

# Influence of EPS bead fusion on pattern degradation and casting formation in the lost foam process

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The effects of bead fusion in the pattern on foam degradation and on casting formation have been studied. Injection molded ASTM D638 tensile specimens have been used to develop a microscopic technique to quantify the extent of bead fusion in the pattern. The tensile properties of the polymer have been correlated with the measured degree of bead fusion. A variety of experiments have been conducted to highlight the effects of fusion on foam degradation. The flow behavior of a molten aluminum alloy has been studied in patterns with various levels of fusion. The results indicate that the degree of fusion has a significant effect on bead collapse and viscous residue formation in the polymer. The mold fill times generally increase with increasing bead fusion in the pattern. The temperature at the metal front drops more rapidly as the bead fusion increases.

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## 1. Introduction

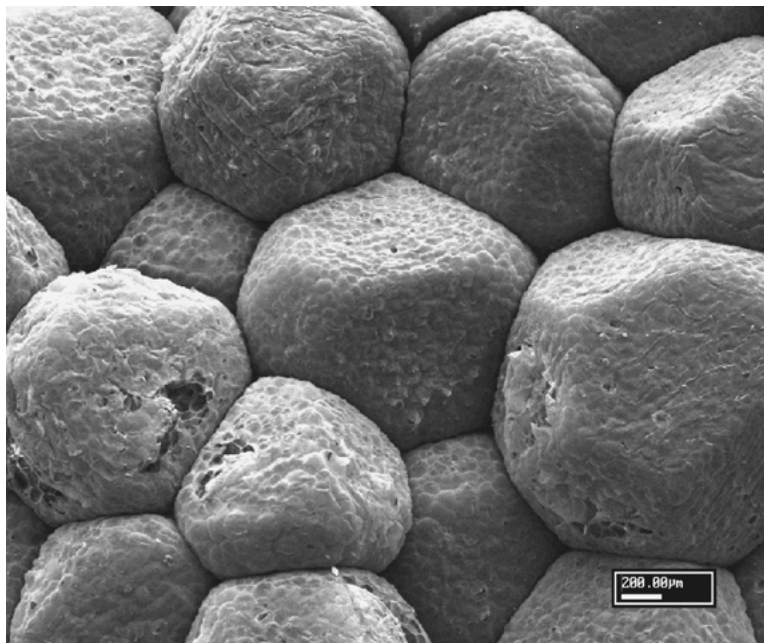
Injection molded patterns with expanded polystyrene (EPS) beads are used for the production of metallic castings in the lost foam process. During the production of the pattern, polystyrene granules (500 to 800  $\mu\text{m}$  in diameter) containing about 6 to 7% *n*-pentane, are expanded by heating above the glass transition temperature ( $T_g$ ) 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 develop the desired 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 resulting structure in the foam 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. 1a). A cellular structure is present within each bead as shown in Fig. 1b. The extent of bead fusion depends on several factors including pentane content and molding time, temperature and pressure. Two extreme examples of bead fusion, one indicating poor fusion and the other highlighting good bead fusion are shown in Fig. 2. The overall mechanical properties of the foamed part depend strongly on the extent of fusion between the beads. Bead fusion in the foamed part has a significant effect on the properties of the foam. It has been shown that the tensile [1], compressive [2], fracture [3] and insulation

[4] properties of the foam improve significantly with enhanced bead fusion.

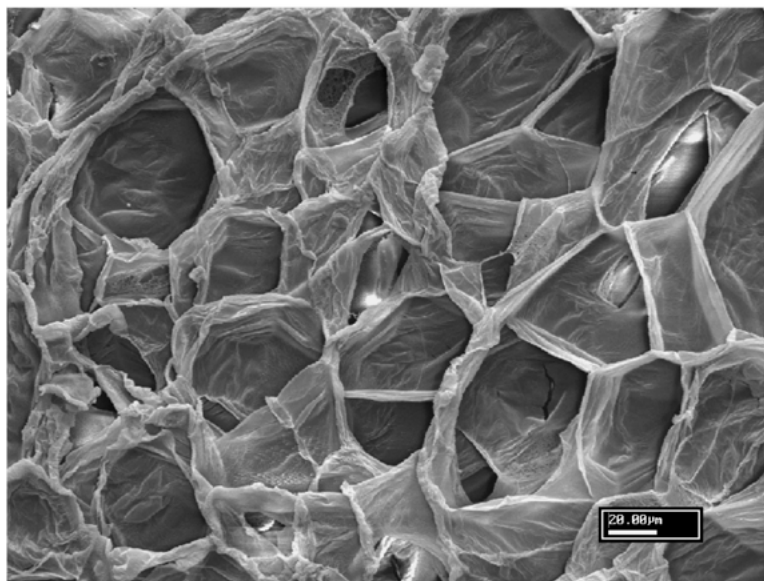
Several factors contributing to fusion between amorphous thermoplastics, that have been brought into contact above  $T_g$ , have been identified in the literature [5]. These include surface contact, surface rearrangement, wetting, self diffusion and randomization. When the surfaces are brought into contact, viscoelastic deformation of the surface asperities, result in the growth of the contact area with increasing time [6]. Thus, the potential barriers associated with irregularities at the interface are gradually eliminated and intimate contact between polymeric chains is established. The chains are then free to move across the interface by diffusion, thereby creating entanglements that may lead to improved load transfer. Hence, depending on the level of bead fusion in the pattern, there may be a clear difference in the physical arrangement of the molecules at the bead interface. This difference may affect the degradation characteristics of the polymer and thereby influence casting formation in the lost foam process. The purpose of this contribution is to study the effects of polymer bead fusion on casting formation with aluminum alloys.

## 2. Experimental procedure

The patterns used to study the flow behavior were prepared with either molded ASTM D638 tensile specimens (Fig. 3) or with strips cut from large molded blocks. The ASTM D638 tensile specimens were molded with T beads to achieve a nominal density of



(a)



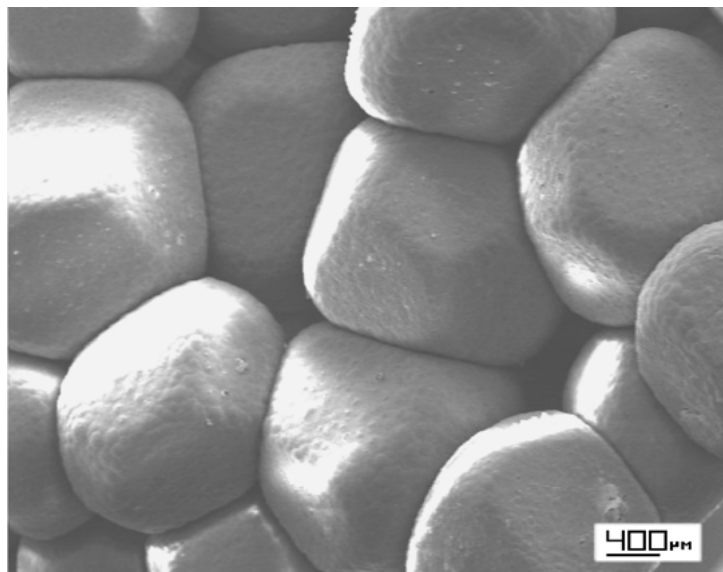
(b)

Figure 1 Typical bead structure in polystyrene foam: (a) closed cell structure of expanded beads and (b) honey-combed cellular structure within a single bead.

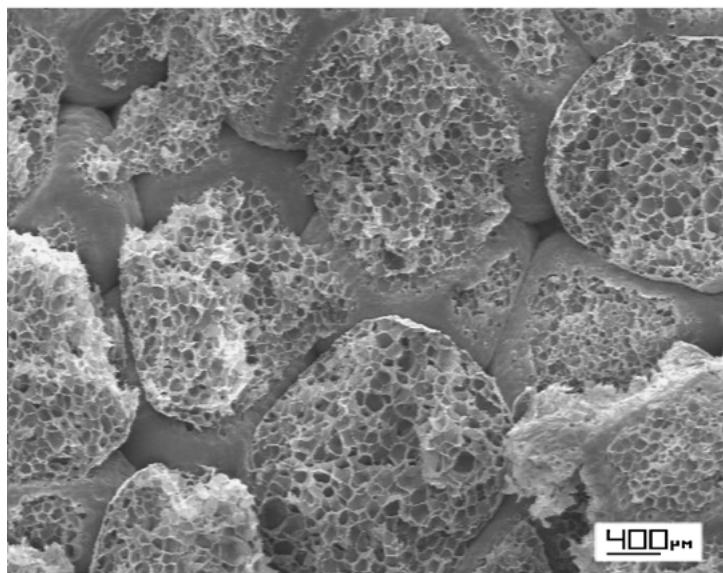
22 kg/m<sup>3</sup>. The molding conditions, molding pressure (0.07 to 0.25 MPa) and time (1 to 13 s), were varied to produce samples with various levels of bead fusion in the foam. Large blocks of polystyrene foam (T beads, density = 20 kg/m<sup>3</sup>, Weight average molecular weight,  $M_w$ , between 270,00 and 300,000 g/mol) with various levels of bead fusion were obtained from commercial suppliers.

The tensile properties in the polymer pattern were measured with an IMS mechanical testing machine according to ASTM D638 Tensile Test Standards [7]. 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. Two basic types of fracture were identified as

shown in Fig. 2. In the first case, beads are not fused well and fracture occurred between the beads, termed *Interbead* fracture (Fig. 2a). In other specimens with better bead fusion, the fracture occurs primarily through the beads, termed *transbead* fracture (Fig. 2b). Image analysis was conducted to determine the projected two-dimensional area fraction of *transbead* fracture (i.e., fracture across the beads) in each photomicrograph [8]. 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. Data were obtained for at least 3 and up to 5 samples produced under identical conditions. 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



(a)



(b)

Figure 2 Fracture surfaces in polystyrene foams highlighting the extent of bead fusion: (a) fracture occurs primarily along the beads (interbead fracture) indicating poor bead fusion and (b) fracture primarily occurs across the beads (transbead fracture) indicating good bead fusion. Depending on the molding conditions, the extent of bead fusion in a real sample may be between the extreme examples shown above. The extent of transbead fracture has been measured by scanning electron microscopy and used as a quantitative measure of the degree of bead fusion [7].

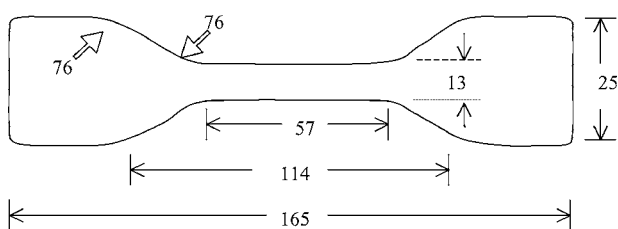


Figure 3 Schematic of the ASTM D638 tensile specimen (all dimensions in mm).

the degree of fusion for a given molding condition. A similar procedure was used to determine the degree of fusion in strips cut from large blocks. The strips were fractured by a simple bending action and the %*transbead* fracture was measured to quantify the degree of bead fusion.

When expanded polystyrene is heated, initially the foam collapses and the resulting polymer undergoes thermal degradation similar to bulk polystyrene [9, 10]. The effects of bead fusion on the initial collapse of beads were studied with the following techniques. Pieces of EPS were sectioned from the tensile bar or the strip and fractured by a simple bending action. The fractured pieces were placed in a preheated oven at the desired temperature for times of up to 30 s. Subsequently, the polymer was removed from the furnace and the extent of bead collapse was examined by scanning electron microscopy. The temperature was increased from 90°C to 250°C, in intervals of 10°C, so as to obtain data over a wide range of temperatures. In other experiments, samples of the polymer were rapidly brought in contact with the liquid aluminum at 750°C and removed. The changes in the bead structure along the

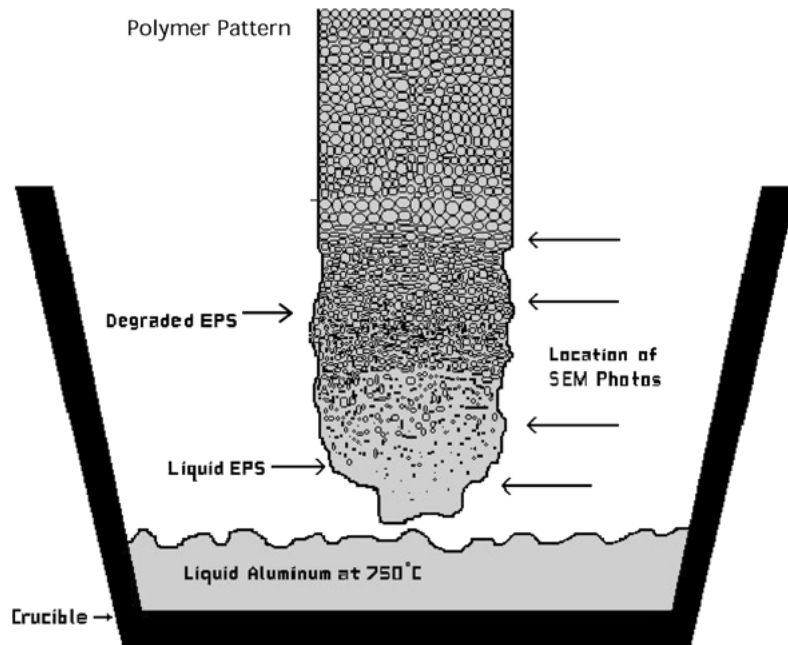


Figure 4 Schematic of the experimental set-up used to study the collapse and degradation of expanded polystyrene. Pieces of the polymer were rapidly brought in contact with the liquid aluminum at 750°C and removed. The change in the bead structure along the length was examined by scanning electron microscopy.

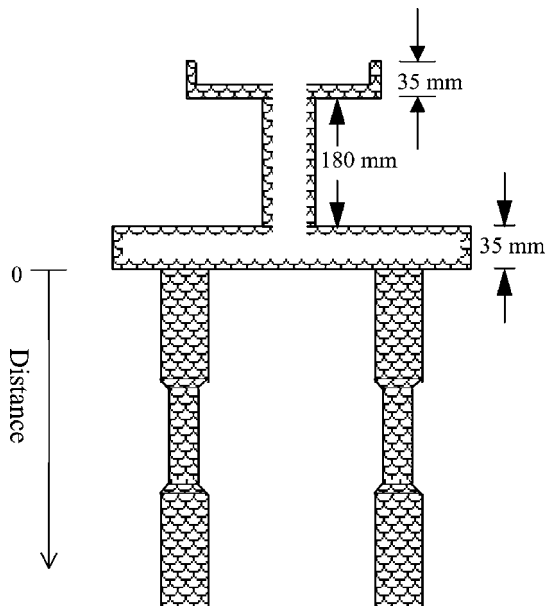


Figure 5 Schematic of the test patterns used to study the flow behavior. Up to 12 thermocouples were placed in each tensile bar along its length. The distance was measured as indicated in the figure.

length of the polymer were examined by scanning electron microscopy (Fig. 4).

The rate of bead collapse was measured by placing a solid piece of aluminum or molten wax at 200°C on a piece of foam that was snugly fit inside a glass tube. The position of the collapsing polymer front was recorded as a function of time [7, 11]. Note that the rates of vaporization of the polymer are negligible below 200°C and hence, the primary mechanism by which a solid or liquid at 200°C can advance into the polymer is through bead collapse [12]. The thermal degradation characteristics of the polymers were also studied by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA).

Castings were produced with the pattern shown in Fig. 5. In the first set of experiments, two tensile bars with varying levels of bead fusion were attached on opposite ends of a runner. In the second pattern, two strips of the desired cross section (typically 12.7 mm × 25.4 mm in cross section and 0.3 m long) that were cut from large blocks with a hot wire cutter,

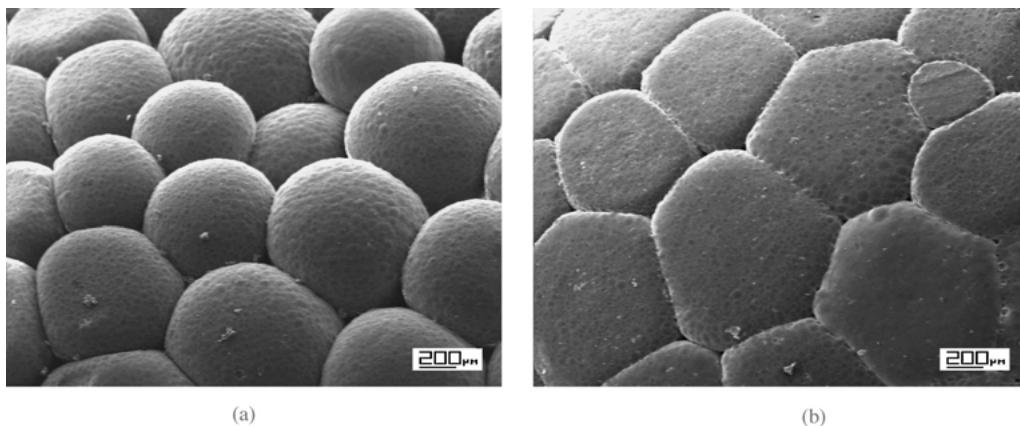


Figure 6 Surface bead structure in polystyrene foams molded to produce varying levels of fusion: (a) low fusion (<2%) and (b) high fusion (>90%).

were attached on opposite ends of the runner, similar to the specimen shown in Fig. 5. The assembled pattern was then coated with a commercial coating slurry so as to obtain a dried coating thickness of 0.2 mm. The coated pattern was instrumented with several chromel-alumel thermocouples and buried in unbonded silica sand (AFS 55). The sand was compacted with a pneumatic compactor at 0.65 MPa for 45 sec. Aluminum alloy A356 at  $765 \pm 5^\circ\text{C}$  was then poured onto the pattern to produce the casting. A data acquisition system was used to record the temperature histories during casting formation.

### 3. Results and discussion

Typical bead structures on the surface of the polymer pattern are shown in Fig. 6. In patterns with low degree of fusion, the beads generally retain their spherical shape and are not packed very efficiently (Fig. 6a). By comparison, in patterns with high levels of fusion, the beads are nearly flat on the surface and are packed together much more efficiently than in the preceding example (Fig. 6b). The extent of *transbead* fracture in

TABLE I Tensile properties of expanded polystyrene as a function of degree of fusion. The tensile properties were obtained from injection molded ASTM D638 test specimens. The degree of fusion was measured as the area fraction of *transbead* fracture in the broken specimen. (*E*: Elastic Modulus, UTS: Ultimate Tensile Strength)

Degree of fusion (%)	<i>E</i> (MPa)	UTS (MPa)	%elongation
0	3.3	0.11	3.4
2	3.8	0.17	4.7
7	4.2	0.30	8.0
35	4.2	0.37	9.1
80	4.2	0.38	12.9
85	4.5	0.41	14.3
93	5.0	0.42	15.0

the fracture surface was between the extreme examples shown in Fig. 2. The tensile strength of molded bars generally improves with the area fraction of *transbead* fracture as shown in Table I. Thus, the area fraction of *transbead* fracture can be used as a quantitative indicator of bead fusion in the foam pattern [8].

When molded patterns are exposed to high temperatures, the nature of bead collapse may depend

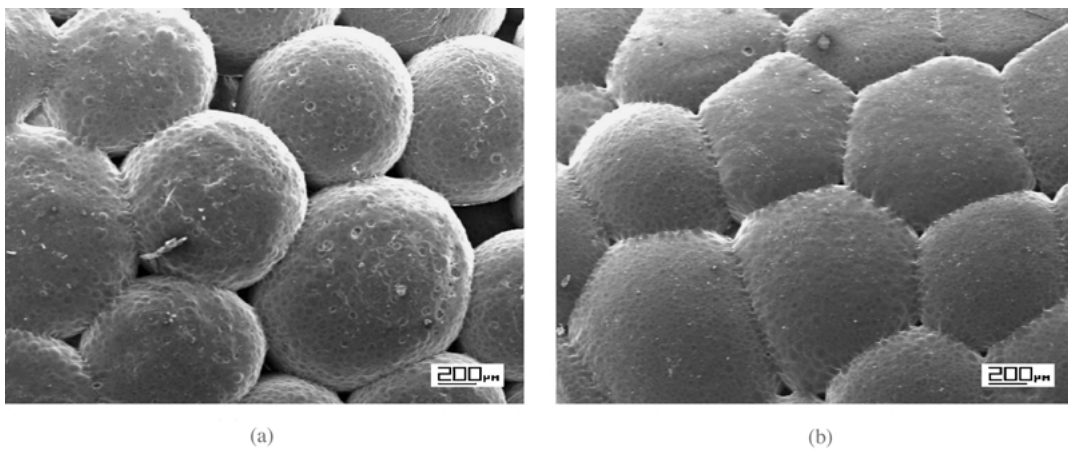


Figure 7 Photographs showing the surface bead structure in polystyrene foams heated to  $110^\circ\text{C}$  for about 2 s: (a) low fusion (<2%) and (b) high fusion (>90%).

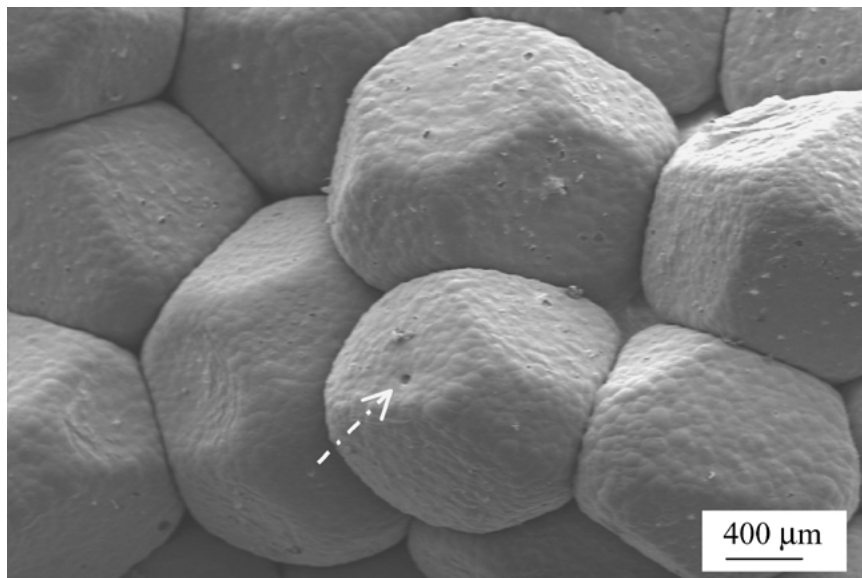
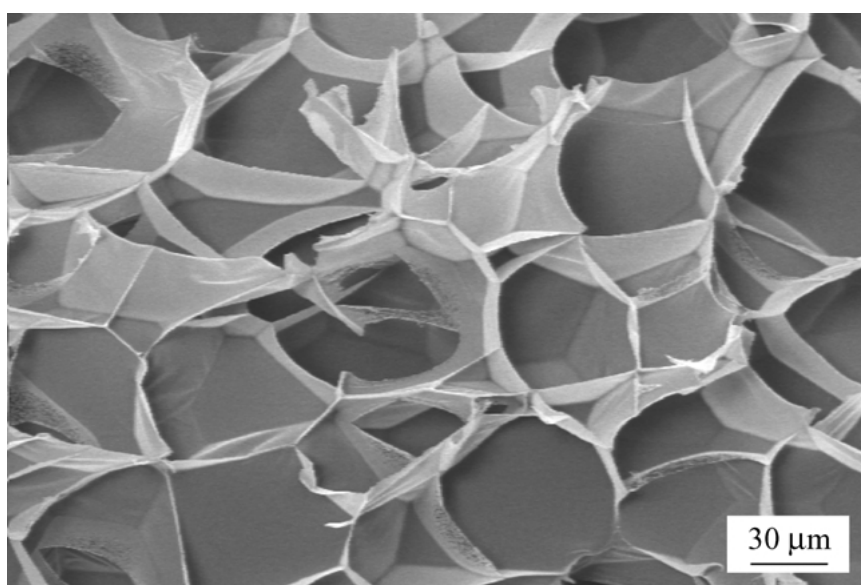


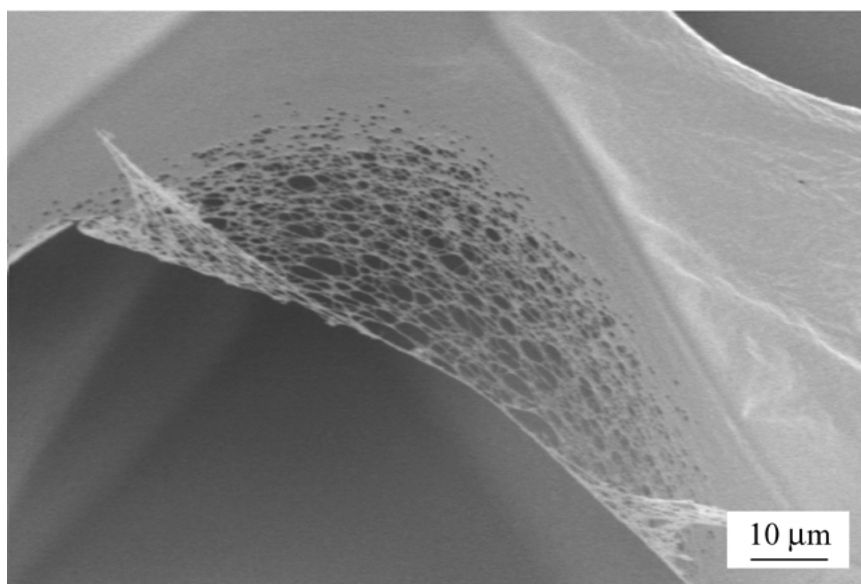
Figure 8 Photograph showing the beginning of collapse of the bead through the formation of dimpled holes at the surface (indicated by arrow).

significantly on the extent of bead fusion. Expanded polystyrene beads begin to collapse as the temperature approaches the glass transition temperature of the polymer (typically around 105°C). Beyond a critical temperature (typically about 160°C), the white beads disappear completely and form a transparent viscous residue [10]. Upon exposure to high temperature ( $T > T_g$ ), the beads may initially expand slightly as any residual pentane within the bead may vaporize (Fig. 7). The collapse then begins on the surface of the bead with the formation of dimpled holes to expose the interior cell structure (Fig. 8). Subsequently, the cell walls gradually disintegrate, enabling the collapse of the expanded bead (Fig. 9). The effect of bead fusion on this collapse behavior is illustrated in Fig. 10. In patterns with low bead fusion the relative shape of the beads is generally preserved as the beads collapse, while their effective

diameter decreases. Significant amount of porosity is also visible between the beads. In patterns with high fusion, however, beads are still connected to each other, the general shape is not well preserved and there are not as many voids between the beads. This behavior is also observed as the collapsed beads start to form the viscous residue at 160°C. There is a significant presence of voids in the transparent viscous layer of plastic in patterns with low bead fusion. In Fig. 10b, the bead structure in the layers below the viscous residue is visible between the voids. In samples with high fusion, however, there appears to be a connected, almost continuous layer of viscous residue, with much fewer and smaller voids between the beads. The same behavior is observed in samples rapidly heated to 750°C (Fig. 11). In this case, the collapse of the beads along the length of the polymer (as illustrated in the experimental set-up of

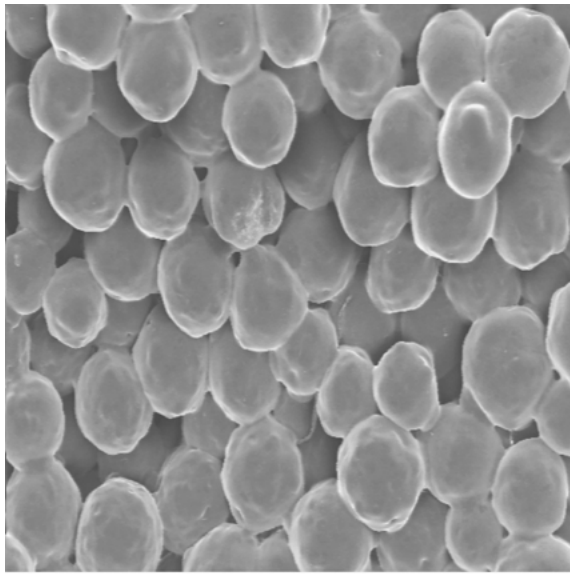


(a)

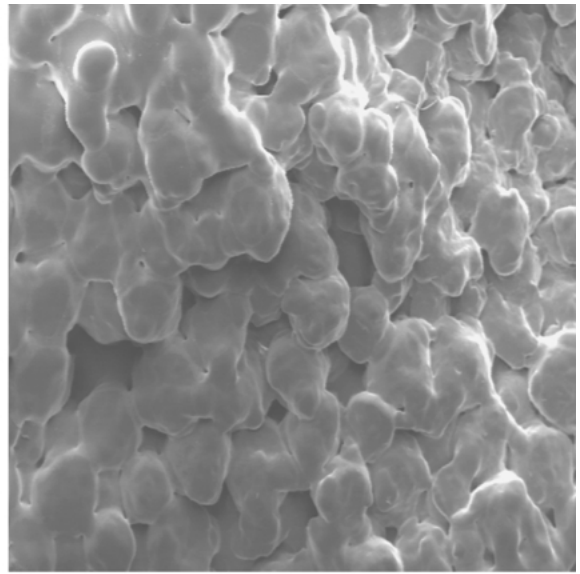


(b)

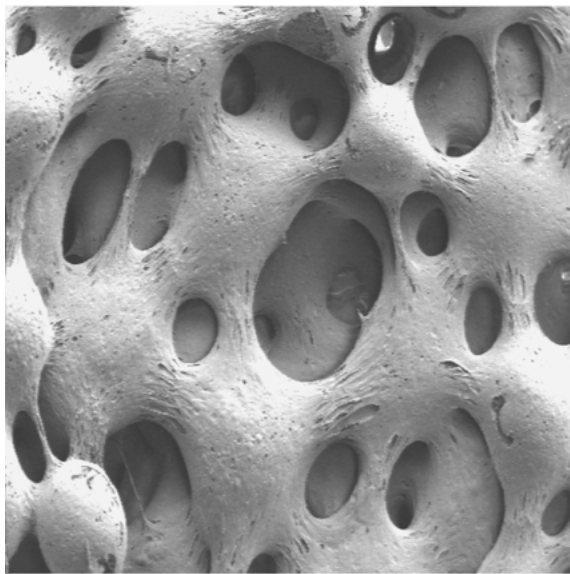
*Figure 9* Photographs showing cell wall structure during the collapse of the expanded beads at 110°C for 30 s. The disintegration of the cell wall can be seen in the high magnification photograph of the cell wall (b).



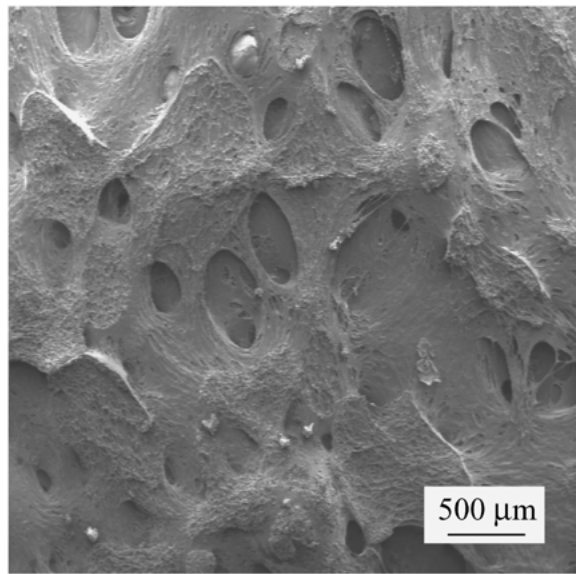
(a)



(b)

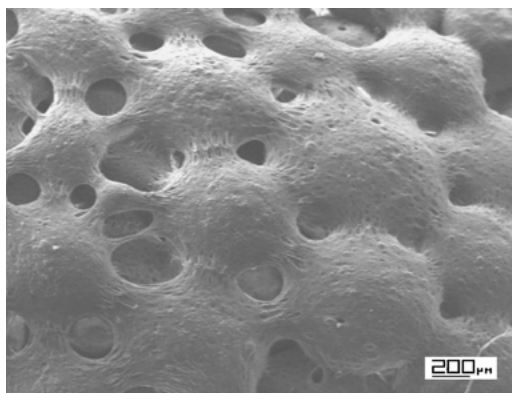


(c)

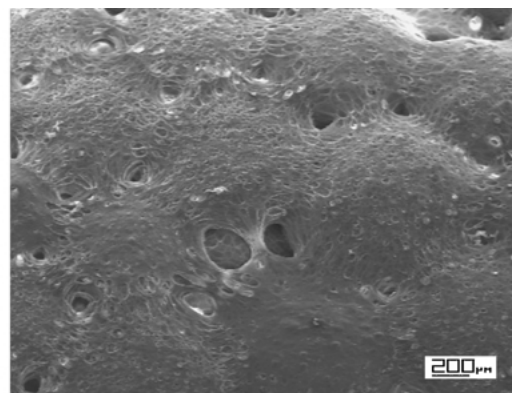


(d)

Figure 10 Photographs showing bead collapse (a, b) and viscous residue formation (c, d) in foams heated to 160°C for 30 s. Photographs (a) and (c) were obtained from samples with low fusion (<2%) while photographs (b) and (d) correspond to high bead fusion (>90%).



(a)



(b)

Figure 11 Photographs showing bead collapse and viscous residue formation on the surface of specimens exposed to 750°C: (a) low fusion (<2%) and (b) high fusion (>90%).

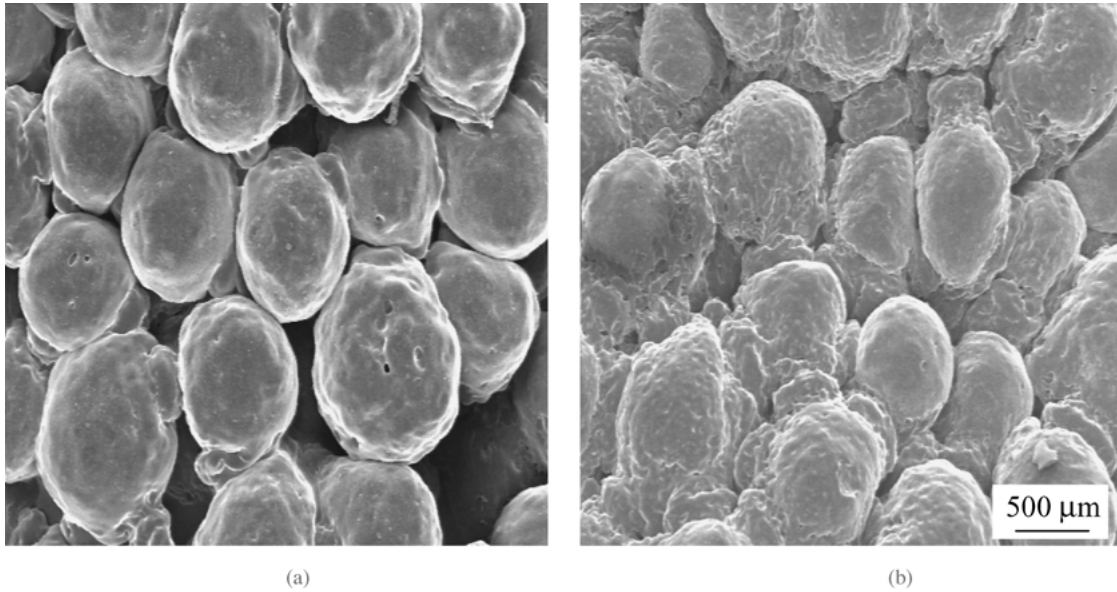


Figure 12 Photographs of bead structure along the length of the polymer for the experimental set-up shown in Fig. 4: (a) low fusion (<2%) and (b) high fusion (>90%).

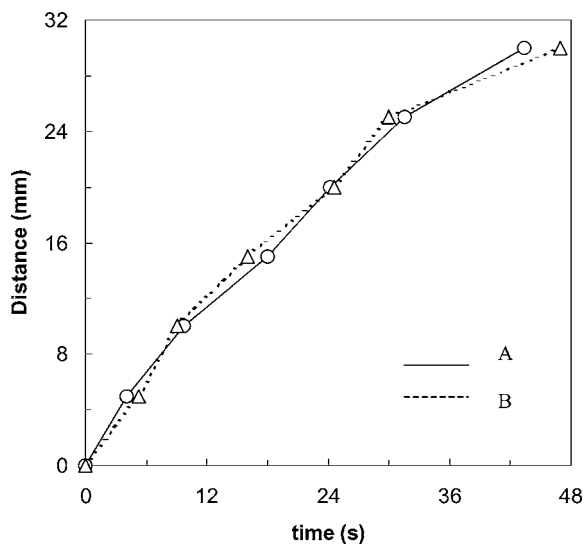


Figure 13 Variation of the position of the collapsing front as a function of time. A solid piece of aluminum or molten wax at 200°C was positioned on a piece of foam that was snugly fit inside a glass tube. The position of the collapsing front was recorded as a function of time: (A) low fusion (<2%) and (B) high fusion (>90%).

Fig. 4) is shown in Fig. 12. As the beads start to shrink deep inside the polymer, a more open structure is observed in samples with a low degree of fusion.

The kinetics of collapse is plotted in Fig. 13, where the position of the collapsing front (when EPS is exposed to molten wax at 200°C) is plotted as a function of time. The average collapse rate can be estimated to be on the order of 0.6 mm/s, much lower than the typical melt flow velocity of 100 mm/s. The rate of collapse and viscous residue formation in EPS, when exposed to radiant heat, has been measured by Baker [13]. The collapse rate from their work is on the order of 0.8 mm/s, in general agreement with the present data. Baker [13] suggests the following equation to describe the kinetics of bead collapse in EPS:

$$y = c(1 - e^{-kt}) \quad (1)$$

where  $y$  is the position of the collapsing front (i.e., distance in Fig. 13),  $t$  is the time and  $c$  and  $k$  are constants. The degree of fusion does not appear to have a significant effect on the rate of collapse as shown in Fig. 13. DSC and TGA data did not show any significant effects of bead fusion on the bulk degradation of the polymer.

The effect of bead fusion on the flow behavior of aluminum alloys is shown in Fig. 14. In this case, data were obtained with ASTM D638 tensile bars. It can be seen that the fill times generally increase with increasing bead fusion in the pattern. Typical fill times have been measured to be on the order of 3 s and 8 s for bead fusions of 0% and 93% respectively. The maximum temperatures registered on the thermocouple during the filling of the mold are shown in Fig. 15. Increasing the bead fusion leads to a greater level of chilling at the metal front as shown in Fig. 15. Note that the maximum temperature after a flow distance of 150 mm

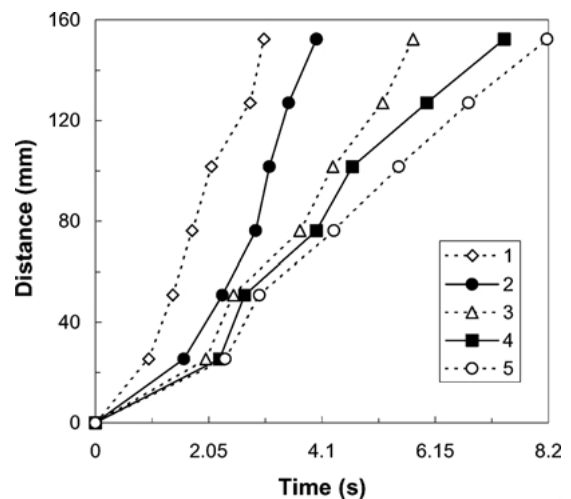


Figure 14 Variation of the distance of flow with time for patterns with various levels of bead fusion (DOF). Aluminum alloy A356 melt at 765 ± 5°C was poured onto the pattern shown in Fig. 5. 1: DOF = 0%, 2: DOF = 7%, 3: DOF = 35%, 4: DOF = 80%, and 5: DOF = 93%.



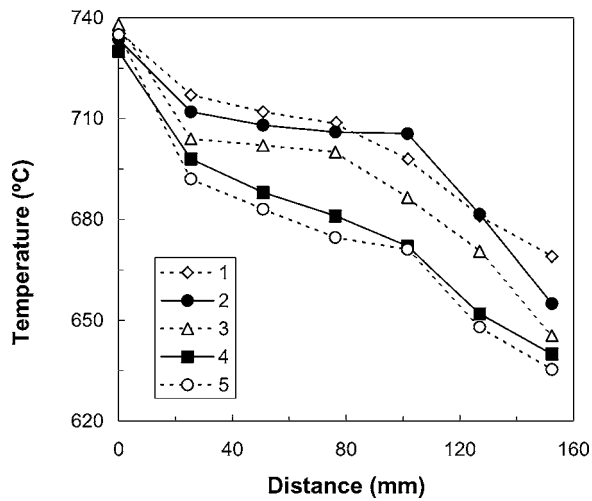


Figure 15 Maximum temperature recorded in the thermocouple with increasing distance of flow into the test pattern. Aluminum alloy A356 melt at  $765 \pm 5^\circ\text{C}$  was poured onto the pattern shown in Fig. 5. 1: DOF = 0%, 2: DOF = 7%, 3: DOF = 35%, 4: DOF = 80%, and 5: DOF = 93%.

is on the order of  $635^\circ\text{C}$  and  $675^\circ\text{C}$  for bead fusions of 0% and 93% respectively. Similar data were obtained with patterns prepared from strips cut from large blocks [11].

A series of complex physico-chemical phenomena occur at the metal front during the formation of the casting. Initially, the pattern at room temperature has to be heated above the glass transition temperature of the polymer. This heating leads to the collapse of the expanded beads and the eventual formation of the viscous residue, as the polymer reaches its rubbery state. As the temperature increases further, the polymer molecules undergo depolymerization. Depending on the level of depolymerization, various fractions of gaseous degradation products (primarily styrene monomer at  $750^\circ\text{C}$ ) and a non-volatile residue (dimers, trimers and other oligomers) may form at the metal front. The results presented above indicate that bead fusion may have a significant influence on bead collapse. In patterns with low bead fusion, the collapse of the beads produces a more open structure, while in patterns with high fusion

a uniform layer with fewer pores is obtained. Since the collapse rates and the kinetics of bulk degradation for the two cases do not differ appreciably (Fig. 13), the influence of bead fusion on filling behavior can be explained as follows. The relative open structure in the collapsed beads produced in foams with low fusion may enable penetration of hot gases deeper into the polymer pattern as shown in Fig. 16. This transport of the hot gases into the pattern may lead to the preheating, collapse and viscous residue formation in the pattern ahead of the metal front. In patterns with high fusion, however, the hot gases cannot penetrate through the bead structure easily and may be eliminated through the coating. Consequently, the zone of degradation ahead of the metal front (heat affected zone in Fig. 16) may decrease as the level of bead fusion increases. It has been shown previously that the presence of small holes in the pattern can increase the flow velocity substantially [14, 15]. The data of Shivkumar and Gallois [14] indicate that the flow velocity increases from 0.1 m/s to almost 0.6 m/s when a hole is positioned along the length of flow. Fu *et al.* [15] have shown that the flow rate of liquid metal can be doubled by drilling vents in the pattern prior to casting. They suggest that the polymer ahead of the metal front was being preheated by the suitable placement of the vents and was, therefore, degrading faster than in the pattern with no vents. Such a model may also explain the observed behavior shown in Figs 14 and 15. Since the beads are collapsing ahead of the metal front in patterns with low fusion, a faster fill rate is observed (Fig. 14). Furthermore, in patterns with low fusion, a significant fraction of the thermal energy for collapse and viscous residue formation may be transferred from the hot gases to the polymer. However, as the bead fusion increases, the transport of the gases through the polymer is reduced and a large fraction of the thermal energy required for collapse and viscous residue formation has to be transported from the metal front. As a result, the temperature drop observed at the metal front increases with bead fusion (Fig. 15). This temperature drop is conducive to defect formation and hence these results suggest that

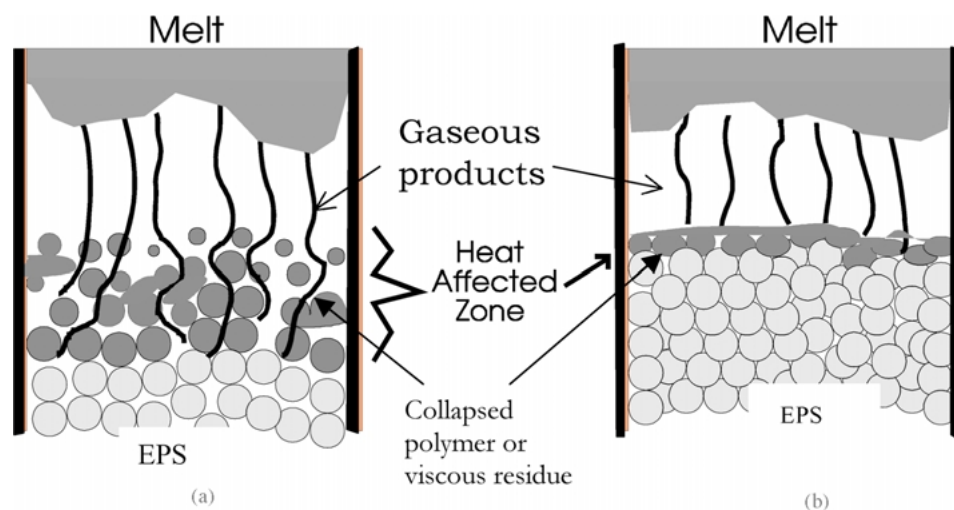


Figure 16 Schematic illustration of the events occurring at the metal front in (a) patterns with low degree of fusion and (b) patterns with high degree of fusion.

a high level of bead fusion may not be desirable in commercial patterns [11]. Clearly, a minimum amount of bead fusion is needed to reduce damage to the pattern during handling, storage and compaction in the sand. Hence, the level of bead fusion in the pattern may need to be optimized for a given part to suit the desired casting conditions.

#### 4. Conclusions

The area fraction of *transbead* fracture can be used as a quantitative estimate of bead fusion. The tensile strength in the foam increases with the measured bead fusion. The level of fusion has a significant effect on bead collapse and viscous residue formation during the degradation of the foam. In patterns with low fusion, the collapse of the beads produces a layer of viscous polymer with significant amounts of voids. As the bead fusion increases, the number of voids is reduced and a connected, almost continuous layer of viscous residue may form. As a result, the heat affected zone in the polymer ahead of the metal front may decrease with increasing bead fusion. The bead fusion does not have a significant effect on the rate of collapse or on the kinetics of bulk degradation of the polymer. Mold fill times generally increase with increasing bead fusion in the pattern. During flow, the temperature drop at the metal front increases with the extent of bead fusion. A minimum amount of bead fusion may be necessary in commercial patterns to reduce damage during storage and handling. However, the results presented here suggest that a high level of bead fusion in the foam may not be desirable for lost foam patterns.

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