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Shielding of electromagnetic fields by mono- and multi-layer fabrics made of metallic glasses with Fe and Co matrix

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Materials

ABSTRACT

Purpose: In the work, influence of chemical composition, as well as magnetic and electric properties on ability of metallic glass screens for shielding of not ionizing electromagnetic fields were analyzed.
Design/methodology/approach: The groups of amorphous metallic alloys with iron, iron and nickel and cobalt matrix were selected for research. Samples of afore-mentioned metallic glasses were examined from the point of view of structure, magnetic, electric and mechanical properties.
Findings: There is possibility of utilization of metallic amorphous materials for screens of not ionizing, electromagnetic fields especially in range of broad-band multi-layers screens with high efficiency of shielding in wide range of frequencies.
Research limitations/implications: Very good magnetic properties and parallel low electric conductivity of metallic glasses are not enough for construction of multi-layer broadband screen. Therefore for constructing broadband screen, which would attenuate much better in wider range of frequencies, we should seek solutions in multi-layers systems consisting of metallic glass fabrics, layers of large conductivity materials and non-magnetic isolating layers. Problems of determining the number of layers, individual thickness of layer, materials in relation to optimum costs of the multi-layers screen metallic glasses are unsolved.
Practical implications: Attenuation of metallic glass screens show very high possibilities of metallic glasses in solution of problem of shielding electromagnetic fields.
Originality/value: There are two general direction of improvement of suppression efficiency of electromagnetic fields screens: research of new constructions of elastic screens, and investigation of new materials for screens join higher magnetic properties at high conductivity. In this second area, any possibilities exist in metallic nanomaterials in form of tapes and nanocomposites consisting magnetic powders with amorphous and nanocrystalline structure.
Keywords: Amorphous materials; Metallic glasses; Screens; Magnetic and electric properties

1. Introduction

Indubitable threat to human health by artificial electromagnetic fields (including also not ionizing) is object of both researches, medical and physical. Influence of electromagnetic field in range of radio frequency is dangerous all the more, it is still inscrutable and probably also distant in effects if refers to long exposure to doses of low intensity. Also growing requirements connected with work environment, concerning legal limitations and conditions of work on more and more complicated electronic devices, call growing interest in results of electromagnetic field's influence on different objects as also in efficient and economic methods of protecting negative influence of electromagnetic fields [1,2,3].

Metallic glasses [4] for the reason of their unorthodox production manner, form of thin flat metallic product (tapes of thickness up to 0,05 mm), unorthodox structure [5] and their mechanical and magnetic properties found various applications [6]. They also became very interesting for producers of electromagnetic field screens with radio frequencies. Hence the interest of this work's authors in utilization of metallic amorphous materials for screens of not ionizing, electromagnetic fields especially in range of broad-band multi-layers screens with high efficiency of shielding in wide range of frequencies.

1.1. Shielding of electromagnetic fields

Concept of electromagnetic wave is understood as a disturbance of electromagnetic field, caused by changes of electric loads' arrangement, dispersing in space. Electromagnetic wave is transverse wave, which one can characterize by vector of electric field and magnetic field's induction vector. These vectors are mutually perpendicular to oneself and lie on the surface perpendicular to wave's speed vector. Most general description of phenomena connected with electromagnetic wave is system of Maxwell's equations.

The theory of electromagnetic waves' movement in matter, based on solutions of Maxwell's equations is too general especially in correlation with detailed requirements of practice. It is connected with the fact, that Maxwell's equations can not be solved accurately, for real fields. All solutions of Maxwell's equations are approximation and only for simple configurations.

Therefore electromagnetic wave's propagation problems are solved with use of approximate, numerical methods but they also not always give satisfactorily exact solutions. For these reasons problems of electromagnetic waves' suppression are dissolved experimentally.

In regard to kinds of fields being extinguished, shielding divides into [7]:

a) shielding of electric fields ,
b) shielding of magnetic fields,
c) shielding of electromagnetic fields.

For shielding electric fields occurrence of electric loads accumulation in state of equilibrium on the conductor's surface is used, independently from how the loads came into being. For particular area's protection from electric field, it is shielded by screen in form of a coat or net creating so-called. Faraday's cage.

Shielding of magnetic fields is used when we deal with slow-changing or static magnetic fields. For shielding such fields we use ferromagnetic screens of large magnetic permeability μ, small magnetic residue B_r, and small coercion H_C. Large value of μ is profitable because of possibility of closing external magnetic stream mostly in the screen's walls.

Shielding alternating electromagnetic fields of small and middle frequency requires screens, joining good magnetic properties and good conductivity (such set of properties most often can be obtained for multi-layers screens, made of different materials). Shielding electromagnetic fields with higher frequencies (above 700 kHz) will require ferromagnetic screens with large conductivity. In this range of frequency epidermical effect appears, in result of which electromagnetic wave is extinguished in depths of half wave's length [7].

From the point of view of its destination one can distinguish two kinds of electromagnetic field shields [8]: anti-disturbance or hygienic. Levels of admissible electromagnetic disturbances are specified by different standards, in this also Polish [9].

Shielding effects are qualified by means of coefficients and indicators, that have diversified nomenclature [8,10], however the most often practically used are: shielding coefficient S defined as quotient of the field's intensity behind and before the screen, shielding efficiency being inverse of shielding coefficient, indicator of shielding efficiency K_e, which is quotient of difference of field's intensities before and behind the screen to intensity of field before the screen expressed in percentage, and lastly suppression coefficient b_S which is denary logarithm of shielding efficiencies multiplied by constant 20. The suppressions coefficient is expressed in dB.

Electromagnetic field's suppression by screen is a result of three phenomena connected with absorption and dispersion of energy. Within these phenomena we can distinguish: reflection of electromagnetic wave from the surface of a screen, energy absorption in regard to lack of impedance continuity on the border of phases between air and metal; and reflection of wave from opposite surface of the screen [11,12]. However, generally we can ascertain that suppression depends from the kind of material from which the screen is made, it's thickness, frequencies and intensities of electromagnetic wave falling on the screen. Summing up, we can indicate general rules of screen's material selection:

- for shielding magnetic fields with low frequencies ferromagnetic materials with large magnetic permeability are suitable [7],
- for shielding electric fields the most useful are materials with large electric conductivity,
- for electromagnetic fields with higher frequencies the influence of higher material's conductivity on attenuation of the screen increases,
- at very high frequencies of electromagnetic field, material's properties play secondary part, and the greatest influence for attenuation has electric conductivity,
- for electromagnetic fields with large intensities and middle range of frequency one should use multi-layer screens, composed of material with decreasing magnetic permeability and increasing conductivity, beginning from the surface of the screen on which electromagnetic wave falls.

1.2. Metallic amorphous materials for screens of electro-magnetic fields

Practice shows, that it is the hardest to shield magnetic fields and electromagnetic fields with small frequencies, because for this case, there are necessary materials with large magnetic permeability, small magnetic residue and coercion and little magnetostriction. Large thickness of the screen is also required.

Problem is different when it comes to shielding electromagnetic fields with middle frequency. In this case there are necessary ferromagnetic materials with large conductivity.

For the case of shielding electromagnetic and electric fields with high frequencies it is sufficient for that screen's material to be a good electric conductor.

Very good magnetic properties and small magnetostriction of metallic glasses, especially those with cobalt matrix, causes that they are good materials for shielding magnetic and electromagnetic field, which succeed in competition with conventional materials. One of the first materials of this type, industrially produced by Allied Signal, was Metglas $Fe_{40}Ni_{40}P_{14}B_6$ from which screens under commercial name Metshield [13] were made. Metshield was used for shielding cables on the space station Voyager 1 and 2 [14].

Magnetic permeability of this alloy amounts to about 60000. Also other metallic glasses with large magnetic permeability were used for shielding e.g. $Fe_{40}Ni_{38}Mo_4B_{16}$ (Metglas 2826 MB), $Co_{70}Fe_5$ $Si_{10}B_{15}$ and $Fe_{62}Ni_{16}Si_{18}B_{14}$ (Amomet) [15]. Afore-mentioned alloys have permeability in range 50000-70000 and coercion 0,4-1,6 A/m at smaller, than crystalline alloys, conductivity [16]. Also a German firm, Vacuumschmelze Gmbh offers amorphous alloy for shielding, named Vitrovac with maximum widths 50 mm and thicknesses 0,03 mm. Maximum permeability for this alloy amounts to 100 000 and coercion < 0, 01 A/cm [17]. Large strength at simultaneous elasticity of metallic glass tapes creates possibility of production shielding wind screens for telecommunication cables [18]. Little value of primary permeability for most of metallic glasses is a reason of their smaller efficiency in suppression for fields with little intensities. However alloys with cobalt matrix and almost zero magnetostriction are also characterized with good suppression of fields with intensity even below 10 A/m [18].

The article's authors, in this area, made many investigations which in a number of journals were published [19,20,21,22,23,24,25,26,27,28].

2. Materials, samples and experiments

The groups of amorphous metallic alloys with iron, iron and nickel, and cobalt matrix were selected for research. Chemical compositions of these metallic amorphous alloys were as follows (chemical compositions in atomic %): $Fe_{78}Si_9B_{13}$, $Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$, $Co_{68}Fe_4Mo_{1,5}Si_{15,5}B_{13}$, $Co_{69}Mo_2Fe_4Si_{14}B_{11}$, $Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$. Metglas 2605 alloy – $Fe_{78}Si_9B_{13}$ was bought in Allied Signal in form of tapes of 300 mm width and 0,026 mm thickness and were cut to 10 mm wide pieces. Alloys with cobalt matrix were produced in a laboratory, also by "chill melt block spinning" method in form of tapes 10 mm wide and 0,02-0, 045 mm thick. Samples of afore-mentioned metallic glasses were examined from the point of view of structure, magnetic, electric and mechanical properties. The structure and diffraction pattern for $Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$ metallic glass are shown as an example on Fig. 1 and 2.

Magnetic properties' study, that is delimitation of original magnetization curve, hysteresis loop, magnetic remanence, coercion, maximal induction, intensity of magnetic field, initial and maximal magnetic permeability, was carried out for frequencies of the field 50, 400, 1000, 5000, 20000 Hz. Magnetic properties' measurement was performed by ring method on toroidal cores rolled up from metallic amorphous tapes with dimensions: internal diameter 30 mm and external diameter 35 mm, width 10 mm. Additionally, selected cores were subjected to magnetic thermal treatment in temperatures 360 and 405^{o}C, under action of field 10 Oë. Then the cores were again put to measurement of magnetic properties.

Examination of electric conductivity was performed by resistance measuring of amorphous tapes' sections with length 2m, by means of full Thompson's bridge, and counting conductivity's value from expression:

$$\gamma = \frac{L}{R \cdot a \cdot b} \qquad (1)$$

where: γ - conductivity, R – resistance of samples, a - width of sample, b - thickness of sample, L - length of sample

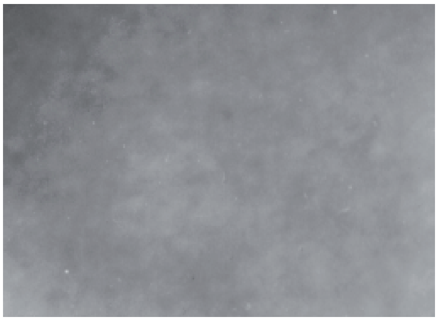

Fig. 1. Structure of $Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$ amorphous alloy at quenched state, with characteristic contrast (TEM, thin foil, magnification 80 000x)

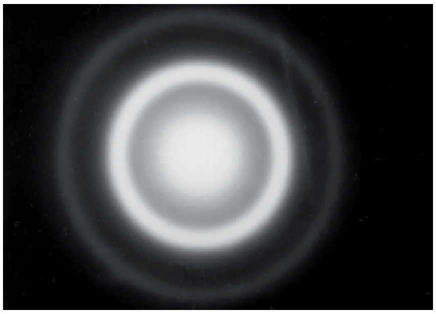

Fig. 2. Electron diffraction of $Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$ amorphous alloy

The tensile test of types were performed on Instron 1195 machine which was equipped in special jaws adapted to lock thin tapes. Tensile tests were carried for 10 samples for each material, with gauge length 50 mm and width 10 mm. Tensile test took place at speed 5 mm/min, and measurement of strength by means of dynamometric head with measuring range 1000 N. Measurements of hardness were realized by Vickers' method at load 0,5 N, using device produced by Reichert .

Electromagnetic field screens were made in form of fabrics with straight line entanglement, from afore-mentioned metallic glasses, separately for each alloy. For the purpose of manufacturing, these fabrics a loom allowing manual weaving of metallic glass tapes was built. By means of the loom, the fabrics with dimensions about 500 mm x 500 mm were made by interlacing mutually tapes 10 mm wide with thickness 0,02-0,04 mm and preventing the crevices between the strands from appearing. In every case, thickness of the fabric was double thickness of the tapes from which it was prepared, what resulted from used manner of interlacing. For protection (from destruction), the fabrics' edges were stuck with plastic tape.

The measurements of electromagnetic fields' attenuation were performed in accordance with American Standard MIL-STD 285 by measuring system consisting of: the net's analyzer HP8752A, transmitting and receiving antennas, optoelectronics transducer, optical wave-guide, optical link, shielded chamber and high frequencies' power amplifier (Fig. 1).

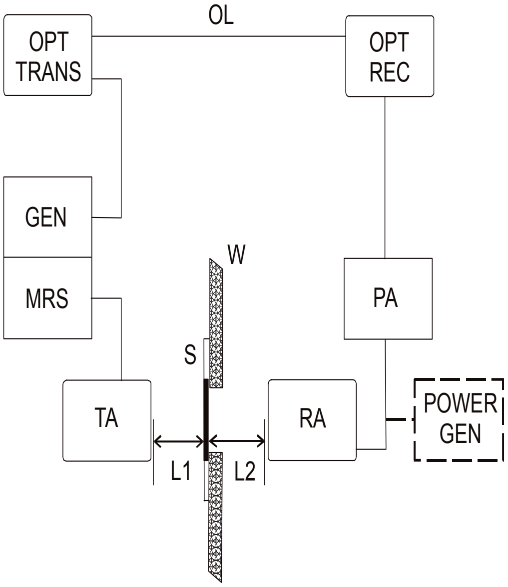

Fig. 3. Scheme of measuring system for the shielding effectiveness' test-: TA – transmitting antenna, RA – receiving antenna, MRS – measuring receiver; the net's analyzer HP8752A, OPT REC – optoelectronics receiver, GEN – generator, source of the signal, OPT TRAN – optical wave-guide's optoelectronics transmitter, OL - optical link of the optical wave-guide, PA - high frequencies' power amplifier, W - wall of the shielded measurement chamber, S - sample of the examined material, L1 - distance of receiving antenna from given samples, L2 - distance of transmitting antenna to tested samples

In order to measure the electromagnetic field's shielding fficiency and attenuation of tested metallic fabrics, a measuring system (Fig. 1) was calibrated, and the opening (diameter 30 cm) in the wall of the shielded measurement chamber, was closed by these metallic fabrics. Tested screen was fastened to the wall by a grounded ring. Four kinds of transmitting and receiving antennas (Tab. l.) were used: rod antenna 1 m long for frequencies 0,3 to 30 MHz, broadband antenna UNA-1 type for 70-250 MHz and logarithmic-periodic broadband antenna for 300-1000 MHz in case of determining electric component of electromagnetic fields, and frame antenna with diameter of frame 12 cm for frequencies 100 Hz to 1 MHz for case of measuring magnetic component of electromagnetic fields. Dependent on electromagnetic field's frequencies, appropriate measurement's conditions were selected (antennas' distance from the screen) and then measurements were taken using either continuous or point method.

Suppression's measurement for electric component of electromagnetic fields was carried through in three sub scopes of frequencies:

- range: 1 ÷ 30 MHz close field $L2<\lambda/2\pi$
- range: 70 ÷ 250 MHz distant field $L2>\lambda/2\pi$
- range: 300 ÷ 1000MHz distant field $L2>\lambda/2\pi$

In range of frequency: 1÷30MHz - rod measuring antenna placed vertically was used; in range of frequency: 70÷1000MHz - symmetrical measuring antenna placed horizontally over surface of the Earth was used (electric component of electromagnetic field oriented horizontally).

Measurement of electromagnetic field's magnetic component's suppression were executed in range of frequency: 100 Hz ÷1 MHz (Tab. 1).

Attenuation of screens, in this paper, is expressed as suppression's coefficient b_S and was calculated:

$$b_S\,[\mathrm{dB}] = 10 \log P_1/P_2 = 20 \log U_1/U_2 \quad \text{for } R_1 = R_2 \qquad (2)$$

where: P_1, P_2 - adequately power of the transmitting and receiving antenna, U_1, U_2 - adequately voltage of the transmitting and receiving antenna, R_1, R_2 - adequately resistance of the transmitting and receiving antenna

3. Results and discussion

Results of magnetic properties' measurement of the tested alloys in the as quenched state for five different frequencies, indicate essential differentiation of magnetic permeability of metallic glasses in relation to their chemical composition and measurement's frequencies (Tab. 2).

On the basis of primary curve of magnetizing analysis, it is certain that from alloys with cobalt matrix, $Co_{69}Mo_2Fe_4Si_{14}B_{11}$ alloy has the greatest magnetic permeability for which at frequency 50 Hz, μ_{rmax}=188237 and μ_{rstart} = 73627.
The lowest magnetic permeability (but still good) has alloy with iron matrix $Fe_{78}Si_9B_{13}$ for which $\mu_{r\ max}$ = 65678 and $\mu_{r\ start}$ = 6043. Values of magnetic permeability decrease while magnetic field frequency increases. We know from the hysteresis' loop that along field's frequency increase, soft magnetic properties of alloys are getting worse (Tab. 3). Greatest values of magnetic remanence and coercion were ascertained for alloy $Fe_{78}Si_9B_{13}$ for which B_r = 0,74 T and H_C = 0,134 A/cm (for 50 Hz), and smallest for alloy $Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$ for which H_C = 0, 016 A/cm, whereas B_r = 0,301 T

For instance, magnetic hysteresis loops for alloys: $Fe_{78}Si_9B_{13}$ and $Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$ are presented on Fig. 2 and 3. Obtained results and tendencies in range of magnetic properties and electromagnetic field's frequencies' influence on them are in accordance with prognosis worked out earlier on the ground of given literature.

The results of magnetic properties' measurement after magnetic thermal treatment of metallic glasses seem to be a little different (Tab. 4, 5).

Table 1.
Conditions of measurements of screens attenuation

CONDITIONS OF MEASUREMENTS				
	Electric component E			Magnetic component H
Frequency	1 ÷ 30 MHz	70 ÷ 250 MHz	300 MHz ÷ 1 GHz	100 Hz – 1 MHz
Receiving antenna	Rod length 1m	Broadband type UNA - 1	Broadband logarit. - period. type DLA	Frame, diameter. 12 cm
Transmitting antenna	Rod lenght 1m	Broadband type UNA - 1	Broadband logarit. - period. type DLA	Frame, diameter. 12 cm
L1	30 cm	30 cm	30 cm	5 cm
L2	30 cm	1,3 m	1,3 m	5 cm

Table 2.
Magnetic properties of metallic glasses read from primary curve of magnetizing and permeability curve

No.	Material	f [Hz]	H_{max} [$^{A}/_{cm}$]	B_{max} [T]	$\mu_{r\,max}$	$\mu_{r\,start}$
1	$Fe_{78}Si_9B_{13}$	50	0,08	0,65	65678	6043
		400	0,15	0,65	36418	4763
		1000	0,16	0,47	23009	3102
		5000	0,54	0,72	11136	2801
		20000	0,65	0,63	7725	2382
2	$Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$	50	0,01	0,29	135620	51022
		400	0,03	0,34	98348	17429
		1000	0,05	0,40	82832	9354
		5000	0,08	0,46	48200	7680
		20000	0,14	0,51	27606	4581
3	$Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$	50	0,01	0,24	131644	53081
		400	0,02	0,29	94898	19439
		1000	0,03	0,35	78348	13414
		5000	0,05	0,34	52033	10080
		20000	0,11	0,41	30781	6239
4	$Co_{69}Mo_2Fe_4Si_{14}B_{11}$	50	0,01	0,35	188237	73627
		400	0,03	0,39	111101	21371
		1000	0,05	0,46	91081	19333
		5000	0,06	0,46	55312	18534
		20000	0,13	0,48	29691	17158
5	$Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$	50	0,04	0,64	130261	44030
		400	0,07	0,67	89711	9801
		1000	0,08	0,68	74907	7075
		5000	0,19	0,74	47757	6531
		20000	0,19	0,61	25863	1841

Table 3.
Properties of metallic glasses read from hysteresis' loop

No.	Material	f [Hz]	H_{max} [$^{A}/_{cm}$]	B_{max} [T]	B_r [T]	H_c [$^{A}/_{cm}$]
1	$Fe_{78}Si_9B_{13}$	50	1,63	0,80	0,740	0,134
		400	1,65	0,85	0,729	0,199
		1000	1,64	0,85	0,738	0,263
		5000	1,74	0,85	0,741	0,382
		20000	2,32	0,83	0,727	0,454
2	$Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$	50	0,51	0,41	0,414	0,045
		400	0,76	0,62	0,452	0,067
		1000	0,72	0,55	0,368	0,073
		5000	0,77	0,58	0,404	0,135
		20000	0,55	0,58	0,440	0,256
3	$Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$	50	0,82	0,59	0,301	0,016
		400	0,79	0,62	0,330	0,021
		1000	0,79	0,60	0,309	0,021
		5000	0,86	0,61	0,395	0,045
		20000	0,81	0,61	0,483	0,109
4	$Co_{69}Mo_2Fe_4Si_{14}B_{11}$	50	0,80	0,62	0,397	0,020
		400	0,80	0,63	0,397	0,023
		1000	0,80	0,64	0,395	0,025
		5000	0,81	0,63	0,466	0,054
		20000	0,79	0,61	0,537	0,128
5	$Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$	50	0,83	0,79	0,664	0,041
		400	0,80	0,81	0,649	0,044
		1000	0,80	0,80	0,655	0,052
		5000	0,87	0,81	0,648	0,088
		20000	2,83	0,78	0,693	0,145

Table 4.
Properties of metallic glasses after magnetic thermal treatment read from primary curve of magnetizing and from permeability curve

No.	Material	f [Hz]	H_{max} [$^{A}/_{cm}$]	B_{max} [T]	$\mu_{r\,max}$	$\mu_{r\ start}$
1	$Fe_{78}Si_9B_{13}$	50	0.60	1.18	153800	55700
		400	0.11	1.26	93100	4300
		1000	0.16	1.23	68100	3700
		5000	0.60	1.37	25000	2900
		20000	0.50	1.10	18000	2300
2	$Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$	---	---	---	---	---
3	$Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$	50	0.008	0.36	333800	175000
		400	0.010	0.41	241500	116000
		1000	0.014	0.44	193500	93600
		5000	0.030	0.49	108800	58300
		20000	0.060	0.38	47800	21000
4	$Co_{69}Mo_2Fe_4Si_{14}B_{11}$	50	0.01	0.35	225500	137100
		400	0.02	0.45	183400	99900
		1000	0.02	0.44	152000	82400
		5000	0.03	0.35	80200	50500
		20000	0.09	0.39	36300	18300
5	$Co_{70,5}Fr_{2,5}Mn_4Mo_1Si_9B_{15}$	50	0.50	0.42	79400	48800
		400	0.80	0.58	64300	30600
		1000	0.13	0.68	53800	23800
		5000	0.18	0.73	37500	13500
		20000	0.29	0.69	23900	5900

Table 5.
Properties of metallic glasses after magnetic thermal treatment read from hysteresis' loops

No.	Material	f [Hz]	H_{max} $[^{A}/_{cm}]$	B_{max} [T]	Br [T]	H_c $[^{A}/_{cm}]$
1	$Fe_{78}Si_9B_{13}$	50	0.8	1.50	1,436	0.084
		400	0.81	1.50	1,420	0.107
		1000	0.83	1.50	1,429	0.137
		5000	1.58	1.51	1,438	0.229
		20000	0.88	1.28	1,278	0.347
2	$Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$	---	---	---	---	---
3	$Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$	50	0.48	0.61	0,427	0.011
		400	0.49	0.62	0,455	0.012
		1000	0.42	0.63	0,442	0.014
		5000	0.52	0.62	0,545	0.029
		20000	1.10	0.59	0,580	0.088
4	$Co_{69}Mo_2Fe_4Si_{14}B_{11}$	50	0.51	0.61	0.372	0.012
		400	0.50	0.64	0.403	0.014
		1000	0.50	0.63	0.409	0.017
		5000	0.81	0.63	0.509	0.044
		20000	1.77	0.60	0.556	0.113
5	$Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$	50	0.79	0.80	0.410	0.050
		400	0.79	0.81	0.426	0.059
		1000	0.80	0.82	0.456	0.069
		5000	0.71	0.84	0.548	0.102
		20000	0.21	0.80	0.580	0.193

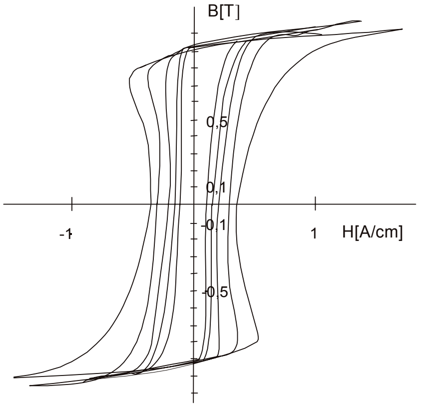

Fig. 4. Hysteresis' loops for $Fe_{78}Si_9B_{13}$ alloy for different frequencies of field in range 50 to 20000 Hz

In this case the greatest value of magnetic permeability has $Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$ alloy for which μ_{rmax}=333800 and μ_{rstart}=175000, and the smallest $Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$ alloy for which $\mu_{r\,max}$ =79400 and $\mu_{r\,start}$ = 48800. Good results are observed for $Fe_{78}Si_9B_{13}$ alloy for which magnetic permeability is: $\mu_{r\,max}$=153800, and $\mu_{r\,start}$ = 55700 (for 50 Hz).

The results of magnetic properties' measurement after magnetic thermal treatment of metallic glasses seem to be a little different (Tab. 4, 5). In this case the greatest value of magnetic permeability has $Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$ alloy for which μ_{rmax}=333800 and μ_{rstart}=175000, and the smallest $Co_{70,5}Fe_{2,5}Mn_4Mo_1Si_9B_{15}$ alloy for which $\mu_{r\,max}$ =79400 and $\mu_{r\,start}$ = 48800. Good results are observed for $Fe_{78}Si_9B_{13}$ alloy for which magnetic permeability is: $\mu_{r\,max}$=153800, and $\mu_{r\,start}$ = 55700 (for 50 Hz).

Properties of metallic glasses after magnetic thermal treatment read from hysteresis loop, are similar to alloys not yet worked on - they have the greatest values for alloy with iron matrix $Fe_{78}Si_9B_{13}$ and are B_r=1, 436 T and H_C= 0,084 A/cm (for 50 Hz). The smallest values are for $Co_{69}Mo_2Fe_4Si_{14}B_{11}$ alloy and B_r= 0,372 T and Hc= 0,012 A/cm (Tab. 5). Examples of magnetic hysteresis' loops after magnetic thermal treatment for $Fe_{78}Si_9B_{13}$ and $Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$ alloys are shown on Fig. 4 and 5.

Very good results of magnetic properties, especially magnetic permeability obtained after magnetic thermal treatment, which decide about very good suppression of magnetic component of electromagnetic fields, can be used in practice to build screens only in limited degree, because after magnetic thermal treatment metallic glasses show brittleness. This inconvenience refers particularly to screens which for some reason should be elastic.

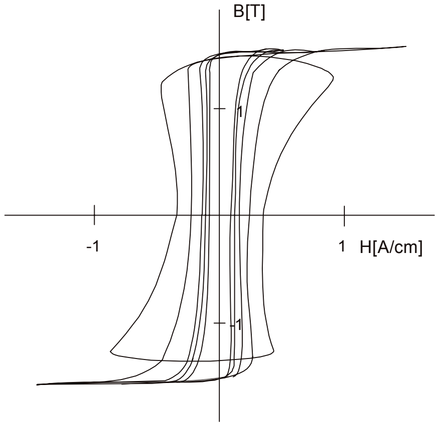

Fig. 5. Hysteresis' loops for $Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$ alloy for different frequencies of field in range 50 to 20000 Hz

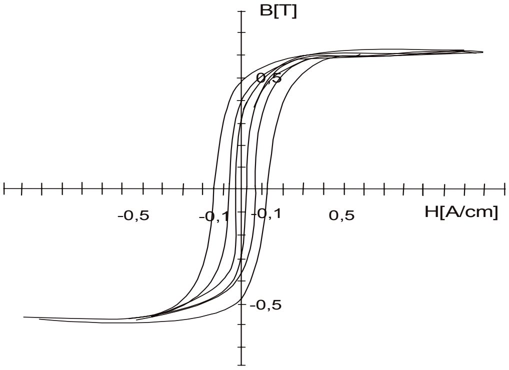

Fig. 6. Hysteresis' loops obtained for alloy $Fe_{78}Si_9B_{13}$ after magnetic thermal treatment at 360 ^{o}C / 2h, for frequencies of field in range 50 to 20000 Hz

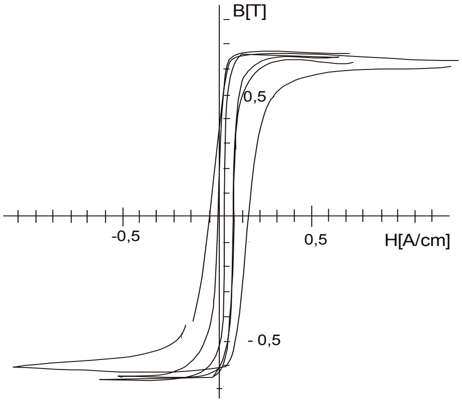

Fig. 7. Hysteresis' loops for $Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$ alloy after magnetic thermal treatment at 405^{o}C/15min, for frequencies of field in range 50 to 20000 Hz

Other types of stationary screens can be subjected to magnetic thermal treatment, but in this case limitations result from sizes, required shape of the screen and accessibility of appropriate devices for magnetic thermal treatment. In our case, the magnetic thermal treatment was performed for toroidal cores made of metallic glasses, which during unwinding would break into short segments.

From given literature, as also from own experiences, it is known that metallic amorphous materials have worse electric conductivity than their crystalline equivalents and is many times lower in comparison to best conductors as silver or copper.

Conductivity of metallic glasses changes along with the temperature similarly as in case of crystalline metals, however metastable structure of metallic glasses, often even in relatively low temperatures undergoes transformations in structure, which are more stable, what is connected with changes of conductivity. Increase of brittleness accompanies this phenomenon very often. Measurements of metallic glasses' conductivity were realized mostly to compare with conductivity of good conductors, which well suppress electric component of electromagnetic fields in middle and high range of frequency. Results of conductivity measurements of tested metallic glasses are presented in Tab. 6. All tested metallic glasses showed similar conductivity of range 0, 55 - 0, 67 10^6 S/m, when copper has about 60 $\cdot$ 10^6 S/m, that is value about 100 - times greater.

Elastic screens of electromagnetic fields can be also used as casings against mechanical action, hence mechanical properties of metallic glasses used to make screens are also important. The list containing results of strength and hardness measurements of metallic glass tapes used for weaving screens is shown in Tab. 7.

Table 6.
Results of conductivity's measurements

No.	Material	Conductivity x 10^6 [S/m]
1	$Fe_{78}Si_9B_{13}$	0,669 ± 0,014
2	$Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$	0,540 ± 0,012
3	$Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$	0,561 ± 0,010
4	$Co_{69}Mo_2Fe4Si_1\ B_{11}$	0,569 ± 0,007
5	$Co_{70,5}Fr_{2,5}Mn_4Mo_1Si_9B_{15}$	0,644 ± 0,013

The alloy with iron matrix $Fe_{78}Si_9B_{13}$ shows the highest properties. Tensile tests have proved that strength of metallic glasses of width 10 mm, carries out on average 1696 MPa at standard deviation $\sigma = 210$ MPa. The rest of tested alloys with cobalt matrix have strength in range 969 - 1230 MPa. Relatively low strength of metallic glasses is a results of inequality of the tape's edges, what has influence on value of tensile force.

Table 7.
Strength R_m and hardness' HV 0,5 results of tested metallic glasses

No.	Material	Strength R_m [MPa]	Hardness HV 0,05
1	$Fe_{78}Si_9B_{13}$	1696 ± 210	1157
2	$Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$	1230 ± 175	980
3	$Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$	969 ± 215	956
4	$Co_{69}Mo_2Fe_4Si_{14}B_{11}$	1057 ± 190	963
5	$Co_{70,5}Fr_{2,5}Mn_4Mo_1Si_9B_{15}$	1030 ±291	972

Results of attenuation's measurements (coefficient of suppression b_S), in full range of investigated frequencies, showed very efficient suppression of electromagnetic field's electric component by screens made of tested metallic glasses with tendency to diminish with increase of field's frequency (Tab. 8, Fig. 6). For all examined screens, there is minimum of suppression for middle range frequency (20 to 100 MHz). In frequency range to 10 MHz and above 250 MHz suppression of electric component of electromagnetic field is very efficient.

Magnetic component of electromagnetic field, seems to have smaller suppression which increases with increase of frequency (Fig. 7). Best efficiency of suppression was ascertained for screen made of $Co_{69}Mo_2Fe_4Si_{14}B_{11}$, what confirms our results for this alloy, stating of the greatest magnetic permeability and conductivity similar to the other alloys. Simultaneously, very essential influence of the screen's thickness was determined (i.e. $Co_{69}Mo_2Fe_4Si_{14}B_{11}$ alloy is presented in Tab. 9). Characteristics of tested screens' suppression in the range of higher frequency are very alike, however in certain range the levels of suppression differ, what is doubtlessly a result of their diversified thicknesses. For this reason we should acknowledge, that all obtained results of investigations refer in detail to concrete screens with definite entanglement made of tapes with definite widths and thicknesses.

During analysis of attenuation's results of presented alloys it should be underlined, that certain disturbance might introduced by the fact, that thickness of the tapes and so also of the screens made of metallic glasses were not identical. Change of the tapes' thickness is a result of the alloys casting technology. Metglas tape - $Fe_{78}Si_9B_{13}$ alloy - was produced by industrial method, therefore it had large stability of dimensions. Cobalt

Table 8.
Suppression of electric component of electromagnetic fields for metallic glasses screens in [dB]

	Material	Thickness of screen [mm]	Frequency [MHz]						
No.			Punctual measurement					Continuous measurement	
			0,3	1	10	20	30	70-250	300-1000
1	$Fe_{78}Si_9B_{13}$	0,052	›75	73	58	46	44	31-39	41-43
2	$Co_{60}Ni_{10}Fe_5Si_{11}B_{14}$	0,088	›75	73	54	48	47	46-53	51-56
3	$Co_{68}Fe_4Mo_{1,5}Si_{13,5}B_{13}$	0,058	›75	›75	55	50	47	41-46	49-58
4	$Co_{69}Mo_2Fe_4Si_{14}B_{11}$	0,062	›75	›75	55	51	49	56-58	59-68
5	$Co_{70,5}Fr_{2,5}Mn_4Mo_1Si_9B_{15}$	0,088	›75	75	49	43	41	34-41	42-49

Table 9.
Suppression of magnetic component of electromagnetic fields for single layer screens made from tapes with different thickness from $Co_{69}Mo_2Fe_4Si_{14}B_{11}$ metallic glass in [dB]

Thickness of screen [mm]	Signature of screen	Frequency. [kHz]	0,1	1	10	50	100	200	500	1000
0,062	E1	[dB]	5,2	5,2	5,2	6	6,4	6,4	8,4	8,8
0,082	E2	[dB]	10,8	11,2	11,2	12,8	12,4	12,4	13,6	13,6
0,074	E3	[dB]	7,6	7,6	8	8,4	9	9,6	11,2	11,6
0.062	E4	[dB]	5,2	5,2	5,6	6,4	6,8	6,8	8,4	9,6
0,088	E5	[dB]	12,4	12,4	13,2	16,2	16,6	16,6	17,2	17,2

Table 10.
Results of suppression of magnetic component of electromagnetic fields by multi-layers screens made of $Co_{69}Mo_2Fe_4Si_{14}B_{11}$ alloy

Number of layers	[kHz]	0,1	1	10	50	100	200	500	1000
E1 (1)	[dB]	5,2	5,2	5,2	6	6,4	6,4	8,4	8,8
E1+E2 (2)	[dB]	20	20	20	24,8	28,2	31,6	36,4	36
E1+E2+E3 (3)	[dB]	21,5	26	29,2	38,4	45,6	52,4	57,6	55,6
E1+E2+E3+E4 (4)	[dB]	>21,5	32,8	32,8	47,2	56,4	64,5	72	>72
E1+E2+E3+E4+E5 (5)	[dB]	>21,5	>32,8	38	63	> 75	> 80	>80	>80

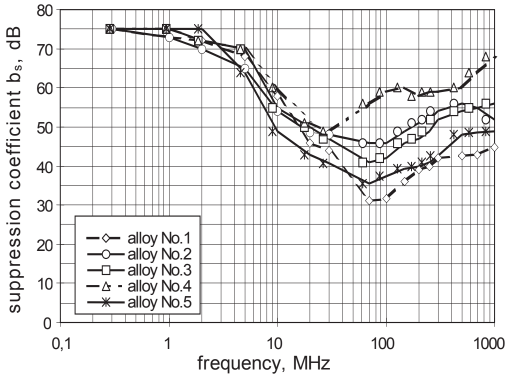

Fig. 8. Suppression of electromagnetic field's electric component in function of frequencies for tested screens (signature of samples according to the numeration in tables 2-8)

alloys were produced by laboratory methods - what has influence on change of the geometry, tape's thickness and length for each casting. Average thickness of all screens are collected in Tab. 8 and 9.

In order to increase efficiency of electromagnetic field's magnetic component's suppression, possibilities which result from use of multi-layer screens produced from $Co_{69}Mo_2Fe_4Si_{14}B_{11}$ alloy were also analyzed. Results for mono- layer screens with different thickness are presented in Tab. 9, and results of shielding efficiency obtained thanks to adding next layers are presented in Tab. 10 and on Fig. 8.

Suppression's measurement of magnetic component for multi-layer screens with different number of layers from afore-mentioned fabrics E1 to E5, showed good suppression, on level of 30 dB, for frequency range up to 10 kHz when using screens with five layers. Above 10 kHz suppression increases for multi-layer screens attaining values above 70 dB for screens with four and five layers, and field's frequency 1000 kHz.

4. Conclusions

Presented and discussed results of attenuation of metallic glass screens show very high possibilities of metallic glasses in solution of problem of shielding electromagnetic fields. However very good magnetic properties and parallel low electric conductivity of metallic glasses are not enough for construction of multi-layer broadband screen. Therefore the obvious conclusion is that for constructing broadband screen, which would attenuate much better in wider range of frequencies, we should seek solutions in multi-layers systems consisting of metallic glass fabrics, layers of large conductivity materials and non-magnetic isolating layers. Obtained results are very interesting from the point of application, although the problems of determining the number of layers, individual thickness of layer, materials in relation to optimum costs of the multi-layers screen and its, possibilities of utilizing other good properties of metallic glasses and their connection with good extinguishing properties are unsolved. From this discussion resulting two general direction of improvement of suppression efficiency of electromagnetic fields screens. First it is research of new constructions of elastic screens, and second is research of new materials for screens join higher magnetic properties at high conductivity. In this second area, any possibilities exist in metallic nanomaterials in form of tapes and nanocomposites consisting magnetic powders with amorphous and nanocrystalline structure.

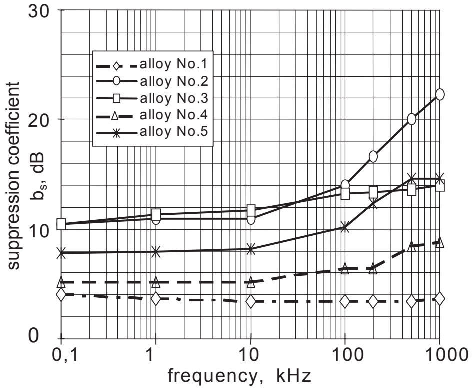

Fig. 9. Dependence of suppression's coefficient b_S for electromagnetic field's magnetic component in frequencies 0,1 – 1000 kHz for tested screens. (signature of samples in tables 2-8)

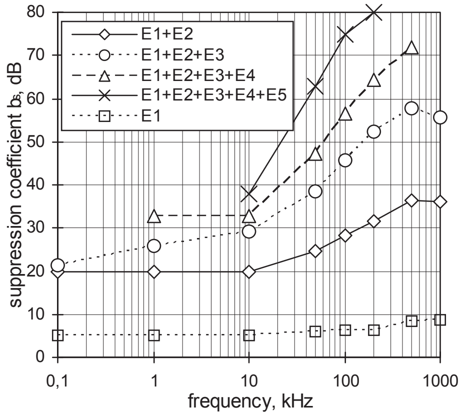

Fig. 10. Suppression of magnetic component of electromagnetic field in function of frequency, for multi-layer screens made of $Co_{69}Mo_2Fe_4Si_{14}B_{11}$ metallic glass tapes with different thickness in [dB]

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