Bead fusion in polystyrene foams

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A quantitative technique has been developed to measure the extent of fusion between expanded beads in molded polystyrene foams. Experiments were conducted with ASTM D638 tensile test specimens that were molded under conditions to produce various levels of bead fusion in the foam. The tensile properties of the foam for various levels of bead fusion were measured according to ASTM D638 standards. The fracture surfaces of the tensile specimens were analysed by quantitative image analysis techniques to measure the degree of bead fusion in the sample. This technique was then used on a commercial pattern to map the variations in bead fusion at numerous locations in the molded part. The results indicate that there is a good correlation between the tensile properties and the measured bead fusion. Significant variations in bead fusion may be present in a single molded part. © *2003 Kluwer Academic Publishers*

1. Introduction

Foamed polystyrene is used in many applications including packaging, thermal insulation, beverage containers and electronic devices [1]. Recently, molded polystyrene foam parts have also been used as precursors to produce metallic castings [2]. In all these applications, the physical and mechanical properties of the foam are influenced by many factors such as the raw material, molding conditions and the extent of post-processing operations [3]. The foaming starts with the expansion of polystyrene granules, typically about 500 to 800 μm in diameter, into which about 6 to 7% *n*-pentane has been diffused. The granules expand significantly when heated above the glass transition temperature of the polymer. The ratio between the bulk volume of the expanded beads to the bulk volume of the unexpanded granules is between 5 to 10. The expanded beads may be aged to allow some diffusion of air and to produce the right conditions for molding. The expanded beads are then injected into the mold, where they are again heated above the glass transition temperature. The remaining blowing agent expands the beads further and the counterpressure created leads to bead fusion, thus forming a foamed pattern in the shape of the mold cavity. The extent of bead fusion depends on several factors including pentane content and mold temperature. The structure of polystyrene foams can be visualized at two levels. At the macroscopic level, the foamed pattern consists of closed beads, typically with a diameter on the order of 2 to 4 mm (Fig. 1). A cellular structure is present within each bead as shown in Fig. 2. The overall mechanical properties of the foamed part depend strongly on the extent of fusion between the beads. The purpose of this contribution is to develop a quantitative technique to measure the bead fusion in commercial foams. This technique is then used to eval-uate the variations in bead fusion at different locations in a single molded part.

2. Experimental procedure

Two types of patterns were used in this study as shown in Fig. 3. The first consisted of ASTM D638 tensile specimens that were molded with T beads to achieve a nominal density of 22 kg/m^3. The second pattern was a fairly complex commercial part that consisted of ribs, bosses, thick and thin sections as shown in Fig. 4. The molding conditions, molding pressure (0.07 to 0.25 MPa) and time (1 to 13 s), were varied to produce samples with various levels of bead fusion in the foam. Test specimens were produced for densities ranging from 19 kg/m^3 to 34 kg/m^3. Samples were also obtained at two different weight average molecular weights: 152, 169 g/mol and 304, 167 g/mol. The tensile properties were measured with an IMS mechanical testing machine according to ASTM D638 Tensile Test Standards. The testing was conducted at a strain rate of 5.08 mm/min with a 900 N Load cell. At least 10 samples were tested for each condition. The fracture surfaces of the tensile specimens were used to determine the extent of bead fusion in the foamed pattern. The fracture surface from each sample was observed in an AMRAY 1610 scanning electron microscope. Photomicrographs were digitally collected at several random locations on each fracture surface. Two basic types of fracture were identified as shown in Fig. 5. In the first case, beads are not fused well and fracture occurred between the beads, termed *Interbead* fracture (Fig. 5a). In other specimens with better bead fusion, the fracture occurs primarily through the beads, termed *transbead* fracture (Fig. 5b). Image analysis was conducted to determine the projected two-dimensional area fraction of
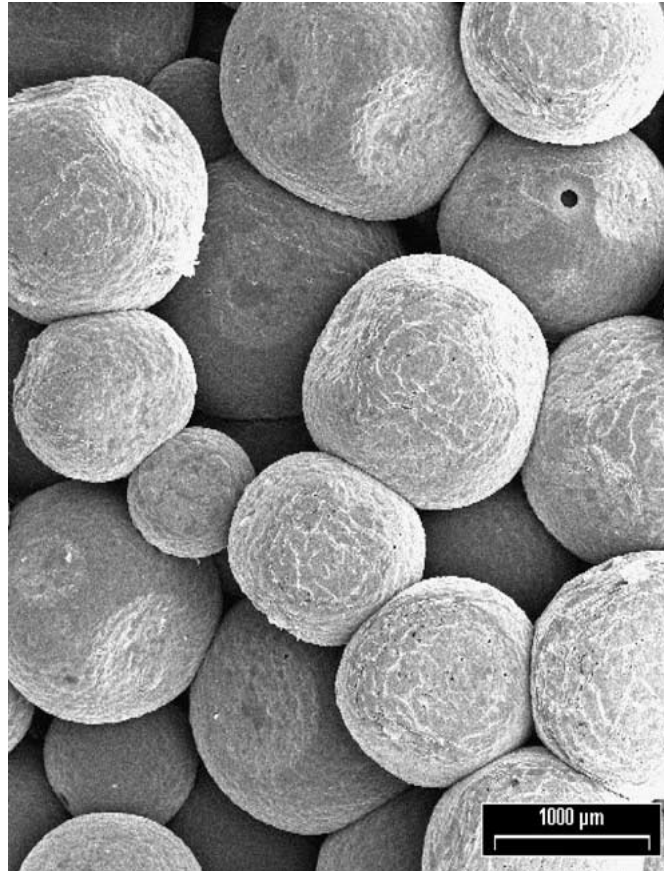
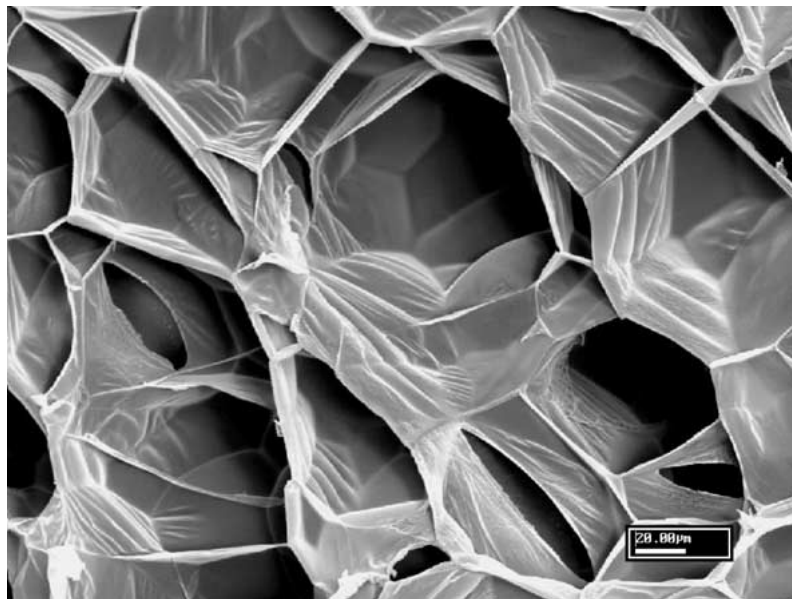*Figure 1* Photograph showing the bead structure in expanded polystyrene.

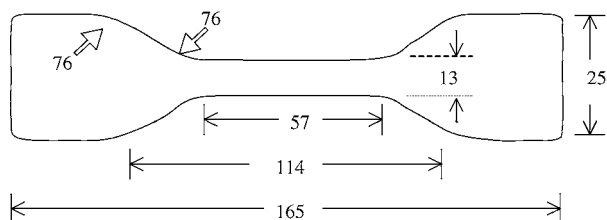*Figure 2* Photograph of the cellular structure within a single expanded bead.

Figure 3 Schematic of ASTM D638 tensile test specimen (All dimensions in mm).

transbead fracture (i.e. fracture across the beads) in each photomicrograph [4]. The images were analyzed at a magnification of 20× to cover the entire fracture surface and thus obtain an average area fraction of *transbead* fracture. The fraction of *transbead* fracture area in all specimens molded under identical conditions was averaged to determine an overall mean value for that condition. This average value will be referred to as the degree of fusion for a given molding condition. The commercial pattern shown in Fig. 4 was fractured at
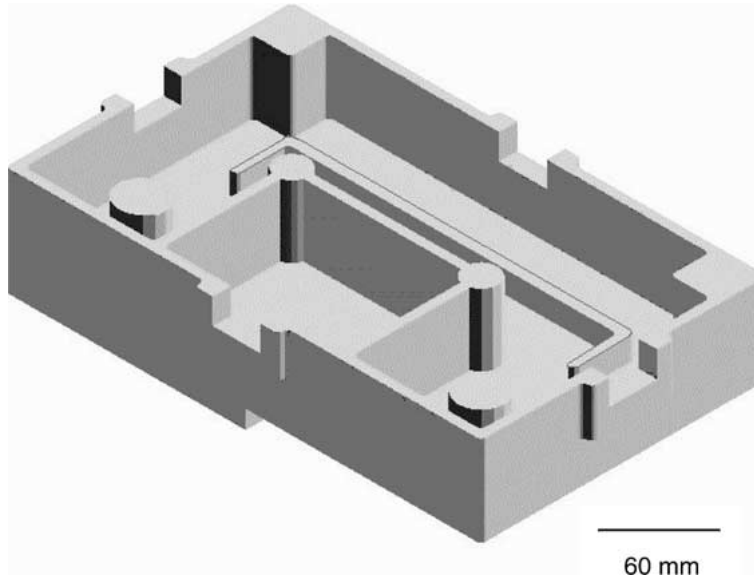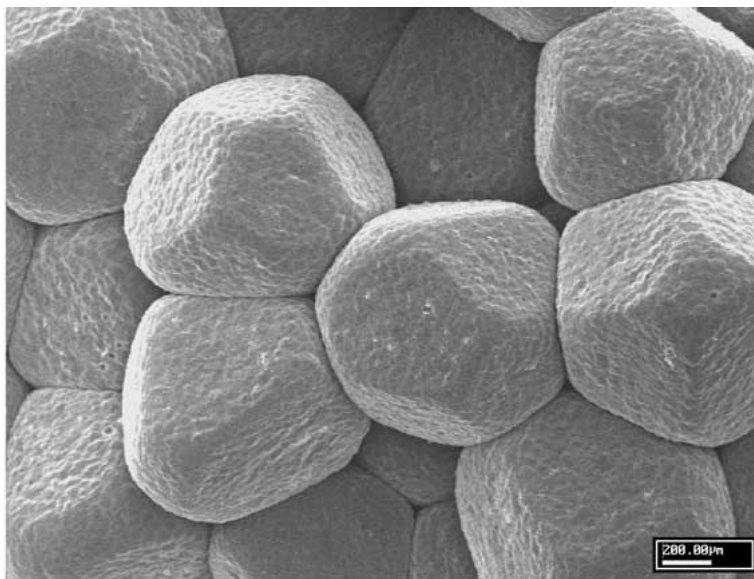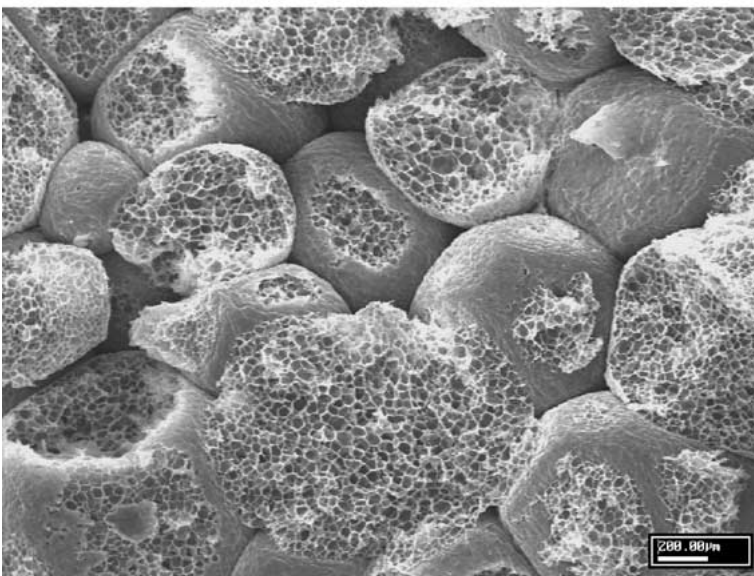
60 mm

Figure 4 Photographs of the fracture surface in tensile specimens. The fracture occurs between the beads, interbead fracture (a) or through the beads exposing the cellular structure within the beads, transbead fracture (b).

200.00μm

(a)

200.00μm

(b)

Figure 5 Schematic of the commercial test pattern used to determine the degree of fusion at various locations.
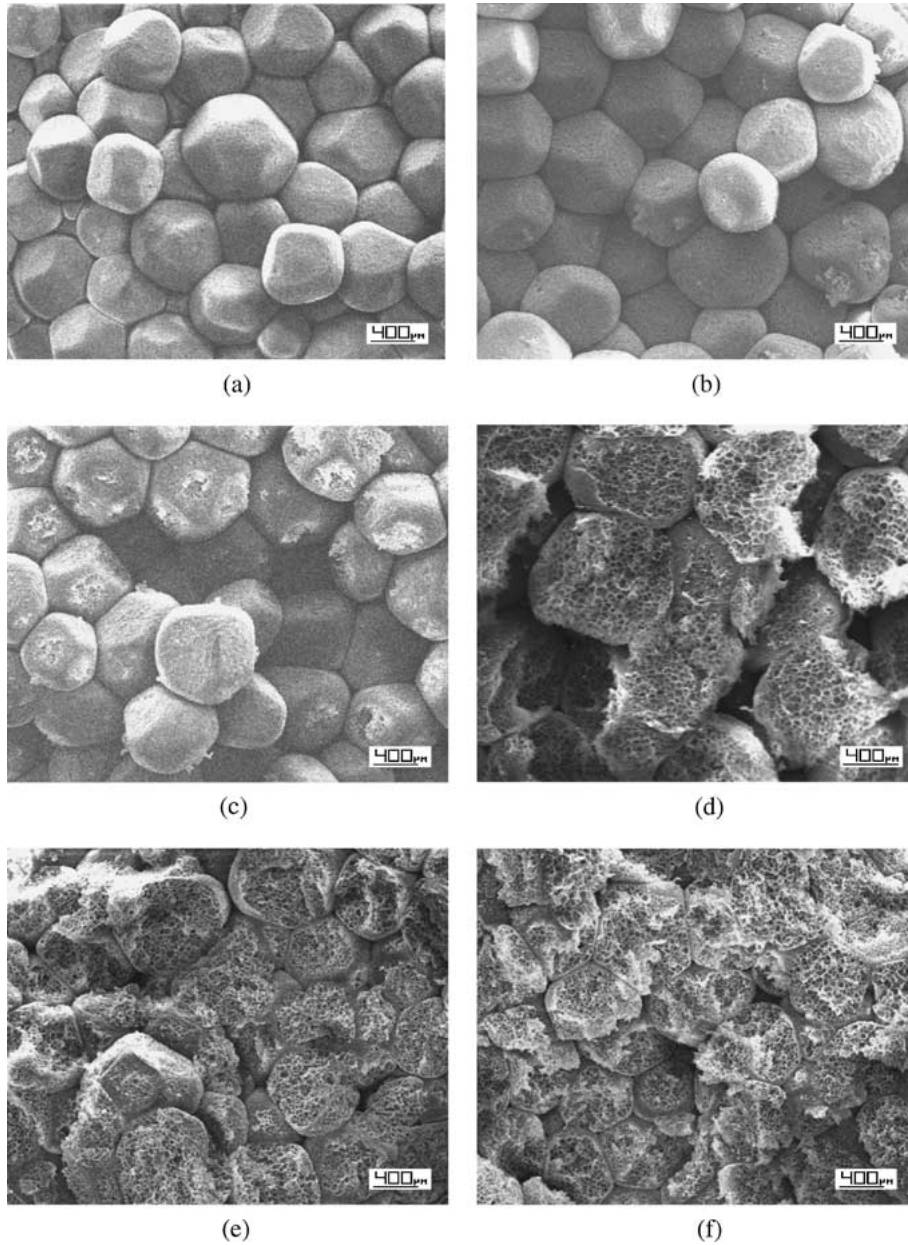
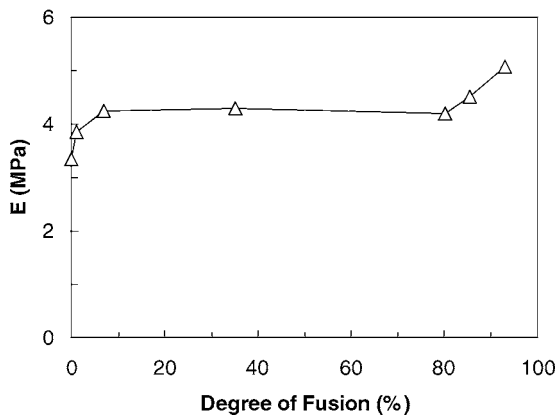*Figure 6* Photomicrographs of the fracture surface for samples with increasing levels of bead fusion.

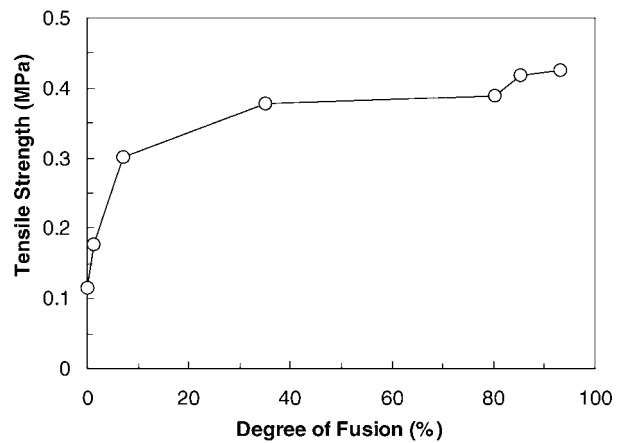*Figure 7* Variation of the elastic modulus with the measured degree of fusion.

Figure 8 Variation of the tensile strength with the measured degree of fusion.

many locations to assess the variations in bead fusion at different locations in a single pattern. The pattern was initially cut with a hot wire cutter and different segments were subjected to a simple shearing action to produce the fracture. The fracture surface was used to measure the local bead fusion according to the technique described above. Experiments were conducted with patterns that were molded at various times during the production cycle.
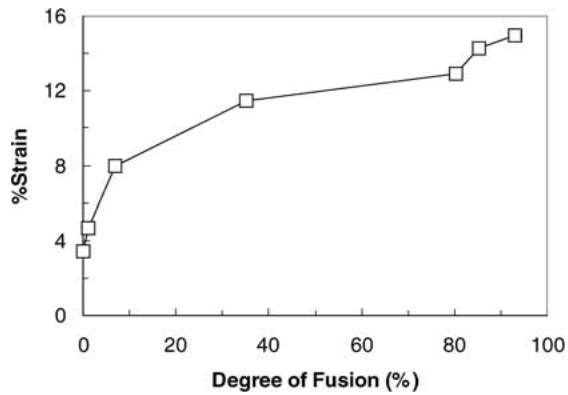
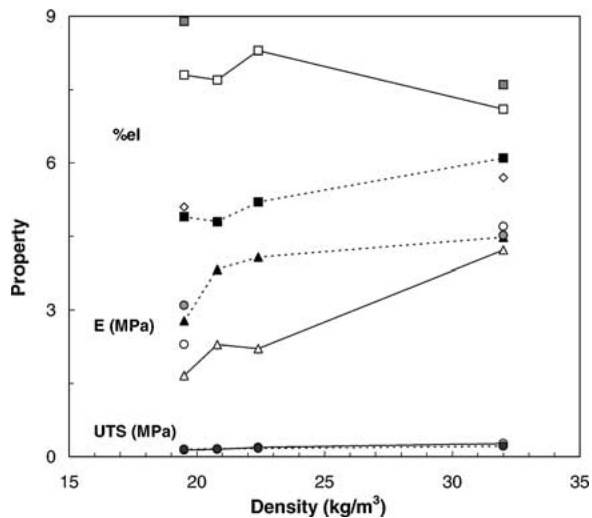*Figure 9* Variation of the breaking strain with the measured degree of fusion.

Figure 10 Variation of elastic modulus (*E*), %elongation (%el) and tensile strength (UTS) with density of foam. Solid lines correspond to polymers with a weight average molecular weight (MW) of 152, 169 g/mol and a degree of fusion (DOF) of 35%. Dotted lines are for polymers with a MW of 304, 167 g/mol and a DOF of 35%. In addition, data are also shown for samples with a DOF of 80%: *E* for MW = 304,167 g/mol, DOF = 85%, *E* for MW = 152, 169 g/mol, DOF = 85%, %el for MW = 304, 167 g/mol, DOF = 85%, %el for MW = 152, 169 g/mol, DOF = 85%.

3. Results and discussion

Two basic shapes of the beads were observed in all the specimens: a) nearly spherical (Fig. 1) and b) polyhedral (Fig. 5). During molding, the spherical beads are expanded in the constricted spaces of the mold cavity. As the beads expand, they may impinge on one another and thereby develop a polyhedral shape. Depending on the level of local impingement conditions, the beads may retain their nearly spherical shape or develop into regular polyhedra. The typical fracture surfaces in tensile samples molded under different conditions are shown in Fig. 6. The extent of *transbead* fracture corresponds to the anticipated bead fusion based on molding conditions. The measured degree of fusion in the samples varied from 0% to nearly 95%. In general, the bead fusion increased with molding pressure and time [4, 5]. The data indicate that there is a direct correlation between the tensile properties and the degree of fusion as shown in Figs 7 to 9. The tensile properties increase with the degree of fusion up to about 40% and then seem to reach a peak value. This result is in agreement with previous measurements [6]. The degree of fusion seems to have the greatest effect on the breaking strain. It has also been shown previously that increased bead fusion in the foam can improve compressive properties and fracture toughness [7, 8].

The basic mechanism by which the bead fusion improves mechanical properties in a cellular plastic can be explained as follows. When two thermoplastics above the glass transition temperature are brought together, viscoelastic deformation of the surface asperities causes local contact areas to grow in size with increasing contact time [7]. The contact being established, the molecular chains are now free to move across the interface by diffusion. This self diffusion enhances the number of chain entanglements and therefore improves bead fusion. The increase in the number of molecular links can improve load transfer from bead to bead and thereby improve strength and toughness [9]. In many applications of polystyrene foams, it is necessary to quantify
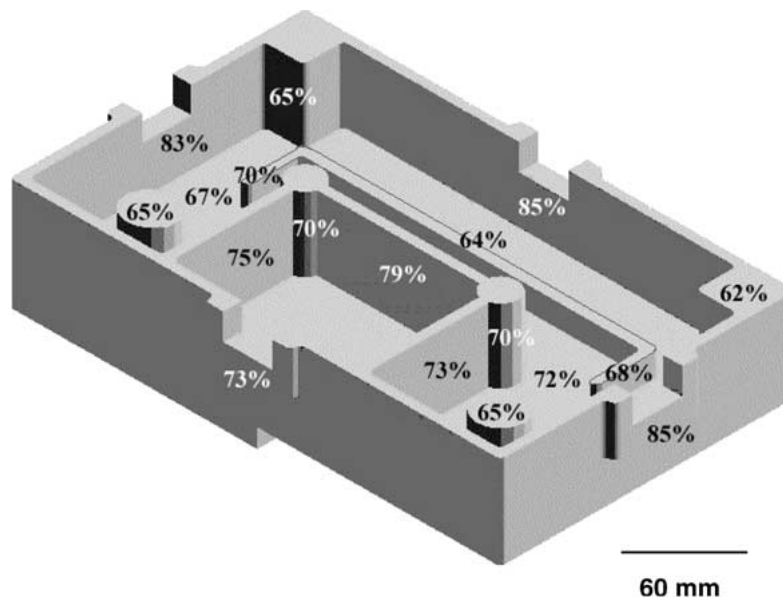

Figure 11 Variation of the measured bead fusion in a single pattern at various locations. The pattern was molded under conditions normally used to produce a high level of fusion.
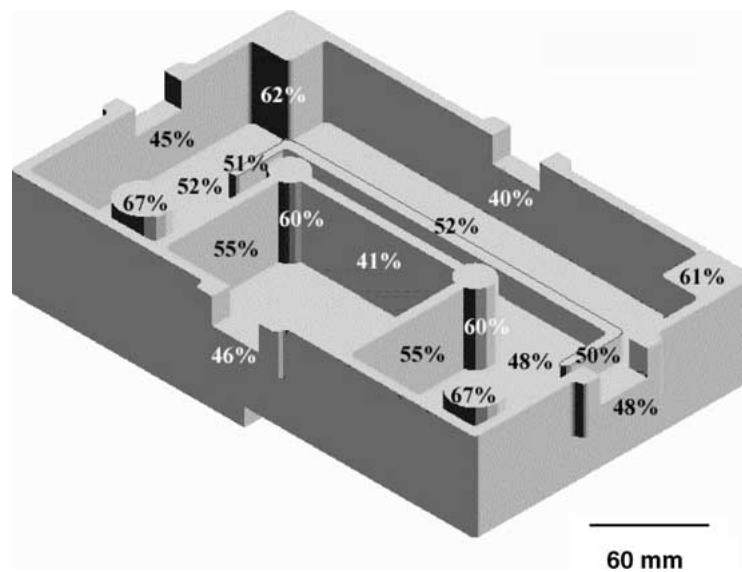
Figure 12 Variation of the measured bead fusion in a single pattern at various locations. The pattern was molded under conditions normally used to produce a moderate level of fusion.

the extent of bead fusion for overall quality control in the process. Bead fusion can also affect the thermal and insulation properties of the foam [10]. The results presented above indicate that the tensile properties can be used as good indicators of the extent of bead fusion.

Several factors associated with the polymer and the molding conditions may affect the properties of the foam. These include molding time, molding pressure, foam density, molecular characteristics and glass transition temperature. Clearly, as the density increases, the modulus, strength and ductility in the foam increase as shown in Fig. 10. Increasing the molecular weight improves the elastic modulus and lowers the %elongation, because of the additional resistance to chain slippage. The density and molecular characteristics may also affect the bead fusion, and hence the mechanical properties, as shown in Fig. 10. As the density increases, the effective local contact area per molecule at the junction of two beads decreases [9]. Consequently, a lower degree of fusion may be obtained at high densities. Similarly, as the molecular weight increases, diffusion at the junction of beads becomes more difficult. Thus, as the molecular weight increases, a lower degree of fusion may be obtained for the same molding conditions. This behavior is generally reflected in the data shown in Fig. 10.

The bead fusion can vary significantly within a single pattern as shown in Figs 11 and 12. In thick sections, it was observed that the degree of fusion in the interior was generally less than on the surface. Further, the last areas to fill during molding generally had a lower fusion than the bulk of the pattern. The different levels of fusion may contribute to variations in mechanical and insulation properties.

4. Conclusions

The fusion between expanded beads in the foam is an important parameter that may have a significant effect on mechanical, thermal and diffusional properties. A microscopic technique has been developed to quantify the extent of bead fusion in polystyrene foams. Fracture occurs between the beads at low levels of fusion.

As the level of fusion increases, the fracture also occurs across the beads (*trans* bead fracture). The area fraction of this *trans* bead fracture can be used as a microstructural parameter to quantify the extent of bead fusion. The elastic modulus, strength and ductility generally improve with increased bead fusion. The degree of fusion seems to have the greatest effect on the breaking strain. The density of the foam and molecular characteristics of the polymer may also influence the level of bead fusion. The extent of bead fusion is inversely proportional to the foam density and polymer molecular weight. In complex patterns, the extent of fusion may vary significantly depending on location. In thick sections, the degree of fusion in the interior may be less than on the surface. The last areas to fill during molding may have a lower fusion than the bulk of the pattern.

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