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# Past and present developments in polymer bead foams and bead foaming technology

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ABSTRACT

Polymer bead foaming technology has expanded the market for plastic foams by broadening their applications because of the breakthrough in the production of low-density foamed components with complex geometrical structure. This review presents the recent advances in the processing, sintering behaviour and properties of bead foam products, which possess unique advantages such as excellent impact resistance, energy absorption, insulation, heat resistance, and flotation. The key features such as the mechanical properties of the commercially available bead foams, namely expanded polystyrene (EPS) and expanded polypropylene (EPP), are presented. Furthermore, recent developments of new types of bead foams based on biopolymer such as expanded polylactide acid (EPLA) and engineering thermoplastics such as expanded thermoplastic polyurethane (ETPU) and expanded poly(butylene terephthalate) (EPBT) are discussed.

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## 1. Introduction

The parts manufactured from polymer bead foams consist of numerous foamed particles, which are welded with each other into three dimensionally shaped products with densities in the range of 15–120 g/l. Generally, they show similar properties as extruded foams of the same density range with regards to the mechanical properties (as high energy adsorption at impact [1]), low thermal conductivity and acoustical insulation [2]. Compared to extruded foams, their main advantage is that extremely lightweight parts with complex geometries and a high dimensional accuracy can be produced [3]. In fact, bead foams are the only foams that combine a relatively free choice of shape with a very low density below 2% of the unfoamed polymer. Therefore, they are not only used in packaging i.e. for electronic devices but also for insulation and furniture [4]. Recently, bead foams have received a lot of attention in the automotive industry due to their unique combination of low density and free shapeability making them interesting candidates for parts, which have to withstand comparatively small stresses only, e.g. in the interior of the automobile like sun visors [5]. Furthermore, bead foams are also gaining popularity for structural parts in automotive industry, such as crash absorbers in bumpers, due to their high specific energy absorption at impact [6]. The driving force for the growing use of bead foams is weight-reduction, which correlates directly to saving fuel and material.

Currently, bead foams made of three base-polymers are established in the market as expanded/expandable beads, namely expandable polystyrene (EPS), expanded polyethylene (EPE) and expanded polypropylene (EPP) as well as blend-systems.

EPS is the oldest bead foam product, which was invented 1949. In 2011, the worldwide demand of EPS has grown to 5.8 million tons a year [7]. In the 1970s, EPE was released into the market, followed by EPP in the early 1980s [8].

Since not every polymer can fulfil the requirements for bead foaming like the ability for welding (also referred to as sintering), the focus of scientific interest went in the direction of modification of these less appropriate materials with the aim to make more and more polymers suitable for bead foaming and thereby widening the area of possible applications. For example, the development of bead foams made of bio-based polymers like PLA is a major field of development. Also an improvement in mechanical properties and especially an enhanced thermal stability of beads foams is desired, which is a critical requirement for the application in the motor compartment of cars.

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To achieve the goal of using bead foams for the motor compartment, the development of high-temperature steam-chest moulding for bead foams made of technical thermoplastics is crucial. Another trend goes towards more energy-efficient processing of the beads by optimisation of the steam-chest moulding process.

This article will focus mainly on the unique properties and processing of EPS and EPP, but also present the efforts made with different, alternative materials and give an overview of future prospects of bead foaming technology. Besides the above-mentioned commodity thermoplastic polymers (EPS and EPP), there is a huge interest on the processing of bead foams and products based on advanced polymers and biopolymers, which is also presented in this review literature.

## 2. Basics of foaming

In order to understand the morphological development of bead foams and their processing techniques, knowledge of the general background of foaming is necessary. This is explained in many publications [9,10], so the subject will be explained only briefly. The foaming process can be divided into four steps:

1. Creation of a homogeneous polymer/gas mixture
2. Nucleation of cells
3. Cell growth
4. Cell stabilisation

The first step, the homogenisation of the polymer with the blowing agent, is mainly determined by mass-transfer process. During this step, the blowing agent has to diffuse into the melt or solid bead and remain in the polymer–gas solution. The well-known second Fick's law can describe the temporal and spacial dependency of this transport. Besides temperature, diffusion also depends on pressure and gas-concentration in the polymer [11]. So, it is time and space dependent. For diffusion, the free volume of the polymer is important [12] as with increasing free volume, diffusivity is increased. In contrast to diffusion, the solubility of the gas in the polymer is highly dependent on pressure. Henry's law describes the pressure dependent concentration of a dissolved blowing agent in a polymeric melt. The temperature dependency of solubility is exponential in a negative manner: with higher temperature solubility is reduced. Furthermore, high shear-rates reduce the solubility of the blowing agent in the polymer melt due the decrease in the free volume caused by the aligning polymer chains [13].

The second step of the foaming process, nucleation of cells in the polymer, is the creation of nuclei, which act as centre for cell growth after a pressure drop for example in an under-water pelletizing system or autoclave. A sudden pressure drop causes a reduction of solubility (the melt becomes super-saturated) creating a driving force to reduce the gas-content of the polymer–gas-mixture. Alternatively, a sudden drop in solubility can be achieved by a temperature jump.

Nucleation can be either homogeneous or heterogeneous. The latter mechanism dominates the nucleation process, if a solid second phase exists (e.g. a particle or surface of the processing equipment), gas will diffuse to micro-voids on this surface and form a bubble.

According to nucleation theory, nucleation starts at clusters of gas-molecules inside the melt [14]. Those voids act as nucleating sites. The homogeneous nucleation rate is heavily dependent on the pressure drop. A high pressure drop leads to a high nucleation rate. From the material's side it is dependent on the surface tension between polymer-melt and gas. Another nucleation process is stress, both in elongation and shear [15,16]. Extensional stress around growing cells is responsible for pressure fluctuations, which reduces solubility and thereby increases super-saturation [17]. Shear introduces micro-voids and causes an elongation of already existing bubbles. Those mechanisms lead to an increased nucleation rate and higher cell densities.

After nucleation, cell growth takes place. During cell growth the stored gas diffuses out of the melt to the nucleation sites. The driving force behind this process is super-saturation caused by the pressure drop or temperature increase. So, typical quantities determining this process are temperature, which is influencing diffusion, pressure drop rate and the actual pressure [17]. Another important factor for foaming is the visco-elastic properties of the melt, since the melt is subjected to elongational deformation during bubble growth [18].

To obtain foams with a favourable cell size, cell size distribution and thereby good properties (e.g. mechanical behaviour or thermal transport properties), the morphology must be stabilised and cell growth has to cease, otherwise cell coalescence or coarsening (large cells grow at expense of small ones) takes place and deteriorates the final foam morphology. The main factor for stabilisation is a reduction of the polymer's temperature due to which the melt's viscosity increases. As the blowing agent is diffusing out of the polymer, the viscosity increases even further, because dissolved gas in a polymer acts as a plasticising agent [19]. At large elongations strain-hardening is important. It raises elongational viscosity above the linear value due to the stretching of chains [20]. Due to strain hardening thin sections of a cell wall are more difficult to extend than thicker ones (thinner sections are subjected to higher strains and thereby a higher degree of stretching of chains). So the thick sections are extended preferentially, the so called self-healing effect [21]. Strain-hardening can be induced by long chain branching [22–25], the introduction of high-aspect-ratio nano-additives [26–29] or by blends having a fibril morphology [30]. Effects countering cell stabilisation are the creation of crevices by large and fast deformations and rupture of cell walls [10].

## 3. Production of foamed beads

In principle, two approaches for the production of foamed bead exist: a) the creation of expandable beads, which must be pre-expanded and b) the production of already expanded beads. The first approach can be applied for amorphous thermoplastic resins only, like polystyrene, since only they retain a blowing agent in solid state (temperature below $T_G$). Expandable beads are polymer granules in which a blowing agent (e.g. pentane) is trapped and the impregnated polymer granules are expanded in a separate step (i.e. pre-expansion step) before the actual welding-process (i.e. sintering). Efficient transportation of the unfoamed blowing agent impregnated polymer material and control of density by the part-manufacturer are main advantages compared to expanded beads [3].

Expanded beads are produced from semi-crystalline thermoplastics, since the presence of crystalline domains prevents the storage of a blowing agent inside the solid bead [31]. An overview of the possible methods for producing polymer bead foams is given in Fig. 1.

The most often used method to produce high quantities of expandable beads of polystyrene is the suspension-polymerisation with a blowing agent [32]. This process consists of two steps, namely the polymerisation where the granules are formed and the addition of pentane and/or other blowing agents, which diffuse into the granules [33]. After this process the beads are sieved to get several fractions with a narrow size distribution and coated with antistatic agents to prevent agglomeration [32]. Problems arise

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