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Active infrared thermography with forced cooling for composites evaluation

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Abstract

Non-destructive testing of composite materials, due to their increasing popularity, is important in modern industry. Active infrared thermography is one of the leading techniques for detecting the materials damages. In the case of active thermography, heating is the natural choice of the excitation used to obtain the temperature difference in defect area. It can be shown, that it is reasonable to use also the combination of heating and forced cooling, or even cooling itself. In this work, we will present the results of the numerical analysis of the phenomenon of forced cooling and the results of experiments conducted with the cooling device.

1. Introduction

High mechanical strength, high modulus, excellent strength to weight ratio and low price, are the main properties causing the glass fiber reinforced polymer composites to be extremely popular in the all branches of engineering. Unfortunately, errors made during the manufacturing process of the composite materials may result in some kind of defects. Moreover, it is important to note, that final properties of both the material and product strongly depend on the quality of the manufacturing process. The flaws occurring in the production can be caused by imperfectness of the mould, gel coat, polymer matrix or the reinforcement. Defects may also arise during exploitation, such as delamination, humidity penetration, impact caused defects and another. Examples of the most common composites flaws are voids, delaminations and inclusions.

The Non-Destructive Testing methods (NDT) commonly used to composite materials evaluation are X-ray inspection, ultrasonic phased array, thermography [1-6] and sheareography. However, the golden standard of the procedure of quality control has not been yet developed, and there is still an open research field.

In case of active thermography the proper excitation source needs to be chosen to produce the temperature difference observable using thermovision camera. As it is known, In case of composites the heat conduction coefficient is small comparing to conductive materials. Therefore the heating rate is low and obtained results are difficult to process and assessment. It this study we propose using forced cooling as additional excitation [7, 8]. This approach is useful in obtaining more accurate results, which was also confirmed by preliminary numerical modelling [9].The forced cooling affects the heat dissipation within the material and thus causes more rapid changes of temperature in the defects' vicinity.

First the numerical study of the problem, providing the better understanding of the physical phenomena accompanying the forced cooling of the composite samples, will be shown. Moreover, the dedicated cooling apparatus with the thermoelectric modules will be presented and used to test composite samples with artificial defects..

2. Numerical modelling

In this article the numerical study of described effect is presented. The numerical model was prepared with COMSOL Multiphysics software and solved using Finite Elements Method (FEM). In the examined model the influence of cooling on the defects visibility was tested. In case of discussed phenomena, we observe all three mechanisms of heat transfer: by radiation, conduction and convection. The forced cooling may be simulated in many ways, here it is modelled by convective heat transfer coefficient, and applied into the model using convective heat flux boundary condition

2.1 Model geometry and applied boundary conditions

To examine the influence of forced cooling on the defects detection, the numerical model of composite sample, characterized by the low value of thermal conductivity, with a set of flaws was prepared. Delamination, chosen as the defect type, were modelled as the air inclusions of different sizes and located at different depths inside the sample. The model geometry and its sizes are presented in Fig. 1. In the model all the mechanism of heat transfer, i.e. conduction, convection and radiation are included. Infrared heater is modelled as the array of points with given temperature and power, simulated by the external radiation source, which contributes to the incident radiative heat flux interacting with the sample with the factor proportional to the total source irradiation *G*. The interaction between the sample and radiation sources is realized by diffusive surface boundary condition, given by the formula:

$$q_r = \varepsilon\big(G - e_b(T)\big),$$

where q_r - incident radiative heat flux, ε - is the surface emissivity and $e_b(T)$ - is the blackbody hemispherical total emissive power.The forced cooling is applied using convective heat flux boundary condition, with defined air velocity and temperature, given by the formula:

$$q_c = h(T_{ext} - T),$$

where q_c - incident convective heat flux, h - is the heat transfer coefficient and T_{ext} - is the external temperature dependent on the geometry and defined ambient flow conditions.

Sample is heated from the back side (transmission mode), whereas the forced cooling is applied on the front surface, the same where the temperature is measured (Fig. 2). In the Table 1, all the important parameters of the model are gathered.

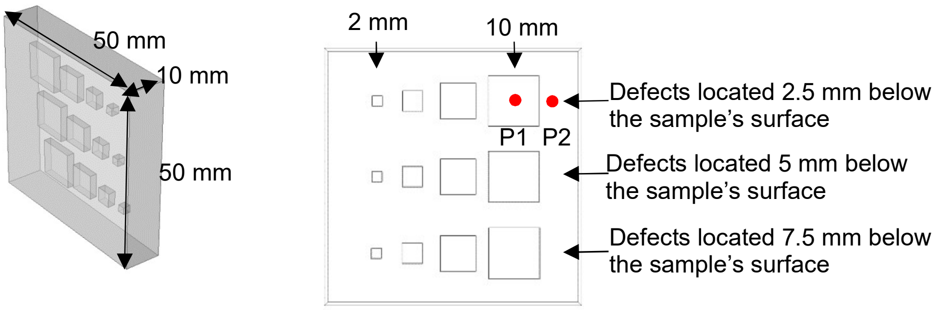


Fig. 1 *3D geometry utilized in the numerical modelling. The composite sample (50x50x10 cm) with set of rectangular air inclusions (2x2 mm, 4x4 mm, 7x2 mm, 10x2 mm), located on three different depths (2.5, 5 and 7.5 mm below the samples surface) was simulated*

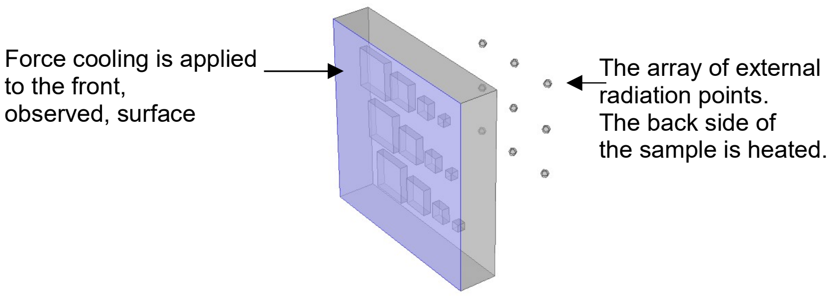


Fig. 2 *Numerical modelling details*

Table 1 *Chosen model parameters*

Sample material properties		
Density	1420	kg/m^3
Heat capacity	1700	J/(kg*K)
Thermal conductivity	1	W/(kg*K)
Heating source		
Total Power	900	W
Source temperature	1000	degC
Forced cooling		
Air temperature	-5	degC
Air velocity	10	m/s

3. The results of numerical modelling

To assess the influence of forced cooling on the defects detectability in a quantitative manner, the set of numerical models were prepared and compared. Four scenarios were analysed: heating and then natural cooling (H) (without the forced cooling, to acquire the basic ground for further comparisons), heating and then forced cooling (HC), heating with simultaneous forced cooling (H+C) and forced cooling and then natural temperature equalization (C). The time of heating or forced cooling in each scenario was set to 30 s, the overall time of the simulation was set to 60 s. In the Fig. 3 the chosen results of numerical modelling are gathered. Only the front sample's side is shown, to simulate the real observation using thermovision camera. Two images for each scenario are shown: obtained after 30 seconds of simulation (after the heating/cooling stage) and after 60 seconds of simulation.

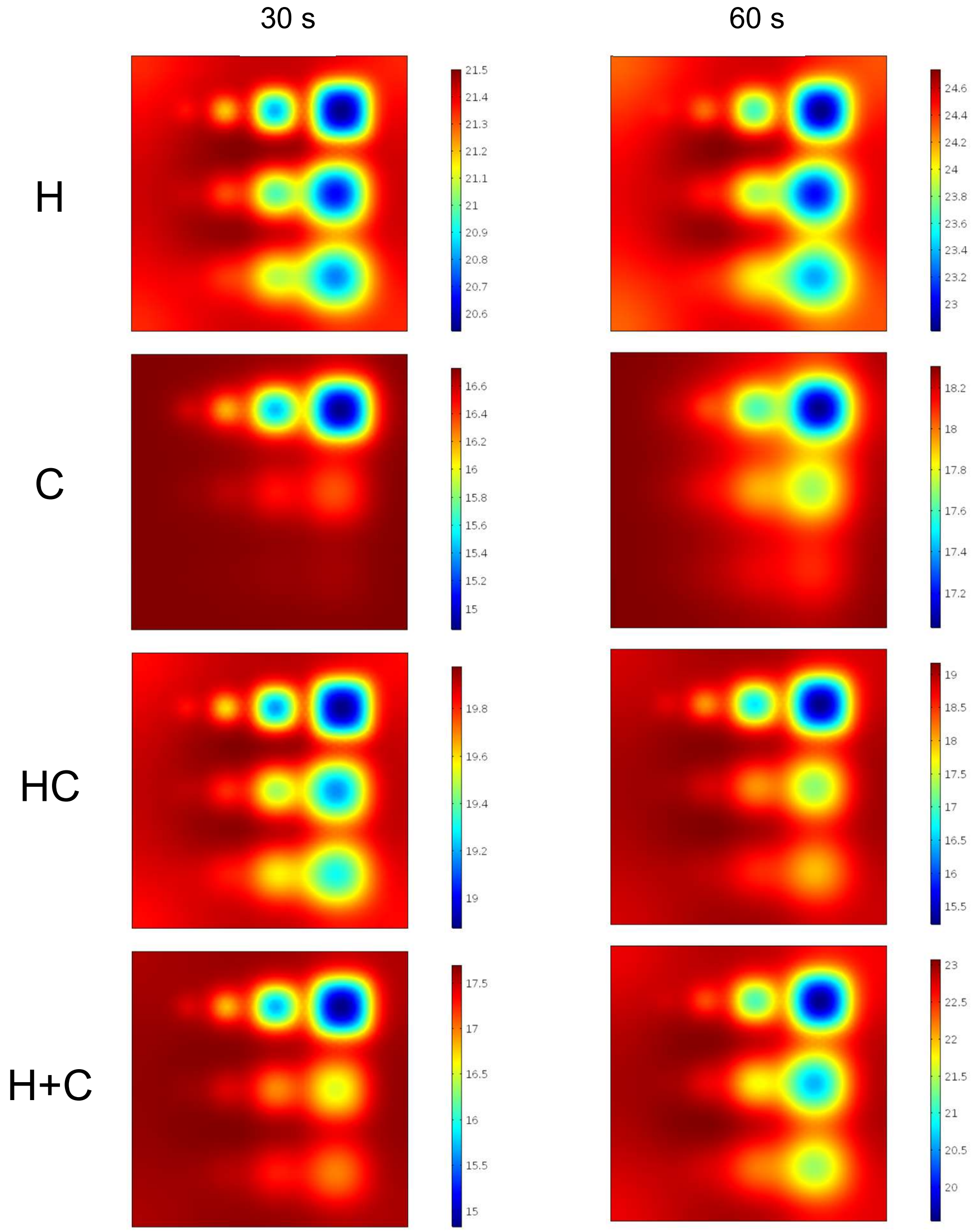


Fig 3 *Temperature distribution observed at the front side of modelled sample after 30 seconds and 60 seconds of simulation time. H - 30 s of heating, C - 30 s of forced cooling, HC - 30 seconds of heating and then 30 seconds of forced cooling, H+C - 30 seconds of heating with forced cooling*

In Fig 3 each image is presented in separate scale to show the overall defect detectability. It can be noticed that H, HC and H+C scenarios are comparable. The C scenario enables to detect only those inclusions, that are located shallowly under the sample's surface. In the real life measurements it is important to receive the high temperature difference between the defect and the background. Obviously, the higher the difference, the higher the probability of defect detection. To quantitative comparison the proposed experiment methodology, the difference between the temperature measured in the defect centre and in the point located in the sound area, near the defect was computed. The location of chosen points P1 and P2 are shown in Fig. 1. The result is shown in Fig 4. It can be easily noticed, that in HC and H+C (blue and orange line respectively) scenarios the temperature difference is much higher (by maximum 2 degC) than in H and C scenarios (purple and yellow line respectively). This comparison shows, that using the forced cooling combined with heating might be useful in overall defect detection using thermography.

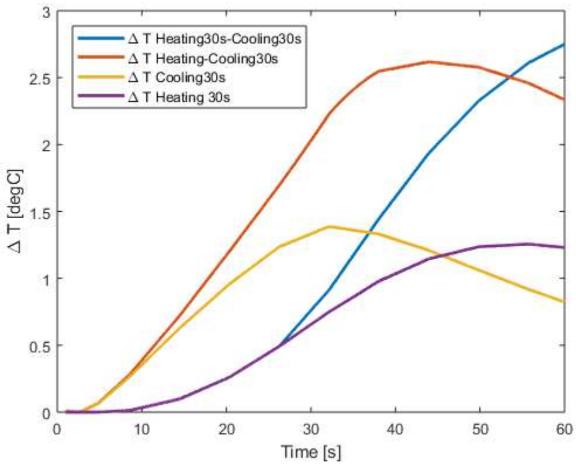


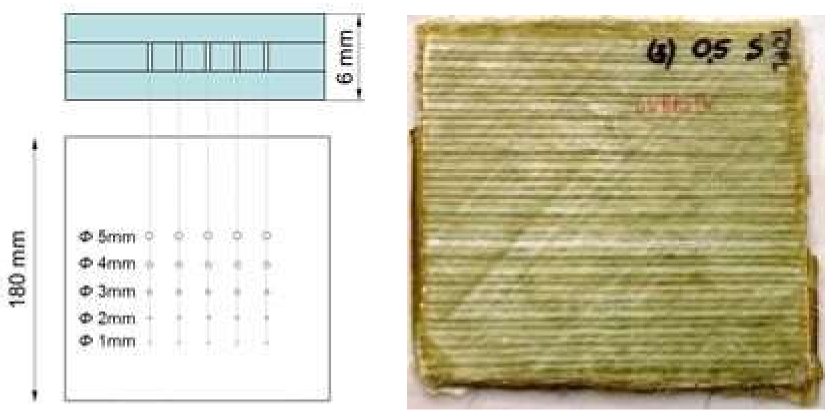
Fig. 4 *The temperature difference between the defect and the background (for chosen defect) plotted against the time for each proposed numerical modelling scenario. Blue line – HC scenario, orange line – H+C scenario, yellow line – C scenario, purple line – H scenario*

4. Experiments

4.1. Samples and experimental methods

Experimental system (Fig. 5) consists of a thermal imaging infrared camera Flir A325 and a dedicated cooling unit [8] to introduce the forced cooling of the sample. Additionally, the rear side of the sample was heated using ceramic infrared heater. The cooling unit [8] consists of water cooled thermoelectric Peltier modules and fan directing chilled air towards the object under test. This unit allows the air to cool to about -5 degC at ambient temperature of 22 degrees. The evaluated sample was a composite made of poliester resin: CRYSTIC2-420 PA (Scott Bader) + LUPEROX K1G with 6 layers of glass fiber mate 900g/m², thickness 6 mm was used for the experiments. In the 3rd layer of the glass fiber mate a set of holes with diameters from 1 to 5 mm was manufactured. Photo and the internal structure of the sample is shown in Fig. 6

Fig. 5 *The experimenatal setup [8]*



Fig, 6 *The evaluated sample. Left : the internal structure scheme, right : photo of evaluated sample*

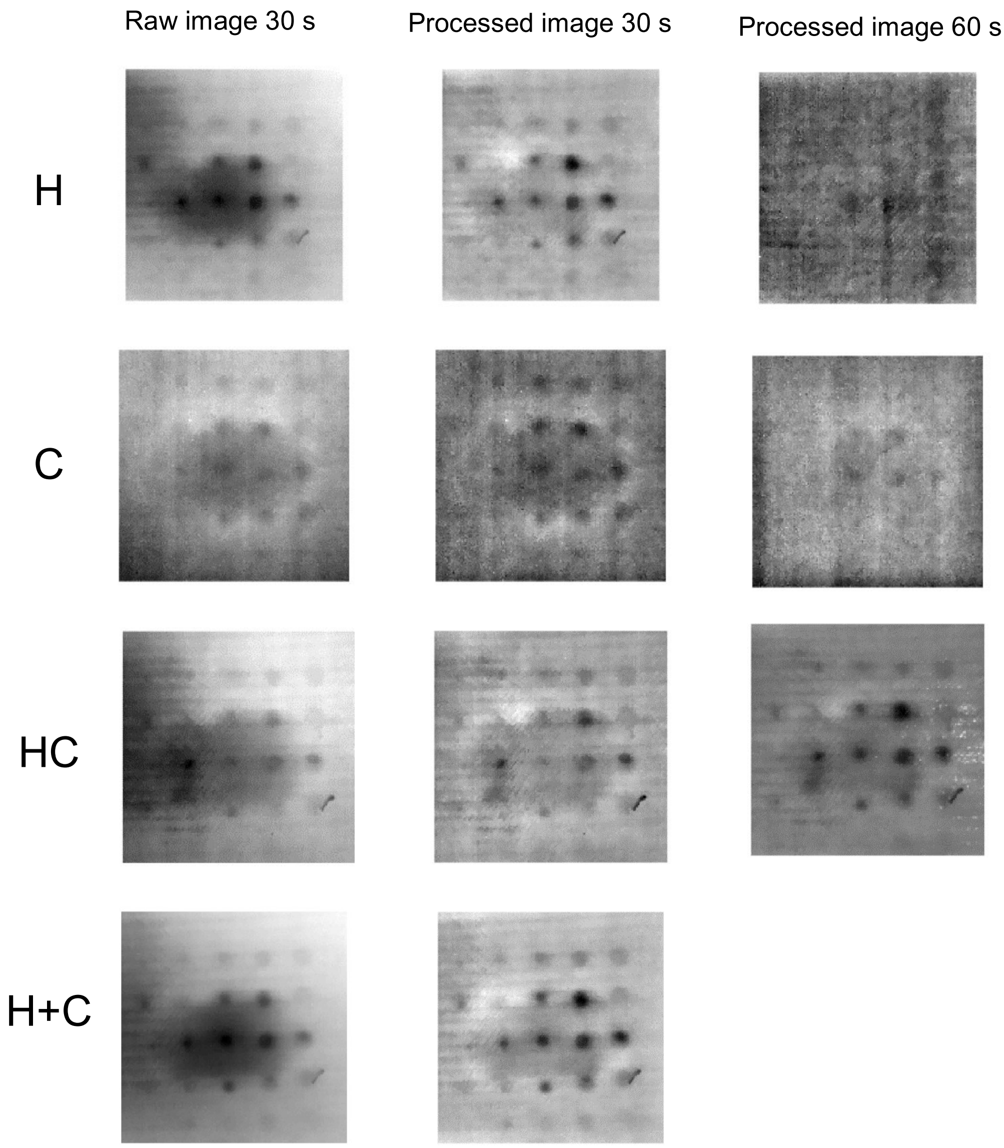


Fig. 7 *The chosen results of experiments for presented for all experiment scenarios.*

The experiments, similarly to numerical modelling, were divided into four separate scenarios :

- heating itself for 30 seconds (after the heating the sample was observed for additional 30 seconds of natural cooling down) – H,
- forced cooling itself for 30 seconds (after the cooling the sample was observed for additional 30 second of natural temperature equalization process) – C,
- heating for 30 seconds and then forced cooling for 30 seconds – HC,
- forced cooling with simultaneous heating for 30 seconds – H+C .

The results of experiments are gathered in Fig. 7. For each scenario (noted by the acronym presented above) three normalized temperature distribution images are presented : raw thermogram obtained after 30 seconds of experiment (after the heating phase in H and HC scenarios, after the forced cooling phase for C scenario and after the experiment for H+C scenario) and two thermograms (obtained after 30 seconds and 60 seconds of experiment) after the background removal procedure. The background removal procedure is based on the median filtering with the large mask [10]. Using this image processing allows to enhance the visibility of the defects. It can be noticed, that the defects matrix is visible in every scenario after 30 seconds of experiment and results are comparable. For three scenarios the additional image, obtained after 60 seconds of the experiment is presented. Only in the HC scenario the defects matrix is clearly visible. To quantitatively assess the defects detectability, the temperature difference between the defect and sound area (located near the defect) was computed. The results are shown in Fig. 8. The curve fitting tool was used to obtain the presented curves, the data were normalized. It can be easily observed, that the biggest temperature difference between the defect and background was obtained in HC scenario (this result is in line with the numerical modelling results), the differences obtained in case of the C and H scenarios are much smaller, which is visible in the second part of the experiment.

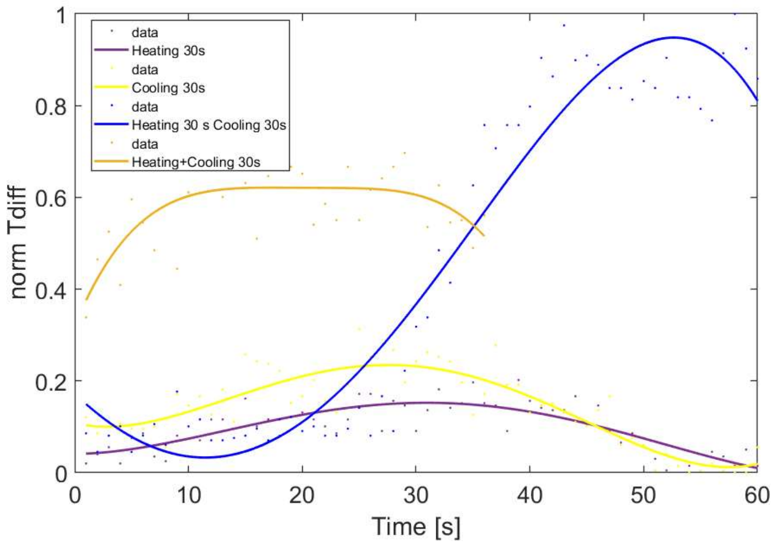


Fig. 8 *The temperature difference between the defect and the background (for chosen defect) plotted against the time for each proposed experiment scenario. Blue line – HC scenario, orange line – H+C scenario, yellow line – C scenario, purple line – H scenario*

Conclusions

In this paper the phenomena of forced cooling used in active thermography for composites evaluation was presented. The numerical modelling results confirmed, that forced cooling might be useful in shallowly located defects detection (it is especially important when evaluating thin samples). The forced cooling combined with heating shown to be more effective than the heating itself. The forced cooling with simultaneous heating gives the good defects detectability, by producing high temperature difference between the defect and the sound area, which is maintained for all the experiment phase. The best detectability (in terms of highest temperature difference between the defect and the sound area) is obtained in heating followed by forced cooling scenario. The experimental results shown a good agreement with the numerical modelling. In case of experiments, the highest defect detectability was observed in HC scenario. The forced cooling with simultaneous heating allowed for defects detection during the whole time of the experiment.

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