Ultrasonic IR Thermography Detection of Defects in Multi-layered Aramide Composites

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Abstract. Little mass and the resistance against the perforation with bullets and fragments are basic requirements of contemporary armors. These requirements could be met by using composites. Due to the progress in polymer chemistry it is possible now to manufacture materials that provide effective protection against small-calibre projectiles and shell fragments. Woven materials (fabric) are mostly used and joined together by means of a plastic binder into multi-layer composite materials. They are used to manufacture personal ballistic protections (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. Defects which can appear in this type of multi-layered composite materials usually are inaccuracies in gluing the composite layers and stratifications and delaminations occurring under hits of fragments and bullets. A method that possibly can be used to non-destructive testing of this type of materials and detection of internal defects deploys infrared thermography.

In active thermography it is necessary to bring some energy to an inspected sample in order to obtain significant temperature differences witnessing the presence of subsurface anomalies. There are different methods of thermal stimulation applied on testing material like heating lamps, laser, ultrasounds or microwaves. Ultrasonic stimulation is one of these methods used for detection of defects in composite materials. In this context the parts to be tested are heated up by ultrasonic source and the temperature profile generated thereby on the surface of the component is recorded with a thermographic camera. The anomalies in main material disturb the flow of ultrasounds and change the temperature distribution as well. This changed temperature distribution can be detected thermographically with a very high resolution. Ultrasound activated thermography is a defect selective “dark field” NDT-technique as only defects produce a signal.

The paper includes some results of simulation representing possibilities for the use of ultrasonic IR thermography method to test multi-layered aramide composite both with experimental test results.

Introduction

Over the past few decades, we have invented new and modified existing materials with high strength fibers. Among them are carbon fibers, glass fibers, and polymeric fibers, including new aramide fibers and polyethylene fibers. As ballistic covers, these materials are often used in the form of loose fabrics or laminates.
The common use of aramide fabric in ballistic shields is decided by the very high levels of mechanical strength, especially tensile strength, flexural strength and compressive strength, of the yarns made of aramide filaments. These excellent characteristics are due primarily to the highly ordered structure and the linearity of fiber plastic polymer molecules with a large number of strong hydrogen bonds. The presence of molecules of aromatic rings provides added durability and resistance [1].

Aramid fibers are used widely in the manufacture of products for ballistic protection, such as personal protection (e.g. vests, helmets and bullet-proof shields), security vehicles and fixed objects. These types of covers are designed to protect against the impacts of small-caliber bullets and fragments.

At the moment of impact into the laminate (i.e. the multi-layered aramide composite), a projectile is stopped by a large number of individual fibers. As a result of the impact, fibers stretch and break to absorb the kinetic energy of the projectile casing. Moreover, the stretching of fibers in the fabric transfers the projectile’s energy to adjacent fibers and by that disperses the energy over a large area [2]. This creates a subsurface defect in the composite structure with a much greater area than the caliber of the projectile.

Accordingly, there is a need for a method of non-destructive testing by means of which the inner zone of multilayer composite destruction can be determined due to the impact by a projectile (or fragment).

1. Ultrasonic Infrared Thermography

One of the active IR thermography methods used in non-destructive testing is vibrothermography. The term vibrothermography was created in the 1990s to determine the thermal test procedures designed to assess the hidden heterogeneity of structural materials based on surface temperature fields at cyclical mechanical loads. A similar procedure can be done with sound and ultrasonic stimulation of the material, because the cause of an increase in temperature is internal friction between the wall defect and the stimulation mechanical waves. If the cyclic loading does not exceed the flexibility of the material and the rate of change is not large, the heat loss due to thermal conductivity is small, and the test object returns to its original shape and temperature.

The most commonly used method is ultrasonic stimulation, and the testing technique is ultrasonic infrared thermography [3, 4]. Ultrasonic IR thermography is based on two basic phenomena. First, the elastic properties of defects differ from the surroundings, and acoustic damping and heating are always larger in the damaged regions than in the undamaged or homogeneous areas. Second, the heat transfer in the sample is dependent on its thermal properties. The heat flow is much smaller in damaged areas than in intact areas, so the temperature rises due to less heat diffusion. Consequently, both of these phenomena – defects and inhomogeneous structures – can be observed as a thermal anomaly in the test sample, which can be displayed and measured by an IR camera [5, 6].

The phenomenon of mechanical hysteresis seems to vanish in the range of typically used ultrasonic frequencies and electrical powers (from 20 to 40 kHz and up to a few kW, respectively) [7, 8]. Therefore, a sound composite remains ‘cold’ during stimulation while noticeable temperature signals appear in defective areas due to internal friction.

2. 3-D Modeling and Simulation

The ThermoSon computer program, developed at Tomsk Polytechnic University, Russia, was used to optimize the heating parameters in the detection of subsurface defects in
composite materials. The program allows the analysis of transient heat conduction and ultrasonic wave propagation phenomena in solids [9]. ThermoSon implements the solution to a 3D Cartesian-coordinate transient heat conduction problem for a six-layer parallelepiped-shaped body that contains up to nine infinitely thin defects (cracks). The cracks generate thermal energy due to friction of their edges (see Figure 1). Both the front and the rear surfaces are cooled down according to Newton’s law. Thermal properties of the specimen and the defects can be specified separately in three spatial directions, thus modeling a fully anisotropic material. The specimen side surfaces are adiabatic. On the boundaries between the specimen layers and between the host materials and the defects, the temperature and the heat flux continuity conditions take place. In ThermoSon, the so-called concept of capacitive defects is realized. This means that, unlike resistive defects involved in some other NDT (non-destructive testing) models, both defect thermal diffusivity and conductivity are taken into account. This provides the most correct description of the physical phenomena occurring in the defect areas.

To verify the possibilities of detection of the damaged area in multi-layered aramide composite by ultrasonic IR thermography, a model sample of this material with dimensions of 200x200 mm and with 10 mm thickness of impact damage was used for computer simulation. Impact damage was modeled as a cone or a pyramid containing multiple delaminations. A particular cross-section of this pyramid (Figure 1) represents the delaminations that generate thermal energy under ultrasonic stimulation. This particular impact damage was modeled as a set of 9 parallelepiped-like air-filled heat sources each having a thickness of 1.0 mm. The distance between the adjacent layers was 0.1 mm.

![Fig. 1. Modeling impact damage as a set of multiple delaminations (pyramid-like defect shapes).](image)

Thermal and strength properties of the composite were determined experimentally (Table 1). Procedures of their evaluation are described in paper [10]. The thermal properties of defects (air-filled spaces) are taken from the literature (Table 2) [4].

**Table 1.** Thermal and strength properties of aramide composite

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat</td>
<td>1070</td>
<td>J/kg·K^{-1}</td>
</tr>
<tr>
<td>Density</td>
<td>1450</td>
<td>kg·m^{-3}</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.22</td>
<td>W·m^{-1}·K^{-1}</td>
</tr>
<tr>
<td>Poisson’s coefficient</td>
<td>0.36</td>
<td>-</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>1.2</td>
<td>GPa</td>
</tr>
</tbody>
</table>

**Table 2.** Thermal properties of air (in thin gaps)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat</td>
<td>1005</td>
<td>J/kg·K^{-1}</td>
</tr>
<tr>
<td>Density</td>
<td>1.2</td>
<td>kg·m^{-3}</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.07</td>
<td>W·m^{-1}·K^{-1}</td>
</tr>
</tbody>
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The graph (Figure 2) shows the increase of temperature at the sample surface over the center of the defect (Figure 1) for a simulated ultrasonic heating of the sample. Ultrasonic signals were simulated at a frequency of 35 kHz and vibration amplitude ±8 µm. The time of signal generation was 5 s and the total computation time was 10 s.
3. Experimental Testing

The experiments at MIAT (Military Institute of Armament Technology) have been fulfilled by means of a FLIR SC 7600 IR imager (image format 640×512, acquisition frequency 5 Hz, up to 1600 images in a sequence). Continuous ultrasonic stimulation was performed with a piezoelectric unit at the frequency of 35 kHz with the power set from 80 to 130 W (the maximum allowed power was 2 kW). The ultrasonic signal was generated by 5 s. Figure 3 presents the set-up used for the thermographic tests containing an ultrasonic thermal stimulation.

Figure 4 shows a sample from a multi-layer ballistic cover made of combined resin layers of aramide fiber fabrics. A sample of this composite having a thickness of about 10 mm and lateral dimensions of 400×400 mm is shown after destructive tests. As can been seen, the sample was shot four times with 9 mm projectiles. However, the sample of ballistic cover was not pierced by the projectiles. The residuals of projectiles stuck in the back layers of specimen are found.
Figure 5 shows an example thermogram of non-destructive testing using ultrasonic IR thermography. A good image of the place hit by projectile is visible, which is located in the upper left corner of the photograph (Figure 4). The whole damaged area of the internal structure of composite is also visible.

Figure 6 shows changes of the temperature field on the defect registered thermal imaging camera (picture 5) at the time of 7.65 sec from start of the testing. At this time, the temperature increase was greatest. Subsequent cooling of the sample temperature starts to cool. The analysis of the registered sequence of temperature over the defect still grew by 2.65 seconds from the end of the stimulation thermal ultrasound.
4. Conclusions

Computer simulations and experimental testing suggest that ultrasonic IR thermography can be an effective method of non-destructive testing for the detection of defects in multi-layered aramide composites. The compatibility between the results of numerical and experimental studies was satisfactory. The maximum temperature increase in the numerical calculations was 0.55ºC, and on the basis of experimental tests can be accepted as approx. 0.6ºC. An estimate of the results of experimental tests arises from the fact that temperature increase was also influenced by the projectile sticking into the back layers of the sample behind the center of the damaged area. In addition, the times of the largest temperature increase were similar for the numerical calculations (7.65 s) and the experimental testing (7.1 s).

In further studies we intend to apply the ultrasonic stimulation of different frequencies, which will allow the most effective frequency range to be chosen for this type of composite.

References