ABSTRACT

The presented work aims to establish a numerical material model to predict the mechanical behaviour of polymeric bead foam under mechanical loading. Special attention is paid to the influence of different temperatures, the microscopic cell structure and the occurrence of plasticity. In order to fulfil these tasks, a set of experimental and morphological analyses concerning the structural behaviour under loading was performed. To simulate the structural behaviour of the foam under mechanical loading, RVEs were built up. CT-scans of the unloaded foam were performed in order to model the architecture of the cellular structure taking into account the above mentioned effects.

Keywords: bead foam, micro structure, representative volume element.

INTRODUCTION

Polymeric bead foams are used in a wide range of different industrial sectors like packaging, automotive and sport articles [Bürkle, 2016]. Thanks to their unique combination of low density, high insulation capability, outstanding damping behaviour as well as high flexibility in forming, their potential for further applications is far from being exhausted. In contrast to these advantages, some properties like poor surface quality and low mechanical performance limit the usage of bead foams for structural components. A promising strategy to address this problem is the development of hybrid materials, e.g. by combining the bead foam process with overmoulding. In order to realise this, basic knowledge about the mechanical behaviour of bead foam materials is required. Especially the compression loads generated during manufacturing are to be compared to the deformation behaviour of the foam. While the processing conditions of bead foam materials have been widely analysed [Raps, 2015], only few published work on the mechanical properties is known, e.g. [Bouix, 2009], which becomes relevant when the material is used in structural applications. Compared to other foam materials, e.g. polyurethane [Weißenborn, 2016], an urgent need for profound investigations focussing on the failure behaviour of bead foams and material modelling in general exists.

MECHANICAL CHARACTERISATION

The work presented in this contribution comprises the mechanical testing of expanded polypropylene (EPP) specimens in both, tension and compression, analyses of the microscopic morphology, and finally the implementation and validation of a material model
being based on the experimental results. To take care of the foam specific cell structure which is composed of single beads with diameters of up to 3 mm, a novel cylindrical specimen geometry with a diameter of 31 mm was developed for the tensile tests which were performed on a Zwick 1475. Compression tests were performed according to DIN EN ISO 844 on a Zwick Z250 testing machine. All specimens were manufactured with a nominal density of 60 g/l and cut to dimensions using a hot-wire foam cutter.

Fig. 1 (left) shows the non-linear tensile behaviour of the EPP foam at room temperature. The elongation at break is between 8 and 11 %. The strength is limited to 0.9 MPa. In Fig. 1 (right) the results of the 4 series of compression tests are shown. The temperature was varied between 23 °C and 135 °C in order to analyse process relevant conditions during a theoretical overmoulding. As can be seen the characteristic stays the same for all test temperatures. Starting with a small linear-elastic deformation the foam reveals a plateau-like behaviour over a wide range of deformation from 2 to 75 % of strain. After this phase of energy absorption the material seems to get compacted and the measured stress values increase progressively.

After compression testing the permanent deformation was analysed by measuring the specimen height. Table 1 gives an overview of the subsequently calculated fraction of plasticity. As can be seen, an increasing temperature results in a more pronounced compaction of the bead foam.

<table>
<thead>
<tr>
<th>Test temperature /°C</th>
<th>Average specimen height before /mm</th>
<th>Average specimen height after /mm</th>
<th>Fraction of plasticity /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 °C</td>
<td>50.28</td>
<td>39.03</td>
<td>22</td>
</tr>
<tr>
<td>60 °C</td>
<td>50.68</td>
<td>34.85</td>
<td>31</td>
</tr>
<tr>
<td>95 °C</td>
<td>50.41</td>
<td>20.59</td>
<td>59</td>
</tr>
<tr>
<td>135 °C</td>
<td>51.01</td>
<td>11.72</td>
<td>77</td>
</tr>
</tbody>
</table>

MORPHOLOGICAL ANALYSES

In order to gain improved knowledge about the deformation behaviour, micro-sections of the EPP specimens formerly tested in compression were prepared. Specimens deformed at 23 °C...
and 135 °C, respectively, are depicted in Fig. 2 (the view is perpendicular to the testing direction). In some areas of the 135 °C specimen the pores seem to be completely fused and to form a compact material again. The 23 °C specimen on the other hand does not show any preferred direction or noticeable defects.

As the foam micro structure is expected to have significant impact on the mechanical behaviour further morphological analyses were necessary to assess the geometrical properties in more detail. Computer tomography (CT) scans were performed on cubic EPP specimens with an edge length of 8 mm. For post-processing the data VGSTUDIO MAX 3.0 from Volume Graphics GmbH was used, see figure 3.
The detected pores were evaluated with Foam Structure Analysis module according to the key characteristics: size, wall thickness and compactness, being defined as the ratio between the cell volume and the volume of the circumscribed sphere. Average values of different specimens are shown in Table 2. As expected it can be seen that the cell size is decreasing with rising test temperature. A similar effect can be observed for the compactness, while the average wall thickness does not show any particular tendency. Hence, the deformation phenomena correspond to a folding or buckling mechanism of the foam micro structure.

Table 2 - Results of CT post-processing analysis of compression specimens

<table>
<thead>
<tr>
<th>Test temperature /°C</th>
<th>Average cell size after testing /mm³</th>
<th>Compactness after testing</th>
<th>Average wall thickness after testing /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not tested</td>
<td>0.0033</td>
<td>0.270</td>
<td>0.027</td>
</tr>
<tr>
<td>23 °C</td>
<td>0.0026</td>
<td>0.253</td>
<td>0.029</td>
</tr>
<tr>
<td>60 °C</td>
<td>0.0025</td>
<td>0.236</td>
<td>0.027</td>
</tr>
<tr>
<td>95 °C</td>
<td>0.0024</td>
<td>0.222</td>
<td>0.028</td>
</tr>
<tr>
<td>135 °C</td>
<td>0.0014</td>
<td>0.208</td>
<td>0.032</td>
</tr>
</tbody>
</table>

NUMERICAL MODELLING OF MICRO FOAM STRUCTURE

In order to reproduce the mechanical behaviour of the EPP material a representative volume element (RVE) was modelled according to the previously described CT data using the software DIGIMAT 2016.1. Required material input information is the density, the wall thickness and the particle size. As a first approximation the pores were modelled as icosahedrons being the basic geometry. The dimensions of the representative volume element were 1x1x1 mm³. Consequently, the chosen cell size is somewhat larger than originally measured; Fig. 4 (left) which will be adjusted in further investigations. The closed cell material was modelled by defining the coating material as polypropylene having elasto-plastic properties. The pores and the inter-bead gaps were defined as air and excluded from mesh generation with 2-D shell elements (type: S3 and S4).

Fig. 4 - numerical testing of a RVE - left: deformation during virtual compression; right: stress-strain diagram, comparison between experiment and FEM
Using the 2-D elements, it is possible to vary the wall thickness of the cell walls. By this the different foam densities can be investigated numerically using only one RVE. The faces in contact with the foam were defined as rigid bodies and a friction coefficient of 0.1. For evaluation the reaction force of a master node being situated in the upper surface was used. Compared to the test data, the described approach allows a realistic replication of the complex compression deformation behaviour, see Fig. 4 (right).

For the numerical structure analysis of macroscopic components, the material properties obtained experimentally were used for the ABAQUS 2017 material model LOW DENSITY FOAM. The modelling effort could be significantly reduced, since the modelling of the complex inner material structure can be omitted. In order to validate the material model the real compression test was analysed numerically using continuum elements (type: C3D8I), see Fig. 5 (left). The virtual test was conducted without any contact conditions and with deformation control. A master node was connected kinematically to an additional node and used for reaction force evaluation. The comparison of experimental and numerical results shows that qualitative and quantitative agreement can be achieved, Fig. 5 (right).

RESULTS AND CONCLUSIONS

Bead foam materials like EPP exhibit extraordinary properties, like an extreme low density and high flexibility in processing. These are to date not fully exploited for structural applications. In combination with other materials and processes, e.g. injection moulding, bead foams can potentially be used for novel high performance lightweight solutions. In order to realise this, basic knowledge about the mechanical properties is required. The work presented in this paper aims to develop a modelling methodology which efficiently predicts the deformation behaviour of EPP foam for different kinds of mechanical loading. After performing basic material tests in tension and compression mode, morphological analyses of the specimens were conducted. The material micro structure, defined by pore size, cellular structure and cell wall thickness was used for setting up a RVE. This micro model was employed to analyse the compression deformation behaviour of the foam. Subsequently the macroscopic compression test was reproduced with continuum elements using a suitable material model. It was shown that the complex behaviour can be correctly simulated without considering the complex material structure.

In sum the results show that an efficient modelling of the complex foam behaviour is possible. Future work will focus on the influence of the statistical pore size distribution, strain rates and
test temperature on the deformation behaviour. For this virtual testing will play a major role in order to reduce the experimental effort.

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