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Experimental Testing of Aramid Composite Applied in Ballistic Armour using Ultrasonic IR Thermography

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Abstract. Reference samples, in which artificial discontinuities (defects) are fabricated, are used to verify non-destructive testing procedures. Artificial discontinuities are known defects of reference samples and enable verification the possibilities of using the chosen NDT method for the identification of location and depth of discontinuities. In thermographic methods the tests of reference samples also allow (helps) to determine the required thermal stimulation source parameters of the tested sample. This paper presents the results of experimental testing of defects detection in a multi-layer aramid composite used in light ballistic armour using ultrasonic infrared thermography. Samples of the aramid composite included artificial defects and were tested using different ultrasonic frequencies. The tests of the same samples were carried out with optical thermography and X-ray method and their results were compared to those determined with ultrasonic IR thermography.

Keywords: ballistic armour, IR thermography, ultrasounds, composite materials

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1. INTRODUCTION

Composite materials have seen an increasing use in military applications, including ballistic armour. The most common composites in these applications are textiles combined with plastic materials as the composite matrix (binder), forming multi-layer composite materials used for personal ballistic protection, additional armour of vehicles, aircrafts, ships, and other applications of ballistic protection. The composite materials are usually made from extremely durable fibres (polyethane or aramid) bound by resins (among others phenolic or polyurethane) and rubber compounds. The resulting composite materials are light in weight, corrosion-resistant and they can be easily formed resulting in a better fit to the protected surfaces. The composite materials can be applied in combination with steel plates and ceramics for enhanced protection against projectiles and fragments [1].

The potential defects in multi-layer aramid composite include inaccuracies in gluing composite layers~~,~~ and delamination occurring during mechanical impacts caused by shots with projectiles and fragments.

Verification and development of NDT (non-destructive testing) procedures are done with reference samples which feature artificial, purpose-made discontinuities. In IR thermographic NDT, materials of reference samples should exhibit known thermophysical properties [2]. Artificial discontinuities and “artificial defects” in reference samples help verify the methods aimed at determining the location and depth of discontinuities in materials. The increasingly common technology of preparing reference samples consists in placing another material (e.g. Teflon inserts) between composite layers [3]. IR thermographic NDT can be divided into passive and active test procedures [4, 5]. Defectoscopy of composite materials is largely based on active IR thermographic NDT procedures.

2. EXPERIMENTAL TESTING WITH USE OF IF THERMOGRAPHY

Experimental testing was carried out on samples with artificial defects to assess the capability of ultrasonic IR thermography to detect defects in multi-layer aramid composite materials. Test samples sized 100x100 mm each included artificial defects formed by air voids, each sized 10x10 mm and approximately 0.1 mm thick. The defects were located between layers no. 1 and 5 (defect D1), 8 and 12 (defect D2) and 16 and 20 (defect D3) of the aramid composite (Fig. 1).

A sample of the aramid composite with the defects in the form of air voids is shown in Fig. 2.

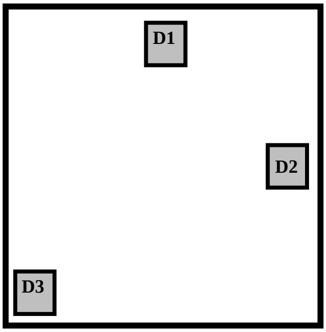


Fig. 1. Location of defects in the test sample

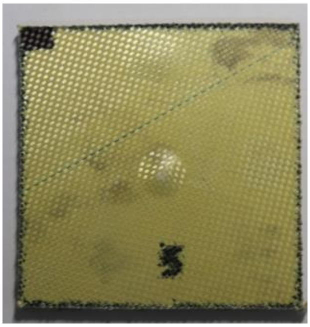


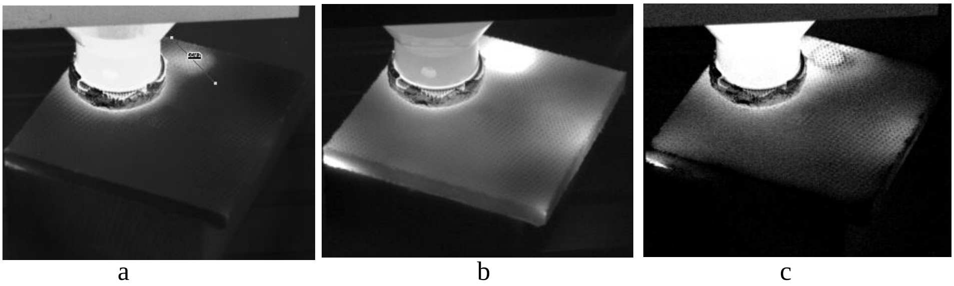
Fig. 2. The test sample

The aramid composite samples were tested with an ultrasound generator. During the stimulation the ultrasound frequency was from 15 kHz to 23 kHz. The changes in the temperature field resulting from ultrasonic exposure of the samples were detected with an IR camera. The changes in the temperature field on the surface of the sample were recorded with an IR camera.

2.1. Test results

The following provides examples of the test results achieved for selected ultrasonic frequencies. Figure 3 shows examples of a phase image and an amplitude image obtained during ultrasonic thermography tests on which areas of all three defects are visible.

Figure 4 shows the temperature profile of the sample surface over defect D1 for the ultrasonic frequency 22 kHz (along the line shown in the thermogram, Fig. 3 a). The maximum temperature differential Δ*T* (the difference between the temperature recorded during the heating and cooling phase and the initial temperature) was 1.32°C for defect D1.



a b c

Fig. 3. (a) Thermogram of the sample front surface; (b) Phase image; (c) Amplitude image

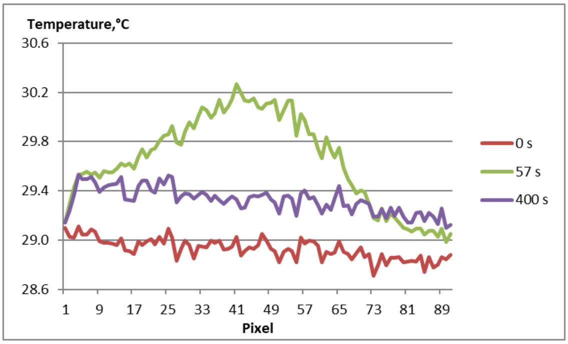


Fig. 4. Temperature profile on the front surface of the sample over the defect D1 at 0 s, 57 s and 400 s

Figure 5 shows the test results at 20 kHz ultrasounds frequency. Figure 6 is the temperature profile on the sample surface over defect D2 (along the line shown in the thermogram, Fig. 5 a). In the case at hand, the maximum value of ΔT was 0.84°C for defect D2.

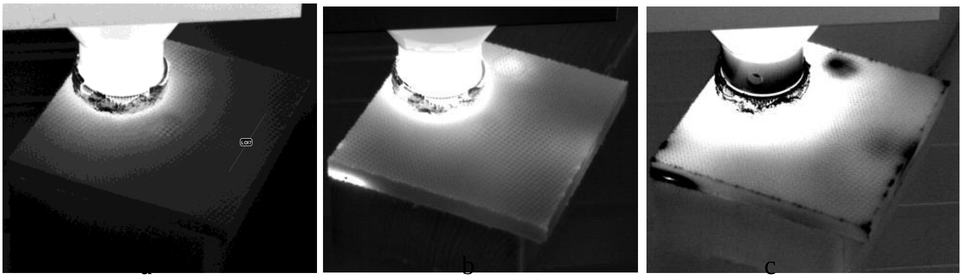

a b c

Fig. 5. (a) Thermogram of the sample front surface; (b) Phase image; (c) Amplitude image

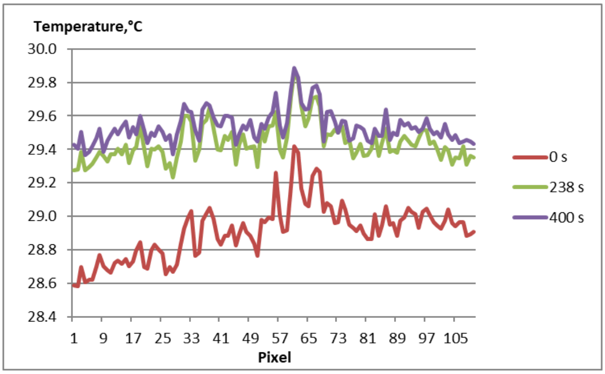
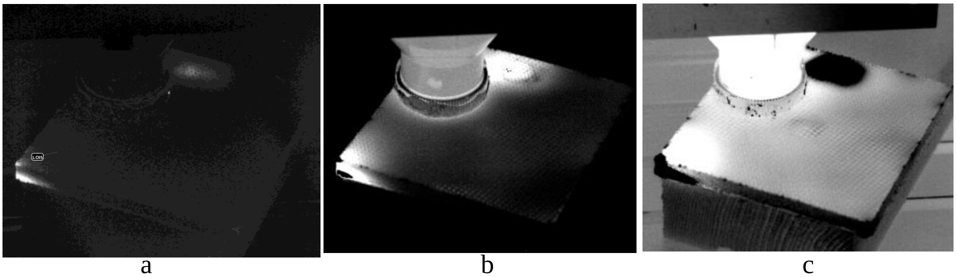


Fig. 6. Temperature profile on the front surface of the sample over defect D2 at 0 s, 238 s and 400 s

Figure 7 shows the test results at 15 kHz ultrasounds frequency. Figure 8 is the temperature profile on the sample surface over defect D3 (along the line shown in the thermogram, Fig. 7 a). The maximum value of Δ*T* was 0.83°C for defect D3.



a b c

Fig. 7. (a) Thermogram of the sample front surface; (b and c) Phase image

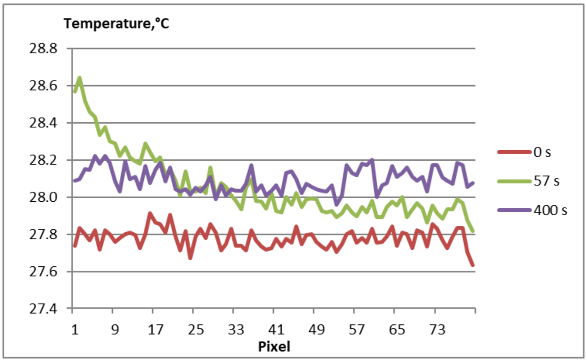


Fig. 8. Temperature profile on the front surface of the sample over defect D3 at 0 s, 57 s and 400 s

3. TESTS USING OPTICAL THERMOGRAPHY

During the experimental testing discussed here, one of the most popular NDT methods applicable to composites was used: pulsed thermography. A lamp for generating a thermal excitation pulse was used for the tests. The test was carried out using the reflection method also known as the one-sided procedure. The thermal stimulation source and the temperature recorder were located on the same side of the tested object [3].

During the tests, an aramid composite was heated with 6 kJ thermal pulse~~s~~, each 5 ms in duration, generated by the flash lamp. The changes of the temperature field on the sample surface were recorded with an FLIR SC 7600 camera in a sequence consisting of 1500 images (thermograms) with a resolution of 640x512 pixels, recorded at 5 Hz.

Figure 9 shows a schematic diagram of the setup for testing by pulsed thermography using the reflection method.

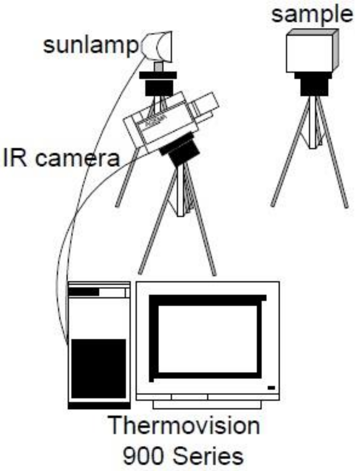


Fig. 9. Diagram of the test stand for reflection method

3.1. Test results

Figure 10 shows the recorded thermogram after switching off the radiation source in the cooling phase during the pulsed thermography test. The surface condition of the sample (Fig. 2, i.e. roughness, unevenness, colour, stains and markings) affected its emissivity. The inhomogeneity's of the composite surface caused a noise temperature contrast.

Figure 11 presents a temperature profile on the sample surface over the defect D1 (along the line shown in the thermogram, Fig. 10 a).

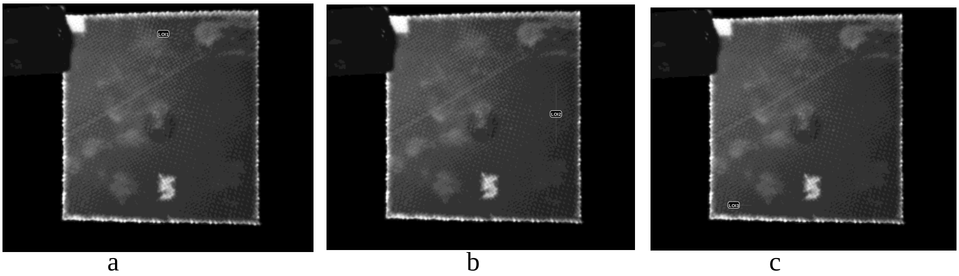


Fig. 10. Thermogram of the sample's front surface recorded at the time of 1 s during the pulsed thermography test

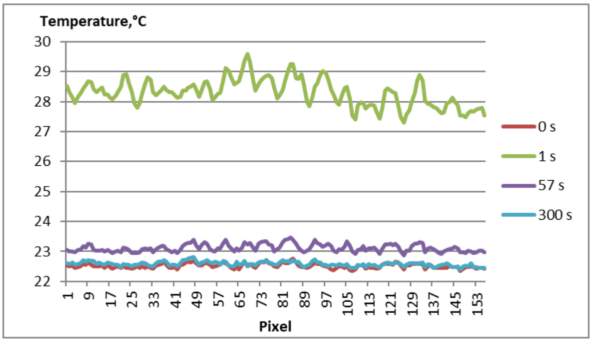


Fig. 11. Temperature profile on the sample front surface over defect D1 at 0 s, 1 s, 57 s and 300 s

Figure 12 presents a temperature profile on the sample surface over defect D2 (along the line shown in the thermogram, Fig. 10 b).

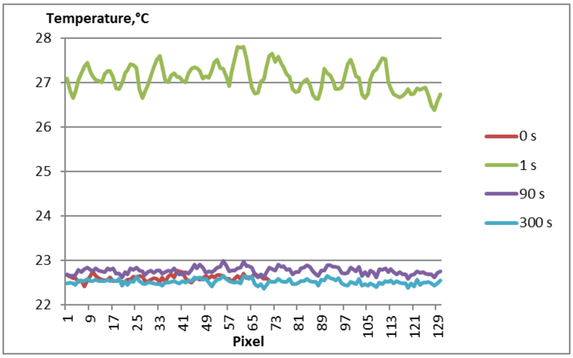


Fig. 12. Temperature profile on the sample front surface over defect D2 at 0 s, 1 s, 90 s and 300 s

Figure 13 presents a temperature profile on the sample surface over defect D3 (along the line shown in the thermogram, Fig. 10 c).

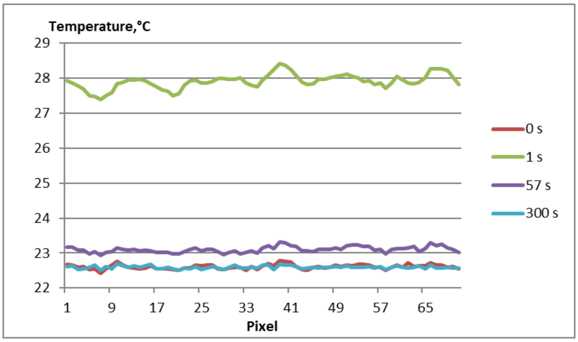


Fig. 13. Temperature profile on the sample front surface over defect D3 at 0 s, 1 s, 57 s and 300 s

4. TESTS USING X-RAY METHOD

The sample with deliberately introduced defects has been subjected to non-destructive testing using an X-ray diagnostic system. The samples were tested with the YXLON MU-17F-225-9 X-ray apparatus.

4.1. Test results

The exographs of the sample on which defects were revealed are shown in Fig. 14.

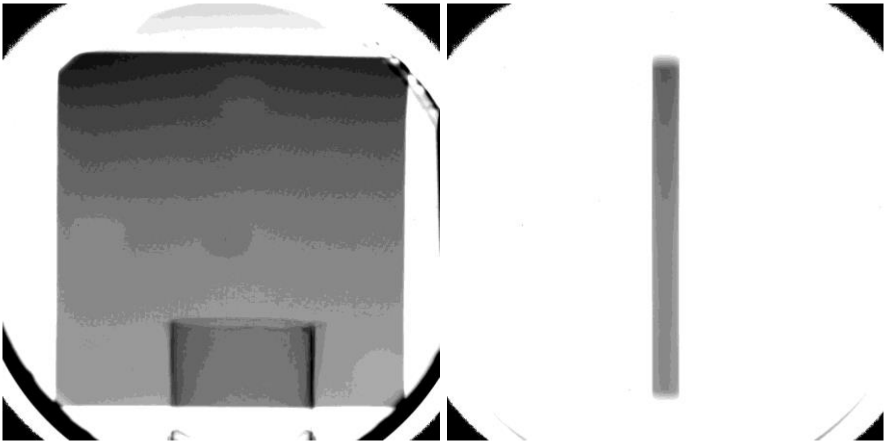


Fig. 14. Exographs of a test sample

5. CONCLUSION

The experimental tests of samples with deliberately introduced defects in sound/ ultrasound stimulation have shown that aramid composite are a suitable material for inspect by IR thermography. In this material hidden defects generate significant temperature signals who's the amplitude depends on the physical and geometrical properties of the sample/ defect, defect depth, frequency and time of stimulation and the distance of the defect from the stimulation point.

All defects were revealed on exographs. Based on the obtained exographs it was revealed that defect D3 in comparison to other defects was located close to the edge of the sample. The X-ray results were consistent with the results obtained by ultrasonic IR thermography.

The presented results of detecting subsurface defects in the aramid composite using ultrasonic infrared thermography indicate, compared to the results obtained by pulsed thermography, that thermal stimulation with an ultrasonic source is more effective, especially when detecting defects deeper under the material surface. As shown in Fig. 11 to 13 at surface optical heating, excessive temperature signal is created not only over the defect but also in zones without defects. This leads to the appearance of the current noise contrast caused by the inhomogeneity's of the composite surface.

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Badania eksperymentalne kompozytu aramidowego stosowanego w osłonach balistycznych metodą ultradźwiękowej termografii w podczerwieni

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Streszczenie. Do sprawdzenia procedur badań nieniszczących są stosowane próbki wzorcowe, w których wprowadzono sztuczne nieciągłości (defekty). Nieciągłości sztuczne wprowadzone w próbkach wzorcowych umożliwiają zweryfikowanie przede wszystkim możliwości zastosowania wybranej metody do określenia położenia i głębokości nieciągłości. W metodach termograficznych badania próbek wzorcowych pozwalają również określić potrzebne parametry źródła stymulacji cieplnej badanej próbki. W artykule przedstawiono wyniki badań eksperymentalnych wykrywania defektów w wielowarstwowym kompozycie aramidowym stosowanym w konstrukcji lekkich osłon balistycznych metodą ultradźwiękowej termografii w podczerwieni. Badania próbek kompozytu aramidowego z celowo wprowadzonymi defektami, przeprowadzono przy zastosowaniu różnych częstotliwości ultradźwięków. W celu porównania uzyskanych wyników badań, wykonano badania metodami optycznej termografii i rentgenografii.

Słowa kluczowe: osłony balistyczne, termografia w podczerwieni, ultradźwięki, kompozyty.