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USE OF THE LOCK-IN IR THERMOGRAPHY METHOD FOR EVALUATION OF LIGHT COMPOSITE ARMOURS

Abstract: The article presents problems related to assessment of subsurficial damage resulting from destructive tests of light composite armours that constitute multi-layer structures made from various materials. The active method of optical lock-in thermography was used as the non-destructive method of the damage area assessment. Determination of the size of internal damage area allows for comparison of armours made from various materials. Basing on the tests conducted it was found out for the light armour samples tested that the area of subsurficial damage of material from the side of impact of a projectile simulating a shell splinter can be three times larger than the projectile's calibre; on the other side this area can be 15-times larger than the calibre.

1. Introduction

Composite materials are more and more often used to make light ballistic covers. An interest in light ballistic covers results from threats which troops participating in stabilisation missions are exposed to. Usually they are equipped with motor vehicles exposed small-calibre weapon fire and mine explosions. Therefore it is necessary to provide an effective protection to these vehicles in order to guarantee an adequate safety level to their crews.

Due to the progress in polymer chemistry it is currently possible to manufacture materials that provide an effective protection against small-calibre projectiles and shell fragments. Most often woven materials (fabric) are used, combined together by means of a plastic into multi-layer composite materials. They are used to manufacture personal ballistic covers (vests) as well as armours for motor vehicles and fixed facilities. Composites of this kind are usually made from very strong aramid and polyethene fibres combined together by means of phenol or polyurethane resins or rubber mixtures. They can be also used in combination with steel metal sheets and ceramics to increase their effectiveness of protection against projectiles and fragments. Composite armours are easily replaceable and in case of damage the damaged elements can be replaced by new ones without necessity of dismantling the whole cover [1].

Given the fact that light ballistic covers are usually several to more than 10-mm thick and are made of materials thermo-physical properties of which are definitely different than those of potential defects that may occur in these materials, non-destructive testing by means of thermographic methods can be effective in detection of defects in them.

2. Destructive ballistic tests

Features characterising a composite armour irrespectively of a technology used to manufacture it includes the minimum critical distance between adjacent hits. In case of laminates made of high-strength fibres or layered armours made of ceramics and laminates, the damage area inside the composite (around the projectile impact point) can be even more than ten times larger than the material removal area caused as a result of a projectile hit and visible by naked eye. Impact of another projectile in the damage area often results in armour penetration [2].

For a fragment resistance a widely recognised test allowing for comparison of various materials, first of all in terms of their surface density, is determination of the V_{50} ballistic limit by means of a projectile that simulates a fragment of 1.1 g weight (Polish standards specify it as the standard fragment). The basic NATO document that specifies requirements for this test is STANAG 2920 „Ballistic test method for personal armour”. This test is also described in Polish standard PN-V-87000.

The V_{50} ballistic limit is determined as an average of 6 perpendicular impact velocities (three lowest velocities ended with a complete penetration and three highest velocities ended with a partial penetration). A spread of up to ±20m/s between the lowest and highest projectile velocities is allowed in determination of ballistic limits. Only in cases when the lowest velocity at which complete penetration occurred is lower by more than ±20m/s than the highest velocity of a partial penetration, the ballistic limit is calculated as an average of ten velocities (5 lowest velocities of complete penetration and 5 highest velocities of partial penetration).

3. Non-destructive tests

Infrared thermography is an area of technology dealing with detection, recording, processing and imaging of invisible infrared radiation emitted by an object. Its result is a picture (thermogram) that represents a temperature distribution on the surface of the examined object.

There are passive and active methods of non-destructive tests using infrared thermography [3, 4]. In the passive methods the object of the tests is assessed basing on its characteristic temperature field occurring when it functions. Because of this the passive procedures are used chiefly for tests of equipment or its elements during functioning or shortly after, when the temperature field on the surface allows for detecting of defects.

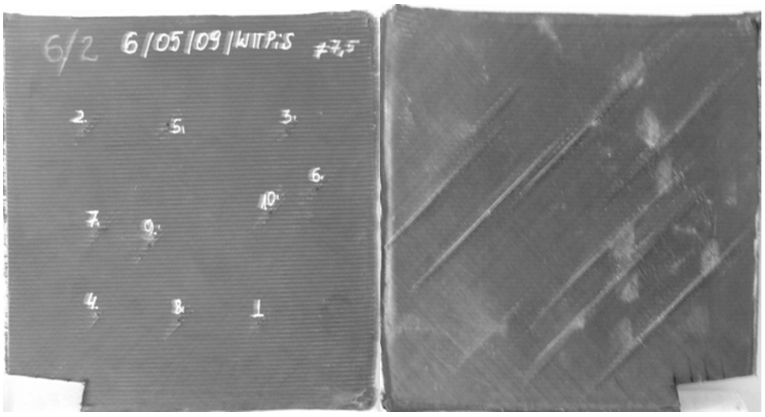
In the active methods an additional source of thermal stimulation (warming or cooling) of the test object is used. Material of the object that has the same temperature as its defects, equal to an ambient temperature, does not generate any “useful” temperature signals and requires warming or cooling of the whole object or its part. A variable temperature field is generated during the test and test results are a function of the observation time. Special data processing procedures are usually used in the active methods.

3.1 Samples tested

The non-destructive tests were conducted on samples of light ballistic covers made of aramid fibre laminate, glass fibre laminate, polyester-glass laminate and carbon fibre laminate as well as a laminate made by combining layers made from carbon and glass fibres. The following samples were tested:

- Four samples of the aramid fibre laminate, made of various numbers of layers: 6 , 9, 12 and 15 layer;
- Three samples of glass fibre laminate, made of 10, 15 and 20 layers;
- Two samples of polyester-glass laminate, made of 8 and 12 layers;
- Two samples of carbon-glass laminate, made of 12 and 16 layers;
- Three samples of carbon fibre laminate, made of 10, 12 and 15 layers.

Prior to the non-destructive tests all samples underwent destructive tests using the V_{50} method. Fig. 1 shows exemplary pictures of the sample made of the above-mentioned laminates. The graph in Fig. 2 presents results of ballistic strength for samples of aramid fibre laminate and those of glass fibre, obtained during the destructive tests using the V_{50} method.



a) b)

Fig. 1. Sample of the carbon fibre laminate after V_{50} destructive tests: a) on the impact side, b) on the other side

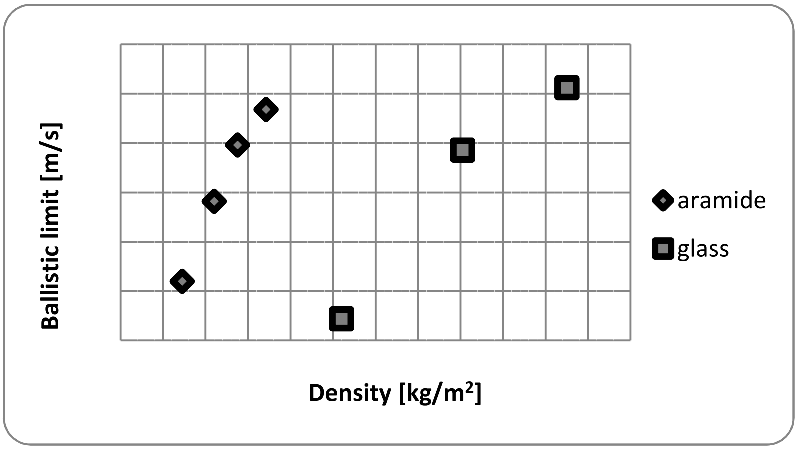


Fig. 2. Experimentally determined V_{50} ballistic limit for the tested samples of aramide and glass fibre laminate

3.2 Research method applied

The following main methods of active thermographic tests are presented in the X. Maldague’s paper [5]:

- Pulsed Thermography – PT;
- Step Heating – SH;
- Lock-in Thermography – LT;
- Vibrothermography – VT.

Basing on previous experiences referring to tests of ballistic covers made of composites reinforced with both glass and aramid fibres, described in the papers [6, 7], the most effective optical lock-in thermography, so called four-point method, was selected. Its advantage is that this method can be used to test quite large surfaces in a short time, without any interference with the material tested. This method is also known as the heat wave thermography. In the optical lock-in thermography method the object is stimulated by a harmonic heat stream, generated by a heating lamp. The object’s thermal stimulation is of a sinusoidal nature and thus, basing on the known frequency of the stimulating signal and the recorded system response, both amplitude and phase shift angle (amplitudegram and phasogram) of this response can be determined [8, 9]. The thermal field resulting from the object response to stimulation has also a sinusoidal nature and its parameters can be determined basing on four signal samples of the same mutual distance, taken within a single period and analysed by means of the Fourier method.

Next both the phase and amplitude is calculated for every point of the image according to the following equations:

$$\varphi = \arctan\left(\frac{S_1 - S_3}{S_2 - S_4}\right). \tag{1}$$

$$A = \sqrt{[S_1 - S_3]^2 + [S_2 - S_4]^2}\ . \tag{2}$$

Fig.3 shows the test stand in which the AGEMA lock-in module was used, working with the AGEMA 900LW camera and heating lamp of 1 kW power output.

3.3 Tests results

Fig. 4 shows exemplary phasograms of the carbon fibre laminate (Fig. 1), presenting internal damage of the laminate structure on both the projectile entry side (Fig.4a) and the exit side (Fig. 4b). The damage area was determined as a diameter of a circle that contained internal damage of the material caused by an impact of the projectile shot at the sample.

Basing on the analysis the results of internal laminate damage detection by means of the V_{50} destructive test method, the authors found out that:

- In all cases the internal material damage area on the projectile entry side was smaller than the damage area on the exit side;
- Together with an increase of the number of the layers (laminate thickness) smaller and smaller differences in damage areas (for both complete and partial penetration) occur on the projectile entry side;

- Minimum damage area on the projectile impact side was not smaller than 1.5 cm and at the exit it was not smaller than 3.5 cm;

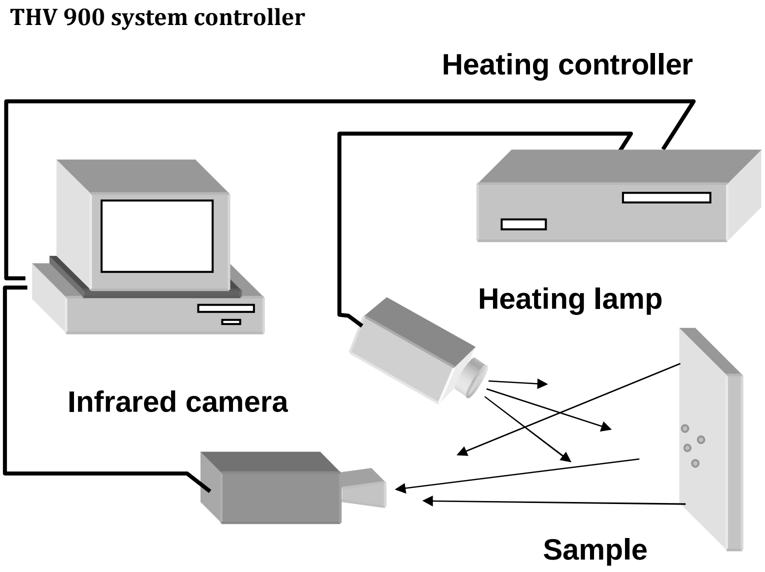
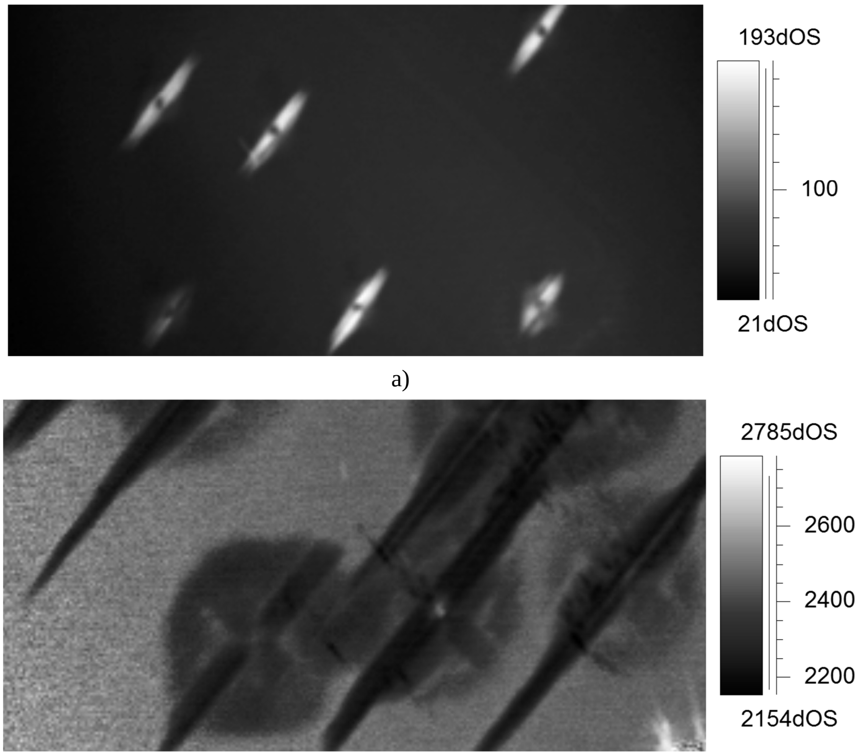


Fig. 3. The test stand



a)

b)

Fig. 4. Phasograms of the carbon fibre laminate: a) on the impact side (0,06 Hz), b) on the other side (0,117 Hz)

- Clearly visible is an effect of the material structure weakening, resulting from a previous projectile impact, on the size of damage caused by projectile another impact at the area of the previous damage. This causes a visible increase of the damage area on the side of previous material structure damage;
- In many cases the material damage area on the projectile entry side was larger for a partial penetration than for complete one, despite the fact that the impact energy was lower in such a case.

Fig. 5 presents exemplary dimensions of the material structure damage in the 6-layer aramid laminate, on both the projectile entry and exit side, for both complete and partial penetration.

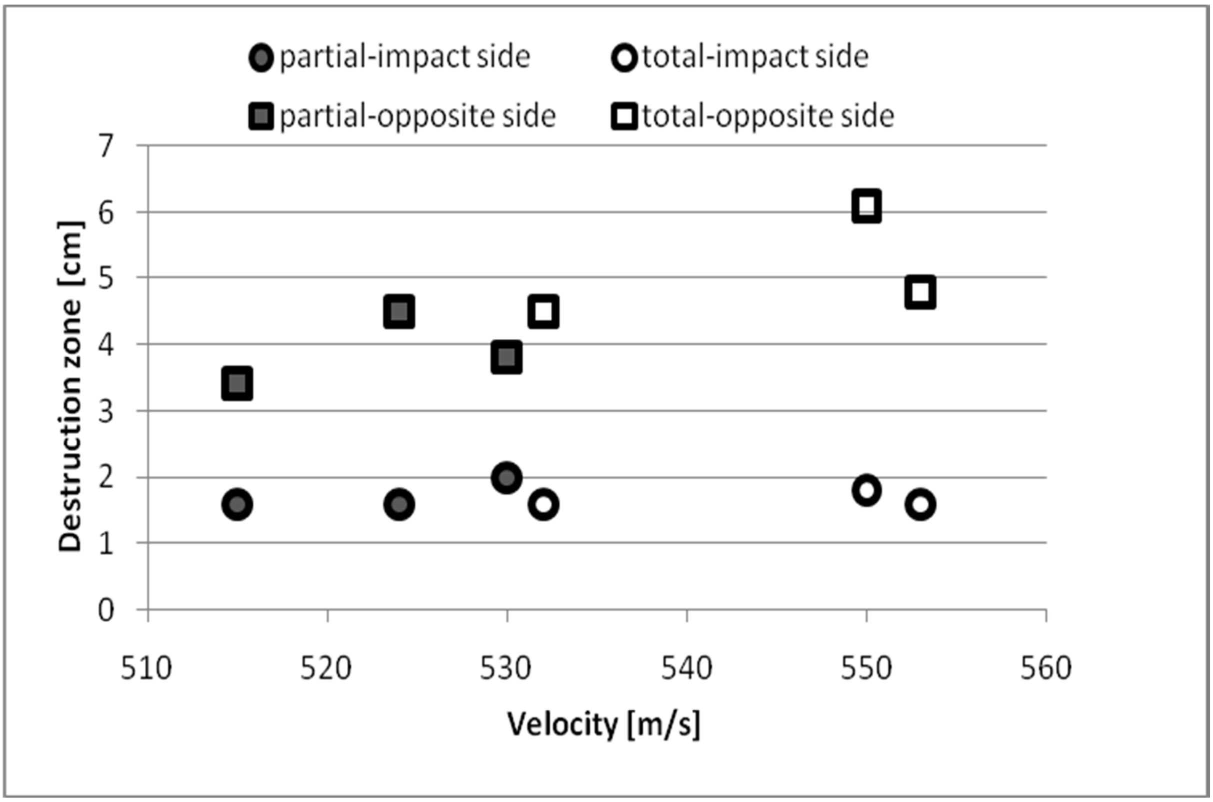


Fig. 5. Damage areas in the 6-layer aramid laminate

Figs. 6 and 7 shows a comparison of average sample damage areas for both complete and partial penetration, for samples of all laminates tested, of a comparable thickness of approx. 7 mm.

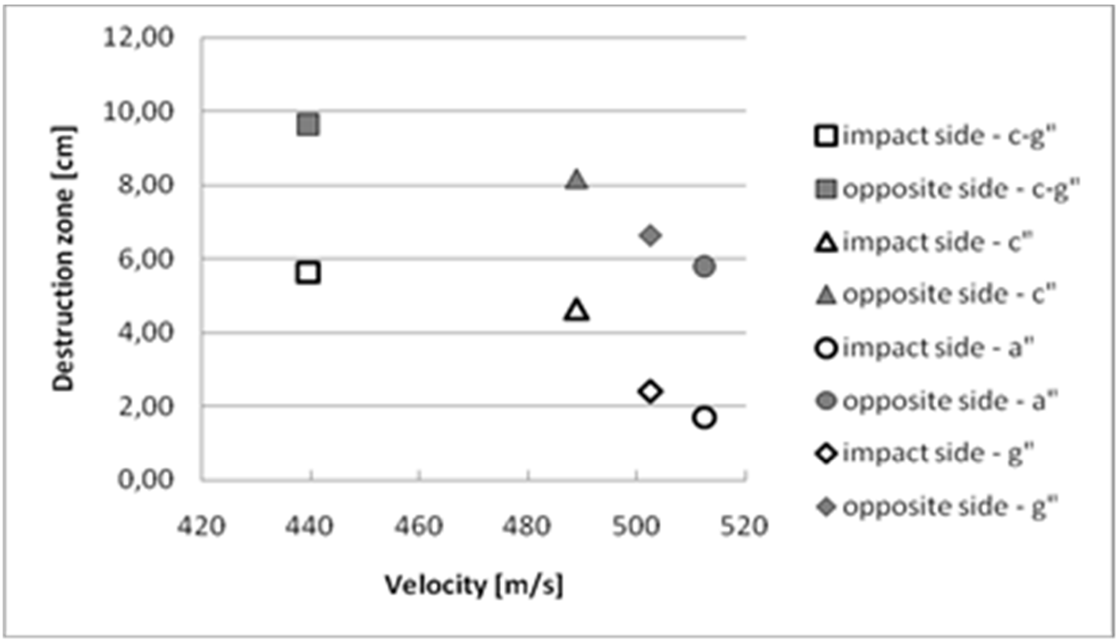


Fig. 6. Comparison of material damage areas at incomplete penetration of the samples tested

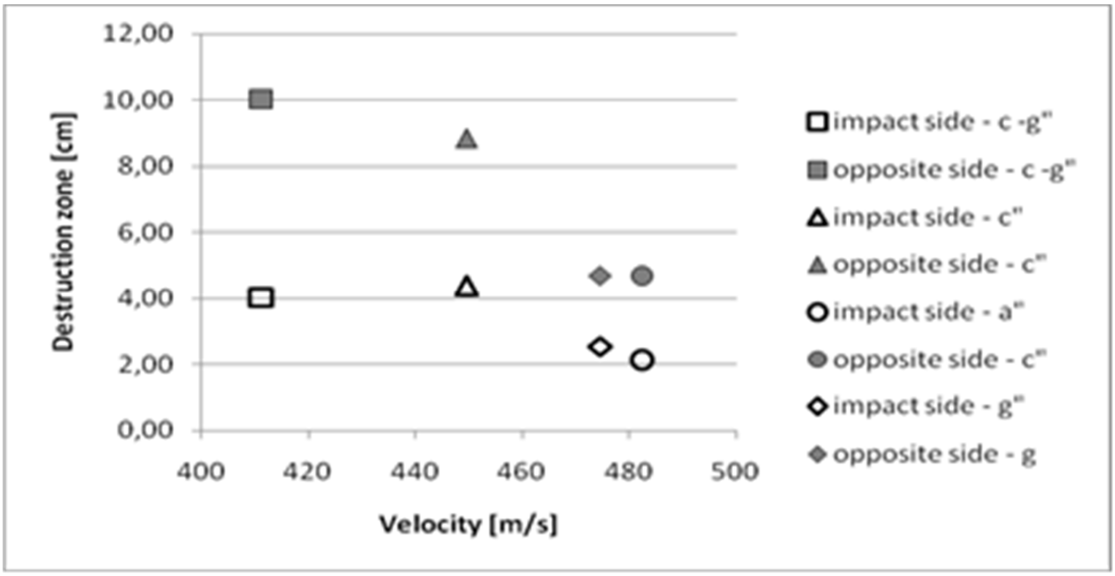


Fig. 7. Comparison of material damage areas at complete penetration of the samples tested

4. Conclusion

The conducted comparative non-destructive tests of ballistic covers made of various materials have shown that:

- The optical lock-in infrared thermography method can be effective for detection of damage in light ballistic covers made of various materials because for all samples tested it was possible to determine the subsurficial sample material damage area;

- There are large differences in the size of subsurficial material damage between the side of projectile impact on the sample tested and the other side (the side of projectile exit or incomplete penetration);
- The subsurficial material damage area in the samples tested, compared to the calibre of fragment-simulating projectile (.56 cm) can be 3 times larger on the projectile impact side and 15 times larger on the other side;
- Dimensions of the subsurficial material damage area depend on the impact energy (projectile velocity), sample penetration, material used and a pattern of fibres in the laminate layers.

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