Journal of Energy

VOLUME 70 Number 2 | 2021 | Special Issue

journal homepage: http://journalofenergy.com/

Lovre Krstulović-Opara
Faculty of Elec. Eng., Mech. Eng.and Naval Arch., University of Split
Lovre.Krstulovic-Opara@fesb.hr

Petra Bagavac
Faculty of Elec. Eng., Mech. Eng. and Naval Arch., University of Split
Petra.Bagavac@fesb.hr

Antun Božanić
Faculty of Elec. Eng., Mech. Eng.and Naval Arch., University of Split
Antun.Bozanic@fesb.hr

Željko Domazet
Faculty of Elec. Eng., Mech. Eng.and Naval Arch., University of Split
Zeljko.Domazet@fesb.hr

NDT of Composites Based on Active Infrared Thermography and Ultrasound Testing

SUMMARY

Composite materials, such as glass and carbon reinforced ones, are characterized by inhomogeneous structure that requires non destructive testing based on uncommon evaluation methods. The presented approach is based on the active infrared thermography, supported by the A-scan ultrasound testing. The heat wave propagation induced by halogen or xenon bulbs, due to the differences in thermal conductivity, reveals material structure and anomalies. In our previous work we have developed several signal processing and depth evaluation methods, but the real engineering approach requires additional approval testing methods such as the A-scan ultrasound is. The A-scan ultrasound, based on the low frequency probe, enables approval of anomalies located by infrared thermography. The active infrared thermography, as a full field method, enables evaluation of the whole scanned area. The A-scan, as a point-wise method, does not provide the image of whole area of interest. By combining these two methods, robust and reliable approach to analysis of composite structure is enabled.

KEY WORDS

non destructive testing, ultrasound testing, infrared thermography

INTRODUCTION

Non destructive testing (NDT) of polymer composite materials is mostly covered by unconventional methods of evaluation. Polymer composites such as glass reinforced polymers (GRP), or carbon reinforced polymers (CRP) are characterized by an inhomogeneous structure. The low heat conductivity enables methods of testing based on the active infrared thermography (IRT) and halogen lamps as a heat source, contrary to metals where Xenon flesh bulbs are required. As a method that enables better identification of indications reviled by IRT, the A-scan ultrasound testing (UT) is used. When applying UT to polymer composites, particular attention has to be paid on interpretation of readings due to the significant inhomogeneity of composites. The radiographic control, that similar to UT a volumetric method, is not applicable to polymer composites. Production process of composites, e.g. manual laying of resin or vacuum procedure, can cause significant variations in homogeneity. In our previous research we have shown and developed methods for NDT of composites based on the active IRT [1, 2]. In this paper we present procedure of A-scan UT control as a method parallel to IRT with goal to better interpret findings.

The active IRT is a NDT method based on observing heat flow generated by light source. This research is based on halogen lamps and 1kW of heat source. Xenon flash bulbs can be used for polymer composites as well, but according to our experience when using 6 kJ flash excitation, damage of polymer matrix occurred. As mostly the heating period is around 2 minutes, resulting in 120 kJ of introduced heat energy, it will not cause the damage of matrix, as it is the case for the 6 kJ of heat energy introduced during few milliseconds. Due to the short time of energy flow to material, Xenon lamps are causing damage of polymer matrix. When using the active IRT, the simplest approach is to apply halogen light for approximately 2 minutes, and record first moments (seconds) after heat source is turned off. Such image can be enhanced, e.g. by using gradient based approach [4]. Another approach is to apply the sinusoidal heating where sequence of images is processed by the Fast Fourier Transform (FFT) image processing methods. In FFT the time domain (consequent thermal images) is transformed in the amplitude and phase domain, where mostly phase domain is the one that enables better sensitivity to detection of anomalies.

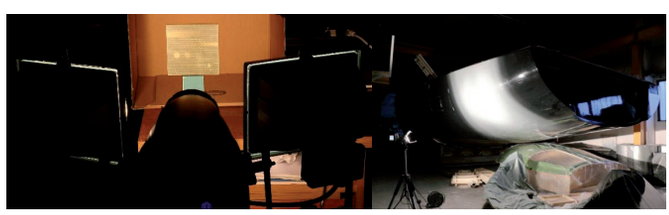

Figure 1. Active IRT, halogen lamp as a heat source applied on GRP specimen and 67 feet sailing yacht

Lovre Krstulović-Opara, Petra Bagavac, Antun Božanić, Željko Domazet, NDT of Composites Based on Active Infrared Thermography and Ultrasound Testing, Journal of Energy, vol. 70 Number 2 (2021) Special Issue, p. 3–6
https://doi.org/10.37798/202170210

The A-scan ultrasound is a commonly used NDT method, used in control of metallic structures. Typical cases are control of weldments, measurements of thickness (thickness gauging), evaluation of material homogeneity, material inclusions etc. For the case of steel or cast iron, mostly straight and angled probes with frequency between 2 and 10 MHz are used. Bigger material grain size requires probes with lower frequencies, e.g. 2 Hz. The probe size (standard or miniature) is determining focus and intensity of a sound beam. Probes with frequency of 5 MHz and above, are mostly used for thickness gauging because signal for homogeneous materials is strong, sharp and easy to read. Probes with frequency of 1 MHz are rarely used. Their signal is not so narrow and sharp (Figure 2, right). There is no need for such probes when steel is evaluated, except for cases such as the inspection of heat-affected zone (HAZ) in weldments of Duplex steels. The UT probe size is influencing reading capabilities, so standard probe size will enable better penetration and narrow sound beam in comparison to miniature probe. As composites are generally of small thickness, a fiberglass probe delay block is needed to focus the UT beam on the surface of the object. Thus, for the case of a polymer composite material, 1 MHz straight probe with the probe delay is needed as 4 MHz, or 2 MHz probe will not penetrate the material. Figure 2 depicts comparison of 4 and 1 MHz probe applied on the K1 calibration steel block. The 4 MHz is enabling sharper more concentrated signal easier for A-scan reading and evaluation, while 1 MHz signal is wider and such probe will only be used in cases when no penetration can be obtained with the 4 MHz one.

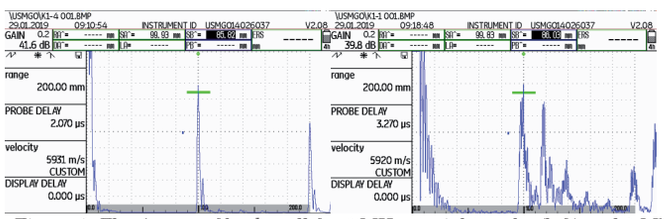

Figure 2. The A-scan of back wall for 4 MHz straight probe (left) and 1 MHz straight probe (right)

The NDT based on active thermography enables detection of composite layers, homogeneities, reinforcements, inclusions, cracks and delamination. Detection of osmotic damage in polymer composites is an extreme case due to the extremely week signal, both for ultrasound and active thermography recognition.

Osmotic damages are common damages of glass polymer vessels caused by humidity migrations from water/sea into air bubbles trapped within resin. Due to the hydrolysis, water reacts with material causing hydrochloric acid, acetic acid or glycol. As inner pressure appearing in foci is increasing, it delaminates material and by osmotic process absorbs more water. Typical damage appears in form of blisters and material delamination (appears like there is no resin in composite). Vacuum curing technologies reduces or eliminates osmosis due to elimination of trapped air bubbles. Epoxy based resins are reducing moisture migrations and osmotic process. Scientific literature in this field is limited, as the phenomena of osmotic damage is not elaborated enough. There are several repair approaches with not so clear long-term stability. Often decades are needed for damage to appear, so all new approaches to eliminate osmotic damage are dubious. Although this problem, as it only matters old vessels, does not seem economically significant, it is a big ecological problem due to reduced recycling possibilityof composite materials. Often old vessels are put on fire or sank. There are initiatives on the EU level where taxes on polymer composite boats should be introduced to encourage market not to buy composite boats in favor of recyclable materials such as aluminum, steel or wood.

2. DETECTION AND EVALUATION OF OSMOTIC DAMAGES

As an example, a sailboat built in 1986 with osmotic damages near surface is inspected and proposed methods, active lock-in IR thermography and A-scan UT, are presented. The combination of these two NDT methods enables proper evaluation of boat's hull. The A-scan UT is giving information about homogeneity of material, thickness of layers and depth of osmotic blisters and delaminations. The UT is a volumetric method that in control of metals is often combined with surface methods such as magnetic particles testing (MT) or penetrant testing (PT). Active IR thermography enables obtaining temperature distribution on the surface of material that is strongly influenced by the heat flow within material, thus enabling the voloumetric control as well. The ultrasound is a reliable confirmation of anomalies located by the IR method. This is similar to humidity evaluation in buildings where moisture gauges are used to prove the moisture.

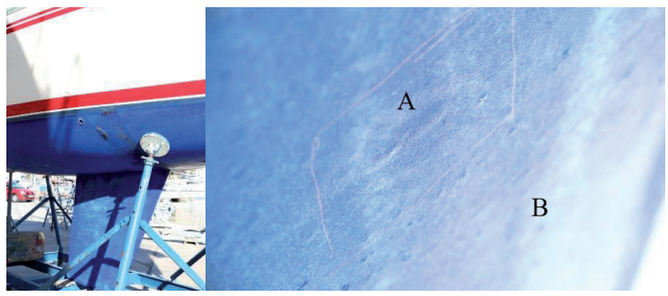

Figure 3. The osmotic damage on a boat hull in form of a blister

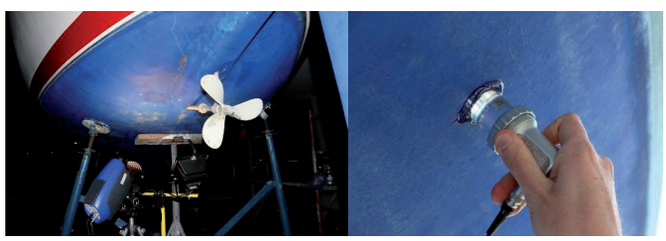

Figure 4. Active thermography experimental setup and the UT probe with the probe delay

3. A-SCANS OF EVALUATED ZONES

Figure 5 depicts typical A-scans of glass reinforced polymer boat hull. Peaks are reflections from various layers, such as anti-fouling paint and epoxy primer paint, gelcoat, roving, inner gelcoat. In left image of Figure 5, the loss of signal, i.e. zone without reflections, is a beam trough the blister, after which there are again reflections of layers. The shape of A-scan depends if the vessel was recently docked (presented case), or it is for some time out of water. Conductivity of sound is better for the wet hull, opposite of the case when it is for long period after water. Locating osmotic damage is clearer for the wet hull due to the differences in the impedance between two acoustic media (water and composite). After few weeks out of water blisters will not be visible any more. As soon as a vessel is back to water, the water penetrates the damaged area. In this particular case (Figure 5, left) the damage is 7 mm deep, after which the signal is significantly reduced. Signal peaks at depth of 12 mm are back wall reflections of layers of composite. When compared to steel, such signal has no clear peaks. Measured values (depths) are not exact due to the different sound velocity in comparison with the calibration on the vacuum treated reference block.

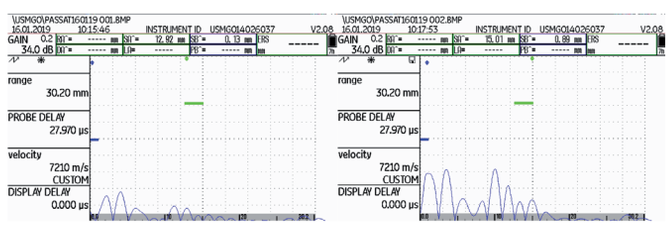

Figure 5. A-scan of osmotic blister (left) and of sane material (right)

4. THE ACTIVE LOCK-IN INFRARED THERMOGRAPHY

The most important condition of infrared (IR) thermography is to provide useful results with enough of temperature difference or thermal contrast between features of interest, e.g. internal flaw – the contrast between the osmotic blister and its surrounding. The active approach is used on materials or systems that do not present significant differences in temperature with respect to their surroundings. For the active approach, the thermophysical properties of the internal defect have to be different from those of the specimen's material. Without this condition, defect detection is impossible. The active thermography, as a NDT method, is based on generating outer heat impulse and acquiring material response during the period of observation. In presented example two halogen lamps (500 W each) and time controller enabling sinusoidal heat flow are used. The method of si-

Lovre Krstulović-Opara, Petra Bagavac, Antun Božanić, Željko Domazet, NDT of Composites Based on Active Infrared Thermography and Ultrasound Testing, Journal of Energy, vol. 70 Number 2 (2021) Special Issue, p. 3–6
https://doi.org/10.37798/202170210

gnal processing is based on the sinusoidal fidelity, commonly called the "Lock-in" thermography. The concept of the method is based on the fact that the sinusoidal heat source flow, when travelling through the material, will remain sinusoidal, but with shift in phase and amplitude. Frequency of sinusoidal wave will remain the same. Inhomogeneities in material will reflect and change heat flow, hence reflected sinusoid flow will be different when reflected from surrounding material or feature of interest, e.g. damaged area material. The material heat response, reflected for the reflective thermography and transmitted for the transient thermography, will reach the object surface where it will be recorded by the IR camera. The reflected heat flow will retain same frequency as the heat source, but the phase shift and the amplitude will differ, depending how much heat flow will be damped by inhomogeneities. The amplitude and the phase shift of each image pixel is calculated according to relations:

$$A_{tw}(x,y) = \sqrt{[S_1(x,y) - S_3(x,y)]^2 + [S_2(x,y) - S_4(x,y)]^2} \quad (1)$$

$$\phi_{tw} = arctan\frac{S_1(x,y) - S_3(x,y)}{S_2(x,y) - S_4(x,y)} \quad (2)$$

where points S_i are readings within one period of sinusoid of reflected heat flow [6].

When assembled back to the image, phase shift reveals material inclusion, damage, and other anomalies, where the obtained contrast between sane and damaged material is, when comparing to raw thermograms and amplitudegrams, much better. Phasegrams obtained at higher frequencies are revealing anomalies near the surface. Lowering the frequency, deeper layers of material are evaluated as heat wave penetrates deeper in the structure. As the penetration depth is related to the heat source frequency, the depth of anomaly can be evaluated. Due to the inhomogeneity of composite material, sometimes it is not possible to find exact depth. The A-scan ultrasound is enabling better recognition of the depth. As mentioned before, the ultrasound is affected by the inhomogeneity, but location of the structure back-wall helps to locate the position of anomaly.

The experimental setup (Figure 4) included two controlled 500 W halogen lamps, middle wave cooled InSb FLIR SC 5000 thermal camera, GE Krautkramer USM GO A-scan ultrasonic flaw detector and 1 MHz straight probe with probe delay.

Figure 6 depicts phase shifts (phasegrams) of the zone in figure 3 for different excitation frequencies. Osmotic damages in zones A and B (blisters A and B in Figure 3) are in layers close to the surface. The damage A is shallower from the damage B, where for the excitation frequency of f=0,0083 Hz the damage A is not visible. The depth of the damage A is between excitation frequencies of 0,0083 Hz and 0,0139 Hz. The A-scan located the damage A at the depth of 7 mm. As the damage B is still visible for excitation frequency of 0,0083 Hz, lower excitation frequencies should be used to locate the depth where material is not damaged. Figure 7 depicts the same region after removing antifouling paint and protective epoxy primer.

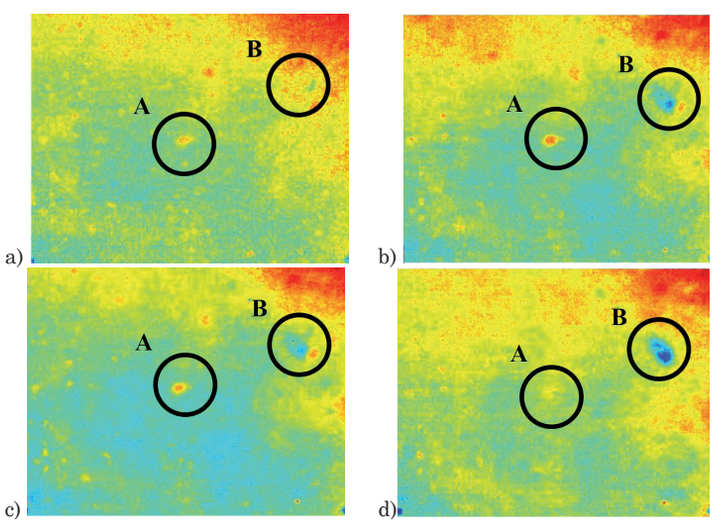

Figure 6. The phase shift images at excitation frequencies of. a) f=0.04167 Hz b) f=0.0208 Hz c) f=0.0139 Hz d) f=0.0083 Hz.

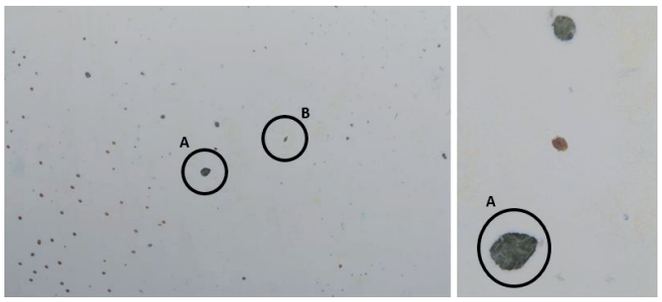

Figure 7. The osmotic damage on the hull surface after grinding the antifouling paint and protective epoxy primer

Figure 8 depicts phase shifts for the location in Figure 4 (left) where smaller blisters have been located. After grinding antifouling paint and epoxy primer, it turned to be that blisters were between gelcoat and epoxy primer so there was no damage of boat hull (Figure 9). Phasegrams show anomalies in zones close to the surface, while for deeper zones they are not visible.

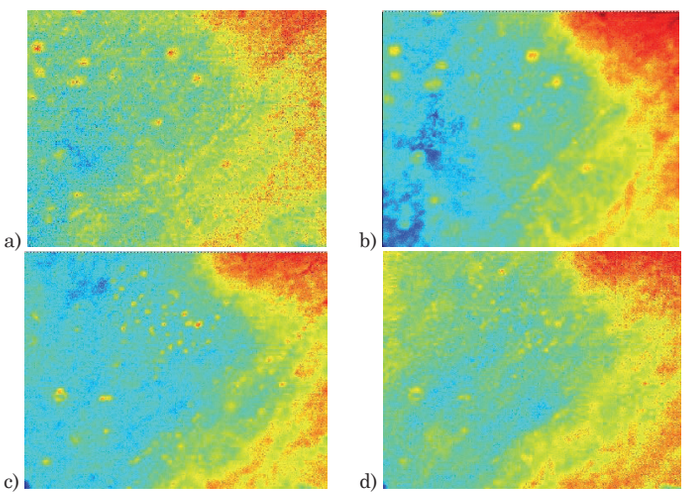

Figure 8. The phase shift images at excitation frequencies of. a) *f*=0.04167 Hz b) *f*=0.0208 Hz c) *f*=0.0139 Hz d) *f*=0.0083 Hz.

Figure 9. The sane hull surface after grinding the antifouling paint and protective epoxy primer

Lovre Krstulović-Opara, Petra Bagavac, Antun Božanić, Željko Domazet, NDT of Composites Based on Active Infrared Thermography and Ultrasound Testing, Journal of Energy, vol. 70 Number 2 (2021) Special Issue, p. 3–6
https://doi.org/10.37798/202170210

5. CONCLUDING REMARKS

This work is an overview of an infrared approach to NDT. The osmotic damage is used as an extreme example that is characterized by extremely low thermal contrast where simple pulsed thermography, without additional signal processing, will not reveal damage. The A-scan ultrasound is used as additional NDT method with the goal to prove findings and to better locate the depth of detected anomalies. The method is reliable and was already used to find the productions faults of new delivered yacht as a part of reclamation claim.

REFERENCES

1. L. Krstulović-Opara, Ž. Domazet, E. Garafulić, "Detection of osmotic damages in GRP boat hulls", Infrared Physics & Technology, 60, 359-364, 2013
2. P. Bagavac, L. Krstulović-Opara, Ž. Domazet, "Pulse Phase Thermography Impact Damage Retrieval", Materials Today: Proceedings, 5, 26578–26583, 2018
3. P. Bagavac, L. Krstulović-Opara, Ž. Domazet, "The Defect Depth Characterization Using Pulsed Thermographic Data", 9th International Congress of Croatian Society of Mechanics, Split, Croatia, 18.-22.9. 2018, 26-31
4. L. Krstulović-Opara, E. Garafulić, B. Klarin, Ž. Domazet, "Application of gradient based IR thermography to the GRP structures inspection", Key Engineering Materials, 488-489, 682-685, 2012
5. A. Božanić, " The influence of ultrasound frequency on composites and materials with large grain size", diplom thesis, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture , Split, Croatia 2016 (in Croatian)
6. P. Bagavac, L. Krstulović-Opara, Ž. Domazet, "Lock-In Thermography in Detection of Osmotic Damage", The 33rd Danubia Adria Symposium on Advances in Experimental Mechanics, Portorož, Slovenija 20.-23.9. 2016., 53-54