Optimizing the Cut Sheet Thermoforming Process with Syntactic Foam

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Abstract

Common problems encountered in the cut sheet thermoforming process include thin spots, webbing, poor part definition and plug/pusher mark off. Syntactic foam can be used in various ways with both positive and negative tooling to alleviate these issues. Syntactic plugs result in improved material distribution leading to opportunities for down-gauging. Compared to other common plug/pusher materials such as wood and felt-covered wood, syntactic foam results in minimal plug mark-off and improved plug durability. The diverse uses of syntactic foam will be covered along with two case studies that illustrate its benefits.

Background

Syntactic foam is class of material containing pre-formed hollow spheres held in position by an epoxy, a urethane or a thermoplastic binder. For heavy gauge thermoforming grades of syntactic foam, the most common combination is hollow glass spheres bound together in an epoxy matrix. A magnified view of hollow glass microspheres is shown in Figure 1. The resulting product, easily machined to smooth surface, is approximately 50% air by volume.

This high air content gives syntactic foam its key property of low heat transfer. The thermal conductivity of commercially available grades typically ranges from 0.11 to 0.19 W/m°K. This low heat transfer property makes syntactic foam an ideal material for use in the thermoforming process to address any issue caused by excessive cooling of the sheet being formed.

Figure 1. Hollow glass microspheres.

Traditionally, cut sheet thermoformers have used forming assists called plugs and pushers to improve material distribution and quality of parts. The term plug applies to an assist that is used to pre-stretch the sheet being formed across the entire area of the tool. Typically, plug volume is equal to 80 to 90% of the tool volume. The term pusher applies to an assist that is used to pre-stretch the sheet in a localized area. Syntactic foam has become popular as a replacement for plug/pusher materials made of wood, felt covered wood and aluminum.

One of the critical properties of a plug/pusher material is low heat transfer to ensure that chilling of the sheet during contact with the assist is minimized. In order to meet this requirement, the material needs low thermal conductivity, low specific heat and the ability to maintain uniform temperature. Coefficient of friction at the plug/sheet interface is also critical since this will determine how much material the plug/pusher can carry into the tool. Coefficient of friction is dependent on the plug material itself, the sheet being formed and the sheet surface temperature. A high-friction plug assist material will tend to pull more material into the tool and require smaller plug geometry (greater clearance between the plug and the tool). Conversely, a low-friction assist material will tend to require larger plug geometry.

Other important plug/pusher properties are: durability/stability, value/cost ratio, machining/preparation characteristics and design predictability. Toughness of the material will determine how well it survives the production environment. Ideally, the material should be dimensionally stable with a low coefficient of thermal expansion and be non-hygroscopic. Hygroscopic materials such as wood tend to swell in humid environments and contract and crack in dry environments. The plug/pusher material should be consistent from lot to lot to achieve good design predictability.

Traditionally, wood, felt or foam covered wood, and aluminum have been used as plug assist materials for cut sheet thermoforming. Wood and felt are good insulators, easy to machine and low cost. However, wood is not dimensionally stable. The coefficient of thermal expansion is dependent on the grain direction so it can be difficult to build a dimensionally stable part. In addition, wood is hygroscopic and will change dimensions as the relative humidity of the environment fluctuates. Although wood is a good insulator, it tends to build heat over time which leads to poor part repeatability. Wood "marks off" on the part being formed. Covering wood with felt can reduce mark-off but felt can stick to the sheet being formed. Finally, wood has limited temperature resistance.

Aluminum is commonly used as a plug assist for heavy gauge applications. The benefits of aluminum include its durability and excellent surface characteristics. However, aluminum does not meet the key attribute of low heat transfer. Aluminum has high thermal conductivity and readily transfers heat. In order to get an aluminum plug to work well, it must be heated and the temperature has to be precisely controlled. Aluminum is high cost material and heating the plug increases the cycle time.

Unlike aluminum, syntactic foam does not require heating and temperature control. Syntactic foam is also lightweight, heat resistant and dimensionally stable. Syntactic foam has low coefficient of thermal expansion (ranges from 18 to 23 x 10^{-6} in/in^{o}F) and is not affected by humidity. Syntactic foam has been engineered specifically for use with thermoformed plastics and is available in a variety of grades to control the surface friction and release characteristics. The disadvantages of syntactic foam are cost and manufacturability. The cost ranges from about $500 to $1,000 per cubic foot. The manufacture of large plugs can be challenging but major advances have been recently made.

Syntactic Foam with Positive Tooling

When most people think of syntactic foam as an assist for thermoforming, they think of it being used as a positive plug or pusher with negative tooling. In reality, syntactic foam may be used anywhere that excessive cooling of the sheet is an issue, often with positive tooling used as a negative plug or pusher to eliminate webbing and improve material distribution. Improved material distribution allows for down-gauging of the starting sheet thickness and therefore offers opportunities for raw material cost savings. Examples of full size negative plugs, which are approximately 24 inches x 36 inches, are shown in Figures 2 and 3.

Figure 2. Full size negative plug assist.

Poor part definition around sharp details on a positive mold is an issue which can be addressed with a syntactic foam mold insert. Since the foam has low heat transfer, the sheet will have more time to conform to the mold surface before chilling off. For the same reason, syntactic foam can be used on the clamping frame. Excessive chilling of the sheet in the vicinity of the clamping frame can be an issue

Figure 3. Full size negative plug assist.

when high heat transfer materials such as steel and aluminum are used. Syntactic foam on the clamp frame will minimize chilling of the sheet giving it time to stretch properly before solidifying. Another use for syntactic foam with positive tooling is prototype or low volume tooling for applications such as windshields for recreational vehicles.

Syntactic Foam with Negative Tooling

When syntactic foam is used as a positive plug or pusher with negative tooling, the function of the foam is to pre-stretch the polymer sheet to provide better material distribution. Improved material distribution eliminates thin spots and webbing while providing an opportunity to down-gauge the starting sheet thickness. Compared to other plug assist materials, syntactic foam provides better clarity and gloss while minimizing chill marks. In addition, process consistency and productivity improves.

When deciding whether to go with a full-size plug (80 to 90% of cavity volume) or a pusher, run volume is one of the main considerations. For parts run in high volume, the cost of a full-size syntactic plug can be easily justified by the 15 to 20% savings per part. The bulk of this savings is achieved through better material distribution which allows for down-gauging of the starting sheet thickness. In addition to raw material cost savings, down-gauging leads to reduced cycle time and lower energy costs. A thinner sheet will require less time and energy to heat up and cool down. Other considerations when deciding between a plug and a pusher are design requirements, equipment limitations and the limited history of plug design for cut sheet.

While the manufacture of large full-size plugs can be challenging, the manufacture of pushers is relatively straightforward. Syntactic foam producers supply the foam in standard stock sizes of sheet and rod. Small pushers can easily be machined from a standard stock size as illustrated by the fog light cavity pusher in Figure 4. If a the pusher geometry does not fit well with a standard size, syntactic producers can either custom cast a near-net billet or custom cast directly into a part or mold.

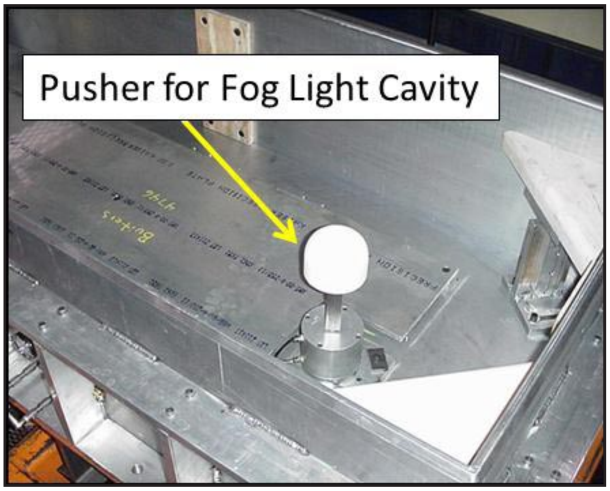

Figure 4. Fog light cavity pusher.

Large plugs can be manufactured in different ways. If the plug is made of wood, pieces are often bonded together and then machined. Downsides to bonding include mark-off on the thermoformed part due to bond lines, coefficient of thermal expansion mismatch and cracking. Alternatively, if a large plug is made of syntactic foam, it can be formed as a solid syntactic casting or made from a two-part system. Heat generated as the epoxy cures limits the size of solid syntactic castings to 12 to 15 inches in thickness. Too much heat results in stress in the finished part, which can then lead to cracking of the plug. Too high of an exotherm can cause stresses in the finished part which can then lead to cracking.

A unique two-part system has been developed to manufacture plugs greater than 15 inches thick. The system consists of an inner core made of reinforced composite spheres and an outer shell of solid syntactic foam, as shown in Figure 5. The composite core reduces stress in the final part. The core also reduces the weight and cost of the part compared to a solid syntactic.

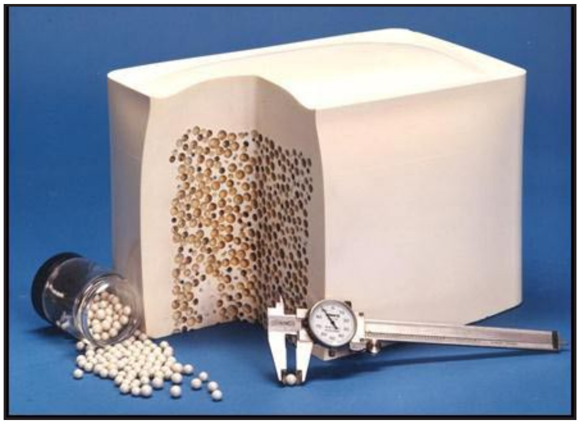

Figure 5. Two-part large plug system.

The two-part system is available in several different types of syntactic foam including epoxy-based, copolymer syntactic and copolymer syntactic with PTFE. Epoxy-based syntactic is an entry-level material that provides good material distribution at low cost. However, it is dusty to machine and tends to be brittle, lowering its abuse resistance. Copolymer syntactic is a new class of material that offers improved toughness and durability versus standard epoxy syntactics. The unique composition forms chips rather than dust when machining and improves the processing of the material. In addition, copolymer syntactic improves material distribution while reducing mark off. Copolymer syntactic with PTFE has good durability and machinability with the added benefit of excellent release of tacky materials.

Large plugs made of the two-part system can either be manufactured as a custom cast or a near-net billet. During custom casting, a customer part or mold is used as the starting cavity. As illustrated in Figure 6, the composite core is formed smaller than the cavity to allow for a solid syntactic shell. The core is then placed in the cavity and syntactic is cast around and through the core, as shown in Figure 7. The part is cured at a low temperature, demolded and post-cured to minimize stresses and maximize durability. Figure 8 shows the finished plug made from the customer part shown in Figure 6.

Figure 6. Customer part and core.

Figure 7. Syntactic is cast around and through core.

Figure 8. Finished two-part plug.

If a part or tool is not available to cast into, a two-part large plug can be made as a near-net billet. In this case, a low cost wood mold is made slightly larger than the finished size to account for machining. The composite core is made smaller than the wood mold to end up with a solid syntactic shell along the outer surfaces. The core is placed in the mold and syntactic is cast around and through it. An example of a near-net two-part billet is presented in Figure 9. The near-net billet would then be processed at a machine shop to the final plug dimensions.

Figure 9. Near-net two-part billet.

Case Studies

In order to illustrate the benefits of syntactic foam over other materials for plug/pusher applications, two case studies were run. The first case study involves a pusher application while the second study shows the benefits of a full-size syntactic plug.

In the first study, a pusher material comparison trial was run for a truck parts manufacturer. The manufacturer was forming truck bedliners from 0.195 in black HDPE sheet with an anti-skid layer on one side. The anti-skid layer became tacky during the forming process and transferred to the surface of the wood pushers being used to pre-stretch the corners. The pushers required a high degree of maintenance and caused significant downtime due to the build-up issue.

To simulate the application, plugs made of wood, HYTAC®-W (W), HYTAC®-WF (WF) and HYTAC®-FLXT (FLXT) were evaluated. W and WF are standard epoxy based syntactics while FLXT is a copolymer syntactic that is impregnated with PTFE for excellent release properties. Sheet surface temperature was varied from 450°F to 610°F. To evaluate the results, the plugs were assessed visually for signs of build-up and any deterioration. In addition, the formed parts were cut in half and measured for thickness along the cross-section.

The wood and W plugs had issues with immediate build-up of the anti-skid layer on the plug surface even at the lowest sheet temperature of 450°F. The wood plug exhibited poor durability and started to crack and splinter at 500°F. With the W plug, some of the microspheres on the surface of the plug pulled out of the epoxy matrix due to the tacky nature of the anti-skid layer. The WF and FLXT plugs showed no signs of build-up until the sheet temperature reached 600°F. Of the two materials, FLXT had the least amount of build-up and was easily wiped clean. At 600°F, the sheet was smoking and there were concerns that the HDPE would degrade. Both WF and FLXT exhibited excellent durability and showed no signs of deterioration.

In terms of material distribution, the syntactic foam plugs performed better than the wood plug at optimum sheet surface temperatures of 450°F to 520°F. Within this temperature range, the average minimum thickness achieved with syntactic foam was 0.012" greater than that achieved with wood, as illustrated in Figure 10. The wood plug was capable of providing higher minimum thickness values but only at extremely high sheet temperature between 600°F and 610°F. The syntactic plugs allowed the sheet to be run at lower temperatures than the wood plug and still achieve acceptable minimum thickness values. The data indicated that the starting sheet thickness could be down-gauged by 5% with a syntactic plug.

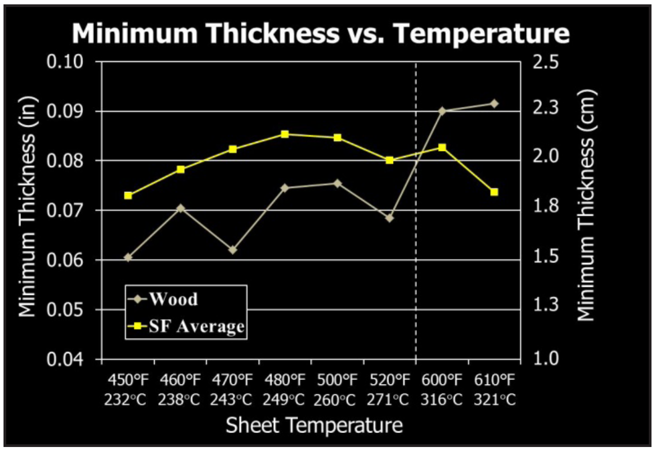

Figure 10. Minimum thickness.

The first case study showed that FLXT could be used to minimize plug build up and improve plug durability. These improvements lead to significant savings due to lower maintenance costs and less machine downtime.

In the second case study, the benefits of a full-size two-part syntactic plug assist were assessed for an appliance manufacturer. The manufacturer was forming a 17 foot^3 (0.48 m^3) freezer linerout of 0.170 inch (4.32 mm) thick HIPS using a full-size heated aluminum plug. The corners of the liner were below the minimum target of 0.030 inch (0.76 mm) and had to be reinforced in a secondary operation. The goal of the project was to achieve material cost savings and eliminate the reinforcement step.

Trials were run on a Brown rotary four station machine with the following stages: 1) Preheat – gas catalytic preheat on both sides of sheet, 2) Heating – ceramic heaters on both sides, 3) Forming – positive plug on top, negative tool on bottom, and 4) Load / Unload station. A baseline trial with the standard 0.170 inch (4.32 mm) thick sheet and heated aluminum plug was run. Then the changeover to the syntactic plug shown in Figure 11 was made and trials with 0.170 inch (4.32 mm) and 0.150 (3.81 mm) sheet were run. When the changeover to the syntactic plug was made, the cycle time per stage was kept constant at 59 s but the heat input was adjusted to account for the low heat transfer properties of the plug. In addition to eliminating heating of the plug, the gas catalytic preheat step was eliminated. To evaluate the results of the trials, ultrasonic thickness measurements were made in forty-four locations per liner.

Figure 11. Syntactic foam plug for freezer liner.

The material distribution results for the trials are shown in Figure 12 with a plot of thickness versus location. In addition, a table with the thickness values is included in Figure 13. The white line shows the data for the heated aluminum plug. As seen in the plot, the critical corner thickness is well below the minimum target of 0.030 inch (0.76 mm). In addition, there are extreme high spots on the back and bottom of the liner. The yellow line shows the data for the combination of the syntactic foam plug and the 0.170 inch (4.32 mm) sheet. The thickness of the critical corner area increased 58% by switching to the syntactic plug. The green line represents the data for the syntactic plug with the 0.150 inch (3.81 mm) sheet. Even with the down-gauged sheet, the syntactic plug increased the corner thickness by 38% and met the minimum requirement of 0.030 inch (0.76 mm).

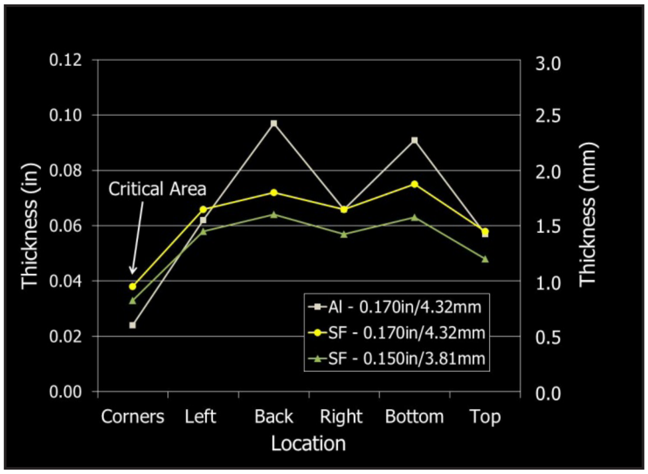

Figure 12. Freezer liner thickness profiles.

Starting Sheet Thickness:	0.170 in 4.32 mm	0.170 in 4.32 mm	0.150 in 3.81 mm
	Plug Type		
	Aluminum	Syntactic	Syntactic
Corner – Average Thickness	0.024 in 0.61 mm	0.038 in 0.97 mm	0.033 in 0.84 mm
Increase vs. Aluminum		0.014 in 0.36 mm	0.009 in 0.23 mm
Increase vs. Aluminum		58%	38%
Corner - Relative Std Dev.	38%	13%	24%
Overall - Relative Std Dev.	25%	12%	15%

Figure 13. Freezer liner thickness data.

The second case study illustrates the benefits of a full-size syntactic foam plug versus a heated aluminum plug. The manufacturer was able to reduce material cost by 12% through down-gauging while secondary reinforcement of the corners was eliminated. In addition, significant energy savings were achieved through elimination of both the gas catalytic preheat step and heating of the plug. Based on material cost savings alone, the payback for the syntactic plug was two weeks.

In conclusion, syntactic foam offers improvement anywhere that chilling of the sheet causes issues with cut sheet forming. It can be used with positive or negative tooling as a plug/pusher to improve material distribution, eliminate webbing and allow for down-gauging. With full-size plugs, using syntactic foam instead of other materials can result in a 15 to 20% total cost savings. Syntactic foam can also be used on the clamping frame and as prototype tooling. The benefits of syntactic foam include no bond lines, improve durability compared to other materials, ease of machining and minimal mark off.

Author

Kathleen Boivin is a Materials Engineer at CMT Materials, Inc. working in process and materials development of syntactic foam for thermoform tooling. She has a career history of development of polymer products and processes working for diverse companies such as Texas Instruments, Mobil Chemical, Eastman Kodak, Bixby International and Fortifiber Corporation. Ms. Boivin holds a BS in Chemical Engineering from Clarkson University and an MS in Plastics Engineering from the University of Massachusetts at Lowell.