Effect of Polymer Properties on Bubble Growth in Polymer–Paperboard Composites

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ABSTRACT: Foamed paperboard is a composite material used in thermally insulated food packaging and beverage containers. The paperboard is sandwiched between a layer of low-density polyethylene and a barrier layer, and the low-density film is foamed through heating. The moisture inside the paperboard vaporizes and serves as the driving force for creating the foam. The bubble growth on the paper surface has been tracked with high-speed photography. The number of generated bubbles has been found to depend on the number of pores on the surface of the paperboard; there is little or no dependence on the properties of the polymer, at least across the range of properties studied. In contrast, the thickness of the foam is relatively insensitive to the paperboard properties but has a strong dependence on the thickness of the initial polymer film, the nature of the polymer, and the speed at which it is extruded onto the paperboard. It is believed that some of these variations arise from differences in the degree of adhesion between the polymer and the paperboard. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 3786–3791, 2008

Key words: coatings; composites; extrusion; interfaces; polyethylene (PE)

INTRODUCTION

Foamed paperboard is a relatively new product used in beverage containers such as coffee cups and in food packaging. A paperboard–polymer composite is prepared, with the board being sandwiched between extruded polymer layers of different densities. Upon heating, the moisture in the board vaporizes and foams the low-density polymer face, thereby creating a surface that provides thermal insulation for hot liquids and foods.[1] We have previously shown that the properties of the paperboard surface control the number of bubbles initially created in the foam.[2] In this study, we examine the relationship between the paperboard and polymer properties and extrusion speed used to coat the polymer on the paper and the thickness of the foam. In particular, we demonstrate that although the paperboard properties control the bubble count, the properties of the polymer and the speed at which it is extruded onto the board govern how the initially formed bubbles develop into a foam.

EXPERIMENTAL

Samples were prepared on a full-scale commercial paper machine (machine-made) and on a laboratory sheet former (handsheets). The samples were prepared at 250 g/m^2 from a 3:1 mixture of Southern hardwood and softwood pulps as described earlier.[2] The polyethylene samples were obtained from Westlake Polymers (Houston, TX). The boards were extruded with low-density polyethylenes (LDPEs) of different grades, the properties of which are shown in Table I; they were extruded on one side at 61–213 m/min to produce a 17–45-μm-thick polymer layer. For the handsheets, LDPE was extruded onto the wire side of the sheet. The other side was sealed with packaging tape to form a barrier layer, as shown in Figure 1. The barrier for the commercially obtained paperboards was a blend of 90% LDPE and 10% high-density polyethylene; packaging tape was used as a barrier for the handsheets. The board–polymer composite, illustrated in Figure 1, was conditioned in a moisture-controlled room under TAPPI standard conditions of 50% relative humidity and 23°C until the moisture content reached 6–8%.[3] The composites were foamed in a convective oven at 132°C for 90 s; these set points are similar to those used in industry.

The development of bubbles on the surface of the board was imaged with a Phantom version 4.2 high-

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TABLE I
Properties of the Low-Density Polymers

	Melt index (g/10 min)	Density (g/cc)
EC 479	5.7	0.921
EC 482	12	0.918
EC 476	13.7	0.9165

speed camera from Vision Research (Wayne, NJ) at 100–2000 frames per second as described earlier.[2] The onset of foaming was indicated by the light reflected from the bubble surface. The number and size of the reflected spots were analyzed with Image J software.[4] The area of the bubble surface reflecting the light was less than the total area of the bubble. The area of a square that enclosed a bubble was measured manually for 50 bubbles of different sizes and was found to be 10 times that of the corresponding spot created by the reflected light. The factor of 10 was then applied to all the spots to obtain the total area of the bubbles. All measurements were made at least twice.

The final foam thickness was measured by the TAPPI 551 soft platen method,[5] which compensates for surface roughness effects and also partially compensates for compressibility. This method gives the effective thickness, which is the theoretical thickness calculated from the relation between the extensional stiffness and bending stiffness. The results reported here are from measurements made on a 200 ± 5 mm^2 area of the sheet. Five separate readings were taken from different areas of the foamed board, and the mean was calculated. The error bars represent the total standard deviation from mean values. Foam thickness was also measured with the TAPPI 411 hard platen method.[6] The results were within 5% of those results obtained with the soft platens, and this indicated that the foam was not significantly crushed during the measurement.

RESULTS AND DISCUSSION

We have previously shown that heating the paperboard–polymer composite initially leads to the formation of a large number of small bubbles.[2] These then grow, collapse, or coalesce so that the bubble count decreases after an initial spike. The manner in which the board is constructed affects the pore structure of the sheet and, therefore, the number and geometry of the bubbles formed.[2] The polymer is integral to the foaming process and must play a role in the growth of the foam. Although bubble growth in polymer foams has been studied extensively,[7–15] the corresponding process on a porous paper substrate is very different and has not been addressed before.

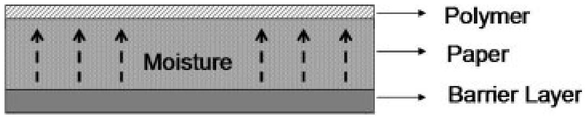

Figure 1 Schematic of the extruded board composite.

Effect of the paperboard properties

The number of bubbles formed initially is related to the uniformity of the pores on the paperboard surface and the resistance to vapor transport inside the board.[2] Machine-made boards are more uniform[2,16] and give rise to a larger number of bubbles. The nature of the fibers, hardwood or softwood, used to construct the board seems to be relatively unimportant to the bubble profile, as Figure 2 demonstrates. This is surprising; we had expected the hardwood fibers to provide a more uniform pore distribution. It appears that although the pore structure changes somewhat with the mix of fibers used, the manner in which the board is constructed is more important. The handsheets were made on a Formette Dynamique unit (Allimand, Grenoble, France), which constructs a sheet layer by layer,[17,18] whereas the fiber slurry was sprayed on the wire for the machine-made paper and the sheet was drained all at once. The layering effect leads to greater tortuosity and a more complex pore structure in the Formette handsheets, as confirmed by permeability measurements.[2]

The differences in the number of bubbles carry over to the thickness of the foam, which was determined by the subtraction of the initial thickness from the final thickness. The degree of coalescence is clearly higher for the machine-made sheets in Figure 3

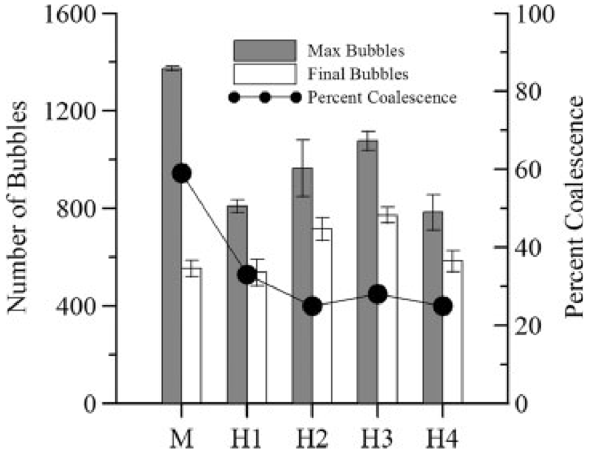

Figure 2 Effect of paperboard properties on bubble growth (M = machine-made, H = handsheets). The hardwood/softwood ratios were (1) 100:0, (2) 75:25, (3) 50:50, and (4) 0:100. The polymer (EC 482) film was 42.2 μm and was extruded at 61 m/min.

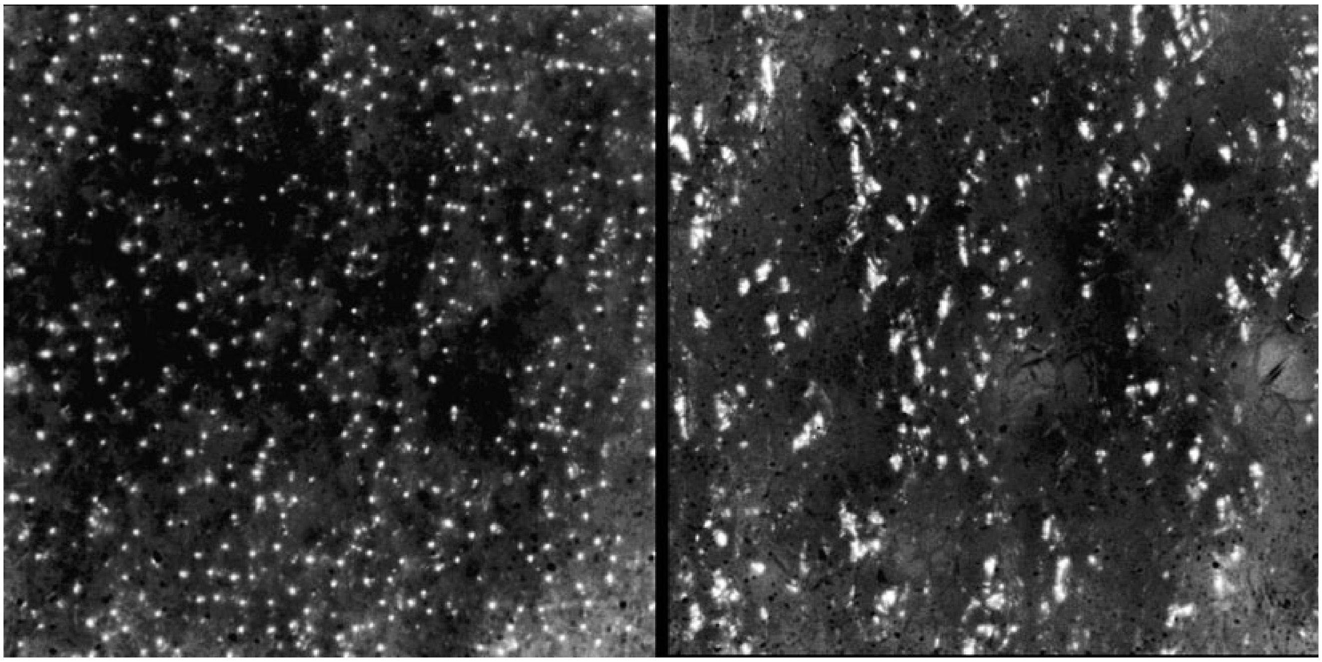

Figure 3 Effect of coalescence on the bubble size distribution at 90 s. The left and right panels reflect handsheets and machine-made board, respectively.

than for the handsheets. This was expected because a higher bubble density would reduce the distance between bubbles and increase their propensity to coalesce. Larger bubbles would also tend to increase the foam thickness because of their greater diameter. This is illustrated in Figure 4, which shows that the machine-made sheet gives rise to a thicker foam than any of the handsheets.

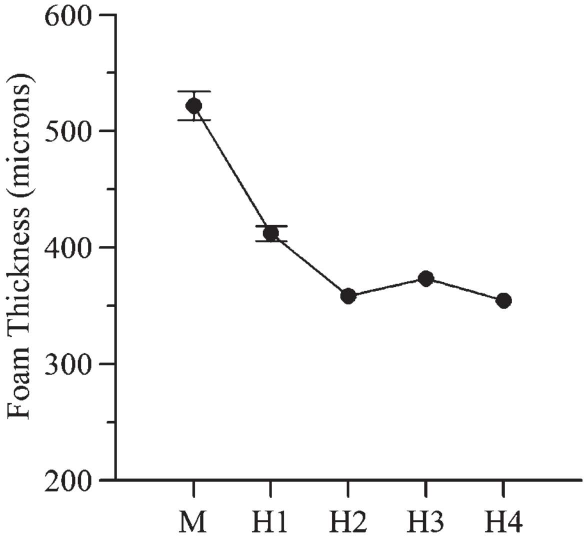

Figure 4 Effect of paperboard properties on foam thickness (M = machine-made, H = handsheets). The hardwood/softwood ratios were (1) 100:0, (2) 75:25, (3) 50:50, and (4) 0:100. The polymer (EC 482) film was 42.2 μm and was extruded at 61 m/min.

Effect of the polymer properties

Two LDPE grades differing in their melt indices were used. The melt index is inversely proportional to the molecular weight and viscosity and is related to the flow properties of a polymer.[19,20] Figure 5 shows that the bubble growth rate curves for the high- and low-melt-index polymers are similar, and this further confirms that the properties of the paperboard rather than those of the polymer dominate

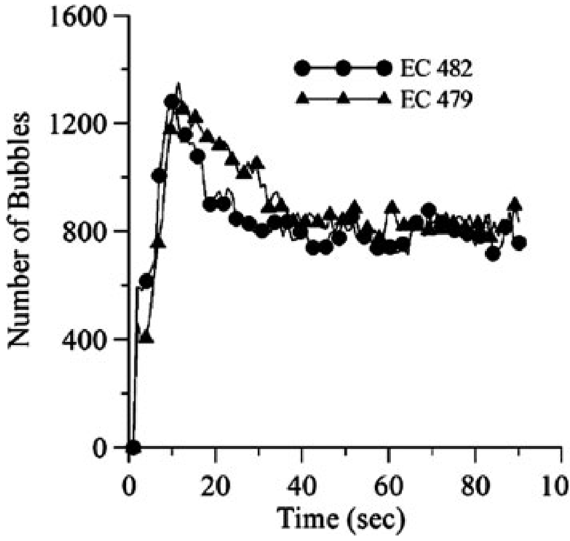

Figure 5 Effect of polymer properties on foaming. The polymer film thickness was 42.2 μm, and the extrusion speed was 137 m/min.

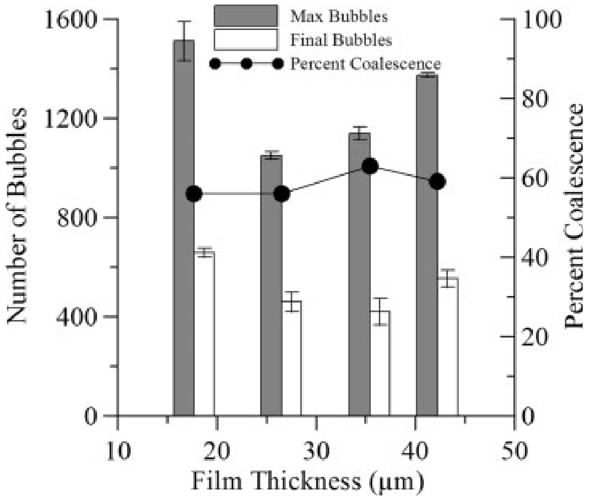

Figure 6 Effect of the polymer (EC 482) thickness on bubble growth. The extrusion speed was 61 m/min.

bubble creation. As shown in Figure 6, the effect of film thickness on the number of bubbles formed is also quite small for the same reason.

Figure 7 illustrates the relationship between the thickness of the initial polymer film and the final foam thickness. The thicker film leads to the thicker foam, even though it must offer greater resistance to foaming; this suggests that the film resistance is not controlling. A lower coated weight reduces the amount of polymer that can be nipped into the voids between the fibers, thereby reducing the area of contact between the polymer and the fibers.[21] This would lead to poorer bonding with the paper surface and increase the likelihood of vapor leakage at the interface.

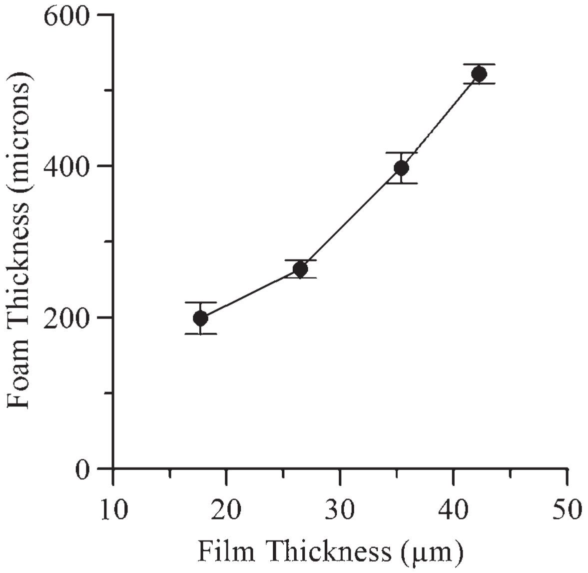

Figure 7 Effect of the polymer (EC 482) thickness on foam thickness. The extrusion speed was 61 m/min.

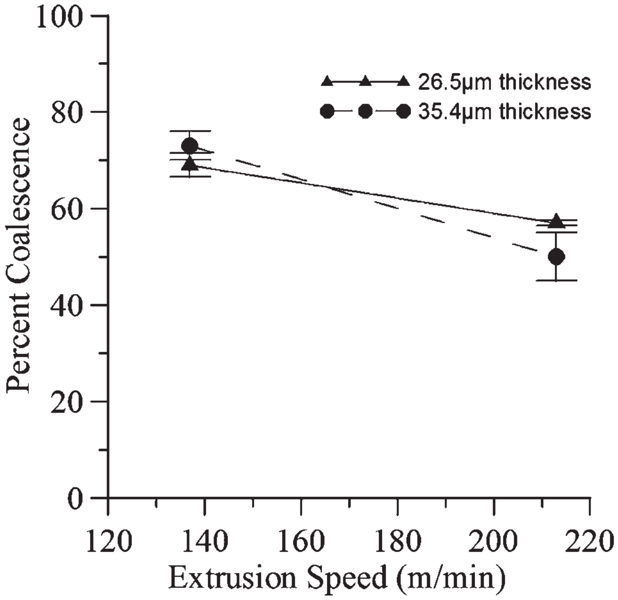

Figure 8 Effect of the extrusion speed on bubble growth for the EC 476 polymer.

Effect of the extrusion speed

The physical properties of the interface between the polymer and paperboard depend on the process parameters used in extrusion.[21] During extrusion, a thin film of molten polymer is pressed onto the paperboard. Parameters such as the line speed, extruder temperature profile, chill roll temperature, and press roll pressure all affect the properties of the board–polymer interface. Different morphological properties of the polymer are influenced by variations in these process conditions.[22–24] For example, line speed affects the shear forces applied to the

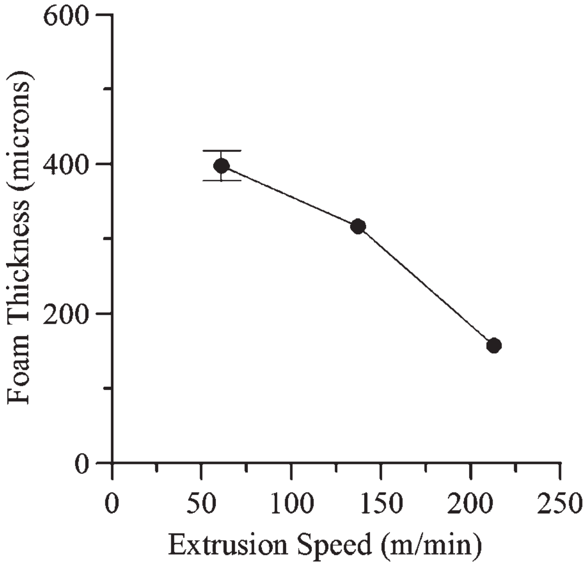

Figure 9 Effect of the extrusion speed on foam thickness for the EC 482 polymer. The film thickness was 35.4 μm.

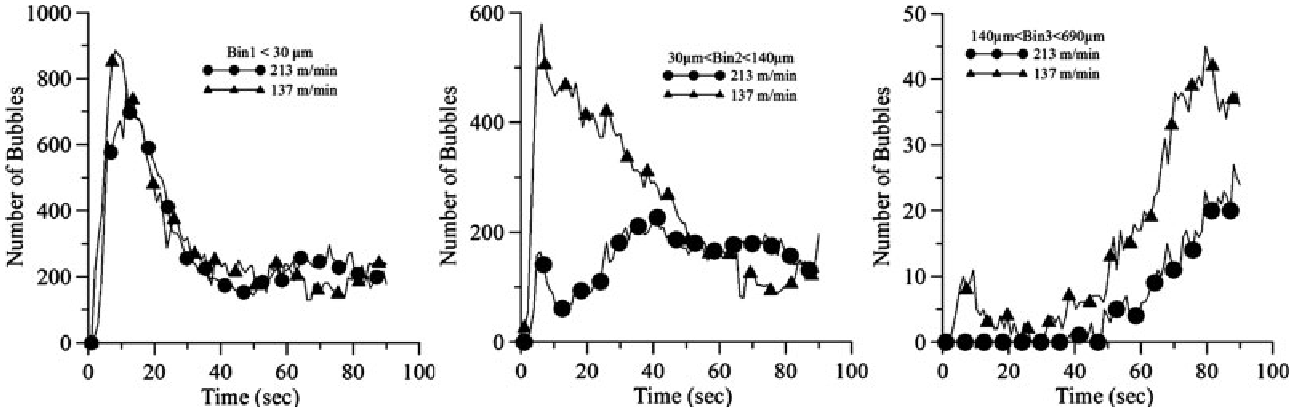

Figure 10 Bubble size distribution on boards coated with EC 476 polymer. The bin sizes were (1) 0–30, (2) 31–140, and (3) 140–690 μm.

polymer and influences its adhesion to the paperboard surface and the orientation of the polyethylene chains. Scanning electron microscopy images of paper–polymer interfaces showed the presence of open, flat bubbles at the interface,[16] which was attributed to the evaporation of water from the board caused by heat flow during extrusion.[24]

The two extrusion line speeds used here were chosen to mimic those employed commercially. IR thermography confirmed that the temperature of the board during foaming exceeded the differential scanning calorimetry melting point of the polymer. Figure 8 shows that the degree of coalescence decreased with increasing extrusion speed. This was expected because increasing the extrusion speed is known to decrease the adhesion of the polymer to the board.[25] The reduced bonding between the polymer and paperboard would promote vapor leakage from the interface during foaming and lead to smaller bubbles and, therefore, to a thinner foam. This can be seen in Figure 9. The extrusion speed did not have a significant influence on the number of bubbles formed. This behavior follows from our previous observations that the paperboard properties control the number of bubbles generated.

Control of the bubble size distribution

The bubble size distribution should be a function of both the pore size and the degree of coalescence. Figure 10 shows the size distribution resulting from the two extrusion speeds used on machine-made paper. The bubbles are divided into three bins of increasing size. The bubble profiles for the two extrusion speeds in Figure 10(a) are very similar, as are the final bubble counts in Figure 10(b). However, faster extrusion leads to fewer large bubbles, as shown in Figure 10(c). Overall, the total bubble volume in the foam decreases with increasing extrusion speed, and this is consistent with our findings in Figure 9.

The bin 1 bubbles are the most numerous and are formed early in the process. As noted earlier,[2] each originates from a single pore in the paperboard, and this implies a direct dependence on the pore size distribution of the paper surface. The bubble profiles in bins 1 and 2 are similar for the slower extrusion speed; they both peak at about 10 s and then fall. The fall is less steep in bin 2 because bubbles are coalescing both into and out of this bin. The bubble profiles for the faster extrusion speed are more complex. The bin 1 bubbles track those for the slower speed, and this is consistent with coalescence. However, the early spike in bin 2 seen for the slower speed is absent for reasons that are not understood. The faster speed leads to a weaker interface. As dis-

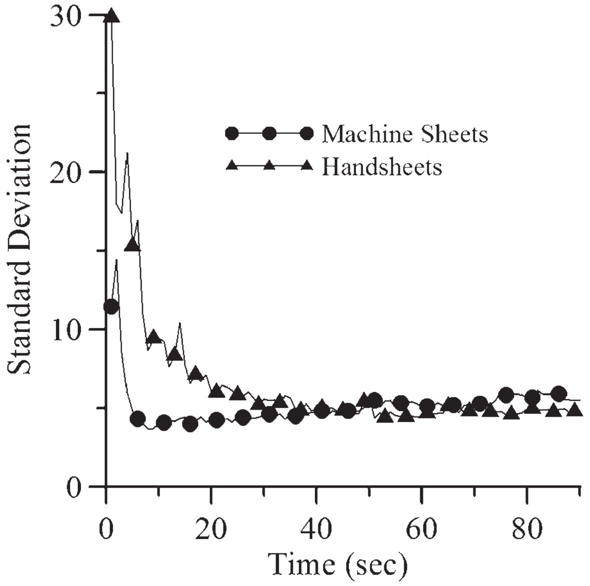

Figure 11 Variation of the standard deviation of the shortest distance between bubbles.

cussed earlier, it is possible that vapor leakage at the interface reduces the degree of foaming.

The position of each bubble was tracked during foaming. Coalescence is most likely to occur between adjoining bubbles, such as the clustered bubbles in Figure 3 (left panel) as opposed to the isolated ones (right panel). The distance between a bubble and its nearest neighbor was calculated for all the bubbles in the image at various stages of bubble formation. Figure 11 shows that the standard deviation of the mean of these distances drops sharply and levels off at about 10 s. This is also the time at which the number of bubbles in bin 1 in Figure 10 peaks because coalescence begins at this point. The machine-made sheets experience a sharper decrease in the standard deviation because a more uniform bubble distribution promotes coalescence.

CONCLUSIONS

This study elaborates on the mechanism of foaming on paperboard and identifies the dependence of the bubble count and foam thickness on the paperboard and polymer properties. There are two elements to foaming: the number of bubbles and the thickness of the foam. Optimal foaming occurs when a large number of pores are uniformly spaced and the internal structure of the substrate (paperboard) presents several low-resistance paths for the vapor to feed the bubble growth at different pores. The final bubble size distribution primarily depends on the size of the pore, the thickness of the polymer, the vapor flow rate into the pore, and the degree of coalescence. The bubble count is controlled by the uniformity of the paperboard surface. Foaming is caused by water vapor escaping from the board through the pores at the interface and into the molten polymer. Thus, the distribution of the paperboard pore structure controls the number of bubbles formed and their distribution. Clustered bubbles are able to coalesce to form larger bubbles. As expected, the properties of the polymer and the film thickness do not influence the number of bubbles created, at least within the range studied. In contrast, the thickness of the foam depends principally on the properties of the polymer rather than those of the board. The foam thickness fell as the extrusion speed at which the polymer was deposited onto the paperboard increased. It is likely that the faster speed caused poorer bonding between the polymer and paperboard and promoted vapor leakage from the interface during foaming.

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