Inverse Problem Solution in Landmines Detection Based on Active Thermography

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Abstract. *Landmines still affect numerous territories in the whole world and pose a serious threat, mostly to civilians. Widely used non-metallic landmines are undetectable using metal detector. Therefore, there is an urging need to improve methods of detecting such objects. In the present study we introduce relatively new method of landmines' detection: active infrared thermography with microwave excitation. In this paper we present the optimization based method of solving inverse problem for microwave heating. This technique will be used in the reconstruction of detected landmines geometric and material properties.*

Keywords

Microwave heating, landmines detection, active thermography, inverse problems.

1. Introduction

Nowadays, metal detector is still the most popular device used in demining. It is able to detect landmines containing metallic parts, nevertheless it is almost completely useless in case of the most common, nonmetallic (with bakelite, PVC, and polyethylene casings) devices. Therefore, it is extremely important to work on improving the methods of landmines' detection and removal. Currently the intensive investigations of several new methods of landmine detection are conducted [1]. In the present study, we introduce the relatively new method of landmines' detection: active infrared thermography with microwave excitation [2], [3], which can be considered complementary to the metal detector. Microwave enhanced infrared thermography combines two phenomena: microwave heating and thermal imaging. The volumetric microwave heating induces the thermal contrast between the landmine and soil. Thermal patterns obtained at the ground's surface are observed using sensitive thermovision camera. This method is able to detect an object, determine its size and approximate its location.

Active infrared thermography with microwave excitation can be used to detect objects buried below the ground, regardless of what material they are composed of. It is undoubtedly the basic advantage of this method. However buried stones, branches, and various types of waste can produce similar thermal signatures to antipersonnel landmines while heated by microwaves. It is therefore important to not only detect an object that can be possibly a landmine, but also to determine some of its parameters to classify the object to the group of potentially dangerous [4]. In this paper the method of solving inverse problem for microwave heating will be presented. The proposed technique will be used in estimation of chosen geometric and material properties of landmines. Both numerical and experimental results will be shown.

2. Numerical Modeling − Forward Problem

The phenomenon of microwave heating can be simulated using finite element method (FEM). The propagation of microwave through a dielectric material is governed by the electromagnetic wave equation [5]:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \vec{E} \right) - \left(\varepsilon_r - j \frac{\sigma}{\omega \varepsilon_0} \right) k_0^2 \vec{E} = 0 \quad (1)$$

where μ_r is the relative permeability, ε_0, ε_r are permittivity of vacuum and material, respectively, σ is the material conductivity, k_0 *is* the wave number and $\vec{E}$ is electric field vector. The heat transfer equation can be written as follows:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla (k \cdot \nabla T) = p \quad (2)$$

where ρ, C_p, k indicate material's density, specific heat capacity and thermal conductivity, respectively and $p = 2\pi f \varepsilon_0 \varepsilon'' E^2$ is the volumetrically dissipated power, dependent on wave frequency f and dielectric properties of material.

2D simulations were conducted using commercial software COMSOL Multiphysics to obtain the data which may be used in inverse problem using optimization method (described in the subsequent section). The proposed geometry is presented in Fig. 1.

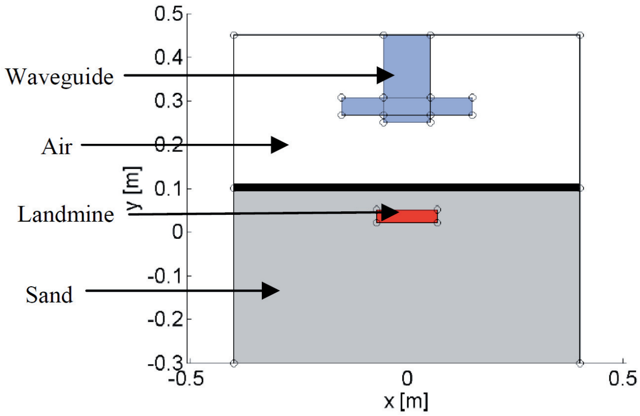

Fig. 1. 2D numerical model geometry.

3. Inverse Problem in Infrared Landmine Detection

The chosen parameters of the landmine can be reconstructed by solving the inverse problem [6]. In our case, the inverse problem is to determine the parameters of the landmines buried in the sand on the basis of the temperature distribution along the sand surface. This distribution can be obtained from the sequence of thermal images. In Fig. 1 one may see black line indicating the boundary from which the temperature distributions were read. The main assumption of our method is a strong relationship between the geometric parameters and material properties of buried landmines and the shape of lines presenting temperature distributions along marked boundary.

The total time of observation was set to 1200 seconds, with 600 seconds of microwave heating. The temperature distribution was measured during the whole time every 40 seconds. As the result we received 30 linear temperature distributions to work with. Reconstructed parameters are: object's size (width and height), the depth at which the object is buried and the position of the object in the relation to the centre of waveguide aperture (geometric parameters are shown in Fig. 2). Additionally, one material parameter − the value of imaginary part of complex dielectric permittivity, was also taken into account. This parameter was chosen after the study of the system's sensitivity to modification of all of the material parameters (i.e. density, specific heat, thermal diffusivity, complex dielectric permittivity).

The optimization algorithm, composed of combined Genetic Algorithms (GA) [7] and Pattern Search (PS), is presented in Fig. 3. The minimized function is defined as summed minimal square errors between the optimal temperature distribution and the distributions obtained in every iteration of the algorithm:

$$MSE_T = \sum_{l=1}^{30} \frac{1}{N} \left(\sum_{k=1}^{N} \left(f_{desT}(x_k, l \cdot \Delta t) - f_T(x_k, l \cdot \Delta t) \right)^2 \right) \quad (3)$$

where $f_{des\,T}$ indicates the desired temperature distribution, f_T is the distribution obtained in every iteration, Δt indicates the time step, x − coordinate of the measurement point, N is the number of measurement points.

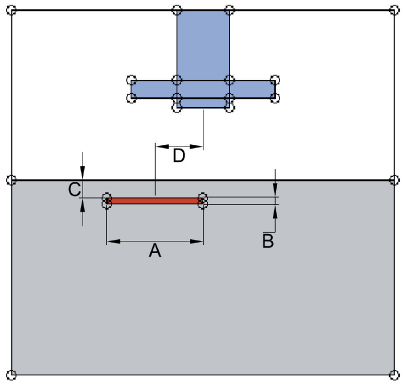

Fig. 2. Estimated geometrical properties: A - width, B - height, C - depth of burial, D - position against the waveguide.

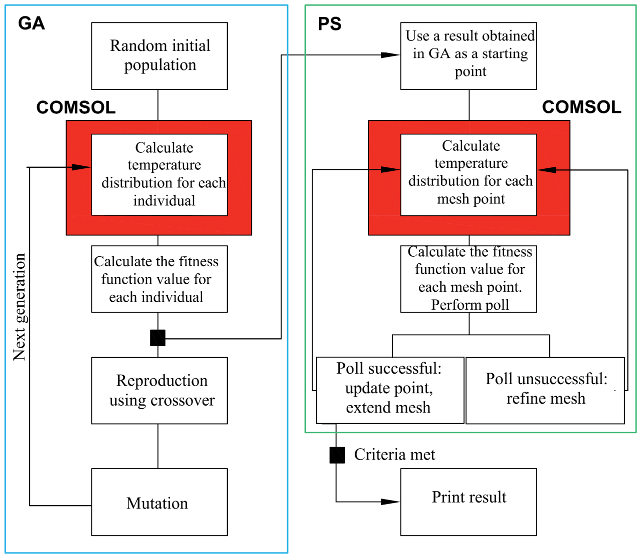

Fig. 3. Flowchart of optimization algorithm.

4. Results − Numerical Data

In order to verify the proposed algorithm's efficiency, the analysis including four sets of numerical data was conducted. The optimization goal in the first case was a landmine of width 0.2 m, height 0.01 m, buried at 0.2 m below the ground and located 0.1 m from the waveguide aperture centre, and in the second case a landmine of width 0.14 m, height 0.03 m, buried at 0.05 m below the ground and located centrally under the waveguide. The imaginary part of complex dielectric permittivity was set to 0.23 in the second case. The first set of numerical data was used to prove the efficiency of the proposed algorithm of estimating the landmine properties in case when there is an offset between the feed and the landmine. In the second case besides the geometric properties complex dielectric permittivity was also estimated. In the third and fourth case the Gaussian noise of 5 % was added to both previous data sets. In Fig. 4 the optimal temperature distributions obtained as a result of forward problem solution for all of the cases are presented.

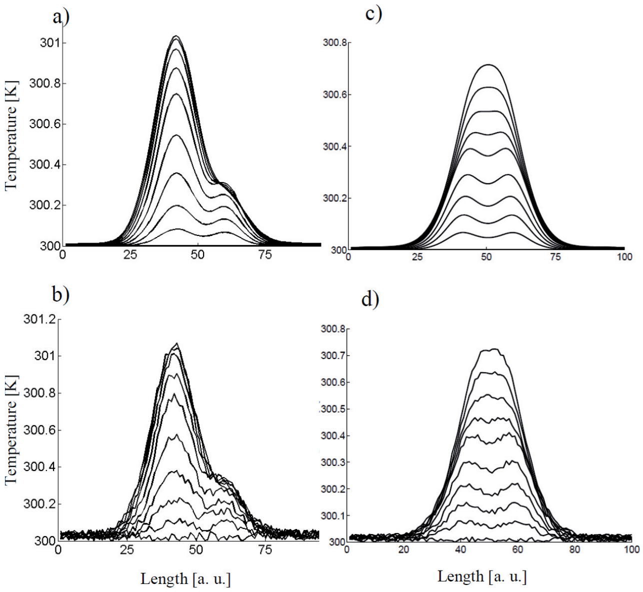

Fig. 4. The optimal temperature distributions. a) and b) for the mine of width 0.2 m, height 0.01 m, buried at 0.2 m below the ground and located 0.1 m from the waveguide aperture centre for the case without noise and with noise, respectively c) and d) for the mine of width 0.14 m, height 0.03 m, buried at 0.05 m below the ground and located centrally under the waveguide for the case without noise and with noise, respectively.

In all cases, the genetic algorithm using the population of 10 individuals was used. The generations number for GA was set to 10. The solution from GA was used as the starting point in the pattern search algorithm, which ran in 50 iterations. As the result of the optimization process is the reconstructed geometrical object parameters. Additionally, for the second case (the mine of width 0.14 m, height 0.03 m, buried at 0.05 m below the ground and located centrally under the waveguide) the imaginary part of complex dielectric permittivity was found. Figure 5 presents the comparison between optimal temperature distribution and those obtained in the optimization process for all sets of data. The results for the four test cases are gathered in Tab. 1–4. It may be noticed that in the case of data with added noise the results are significantly worse: especially the object width was estimated with maximum 90% error. However, in the case of relatively large objects like landmines, the correct estimation of location parameters (depth, position against the aperture center) seems to be more important. Moreover the imaginary part of dielectric permittivity was estimated with error of absolute value equal to 4 %. Therefore, it can be expected that the method of parameter estimation may be used not only for the exact location of the object, but also to verify the type of material from which the object is constructed.

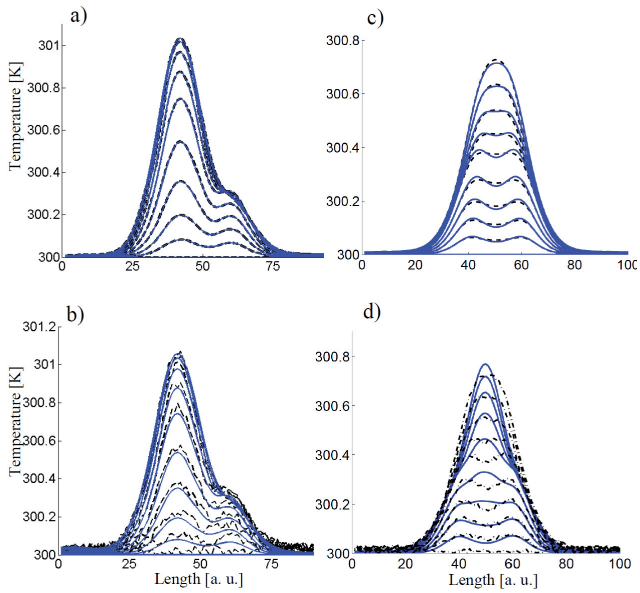

Fig. 5. Comparison between goal temperature (blue line) and reconstructed temperature (black line) distributions along ground surface. a) and b) for the mine of width 0.2 m, height 0.01 m, buried at 0.2 m below the ground and located 0.1 m from the waveguide aperture centre for the case without noise and with noise, respectively. c) and d) for the mine of width 0.14 m, height 0.03 m, buried at 0.05 m below the ground and located centrally under the waveguide for the case without noise and with noise, respectively.

Parameter	Desired value	Estimated value	Error
Width [m]	0.2 m	0.19 m	-5%
Height [m]	0.01 m	0.01 m	0%
Depth [m]	0.025 m	0.025 m	0%
Position against aperture [m]	0.1 m	0.1 m	0%

Tab. 1. Estimated parameters for the mine of width 0.2 m, height 0.01 m, buried at 0.2 m below the ground and located 0.1 m from the waveguide aperture centre. Without noise.

Parameter	Desired value	Estimated value	Error
Width [m]	0.2 m	0.38 m	90%
Height [m]	0.01 m	0.01 m	0%
Depth [m]	0.025 m	0.026 m	4%
Position against aperture [m]	0.1 m	0.108 m	8%

Tab. 2. Estimated parameters for the mine of width 0.2 m, height 0.01 m, buried at 0.2 m below the ground and located 0.1 m from the waveguide aperture centre. With noise.

Parameter	Desired value	Estimated value	Error
Width [m]	0.14	0.14	0%
Height [m]	0.03	0.06	100%
Depth [m]	0.05	0.06	20%
Position against aperture [m]	0	0	
ε''	0.23	0.24	4%

Tab. 3. Estimated parameters for the mine of width 0.14 m, height 0.03 m, buried at 0.05 m below the ground and located centrally under the waveguide. Without noise.

Parameter	Desired value	Estimated value	Error
Width [m]	0.14	0.07	-50%
Height [m]	0.03	0.06	100%
Depth [m]	0.05	0.04	20%
Position against aperture [m]	0	0	
ε''	0.23	0.19	-4%

Tab. 4. Estimated parameters for the mine of width 0.14 m, height 0.03 m, buried at 0.05 m below the ground and located centrally under the waveguide. With noise.

5. Results − Experimental Data

The next stage of the study was devoted to evaluate the effectiveness of the proposed algorithm for the case of experimental data [8]. The experimental setup, shown in Fig. 6, consists of a microwave heating device and thermovision camera (computer controlled FLIR A325, able to record thermal images and videos). The microwave heating device system is based on a magnetron, generating microwaves (frequency 2.45 GHz) of maximum power of 1000 W. The magnetron is connected to the rectangular waveguide with a proper flange. The waveguide is placed above the container with sand, in which the inert landmines are buried. Sand surface is observed using a thermovision camera FLIR A325.

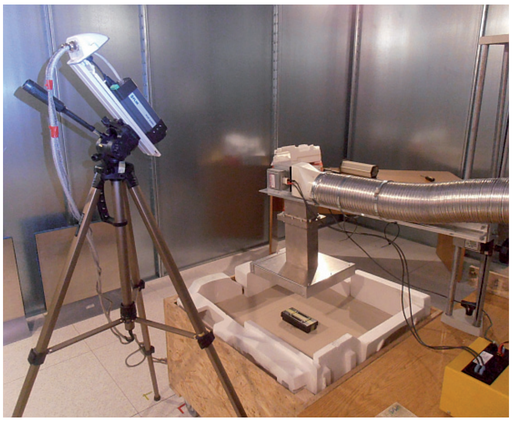

Fig. 6. Experimental setup.

In the experiment, inert landmine PMA-1 (width 0.14 m, height 0.03 m), with bakelite casing was used. The landmine was buried to a depth of five centimeters. The sand with buried landmine was heated for 10 minutes and then the system was observed with themovision camera for another ten minutes of natural cooling. During this time, the sequence of 600 thermograms, presenting the temperature distribution on the surface of the sand, was recorded. In each thermogram, the temperature values were collected along a single line passing through the central part of the heated space, as shown in Fig. 7. As a result, the 600 temperature distributions (shown in Fig. 8) were obtained.

It can be noticed, that obtained linear distributions are noisy. As it was observed in the previous section, the proposed algorithm of parameters estimation gives distinctly worse results for data with added noise. Therefore, the

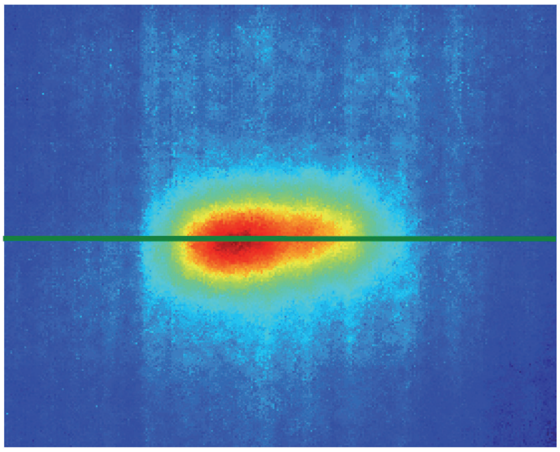

Fig. 7. Exemplary thermogram obtained for PMA-1 landmine. Temperature values were collected from marked green line.

procedure of filtering out the noise is used. In the first step, the Matlab Curve Fitting Toolbox was used to approximate the temperature distribution curves. Data were approximated by Fourier functions, defined as follows:

$$f(x) = a_0 + a_1 \cdot \cos(wx) + b_1 \sin(wx) + \ldots + \\ + a_5 \cos(5wx) + b_5 \sin(5wx) \tag{4}$$

where the parameters $a_0,\ldots, a_5, b_1,\ldots, b_5, w$ were selected using non-linear least squares method.

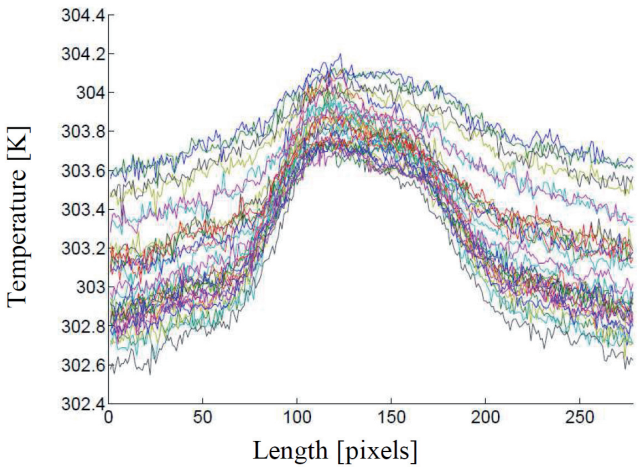

Fig. 8. Temperature distributions collected from thermograms.

As a result of approximation, 600 curves presented in Fig. 9 were obtained. Presented data was used as input to the optimization procedure.

The parameter estimation procedure was carried out just like in the case of numerical data, described in the previous section. Again the genetic algorithm using the population of 10 individuals was used. The generations number for GA was set to 10. The solution from GA was used as the starting point in the pattern search algorithm, which ran in 50 iterations.

Figure 10 shows the comparison between the exemplary temperature distributions obtained in the optimization

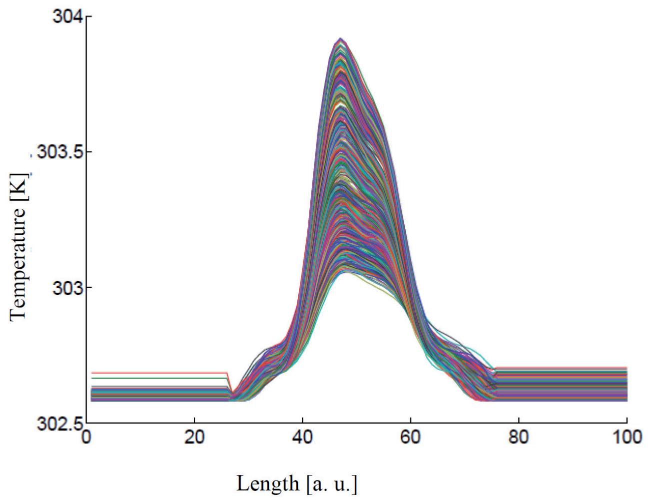

Fig. 9. Approximated temperature distributions.

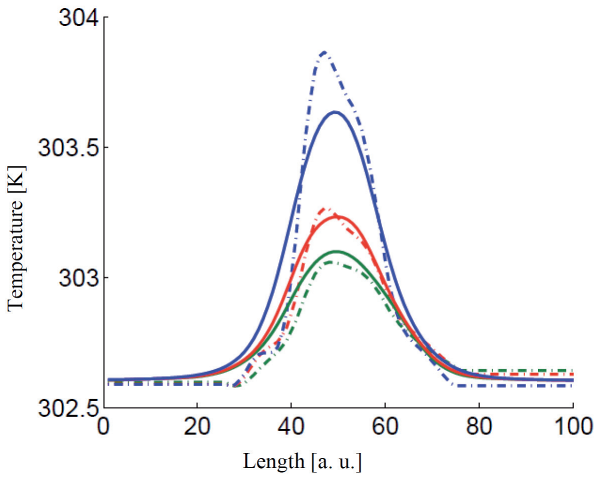

Fig. 10. The comparison between the exemplary temperature distributions obtained in the optimization process (solid lines) and those obtained experimentally (dashed lines).

process and those obtained experimentally. In Tab. 5 the estimated parameters are gathered. The good agreement between the results of estimation and the actual parameters of the detected object may be noticed. In the case of the geometrical parameters, the largest error occurs in the estimation of the mine height, while the width, the depth of burial and location of mine are estimated with a small error. Imaginary part of the complex dielectric permittivity was estimated to 0.28 (compared to ε''= 0.23, for bakelite). Estimation of material properties is essential in this study, since it can be used to determine the approximate type of material.

Parameter	Actual value	Estimated value	Error
Width [m]	0.14	0.13	-7%
Height [m]	0.03	0.08	167%
Depth [m]	0.05	0.06	20%
Position against aperture [m]	0	0.02	5%
ε''	0.23	0.28	22%

Tab. 5. Estimated parameters for the case of experimental data.

6. Conclusions

It was shown, that the proposed algorithm may be used to estimate chosen parameters of the landmines. Solution of the inverse problem allowed the estimation of geometric parameters and one material parameter of the object. The imaginary value of the complex dielectric permittivity may be used to approximate determination of the type of material. It may be especially useful to distinguish between variety types of plastic (used to landmines' casings construction) and other materials, which often contaminate the minefields (like rocks, metal parts and wood chunks). The estimation of the burial depth seems to be very important, since this information may be crucial for the safety of deminers.

References

[1] MACDONALD, J., LOCKWOOD, J. R. *Alternatives for Landmine Detection*. RAND, 2003.

[2] MENDE, H., DEJ, B., KHANNA, S., APPS, R., BOYLE, M., ADDISON, F. Microwave enhanced IR detection of landmines using 915 MHz and 2450 MHz. *Defence Research Reports*, no. DRDC-OTTAWA-TM-2004-266. Ottawa (Canada): Defence R&D, 2004.

[3] MALADEGUE, X. *Theory and Practice of Infrared Technology for Nondestructive Testing*. New York (USA): John Wiley and Sons, 2001.

[4] THANH, N. T., SAHLI, H., HAO, D. N. Infrared thermography for buried landmine detection: Inverse problem setting. *IEEE Transactions on Geoscience and Remote Sensing*, 2008, vol. 46, p. 3987–4004.

[5] SZYMANIK, B., GRATKOWSKI, S. Numerical modelling of microwave heating in landmines detection. *International Journal of Applied Electromagnetics and Mechanics,* 2011, vol. 37, no. 2-3, p. 215–229.

[6] SZYMANIK, B. Objects' parameters reconstruction in landmines' detection based on active thermography. In *International Interdisciplinary PhD Workshop IIPhDW* 2013. Brno (Czech Republic), 8-11 September, 2013.

[7] GOLDBERG, D. E. *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley Publishing Company Inc. 1989.

[8] SZYMANIK, B. Zastosowanie aktywnej termografii podczerwonej ze wzbudzeniem mikrofalowym do wykrywania niemetalicznych min lądowych. (The use of active infrared thermography with microwave excitation for detection of non-metallic landmines.) *PhD Thesis*. West Pomeranian University of Technology, Poland, 2013 (in Polish).

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Barbara SZYMANIK was born in 1982. She received her master's degree in Mathematics in 2006 and in Physics in 2009. In 2013 she defended her doctoral thesis and received her PhD degree in Technical Sciences. Her scientific interests are mainly NDT of materials using active infrared thermography.