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EPS bead fusion effects on fold defect formation in lost foam casting of aluminum alloys

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The effects of bead fusion in the polymer pattern on fold defect formation in castings produced by the lost foam process have been investigated. Castings of aluminum alloy 319.1 were produced with commercial patterns that were molded with varying levels of bead fusion. Each casting was broken into over 40 pieces to identify the fold defect on the fracture surface. The results indicate that castings produced with patterns with high bead fusion exhibit a greater number and a larger area of folds than parts obtained by using foams with low bead fusion.
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1. Introduction

Expanded polystyrene (EPS) patterns that have been injection molded to the desired shape are used for the production of metallic castings in the lost foam process [1]. EPS is a closed cell foam with a duplex structure (Fig. 1). At the macroscopic level, the structure in the foam consists of closed beads, typically with a diameter on the order of 2 to 4 mm [2]. Inside each bead is a cellular structure, with the polymer being present at the cell walls. The cell size is determined by the amount of expansion that the bulk polystyrene granules undergo during the initial stage of foam production (preexpansion). [3]. During the molding of the pattern, the preexpanded beads are injected into the mold, where they are heated above the glass transition temperature of the polymer. The remaining blowing agent in the beads leads to further expansion of the beads. The counterpressure generated during this process results in a rearrangement of the molecular structure at the surface between beads [4]. This process, referred to as bead fusion, has a significant effect on the properties of the foam [5,6]. The degree of fusion between the beads is essentially governed by the molding conditions used for the production of the pattern. The pattern molding conditions can be controlled to produce foams between two extreme conditions: a) total *inter*-bead fracture when the foam is broken (corresponding to *low* bead fusion) or b) total *trans*-bead fracture (corresponding to *high* bead fusion). The area fraction of *trans*-bead fracture when the foam is broken can be used as a measure of the degree of bead fusion (Fig. 2) [6]. It has been shown that the degree of bead fusion in EPS may have a significant effect on the mechanical properties of the foam and on its degradation characteristics [7].

During the production of the cast part, several defects that are unique to the lost foam process may form in the casting. One particular defect that has received a lot of attention is the fold defect [8]. A fold is an important defect observed on the fracture surface of aluminum alloy parts produced by the lost foam process. A photograph of a typical fold is shown in Fig. 3 [9]. This defect may affect the mechanical properties and the pressure tightness of the cast part. Further, fold defects cannot be identified in the casting through standard non-destructive quality control techniques. The formation of folds in the casting is a complex process and may be linked to a combination of factors including foam properties, pattern geometry, gating system, mold media properties, alloy composition and melt temperature. The purpose of this contribution is to study the effects of the degree of bead fusion in the foam pattern on fold formation in aluminum alloy castings.

2. Experimental procedure

The commercial test pattern used in this study consisted of ribs, bosses, thick and thin sections as shown in Fig. 4. Such a pattern was intentionally designed to exacerbate the problem of fold formation in the casting. Polystyrene with a weight average molecular weight of 304,000 g/mol (Polydispersity index = 2.23) was used to produce the molded patterns. The nominal density of the foam after

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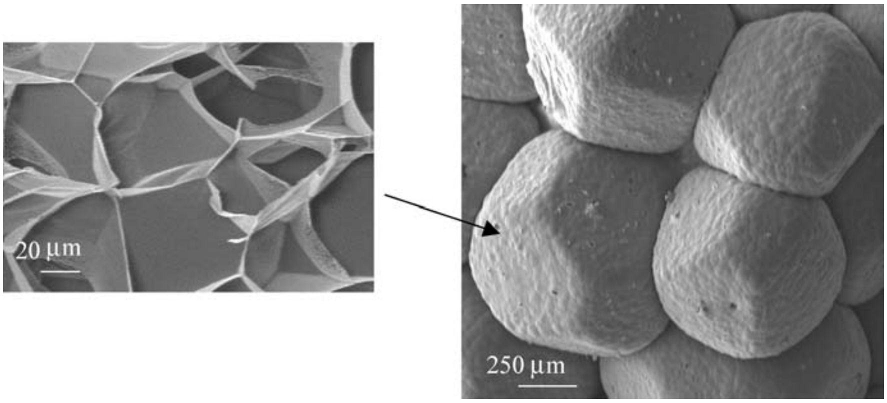


Figure 1 Photographs showing the duplex structure of EPS foams. At the macroscopic level, the structure consists of closed beads. Within each bead is the cellular structure shown on the left [2].

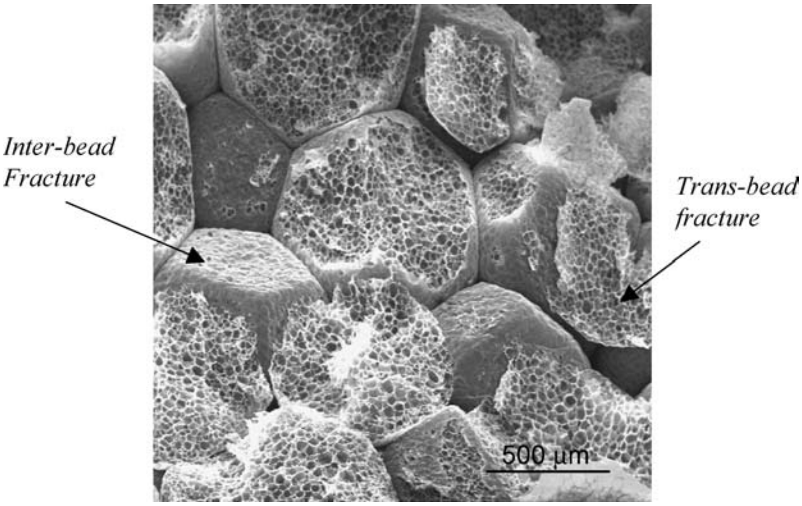


Figure 2 Photograph showing the structure on the fracture surface. The fracture can occur between the beads (Inter-bead fracture) or across the beads (Trans-bead Fracture). The fraction of Trans-bead fracture increases with bead fusion. The area fraction of trans-bead fracture in the specimen can be used as a measure of the degree of bead fusion in the foam [6].

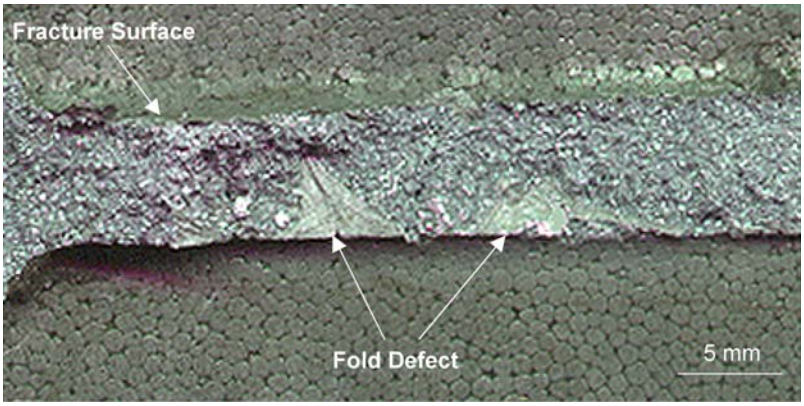


Figure 3 Photograph showing a fold defect on the fracture surface [9].

molding was measured to be 22.2 kg/m^3. 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. The procedure for measuring the degree of bead fusion (DOF) has been described previously [9]. In principle, it consists of breaking a piece of foam with a simple bending action and measuring the area fraction of *trans*-bead fracture through scanning electron microscopy. The pattern was initially sectioned with a hot wire cutter into various segments. Each segmented fraction was fractured into many pieces with a simple bending action. The entire polymer pattern was broken

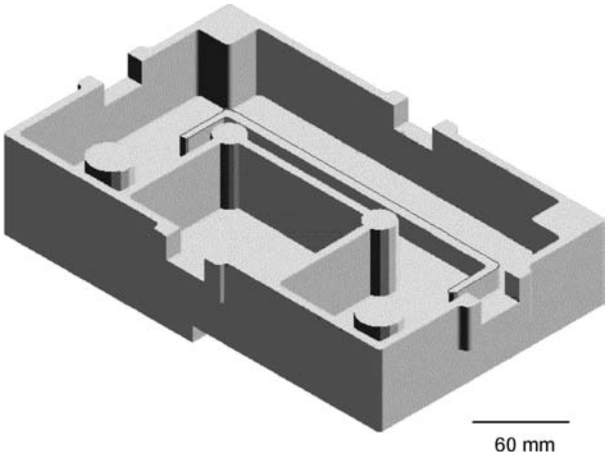


Figure 4 Schematic of the test pattern used in this study.

into over 40 pieces by the aforementioned procedure. The exposed fracture surface on each piece was examined with an AMRAY 1610 scanning electron microscope at a magnification of 20X. The projected area fraction of *trans*-bead fracture was determined by image analysis techniques and used as a measure of the local degree of fusion. The degree of fusion at several locations in the pattern was used to obtain an average value of DOF for a given molding condition [6]. At least 5 and up to 10 patterns, produced under identical conditions, were examined to determine the overall average DOF reported in Table I.

In order to produce the casting, two test patterns were attached to a common gating system consisting of a pouring basin, a hollow downsprue, and three ingates as shown in Fig. 5. The gating system was cut from EPS boards with a nominal density of 22 kg/m^3. The pattern and the gating system were coated with Styrokote 145.3 refractory coating. The dried coating thickness was adjusted to be between 1 to 2 mm. The pattern was placed in a molding box and invested with silica sand (AFS 55). Pneumatic vibrators were used to compact the sand. In several experiments, chromel-alumel thermocouples were positioned at various locations in the pattern to monitor the mold filling behavior. Up to 26 thermocouples were used in a

TABLE 1 Arrival time for the liquid metal at various locations in the pattern. Data are shown for patterns with 2 average values of fusion. The numbers in the location column correspond to the sections shown in Fig. 6. The local degree of fusion (L-DOF) measured in various sections is indicated.

	Average DOF = 76%4		Average DOF = 51%	
Location	Time (s)	L-DOF(%)	Time (s)	L-DOF(%)
6	13.1	85	6.1	40
10	9.5	64	6.5	52
9	10.1	77	5.6	44
1	11.6	73	5.8	46
3	5.6	65	5.7	67
8	5.9	65	6.6	67

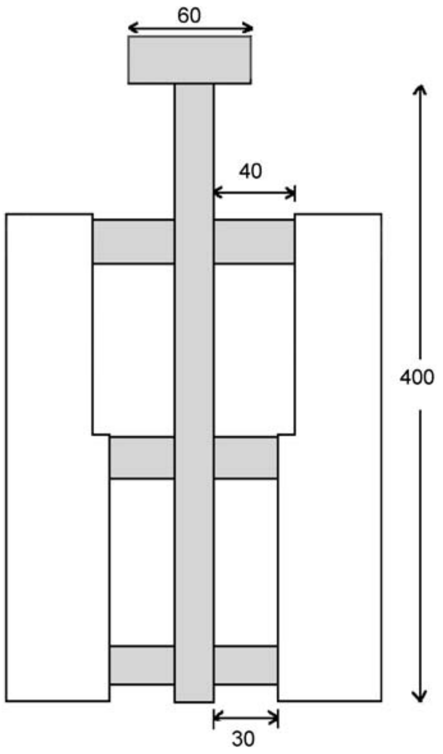


Figure 5 Schematic of the gating system used to produce the casting. Two test patterns shown in Fig. 4 were glued to a common gating system with a hollow downsprue. (All dimensions in mm.)

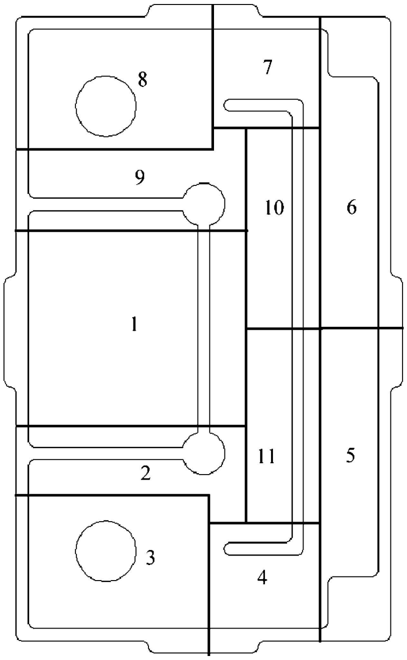


Figure 6 Sectioning procedure used to identify the fold defects in the casting. Initially, the casting was sectioned with a saw as shown above. Each sectioned piece was then placed in a vice grip and hammered at various locations to fracture the specimen. The fractured surface was examined to identify the location, size and number of fold defects in the casting. Each casting was fractured into more than 40 pieces by this procedure.

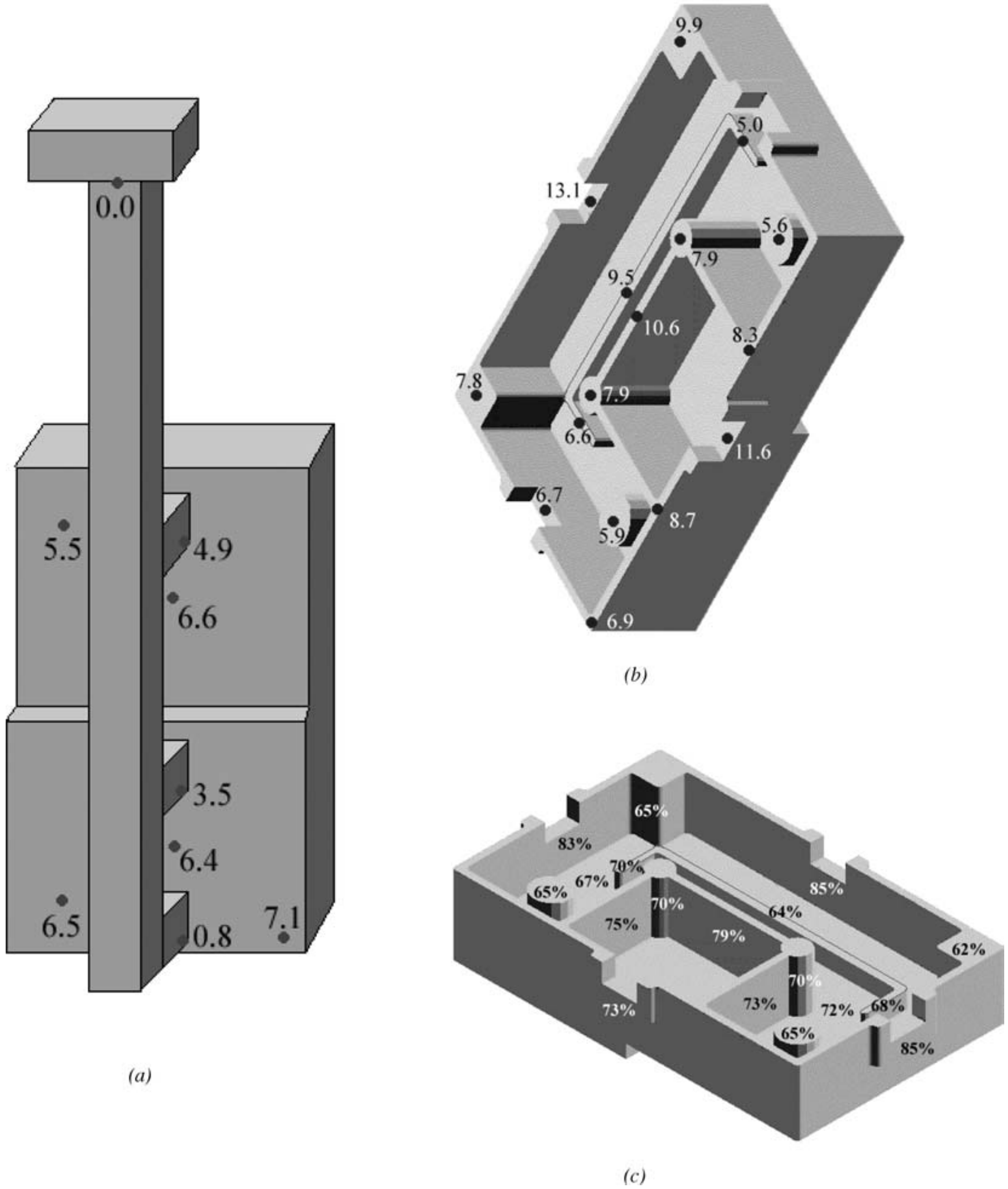
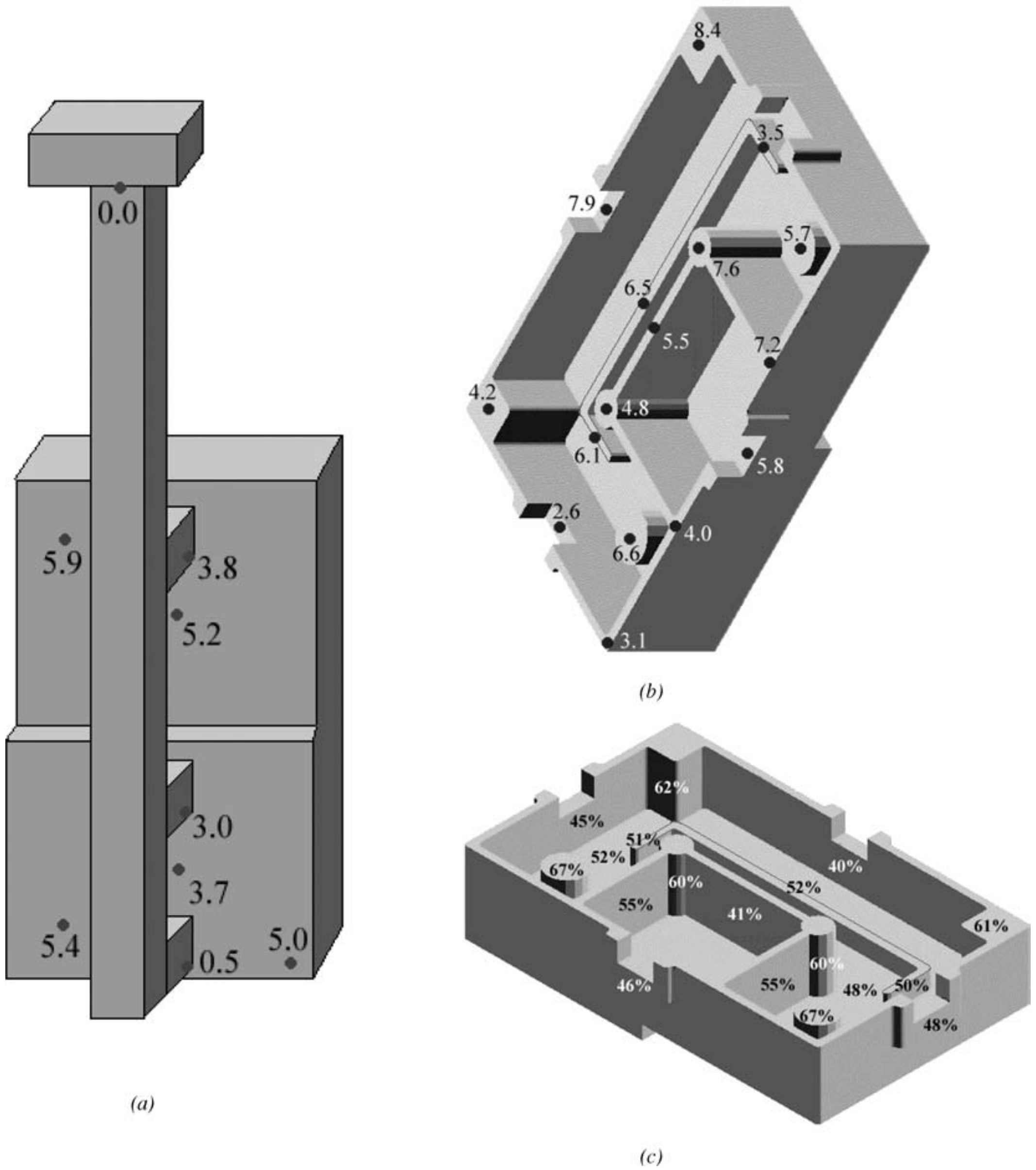


Figure 7 Mold filling time (s)at various locations in the casting (a) and (b). The filling time was determined from the responses of chromel-alumel themocouples positioned at various locations during the production of the casting. The average degree of fusion in the pattern was measured to be 76%. The variation of degree of fusion at various locations in the pattern is shown in (c) [6].

single pattern. Aluminum alloy 319.1 at a temperature of 750 ± 5°C was used to produce the castings. At least 5 and up to 10 castings were produced under each condition. The castings were sectioned at various locations to determine the position and size of folds (Fig. 6). Each sectioned piece was placed in a vice grip and hammered at various locations to fracture the specimen and expose the defect. This procedure is typically used to identify fold defects in commercial castings since these defects generally cannot be detected through non-destructive techniques. Hence, after this procedure, each casting was broken into over 40 pieces. The fracture surface of each piece was examined visually to determine the number, size, shape, and location of folds in the casting.

3. Result and discussion

The mold filling times for conditions corresponding to two values of bead fusion used in this study are shown in Figs 7 and 8. Mold fill times are on the order of 9 s and 14 s for average degree of fusions of 51% and 76% respectively. Further, the degree of fusion in the pattern may vary significantly depending on location as shown in Fig. 1 [6]. For example, at an average degree of fusion of 51% in the pattern, the local degree of fusion in the thick corner rib was 62% (Fig. 8(c)), while in the thinner areas, the DOF was on the order of 40%. This variation in bead fusion within the pattern may also influence the local filling times as shown in Table I. In general, areas with low degree of fusion exhibit a smaller mold filling



(a)

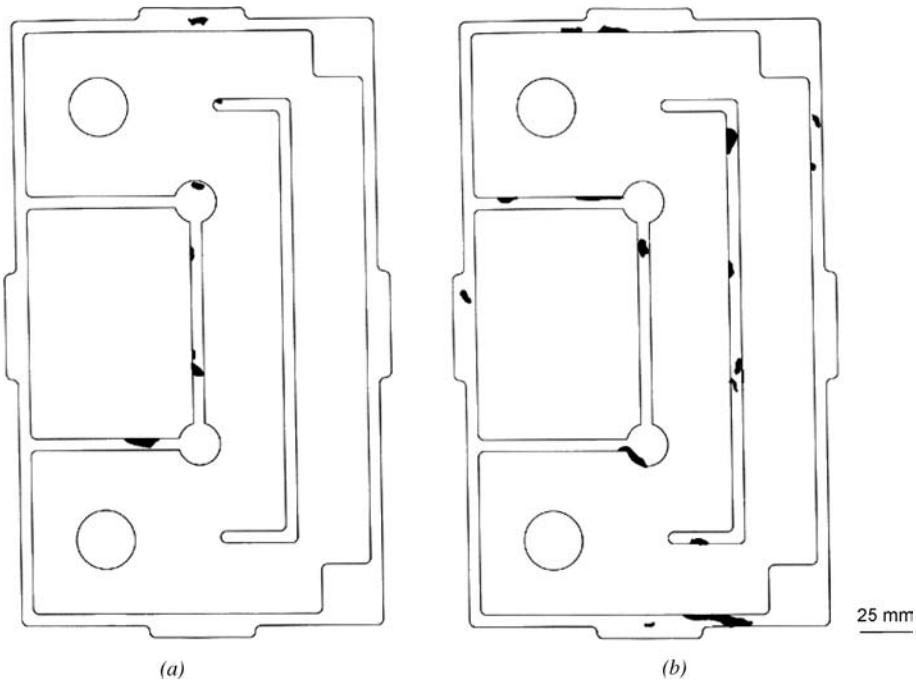
(b)

(c)

Figure 8 Mold filling time (s) at various locations in the casting (a) and (b). The filling time was determined from the responses of chromel-alumel themocouples positioned at various locations during the production of the casting. The average degree of fusion in the pattern was measured to be 51%. The variation of degree of fusion at various locations in the pattern is shown in (c) [6].

time. The observed variation of fill behavior with degree of fusion may be explained based on the differences between bead collapse and viscous residue formation during the degradation of the foam [7]. In patterns with low fusion, the collapse of the beads produces a layer of viscous polymer with significant amounts of voids. The hot gases formed at the metal front can then permeate through this porous layer and lead to collapse and melting of the beads ahead of the metal front. As the bead fusion increases, however, the number of voids is reduced and a connected, almost continuous layer of viscous residue may form. In this case, the hot gases cannot penetrate deep into the foam ahead of the metal front. The heat affected zone ahead of the metal front, therefore, decreases with increasing bead fusion. As a result, the flow velocity decreases with increasing DOF. Further, the temperature at the metal front drops more rapidly as the bead fusion increases.

The typical distribution of fold defects is shown in Fig. 9. The defects generally formed at edges and corners between horizontal and vertical sections of the pattern. The size of the defect varied from about 3 mm to 40 mm. A greater number of defects were consistently observed in patterns with 76% DOF than in samples with a DOF of 51%. The average number of folds in the casting was measured to be about 16 at DOF of 76% and 8 at DOF of 51%. In addition, the castings produced with high DOF patterns contained many large folds as shown in Fig. 10. The area of the folds varied from about 4 mm^2 to 62 mm^2 for a DOF of 51% and 3 mm^2 to 96 mm^2 for a DOF of 76%. The overall average area of the fold (cumulative



(a) (b)

Figure 9 Schematic illustration of the location, size and number of fold defects in the casting (a) DOF = 51% (b) DOF = 76%.

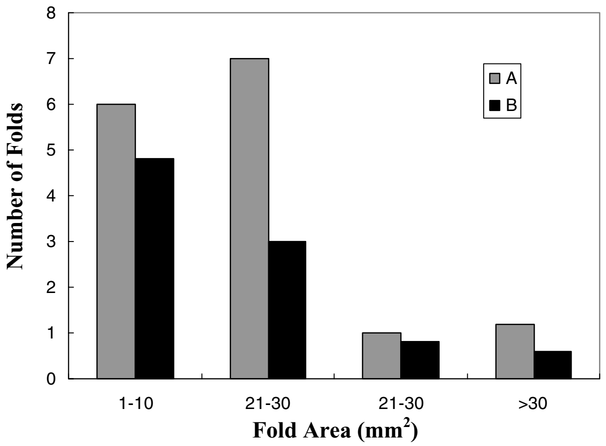


Figure 10 Typical size distribution of folds in the casting for a DOF of 76% (A) and for a DOF of 51% (B).

average from all the castings) was measured to be 10.7 mm^2 at DOF of 51% and 14.8 mm^2 at DOF of 76%.

The formation and elimination of polymer degradation products plays a vital role in fold formation. One possible mechanism by which folds may form is through bubble collapse [9]. The gases formed during polymer degradation may escape by reaching the surface. If the local permeability of the mold media is not adequate, the gas bubble may be trapped in the solidifying metal. The gases in the bubble (typically styrene gas) may undergo additional fragmentation (to lighter hydrocarbons) and increases the pressure in the bubble. The bubble may then collapse, but the surface of the bubble may have cooled and oxidized. Hence, when the bubble collapses, the mating surfaces do not blend together and a fold defect may be created. This problem may be exacerbated by the presence of the partially degraded viscous residue. It should be noted that a large fraction (>60%) of the polymer initially transforms to a partially depolymerized viscous residue containing dimers, trimers, tetramers and other oligomers [10]. The viscous residue entrapped in the liquid metal may gradually depolymerize further to produce gaseous products and may lead to fold formation by the aforementioned mechanism. Based on this description, the effects of bead fusion on fold formation can be analyzed. The endothermic losses at the metal front lead to a greater chilling of the metal front in patterns with high degree of fusion than with low DOF [7]. This rapid temperature drop at the metal front is conducive to fold formation. Further, it was shown previously at low bead fusion, collapse of the foam at the metal front leads to a relatively open layer of collapsed polymer. The hot gases formed at the metal front may infiltrate through these open layers and may cause collapse of the beads at relatively large distances away from the metal front. This collapsed polymer may reach the coating rapidly and may not be entrapped in the liquid metal. By comparison, at high DOF, the collapsed polymer forms an almost a continuous layer and thus the polymer degradation products are forming at the metal front. Local turbulence effects may lead to entrapment of these polymer degradation products and favor fold formation. These results indicate that a high degree of fusion is not desirable in commercial patterns. A minimum bead fusion is necessary, however, to control the shrinkage of the foam and to minimize damage to the pattern during handling and molding. An optimum level of bead fusion may be needed for each pattern based on polymer properties, casting conditions and melt chemistry.

4. Conclusions

The level of bead fusion is an important parameter that may have a significant on casting formation in the lost foam process. Bead fusion is typically controlled by adjusting the molding conditions. The tensile strength of the foam increases with bead fusion and hence, the foams exhibit better handling properties at high levels of bead fusion. However, bead fusion affects the degradation characteristics of the foam, specifically the bead collapse that occurs initially at the metal front. Consequently, as the bead fusion increases, the flow velocity decreases and a greater temperature drop is observed at the metal front. A greater number of defects were consistently observed in patterns with an average DOF of 76% DOF than in samples with an average DOF of 51%. The average area of the fold was measured to be 10.7 mm2 at DOF of 51% and 14.8 mm^2 at DOF of 76%. These results indicate that a high degree of fusion may not be desirable in commercial patterns. The need to minimize pattern damage during handling and investment necessitate a minimum level of bead fusion. An optimum level of bead fusion may be needed for each pattern based on polymer properties, casting conditions and melt chemistry.

Acknowledgments

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