Non-Destructive Testing of Composite Helmets Using Ultrasonic Thermography

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Abstract: Due to the shape and material of composite helmets, ultrasonic thermography is the most effective method of detecting subsurface defects using non-destructive testing methods. This method was created by combining the ultrasonic method with infrared thermography. Ultrasonic waves flowing through the tested material cause vibrations at the edges of material discontinuities, which results in heat release. A thermal camera is used to locate places on the surface of the helmet with elevated temperature. Defects are located in these places. Since changes in temperature above defects often do not exceed the noise level, various methods of image processing (thermograms) are used to improve the effectiveness of detecting defects. The article presents the results of tests of composite helmets with intentionally introduced defects and helmets after many years of use. It also shows the possibilities of improving the results of defect detection using various image processing methods.

Keywords: ultrasonic thermography, non-destructive testing, image processing, composite helmet, aramid fibers

1. Introduction

Personal ballistic covers, i.e. composite helmets (and armor vests), use multi-layer composite materials, which are woven materials (including aramid fibers) connected with plastic as a binder. These types of materials are characterized by the fact that they are light, resistant to corrosion, and can be easily formed, which allows them to be adapted to the surface they are intended to protect. Light ballistic shields are most often several to a dozen or so millimeters thick. Defects that may occur in multi-layer composite materials include defects resulting from the technological process and use. These defects affect the properties of the composites, i.e. their number, dimensions, shape and arrangement. Technological defects are related to the method of producing the cover and arise during an incorrectly conducted technological operation. Defects that may occur in this type of composite materials include: inaccuracies in gluing the composite layers, disbanding, thin gas gaps, most often filled with air, delaminations occurring between the composite layers, occurring during impacts caused by impacts, fragments and shell fire as a result of destructive ballistics tests, material discontinuities, inclusions of foreign materials, flat cracks, etc. The above-mentioned defects may also occur together.

Each composite helmet is individual equipment and is used differently by each user. In addition to objective factors affecting its efficiency, such as climatic conditions, its technical condition after many years of operation is also influenced by the user himself. The user influences the technical condition of the helmet by demonstrating technical culture and attention to compliance with the manufacturer's operational requirements by independently carrying out a visual inspection of the condition of the helmet, especially after its use, in order to detect damage or disruption of the continuity of the outer layer of the helmet. It is also important to exercise appropriate supervision and control over maintaining appropriate storage conditions of helmets, inspecting them and transporting them in appropriately designed transport packaging.

Due to the complicated shape of composite helmets, many non-destructive testing methods are not effective in detecting defects that may occur in them. Among the tests carried out at the Institute using various non-destructive testing methods for helmets, the best results were obtained using ultrasonic thermography.

2. Ultrasonic thermography

Ultrasonic infrared thermography [1–3] is a method of active non-destructive testing based on ultrasound and infrared thermography. After introducing them into the sample, ultrasonic waves will move freely through the homogeneous material. However, an internal defect causes a complex combination of absorption, scattering, beam dispersion and wave dispersion, which will ultimately be in the form of heat. The heat will then move by conduction in all directions. If an infrared (IR) camera is pointed at one of the sample surfaces, a trace of the defect can be detected. The advantage of using this method is the ability to identify the defect regardless of its orientation in the sample and the ability to detect both internal and open surface defects. Hence, this method is useful for detecting delaminations and cracks. The ultrasonic wave is produced by a transducer composed of a stack of piezoelectric elements. The

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Artykuł recenzowany
nadesłany 11.06.2025 r., przyjęty do druku 09.09.2025 r.

transducer relay should be properly pressed against the sample to ensure proper ultrasonic transmission, otherwise poor ultrasonic transmission may occur or cause unwanted heat near the point of ultrasound introduction [4].

Compared to optical (external) techniques, the heat wave travels half the distance in ultrasonic thermography studies. This is because heat propagates from the defect to the surface (for optical techniques, heat moves from the surface to the defects and back to the surface). Therefore, ultrasonic thermography tests are quick. Damage just beneath the surface can become apparent within seconds of initiating thermal stimulation with an ultrasonic signal. Of course, longer heating times are required to detect remaining defects. The deepest defects can be located during the cooling phase. Additionally, the longer the transducer operates on a surface, the more heat is released at the contact surface, increasing the likelihood of damage to the area. It should be borne in mind that the pressure exerted on the sample has a large impact on the thermal response [4]. Although ultrasonic thermography examinations are fast compared to optical heating (because they do not require reducing the impact of uneven heating of the tested surface on the obtained results – the testing time using optical methods can be several times longer), to inspect a large area it is necessary to move the transducer and re-immobilize the sample.

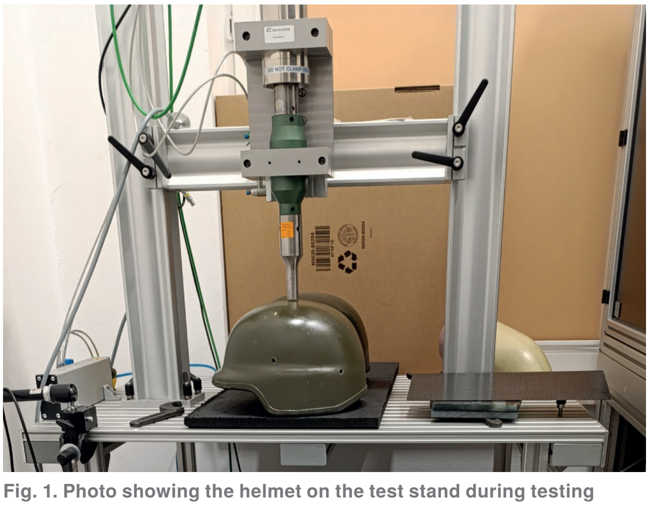


Fig. 1. Photo showing the helmet on the test stand during testing
Rys. 1. Zdjęcie przedstawiające hełm na stanowisku badawczym podczas badań

The experiments at the Military Institute of Armament Technology (MIAT) was made using a FLIR SC 7600 IR imager (image format 640 × 512) in a sequence of 300 thermograms. Ultrasonic stimulation was performed with an ultrasound generator at the frequency from 15 kHz to 25 kHz. Output power was from 300 W to 0.9 kW (the maximum allowed power was 2 kW). The ultrasonic signal was generated from 50 s to 100 s. While the registration time was from 120 s to 240 s. Figure 1 presents the set-up used for the thermographic tests containing an ultrasonic thermal stimulation.

3. Results

3.1. Helmes with intentionally introduced defects

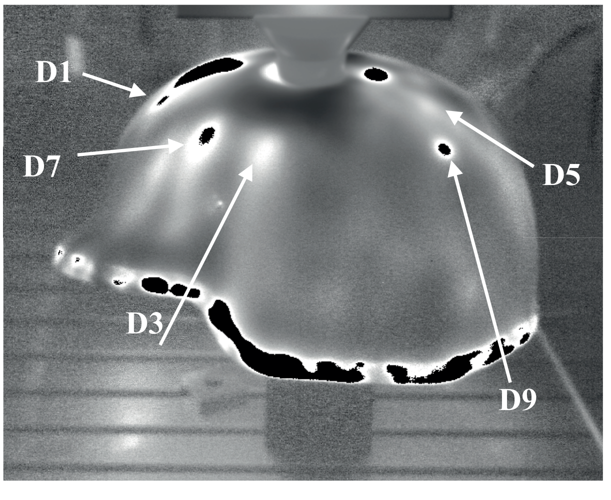
Our previous research presented in publications [5, 6] carried out on helmets with intentionally introduced defects into the internal structure of the helmet showed that the ultrasonic thermography method can be effective in detecting internal defects in composite helmets. The publication [7] presents the possibilities of detecting defects in the form of inclusions of other materials and those located at various depths under the helmet surface, as shown in Figures 2 and 3. Figure 2 shows a thermogram of the composite helmet with the detected defects. The square-shaped defects introduced into the helmet were approximately 0.1 mm thick and had different areas of 0.5 cm^2 (defects D1, D2 and D3), 1 cm^2 (D4, D5, D6) and 1.5= cm^2 (D7, D8, D9). The defects were located at various depths under the upper surface of the helmet, i.e. between the 1st and 5th layers (D1, D4, D7), the 8th and 12th layers (D2, D5, D8) and the 16th and 20th layers (D3, D6, D9). The defects were introduced during the technological process of making the helmet in the manufacturing plant.

The distribution of defects in the helmet is shown in Figure 3 [7].

In order to select the most effective ultrasound frequency for the type of composite (aramid) considered in this work, experimental tests were carried out using samples with deliberately introduced defects at different ultrasound frequencies [8].

Samples with dimensions of (100 × 100) mm contained introduced defects in the form of air gaps, each with dimensions of (10 × 10) mm and a thickness of approx. 0.1 mm. The defects were located between the 1st and 5th aramid layer (D1 defect),

a)



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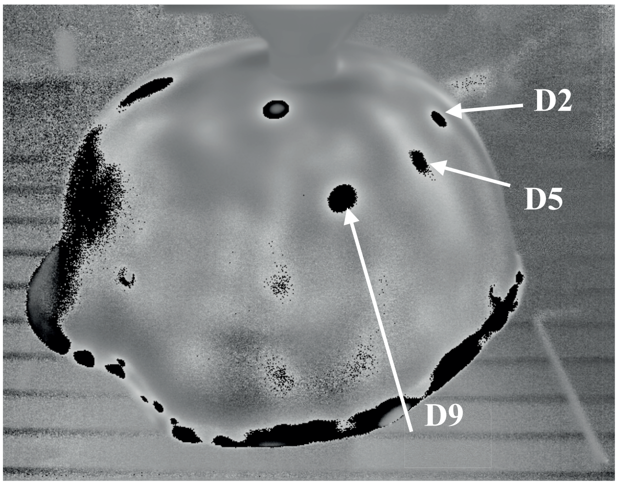


Fig. 2. Results of helmet tests using ultrasonic thermography – phasograms (view from the left side of the helmet) obtained for various test parameters: a) generator power 0.9 kW, stimulation time 100 s, frequency 23,5 kHz, recording time 240 s; b) generator power 0.9 kW, frequency 22 kHz, stimulation time 80 s, recording time 240 s
Rys. 2. Wyniki badań hełmów z wykorzystaniem termografii ultradźwiękowej – fazogramy (widok z lewej strony hełmu) uzyskane dla różnych parametrów badania: a) moc generatora 0,9 kW, czas stymulacji 100 s, częstotliwość 23,5 kHz, czas rejestracji 240 s; b) moc generatora 0,9 kW, częstotliwość 22 kHz, czas stymulacji 80 s, czas rejestracji 240 s

between the 8th and 12th aramid layer (D2 defect) and between the 16th and 20th aramid layer (D3 defect) (Fig. 4).

During stimulation, the ultrasound frequency ranged from 15 kHz to 23 kHz. Changes in the temperature field on the sample surface were recorded with a thermal imaging camera.

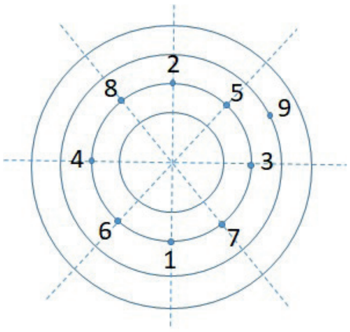


Fig. 3. Diagram of locating defects in the helmet
Rys. 3. Schemat lokalizacji uszkodzeń w hełmie

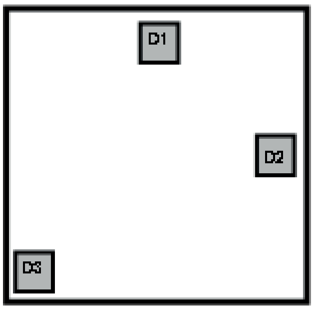


Fig. 4. Distribution of defects in the test sample
Rys. 4. Rozkład defektów w próbce testowej

The obtained ΔT results for individual ultrasound frequencies (using 80 % of the generator power) are presented in Table 1. The parameter ΔT in the table was determined as the maximum difference between the temperature on the front surface of the sample above the defect located at a given depth under the sample surface, recorded during the heating and cooling phase, and the initial temperature for the same point in the sample. The camera error was 1–2 % of the measurement range.

3.2. Helmets after 10 years of use

3.2.1. Image processing

Non-destructive testing using thermographic methods, as well as other test methods, has limitations relating to types, geometric dimensions, and depth of defect position below the surface of tested materials. Relevant techniques are used to process images (thermograms) obtained during experimental testing. In the process of analyzing hundreds of images containing details, they are replaced by a limited set of distinct features, prone to use of methods and algorithms for recognition. In addition to standard methods used in digital image processing, special data processing techniques are used, the most important of which are: thermal tomography, Fourier transform, wavelet analysis, thermographic signal reconstruction, dynamic thermography standardization, principle component analysis, neural networks especially deep learning and data synthesis.

In the case of improving the imaging of defects in non-destructive tests carried out using ultrasonic thermography of helmets, the best results were achieved by two methods: principal component analysis (PCA) and wavelet analysis.

Principal Component Analysis (PCA) is a transformation that turns a large amount of information contained in the interrelated input data into a set of statistically independent components according to their importance. It is therefore a form of lossy compression, known in information theory as the Karhunen-Loeve transform [9]. It is used in statistical procedures, which in recent years have become more and more popular in the issues of image recognition and data compression, especially data of very large volumes [10].

The principal components method has been used relatively recently in thermographic tests. The PCA uses the decomposition method to extract both spatial and temporal information from a thermographic data matrix. Three-dimensional matrix (the sequence of thermal images recorded) is converted into two-dimensional, wherein the time values are arranged in columns a spatial data in rows. Thereafter, the two-dimensional matrix is decomposed and the resulting matrix can again be represented as an image sequence.

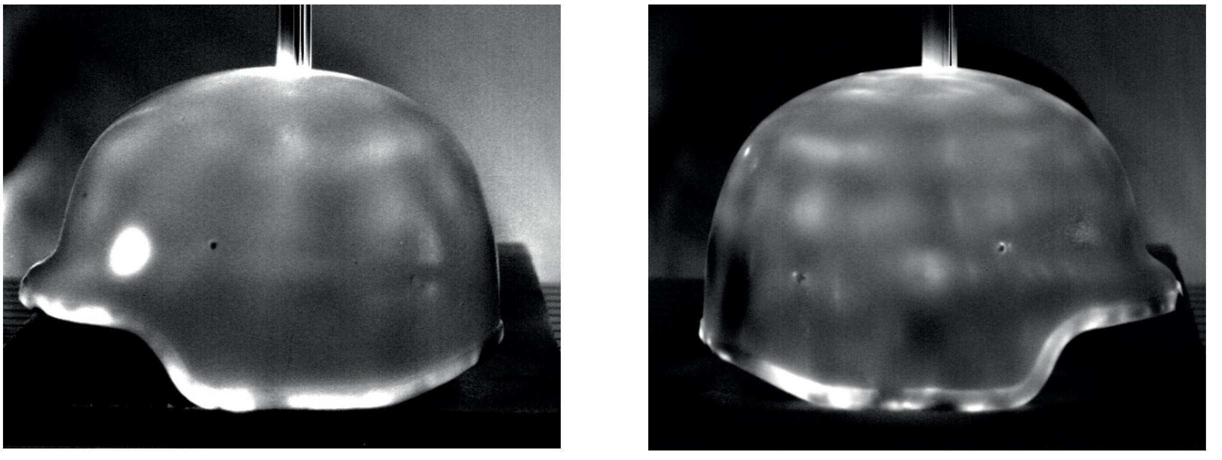
The most common use of this method is to reduce the size of the data set. The task is to describe large-dimension data (high number of features) with fewer features, while keeping maximum information. In the case of PCA, this information is measured by variance, which in statistics is a classic measure of volatility. Principal components analysis allows to describe multivariate data with a small number of uncorrelated coordinates (determined by the eigenvectors of the covariance matrix), maintaining the dispersion between the data. The dimension of the new space will depend on how much of the features we want to keep [11].

Table 1. ΔT values obtained from the experimental tests
Tabela 1. Wartości ΔT uzyskane na podstawie przeprowadzonych badań doświadczalnych

Frequency [kHz]	**15**	**16**	**17**	**18**	**19**
[°C] D1	0.73	0.83	0.80	1.34	0.93
[°C] D2	0.17	0.33	0.27	0.59	0.54
[°C] D3	0.83	0.45	0.21	0.68	0.48
Frequency [kHz]	**20**	**21**	**22**	**23**	**15***
[°C] D1	1.21	1.16	1.32	0.74	0.98
[°C] D2	0.84	0.52	0.39	0.32	0.42
[°C] D3	0.56	0.55	0.43	0.16	0.61

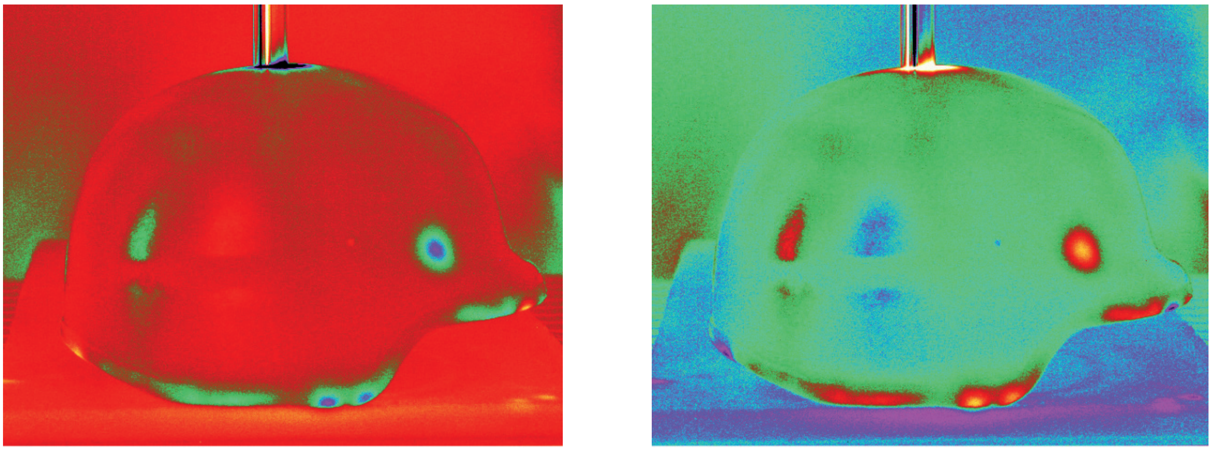
* generator power 100 %

The wavelet transformation enables a simultaneous representation of time and frequency signals and it leads to the approximation of the signals by isolating their characteristic structural elements. In contrast to the Fourier transform, the wavelet transform decomposes the signal into elementary signals called wavelets, which are continuous waveforms of a different duration and different spectra [12]. The disadvantage of the Fourier transform, which is the most popular method of analysing temperature signals, is that switching from time-value to frequency-value results in the loss of time information. On the other hand, the wavelet transform enables the analysis of the signal frequency change as a function of time. The wavelet analysis is a useful tool for analysing short time signals, transient data or complex images. ThermoFit™ Pro software allows you to perform wavelet analysis using two methods: CWT and Complex CWT. CWT (*Continuous Wavelet Transform*) and Complex CWT (*Complex*



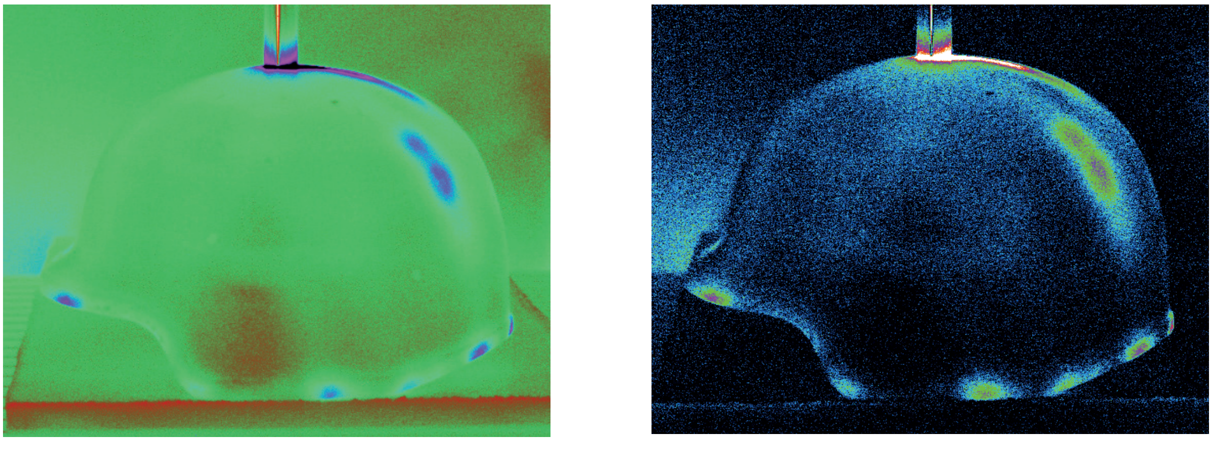
a) b)

Fig. 5. Source thermograms of helmet No. 1 obtained by ultrasonic thermography: a) left side, b) right side
Rys. 5. Źródłowe termogramy hełmu nr 1 uzyskane metodą termografii ultradźwiękowej: a) strona lewa, b) strona prawa



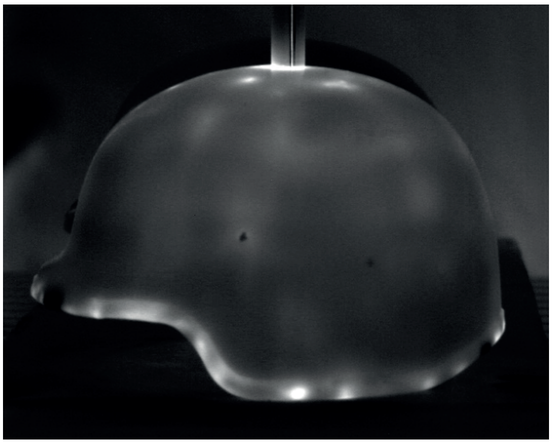
a) b)

Fig. 6. Images of helmet No. 1 (left side) with visible defects: a) PCA (second component), b) CWT wavelet analysis (Morlet, a = 9, b = 10)
Rys. 6. Obrazy hełmu nr 1 (lewa strona) z widocznymi defektami: a) PCA (druga składowa), b) CWT analiza falkowa (Morlet, a = 9, b = 10)



a) b)

Fig. 7. Images of helmet No. 1 (right side) with visible defects: a) PCA (second component), b) CWT wavelet analysis (Morlet, a = 8, b = 11)
Rys. 7. Obrazy hełmu nr 1 (strona prawa) z widocznymi defektami: a) PCA (druga składowa), b) CWT analiza falkowa (Morlet, a = 8, b = 11)



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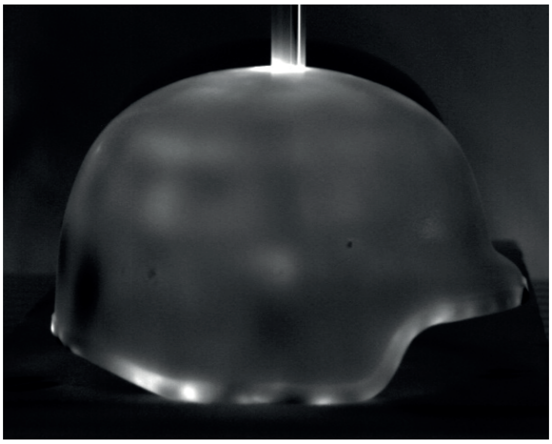
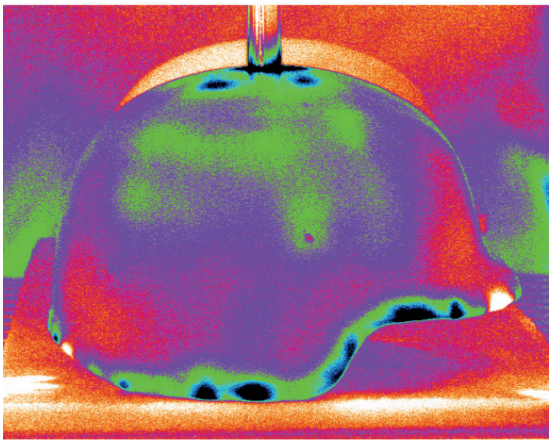


b)

Fig. 8. Source thermograms of helmet No.2 obtained by ultrasonic thermography: a) left side, b) right side
Rys. 8. Źródłowe termogramy hełmu nr 2 uzyskane metodą termografii ultradźwiękowej: a) lewa strona, b) prawa strona



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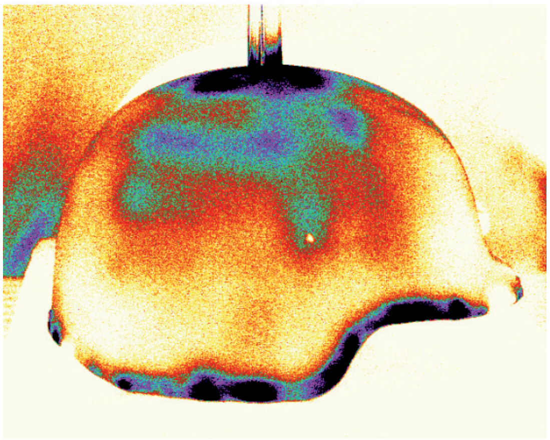
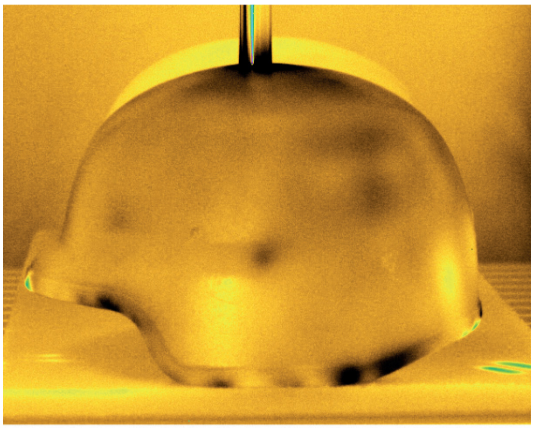


b)

Fig. 9. Images of helmet No. 2 (right side) with visible defects: a) PCA (second component), b) CWT wavelet analysis (Morlet, a = 14, b = 8)
Rys. 9. Obrazy hełmu nr 2 (strona prawa) z widocznymi defektami: a) PCA (druga składowa), b) CWT analiza falkowa (Morlet, a = 14, b = 8)



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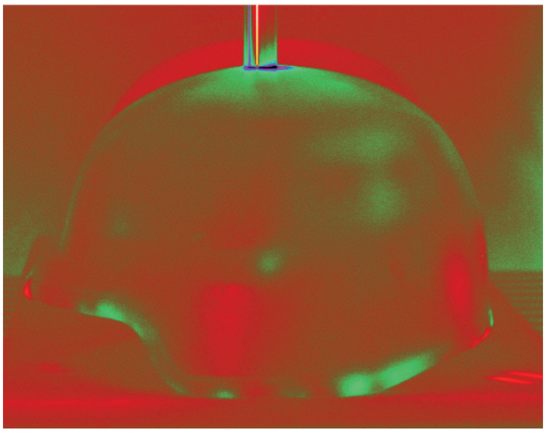

b)

Fig. 10. Images of helmet No. 1 (left side) with visible defects: a) PCA (second component), b) CWT wavelet analysis (Morlet, a = 16, b = 11)
Rys. 10. Obrazy hełmu nr 1 (lewa strona) z widocznymi defektami: a) PCA (druga składowa), b) CWT analiza falkowa (Morlet, a = 16, b = 11)

Continuous Wavelet Transform) are two different signal analysis methods that use wavelet transforms. They differ primarily in the type of wavelets used and the interpretation of the results. CWT uses real wavelet functions, while Complex CWT uses complex wavelets, which allows for analysis of the signal phase and amplitude. CWT is a real-valued function of scale and position [13]. CWT is a real-valued function of scale and position. In the software used, the maximum scale is a = 20 and the position is also b = 20.

3.2.2. Results of helmets after 10 years of use

A production batch of composite helmets after intensive use was subjected to non-destructive testing using ultrasonic thermography. The aim of the non-destructive testing was to assess the condition of all helmets and to select those in which damage was detected. Helmets in which damage was detected were subjected to destructive shooting tests. The weakening of the ballistic resistance of these helmets was assessed. Figures 5 and 8 present selected test results for two example helmets. They present source thermograms with the most visible changes in the internal structure of these helmets. A sequence of 300 images was recorded at a frame rate of 2 Hz. The figures show the last source thermogram.

Image processing methods were used to select the areas in the helmets where the damage was greatest. The ThermoFit™ Pro software developed by prof. Vavilov [14]. This software enables the use of various thermogram processing algorithms. The Program is able to treat IR image sequences produced as sets of single image files. The number of images in analyzed sequences can be arbitrary. All ThermoFit™ Pro processing algorithms are applied to all images in a sequence except the first image. It is assumed that the first image in a sequence is recorded at the ambient (initial) temperature, i.e. before heating/cooling. It can be subtracted from each image in the sequence or skipped in further processing. An ambient temperature image can be added separately to any sequence.

A certain disadvantage is that as a result of dividing the sequence of thermograms into individual thermograms using the MATLAB software, we have a mirror image of the thermograms in the ThermoFit™ Pro software.

As can be seen in the source thermograms, in addition to visible areas where defects may occur, the internal structure of composite helmets is also visible. In order to visualize the places where defects occur, two most effective methods were used: principal component analysis and wavelet analysis. Very similar results were obtained, as can be seen in the images presented in Figures 6, 7, 9 and 10.

4. Conclusions

The presented results confirm the potential of infrared ultrasonic thermography in the examination of objects made of aramid fiber-reinforced composites with complex shapes, such as composite helmets.

The presented method enables testing of composite helmets of various shapes and sizes. The usefulness and effectiveness of image analysis methods have also been confirmed, which enable more precise localization of places where potential defects may occur.

In future work, we want to automate the process of detecting defects in composite helmets to shorten their examination time.

Acknowledgements

The research was co-financed by the National Center for Research and Development (Project no. DOB-SZAFIR/02/A/001/01/2020).

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Badania nieniszczące hełmów kompozytowych z wykorzystaniem termografii ultradźwiękowej

Streszczenie: Ze względu na kształt i materiał, z którego wykonane są hełmy kompozytowe, termografia ultradźwiękowa jest najskuteczniejszą metodą wykrywania wad podpowierzchniowych przy użyciu metod badań nieniszczących. Metoda ta została stworzona poprzez połączenie metody ultradźwiękowej z termografią w podczerwieni. Fale ultradźwiękowe przepływające przez badany materiał powodują drgania na krawędziach nieciągłości materiału, co powoduje wydzielanie ciepła. Kamera termowizyjna służy do lokalizowania miejsc na powierzchni hełmu o podwyższonej temperaturze. W tych miejscach znajdują się wady. Ponieważ zmiany temperatury powyżej wad często nie przekraczają poziomu szumu, stosuje się różne metody przetwarzania obrazu (termogramu) w celu poprawy skuteczności wykrywania wad. Artykuł przedstawia wyniki badań hełmów kompozytowych z celowo wprowadzonymi wadami oraz hełmów po wieloletnim użytkowaniu. Pokazuje również możliwości poprawy wyników wykrywania wad przy użyciu różnych metod przetwarzania obrazu.

Słowa kluczowe: termografia ultradźwiękowa, badania nieniszczące, przewarzanie obrazów, hełmy kompozytowe, włókna aramidowe

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