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BADANIA KRYMINALISTYCZNE NADRUKÓW MAGNETYCZNYCH OPARTE NA POMIARACH MAGNETYCZNYCH

FORENSIC INVESTIGATION OF MAGNETIC PRINTING BASED ON MAGNETIC MEASUREMENTS

Streszczenie
Celem badań była eksperymentalna weryfikacja przydatności topogramów magnetooptycznych (MO) do rozwiązywania problemów kryminalistycznych z dokumentami drukowanymi magnetycznie. Artykuł rozpoczyna się od przedstawienia niezbędnej wiedzy dotyczącej pola magnetycznego na powierzchni obiektu, na podstawie której zaprezentowano czynniki wpływające na jego parametry. Następnie omówiono metodę wizualizacji pola magnetycznego oraz urządzenie do topografii MO. Przeprowadzono badania eksperymentalne obiektów w warunkach stałego namagnesowania z wykorzystaniem dwuwymiarowego skanera MO. Podane przykłady badań pokazują, że topogramy MO obiektów mogą być wykorzystywane do identyfikacji źródła druku magnetycznego i wykrywania wstawek tekstowych, gdy zostały one dodane za pomocą innego urządzenia drukującego, a także do uwierzytelniania banknotów z zabezpieczeniami magnetycznymi. Dalsze badania prowadzone były w warunkach zmiennego namagnesowania, co pozwoliło na uzyskanie charakterystyk histerezy magnetycznej dla interesujących

nas próbek. Badania te wykonano za pomocą histerezygrafu MO. Podano przykład MO charakterystyki histerezy fałszywego banknotu, pokazując, że zamiast oryginalnego atramentu magnetycznie twardego o niskiej koercji [LoCo Hard ink] zastosowano obcy atrament magnetycznie półtwardy (Semihard).

Słowa kluczowe: kryminalistyczne badanie dokumentów, druk magnetyczny dokumentów, dokumenty zabezpieczone, druk z tonerem, topografia magnetooptyczna, histereza magnetyczna

Summary

The research objective was to experimentally verify the suitability of magneto-optical (MO) topograms for solving forensic problems with magnetic printing documents. Paper starts with presentation of necessary knowledge regarding magnetic field on the surface of an object, from which factors that affects its parameters are presented. Secondly, a method of visualization of magnetic fields and MO topography device are presented. Experimental research of objects under conditions of constant magnetization were carried out using a two-coordinate MO scanner. The given examples of research show that MO topograms of objects can be used to identify the source of magnetic printing and to detect text insertions when they have been added using another printing device, as well as to authenticate banknotes with magnetic security features. Further research was carried out under conditions of variable magnetization, which made it possible to obtain magnetic hysteresis characteristics for the specimens of interest. This research was carried out using a MO hysteresigraph. An example of the MO of the hysteresis characteristic of a counterfeit banknote is given, showing that instead of the original magnetic Low-Coercivity [LoCo] Hard ink, a foreign ink of the Semihard magnetic type was used.

Keywords: forensic examination of documents, magnetic printing of documents, security documents, toner printing, magneto-optical topography, magnetic hysteresis

Introduction

Forensic technology and tools for the examination of documents require constant improvement and must develop at a faster pace than progressive document printing technologies. At the same time, some part of the documents are made using electrographic printing on laser printers, and some types of security documents, contain specialized elements of magnetic protection.

It is known that magneto-optical (MO) transducers with high sensitivity to magnetic fields and high spatial resolution are successfully used to visualize and evaluate the geometry of magnetic printing[1]. The principles of MO magnetic measurements proposed in the literature[2] have been further developed and modern technical implementation in the form of MO measuring devices specialized for magnetic printing research[3]. That, in turn, generated interest of researchers in MO measurements of the magnetic parameters of magnetic printing objects for solving forensic problems, as evidenced by publications[4]. In particular, W.D. Mazzella and B. Li noted the phenomenon of non-uniformity of the magnetic flux distribution over the page of printed printer text, probably due to the non-uniformity of the toner distribution, and the connection of this phenomenon with the structural elements of the printer[5]. In addition in C. Polston et al.[6], based on the analysis of data from MO magnetic measurements, a methodological approach was proposed for detecting the inserted text of magnetic printing.

A separate direction is research on the magnetic hysteresis characteristics of magnetic printing in documents, which makes it possible to significantly refine verification capabilities by examining inherent characteristics of the magnetic particles rather than acquired characteristics (which can be influenced during the printing process). This potential application was demon-

[1] V.G. Vishnevskii, V.N. Berzhansky, A.S. Nedviga, A.G. Nesteruk, *Visualizer of magnetic protection of securities and banknotes*, „Sensor Letters" 2009, Vol. 7, No. 3, p. 1–4; Yu.S. Ahalydy, P.V. Kozhukhar', S.V. Levyi, A.M. Machnev, *Nerazrushaiushchyi kontrol elementov mahnytnoi zashchyty dokumentov*, „Visnyk NTUU": KPI, seriia Pryladobuduvannia 2009, No. 38, p. 43–50.

[2] V.V. Randoshkyn, A.Ya. Chervonenkys, *Prykladnaia mahnytooptyka*, Enerhoatomyzdat, Moskva 1990; N.F. Kubrakov, *Metod MO vyzualyzatsyy y topohrafyrovanyia prostranstvenno neodnorodnykh mahnytnykh polei*, Trudy YOFAN, Nauka, Moskva 1992, Vol. 35.

[3] Yu.S. Agalidi, P.V. Kozhukhar', S.V. Lievyi, A.M. Machnev, S.L. Ponomarev, *Study of inducted magnetic scattering fields of thin-film dispersive ferromagnetics*, „Radioelectronics and Communications Systems" 2012, Vol. 55, No. 15, p. 204–212.

[4] K. Herlaar, M. Mieremet, M. Fakkel, *Measuring magnetic properties to discriminate between different laser printers*, „Journal of the American Society of Questioned Document Examiners" 2015, Vol. 18(2), p. 51–66; A. Biedermann, S. Bozza, F. Taroni, M. Fürbach, B. Li, W.D. Mazzella, *Analysis and evaluation of magnetism of black toners on documents printed by electrophotographic systems*, „Forensic Science International" 2016, Vol. 267, p. 157–165; W.D. Mazzella, B. Li, *Is magnetic flux a valuable tool for the analysis of electrophotographic printed documents?*, „Journal of Forensic Science and Medicine" 2018, Vol. 4, p. 197–201; C. Polston, W. Mazzella, M. Fürbach, P. Buzzini, *Assessing the repeatability and reproducibility of magnetic flux measurements and their potential to discriminate toner printed documents*, „Journal of the American Society of Questioned Document Examiners" 2018, Vol. 21, No. 2, p. 45–56.

[5] W.D. Mazzella, B. Li, op. cit., p. 197–201.

[6] C. Polston, Y.S. Agalidy, A.A. Mamedov, P. Buzzini, *Technical note: A preliminary evaluation of a method for the examination of text substitutions using magneto-optical measurements*, „Forensic Science International" 2021, Vol. 323, p. 2–7, www.elsevier.com/locate/forsciint [access: 29.03.2023].

strated in a different discipline, where a measuring scheme based on the use of a MO transducer was used by P. Novotný and J. Voříšek[7] to construct fragments of the limiting hysteresis loop and estimate the coercivity of the FeCr component in the alloy under research. However, unlike the objects of research examined by P. Novotný and J. Voříšek[8], where metal samples had macroscopic dimensions, objects of magnetic document printing contain microscopic amounts of magnetic material, which significantly complicates the tasks of measuring and constructing magneto-hysteresis characteristics. Therefore, experimental research of hysteresis objects of magnetic printing of characteristics became possible only after the development of innovative technical solutions underlying the MO hysteresigraph[9].

The results of numerous publications[10] show the current state of the problem of MO research of magnetic printing as a need for development and approbation of applied techniques, which allows us to formulate the problem statement for this work. The object of the research is magnetic printing materials (printer printing documents, security printing documents). The subject of research is the spatial distribution of the magnetic field on the surface of an object. The research method is MO topography of the magnetic field on the surface of the object. The research objectives are to experimentally verify the suitability of MO topograms for solving forensic problems, specifically the identification of magnetic printer printing, detection of text inserts in magnetically printed documents, and authentication of magnetic security features of banknotes.

Theoretical model of the object

The model under consideration shows a scheme of an object (Fig. 1a) containing a non-magnetic paper substrate, as well as a line of idealized magnetic printing. In the vicinity of a magnetized line of magnetic printing, there is its magnetic stray field with strength H_{obj}, which is expediently pre-

[7] P. Novotný, J. Voříšek, *Duplex steels investigated by magnetooptical sensors*, NDT Net, http://www.ndt.net/article/defektoskopie2009/papers/Novotny-8.pdf [access: 29.03.2023].

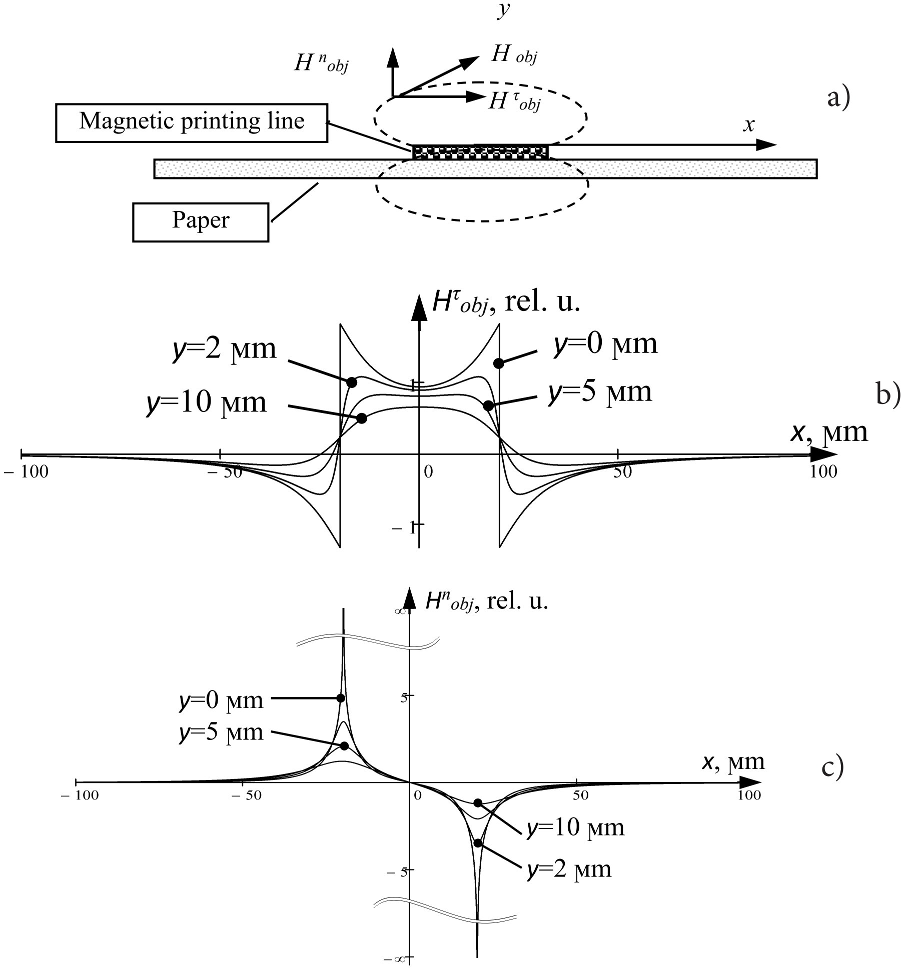
[8] Ibidem.

[9] P. Kozhukhar', *Magneto-Optical Hysteresigraph MOHyster Regula 7708 for Analysis of Soft, Semihard & LoCo-Hard Magnetic Printing*, High Security Printing EMEA, 9–11 March 2020, Lisbon, Portugal, https://hsp-emea.com/review-2020/ [access: 29.03.2023].

[10] K. Herlaar, M. Mieremet, M. Fakkel, op. cit., p. 51–66; A. Biedermann, S. Bozza, F. Taroni, M. Fürbach, B. Li, W.D. Mazzella, op. cit., p. 157–165; W.D. Mazzella, B. Li, op. cit., p. 197–201; C. Polston, W. Mazzella, M. Fürbach, P. Buzzini, op. cit., p. 45–56; C. Polston, Y. S. Agalidy, A. A. Mamedov, P. Buzzini, op. cit., p. 2–7; P. Kozhukhar', op. cit.

sented as projection components: the tangential component H^{τ}_{obj} (Fig. 1b) and the normal component H^{n}_{obj} (Fig. 1c).

Fig. 1. Spatial distribution of the magnetic field strength H_{obj} above the surface of the object in the area of the magnetic printing line: a) scheme of the object; b) is the tangential component H^{τ}_{obj}; c) is the normal component of H^{n}_{obj}



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An analysis of the behavior of the functions H^{τ}_{obj} and H^{n}_{obj} shows that the value of the magnetic field of the objects decreases significantly with the distance along the *y* coordinate from the surface of the magnetic line, while the shape of the magnetic response of the magnetic line also changes (smoothed out). These circumstances show that the measurement of the field of an object should be carried out as close as possible to its surface, which is easy to implement for thin-film MO sensors ($y \approx 5$ *мm*) and difficult for other types of sensors (induction, Hall) due to their large dimensions.

The model presented by Agalidi et al.[11] defines a number of functional dependencies between the parameters of the object and the investigated value of the magnetic field strength of the object H_{obj}. Thus, the significant parameters are: the geometric dimensions of the magnetic ink strip (width λ and thickness D), orientation with respect to the magnetizing field (intensity H_{exc}), magnetic characteristics of the ink material (magnetic permeability μ_{obj}, magnitude and direction of the initial magnetization M_{obj}).

Description of the experimental equipment

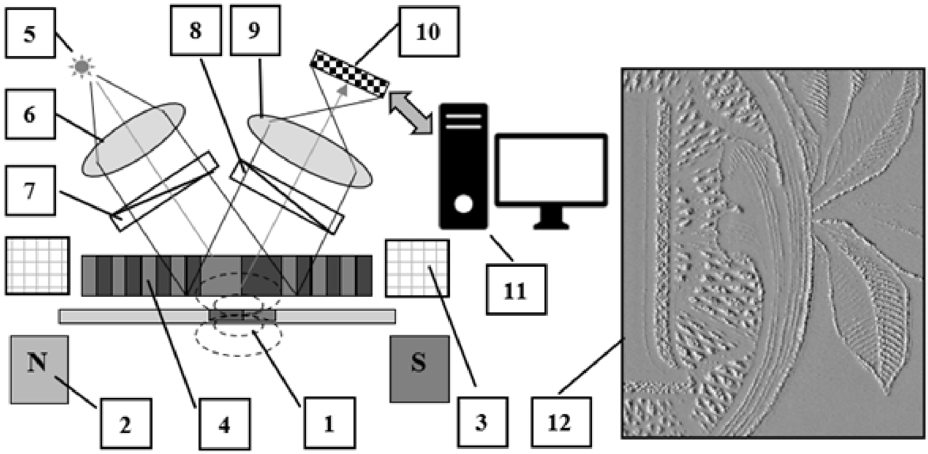
The functional scheme of the MO topography device is shown in Fig. 2. The scheme contains an object of research (1) with a spatially non-uniform distribution of magnetic ink particles. To magnetize the object, a (regulated or non-regulated) source of magnetic excitation (2) with strength $H_{exc,}$ is used, which generates a stray field of the object with strength H_{obj}. The source of the adjusTab. magnetic field compensation (3), which is a part of the measuring circuit, locally compensates the normal component of the object's stray magnetic field H^n_{obj} by the opposite field H_{comp} in the plane of the MO transducer (4). The MO transducer (4), using the MO Faraday effect, converts the superposition of the magnetic fields of the object H^n_{obj} and the compensation circuit H_{comp} into a local rotation of the light polarization plane, which is then converted into a spatial distribution of brightness - i.e. MO image of the magnetic field. To observe the MO Faraday effect (obtaining a MO image of the magnetic field), a polarization optical scheme is used, containing: a light source (5), a collimator (6), a polarizer (7), an analyzer (8), a projection lens (9) and a video camera (10).

The process of magnetic measurements for each point in the coordinate space of the MO imaging (x, y, z) consists of selecting the value of the magnetic field strength H_{comp} (or magnetic induction B_{comp}), which provides full compensation for the magnetic stray field of the object $H^n_{obj} = -H_{comp}$ (or $B^n_{obj} = -B_{comp}$). The achieved state of compensation of magnetic fields means that for each point in the space of coordinates of the visualization

[11] Yu.S. Agalidi, P.V. Kozhukhar', S.V. Lievyi, A.M. Machnev, S.L. Ponomarev, op. cit., p. 204–212.

MO (x, y, z) the values of the measured quantity H^n_{obj} or B^n_{obj} are determined, which are numerically equal to the values $-H_{comp}$ or $-B_{comp}$, known from the calibration data of the source of the controlled magnetic field compensation (3). The process of magnetic measurements is provided by special software algorithms in the PC (11).

Fig. 2. Functional scheme of the MO topographic device



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The result of magnetic measurements is the MO topogram (12) – a halftone MO image of the magnetic field, where for each point of the image the value of the normal component of the magnetic induction B^n_{obj} is determined (and encoded in its brightness). The MO topogram data (12) can be decoded and graphically displayed as a magnetic induction histogram, where the scale of magnetic induction values [мT] is plotted along the horizontal axis, and the number of MO topogram points with the corresponding magnetic induction value B^n_{obj} is plotted along the vertical axis. Also, according to the MO data of the topogram (12), the following are calculated: the integral estimate of the magnetic field – the value of the modulus of the normal component of the magnetic flux | Φ^n_{obj} | [ηWb]; interval estimation of magnetic induction - the values of its maxima $+B_m$ and $-B_m$ is estimated.

The MO transducer (4) of the experimental equipment (Fig. 3) is made on the basis of a perpendicularly anisotropic garnet ferrite film (GFF) produced using liquid-phase epitaxial technology on an isomorphic $Gd_3Ga_5O_{12}$ (GGG) substrate. The main chemical composition of the epitaxial layer is

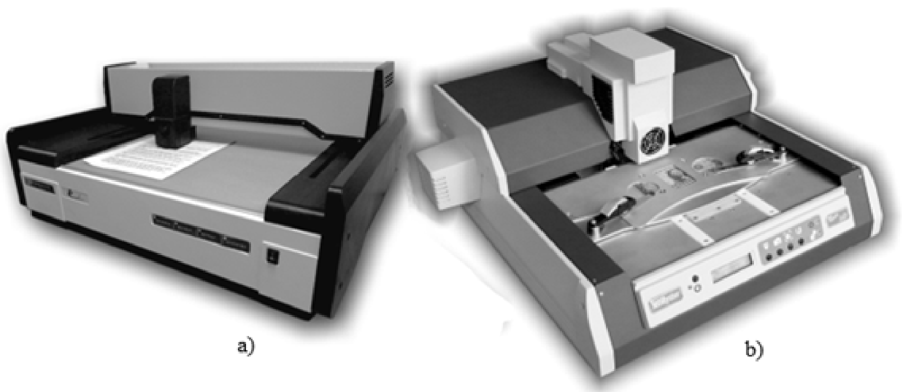
$(Bi, Eu, Lu)_3(Fe, Ga, Al)_5O_{12.}$ The thickness of the MO film is 4–5 µm, the effective field of uniaxial anisotropy is 3–3.5 kOe (240–280 kA/m), the period of the equilibrium domain structure is 35–40 µm, and the coercive force is 0.5–0.8 Oe (40–64 A/m), specific Faraday rotation – 2.2–2.3 °/µm (for a wavelength $\lambda = 0.53\ \mu m$).

Experimental research of objects under conditions of constant magnetization were carried out using a two-coordinate MO scanner (model "Regula 7701M", Fig. 3a), which has the following characteristics: measurement range 0 – 5.6 mT with a sampling step of 0.175 mT, MO topogram point size 15 µm, permanent magnetizing field 50 kA/m.

Experimental research of objects under conditions of variable magnetization were carried out using a MO hysteresigraph (model "Regula 7708", Fig. 3b), which has the following characteristics: measurement range 0–11.2 mT with a sampling step of 0.175 mT, MO topogram point size 15 µm, magnetizing field in the range of 0–100 kA/m with a sampling step of 5 kA/m.

To analyze the data of MO histograms, special software version CADR v.99 was used.

Fig. 3. Experimental equipment: a) two-coordinate MO scanner; b) MO hysteresigraph



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Experimental research of objects

MO topography under constant magnetization (50 kA/m)

The task of identifying printer printing

Objects of research (Fig. 4): samples of magnetic printer printing containing the same text, formatting and font parameters (Arial 11), but printed on different laser printers – HP LG2050 and Canon MF3110. Visually, the print density of objects looks the same.

The "Print Identity" interface for analyzing MO topogram data (Fig. 4) contains the following areas: (A) – document image No. 1 (printer HP LG2050); (C) – document image No. 2 (Canon MF3110 printer); (C1) – the average value of B_m by the horizontal (upper – document No. 1, lower – No. 2); (C2) – standard deviation B_m by the horizontal (upper – document No. 1, lower – No. 2); (D) – calculated values of the "Similar" probability; (E) – 3D view of B_m data distributions; (F) – is the location of B_m distributions in the current section (leftward shifted – document No. 2, rightward shifted – document No. 1).

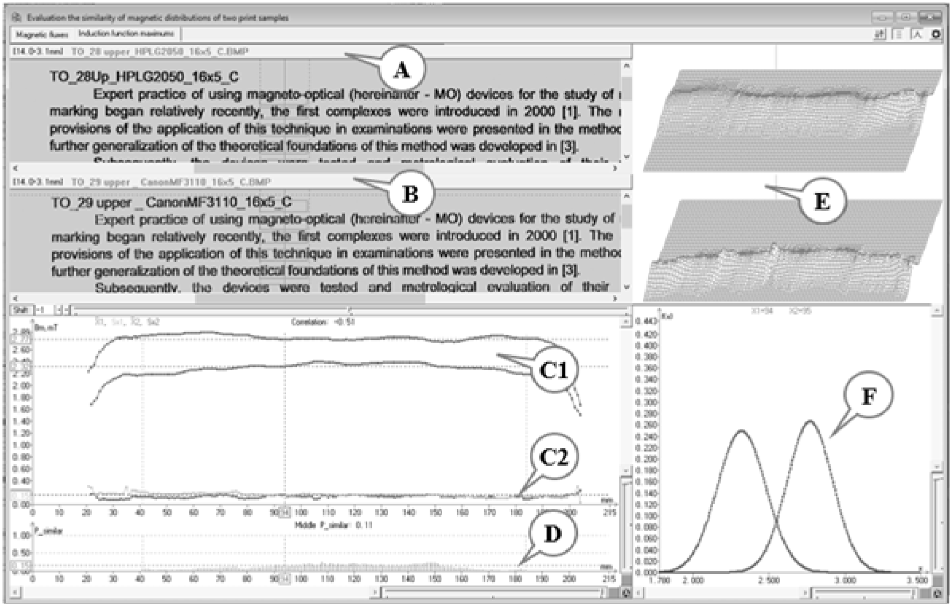
To evaluate the identity of samples of magnetic printer printing of text documents, 2 parameters were used:

• the value of the linear Pearson correlation coefficient (Correlation), determined by the sliding analysis window for functions (C1);

• the average value of the probability "Similar" (Middle P_Similar), determined for the set of areas of overlapping distributions (F).

The criteria for the identity of magnetic printer printing are proposed: Correlation $\geq +0.5$ and P_Similar ≥ 0.5.

Fig. 4. Evaluation of print identity for a pair of samples printed on different printers (HP LG2050 and Canon MF3110)



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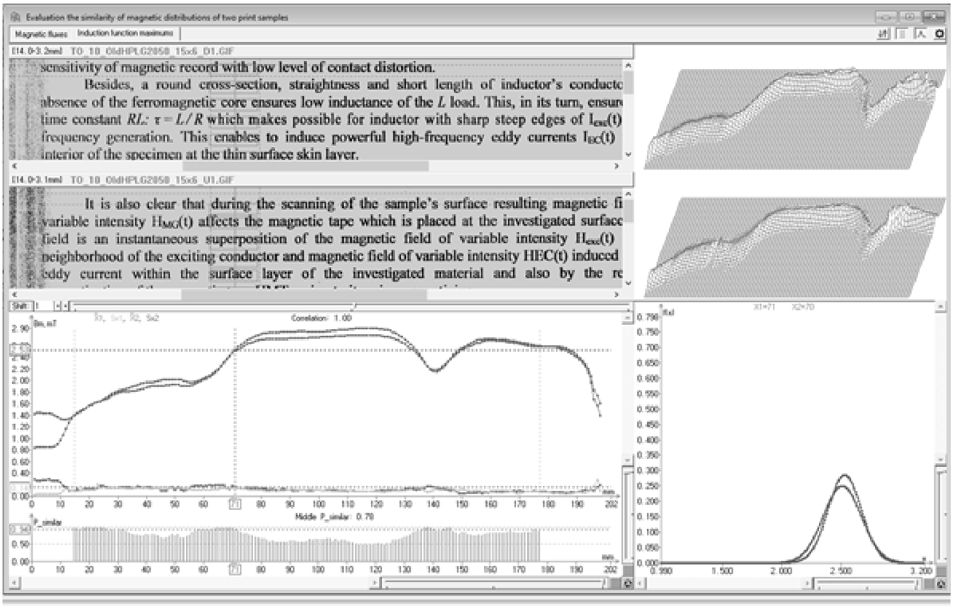
The results of the analysis of MO topogram data (Fig. 4) show that the samples are not identical according to both similarity assessment criteria (Correlation = –0.51 < 0.5 and Middle P_Similar = 0.11 < 0.5). In addition, the graphs of the functions the average value of B_m by the horizontal (C1), which characterizes the distribution density of the toner along the lines, look different in shape and magnitude.

Objects of research (Fig. 5): magnetic printer print samples containing different text, similar formatting and font settings (Times New Roman 10) printed by the same HP LG2050 laser printer. Visually, the print density of objects looks the same.

Fig. 5. Evaluation of print identity for a pair of samples printed on the same printer (HP LG2050)



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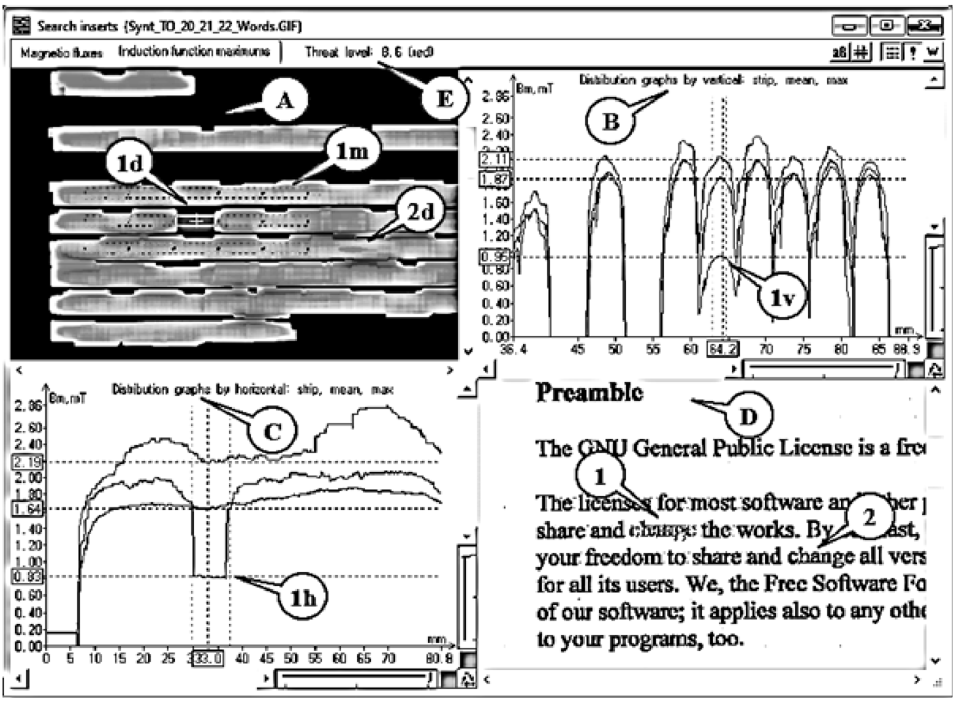
The results of the analysis of the MO topogram data (Fig. 5) show that the samples are identical according to both similarity assessment criteria (Correlation = 1.00 > 0.5 and Middle P_Similar = 0.78 > 0.5). In addition, the graphs of the functions the average value of B_m for the horizontal (C1), which characterizes the distribution density of the toner along the lines, look the same in shape and magnitude.

It is important to note that the HP LG2050 printer shown in the examples in Fig. 4–5, is the same printer, but, in Fig. 5 – before replacing the cartridge, and in Fig. 4 – after replacement. The replacement of the cartridge radically affects the spatial distribution of the magnetic values of the print samples, which makes it possible to methodically judge only the identity of the samples (indicating the invariance of the printing conditions) only if the condition of the identity of the samples is met – the identification of the printer.

The task of detecting text insertions

Object of research (Fig. 6): a sample of magnetic printing containing text with the same formatting and font parameters (Arial 11), but printed on 3 different laser printers: main text – printer HP LG2050; insertion (1) the word "change" in the 4th line – HP GLMFPM 130A; insertion (2) the word "change" in the 5th line – Canon MF3110. Visually, text insertions are not noticeable, since the intensity of all toners is approximately the same.

Fig. 6. Detection of text insertions for a sample printed on 3 different printers: (1) and (2) – detected word insertions



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The "Search for inserts" interface for analyzing MO topogram data (Fig. 6) contains the following areas: (A) – 2D distribution of the B_m function; (B) – vertical distribution of the function B_m; (C) – horizontal distribution of the function B_m; (D) – an image of a document with a color "threat map"; (E) – assessment of the level of threat. Also, in fig. 6 there are designations of detected text inserts: (1) – HP GLMFPM 130A printer insert; (1d), (1h) and (1v) – respectively, its mapping in the space of 2D distribution of the function B_m, its horizontal and vertical distributions; (1m) – 3*5 environment matrix; (2) – Canon MF3110 printer insert; (2d) – its mapping in the space 2D distribution of the function B_m.

As can be seen from the image of the 2D distribution of the B_m function on the background of the main print, 2 areas of a different color (i.e., a different B_m value) are observed: the insert (1d) and the insert (2d). Indeed, insert (1) is more than 2 times weaker in magnitude B_m relative to the surrounding text, as can be seen from graphs (1h) and (1v).

To detect text inserts for magnetic printing samples of text documents, the "threat level" estimation parameter (E) was used. The "threat level" estimation parameter (E) calculated using the formula $|X_{A\,ENV} - X_C|/STD_{ENV,}$ where: X_C – current value of B_m for central element of the environment matrix; $X_{A\,ENV}$ – average value of B_m for other elements of the environment matrix; STD_{ENV} – standard deviation for the distribution of B_m for other elements of the environment matrix.

The value of the assessment (E) of the "threat level" = 8.6 obtained in this example for insertion (1) means that the deviation of the current value of B_m from the average value of the environment matrix (1m) is 8.6 times greater than the standard deviation for the environment matrix (1 m). The probability of such an event within the normal distribution law and subject to the reliability of the sample is negligible ($P < 10^{-12}$), which gives statistical grounds for the assertion that the word "change" in the 4th line of the visual field is most likely printed different printer than the surrounding text. For insert (2), the value of the assessment (E) of the "threat level" = 2.4 (probability of the event $P < 0.05$) was obtained, which does not give grounds for a categorical conclusion, but it justifies further examination of this area by alternative methods.

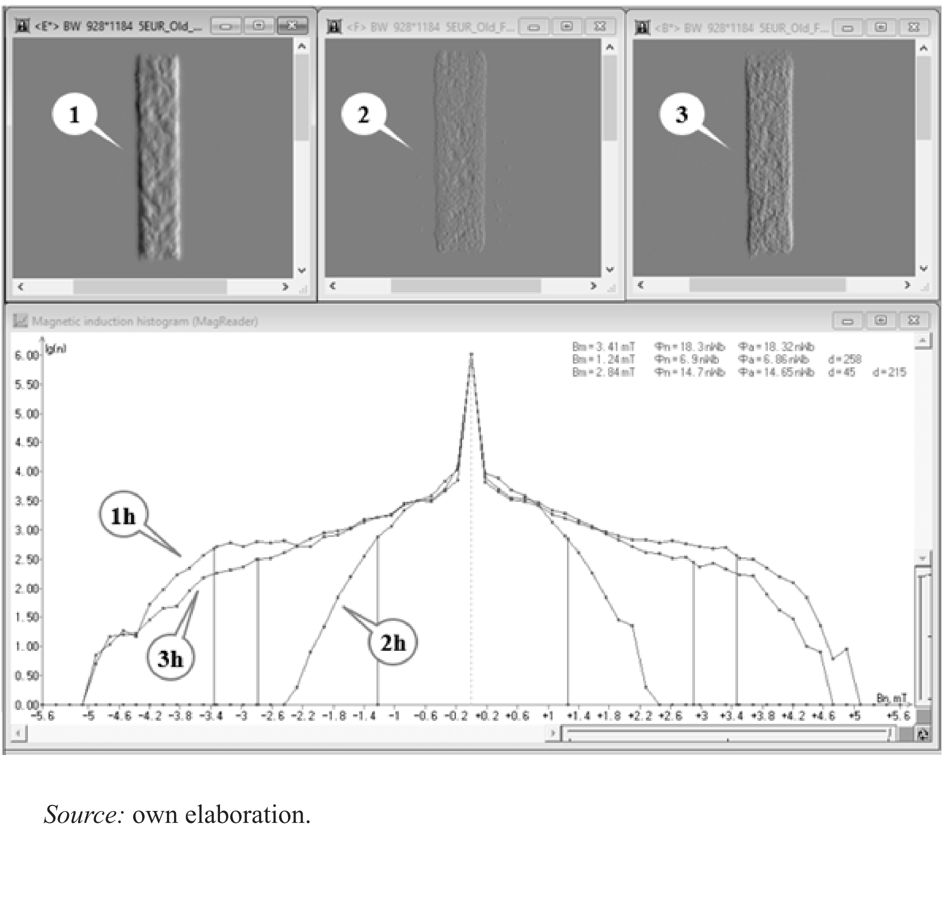
The task of verifying the authenticity of banknote magnetic security features

The objects of research (Fig. 7) are represented by their MO topograms: (1) – reference sample of the 5EUR banknote (protective Thread area); (2) and (3) – questioned samples (protective thread area). The results of measurements, respectively, are presented in the form of magnetic induction topograms: (1h) – red graph; (2h) – green chart; (3h) – blue graph.

To assess the identity of the banknote magnetic security samples, 2 parameters were used: $\Delta B_{mi} = B_{mi}/B_{m1}$; $\Delta \Phi^n{}_i = \Phi^n{}_i/\Phi^n{}_1$, where $B_m 1$ and $\Phi^n 1$ are the values for the reference object, B_{mi} and $\Phi^n{}_i$ – for the questioned one. Verification criteria: $0{,}5 < \Delta B_{mi} < 2$ and $0{,}5 < \Delta \Phi^n{}_i < 2$.

Analysis of the results of magnetic measurements shows that (1) the reference sample (B_{m1} = 3,41 мT; $\Phi^n{}_1$ = 18,3 ηWb) differs significantly in magnetic parameters from (2) the control sample (B_{m2} = 1,24 мT; $\Phi^n{}_2$ = 6,9 ηWb), but not significantly different from (3) control sample (B_{m3} = 2,84 мT; $\Phi^n{}_3$ = 14,7 ηWb). Thus, the control sample (2) is not identical (ΔB_{m2} = 2,75 > 2; $\Delta\Phi^n{}_2$ = 2,65 > 2). The control sample (3) formally meets the identity criteria (0,5 < ΔB_{m3} = 1,2 < 2; 0,5 < $\Delta\Phi^n{}_2$ = 1,24 < 2), however, since the image of its MO topogram and the shape of the B_m histogram differ from the sample (1) – it needs additional verification under conditions of variable magnetization (see Fig. 10).

Fig. 7. Checking the authenticity of the banknote magnetic protection: (1) and (1h) – MO topogram and histogram Bm of the reference sample of the 5 EUR banknote (protective "threat area"); (2), (2h), (3) and (3h) are the corresponding data of questioned samples.



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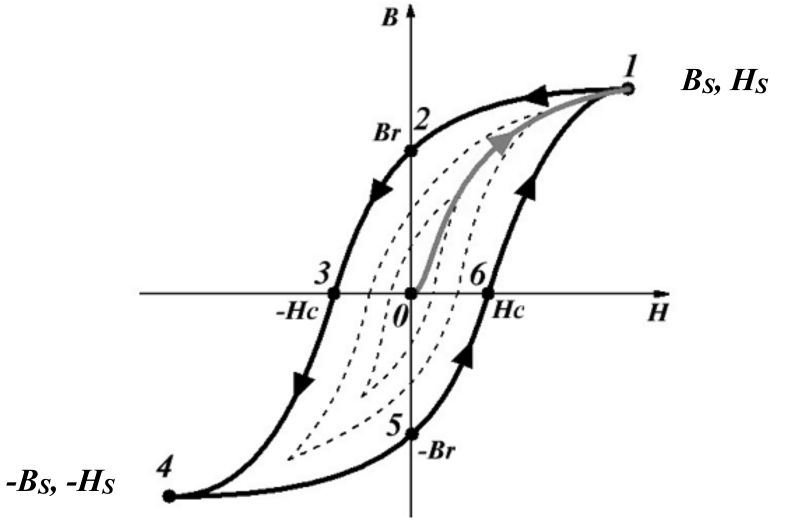
MO topography under conditions of variable magnetization (0–100 kA/m)

Fig. 8 shows a general view of the magnetic hysteresis characteristic of the *B–H* type, reflecting the dependence of the magnetic induction *B* of the sample on the strength *H* of the magnetizing field, where its characteristic points are marked: H_S, B_S – strength and induction of the saturation magnetic field; B_r is the residual magnetic induction; H_C – coercive force. The coercive force H_C, determined by the limiting hysteresis loop of the *B–H* type, is an indicator used to classify the type of ferromagnetic material[12]. As an indicator characterizing the energy consumption for magnetization reversal, the integral over the loop area is used, which is calculated as $W = \int BdH$.

Fig. 8. General view of the magnetic hysteresis characteristic of the B–H type



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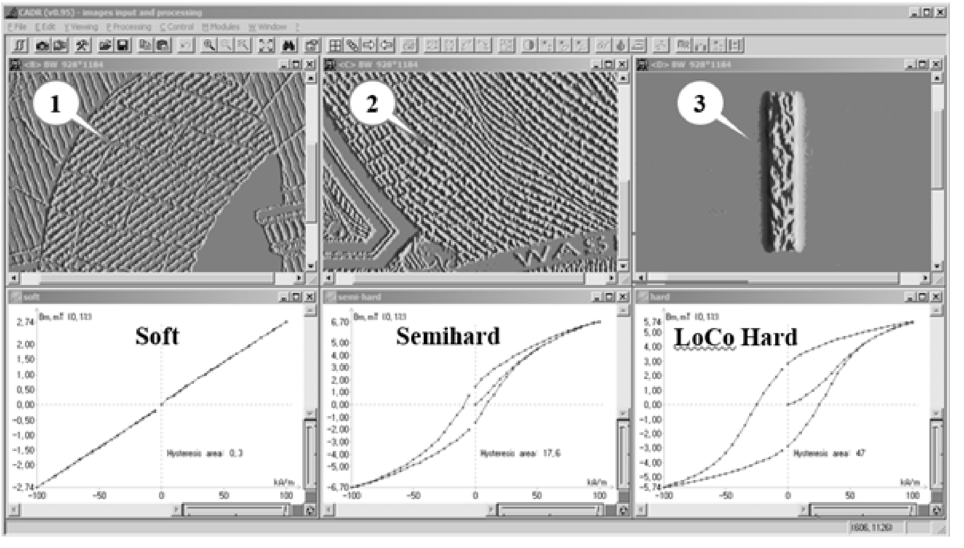
On Fig. 9 the experimental data obtained on the equipment of Fig. 3b are presented – magnetic hysteresis characteristics for banknote samples with different types of magnetic material. Real soft magnetic materials (1) have a narrow hysteresis loop (H_C < 0.8 kA/m), and the ideal soft magnet-

[12] G.Y. Chin et al., *Magnetic materials: An overview, basic concepts, magnetic measurements, magnetostrictive materials*, in: D. Bloor, M. Flemings, S. Mahajan (ed.), *The Encyclopedia of Advanced Materials*, 1st ed., Pergamon Press, Tarrytown, NY 1994, p. 1423.

ic characteristic can be represented as a single line, where all hysteresis branches overlap each other.

Fig. 9. Magnetic hysteresis characteristics for banknote samples with different types of magnetic material: (1) – 5EUR Intaglio print (H_C≈ 0 kA/m); (2) – 1USD Intaglio seal (H_C= 11.2 kA/m); (3) – 5 EUR Protective Thread (H_C= 23.4 kA/m)

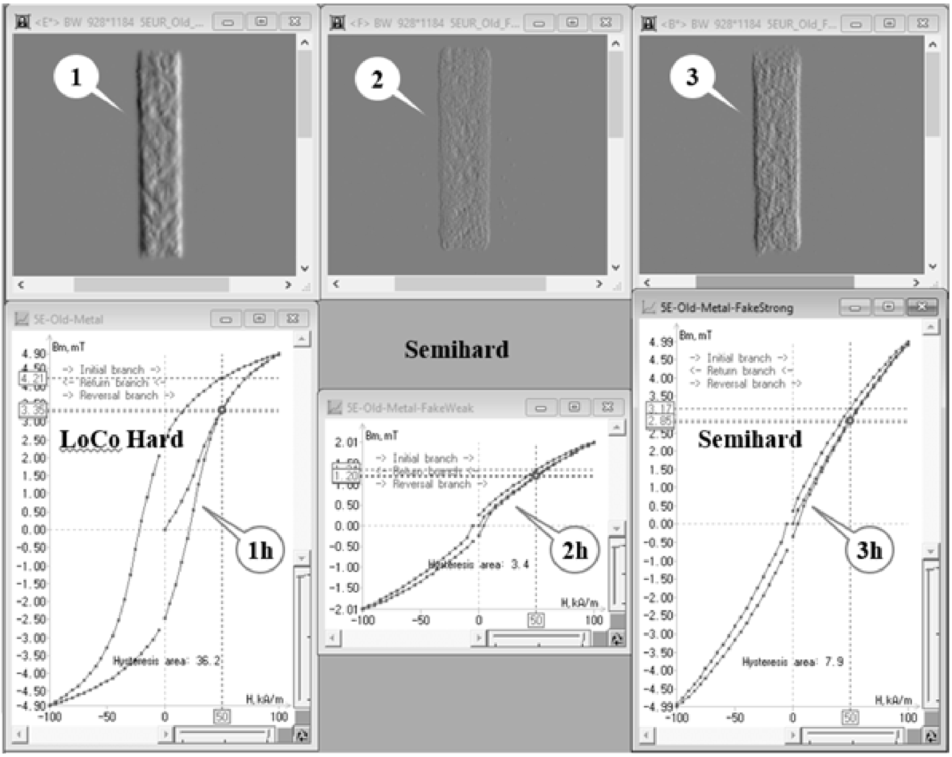


Source: own elaboration.

Real hard magnetic materials (3) have a wide hysteresis loop (H_C > 12 kA/m), and the ideal hard magnetic characteristic can be represented as a rectangle or parallelogram. An intermediate position between them is occupied by Semihard (2) magnetic materials (0.8 kA/m < H_C < 12 kA/m). In addition, hard magnetic materials are sometimes divided into subgroups: low-coercivity LoCo (H_C ≈ 24 kA/m) and high-coercivity HiCo (H_C ≈ 320 kA/m).

For the objects considered earlier (Fig. 7), the results of research under conditions of variable magnetization were obtained (Fig. 10): (1h), (2h) and (3h) – magnetic hysteresis characteristics for the corresponding samples.

Fig. 10. Authentication check of banknote magnetic protection: (1) and (1h) – MO topogram and magnetic hysteresis characteristic of type *B-H* for the reference sample of 5 EUR banknote; (2), (2h), (3) and (3h) are the corresponding data of control samples



Source: own elaboration.

Three parameters were used to evaluate the identity of banknote magnetic security samples: $\Delta B_{ri} = B_{ri} / B_{r1}$; $\Delta H_{Ci} = H_{Ci} / H_{C1}$; $\Delta W_i = W_i / W_1$, where: B_{r1}, H_{C1} and W_1 - values for the reference object; B_{ri}, H_{Ci} and W_i – for the control. Identity criteria: $0,5 < \Delta B_{ri} < 2$; $0,5 < \Delta H_{Ci} < 2$; $0,5 < \Delta W_i < 2$.

Analysis of the results of magnetic hysteresis characteristics shows that (1) the reference sample (B_{r1} = 2,48 мT; H_{C1} = 21,6 kA/m; W_1 = 36,2) differs significantly in magnetic parameters from (2) the control sample (B_{r2} = 0,24 мT; H_{C2} = 5,0 kA/m; W_2 = 3,4), and significantly differs from (3) control sample (B_{r3} = 0,36 мT; H_{C2} = 5,0 kA/m; W_2 =7,9).). Thus, the control sample (2) is not identical (ΔB_{r2} = 10,33 >> 2; ΔH_{C2} = 4,32 > 2; ΔW_2

= 10,65 >> 2). The control sample (3) is not identical (ΔB_{r3} = 6,89 > 2; ΔH_{C3} = 4,32 > 2; ΔW_3 = 4,58 > 2). In addition, from a comparison of the values of the coercive force H_C, it is clear that: (1) the reference sample is made with original LoCo Hard magnetic material, and (2–3) control samples are made with a foreign type of the Semihard magnetic material.

Conclusions

As a result of the analysis of the theoretical model of the object and the principles of MT topography, it was found that the function of magnetic induction on the surface of the object $B^n_{obj}(x, y)$ depends on the parameters of magnetic printing: the geometric dimensions of the strip of magnetic ink (width and thickness), orientation with respect to the magnetizing field, magnetic characteristics of the printing material (magnetic permeability, magnitude and direction of the initial magnetization).

Experimental research of objects by MO topography under conditions of constant magnetization (50 kA/m) showed the following results:

The task of identifying samples of magnetic printer printing can be solved using the estimated parameters (the value of Pearson's linear correlation coefficient (Correlation), the average value of the probability "Similar" (P_Similar)) and identity criteria (Correlation ≥ +0.5 and P_Similar ≥ 0.5). It has been established that the replacement of the cartridge has a radical effect on the spatial distribution of the magnetic values of the print samples.

The task of detecting text insertions for magnetic printer print samples can be solved using the parameter (modulus of deviation of the current B_m value from the average for the environment matrix, normalized to the standard deviation of the values of the environment matrix) and a probabilistic estimate of its value.

The task of checking the authenticity of banknote magnetic protection can be solved using the estimated parameters (ratio of magnetic induction maxima ΔB_{mi}; ratio of magnetic fluxes $\Delta \Phi^n_i$) and identity criteria (0,5 < ΔB_{mi} < 2 and 0,5 < $\Delta \Phi^n_i$ < 2).

The task of checking the authenticity of magnetic protection was also solved by MO topography under conditions of variable magnetization (0–100 kA/m). The experimentally obtained magnetic hysteresis characteristics made it possible to clarify the differences in the magnetic properties of the compared samples in terms of: B_r – **is the residual magnetic induction;** H_C – coercive force; W – energy costs for magnetization reversal. In particular, it was found that instead of the original magnetic material of the

LoCo Hard type, foreign material of the Semihard magnetic type was used in the control samples.

The practical implementation of MO technology in the field of applied forensics may be associated with a certain labor intensity of additional experimental studies necessary for its testing, and will also require further development of scientific and methodological aspects.

At the same time, the results obtained generally show the prospects for the use of magnetic measurements in the research of objects of magnetic printing, MO topograms contain a significant amount of objective information about objects, which can contribute to the successful resolution of a number of tasks relevant to forensic examination of documents in the following areas: identification of magnetic printer printing and detection of text inserts; authentication of magnetic security features of banknotes.

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execution of topograms and their verification, research work, analysis of results and their description, work on the manuscript

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preparation of research environment using two-dimensional MO scanner, participation in research work, work on manuscript

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