Ultrasound Excited Thermography - Advances Due To Frequency Modulated Elastic Waves

by T. Zweschper *, G. Riegert *, A. Dillenz **, and G. Busse *

** Institute of Polymer Testing and Polymer Science (IKP), Dept. of Non-destructive Testing, University of Stuttgart, Pfaffenwaldring 32, D-70569 Stuttgart, Germany*
*** Edevis GmbH, Nobelstr. 15, D-70569 Stuttgart, Germany*

Abstract

Ultrasound excited thermography allows for defect selective imaging using thermal waves that are generated by elastic waves. The mechanism involved is local friction or hysteresis which turns a dynamically loaded defect into a heat source which is identified by a thermography system. If the excitation frequency matches to a resonance of the vibrating system, temperature patterns can occur that are caused by standing elastic waves. These undesirable patterns can affect the detection of damage in a negative way. We describe a technique how the defect detectability of ultrasound activated thermography can be improved. With the objective of a preferably diffuse distributed sonic field we applied frequency modulated ultrasound to the material. That way the standing waves can be eliminated or reduced so that the detectability is significantly improved.

1 Methods of Ultrasound Excited Thermography

1.1 Ultrasound Lockin Thermography ULT

Ultrasound excited lockin thermography (ULT) is a method where a defect responds selectively so that the image displays only the defect and not the confusing background of the intact structure. Defects differ from their surroundings by their mechanical weakness. They may cause stress concentrations, and under periodical load there may be hysteresis effects or friction in cracks and delamination. As defects may be areas where mechanical damping is enhanced, the ultrasound is converted into heat mainly in defects [1,2]. Modulation of the elastic wave amplitude results in periodical heat generation so that the defect is turned into a local thermal wave transmitter. Its emission is finally detected via the temperature modulation arriving at the surface which is analyzed by lockin thermography tuned to the frequency of amplitude modulation [3]. The ultrasound transducer is attached at a fixed spot from where the acoustic waves are launched into the whole volume where they are reflected until they disappear preferably in a defect and generate heat. These high frequencies are very efficient in heating since many hysteresis cycles are performed per second.

1.2 Ultrasound Burst Phase Thermography

Ultrasound Burst Phase Thermography (UBP) is derived from the ULT method mentioned above. In comparison to the sinusoidal excitation, UBP uses only short ultrasound bursts to derive phase angle images [4,5]. The heating up followed by a cooling down period is recorded by the infrared camera. The local spectral components of that signal provide information about defects in a way similar to the Lockin technique but with an improved robustness against coupling problems and with a reduced measuring duration. As the characteristic defect signal is contained in a limited spectral range while the noise typically is distributed over the whole spectrum, one can reduce noise as well. That kind of evaluation technique using Fourier [6,7] or Wavelet transformations [8] is also applicable to flash-light excited thermography. The signal to noise ratio of ULT and UBP images (and hence defect detectability) is significantly better than in the best single temperature image taken from the recorded sequence. UBP allows for faster measurements at an enhanced reproducibility while the advantages of phase images are the same: depth resolved recognition of defects, suppression of inhomogeneous emissivity and of temperature gradients.

2 Frequency Modulated Ultrasonic Excitation

By applying a monofrequent excitation to a sample it is not unlikely that this frequency matches to a resonance of the vibrating system. The result is probably a standing wave pattern. Due to hysteretic losses in the elongation maximum, these standing elastic waves can appear as temperature patterns causing misinterpretations: In the worst case the defect could be hidden in a node ("blind spot") while the standing wave maximum might appear as a defect. This can be avoided by using two or more ultrasound transducers operating simultaneously at different frequencies or, even better, by frequency modulation of a sinusoidal signal. In these cases the standing wave pattern is superimposed by a field of propagating waves giving sensitivity also where only nodes existed before. Figure 1 indicates the different excitation signals: monofrequent ultrasound excitation (burst and lockin method) in comparison to frequency modulation.

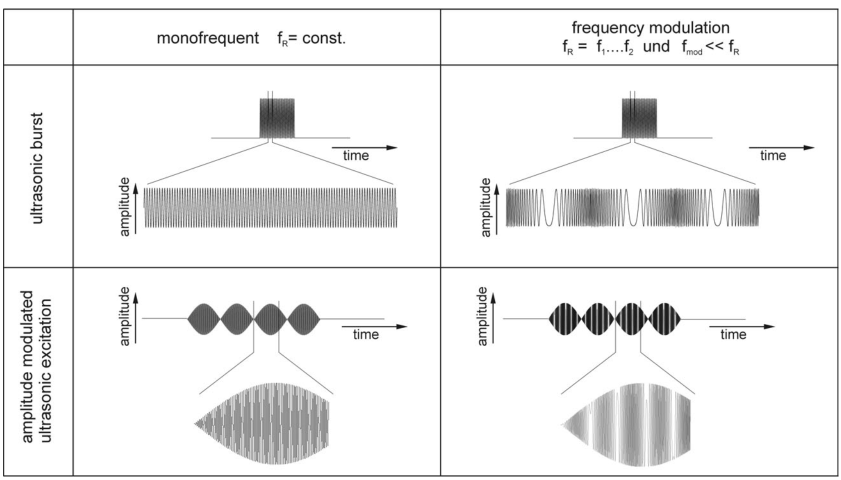


Fig. 1. Monofrequent ultrasonic excitation methods (left) in comparison to a frequency modulated excitation (right).

3 Experimental Arrangement

The experimental set-up is shown in figure 2. We used a non-standard 2.2 kW power supply, driving the ultrasonic welding transducer whose excitation frequency can be modulated in a range from 15 to 25 kHz. The excitation duration typically ranges from 100 ms up to a few seconds for burst phase thermography and up to some minutes for lockin thermography. A digital to analogue converter triggers the modulation frequency and if required the lockin frequency for amplitude modulation. The temperature sequences were acquired with focal plane array IR cameras (CEDIP Jade MWIR (320 x 240 InSb) and CEDIP Emerald MWIR (640 x 512 InSb)). Both detector arrays respond to radiation in the 3-5 µm spectral band. A personal computer performs an online Fourier transformation and subsequent image processing.

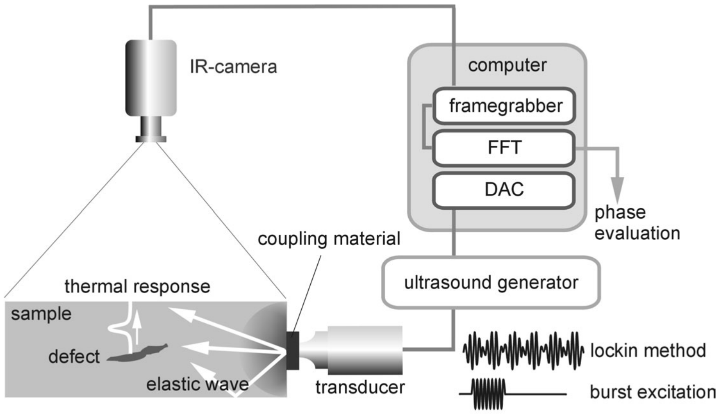


Fig. 2. Principle set-up of ultrasound excited thermography.

The tip of the welding horn is pressed against the component to be tested. For an efficient ultrasound coupling tight contact as well as impedance matching is important. The acoustic impedance *Z* is given by the product of the density ρ and the elastic wave velocity *v* in the material

$$Z = \rho v \tag{1}$$

In close analogy to optical techniques it is advantageous if the acoustic impedance of the coupling material matches with the geometric mean of the acoustic impedance of the material to be tested and the material of the welding horn, in our case a titanium base alloy

$$Z_{cm} = \sqrt{Z_h \cdot Z_s} \tag{2}$$

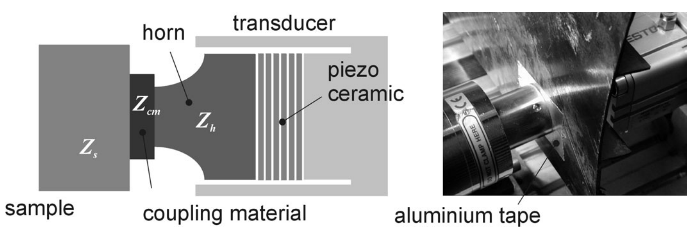


Fig. 3. Impedance matching for efficient ultrasound coupling.

In terms of optimized ultrasound coupling in CFRP, good results were obtained on a thin sheet of adhesive aluminium tape whose acoustic impedance is close to the square root mentioned above. In comparison to the direct coupling without any coupling material an increase of the efficiency of 35 per cent was achieved. Such materials do not only improve the ultrasound coupling but also the component surface was protected against external damage caused by mechanical and thermal load during the ultrasonic burst.

4 Results

4.1 Quality Control Of Adhesive Bonding

Adhesive bonding as a joining technique that is increasingly being used in vehicle production. Modern lightweight design, safety and modular concepts require improved rigidity, increased energy absorption capacity, and fatigue strength. Adhesively bonded joints – totally over 100 m length per modern automobile – became safety relevant and therefore have to be inspected during the production process. The ULT/UBP methods provide a new opportunity for the quality control of such joints. Defects to be detected are entrapped air, poor adhesion, kissing bonds, and non cured or missing adhesive. The following two figures show potential applications: the detection of poor adhesion (figure 4) and missing glue (figure 5).

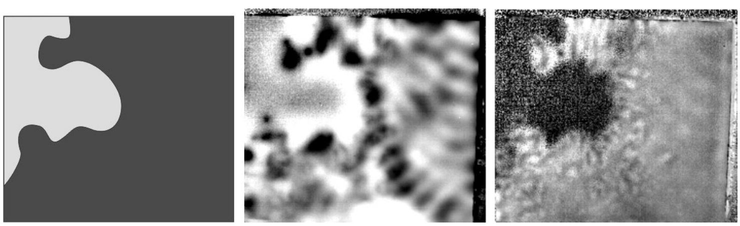


Fig. 4. Detection of poor adhesion in the bright grey area (substrate: aluminium, d= 2 mm). ULT phase images with monofrequent excitation (middle) and enhanced defect detection using frequency modulated elastic waves (right).

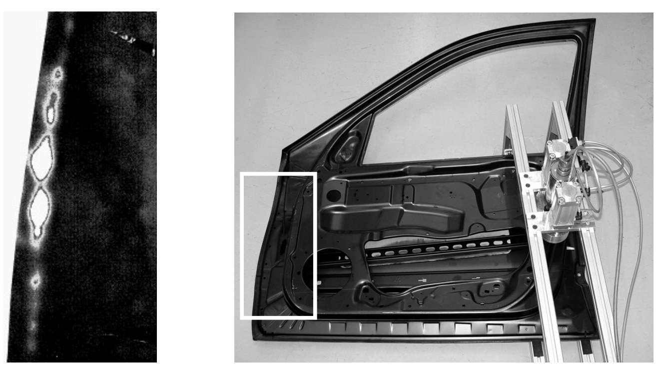
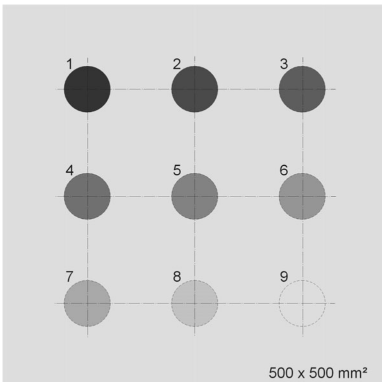


Fig. 5. Artificial defect in a automotive test door. To avoid standing wave patterns, amplitude and frequency of the ultrasonic excitation signal were modulated. In the phase evaluation (left) the missing glue appears as bright areas.

4.2 Characterization Of GLARE®

GLARE® („Glass fibre Reinforced Aluminium Laminate") is a new hybrid aircraft material consisting of alternating bonded layers of aluminium and strong fibreglass. One of the particular advantages is that the material provides more protection in case of fire and is more resistant to impact damages, corrosion, and lightning. In addition it shows excellent properties in fatigue. Airbus selected GLARE® for the upper part of the fuselage of the new large passenger aircraft A380 (total quantity 4 t per aircraft).

Figure 6 shows a GLARE® sample with artificial defects. Delamination was simulated with circular PTFE films in different depths. In figure 7 the phase signature of frequency modulated ultrasound Lockin thermography is shown. All nine defect were clearly detected.



Material: Glare® 3-10/9-0.4
10 layers Al (d=0,4 mm)/ 9 layers GFRP
Depth range of defects:
1 layers 1 / 2
2 layers 2 / 3
3 layers 3 / 4
4 layers 4 / 5
5 layers 5 / 6
6 layers 6 / 7
7 layers 7 / 8
8 layers 8 / 9
9 layers 9 / 10

Fig. 6. Artificial defect (debonding simulated with circular PTFE films) in Glare® 3-10/9-0.4

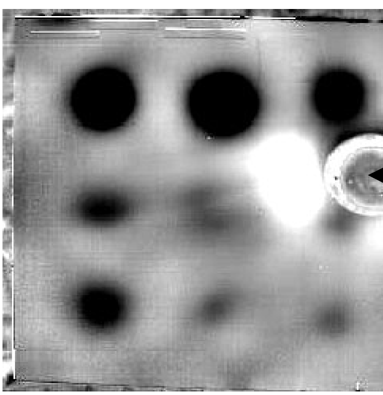


Fig. 7. Artificial defect (debonding simulated with circular PTFE films) in Glare® 3-10/9-0.4. Phase image of Ultrasound Lockin Thermography at 0.01 Hz.

5 Conclusion

Ultrasound excited thermography is an efficient non-destructive tool. As known the phase evaluation of the recorded sequences has clear advantages as compared to one thermal image: Sensitivity variations within the detector array as well as optical sample characteristics such as inhomogeneous temperature distribution and varying emission coefficients on the sample surface are suppressed. Furthermore the signal to noise ratio is improved significantly.

Impedance matching can be achieved if the geometric mean of the acoustic impedance of the material to be tested and the material of the transducer horn matches with the acoustic impedance of the coupling material. By applying a frequency modulated ultrasonic excitation the disturbing temperature patterns caused by standing elastic waves were eliminated. This results in homogenous power density in the material and in a much enhanced defect detectability.

6 Acknowledgements

The authors are grateful to LKT GmbH (Aachen, Germany), Institut fuer Fuege- und Schweisstechnik (Braunschweig, Germany), and to Airbus Deutschland GmbH (Bremen, Germany) for their helpful cooperation and for providing samples. Technical support of CEDIP Infrared Systems (Croissy-Beaubourg, France) and BRANSON Ultraschall (Dietzenbach, Germany) is highly appreciated as well.

REFERENCES

[1] Mignogna, R. B.; Green, R. E. Jr.; Henneke, E. G.; Reifsnider, K.L.: "Thermographic investigations of high-power ultrasonic heating in materials" in *Ultrasonics* **7,** 1981, pp. 159-163.

[2] Stärk, F.: "Temperature measurements on cyclically loaded materials" in *Werkstofftechnik* 13, Verlag Chemie GmbH, Weinheim, 1982, pp. 333-338

[3] Rantala, J.; Wu, D.; Busse, G.: "Amplitude Modulated Lock-In Vibrothermography for NDE of Polymers and Composites" in *Research in Nondestructive Evaluation, Vol.* **7**, 1996, pp. 215-218.

[4] Patent DE 100 59 854.4

[5] Dillenz, A.; Zweschper, Th.; Busse, G.: Elastic wave burst thermography for NDE of subsurface features. In: Insight 42 Nr. 12 (2000), pp. 815-817

[6] Maldague, X.; Marinetti, S.: "Pulse Phase Infrared Thermography" in *J. Appl. Phys*, 79 [5], 1996, pp. 2694-2698.

[7] Maldague, X.; Marinetti, S.; Busse, G.: "Couturier, J.-P.: Possible applications of pulse phase thermography" in *Progress in Natural Science*, Supplement to Vol. 6, 1996, pp. 80-82.

[8] Galmiche, F.; Vallerand, S.; Maldague X.: "Pulsed Phase Thermography with the Wavelet Transform" in *Review of Progress in Quantitative NDE*, D.O. Thompson et D.E. Chimenti editors, Am. Institute of Physics, 19A, 2000, pp. 609-615.