PHYSICS AND CHEMISTRY OF SOLID STATE
V. 27, No. 2 (2026) pp. 420-427

Section: Technology

DOI: 10.15330/pcss.27.2.420-427

Vasyl Stefanyk Carpathian National University

ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 27, № 2 (2026) С. 420-427

Технічні науки

UDC: 621.762

ISSN 1729-4428 (Print)
ISSN 2309-8589 (Online)

D.A. Honcharuk, G.A. Bahliuk, O.I. Khomenko, O.V. Khomenko

Physico-chemical properties of galfenols obtained on the basis of a powder alloy Fe-21.5 (wt.%) Ga

Frantsevich Institute for Problems in Materials Science of NASU, Kyiv, Ukraine, zoneipm@gmail.com

The properties of magnetostrictive materials developed on the Fe-Ga powder alloy, which is an analogue in composition of industrial galfenols - the newest materials used on underwater communications, were determined. Binary and ternary alloys obtained by forming and sintering powder mixtures of the basic composition (Fe-21.5 (wt.%) Ga), as well as with the addition of dispersed particles of carbide or nitride or titanium diboride to this mixture of strengthening powders, were studied. Powdered galfenols have high mechanical properties under compression conditions (yield (conditional) and strength limits reach up to 999 MPa and up to 1447 MPa, respectively). The electrical resistance of those ranges from 55 to 67 μΩ·cm, corresponds to the average level of electrical resistance of industrial galfenols (60–80 μΩ·cm). The magnetostriction coefficients of materials are 210 ppm (basic composition), 180 ppm (basic composition + 5 (vol.%) TiB_2) and 160…165 ppm (basic composition + 5 (vol.%) TiC; basic composition + 5 (vol.%) TiN), fully satisfies the requirements for industrial galfenols. Powder galfenol of the basic composition exhibits the greatest corrosion resistance in an environment imitating sea water and, according to the classification of the 10-point scale of corrosion resistance, belongs to the group of corrosion-resistant materials (4 points). Ternary galfenols have lower corrosion resistance and, have lower corrosion resistance and, depending on their composition, can be classified as moderately resistant materials (5-6 points).

Keywords: magnetostriction, galfenols, Fe-based powder materials, mechanical properties, elasticity, strength, corrosion resistance.

Receive 16 July 2025; Accepted 18 June 2026; Published 30 June 2026.

Introduction

Among materials with high ferromagnetic properties, a separate group by functional purpose is magnetostrictive materials, which significantly change shape and size under the influence of a magnetic field, and which include materials based on the Fe-Ga system. Developed in the early 2000s in the USA, these alloys, called galfenols, are a successful alternative to high-value alloys with a high content of rare-earth elements with low mechanical properties (e.g. Terfenol D, which has the composition Tb0.3Dy0.7Fe2) [1].

Currently, galfenols are actively used in hydroacoustic locators, underwater communication devices, in various remote control devices, etc. In the last two decades, scientific works have appeared on their use in wireless implanted devices and biodegradable implants, and currently, research directions of magnetostrictive alloys are being considered with an emphasis on their potential application in remote cell activation and bone regeneration [2, 3].

The best functional properties in galphenols are achieved at a Ga content of about 16…19 at.% (19…23 wt.%), which provides a large saturation magnetostriction, which can reach 400 ppm (1 ppm = 10^{-6}) in single crystals [4]. It has been established that doping of galphenols, in particular with rare earth metals, and some transition metals or carbides, improves their mechanical characteristics, and at the same time reduces magnetostrictive properties [5]. Which forces to look for certain compromise solutions depending on the requirements of operation.

Galphenols are obtained mainly by casting methods followed by cold and hot rolling [6, 7]. From a technical point of view, rolling cast Fe-Ga alloys is quite difficult due to their tendency to brittle fracture during deformation even at elevated temperatures [8-11].

In the last decade, scientific and technical proposals have appeared on the use of powder galphenols and composite materials containing them [12,13]. The use of powder metallurgy methods allows avoiding problems arising during thermomechanical processing of cast alloys and expanding the scope of application of galphenols, in particular, using them as powders for three-dimensional printing and as fillers for composite materials of various functional purposes. In addition, powder technologies allow relatively simple strengthening of Fe-containing materials by adding refractory and hard compounds chemically inert to the matrix, in particular titanium carbides, nitrides or borides [14], which opens up prospects for their use as alloying agents for strengthening powder galphenols.

A certain uncertainty in the behavior of galphenols in the event of aggressive envFements requires determining the corrosion resistance of the studied materials in conditions close to operational ones. Since one of the most common applications of galphenols is instruments and equipment of sea vessels, testing the corrosion resistance of these materials in an appropriate envFement that simulates sea water is relevant.

In this regard, this work studies some physical and mechanical characteristics and corrosion resistance in simulated sea water of the powder material Fe-21.5% wt. Ga, which by its main composition belongs to the group of industrial galphenols, and the effect of titanium carbides, borides or nitrides as alloying impurities on its properties was investigated.

I. Materials and methods

Sprayed Fe (99.95 (wt.%) Fe, fractions ≤100 μm) and powders of titanium monocarbide, titanium diboride and titanium nitride (99.9 (wt.%) basic comp.), were used as starting materials. Ga (99.99 (wt.%) Ga) was introduced into the mixture as part of the ligature alloy Fe-45 (wt.%) Ga. The ligature was obtained by fusing Fe with Ga at a temperature of 1200°C in pure argon for 2 hours. The mode of alloying of the components was selected according to the state diagram of the Fe-Ga system, according to which the melt of equiatomic composition crystallizes at temperatures below 1037 °C and taking into account the required degree of melt overheating [15]. Cooling of the container to room temperature was carried out together with the furnace. Before mixing with other powders, the ligature was pre-crushed and sieved into fractions <100 μm. Mixtures with different ratios of components were prepared, among which the basic composition is Fe 21.4 wt.% Ga, which, belongs to the comercial galphenols with the best functional properties [1, 2]. In addition, for comparison, technically pure Fe and double and triple compositions based on Fe with the addition of TiC, TiN or TiB$_2$ powders in an amount of 5, 10 and 15 vol. % were used in the experiments.

The finished mixtures were molded into briquettes with a diameter of 20 mm and a height of about 10 mm under a pressure of 700 MPa with the addition of boron nitride as a lubricant. After pressing out of the mold, the samples kept their shape and had no visible cracks. The pressings were placed in the chamber of an induction furnace in a graphite multi-position crucible (pure graphite), which were then filled with completely purified SiO$_2$. The main sintering temperature was 1150°C for 1 h. Previously, for the purpose of degassing, the chamber was discharged 5 times to a vacuum of 10^{-1}MPa, followed by filling with Ar (99.993 % Ar). At the beginning of heating the samples, the Ar pressure in the chamber was 0.2 MPa. The heating rate of the samples to the main sintering temperature was on average 40 degrees/min, after isothermal holding, cooling was carried out to room temperature together with the furnace. The porosity of the samples before and after sintering is presented in Table 1.

Pure Fe powders predictably had good pressability and relatively low porosity after sintering, and the addition of Ga to the mixture did not affect these characteristics. The presence of solid particles of titanium carbide, nitride or boride in mixtures of dual composition with Fe led to a deterioration in the formability of the compacts and a decrease in their shrinkage after sintering. Since such negative trends with an increase in the amount of these

Table 1.

Composition of samples and their porosity before and after sintering.

Composition of samples	Porosity of samples, %	
	Before sintering	After sintering
Fe	8…10	3…5
Basic composition (Fe-21.5 % mas.Ga)	8…10	3…5
Fe – 5 % об. TiC	10…12	6…7
Fe – 10 % об. TiC	12…14	7…8
Fe – 15 % об. TiC	12…14	9...10
Basic composition –– 5 % об. TiC	10…12	6…7
Fe – 5 % об. TiN	10…12	9…10
Fe – 10 % об. TiN	12…14	11…12
Fe – 15 % об. TiN	12…14	11…12
Basic composition –5 % об. TiN	8…10	5…6
Fe-5 % об.TiB$_2$	12…14	2…3
Fe-10 % об.TiB$_2$	12…14	6…7
Fe-15 % об.TiB$_2$	12…14	11…12
Basic composition –5 % об.TiB$_2$	8…10	2…3

compounds in the sample composition, their share in galphenols was minimal.

The phase composition of the synthesized alloys was determined by X-ray phase and quantitative micro-X-ray spectral analyses. The diffractograms were recorded on a DRON-3M spectrometer in the spot mode using the powder method (U = 35 kV, I = 35 mA) in the range 2θ = 20-90ºC. The X-ray spectrum analysis program MATCH! v.1.9. For metallographic analysis, sections were prepared in a standard metod and studied by optical and scanning electron microscope. The distribution of components in the structure of the samples was analyzed on a JEOL microscope model JSM-6490 "CAMECA" (France) at 7-10 "points" in each of the phases on different planes of the section.

Mechanical tests with samples were carried under copression load, the test results were calculated by standard methods of statistical processing to determine the average value with an error at levels up to 10%.

The determination of the specific electrical resistance ρ was carried out by the method that involves measuring the voltage drop along the length of the sample when a current passes through it and comparing this voltage drop with the voltage drop on the reference sample when the same current passes.

The magnetostrictive properties of the materials were determined by measuring the magnetostrictive constant λ , which is a dimensionless quantity and is expressed in ppm (10^{-6}) (λ = Δl/l, where Δl and l are the change in length and the initial length of the material in an external magnetic field, respectively). To observe the dynamics of the magnetization reversal processes of the research material, an experimental and test stand was used, which includes a power supply transformer with an overall capacity of 110 VA, which creates a magnetic field (Fig. 1).

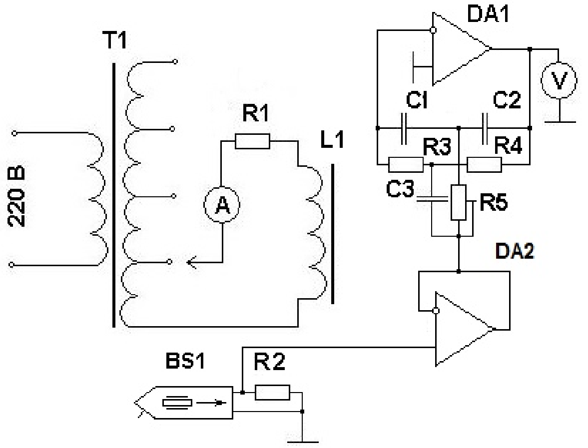


Fig. 1. Schematic electrical diagram of the equipment for recording the magnetostriction of the studied samples.

Resistor R1 with a resistance of 5 Ohm limits the current through the coil L1, the core of which is a sample of the studied material. The magnetic field strength on the coil axis was estimated as the field strength of the solenoid: H = N I / L, (N is the number of coil turns; I is the current strength through the coil, A; L is the coil length, m). The core for the coil was made of the studied materials. As a standard for comparison, a sample of the same shape and size, but made of pure powdered Fe, was used. The measurement conditions excluded parasitic vibration and mechanical resonances. As a sensitive element that perceives the movement of the core in the magnetic field, a piezoceramic head BS1 was used, which excludes extraneous resonances. The increase in the amplitude of reciprocating vibrations, referred to the height of the sample, was used to estimate the value of Δλ - the excess of the relative elongation of the sample of the studied material compared to the elongation of the sample of pure Fe.

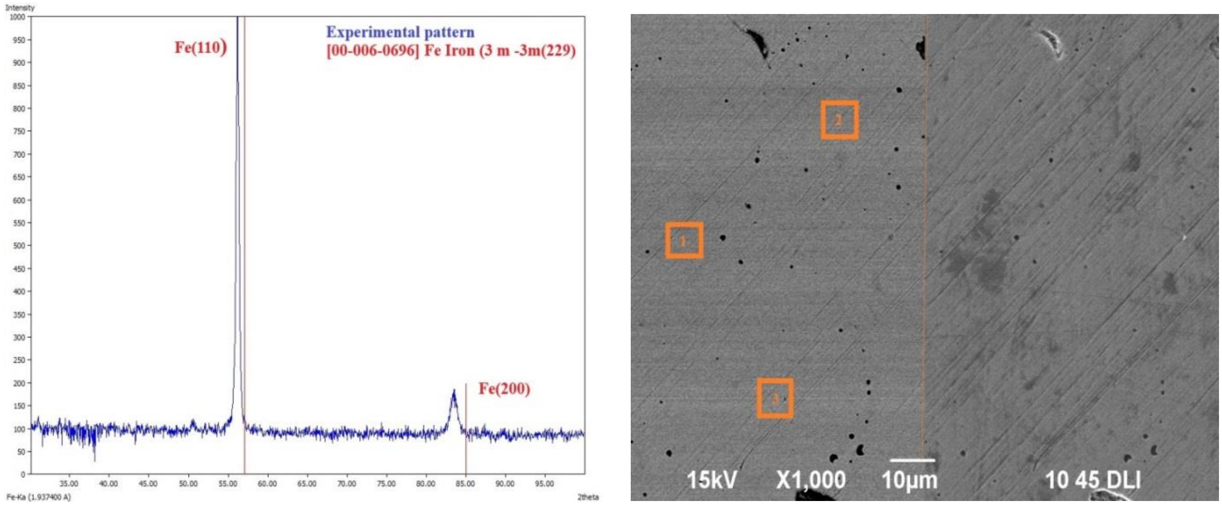
The corrosion resistance of the samples was established by the method of their prolonged immersion (141 h) in an enverement that imitates sea water - an aqueous solution of 3% NaCl (PH≈7) at a temperature of 40±5 °C. In order to prevent stagnation on the surface of the samples, which inhibit oxidation processes, the samples were periodically removed from the solution for 30 min, followed by removal and exposure for 15 min in air at a temperature of 38±5 °C. After testing, the samples were dried and weighed, before and after mechanical cleaning of corrosion product residues and ultrasonic treatment in an ethyl alcohol solution and drying in a vacuum drying oven.

The quantitative assessment of material mass loss due to corrosion was calculated using the negative corrosion index K- [15]: K- = (M_0 - M_1) / (S·τ), g/m^2·year, where: M_0 and M_1 – mass of the sample before corrosion tests and at their end, after cleaning the corrosion product from the surface of the material, g; S – sample surface area, (m^2); τ - time, h. The corrosion depth, which characterizes the reduction in the thickness of the material, is calculated using the formula: Dc = 8,76K- /d, mm/year, where: d – density of the material, g/cm^3; 8.76 – coefficient (reduced to the same dimensional values K- and d). Corrosion was assessed taking into account the change in the area of the corrosion reaction of porous samples. For this purpose, the parameter S(approx) was used, which differed from the geometrically defined S (imaginary area), and was determined based on the results of quantitative metallography of sections, using pore size distribution data (Fere diameter, AMIS program [16]), grouped into 3 main fractions.

II. Results and discussion

The base material consists of one main phase – an Fe-based solid solution, in which, according to the results of X-ray diffraction, Ga and some oxygen are present (Fig. 2a, Table 2). These data are consistent with X-ray diffraction, which showed that the spectrum of the samples does not contain reflections of other compounds, except for the lines of the bcc lattice of Fe (Fig. 2b).

According to the most famous equilibrium diagrams of Fe-Ga, published by O. Kubashevsky [17], the limiting solubility of Ga at room temperature in the bcc lattice of Fe is ~14 at.% Ga, which is significantly less than the solubility of Ga in the solid solution in the material obtained by us (21.5 (wt.%) Ga, or 17.9 (at.%) Ga), which indicates a supersaturation of the Fe solution with Ga. This is also indicated by the lattice parameter of the solid solution determined from the X-ray diffraction data,



a) b)

Fig. 2. – Diffractogram (a) and image of the microstructure of basic composition material with marks of the places of quantitative micro-X-ray spectral analysis (SEM imaging mode - on the left - secondary electrons mode, on the right – backscattered electron mode) (b).

Table 2.

Elemental composition of phases in the structure of basic composition material, determined by the method of quantitative micro-X-ray spectral analysis

N point*	O		Fe		Ga	
	(wt.%)	at.%	(wt.%)	at.%	(wt.%)	at.%
(1)	0,65	2,34	76,22	78,56	23,13	19,10
(2)	0,81	2,90	76,38	78,36	22,81	18,74
(3)	0,84	3,00	76,07	78,03	23,09	18,97

* -see fig.2 (b)

$a_{Fe\text{-}Ga}$=3.5630 Å, which is significantly larger than the lattice parameter for α-Fe (a_{Fe}=2.8665 Å, bcc, Im-3m) [18]. Probably, the formation of a solid solution of Ga in Fe with a certain deformation of the crystal lattice of the solvent causes noticeable changes in the mechanical, electrical and magnetic characteristics of the obtained material relative to Fe, as well as a cardinal change in behavior in a corrosive envFement, which will be described below.

Adding titanium carbides, nitrides or borides to the initial mixture of powdered galfenol, as expected, does not lead to a change in the composition of the solid solution in the sintered material. This is explained by the thermal stability of these alloying components under sintering conditions, which in sintered materials exist in the form of dispersed particles dispersed in the matrix phase based on Fe.

Mechanical tests have shown that galphenol of basic composition remains sufficiently plastic and does not collapse under test conditions, including pure Fe, but damaged with it, has higher characteristics in the elastic region of deformation (proportionality and elasticity limits) (Table 3).

The higher level of elastic properties of galphenol is obviously explained by the strengthening of Fe when dissolved in it by Ga, caused by deformation of the crystal lattice of the solid solution. This is a positive factor for magnetostrictive materials, since reverse magnetostrictive effects are observed precisely during deformation in the elastic region of their loading [1, 2].

The addition of dispersed particles of refractory compounds with titanium to the composition of Fe leads to a decrease in its plasticity, which is manifested in a decrease in the shrinkage deformation at the time of fracture and a deterioration in strength with an increase in the volume fraction of particles in the material structure. This effect is manifested to varying degrees in all the studied systems and is probably associated with an increase in the area of interphase boundaries, the quality of which has a significant impact on the overall strength of the material. The deterioration of mechanical properties with an increase in the number of particles in the structure makes it irrational to increase their number in galphenols above 5 (vol.%). Among galphenols, the material of the composition with TiB_2 has the greatest strengthening effect and this phenomenon may be due to the minimum porosity of the samples after sintering among others (see Table 1), and a probable increase in the adhesive bond at the interface of the refractory particle - matrix in the case of its doping with Ga.

The electrical resistance of all sintered materials of binary and ternary composition is characterized by close values 5,5…6,7 μΩ·cm. The obtained characteristics correspond to the level of electrical resistance of industrial galphenols of the based composition 6,0…8,5 μΩ·cm [19]. This is explained by the similarity of the structure and the closeness of the composition of the solid solution, which is the basis of industrial galphenols and the studied samples of both binary and ternary composition, in the latter case - due to the chemical inertness of the alloying component to the matrix. In general, the relatively high electrical resistance in functional materials that work as magnetostrictive ones contributes to reducing the costs of eddy currents, thereby improving the efficiency of their

Table 3.

Mechanical properties of samples under compression test conditions

Sample compositions	Mechanical characteristics in compression tests			
	Proportio-nality limit, MPa	Yield strength (conditional),MPa	Strength limit, МПа	Compression strain (relative reduction in sample height) %
Fe	314	335	>2761	98
Basic composition	361	379	>2083	99
Fe – 5 vol.% TiC	237	297	1834	81
Fe – 10 vol.% TiC	352	367	888	68
Fe – 15 vol.% TiC	167	204	795	77
Fe – 5 vol.% TiN	293	358	>2083	82
Fe – 10 vol.% б. TiN	212	256	1796	77
Fe – 15 vol.% .TiN	202	227	1841	86
Fe – 5 vol.% TiB_2	236	445	>2138	70
Fe – 10 vol.%	513	621	910	60
Fe – 15 vol.% TiB_2	246	391	402	21
Basic composition– 5 vol.% TiC	198	285	720	27
Basic composition–5 vol.% TiN	448	478	>2513	80
Basic composition–5 vol.% TiB_2	902	999	1447	34

operation.

According to the results of magnetic tests, the dependences of the relative elongation, Δλ, of the samples on the induction of an external magnetic field (compared to the elongation of a core made of pure iron (Fig. 3) were determined.

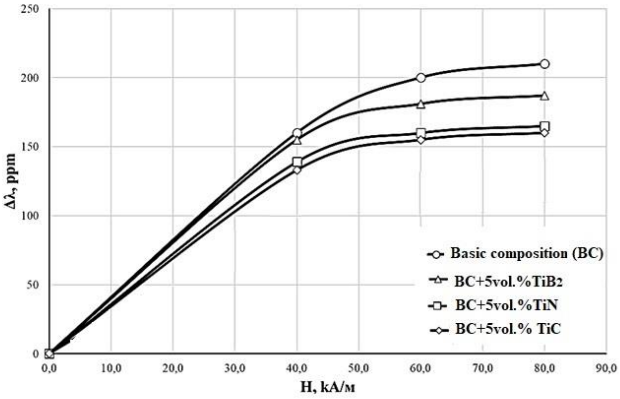


Fig. 3. - Dependences of the increase in the relative elongation of samples, Δλ, on the intensity of the alternating magnetic field.

The obtained graphs are similar to those usually obtained as a result of measurements by the strain gauge method in a constant magnetic field [20]. The test results show that the highest level magnetostriction have materials of basic composition (above 210 ppm). Lower values of magnetostriction are characterized by materials with dispersed particles of refractory compounds, among which, the material containing borides has the maximum value (above 180 ppm). This correlates with the maximum effect of strengthening the basic material in the case of adding titanium diboride to its composition. The magnetostriction of materials with additives of titanium nitride and carbide is approximately the same and is lower than in the material with titanium diboride (above 160 ppm).

According to the electrochemical voltage series, gallium has a more negative potential than pure Fe [21], which gives grounds to assume an increase in the corrosion resistance of Fe when doped with Ga due to a shift in the potential of the Fe-containing phase to a more negative charge. The results of corrosion tests of galphenols in salt solution showed that, depending on the composition, the studied materials really have a sufficiently high corrosion resistance and, on a 10-point scale of metal resistance, they belong to the groups of corrosion-resistant (4-5 points) or low-resistant materials (6 points) (Table 4).

Galfenol of the basic dual composition in terms of corrosion resistance can be compared with some stainless steels, in particular ferritic class (grades 08X18T1 and 12X17) or martensitic-ferritic class (08X13, 12X13), which gives grounds for recommending its operation in conditions of high humidity and marine climate.

The decrease in the corrosion resistance of galfenol when titanium carbides, nitrides or borides are introduced into its composition is probably due to structural factors. So, the presence of phases with different electrical conductivity in one material leads to the fact that the corroding surface of the heterophase material is a short-circuited multi-electrode galvanic cell with a difference in electrode potentials in different areas, which is the main reason for significant differences in the corrosion resistance of homogeneous and heterogeneous materials. Despite the fact that carbides, nitrides and borides of titanium are characterized by high resistance to corrosion in various environments, their presence in the structure of galphenol probably leads to accelerated dissolution (corrosion) in areas, primarily interphase boundaries, the length of which is large in the case of a sufficiently high dispersion of inclusions. But even such negative trends that accompany the alloying of galphenol with particles of refractory compounds, all the studied materials are characterized by significantly better corrosion resistance

Table 4.

Corrosion resistance of samples in laboratory corrosive environments

Sample compositions	Corrosion properties		
	The negative corrosion index K^-, g/m^2·year	The corrosion depth, D^c, mm/year	The number of points on a 10-point scale of metal resistance
Basic composition	0,14	0,02	4
Basic composition – 5 % об.TiC	0,14	0,2	6
Basic composition – 5 % об.TiN	0,09	0,1	5

than ordinary carbon steels (Ст3, 09Г2С), which belong to the group of low-resistant and unstable in non-oxidizing salt solutions (8-10 points). In work [22], the authors studied the corrosion behavior of alloys Fe–(15…27.5) (at.% Ga) in various environments using the polarization resistance method. The authors show that in a simulated marine environment the corrosion rate, depending on the composition and orientation of the crystals, is from 0.65 to 1 mm/year, which corresponds to a corrosion score of 6 on a 10-point scale. We attribute the difference in the obtained data to the peculiarities of the method for measuring corrosion potentials and corrosion rates, which, unlike the method used in our experiments, does not take into account passivation processes that can develop in conditions closer to natural ones.

Conclusions

A group of galphenols was obtained by the powder metallurgy method, among which the basic composition is Fe-21.5 (wt. %) Ga, which is an analogue of industrial materials currently provided by the casting method with subsequent polycyclic rolling. In addition, the group includes materials of ternary composition obtained by adding carbides, or nitrides or borides of titanium to the basic composition. Galphenol of the basic composition has a single-phase structure of a solid solution based on α-iron, crossed with gallium. In the structure of materials of ternary compositions, alloying impurities of the earth in the form of dispersed particles dispersed in a matrix of the same composition as the basic material.

Mechanical testing of samples of materials under compression conditions showed a significant increase in elasticity and strength, due to the deformation of the bcc lattice of α-iron and the strengthening effect of dispersed refractory particles dispersed in a solid solution. The maximum level of elasticity and strength is characterized by the composition of galphenol basic composition – 5 (vol.) % TiB_2 (yield strength - 999 MPa, tensile strength -1447 MPa).

The electrical resistance of all sintered materials of binary and ternary composition is characterized by the level of electrical resistance of industrial galphenols of the based composition.

The maximum magnetostriction coefficient is recorded for galphenol of the basic composition (210 ppm), while galphenols of ternary composition have slightly lower values of this parameter (180…160 ppm), which is due to the decrease in the amount of ferromagnetic phase in the structure of these substances and their heterogeneity.

All powder galphenols are characterized by significantly better corrosion resistance, due to technical iron and ordinary carbon steels, which are unstable in an environment simulating sea water. The highest corrosion resistance is shown by galphenol of basic composition, which is unique for the group of corrosion-resistant materials (4 points on a 10-point resistance scale). The introduction of titanium carbides, nitrides, or borides into the base composition leads to a decrease in the corrosion resistance of galphenols (5-6 points depending on the composition), which is due to the heterogeneity of these materials, in contrast to the base material, which has a homogeneous single-phase structure.

The developed powder materials can be successfully used as magnetostrictive in environments with corrosive effects of sea water.

Honcharuk D. A. – Candidate of Technical Sciences, Senior Researcher;
Bagliuk G. A. – Director of the Institute for Problems of Materials Sciencesof the National Academy of Sciences of Ukraine, Corresponding Member of National Academy of Sciences of Ukraine, Doctor of Technical Sciences;
Khomenko O. I. - Candidate of Technical Sciences, Senior Researcher;
Khomenko O. V. – Candidate of Technical Sciences, Senior Researcher.

[1] J.H. Liu, C.B. Jiang, H.B. Xu. *Giant magnetostrictive materials*. Sci. China, Ser. E: Technol. Sci. 55, 1319; (2012), https://doi.org/10.1007/s11431-012-4810-0.

[2] C. Gao, Z. Zeng, S. Peng & C. Shuai. *Magnetostrictive alloys: Promising materials for biomedical applications*. Bioactive Materials, 8, 177, (2022), https://doi.org/10.1016/j.bioactmat.2021.06.025.

[3] Patent US 8487487 B2. H.J. Timothy, G. Dietz. *Magnetostrictive actuator of a medical ultrasound transducer assembly, and a medical ultrasound hand piece and a medical ultrasound system having such actuator*, (2013).

[4] J. Boisse, H. Zapolsky, A. G. Khachaturyan. *Atomic-scale modeling of nanostructure formation in Fe–Ga alloys with giant magnetostriction: Cascade ordering and decomposition*. Acta Materialia, 59(7), 2656, (2011), https://doi.org/10.1016/j.actamat.2011.01.002.

[5] Q. Xing, Y. Du, R.J. McQueeney, T.A. Lograsso. *Structural investigations of Fe–Ga alloys: Phase relations and magnetostrictive behavior*. Acta Materialia, 2008. 56(16),4536, https://doi.org/10.1016/j.actamat.2008.05.011.

[6] I.S. Golovin, V.V. Palacheva, V.Yu, Zadorozhnyy, J., Zhu. *Influence of composition and heat treatment on damping and magnetostrictive properties of Fe-18%(Ga + Al) alloys*. Acta Materialia, 78, 93, (2014), https://ui.adsabs.harvard.edu/link_gateway/2014AcMat..78...93G/doi:10.1016/j.actamat.2014.05.044.

[7] Na S.M., Flatau A.B. *Deformation behavior and magnetostriction of polycrystalline Fe–Ga–X (X = B, C, Mn, Mo, Nb, NbC) alloys*. J. Appl. Phys.,103, 1, (2008), https://doi.org/10.1063/1.2838772.

[8] A.J. Boesenberg, J.B. Restorff, M. Wun-Fogle, H. Sailsbury, E. Summers. *Texture development in Galfenol wire*. J. Appl. Phys. 113(17), (2013), https://doi.org/10.1063/1.4794186.

[9] I. Gervasyeva, V. Milyutin, N. Nikolaeva. *The structure and properties of* $Fe_{85}Ga_{15}$ *and* $Fe_{87}Ga_{13}$ *alloys after hydroextrusion deformation and subsequent annealing*. Materials Today Proceeding, 19, 2258, (2019), https://doi.org/10.1016/j.matpr.2019.07.591.

[10] D. I. Holsworth, D. L.. Du. Quesnay. *Fatigue properties of Galfenol steels*. Intern. Journal of Fatigue, 128, 105177, (2019), https://doi.org/10.1016/j.ijfatigue.2019.06.037.

[11] T. Takahashi, T. Okazaki Y. , Furuya. *Improvement in the mechanical strength of magnetostrictive (Fe–Ga-Al)–X–C (X = Zr, Nb and Mo) alloys by carbide precipitation*. Scr. Mater., 61, 5, (2009), https://doi.org/10.1016/j.scriptamat.2008.12.032.

[12] T. Grigorieva, S. G. Kovaliova, V. Senyut. *Thermobaric Sintering of Mechanocomposites of the System Fe-Ga*. Journal of Materials Science and Engineering B, 5(8), 270 (2015), https://doi.org/10.17265/2161-6221/2015.7-8.003.

[13] S. M. Na, J. Galuardi, , A. B. Flatau. *Consolidation of (001)-Oriented Fe–Ga Flakes for 3-D Printing of Magnetostrictive Powder Materials*. IEEE Transactions on Magnetics, 53(11), 14, (2017), https://doi.org/10.1109/tmag.2017.2697865.

[14] Chaus A.S. , Dománková M. *Unknown high-speed steel*. Materials Letters, 292, 129653, (2021), https://doi.org/10.1016/j.matlet.2021.

[15] I. Alimov, Z.A. Duriagina. Corrosion and protection of metals from corrosion (Donetsk-Lviv: LLC "Eastern Publishing House", 2012).

[16] Khomenko, A.I., Khomenko, E.V. Microstructural analysis software package. *Powder Metall Met Ceram* **46**, 100–104 (2007). https://doi.org/10.1007/s11106-007-0016-6

[17] Kubaschewski O. Iron-Binary Phase Diagrams. Springer, Berlin, 1982. http://link.springer.com/book/10.1007%2F978-3-662-08024-5.

[18] A. Arblaster, John W. Selected Values of the Crystallographic Properties of Elements (Materials Park, Ohio: ASM International, 2018).

[19] I. S. Golovin, V. V. Palacheva, A. K. Mohamed, A. M. Balagurov. *Structure and Properties of Fe–Ga Alloys as Promising Materials for Electronics*. Physics of Metals and Metallograph, 9, 851, (2020), https://doi.org/10.1134/s0031918x20090057.

[20] Y. He, C. Jiang, W. Wu, and all. *Giant heterogeneous magnetostriction in Fe–Ga alloys: Effect of trace element doping*. Acta Materialia, 109,177, (2016), https://doi.org/10.1016/j.actamat.2016.02.056.

[21] Tables of Standard Electrode Potential. Ed. by G. Milazzo (Wiley: London, 1978).

[22] V. Tanjore, J. N. Srisukhumbowornchai, S. Guruswamy, M. L. Free. *Corrosion studies of single crystals of Fe–Ga alloys in aqueous envFements*. Corrosion Science, 49(10), 4015, (2007), https://doi.org/10.1016/j.corsci.2007.05.010.

Д.А. Гончарук, Г.А. Баглюк, О.І. Хоменко, О.В. Хоменко

Фізико-хімічні властивості галфенолів, отриманих на основі порошкового сплаву Fe-21.5 мас.% Ga

Інститут проблем матеріалознавства ім. І.Францевича НАНУ, Київ, Україна, zoneipm@gmail.com

Визначено властивості матеріалів, розроблених на основі порошкового сплаву Fe-21.5 мас.% Ga, який за складом є аналогом промислових галфенолів – новітніх магнітострикційних матеріалів, що використовуються в підводному зв'язковому обладнанні, пристроях дистанційного керування, біотехнологіях тощо. Досліджено бінарні та потрійні сплави, отримані формуванням та спіканням порошкових сумішей базового складу (Fe-21.5 мас.% Ga), а також з додаванням до цієї суміші порошків зміцнюючи дисперсних частинок карбіду або нітриду чи диборидy титану. Порошкові галфеноли мають високі механічні властивості в умовах стискання (границі текучості (умовної) та міцності сягають до 999 МПа і до 1447 МПа відповідно). Електричний опір розроблених галфенолів коливається від 55 до 67 мкОм·см, що відповідає середньому рівню електричного опору промислових галфенолів (60–80 мкОм·см). Коефіцієнти магнітострикції порошкових галфенолів визначені відносно рівня цього показника для чистого заліза, становлять 210 ppm (базовий склад), 180 ppm (базовий склад + 5 об.% TiB_2) та 160…165 ppm (базовий склад + 5 об.% TiC; базовий склад + 5 об.% TiN), що повністю задовольняє вимогам до промислових галфенолів. Порошковий ґалфенол базового складу проявляє найбільшу корозійну стійкість у середовищі, що імітує морську воду і за класіфікацією 10-бальної шкали корозійної стійкості відноситься до групи корозійностійких матеріалів (4 бал). Галфеноли потрійного складу мають нижчу корозійну стійкість і залежно від складу можуть бути віднесені до групи помірно стійких матеріалів (5-6 бали).

Ключові слова: галфеноли, порошкові матеріали на основі заліза, механічні властивості, магнітострикційні властивості, корозійна стійкість.