Remote photoacoustic imaging for material inspection

T Berer\textsuperscript{1,2}, A Hochreiner\textsuperscript{1}, B Reitinger\textsuperscript{1,2}, H Grün\textsuperscript{2} and P Burgholzer\textsuperscript{1,2}

\textsuperscript{1} Christian Doppler Laboratory of Photoacoustic Imaging and Laser Ultrasonics, Hafenstrasse 47-51, 4020 Linz, Austria
\textsuperscript{2} Research Center for Non Destructive Testing GmbH (RECENDT), Hafenstrasse 47-51, 4020 Linz, Austria

E-mail: thomas.berer@recendt.at

Abstract. We report on (to our knowledge) the first remote contactless photoacoustic imaging with short excitation pulses on semitransparent solid polymer samples for material inspection. In this work solid semitransparent samples are excited with pulses from a short pulse laser. The local absorption of the electromagnetic radiation leads to generation of broadband ultrasonic waves. Ultrasonic waves arriving on the sample surface are detected with a confocal Fabry-Pérot interferometer. After data acquisition the absorbed energy density is reconstructed by utilizing an F-SAFT algorithm. The work shows the potential of photoacoustic imaging on material inspection of semitransparent solid materials.

1. Introduction

In photoacoustic imaging (PAI) - also termed optoacoustic or thermoacoustic imaging - a volume of a semitransparent sample is illuminated with a short pulse of electromagnetic radiation, e.g. a short laser pulse. Depending on the spatially varying optical properties of the sample, the radiation is absorbed and scattered differently. The local absorption in the sample leads to local heating, in sequence to thermal expansion, and finally to the emission of broadband ultrasonic signals. The goal of PAI is to reconstruct the absorbed energy density by measuring the ultrasound signals outside the sample [1]. Thus photoacoustic signals contain information of light absorption at ultrasonic resolution. The used pulses are so short that thermal conductivity can be neglected during pulse time ("thermal confinement"). The imaging modality is therefore different as described in early publications about photoacoustics, e.g. references [2; 3], where photoacoustically generated thermal waves, generated at relatively low frequencies, interact with features of a sample. Although there is frequently confusion about that issue, the term photoacoustic, instead of the alternatively used terms optoacoustic or thermoacoustic, has established in literature.

Various publications about imaging with laser ultrasonic means exist, and also publications of generation of ultrasound waves by laser ultrasonic techniques in (semi)transparent media, e.g. ref [4]. However, up to now photoacoustic imaging with short laser pulses, where the optical absorption at the excitation time is reconstructed in three dimensions, was only applied to biological or medical samples. For these applications the sample is usually immersed in a tank filled with water (or some other fluid). The fluid acts as coupling media between sample and...
Figure 1. Schematic of the setup with the component labels given as follows: M1 mirror; L1 to L6 lenses; HW1 and HW2 half wave plates; PBS polarizing beam splitter; QW quarter wave plate; CFP confocal Fabry-Pérot cavity

detector. Detection of the ultrasonic signals is usually done utilizing piezoelectric transducers, but also detection schemes using interferometric means exist[5–9]. For material inspection, e.g. for in-line process control, a physical contact between sample and detector is a serious limitation. To take advantage of the remote generation of ultrasonic waves also the detection has to be accomplished without physical contact to the sample. In this work we excite ultrasonic waves in solid samples by short laser pulses. For detection we utilize a confocal Fabry-Pérot interferometer (CFPI) which measures the ultrasonic signals directly on the surface of the sample.

2. Measurement Setup
A schematic of the measurement setup is depicted in figure 1. A Q-switched Nd:YAG laser operating at a wavelength of 1064 nm generated pulses with a pulse length of 20 ps and a beam diameter of 9 mm. The polarization of the pulses was adjusted to p-polarization with a half wave plate HW1. Subsequently, the beam was deflected by a mirror onto the sample. The angle between the surface normal of the sample and the incident beam was set to coincide with the Brewster’s angle. Thus most of the incident radiation was transmitted into the sample. Absorption of laser pulses inside the sample lead to broadband emission of acoustic waves. These were detected and demodulated at the sample surface utilizing a confocal Fabry-Pérot interferometer. The interferometer employed a 532 nm continuous wave laser with a power of 1 W which was damped with an optical density filter to about 150 mW. After passing through a half wave plate HW2 the (horizontal polarized) beam was focused onto the sample surface with a lens L1. Light reflected from the sample surface was collected and collimated by a 2” lens L2 and subsequently reduced by a Keplarian telescope formed by the lenses L3 and L4. The beam then passed through a polarizing beam splitter PBS, got circularly polarized by quarter wave plate QW and finally entered the confocal Fabry-Pérot cavity. The transmitted beam was focused onto a photo diode, the signal of which was used to stabilize the cavity. Stabilization was done using a digital controller (based on an ARM processor) and an amplifier. Back reflected light from the CFPI experienced another \( \lambda/4 \) rotation, and was focused onto a fast photodiode after reflection from the polarizing beam splitter. The measured signal of the photodiode corresponds to the surface velocity of the sample. To allow automatic measurements the sample was mounted onto a motorized \( x,y \)-translational stage.
3. Measurements

A sample was made from a 50 × 50 × 3 mm³ white semitransparent polymer board (figure 2a). The polymer is commonly used in automotive industries. The transmission of the 3 mm thick polymer sheet in the visible to the near infrared region was measured to be below 5%. On the back of the polymer plane objects made of a black silicon glue, also commonly used in automotive industries, were placed (see figure 2b). To allow ultrasonic waves to propagate properly the back of the plane was filled with a transparent resin.

Ultrasonic waves within the sample were excited with pulses from the generation laser with a pulse energy of 50 mJ at a repetition rate of 10 Hz. The acquired ultrasonic signals were averaged 24 times. A typical trace measured directly above a piece of black glue is depicted in figure 3. The first pulse at a time of 1.5 µs is the first arriving longitudinal wave. A second pulse arriving at about 3.6 µs is attributed to transversal waves. The signal of the longitudinal wave which is back reflected at the polymer/resin interface can be identified at 4.5 µs.

For three dimensional imaging a sample area of 16 × 16 mm² was measured by moving the sample in two directions with the translational stage. The step size was set to 400 µm for both scan directions. A maximum intensity plot of the measured signals is depicted in figure 4b. To construct the ultrasonic signals at the time of excitation an F-SAFT algorithm [10] was applied on the data. After reconstruction the absorbing structures appear at a depth of 3 mm corresponding to the thickness of the polymer board. Due to the F-SAFT algorithm artifacts from the wave propagation which lead to blurring of the image are removed. A maximum intensity plot of the reconstruction is depicted in figure 4c. For the picture no image enhancement like application of a threshold, filtering of the data or contrast adjustment was applied. As can be seen the F-SAFT reconstruction does not only remove artifacts which arise from the different arrival times of the waves but also increases the signal to noise ratio [11]. For comparison a photograph of the measured area is depicted in figure 4a. To allow a better comparison between photograph, measured data and reconstructed data figure 4a is displayed mirrored at the y-axis. All absorbing objects are well resolved. Also small details like the asymmetry in the objects mouth are well reproduced.
Figure 4. a) Photograph of the measured object. b) Maximum intensity plot of the acquired signals. The scan size was 16 mm \times 16 mm with 41 points on each axis, leading to a step size of 400 \mu m. c) Maximum intensity plot of the F-SAFT reconstruction. Note that no threshold, filtering of the data or contrast enhancement was applied.

4. Conclusion
We have reported on photoacoustic measurements on solid semitransparent polymer samples. Ultrasonic waves within the specimen were excited with pulses from a picosecond pulse laser. The ultrasonic waves arriving the surface of the sample were detected and demodulated utilizing a confocal Fabry-Pérot interferometer. After acquisition the ultrasonic signals at the time of excitation were reconstructed using an F-SAFT algorithm. All features of the measured object are clearly visible. This work shows that photoacoustic imaging may not only be valuable for medical or biological samples but has also great potential for inspecting semitransparent solid samples.

Acknowledgments
This work has been supported by the Christian Doppler Research Association, by the Federal Ministry of Economy, Family and Youth, by the industrial partner INPRO Innovationsgesellschaft für fortgeschrittene Produktionssysteme in der Fahrzeugindustrie mbH, by the Austrian Science Fund (FWF), project number S10503-N20, by the European Regional Development Fund (EFRE) in the framework of the EU-program Regio 13, and the federal state Upper Austria

References
[1] Xu N and Wang L V 2006 Rev. Sci. Instrum. 77 041101
[2] Rosencwaig A and Busse G 1980 Appl. Phys. Lett. 36 725–727
[3] Wong Y H, Thomas R L and Pouch J J 1979 Appl. Phys. Lett. 35 368–369
[4] Matsuda O, Tachizaki T, Fukui T, Baumberg J J and Wright O B 2005 Phys. Rev. B 71 115330
[5] Paltauf G, Nuster R, Haltmeier M and Burgholzer P 2007 Appl. Optics 46 3352–3358
[6] Grün H, Berer T, Nuster R, Paltauf G and Burgholzer P 2010 J. Biomed. Opt. 15 021306
[7] Zhang E, Laufer J and Beard P 2008 Appl. Opt. 47 561–577
[8] Payne B P, Venugopalan V, Mikic B B and Nishioka N S 2003 J. Biomed. Opt. 8 273–280
[9] Carp S A and Venugopalan V 2007 J. Biomed. Opt. 12 064001
[10] Busse L J 1992 IEEE Trans. Ultrason. Ferroelectr. Freq. Control 39 174–179
[11] Blouin A, Lévesque D, Néron C, Drolet D and Monchalin J P 1998 opt. Express 2 531–539