Polymer Testing 32 (2013) 739–747

Contents lists available at SciVerse ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test method

Structural analysis of insulating polymer foams with terahertz spectroscopy and imaging

Andreja Abina [a,*], Uroš Puc [a,b], Anton Jeglič [a,b], Aleksander Zidanšek [a,c,d]

[a] Jozef Stefan International Postgraduate School, Jamova 39, SI-1000 Ljubljana, Slovenia
[b] Faculty of Electrical Engineering, University of Ljubljana, Tržaška cesta 25, SI-1000 Ljubljana, Slovenia
[c] Department of Condensed Matter Physics, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
[d] Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška cesta 160, SI-2000 Maribor, Slovenia

ARTICLE INFO

Article history:
Received 29 December 2012
Accepted 5 March 2013

Keywords:
Insulation material
Macrostructure
Polymer foam
Terahertz pulsed imaging
Terahertz time-domain spectroscopy

ABSTRACT

Structural analysis of polymer foams for insulation enables manufacturers and research facilities to optimise their products and production processes for applications such as building construction. Therefore, two- and three-dimensional investigation of the macro- and microstructure of these materials is important in order to characterize their physical and mechanical properties. In this paper, we present terahertz time-domain spectroscopy and pulsed imaging method to analyse the macroscopic structure of foamed polymers including analysis of voids, inclusions and bead distribution. By measuring the difference between the terahertz waveforms and by calculating the spectroscopic constants we analyse certain material characteristics such as foam density and infrared radiation absorption. Furthermore, we demonstrate that terahertz techniques have several advantages over other technologies, in particular as a non-ionizing alternative to X-ray tomography, and a complementary imaging method to optical or electron microscopy enabling chemical and structural characterization of foamed polymers.

1. Introduction

Industrial production of foamed polymers is increasing globally due to their light weight, high thermal and acoustic insulation properties and high energy absorption capacity. These properties are crucial in applications such as building construction. In recent decades, only a few polymer foams for insulation based on new monomer building blocks have been successfully introduced to the market, mainly because of the relatively high cost of production. However, many modifications of the traditional polymer foams become possible due to new advances in material and technology development. For instance, nanotechnology allows the construction of nanocellular foams in which only one or no gas molecule can occupy individual pores, and thus enhance the thermal insulation properties by preventing the thermal conductivity of gas molecules [1]. Furthermore, the pore size can be reduced to below 100 nm using materials such as aerogel and xerogel [2]. The foam properties such as thermal insulation, structural reinforcement, flame retardant or thickness reduction can be improved with various inclusions including infrared attenuators [2,3], different fibres [4] and composites [5,6]. On the other hand, the environmental issues force industry to return to natural materials. Hence, sustainable and biodegradable polymers, e.g. starch foam [7], are becoming more attractive. In spite of the fact that high-tech polymer foams offer further potential for improvements, they have to compete with traditional materials and achieve lower production cost.

In general, polymer foams are produced by dispersing a gas within a liquid polymer matrix, which creates a characteristic structure of cells, walls and pores when the liquid matrix solidifies [8]. Many physical and mechanical

* Corresponding author. Tel.: +386 1 477 36 02; fax: +386 1 477 31 10.
E-mail addresses: andreja.abina@mps.si (A. Abina), aleksander.zidansek@ijs.si (A. Zidanšek).

0142-9418/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.polymertesting.2013.03.004

Table 1
Properties of polymer foam insulation material samples including mechanical and thermal conductance data summarized from the manufacturer specifications.

Material	Manufacturer	Brand name	Density (kg/m^3)	Thermal conductance (W/mK)	Slab thickness (mm)	Slice average thickness (mm)
Expanded polystyrene (EPS)	Weber	weber.therm family EPS-F	16	0.040	29	3.80
EPS with graphite	Weber	weber.therm clima 032	16	0.032	29	3.10
EPS with graphite	Fragmat Tim	Fragmat Neo Super 100 (Neopor®)	20	0.0312	40	2.97
Extruded polystyrene (XPS)	Weber	weber.therm XPS	30	0.034	29	3.46
Expanded Bakelite	Weber	weber.therm plus ultra 022	40	0.024	30	2.45

properties of polymer foams are thus a direct consequence of their micro- and macrostructure. The macroscopic properties of beads and voids are highly dependent on the local microstructure which is characterized by the cell distribution, cell size and shape as well as the wall thickness. All mentioned parameters are the result of many processing conditions including temperature, pressure, humidity, impurities, chemical composition and cure time [9]. Nowadays, the control of industrial processes is restricted mainly to monitoring the pressure and temperature, while the effect of other factors is still relatively unknown. Among all parameters, the analysis of voids, inclusions, superstructures, defects and material thickness is very important for thermal insulation properties. The laboratory measurements of these values are important both to the manufacturers and the end-users. The available bibliographic data considering these parameters for polymer foams are often incomplete and out of date.

Today, two- (2D) and three-dimensional (3D) investigation of the internal macro- and microstructure of polymer foams is an important method of characterizing its properties and gaining some insight into the formation process [10,11]. The 2D structure of polymer foams (e.g. cell size distribution) is usually analysed with optical or scanning electron microscopy (SEM) [10]. The drawback of this approach is that only the sample surface can be analysed, unless the sample is cut to reveal the internal structures. The alternative to microscopy is X-ray computed microtomography [10,12] which allows 3D imaging but it can be time-consuming and costly. Another 3D imaging method which enables description of the complex internal structure of materials is neutron tomography [13] which is usually provided by a large instrument, not allowing in-situ measurements. Also, both X-rays and neutrons are ionizing radiation. For chemical characterisation and identification of polymer materials, the routinely used techniques are Fourier transform infrared [14] and Raman [15] spectroscopic methods. Hence, it follows that the polymer foam industry is not well supported with non-destructive and contactless analytical techniques. One solution suitable for this purpose could be terahertz (THz) technology which has a significant potential for both chemical and structural characterisation of polymers [16]. Since many polymers feature very low absorption in the THz region [17,18] and the wavelength of THz waves is in the order of sub-millimetre [19], the THz spectroscopy and imaging methods

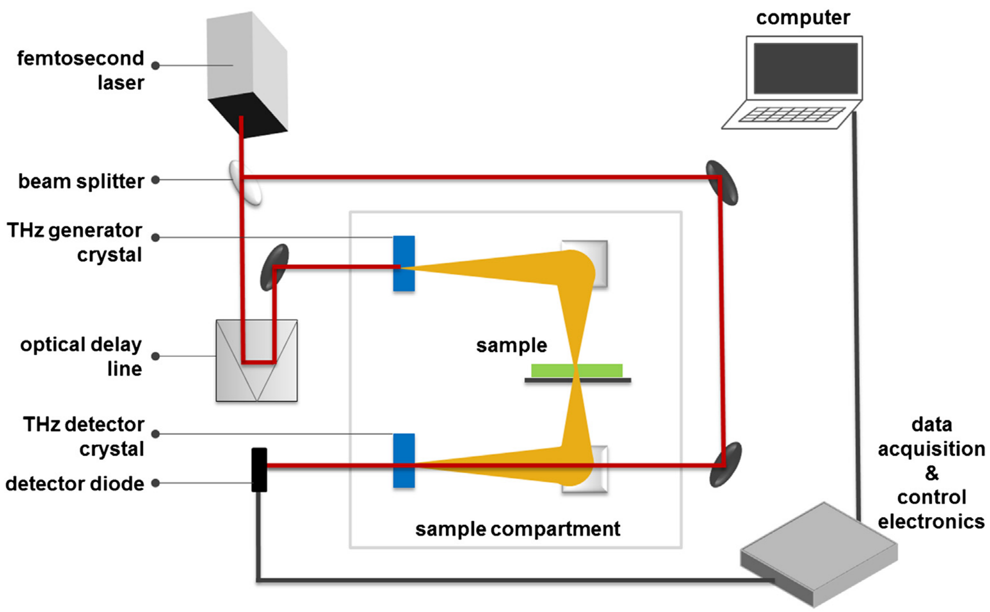

Fig. 1. A schematic drawing of the THz spectroscopy and imaging system in transmission geometry.