, and the time of deposition of each part. Therefore, it can be concluded that the use of an external magnetic field during the electrodeposition process favors the content of the Fe element (see EDX elemental analysis column). The most significant differences in average sample composition from the theoretical one were observed in the case of sample 4 (regardless of its orientation), where the percentage of Fe exceeds the nominal value more than

# U. Klekotka et al.



Fig. 3. SEM images of Fe/Ni layered nanowires deposited with the assistance of an external magnetic field in parallel or perpendicular orientation to the surface plane.

twice. In cases where equal sequences of Fe and Ni layers are deposited, the perpendicular orientation of the external magnetic field causes the presence of a higher amount of Fe in the wires. For unequal deposition time sequences, parallel orientation causes a higher amount of Fe. This trend is observed in samples 3 and 4. A comparison of samples  $2_{\perp}$  and  $5_{\perp}$  shows that the number of layers and the time of electrodeposition are also important factors more repetitions lead to an average wire composition closer to the theoretical one. The correlation of the presented results with our previous studies on the deposition of layered Fe/Ni nanowires without an external magnetic field presence shows that applying the magnetic field influences the amount of deposited elements in favor of Fe deposits [27], but this effect is dependent on not only its orientation but also the number of repetitions, which suggests that some surface/interface effects occur.

## 3.3. X-ray diffraction

Analysis of the crystalline structure of nanowires was performed by X-ray diffraction (XRD). It allows the examination of the modification of the nanowires' crystal structure with respect to the composition and/or magnetic field orientation. For the measurements, a small number of extracted wires were glued via highly viscous oil to a nylon loop and placed in the center of the XRD goniometer. The registered results are shown in series in Fig. 5. Lattice parameters of nanowires' respective phases are given in Table II.

From the XRD patterns presented in Fig. 5, it can be concluded that in the samples assigned as  $1_{\parallel}$  and  $1_{\perp}$ , only the bcc-Fe crystal structure is seen, which is consistent with the composition (where bcc — body-centered cubic). Observed diffraction



Fig. 4. EDX spectra of Fe/Ni nanowires (sample  $3_{|}$ ). Unsigned signals are related to the dissolution of residual elements.

TA	ABLE	) II

Sample	External magnetic	Lattice parameter (Fe) $1^{1}$ $1^{1}$ $+ 0.02$	Lattice parameter (Ni) $[\text{Å}] \pm 0.02$ EDX element analysis [wt%] %Fe±1 %Ni± - 100 -	EDX element		Theoretical	
	field arientation			analysis [wt%]			
	neid orientation	$[A] \pm 0.02$		%Ni±1	%Fe	%Ni	
1		2.86	-	100	_	100	-
1	$\perp$	2.86	-	100	_	100	—
		2.86	3.51	54	46	50	50
2	$\perp$	2.87	3.52	67	33	50	50
3		2.87	3.51	71	29	40	60
	$\perp$	2.87	3.52	65	35	40	60
		2.88	3.53	59	41	25	75
4	$\perp$	2.87	3.53	48	52	25	75
5		2.86	3.50	55	45	50	50
	$\perp$	2.87	3.53	56	44	50	50
6		_	3.52	_	100	_	100
	1	_	3.52	—	100	-	100

Lattice parameters calculated from X-ray diffraction (XRD) data and quantitative elemental analysis from EDX.

maxima can be set to the following Miller indexes: (110), (200), (211), (220) typical for  $\alpha$ -Fe [28]. Samples 2–5, in both magnetic field orientations, show the coexistence of either bcc-Fe and fcc-Ni phases with the corresponding variable ratio (where fcc — face-centered cubic). There, additional peaks typical for the fcc-Ni structure can be identified, namely (111), (200), (220), (311), (222) [29]. Calculated lattice parameters of both phases are in good agreement with theoretical values ( $a_{\rm Fe} = 2.86$  Å;  $a_{\rm Ni} = 3.52$  Å), determined and published for bulk materials [30].

The zoom on the X-axis  $20 \pm 1$  deg of the most intensive peak of the diffractogram (Fig. 5c–d) depicts that the pure Fe  $(1_{\parallel}, 1_{\perp})$  wires composition has a wider peak in comparison to pure Ni  $(6_{\parallel}, 6_{\perp})$ . Moreover, the presence of the Ni layer causes a slight shift toward the lower 2theta angles of the most intensive peak. This effect also depends on the external magnetic field orientation.

## 3.4. Mössbauer spectroscopy

Changes in the magnetic properties of the nanowires were characterized with Mössbauer spectroscopy. All presented samples were measured in the AAO matrix before releasing. Therefore, the incoming  $\gamma$ -ray beam was parallel to the main axis of the wires (perpendicular to the sample surface). Obtained RT Mössbauer spectra are shown in Fig. 6



Fig. 5. XRD patterns registered for respective nanowires — a whole range of (a) perpendicular orientation of the external magnetic field and (b) parallel orientation of the magnetic field; (c) and (d) show zoom on (110) peak  $(20 \pm 1 \text{ deg})$  in (a) and (b), respectively. The red line indicates the maximum position of the (111) Ni peak, and the blue line marks the peak (110) position of Fe.

in two sets according to external magnetic field orientation (present during the growing process). To describe the shapes of the spectra, two components, one doublet (green line) and one sextet (red line), were used. The doublet dominates all measured spectra. The quadrupole splitting of the sextet was fixed and assumed to be zero in fitting procedures. The numerical results of the hyperfine parameters of the sextet are presented in Table III.

The quantitative analysis shows that the isomer shift (IS) and the quadrupole splitting (QS) of the observed doublet are the same (within error bars) for all samples and equal to  $IS = (0.22\pm0.03) \text{ mm/s}$ and  $QS = (0.32\pm0.04) \text{ mm/s}$ , respectively. The same results were obtained in our previous work for Fe/Co and Fe/Ni nanowires grown without the presence of an external magnetic field during the sample preparation [31]. The observed doublet dominates in the measured spectra, and its relative intensities vary from  $100 \pm 3\%$  (sample  $5_{\perp}$ ) to  $56 \pm 3\%$  ( $1_{\perp}$ ) and are greater than those observed in the samples of Fe/Co and Fe/Ni nanowires prepared without an external magnetic field. A discussion of its origin was performed in our previous works [27, 31]. It was concluded that the doublet is an effect of a few factors: the spontaneous oxidation process, grain boundary oxidation caused by no epitaxial growth, and non-oxygen-free experimental conditions. As we can see, using the external magnetic field during the preparation procedure enhances the oxidation process, but the reason for this should be studied in more detail elsewhere.

The observed hyperfine magnetic field (**B**) and isomer shift of the sextet for all measured samples are equal to, respectively,  $B = (33.0 \pm 0.4)$  T and IS =  $(0.01 \pm 0.02)$  mm/s. Those values agree with



Fig. 6. Mössbauer spectra of the layered Fe/Ni nanowires oriented (a) parallel and (b) perpendicular to the external magnetic field during the deposition process.

TABLE III

Hyperfine parameters of the sextet observed in Fe/Ni nanowires prepared in an external magnetic field parallel or perpendicular to the samples' surface, respectively.

Sample	IS $[mm/s]$	B[T]	$(oldsymbol{\gamma}\cdotoldsymbol{m})^2$	Rel. intens.
	$\pm 0.05$	$\pm 0.5$	$\pm 0.04$	$\pm 3\%$
$1_{\parallel}$	-0.01	33.0	0.48	28
$1_{\perp}$	0.00	33.0	0.37	44
$2_{\parallel}$	0.01	32.9	0.38	16
$2_{\perp}$	-0.02	33.1	0.44	19
$3_{\parallel}$	-	_	-	—
$3_{\perp}$	0.02	32.9	0.40	30
$4_{\parallel}$	-0.02	32.9	0.44	41
$4_{\perp}$	-0.03	33.2	0.41	17
$5_{\parallel}$	0.00	33.1	0.48	42
$5_{\perp}$	—	-	-	0

the ones observed for bcc iron at room temperature [32]. There are no components (within the error bars) originating from the alloyed Fe–Ni, which can be expected on the interface between Fe and Ni layers, suggesting that this interface is very thin.

The Mössbauer spectroscopy is a very useful method for determining the magnetic texture of Fe magnetic moments in the sample. From the transition probabilities between nucleus energy levels, one can obtain the average square of the cosine of the angle between the direction of the gamma ray and the direction of the iron magnetic hyperfine field  $(\boldsymbol{\gamma} \cdot \boldsymbol{m})^2$ , where  $\boldsymbol{\gamma}$  and  $\boldsymbol{m}$  are the units vectors of gamma beam direction and magnetic field, respectively [32–34]. In the case of random distribution of magnetic hyperfine field,  $(\boldsymbol{\gamma} \cdot \boldsymbol{m})^2$  is equal to 0.33. In the case of a perpendicular or parallel arrangement, this parameter equals 1 or 0, respectively.

The results of  $(\boldsymbol{\gamma} \cdot \boldsymbol{m})^2$  obtained for all samples indicate the almost random distribution of the magnetic hyperfine field (Table III). The same result was obtained for Fe/Ni nanowires prepared without using an external magnetic field [31]. Therefore, it can be concluded that there is no influence of the external magnetic field used during the sample preparation procedure on the distribution of the hyperfine magnetic field observed in Fe/Ni nanowires (no magnetic texture).

# 4. Conclusions

From the presented data, the following conclusion can be given. The presented SEM images of wires grown in the presence of an external magnetic field do not show any significant changes in their size or shape. The orientation of the applied external magnetic field does not influence these parameters either. Quantitative analysis of energydispersive X-ray spectroscopy shows that the application of an external magnetic field during layered Fe/Ni nanowires' deposition influences their elemental composition. The orientation of the magnetic field differently affects wires with symmetric (the same time of each layer) and not symmetric (different time) deposition. In most cases, the amount of Fe is higher than theoretically expected. Such results of composition analysis are similar to an anomalous co-deposition effect, but here they cannot be explained by it. Since the only coexistence of both elements can be after changes in the deposition bath, the matrix remains wet after the previous solution. This means that a small amount of the previous solution takes part in the deposition of the next layer. During this process, less noble metal (here Fe) is deposited preferentially. The most significant deviations in the Fe:Ni ratio are observed for nanowires in series 3 and 4, where no symmetric deposition is realized. There, significantly more (136% and 77%, respectively) Fe deposition is registered in comparison to the theoretical value (see Table II). XRD data confirms that the layered structure of the nanowires is maintained, and both bcc-Fe and fcc-Ni phases are registered in the diffractograms (Fig. 5). The Mössbauer results show that the application of the external magnetic field during nanowire deposition does not influence the magnetic texture of the iron magnetic moments.

#### Acknowledgments

EU funds partially financed the work via the project with contract numbers POPW.01.03.00-20-034/09-00 and POPW.01.03.00-20-004/11-00.

## References

- L.A. Meier, A.E. Alvarez, S.G. García, M.C. del Barrio, *Proc. Mater. Sci.* 8, 617 (2015).
- [2] K.-Z. Gao, H.N. Bertram, *IEEE Trans.* Magn. **39**, 704 (2003).
- T. Schrefl, G. Hrkac, S. Bance, D. Suess, O. Ertl, J. Fidler, in: *Handbook of Advanced Magnetic Materials*, Eds. H. Kronmüller, S. Parkin, J.E. Miltat, M.R. Scheinfein, Wiley, 2007.
- [4] H. Baqiah, N.B. Ibrahim, A.H. Shaari, Z.A. Talib, J. Supercond. Nov. Magn. 33, 3535 (2020).
- [5] M. Hernández-Vélez, *Thin Solid Films* 495, 51 (2006).

- [6] I.Z. Rahman, K.M. Razeeb, M. Kamruzzaman, M. Seratoni, J. Mater. Process. Technol. 153-154, 881 (2004).
- [7] P.D. McGary, L. Tan, J. Zou, B.J.H. Stadler, P.R. Downey, A.B. Flatau, *J. Appl. Phys.* **99**, 08B310 (2006).
- [8] Y. Cui, C.M. Lieber, Science 291, 851 (2001).
- [9] E. Barrigón, L. Hrachowina, M.T. Borgström, Nano Energy 78, 105191 (2020).
- [10] P. Christian, F. Von der Kammer, M. Baalousha, T. Hofmann, *Ecotoxicology* 17, 326 (2008).
- [11] Q.X. Guo, Y. Hachiya, T. Tanaka, M. Nishio, H. Ogawa, J. Lumin. 119–120, 253 (2006).
- [12] Y. Konishi, M. Motoyama, H. Matsushima, Y. Fukunaka, R. Ishii, Y. Ito, J. Electroanal. Chem. 559, 149 (2003).
- B. Kalska-Szostko, E. Brancewicz,
  P. Mazalski, J. Sveklo, W. Olszewski,
  K. Szymański, A. Sidor, Acta Phys. Pol. A 115, 542 (2009).
- [14] B. Godbole, N. Badera, S.B. Shrivastava, D. Jain, L.S. Sharath Chandra, V. Ganesan, *Phys. Proc.* 49, 58 (2013).
- [15] X.N. Pham, T.P. Nguyen, T.N. Pham, T.T.N. Tran T.V.T. Tran, Adv. Nat. Sci Nanosci. Nanotechnol. 7, 045010 (2016).
- [16] V. Torabinejad, M. Aliofkhazraei, S. Assareh, M.H. Allahyarzadeh, A.S. Rouhaghdam, J. Alloys Compd. 691, 841 (2017).
- [17] O. Aaboubi, K. Msellak, Appl. Surf. Sci. 396, 375 (2017).
- [18] A.M. Białostocka, M. Klekotka, U. Klekotka, B. Kalska-Szostko, *Eksploat. i Niezawodn.* 24, 687 (2022).
- [19] D.M. Dryden, T. Sun, R. McCormick, R. Hickey, R. Vidu, P. Stroeve, *Elec*trochim. Acta 220, 595 (2016).
- [20] S. Hessami, C.W. Tobias, J. Electrochem. Soc. 136, 3611 (1989).
- [21] H. Dahms, I.M. Croll, J. Electrochem. Soc. 112, 771 (1965).
- [22] Z. Li, J. Cai, S. Zhou, Trans. IMF 77, 149 (1999).
- H. Nakano, M. Matsuno, S. Oue, M. Yano,
   S. Kobayashi, H. Fukushima, *Mater. Trans.* 45, 3130 (2004).
- [24] A.M. Białostocka, U. Klekotka, P. Zabiński, B. Kalska-Szostko, Magnetohydrodynamics 53, 309 (2017).
- [25] I. Dobosz, W. Gumowska, M. Czapkiewicz, Arch. Metall. Mater. 64, 983 (2019).

- [26] S. Shamaila, M. Hassan, R. Sharif, A. Salman, *Surf. Rev. Lett.* 28, 2150071 (2021).
- [27] B. Kalska-Szostko, U. Klekotka, W. Olszewski, D. Satuła, J. Magn. Magn. Mater. 484, 67 (2019).
- [28] W. Pepperhoff, M. Acet, in: Constitution and Magnetism of Iron and Its Alloys, 1st ed., Springer, Berlin, 2001, p. 1.
- [29] B.B. Nayak, S. Vitta, A.K. Nigam, D. Bahadur, *Thin Solid Films* **505**, 109 (2006).
- [30] A. Smirnov, D. Hausner, R. Laffers, D.R. Strongin, M.A. Schoonen, *Geochem. Trans.* 9, 5 (2008).

- [31] B. Kalska-Szostko, U. Wykowska, D. Satuła, *Nukleonika* 60, 63 (2015).
- [32] N.N. Greenwood T.C. Gibb, in: *Mössbauer Spectroscopy*, Springer, Dordrecht 1971, p. 80.
- [33] M. Hasiak, M. Miglierini, J. Kaleta, J. Zbroszczyk, H. Fukunaga, Mater. Sci. 26, 167 (2008).
- [34] K. Szymański, D. Satuła, L. Dobrzyńlski, J. Phys. Condens. Matter 11, 881 (1999).