

# Airborne testing of molded polymer compounds

Daniel KOTSCHATE<sup>1</sup>, Saskia WENDLAND<sup>1,2</sup> and Mate GAAL<sup>1</sup>

<sup>1</sup>Bundesanstalt für Materialforschung und -prüfung (BAM), Germany

<sup>2</sup>Technical University of Ilmenau, Germany

Contact e-mail: daniel.kotschate@bam.de

**Abstract:** Modern and energy-efficient materials are essential for innovative designs for aerospace and automotive industries. Current technologies for rapid manufacturing such as additive manufacturing and liquid composite moulding by polymer extrusion allow innovative ways of creating robust and lightweight constructions. Commercially available printing devices often use polylactide (PLA) or acrylonitrile butadiene styrene (ABS) as raw material. Therefore, parameters like the infill ratio, influencing the ability to resist mechanical stress, may have a beneficial impact on the lifetime of components. These manufacturing technologies require a good knowledge about materials and even adapted non-destructive testing technologies and methods. Airborne ultrasonic testing has beneficial advantages for testing those lightweight constructions. It is a contact-free testing method, which does not require a liquid couplant. Therefore, it allows fast test cycles without any unwanted alternations of the material properties due to interactions with any coupling liquid. This contribution deals with the characterisation of printed specimens based on PLA by using airborne ultrasound and presents the current edge of non-destructive testing and evaluation using airborne ultrasonic transducers. The specimens, manufactured by polymer extrusion, are printed as thin plates. The infill ratio, as well as the material thickness, were varied to model density imperfections with different geometric shapes and properties. For better understanding of the limits of airborne ultrasonic testing in transmission, we compared own-developed transducers based on different physical principles: on ferroelectrets, on the thermoacoustic effect, as well as a new type of transducers based on gas discharges.

## 1 Introduction and background

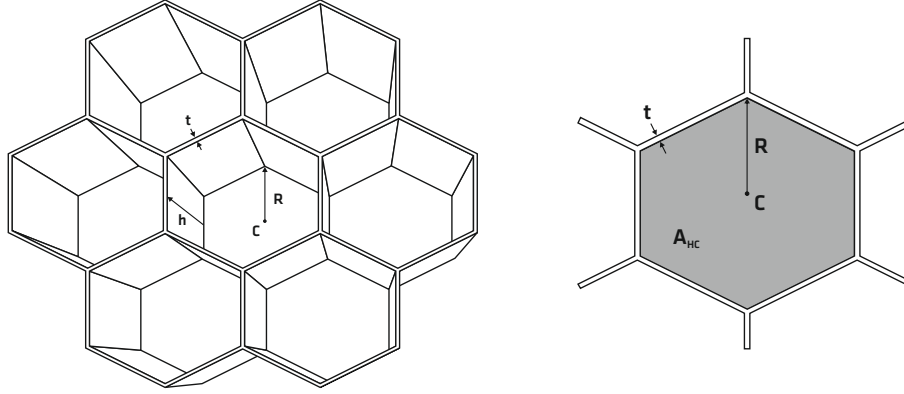
New manufacturing techniques like additive manufacturing and the usage of lightweight and composite materials have received much attention in recent years. They enable lightweight constructions with equivalent durability and offer significant economic benefit. One common and basic additive manufacturing technique is three-dimensional printing technology with molded polymers. It has many possible use cases like biomedicine [1] or as an engineering material. However, the anisotropic structure and the inclusion of different materials (e.g. ambient air or water) during the printing process, make it difficult to test using conventional non-destructive testing (NDT) methods. In this paper, we benchmarked different air-coupled ultrasonic setups in regard to their feasibility for this testing purpose. For reliable results we varied the internal structure of the fabricated specimen to manipulate their acoustic properties. We present a set of criteria for selecting an appropriate testing arrangement and show the current edge technologies for air-coupled testing of highly structured materials.



This contribution deals with the competitive transducer technologies: polarised polypropylene (cPP) transducers [2], thermoacoustic [3] and plasmaacoustic emitters [4, 5].

## 2 Theory

Modern artificial materials achieve their beneficial properties by bonding different compounds and their properties or structures to connect their advantages. In lightweight constructions, higher stability are often reached by using structural elements. The most common structure, the hexagonal or honeycomb structure, achieves the elastic properties by its geometrical properties and dependencies.



**Figure 1.** Regular hexagon/honeycomb structure. The elastic properties depend on the  $A_{HC}$  and the thickness  $t$  of the supports [6].

Figure 1 illustrates a schematic representation and the corresponding geometric properties of this structure. The desired weight and material reduction is reached due varying the geometric parameters of the infill structure. The volume  $V_{HC}$  of a regular hexagon structure depends mainly on the central distance  $R$  and is calculated using

$$V_{HC} = h \times A_{HC} = h \times \frac{3}{2} \sqrt{3} R^2, \quad (1)$$

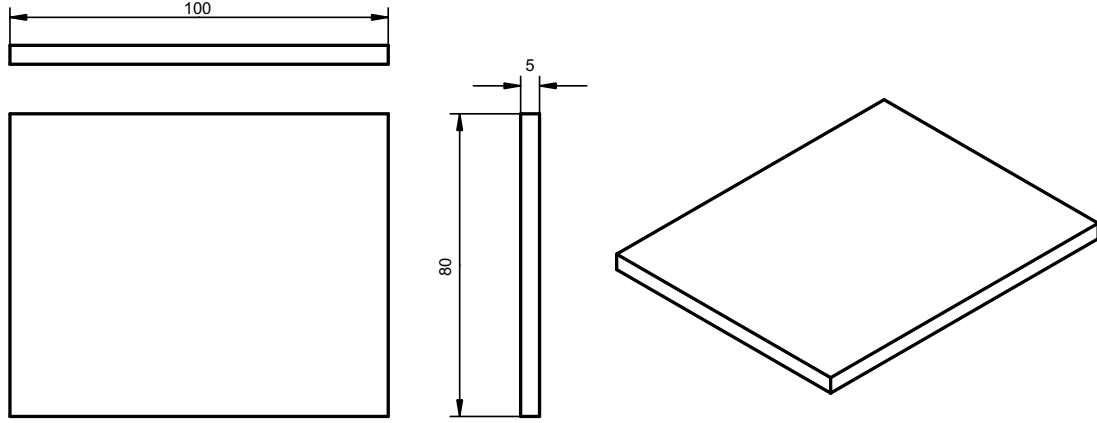
where  $h$  describes height of the hexagonal infill pattern. For achieving a desired printing result in less time, the size of the infill pattern is the most important parameter to build up those structures. Assuming a constant height  $h$  (set by the final geometry) and a constant maximal central distance  $R_{max}$ , a parameter - the infill ratio - is introduced by modifying eq. (1) to

$$V_{HC}(\tau) = h \times \frac{3}{2} \sqrt{3} \left( R_{max} (1 - \tau) \right)^2, \quad (2)$$

where  $\tau$  is the infill ratio and varies the central distance  $R$  in a range  $0 < \tau \leq 1$ . Varying this parameter, also varies the acoustic parameters of the specimen.

## 3 Experiment

For a better comparison between the different transducer technologies, we printed a simple test piece which is shown by fig. 2 and varied the infill pattern. Therefore the fabricated specimens are equal in their dimensions, but differ in the structure size and the ratio between infill structure and raw printing material.



**Figure 2.** Technical drawing of the printed and tested specimen.

### 3.1 Raw material characterisation

Due to the large amount of different polymer mixtures, the density was obtained by printing a solid specimen ( $\tau = 1$ ) to specify the density and the speed of sound of the raw material. Despite the hydrophobic surface of biodegradable polymers [7], they are able to absorb water and therefore the mixture contains two components: PLA and water. The resulting effective density of the raw material is calculated using the rule of mixtures

$$\rho_{eff}(\xi) = \xi \times \rho_1 + (1 - \xi) \times \rho_2, \quad (3)$$

where  $\xi$  is the fractional volume of each component (water or PLA),  $\rho_1$  is the density of PLA ( $\rho_1 \approx 1.24 \text{ g cm}^{-3}$  [7]) and  $\rho_2$  describes the density of the absorbed water ( $\rho_2 \approx 1.0 \text{ g cm}^{-3}$ ). Due to the absorbed water we determined the density of the raw material with  $0.93 \text{ g cm}^{-3}$ . The speed of sound was quantified using a wall thickness measurement device. The resulting speed of sound is  $c_L \approx 2040 \text{ m s}^{-1}$ . The calculated acoustic impedance is calculated using

$$Z_{PLA} = \rho(\xi) \times c_L \approx 2 \times 10^6 \text{ m}. \quad (4)$$

Decreasing the infill ratio would increase the acoustic impedance due to the honeycomb structure inside the specimen. Therefore the transmission loss is modified by varying the size of the infill pattern. We used the printed specimen with 10% infill as reference for transducer characterisation. The signal amplitude and the spatial resolution of the resulting c-scan were evaluated.

### 3.2 Transducers

We tested this specimen (infill 10%) with three different kinds of acoustic sources and sensors: 1. Ferroelectret transducers, 2. thermoacoustic and 3. plasmaacoustic emitters. Ferroelectret transducers are based on coated and polarised polypropylene and show a thickness-mode resonance behaviour. Due to the polarisation by a significant amount of electrical field strength, electric dipoles are generated inside the existing cavities. These transducers provide an excellent signal-to-noise ratio (SNR) and, due to their working principle, a nearly perfect

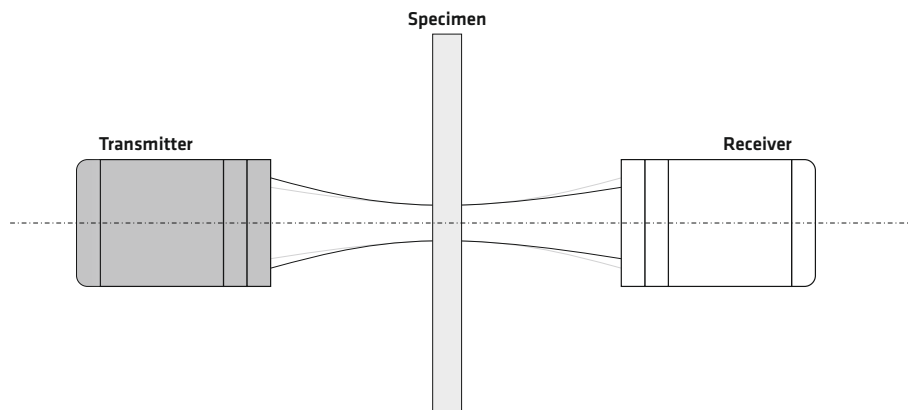
acoustic impedance matching. Thermoacoustic emitters using rapid gas heating to form the formation of an acoustic wave. They consist of a substrate coated with a conducting layer. Similar to the thermoacoustic emitters, plasmaacoustic sources also use the rapid gas heating of the ambient fluidic volume. In contrast to the thermoacoustic ones, the gas heating is achieved by forming a conductive channel and using the energy conversion from chemical energy to thermal energy. Due to the lack of any moving mass, the thermo- and plasmaacoustic emitters are broadband sources without any mechanical resonance behaviour.

**Table 1.** Investigated combinations of different technologies of air-coupled ultrasonic transducers. The abbreviations denote the used transducer technology: ferroelectric (FE), thermoacoustic (TA) and plasmaacoustic (PA).

	Combination 1	Combination 2	Combination 3
Technology	FE / FE	TA / FE	PA / FE
Center frequency [kHz]	282 / 283	wideband / 86	wideband / 86
Aperture [mm]	11 / 11	55 / 27	0.5 / 27
Pulse width [ $\mu$ s]	1.78	2	2
Gain [dB]	64	81	0

### 3.3 Experimental arrangement

Figure 3 illustrates the classic transmission setup as the experimental arrangement for the comparison of transducers. All measurements were recorded using the ultrasonic device for air-coupled ultrasonic testing USPC 4000 Airtech and a scanning and positioning system FlatScan, both by company Ingenieurbüro Dr. Hillger.



**Figure 3.** Setup arrangement for testing specimen in transmission using airborne ultrasound.

Both transducers are positioned in respect to their nearfield or focal length to provide a proper spatial and amplitude resolution for best testing results as possible. Since some of the transducers are spherically focusing, the focal length was calculated using the approximation formula given by [8].

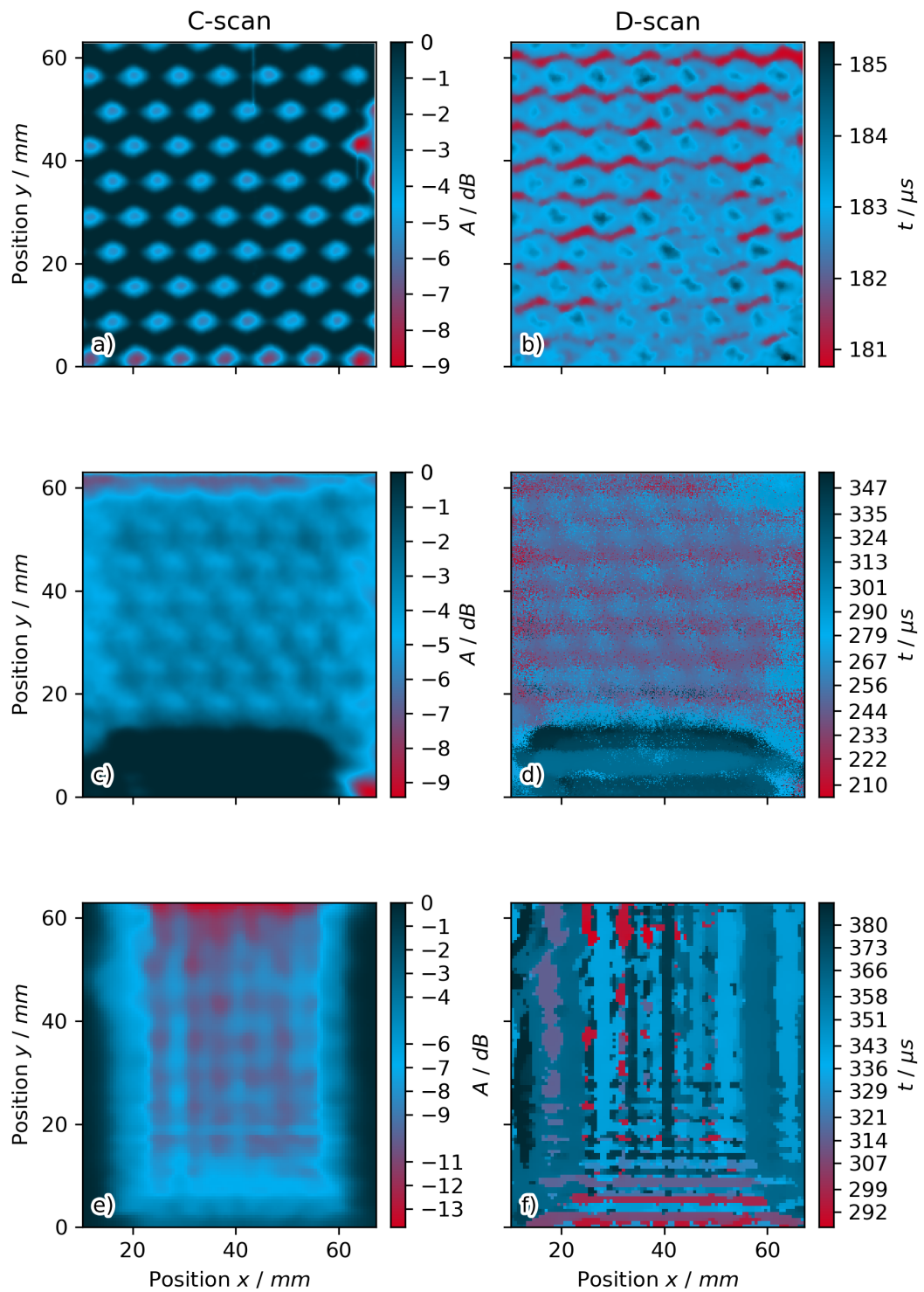
## 4 Results and conclusion

Figure 4 presents the achieved results and illustrates the differences between the performances of the applied transducers. For better comparison, the pre-amplification of each dataset was considered. The left picture (fig. 4 a)) shows the result obtained by a matched pair of ferroelectret transducers. These transducers have a center frequency of 280 kHz and an aperture of 11 mm. Therefore they reach a maximum spatial resolution of 2.75 mm. Figure 4 b) shows the result obtained by using a focused thermoacoustic transducer as transmitter and a ferroelectric transducer (center frequency of 86 kHz and an aperture of 27 mm) as receiver.

Due to the broadband acoustic excitation, the sensitivity is lower compared to the results achieved by the ferroelectric arrangement. The plasmaacoustic result is presented in fig. 4 c). For comparable results, the the same ferroelectric transducer as for the thermoacoustic setup was used as receiver. The plasmaacoustic source generates a much higher acoustic excitation compared to the ferroelectric and the thermoacoustic sources. Unfortunately, due to the small aperture of 500  $\mu\text{m}$  the device acts like a spherical acoustic point source with wide opened directional pattern. Due to this directivity pattern no comparable resolution is achieved, although the reached sensitivity is at least 60 dB higher and may offer new possibilities. Additionally, the aperture of the plasmaacoustic device is over twenty times smaller compared to the smallest transducer combination and offers opportunities for assembling arbitrary shaped transducers or embedding highly integrated structures as transducer arrays. The presented results also illustrate the challenging task of the broadband investigation of highly anisotropic structured specimen. The specimen thickness and the associated acoustic damping is the most important point to tackle. Reducing the thickness and the usage of modern signal processing methods (e.g. denoising) might increase the signal to noise ratio [9]. However, broadband devices also offer great benefits for material characterisation methods like ultrasound spectroscopy, transducer characterisation and they reduce the need to swap the transducer on source side or changing the whole measurement setup.

## 5 Acknowledgment

The presented work and the corresponding results were produced during the preparation of Mrs. Wendlands bachelor thesis. The authors would like to thank Dr.-Ing. G. Lange (Technical University of Ilmenau) for this opportunity.



**Figure 4.** Resulting c-scan and d-scan images examined with three different transducer setups. a+b) cPP transducer combination c+d) thermoacoustic / cPP combination e+f) plasmaacoustic / cPP transducer combination. The images c-d) include reconstruction artefacts due to the clamping of the specimen.

## References

- [1] Marius Murariu and Philippe Dubois. PLA composites: From production to properties. *Adv. Drug Deliv. Rev.*, 107:17–46, 2016.
- [2] Mate Gaal, Viktor Bovtun, Wolfgang Stark, Anton Erhard, Yuriy Yakymenko, and Marc Kreutzbruck. Viscoelastic properties of cellular polypropylene ferroelectrets. *J. Appl. Phys.*, 119(12):125101, mar 2016.
- [3] M. Daschewski, R. Boehm, J. Prager, M. Kreutzbruck, and A. Harrer. Physics of thermoacoustic sound generation. *J. Appl. Phys.*, 114(11):114903, sep 2013.
- [4] Mate Gaal and Daniel Kotschate. New technologies for air - coupled ultrasonic transducers. In *Proceeding 12th Eur. Conf. Non-destructive Test.*, number 1, pages 1–9, 2018.
- [5] Daniel Kotschate, Mate Gaal, and Holger Kersten. Acoustic emission by self-organising effects of micro-hollow cathode discharges. *Appl. Phys. Lett.*, 112(15):154102, apr 2018.
- [6] D. H. Chen and S. Ozaki. Analysis of in-plane elastic modulus for a hexagonal honeycomb core: Effect of core height and proposed analytical method. *Compos. Struct.*, 88(1):17–25, 2009.
- [7] Shady Farah, Daniel G. Anderson, and Robert Langer. Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review. *Adv. Drug Deliv. Rev.*, 107:367–392, 2016.
- [8] Hermann Wüstenberg and Jürgen Kutzner. Empfindlichkeitseinstellung beim Einsatz fokussierender Prüfköpfe in der Ultraschallprüfung an ebenen und gekrümmten Bauteilen. *Mater. = Mater. Test.*, 19(10):441–444, 1977.
- [9] Klaas Bente, Daniel Kotschate, Saskia Wendland, and Mate Gaal. The thermoacoustic effect and its application in air-coupled testing of composite structures. *10th Int. Symp. NDT Aerosp.*, 2018.