must be incorporated into the pattern and mold sizes. Thermoplastic materials expand and shrink when subjected to temperature changes and will therefore experience shrinkage after cooling. For the control of size reduction after forming, the molds are purposely built oversized to compensate for shrinkage. Once the maker is armed with the correct shrinkage rate for the particular plastic, building oversized molds will eliminate most surprises from resulting shrinkage. This is particularly important when producing mating components that must fit together correctly; for example, containers and their lids must have a snug, snap-action fit to serve their purpose.

Each particular type of plastic displays its own shrinkage rates, which should be specified by the specific resin manufacturer or supplier. The shrinkage rate and its range depend largely on the type of resin and its molecular weight or blend. For general purposes, a wide range of shrinkage rate can be used. However, for critical dimension controls, those numbers should be narrowed down to the actual shrinkage values. Table 1 provides the wide shrinkage ranges of some of the most popular thermoplastic materials used in thermoforming.

The shrinkage rates for a critically important fit should be specified and when material changes are anticipated, the material shrinkage levels must be matched between the old and new resin supplies. Discrepancies among shrinkage rates are one of the main causes of improper fitting results between previously well-fitted parts and put a damper on quick, hastily made material substitution. It should be noted that some thermoplastic materials can have such a great shrinkage change that it may affect the product fill capabilities or container capacity of a thermoformed receptacle. Such variations in shrinkage must be investigated before full-scale production is attempted.

In the pattern-making procedure, the pattern itself usually represents an intermediate form of tooling where the pattern should be converted into a more permanent type of tooling. Patterns are generally made of wood, such as gelutong, mahogany, basswood, or sugar pine. These high-quality, uniform-grained woods are ideal to work with for shaping and piecing together a pattern or mold form. Other woods are just as usable, but due to their grain irregularities, the maker must be extremely selective as to what portions of the lumber are usable. Using a choice wood quality usually provides some saving in the labor phase of pattern-making projects. Local wood material availability is also a guiding factor as to the selection of one type of wood over another.

Table 1 Thermoplastic Shrinkage Rates

Material	Shrinkage range (in.)
ABS	0.004–0.009
Polyester	0.015–0.025
Polyethylene	0.015–0.050
Polypropylene	0.010–0.025
Polystyrene	0.002–0.006
PVC	0.001–0.006

The wood pattern by itself can be used as a temporary or sample-making mold. Using wood as a mold material can only be considered temporary. The wood itself does not keep its original dimensions accurately. Ambient humidity conditions may decrease or increase the size of the wood. Since a pattern or wood mold is made up from several pieces of different grain-line direction, each piece may acquire a change in its own dimension, causing "stepdown" or overhangs among the pieced-together components. For that reason, wood molds should be considered only interim structures. It is also true that wood materials provide poor heat transfer qualities. In repeated thermoforming use, each surface contact between the heated thermoplastic sheet will eventually raise the wood mold's temperature to the same heat level as that of the plastic sheet itself. Since the mold's retained heat does not allow sufficient cooling for the plastic to set, the mold will not render any useful quality for further thermoforming past a certain point. At this point, the operation has to be shut down until the heat in the wood mold dissipates. This poor heat transfer quality will never allow reasonably fast cooling times, thus causing long periods of waiting.

When wood patterns are made for temporary molding purposes only, they are made larger than actual size to compensate for the plastic's shrinkage. When the patterns are used for the purpose of casting to produce the permanent metal molds, additional shrinkage factors must be incorporated. This additional shrinkage factor is built into the patterns to account for the shrinkage that takes place when the molten metal cools down. Pattern makers often use "shrink rules" for this purpose. These special rulers resemble standard measuring rulers except that a shrinkage factor is built into their calibration. For example, with styrene materials together with aluminum tool casting, a $^{7}/_{32}$-in. shrink ruler is used. This ruler has $^{7}/_{32}$ in. of shrinkage per foot incorporated into its calibration. The $^{7}/_{32}$-in. shrinkage designation combines a $^{1}/_{16}$-in. allowance for the styrene shrinkage and a $^{5}/_{32}$-in. allowance for the aluminum castings shrinkage. With this total shrinkage allowance, the actual pattern is built to oversized with proportional size increases that have been distributed over all of its dimensions.

When the proper amount of shrinkage is not included into the mold, the outcome of the molding will be a proportionally undersized part. This is true especially when copying an existing item where the newly created mold shape is duplicated directly from an already thermoformed article.

C. Basic Mold Constructions

One of the most beneficial reasons for choosing the thermoforming process over other manufacturing methods is to make useful plastic products with substantially lower mold costs. The mold can be made much more easily and from less costly materials. Both of these factors can be so overwhelmingly advantageous over the tooling costs of other manufacturing methods that this alone often determines the choice of the thermoforming process over other process techniques. The reduction in tooling cost, however, is not the only reason for this choice; the higher output production rates create equally advantageous benefits.

1. Mold Materials

Making molds for the thermoforming process can be accomplished using a wide range of materials. The first thing the user has to establish is the size of the production run. The thermoforming process can be applied feasibly to a short production run and a "temporary" mold can be used for the job. Long production runs that produce a high volume of products need a more durable and "permanent" type of mold. For either purpose, different mold materials should be used, and with them, matching related tooling cost can be obtained. The less costly tooling materials are easier to work with and assemble; however, their life expectancy and dimensional stability make them useful only for temporary or short-term molds. On the other hand, specially treated metallic molds can have substantial "permanence" and years of production longevity unless premature damage or lack of product sales force them to be shelved.

As mentioned earlier, wood is a popular tooling material for thermoforming. Most patterns and temporary molds are made of wood; they can be shaped and worked by all common woodworking tools. Complicated shapes can be put together in sections or segments rather than as a single piece, making them easier to build. The pieces can be glued, nailed, and screwed to one another, creating the final structure.

When the woodworking procedures are finished, a sealing compound can be used to coat and protect their outer surfaces. Vacuum holes and air channels can be built into the wood structures together with metallic threaded mounting inserts. The use of threaded metal inserts is a good idea because frequent screw removal will wear and damage mounting holes used repeatedly. In addition to all the aforementioned advantages, wood molds will usually be subjected to frequent modifications. The ability to make alterations, such as adding or removing surface patterns, makes wood the ideal material for experimental mold making.

One of the drawbacks to wood molds is their reaction to humidity, which causes dimensional changes which affect the highly accurate and sensitive mold dimensions. Another, more serious inadequacy is that the wood itself will retain the heat placed into it by thermoforming. A wood mold quickly becomes unusable due to its noncooling tendency. This will force the thermoforming operations to shut down until the wood mold can cool down. Since wood is an insulating material, cooling may take several hours and may stop the operation entirely for the day. This heat buildup in a wood mold is obviously the direct result of the molding frequency. With fewer molding cycles, the heat buildup will not be as severe or start as soon.

To improve on wood mold qualities and make molds with improved durability, the wood patterns can be converted into plaster or epoxy form. These higher-grade materials provide better dimensional permanency and maintain their quality over a longer period of use. The mold's life expectancy is expanded together with the length of operation. The higher densities of plaster and epoxy make the molds stronger and give them more heat absorbency. The plaster mold is usually made of "hydrocal," a cementlike grade of plaster compound. The white powdery hydrocal is mixed with water to create a slurry, which displays a good liquefied, pourable viscosity. The slurry is poured over the wood pattern, which is prepared with a retaining frame surrounding the pattern body. Prior to the casting, all exposed surfaces of the pattern and the accompanying frames must be coated with some type of release agent. Wax or lacquer mixed with oil compounds or silicon greases provide excellent release after the hydrocal has set. To avoid a large amount of air entrapment or air bubble collection, the slurry viscosity is substantially thinned. After pouring the mixture, the entire setup is subjected to vigorous shaking on a vibrator table to force the bubbles out of the slurry. It might also be placed in a vacuum chamber to undergo air bubble evacuation. With either method, the trapped and encapsulated air is reduced, making the poured casting internally more solid and with fewer surface imperfections that must be patched up later. After the hydrocal has set, the pattern and the hydrocal are separated. The hydrocal will display a reversed impression of the original pattern. If duplication of the original pattern is desired, a repeated hydrocal casting is made. Two things must be remembered when using hydrocal. One is that a moisture-resistant release agent must be used to avoid adhesion of the casting to the original pattern or previously made pattern. The surface bonding can be so severe without the proper release agent that any attempt at separation of the two sides will result in the destruction of both. The second factor to remember is that hydrocal molds must be completely dry before thermoforming is attempted. The heat generated by the process converts the retained moisture into steam within the castings and will develop enough internal pressure to cause cracking or even rupture of the molds. After complete drying, the mold can be sealed with a sealant compound and, if necessary, have pieces inserted or other materials glued to it. A broken or chipped hydrocal mold can easily be mended or patched. The size of repairable damage depends on the repairman's skills and the thermoforming criteria encountered. The repair work may take more effort than that needed to make another hydrocal casting.

There are toolmakers and pattern shops that prefer to work with epoxy casting materials. In this type of casting, the water-based castings of the hydrocal method are replaced by a non-water-based two-part epoxy chemical substance. Since water is not used to create a pourable media, the wood pattern will not experience the pattern reaction to moisture that it does with hydrocal. Epoxy will also not produce grain raising and dimensional moisture-related changes. On the other hand, it may take longer to set up and will generate a much higher level of heat in the setting phase. The higher level of heat generation can be just as destructive or damaging to the pattern as moisture. If low-melting-point components such as wax filets are used in the original patterns, they will be melted away, creating an alteration in the final configuration. All these factors must be worked out prior to casting. Without the use of a proper release agent compound, the epoxy casting material can also lock against the casting surfaces, and removal will inevitably result in disaster.

Epoxy molds offer much improved surface details, dimensional stability, and structural strength. Their density and durability make them ideal materials for making low- to medium-production-volume molds. Their dimensional stability is excellent and their heat absorbencies are not poor, but they are, of course, no match for metallic molds. The heat-transferring quality of the basic epoxy materials can be substantially improved by blending in small metallic particles. Aluminum powder, pellets, shots, and even needles can be blended into the epoxy mass. Their purpose is to improve the epoxy's heat-transferring qualities and at the same time, boost its strength. The closely packed metallic particles tend to allow better heat channeling between the embedded pieces. Further improvements can be obtained by embedding cooling lines of metal tubing. Mold coolant can be circulated through the tubing to enhance greatly the material's cooling ability.

The two-part epoxy materials are usually purchased in premeasured cans. When the two compounds are mixed together, they react to form the epoxy compound. Each epoxy material has a different "pot life," which is the amount of time the material takes to set up after mixing. Shorter pot life makes the casting harden more quickly but allows less time for the mixing and blending of the metal fillers. A longer pot life is more advantageous for getting rid of the entrapped air bubbles that have worked themselves into the mixture. Working with epoxy castings does require some skill to achieve choice mold replicas; such skills are improved when working often with this material. Epoxy suppliers are usually very helpful and will come to the aid of the unexperienced practitioner. Epoxy molds, with their durability, can be considered as production-type molds, ideally suited to short to medium-sized production runs. A well-constructed epoxy mold can be expected to perform well for up to several million production units without major breakdown or failure.

The last group of mold materials are the metallic molds. Metal molds can be produced out of a wide range of available basic metals or their alloys. There are two basic methods for shaping metals into a mold configuration. Metals can be heated, liquefied, and then poured into castings, or they can be mechanically cut, milled, and turned into the desired shape on regular metal-working equipment. Metal tools have substantial permanency and therefore qualify as "permanent" molds. With additional surface treating they can be made virtually indestructible. Of course, like anything else, if they are subjected to abnormal use or abusive practices, they can be destroyed. Metal molds offer the most outstanding heat channeling and heat transfer qualities. This makes them ideal as cooling surfaces for the forming of hot thermoplastics. The most popular metal used in the mold making for thermoforming is aluminum. This metal is ideal because it has specifications that fit the thermoforming process best. Aluminum is lightweight and easy to work with on any common toolmaking equipment. It has one of the best heat transfer qualities among the inexpensive materials. On top of this, aluminum does not corrode easily like steel does. Aluminum's only shortcoming is that it is soft and easily damaged by nicking, scratching, or banging. Otherwise, it is the most ideal mold material in use today and for that reason is the most commonly used.

There are other metals used for mold production that are not as popular as aluminum but are demanded by specific conditions or situations. Brass or titanium alloys provide a much stronger mold composition, making them far more damage resistant than aluminum. They are also less vulnerable to corrosive environments, and tooling made out of them will probably outlast the life expectancy of most product designs. Tooling made of steel or brass alloys can be chromed or nickel plated if the product criteria demand it. They can also be Teflon coated for helping in the release of the formed articles. The possible variations of metal mold composition can be as complex and wide ranging as the thermoforming process itself. Many different materials based on different concepts and intended purposes can be used. Innovation in mold-making technology is a perpetual process. In time, more thermoforming ideas will be developed together with many variations of tool-material combinations.

2. Mold-Making Methods

With all the mold materials available, the mold maker has several options. First, a decision has to be made as to whether a male or female mold is the correct choice for the final mold configuration. Second, plans should be made as to how best to achieve the specific mold features and design as well as the mold arrangements. When all this information has been collected, the third critical factor to be determined is how many thermoformed articles will be needed. Having answered all three basic questions, the tooling-up procedure can begin. The number of articles needed will dictate whether the mold is to be used for temporary, short-term, or long-term production. For small-volume production, molds made of wood, plaster, or epoxy would be the best choice. With at least some basic pattern-making skills, simple-configuration molds can easily be constructed and if necessary, converted from male to female, or vice versa. Sufficient sidewall angles and large radii on the mating surfaces can minimize the release problems when casting is produced. It is not possible to create negative or reversed draft angles or undercuts in any of the castings, and attempts to do so will lock the casting and the original pattern together, prohibiting their separation. All epoxy and most plaster casts will hold their original sizes after casting; however, there are some unique expanding plaster compounds which, after casting and cast removal, tend to grow in size. Such materials may be capable of expanding after casting to gain some of the shrinkage allowances required in plastic production. However, the mold maker should not place too high an expectation on the outcome, and the expanding plaster should be used with some caution. The expansion this material experiences is not in true proportion and some areas may gain satisfactory amounts of shrinkage compensation, whereas others will not, resulting in some design distortion.

As stated earlier, short-run production molds can be made of wood, plaster (hydrocal), or epoxy materials. A cautionary note: These materials are not intended to make molds for pressure-forming techniques, as they do not offer the structural strength and stability to take the force usually induced by pressure-forming methods. Pressurized molds receive on the average 15 to 100 psi of pressure; this could turn these molds into potential bombs, causing them to rupture and even explode. No attempt should ever be made to use these weaker materials for pressure-forming methods.

Large molds for sheet-fed thermoforming operations can also be made out of fiberglass materials. This type of mold is usually made by the customary fiberglass lay-up technique. In this mold-making method, a pattern or sampling shape is used for the lay-up or spray-up of the fiberglass material. Naturally, the pattern or model surfaces are treated with release agents for ease of separation after the fiberglass sets. Fiberglass molds are generally made with thick gel coats to provide strong, solid surface coating; the fiberglass itself will provide the structural strength. Depending on the mold size, fiberglass molds can have from 1/4- to 3/4-in.-thick sidewall members to give sufficient mold integrity for the thermoforming process. The fiberglass material itself provides good heat-absorbing qualities when making surface contact with the heated thermoplastic sheet. Its cooling abilities can be improved further by fan-forced air cooling between the forming cycles. The use of fiberglass molds is employed mostly when large products are thermoformed, such as spas, boats, and large tubs or shower enclosures. The manufacturing speeds and production modes of these products are well suited to this type of mold structure. Fiberglass mold-making methods are also one of the most cost-effective ways to produce molds and to obtain duplicate molds from existing articles. For this particular mold-making procedure, no knowledge or equipment is needed other than the customary fiberglass technology, which is easily acquired. Numerous articles and books are available on fiberglass form-producing procedures.

Molds fabricated from any of the popular tooling metals can be produced by one of two basic fabricating methods. Metals can either be cast into shapes or machined out of a solid metal block. In both cases the metal material content will afford the most durability in strength and long-term service life. The high density of metals provides the best heat exchange rate and therefore the best efficiency in mold cooling. Of course, depending on specific thermoforming criteria, one metal could outperform other metals, which certain metals may not function well at all. Higher costs can also preclude the use of certain metals.

Actual metal molds consist of two basic body components: the mold body and its mounting plates. With metal molds it is most common to produce the mold body out of a softer metal such as aluminum while its mounting plates or surrounding frames are made from harder metals, such as steel. However, it is not inconceivable to choose aluminum for the entire mold construction. Also, there are molds for which most of the components are made out of steel, with portions containing hardened tool steel segments.

The actual body of the mold, which performs the thermoforming function, can consist of just female cavities or just male mold structures or both. The complete molding tool consists of the mold body, the mounting structures, and possibly, elevating "stand-off" legs. Each component of the mold serves a specific purpose. The mounting plates provide the mounting surfaces for the individual mold body or bodies when multi-up mold formats are concerned; they are also used for mounting the mold to the thermoforming machine platens. The stand-offs fill and compensate for distances that are left between the sheet line and the platen's daylight opening, so the mold can close right at the sheet line. The two halves of the mold body must meet when the platens close and must do so in close proximity to the sheet line for ideal forming conditions. If the mold halves mate out of the sheet's stretch range from the sheet line, they will cause undue strain on the outside edges of the sheet and may pull it out of the holding or even cause it to tear. Under- or oversized mold stand-offs always render incorrect mold matings and therefore prevent thermoforming. The correct mold surface elevation to the sheet line should be a part of the specifications for any thermoforming machine. This distance is established by subtracting the combined height of the complete mold body when closed, including the base and mounting plate thickness, from the total platen movement distance. For the purpose of mold weight reduction, the stand-off components can be made of aluminum instead of steel or can contain a number of large cutouts.

In making any metallic mold body, there are two basic manufacturing techniques. The first consists of making the mold configuration by metal casting. In the casting of any metal, a premanufactured pattern is used. The pattern for any metal-casting procedure can be made with any number of design intricacies together with the necessary shrinkage allowances but cannot contain undercut or reversed dart angles. As described in Section I.B, the pattern itself is usually made larger to compensate for both the natural metal cast shrinkage and the plastic material shrinkage, which occur after the forming cycle of the thermoforming.

The various types of casting procedures used for making thermoforming molds closely follow the customary metal-casting methods. The most popular casting method is the sand-casting procedure. In this type of metal casting, the pattern is inserted into fine-grained casting sand within a metal core box and then rammed down tightly to compact the sand around the pattern into an almost solid form. The procedure is performed in such a way that either the pattern or the core box is made with separating halves—when the pattern is detailed on both sides—or the pattern is placed adjacent to a core-box surface plate—when the pattern is flat on one side. In this way the compacted sand will duplicate only one side of the pattern. After the sand is rammed, the core box is opened up and the pattern is carefully removed, creating a female cavity impression of the pattern. Another core box is similarly rammed up to carry either a flat surface or the details of the remaining side of a two-sided pattern. The two core boxes are then assembled face to face. Pour-in funnels are created in the compacted sand for filling purposes. When molten metal is poured into this hollow mold through the filling funnels, the flowing metal will fill the cavity. After several hours of cooling, the poured metal will solidify in the cavity. After removal, the metal will retain the details of the sand cavity and duplicate the shape of the original pattern. The quality of the resulting sand cast is, of course, directly related to the ability of the maker. The use of fine-grained sand will make the surfaces and the details of the casting more refined. Skillful placement of the pour funnel and the risers used to eliminate "sinkholes" is very important for minimizing warping and distortion of the casting. Some castings, depending on their various configurations, will develop more shrinkage at their heavier, bulkier points, while thinner areas undergo substantially less shrinkage. Adding risers or body extensions to the heavier areas will draw the shrinkage from the riser itself instead of at critical body areas. Neutralization of shrinkage and warpage depends on the foundry operator's skill. Some foundries are capable of producing uniform and flawless castings, others produce a high rate of unacceptable castings. Quality castings free of distortions, casting flaws, and surface irregularities are vitally important to the success of thermoforming production. Properly made castings will be consistent to one another in dimensions and will require minimal finishing work. There are improved metal-casting methods and casting variations that could further improve the basic sand-casting methods described here. Such casting methods use "plastic/rubber" casting techniques or "permanent mold casting" methods and in their own way, offer unusual design and quality benefits. However, with each improved casting method, the cost of casting will rise. The choice of casting method should therefore be predicated on the level of quality sought for the particular job in order to help keep costs down. Some thermoformed products, because of their material makeup, will display, from one casting to another, higher levels of postforming distortions within themselves than those of sand-casted metal molds. In such a case, the cast mold body tolerance variation would be far less than the postthermoforming results, which would indicate that the casting method to produce the molds is within a satisfactory tolerance level. More often than not, the casting method is well within the range of the thermoforming mold-making criteria and should be given full consideration.

Molds for thermoforming are generally cast of aluminum, but not exclusively so. Other high-quality metals, such as brass or beryllium alloys, are also used. Aluminum is the most popular metal because of its noncorrosive properties, light weight, ease of shaping, and excellent heat conductivity. It is also readily available at reasonable prices. The most popular aluminum alloy used in thermoforming mold making for casting purposes is No. 356 aircraft alloy. This alloy is easy to work with because it is neither soft nor overly rigid. This alloy does not require aging or stress relieving and does not readily gum up on or adhere to the metal-working tools' cutting edges. There are other metal alloys, with different characteristics, which can serve other purposes and may be more advantageous to use. The choice of alloys and base metals is entirely up to the thermoforming practitioner, who should maintain a close collaboration with the mold maker.

Any cast mold components, whether female or male, require some machining and finishing. The mold arrangement is produced in either a one-up or a multi-up configuration. Each set of mold units is cast as individual parts and then fitted and assembled into the common mold format. Each casting represents a single mold unit, and if in the matched mold arrangement, each will consist of a female casting and its separate corresponding male castings. To ensure proper seating on the mounting plates and proper side-to-side alignment between the individual castings, the mating surfaces must be prepared and machined flat and square—as well as parallel to the other mating surface—in order that they can be stacked and fitted together to create the combined mold setup. Since the castings do come out from the foundry with some degree of distortion and surface flaws, it is always good practice to order two or three more castings than the actual mold configuration requires. In this way, the toolmaker will have a number of castings from which to select. The castings will be checked for quality and those that contain higher levels of distortion or critical surface flaws will be rejected. It is also good practice to finish up one extra casting for the specific mold configuration and thus make the individual castings interchangeable. If any of the castings are damaged in the thermoforming process, the available ready-to-mount extra casting could become a real "lifesaver." If any of the nonessential or rejected castings later become obsolete, they can always be sold back to the foundry for their material value.

When any of the casting procedures are used to make molds for thermoforming, the cast surfaces require some preparation. Even with the finest-quality sand, the surface of the cast will retain some of the roughness of the sand grains. The surface of the casting must receive some smoothing and surface refinements. If the casting surface is left as is, the forming plastic will pick up the surface imperfections and display the same roughness. However, the casting surface, when refined, should not need a complete polishing job. Giving a high-quality polish to the surface could be just as harmful as leaving it untouched. A highly polished mold surface is not only time and labor intensive and adds unnecessarily to the tooling cost, but actually has an adverse effect on the mold release of the formed article. After the plastic article is formed, a highly polished mold surface will result in almost perfect surface contact between the mold and the article. Both surfaces are smooth enough to create a contact that will not permit air to penetrate between; this creates a vacuum-like adhesion that will interfere with release of the plastic article. This interference will remain in effect until the mold surface is altered by sandblasting or other means of surface roughening. It is always embarrassing when a highly polished and visually attractive mold has to undergo destructive surface coarsening to make it function better.

When casting surfaces are worked on for thermoforming molds, knowledge and understanding of the thermoforming process will make the mold maker's life easier compared to other mold-making techniques. In thermoforming, the heated plastic sheet forms only over male protrusions and into cavities that have air relief channeling. With any captive cavity that cannot rid itself of the encapsulated air that develops between a mold surface pit and the forming plastic sheet, the plastic tends to bridge over the cavity and not conform to the pits. Armed with this knowledge, the toolmaker should remove and smooth out the high points of the casting surface but need not work into the pitted surfaces to polish them out completely. If not overly heated or excessively forced by the forming forces, the thermoplastic sheet will bridge the pitted mold surfaces and come out of the mold with a smooth, glasslike finish. The same surface criteria will exist with any of the machined molds, and the highly polished finish is just as undesirable with them as with the casted molds.

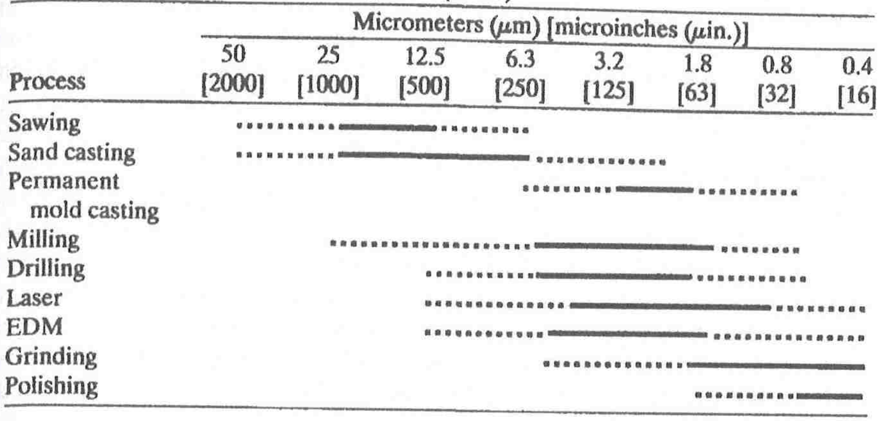
Molds for thermoforming are often made by machine shops on milling machines, lathes, and other customary metalworking equipment. With this type of mold making, tool and die makers will be able to keep tighter dimensional control and far more uniformity among the cavities. In addition, an individual tool shop can have sole manufacturing and financial domination of the entire mold-making project. A mold maker using machining methods to make the mold does not have to get involved with pattern makers or a foundry, which would force a division of the mold-making profits among the shops. However, mold makers who attempt to make the molds by one method only cannot offer the various options of different methods, perform diversified toolmaking, or provide a wide range of price options. In some instances the thermoforming plastic can have far more dimensional distortion by itself than a metal casting would develop. In such cases the casting method is the most satisfactory and economical mold-making method. On the other hand, where the thermoformed products demand outstanding dimensional control from one thermoformed product to another and such consistency is required for a large number of mold duplications, the mold making will rely on the machined quality mold-making technique.

The machined mold-making procedures basically follow all the customary metal machining techniques and are produced on the familiar milling, cutting, sawing, and lathe equipment. The molds are usually cut out of a block of metal which has been selected and purchased for that purpose. They are then subjected to machining, which removes all the excess material. The machine cutting and milling are usually done on a standard mill press using metal-cutting tools that in the milling process create metal shavings and chips. The block of metal is set up on the milling machine table, which moves in two or three axis directions. The depth of the cutting is usually guided by the rotating bit length and by the mill-head distances from the mill table. The movement of the milling table can be guided by an operator or through a computerized equipment setup. The actual milling of the metal, whether done manually or run by automated equipment, is always made gradually, in layers, with the cutaway ending up as an accumulation of metal shavings. The outside surfaces of the mold are milled with the usual multiple passes by the cutting tool until the desired shape and dimensions are reached. At the same time, the inner cavity milling is made by "hogging" out the entire inner cavity of the metal piece. To develop specific cavity contours or radii, special cutting tools are produced for the milling. When specified radii are required for the specific inner corners of a cavity, special cutting tools are ground for that radius so that the milling machine can cut to the exact corner form desired. For flat sidewalls, the milling machine makes a pass on the surface; for a ribbed pattern, the mill will cut indentations at preprogrammed intervals. Automated milling machines can be set up in a robotic way such that the cutting tool follows a preprogrammed path. With automatic milling machines, the entire mold configuration—even in a multi-up mold arrangement—can be cut out of a single piece of metal. Making thermoforming tools out of a single piece of metal is preferred by tool shops but is not in the best interests of the thermoformer. Certainly, it is easy to carve tooling out of a single block of metal using today's automated milling machines. However, if any damage should occur in the thermoforming process, tool repair can result in a lengthy production shutdown. For this reason, a mold assembled from several pieces is a better arrangement for the thermoformer, because the damaged segment can be replaced. The segments can be joined so well that no discernible mating lines will be visible. Although rare, there are mold configurations that cannot be machined out of a single block and are therefore either made with an insert or put together from several components. For that reason, when a single mold unit is pieced together, the adjoining surfaces must be made perfectly or else be made so that the design pattern hides the mating lines. Usually, the corner mating lines or incorporated rib patterns can provide good concealment for adjoining surfaces. Any misalignment between the components will show up on the formed article. This may not jeopardize its functioning but can render either a poor appearance or reveal its mold construction to a competing thermoforming processor.

The machine mold construction, whether in a single mold unit or multi-up mold arrangements made from pieces or from a single block of metal, is made according to the customary metal machining procedure. Qualified metal machining knowledge is required for cutting and milling metals and mold production. Any mistakes made in the metal shaping will be transferred into the plastic through the thermoforming process. For most machined thermoforming molds, aluminum alloys are the most popular material. Again, aluminum is easy to work with, is lightweight, and has excellent heat transfer abilities. However, occasionally brass or brass and beryllium alloys are employed. These exotic and higher-grade metals are frequently justifiable because of their higher resistance to corrosion and surface damage. The machined thermoforming tools obtain a higher-quality surface finish than those made by casting.

There are no standards that could be given for suitable surface roughness. It is always dependent on the specific thermoforming application and the smoothness required in the resulting products. The surface finishes produced by the various machining methods vary over a wide range. Specifying certain metal-working equipment does not guarantee the same surface finish from shop to shop. Table 2 provides a comparison of surface roughness ranges obtainable by the various metalworking methods. Because of the various factors that can affect the surface finish produced by a given machining operation, each shop will provide slight differences in surface finish. It is better to specify surface roughness designation and measurement numbers than specific equipment. As the chart illustrates, an average mill finish will carry 125 rms, while smoothening can refine the surface to 30 rms or better. With a profilometer or tracer instrument, the surface differentiations can easily be established and the finished surface can be made to match most specifications. A surface finish between 30 and 50 rms is smooth enough to work with and permits passage of air between the mold surface and the formed plastic for easy removal. As for inner body imperfections, these will probably not be found in machined tooling. The minimum radius or taper angle of the cutting should not originate with the mold maker. Most specifications requested can be produced, and any limiting factors for those specifications should come from the thermoforming practitioner. Errors made due to overly specified criteria are discussed later in the chapter. The details of actual metalworking procedures are too involved to include here. For further information on these subjects, metalworking or machining publications should be consulted.

Table 2 Obtainable Surface Roughness (RMS)



3. Mold Venting (Air Displacement)

Molds made of any of the materials or mold-making methods described previously must have sufficient venting holes to be functional in the thermoforming process. Through these holes, either vacuum or air pressure (or both) is introduced for the purpose of forcing the heated thermoplastic against the mold configuration. The vent hole placement in the molds is one of the most critical aspects of the molds; without them, the molds are not functional and the entire thermoforming procedure may be disabled. It is through these vent holes and their interconnected channels and plumbing system that the forming forces will be introduced and will force the heated thermoplastic to conform against the mold surfaces. The location and number of vent holes are as important as their size. In the case of a multi-up mold configuration, the interconnection between the individual molds is just as significant as the connection of the first mold to the forming source. The vent hole functions and the actions of forming were discussed in Section I of Chapter 3. The holes placed into the mold must be interconnected by channels in the back side of the mold that travel all the way back to a common plumbing system that connects to the source of the forming force. In the case of a vacuum, the source is a vacuum pump; with pressurized air, the source is an air compressor. The plumbing and all the channeling must be leakproof and be provided with flexible hoses that will not restrict the mold's reciprocating movement. At the same time, the total power of the forming force can be fully realized at the individual mold surfaces. There should be no flow reduction that would restrict the forming power between the mold and the source of the forming force. The errors usually made in this specific area of thermoforming are addressed in Section IV.

The placement of vent holes in a mold is done mostly by drilling. If the mold is cast out of epoxy materials, there is a good chance that instead of drilling, the holes can be cast right into the mold. The technique for making cast-in holes involves the use of small pieces of "piano wire" (hardened steel wire) cut into proper lengths, which are then partly hammered into the pattern surface, which will create an embodiment resembling a porcupine. The wires and pattern surface are well coated with a release agent (e.g., Vaseline) prior to epoxy application. After the epoxy has set, the protruding wires are pulled out of the epoxy cast and the pattern, leaving holes in the casting. The diameter of the wire determines the hole sizes. The determination of the number and location of the holes should follow the common practices used in typical thermoforming mold construction.

Vent holes are usually drilled with the help of power tools, which are either hand held or bench mounted. The actual drilling is done using common industrial drill bits. It is also possible that instead of drilled holes, the mold bottom is made of a separate piece which after installation leaves a narrow slot around its perimeter. Such a narrow gap can also be used for air movement.

a. Vent hole sizes: To begin with, the thermoforming practitioner must establish the maximum hole sizes that the thermoforming process can best handle. The larger the hole size, the greater the forming force that can be introduced through the holes. However, the larger holes can leave marks on the thermoformed article. In most instances, a buttonlike mark will be made by the oversized holes, giving an unacceptable finish to the plastic article. For this reason the mold maker must reduce the size of the holes drilled in the mold. The other factor in these buttonlike imperfections is the thermoplastic sheet thickness. The thinner materials can form into the smaller holes much more easily and therefore will be more visible than the heavier-gauge sheet materials. It has also been found through industry experience that different thermoplastic materials offer different levels of sensitivity, and some are more likely than others to pick up vent-hole patterns from a mold. Armed with this knowledge, only general guidelines can be given as to the correct choice of hole sizes. For particularly sensitive materials, nothing but the minimum drillable hole size should be used. Table 3 lists the selection of functional drill sizes for thermoforming. It is always easier to drill with a larger drill bit. However, there is less chance of obtaining unsightly button markings with the finer drill bits. Since the appearance of unwanted marking is closely related to the thermoplastic material thickness, it is acceptable to use a measure of half of the original material thickness as a guide for the maximum drill size selection. This is a good rule of thumb for sufficiently thick materials. When dealing with extremely thin sheet material or foamed materials, a No. 80 drill bit is the best size. The use of such a small bit can add greatly to the cost of vent-hole making because the bits break easily and their replacement cost is high. Unskilled personnel using these bits can easily run up costs above their actual wages.

Table 3 Drill Size Chart

Fractional size drills (in.)	Wire gauge drills	Decimal equivalent (in.)	Fractional size drills (in.)	Wire gauge drills	Decimal equivalent (in.)
	80	0.0135	1/32	66	0.0330
	79	0.0145		65	0.0350
				64	0.0360
1/64	—	0.0156		63	0.0370
	78	0.0160		62	0.0380
	77	0.0180		61	0.0390
	76	0.0200		60	0.0400
	75	0.0210		59	0.0410
	74	0.0225		58	0.0420
	73	0.0240		57	0.0430
	72	0.0250		56	0.0465
	71	0.0260			
	70	0.0280	3/64	—	0.0469
	69	0.0292		55	0.0520
	68	0.0310		54	0.0550
				53	0.0595
1/32	—	0.0312			
	67	0.0320	1/16	—	0.0625

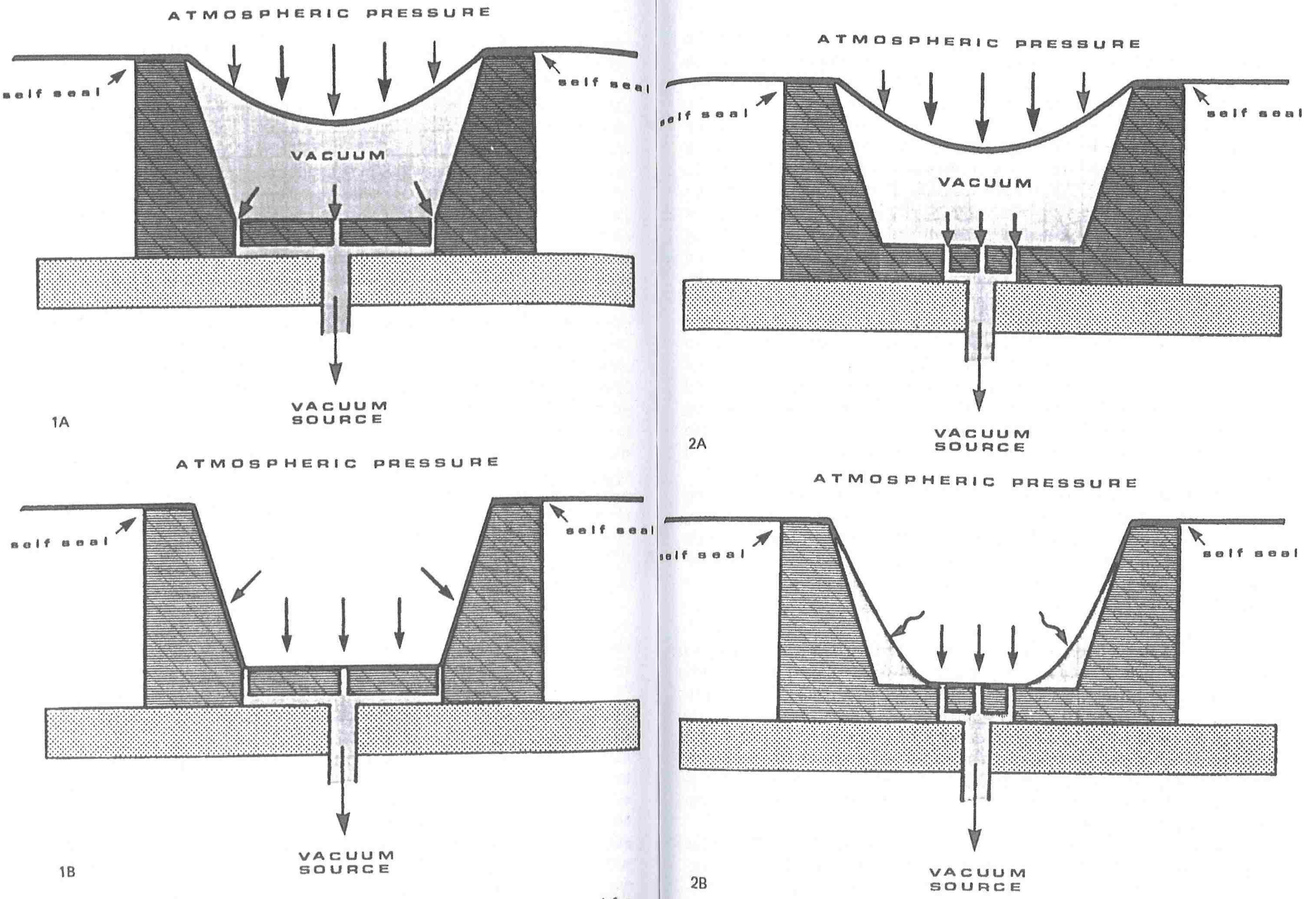


Figure 77 Mold with correct vacuum hole placement: (1A) forming begins satisfactorily; (1B) full detailed forming is made. Mold with incorrect vacuum hole placement: (2A) forming will begin equally well; (2B) centrally located holes covered by forming plastic with some trapped air behind.

b. Vent-hole locations: The second criterion in mold making is the choice of vent-hole locations. To achieve the utmost detail transfer from the mold to the formed plastic, all of the mold's inner air space must be evacuated by either vacuum or displacing pressure forces. Since there should be no trapped air left between the mold surface and the plastic, air must be removed from the vital cavity areas through the holes. Each hole is connected to the main evacuating chamber and consequently, either to a forming power source (vacuum or air pressure) or in some cases for proper venting, to the open atmosphere. For ideal air removal, venting holes must be placed along the corners as well as the bottom and sidewall intersections and also into all ribbing and stiffening detail structures. Holes must even be placed into the engraved patterns and lettering. To gain good detail transfer from the mold, every conceivable bit of trapped air must be removed from between the forming plastic and the mold surface. In this important effort, it is best to treat every mold configuration as a different and individual case where proper preplanning in the hole placement can create an enormous difference. Improperly placed holes (those placed only in a central location, for example) can be rendered useless by the partially forming plastic sheet plugging the holes and trapping the remaining air inside the mold. Figure 77 shows the importance of hole placement into cavity corners for full forming development in a thermoformed plastic part.

The same criteria exist with engraved lettering in a thermoformed product. For good legibility, each individual letter, depending on its configuration, must have one or more vent holes. Details of undercut or reversed-draft-angle forming are also very dependent on proper vent-hole placement and satisfactory air removal. Poor vent-hole placement or a weak airflow rate can reduce the effectiveness of undercuts.

c. The number of vent holes in a mold: The ideal location of vent holes to be placed in a mold involves a large number of holes within the mold structure. To further enhance the speed and quality of the particular thermoforming process, promptness in air evacuation is very important. With either vacuum or air pressure, such evacuation must rely on those holes, and their size or number can greatly influence air movement. The hole size is already curtailed by the thermoplastic sheet thickness to minimize the unwanted impression transfer from the holes. Therefore, the only remaining enhancement provided is an increase in the number of holes.

To determine the number of holes needed in a mold, the mold's volume capacity has to be established. This value actually represents the air displacement that will take place when thermoforming is performed. On simple geometric shapes, it is easy to calculate the mold's displacement value. However, with complicated or irregular shapes, the calculation is not as easy. The values are estimated either by approximating the dimensions to the nearest simple shape, or for closer determination, the mold cavity area can be filled with free-flowing materials (i.e., bird seed, bean bag foam fillers, etc.). Such measurement techniques can help the practitioner arrive at the correct displacement values. In the case of multi-up molds, the value can be factored to calculate the entire mold area. The actual mold displacement value should first be matched with the vacuum pump capacity. If the vacuum pump does not have the necessary volume capacity in gallons per minute, it will either have to be upgraded with a larger-capacity vacuum pump or the pump can be coupled with a second pump. When a very large amount of air is removed from the mold, a "surge tank" can be coupled to the vacuum pump unit. The principle behind the surge tank is that a smaller pump will be able to evacuate the surge tank when no vacuum is called for. Then, when the actual forming cycle takes place, the emptied tank will provide the necessary evacuation capacity to create the vacuum. Between forming cycles, the vacuum pump is given enough time to reestablish full vacuum capacity in the surge tank.

The next factor to be established is the diameter of the vacuum outlet of the pump. This pipe diameter must match the rest of the plumbing. Any restriction in the plumbing lines will cause a drop in the vacuum forces, creating a bottleneck. Furthermore, the plumbing pipe cross section should first be divided by the number of individual molds (ups) and then again by the chosen drill-bit cross section. This calculation is expressed by the formula

$$\frac{P}{U} \div D = \text{number of vent holes required per mold unit}$$

in which P is the pipe cross section, U the number of ups in a mold, and D the drill-bit cross section. For example, how many vent holes should be drilled in a mold cavity with a six-up mold arrangement, a 1-in. plumbing line, and a $^{1}/_{32}$-in. vent-hole size?

$$\frac{(1/2)^2 \times \pi}{6} \div \left(\frac{0.0312}{2}\right)^2 \times \pi = 171$$

This formula gives the minimum number of holes needed to match the pump's vacuum forces within each cavity. It is always a good practice to add 25% more holes to compensate for any holes that might plug up in the course of production. Depending on the hole size as well as prevailing plant conditions and the length of production runs, it is not unusual to have a large number of holes become inoperative through airborne dirt, lint, and moisture combined with corrosion residue.

When the design features of the mold do not require maximum vacuum forces, a simple gate valve installation in line between the pump and the mold can reduce the vacuum force to satisfactory levels. Such valves not only provide the needed flow control, but also the necessary adjustments for fine tuning of the vacuum force.

The number of holes used becomes even more critical when pressure forces are used. Pressure forming is not only more forceful than vacuum forming but is also produced much more quickly. Straight vacuum forming (reaching a maximum 29.92 in. Hg) produces a forming force equivalent to 14.7 psi pressure forming. Most pressure forming, on the other hand, is performed between 50 and 100 psi. Table 4 compares vacuum and pressure force levels. When higher levels of incoming pressure force are applied against the thermoplastic sheet, the trapped air on the other side of the sheet must be ejected or evacuated equally fast. Any restriction in the trapped air outflow can just as easily interfere with the incoming pressure and can jeopardize the outcome of the thermoforming procedure. (The cause and effects of overpowered pressure forming were detailed in Section V.B of Chapter 2.) Overpowered pressure-forming results, coupled with restricted evacuation flow, can result in trapped air pockets within the mold cavity (Figure 78).

Table 4 Conversion Table: Vacuum to Pressure

Vacuum (in. Hg)	Pressure (psi)	Vacuum (in. Hg)	Pressure (psi)
5.00	2.45	18.00	8.66
6.00	2.94	18.36	9.00
6.12	3.00	19.00	9.32
7.00	3.43	20.00	9.81
8.00	3.92	20.40	10.00
8.16	4.00	21.00	10.30
9.00	4.42	22.00	10.79
10.00	4.91	22.44	11.00
10.20	5.00	23.00	11.28
11.00	5.40	24.00	11.77
12.00	5.89	24.48	12.00
12.24	6.00	25.00	12.27
13.00	6.38	26.00	12.76
14.00	6.87	26.52	13.00
14.28	7.00	27.00	13.25
15.00	7.36	28.00	13.74
16.00	7.85	28.56	14.00
16.32	8.00	29.00	14.23
17.00	8.34	29.92	14.70

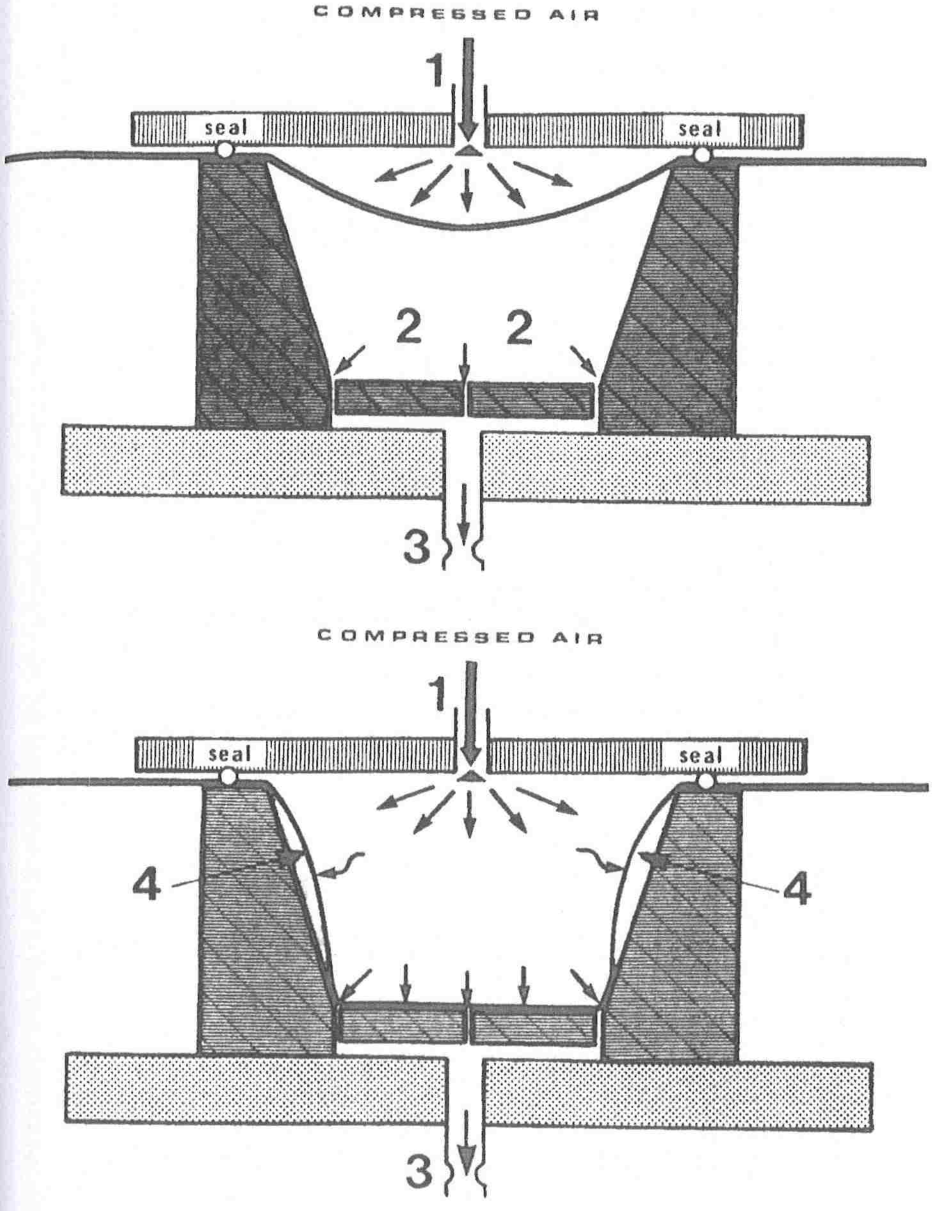


Figure 78 Overpressurized forming condition: (1) incoming pressure force; (2) undersized or small number of vent/vacuum holes; (3) restricted vent/vacuum channel; (4) trapped air pockets.

Table 5 Air Evacuation Flow Rates[a]

Gauge pressure (psi)	Cubic feet of air per minute for single line or combined orifice diameter (in.)										
	1/64	1/32	1/16	1/8	1/4	3/8	1.2	5/8	3/4	7/8	1
3	0.048	0.194	0.77	3.1	12.4	27.8	49.5	77.5	111	152	198
4	0.056	0.223	0.89	3.5	14.3	32.1	57.0	89.2	128	175	228
5	0.062	0.248	0.99	3.97	15.9	35.7	63.5	99.3	143	195	254
6	0.068	0.272	1.09	4.34	17.4	39.1	69.5	109	156	213	278
7	0.073	0.293	1.17	4.68	18.7	42.2	75.0	117	168	230	300
9	0.083	0.33	1.32	5.30	21.1	47.7	84.7	132	191	260	339
12	0.095	0.38	1.52	6.07	24.3	54.6	97.0	152	218	297	388
15	0.105	0.42	1.68	6.72	26.9	60.5	108	242	242	329	430
20	0.123	0.49	1.96	7.86	31.4	70.7	126	196	283	385	503
25	0.140	0.56	2.25	8.98	35.9	80.9	144	225	323	440	575
30	0.158	0.63	2.53	10.1	40.5	91.1	162	253	365	496	648
35	0.176	0.70	2.81	11.3	45.0	101	180	281	405	551	720
40	0.194	0.77	3.10	12.4	49.6	112	198	310	446	607	793
45	0.211	0.84	3.38	13.5	54.1	122	216	338	487	662	865
50	0.229	0.92	3.66	14.7	58.6	132	235	366	528	718	938
60	0.264	1.06	4.23	16.9	67.6	152	271	423	609	828	1082
70	0.300	1.20	4.79	19.2	76.7	173	307	479	690	939	1227
80	0.335	1.34	5.36	21.4	85.7	193	343	536	771	1050	1371
90	0.370	1.48	5.92	23.7	94.8	213	379	592	853	1161	1516
100	0.406	1.62	6.49	26.0	104	234	415	649	934	1272	1661
110	0.441	1.76	7.05	28.2	113	254	452	705	1016	1383	1806
120	0.476	1.91	7.62	30.5	122	274	488	762	1097	1494	1951

[a] This table gives only theoretical flow rates with 1 atm pressures at 70°F. Flow friction will cause a small reduction.

For determination of the ideal number of vent holes in a pressure-forming model, it is always a good idea to provide more holes than would normally be used in the vacuum-forming technique. If a mold does not have enough vent holes, the deficiency will show up in the forming results either in the part's appearance or in slower forming conditions. To estimate air evacuation from the mold and consequent flow rates at various pressure levels, Table 5 should be consulted. For determination of the individual mold evacuation rate, a consolidated hole measurement figure should be calculated.

Smaller holes do not necessarily need to be drilled through the entire bulky mold body. In fact, such drilling is not only time consuming and very difficult but the long, narrow opening can plug up more readily. In most instances the mold maker will mill out a large portion of the back side of the mold, creating an air chamber or interconnected air channels. A larger-diameter drilling can be made from the back side, to as close as $^1/_{16}$ to $^1/_8$ in. from the forming surface. The location of this larger hole is then mechanically transferred to the mold face to implement drilling by the smaller drill bit in the proper location. In this way, the tiny holes need only be drilled through a very thin mass, yet will still lead, by way of the larger holes, to the main air chamber. The larger air channels leading up to the fine holes can provide better flow rates, less chance of plugging, and therefore longer service life for the molds. However, any machining done on the back sides of the mold for the purpose of air chamber creation or air channeling should not substantially reduce the mold's surface contact with the cooling base, therefore reducing its heat exchange qualities.

II. MOLD TEMPERATURE CONTROLS

In the process of thermoforming, the mold has to perform double duty. The first function of the mold is to provide shaping for the plastic. The second, and equally important function is to absorb the heat of the formed plastic in order that the plastic can firm into its newly acquired shape. In any of the rapidly produced thermoforming cycles, the heated plastic will come in contact with the mold more frequently than otherwise. Throughout the vigorously repeated cycle, the mold by itself, or together with the thermoforming machine platens, cannot dissipate the mold's acquired heat. Without cooling, heat will accumulate in the molds and will eventually reach the same heat level as that of the forming thermoplastic sheet. Molds that get hot enough to match the temperature of the incoming heated thermoplastic sheet cannot provide cooling after the forming cycles. This will render the thermoforming process useless and ultimately force it to shut down. To regain the cooling effects of the mold, the mold (or at least the contacting mold base plate) must receive some type of effective cooling that promptly reduces the mold's temperature. An auxiliary cooling method in continuous, rapidly repeated production will maintain mold temperatures throughout the entire operation. Any auxiliary cooling method must be adjustable to increase or decrease its effectiveness. Adjustments in cooling must provide a wide range of temperatures to maintain any desired mold temperatures for the specific thermoforming process. The fewer the contacts made between the heated sheet and the mold, the less will be the cooling demand on the mold. A higher number of repeated contacts, on the other hand, will increase the importance of the cooling aspects of the mold.

In some instances the entire thermoforming operation can be managed without auxiliary mold cooling. The formed article's heat can be dissipated through the mold and into the thermoforming machine platens and frame structures. In addition, part of the heat is eliminated through the formed article surface into the ambient environment. This type of cooling can be enhanced further by fan-forced air cooling. Ventilator fans can be placed above the forming area and are usually operated only when cooling is needed, being turned off in subsequent phases of the cycle. The fans should not face the oven area, as this would create an artificial and undesirable draft. The fans should operate only within the cooling-time segment after the completion of forming. If the ambient air is too warm to cool the plastic effectively, low-volume-output fog-producing units can be positioned in front of the fans directly in the path of the air movement. The fog is created by a small orifice on the fog maker and ordinary city water pressure and is instantly vaporized upon air contact. The vaporization, with its normal heat-reducing characteristics, will reduce the air temperature, and the needed cooling effects are now provided.

When higher humidity conditions prevail, the method is obviously less effective than it would otherwise be. In fact, if not totally vaporized, the fog can produce moisture on the surrounding surfaces. The same adverse effects can be encountered with a higher output level from the foggers or sprinklers. For the best fog creation, greenhouse equipment suppliers should be contacted. These companies offer foggers with volume output rates as low as $^1/_2$ to $^3/_4$ gallon of water per hour. Anything more than this can create unwanted wetness, which can drench and damage the equipment and can cause heavy rusting of the thermoforming machinery.

There is one more option for cooling improvement, which can be implemented when fan or blower forced air cooling is employed. But before it is explained, the two most common errors must be discussed. One of the basic errors is found in the fan or blower location. The fans or blowers are often found right above the molding area, and usually located close to or above the oven's edge. Sometimes this location is chosen because of lack of a mounting place or just to try to avoid unwanted air movement into the oven. The excuse of the unwanted draft avoidance I can accept; however, when this spot is chosen, it is most likely the hottest area of the entire plant. We all know that hot air rises and will accumulate near the overhead area of the plant. Even if the plant has a high ceiling structure the heated air will rise and accumulate and very quickly will fill that upper space with hot air. Blowing this hot air onto the plastic is not an efficient way to cool a freshly produced part. Usually cooling will take longer and that extra time always increases the cycle time and adversely affects the economy of that particular thermoforming. In case the extra cooling demand is ignored, and formed articles are removed before full cooling has taken place, it will jeopardize the quality outcome. Most likely the inadequately cooled part will develop a warpage and postmold-distortions.

The second area of errors is made when the thermoformer is aware of the poor cooling results and concludes that more air movement (power) is needed to accomplish the cooling task. To remedy the presumed under cooling or the drawn-out cooling time, the decision is made to add more fans or blowers to the units already installed. They will attempt to increase the number of cooling motors or increase their air volume capabilities by horsepower. Sometimes you see not only doubling, but quadrupled units installed to provide the desired cooling. Just because there is a lot more noise of air rushing, it may not be necessary that better air movement is achieved and with it improved cooling is accomplished. First of all, the ambient air temperature has not been corrected and when it is hot it will not do a first rate job of cooling. With the presumed increased air movement, it is believed cooling can be accomplished with ease. But, what actually happens is the rushing air quickly fills the molded part's cavity and forms an impenetrable dome over the part, so that no additional air can enter onto the plastic surfaces. It is almost like an invisible dome cover over the formed part, that prevents any further heat exchange to take place. As the fans or blowers fill the cavity all cooling will stop and cannot force more air into the part. I have seen from time to time installation of as many as six to nine blowers with substantial horsepower, and still not doing an adequate cooling job.

It is mandatory to have sufficient airflow in to and out from the formed article to achieve the most efficient cooling. Fewer fans or blowers moving air in a well directed flow pattern is better than blowing air against each other that diminishes the development of an air breeze. Of course in the effort of achieving an ideal flow pattern the practitioner also must watch that there is no "shadow" effect left where air movement is blocked. This blockage or "shadow" is usually found in the cooling of large tublike product configurations, where the nearest wall, under the fan, just does not receive cooling air, due to the angle at which the fan blows the air, and misses that particular portion of the wall.

To create the most ideal solution for a rapid and thorough cooling of the formed article often times we should search for a colder source of air. Since the ambient temperature of the plant is already too hot to satisfactorily use for efficient cooling, it may be necessary to look for other sources of colder air. One way to reduce the temperature of the air is to use fog producers which spray a very fine fog like mist into the blowing air stream. The water as it is sprayed immediately vaporizes and in a low ambient humidity condition can have substantial cooling effect on the air surge. This may reduce the air current temperature by 10°–15°F or even more, depending on the prevalent ambient air's humidity. The negative effects of such a system is that it only works when and where low humidity conditions are present. The other bad side effect of this can be found when misters and not fog producers are used and its spray output rates are much higher. Fog producers emit $^1/_2$ gallon of water per hour versus misters that emit about three times as much, i.e., 1–1$^1/_2$ gallon of water per hour. Heavy spraying will make everything wet and very soon all iron parts will show signs of corrosion and rusting.

To obtain an even better solution for efficient cooling for the thermoformed article one may not have to look any further than the source of outdoor air. Often the outside air temperature is significantly lower than the inside plant's air temperature. This may exist even at the height of summer, of course depending on the geographic location. To draw air from outside into the plant and channel it to the right place where the cooling is needed, will require some duct works. This can be accomplished easily by using standard ducting used by air condition and heating professionals. General purpose air blowers can be installed on the rooftop, right above the thermoforming machines and the air is ducted directly over the area where the part cooling is done. The duct should channel the outside cold air all the way down to the formed part and should exit the ducting in a central location of the mold, allowing it to flow into or over the formed part without any airflow restriction. If normal flow is maintained a continuous cooling will be accomplished. In case a deep drawn female part is to be cooled, the duct system can be extended by a flexible accordion-like ducting, which retracts upward when cooling is no longer needed. Of course, power to the blower also has to be cut off at the "no cooling" times. By lowering the duct work, actually lower than the sides of the article, it will insure not only good cooling but permits excellent air movement and escapement from the cavity as well. The constant air movement and the cooler outside air should be sufficient for the most ideal cooling. With this forced outdoor air cooling it should reduce cooling time to the shortest time limits one can anticipate with any air cooling method.

The utmost preciseness and speed in cooling of a thermoformed article can best be accomplished through the mold surface. To provide both accuracy and rapid repetition in the cooling cycle, the natural dissipation of temperatures must be made aggressively. This accelerated heat removal from the mold can be provided only by the circulation of coolant fluids within the mold body.

In the thermoforming process, a mold referred to as a "cold" mold is not necessarily chilling to the touch. The neutral temperature zone (neither cold nor hot) is always considered at the heat levels of the forming thermoplastic sheet. Mold temperatures lower than those of the softened plastic sheet are labeled "cold," and mold temperatures above the neutral zone are called "hot." For example, molds with an operating temperature range of 120 to 180°F or more can be referred to as cold molds as long as the forming temperatures of the plastic sheets are at higher levels. With mold temperatures that are closer to the forming sheet temperatures, the cooling cycle time must be extended further than with colder temperature molds. Any plastic article that is not sufficiently cooled due to improper mold temperatures or premature removal from the mold can develop deformations and distortions as it cools without proper physical support of the mold. Such thermoformed articles can develop unusable and unsightly distortions in time, well after their removal from the mold. On the other hand, for ideal thermoplastic sheet stretching, molds kept on the warm side would work more effectively, allowing better material distribution in the formed articles.

A. Mold Cooling

The accumulated heat in the mold's body must be removed for the mold to provide its full cooling functions for final setting of the plastic article's new shape. To achieve such a task, the mold temperature must be maintained below the softened sheet temperatures. The greater the temperature spread between the forming sheet and the mold, the shorter the cooling time that will be needed. However, exceptionally cold mold surfaces can produce premature setting, causing poor forming details or even undesirable and uneven stretching in the forming. When uneven stretching is encountered due to the overly chilling effects of the mold, the forming results will show considerably reduced stretching at the contact areas. In contrast to these prematurely set areas, the uncontacted areas of the sheet will undergo relatively greater stretching and with it, excessive thinning. Most "chill marks" can be caused by overly cooled molds causing a step-down (reduced gauge) at the border of the contact area. Chill marks or "chill lines" are measurable by a thickness gauge and can easily be seen as a line on the surface of a thermoformed article—an objectionable flaw. In an effort to eliminate unwanted chill marks, one of the steps that can be taken is not to let the mold become too cold. Another improvement to minimize such unwanted affects is discussed in Section II.B.

It is a well-accepted practice for the mold to receive some type of auxiliary cooling in higher-speed thermoforming productions. In almost all instances, the mold, or at least the mold base, is equipped with built-in cooling channels through which liquid coolant flows. The source of cooling can be provided by a closed-loop mold temperature control unit or from a centralized cooling-water source. In either case, cooling is accomplished through the circulation of coolant fluids. The general makeup of these fluids is mostly water with some chemical treatment, used mostly to inhibit corrosion. A glycol-base chemical can be added to the water as an antifreeze agent. It is rare but not at all inconceivable that a Freon formulation will be used in a closed-loop cooling system. The purpose behind any fluid cooling method is to absorb the heat inside the mold and with the flow of the coolant, carry the heat away from the mold structures.

The first requirement in utilizing this type of cooling is to provide sufficient flow for the coolant. The cooling fluids must be circulated with a pumping force that causes the liquid to move in and out of the mold body. The coupling of the plumbing system between the mold and the outside source of the cooling is usually made through flexible hoses. The plumbing lines are usually equipped with shutoff valves ahead of the juncture with the hoses in order to arrest the cooling fluid flow when the molds are removed and changed in the machine. It is also customary to use quick-disconnecting couplings for ease in fluid-line separation. The shutoff valves installed in both the in- and outflowing ports have another purpose in addition to cutting off fluid flow during mold changes. One of the valves can also be used as a flow regulator to reduce or increase the flow of the coolant fluids, rendering less or more cooling to the molds. Only the outgoing valve should be used as a control. The incoming fluid valve should remain fully open during the operation. In fact, it is highly advisable to paint the outgoing valve bright blue to eliminate confusion and the possible error of using the wrong valve for the flow control. Efficient and uniform cooling can be provided only with a fully filled mold cooling system. Air pockets and air bubble formation created inside a mold body prevent the system from providing sufficient cooling. For this reason, the incoming valve should not be used as a flow regulator. The fluid inside the mold must be circulated at a sufficient rate to prevent it from warming up and decreasing the efficiency of mold cooling.

The second requirement in this type of cooling method is closely related to the fluid flow rate. The flow pattern of the coolant placed into a mold must be designed with ingenious planning to maintain a uniform temperature throughout the mold body. If this requirement is not met, the mold will be cooler where the coolant enters and warmer where the used-up coolant exits. A cooling channel in a mold should not be made in such a way that it snakes through the mold from one end to the other or even so that it branches off at one end of the mold only to reunite at the other end. The ideal cooling conditions can be achieved only with an alternating flow manifolded from side to side or front to back. Specifying to the mold maker ideal coolant flow patterns in a mold can circumvent any suspected possible cooling problems that can be encountered with unknown molds (see Section IV.C and Figure 81). Measurements of mold surface temperatures cannot reveal most improper flow patterns. Even if the wrong coolant flow pattern is proven to be the source of difficulty, the remedy will usually demand major tooling changes. The measurement of incoming and outgoing coolant temperatures can be helpful; however, its interpretation can easily be misleading. The changes in temperature readings can be caused by many factors in addition to the change in thermoforming conditions. Examples are the flow rates of the coolant, plumbing and flow restrictions, coupling of other molds to the system, clogging of the cooling channels, flow-restricting cooling channel surfaces and flow direction changes, and stagnant pooling of the coolant within the mold.

In a high-speed operation where repeated contact with the heated plastic is made at least 35 times a minute, mold cooling must be made all the more efficiently. To achieve such rapid cooling, the majority of the mold body should contain as large a volume of coolant as possible. The mold can be made such that only thin wall structures will separate the coolant from the mold surfaces. In this case the cooling liquid must be pumped with high levels of flow speed and must also receive some turbulent flow characteristics to provide the high-speed cooling effects. Without this turbulence, which eliminates the stagnation in the flow, the cooling efficiencies will drop below satisfactory levels. If further cooling improvements are needed, mold cooling must be made with the help of refrigerants.

Negative aspects of mold cooling can be found whenever thermoforming operation is stopped and started up again. As with any process, the operation temperatures are no longer under control when the operation stops. In a continuous operation, as well as with a continuous cooled mold, the mold will experience more cooling during the stoppage than the process requires. It is not unusual after a shutdown for a mold to collect water condensation on its surfaces. Naturally, such cooled mold surfaces cannot initially be expected to function satisfactorily. However, through a few repeated cycles, the mold can again be raised to running temperatures. Further temperature elevations of the mold will be controlled by the mold cooling system. Production startups cannot generally be made instantaneously. Before obtaining ideal running conditions, numerous out-of-specifications articles will be produced unless both preconditioning and interim adjustments are provided. However, as soon as the running conditions are reached, all interim adjustments should be discontinued and the production line will settle into a smooth-running operation.

B. Mold Heating

There are occasions in the thermoforming process when the mold temperature has to be elevated. It is not unusual to elevate mold temperature to the proximity of the heated plastic sheet temperature. In fact, such warmer mold structures can be beneficial in some specific thermoforming methods. First, in most plug-assisted thermoforming, if the plug-assist temperature is cooler than that of the heated thermoplastic sheet, unwanted cooling of the forming sheet can occur. To avoid such chilling effects on the sheet, the plug-assist temperature must be elevated to the same heat levels as the incoming softened thermoplastic. Second, there are particular plastics, such as the CPET materials (crystallizable polyethylene terephalate), which demand heatable thermoforming molds. With these particular materials, the mold is heated after the normal thermoforming procedures to create crystallization of the plastic. Tray products made of these materials on heated mold bodies, after the crystallization stage, are capable of withstanding conventional oven temperatures (400°F) without destruction. Currently, such ovenable trays are the "hottest" product items for the prepared frozen food and TV dinner industry.

In the heating of a thermoforming mold, several options are open for the processor. One of the most common initial approaches is to heat the mold electrically. Usually, the back side of the mold is predrilled and fitted with a cartridge-type heater. The heat levels are controlled with an embedded thermostat that may work directly on the heater element or, for better control, may register its reading with an outside control panel where even visual temperature readings can be obtained. With most electrically powered internal heating systems, the conveniently small equipment setup offers many possibilities. However, as with most sheet-heating heater elements, the same temperature oscillation will persist and its effects could easily interfere with good thermoforming practices. The oscillation levels can be checked with costly control devices. To obtain mold heating without the slightest chance of temperature fluctuation, either very sensitive electronic devices or closed-loop temperature control units should be used. In this method of mold heating, the mold's elevated temperature is controlled using the same fluid circulating apparatus as that used for mold cooling. Instead of cooling the circulated fluids, however, the equipment will raise the temperatures of the fluids, and through their contact with the mold, the preset heat will be transferred to the mold body. For a less costly mold heating method, the processor can use an ordinary household water heater coupled with a closed-loop plumbing and pump system connected to the mold's heating channels. The water heater's thermostat can be adjusted to the correct heat levels, while the water volume and the action of the circulation pump can maintain the mold's heat at satisfactory levels.

Both electrical and circulating fluid types of heating can produce elevated temperatures in the mold body. However, with these heating methods, the entire mold body will be heated. If the thermoforming operator only needs to heat certain areas of the mold or does not wish to use any outside source of heating, insulating mold materials should be used. Insulating mold materials can consist of those materials which, through the act of thermoforming absorb the heat of the contacting thermoplastic sheet and retain that heat after contact has been broken. This insulation can be provided by wood, phenolic, urea, polyamide formulation, or most popularly, the "syntactic foam" materials. The principle behind these materials for the purpose of mold heating can be found in their ability to pick up readily the higher temperatures of the heated thermoplastic sheet. The material's heat gain is supplied through the forming procedures when contact is made with the heated thermoplastic sheet. Because of their heat-insulating characteristics, the insulating materials will also retain the heat longer in their bodies. The way in which those insulating materials absorb and hold the heat is closely related to their density. Denser materials reach their expected temperature levels more slowly than do the lighter-density materials and require a greater number of and possibly longer contacts in order to reach ideal running temperatures. For example, it is not inconceivable that the phenolic plug-assist material will require 10 to 20 forming cycles before their temperatures will match that of the sheet temperature. However, the syntactic foam materials can boast not only fast heating abilities but also outstanding temperature retention. Syntactic foams are applied to the thermoforming molds; their heat accumulation to reach full production running condition can be attained within a few cycles. Only three to a maximum of six forming cycles are needed before their temperatures will match that of the heated thermoplastic sheet. The real gain with syntactic foam insulating material use is most evident when particular metal mold surfaces are exchanged to this material. In most thermoforming processes, considerable effort is made to produce well-controlled thermoplastic sheet temperatures and to maintain such controls throughout the entire production. With the adaptation of syntactic foams in the mold, no additional controls will be required, because the foam temperature will exactly match the sheet temperatures. The use of insulating materials such as syntactic foam is adapted particularly well to the manufacture of plug assists. However, they are not the only single mold components in which such materials can be useful. To fully illustrate the usefulness of syntactic foam, in Figure 79 comparisons are made between them and standard metal plug-assist materials. Most thermoforming toolmakers shape the entire plug assist out of syntactic foam. This is convenient but not at all necessary. As Figure 79 shows, the plug assist makes contact with the heated thermoplastic sheet only by its leading face. Therefore, capping the plug assist with a $^1/_2$- to 1-in.-thick syntactic foam layer will work just as well as a solid plug assist. In either case, the syntactic foam must be made mountable to a metallic mold component. The foam can be drilled and the holes can be tapped and threaded with any ordinary thread cutter. The material can also be glued to the metal surfaces; however, with the adhesive mounting, the use of locating pins is always a good practice to avoid any misalignments. Syntactic foam materials can

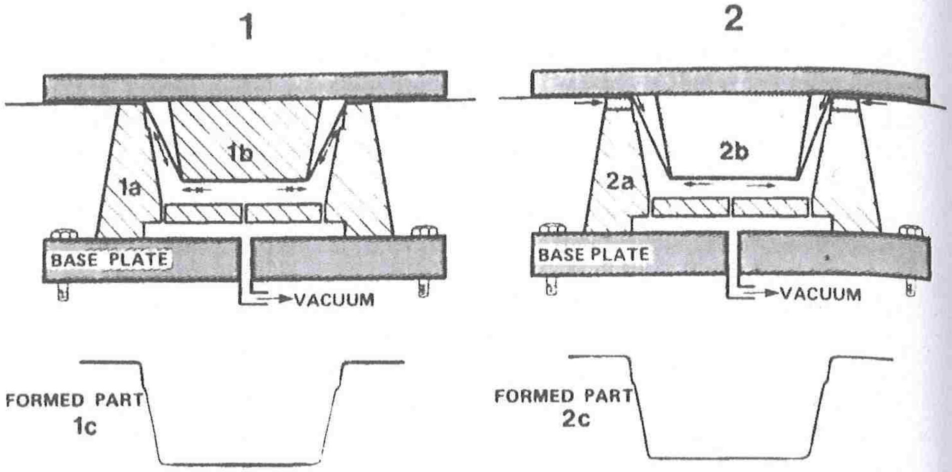


Figure 79 Benefits of using heat-retaining materials in a thermoforming mold. (1) All-metal mold: 1a, cooled all-metal mold cavity; 1b, cool all-metal plug assist; 1c, formed part with heavy flange and bottom, thin sidewalls. (2) Mold with heat-retaining material (syntactic foam): 2a, capped mold cavity lips (warm lip, cool mold body); 2b, syntactic foam plug assist (warm); 2c, formed part with even wall thickness.

be purchased to requested dimensions in premanufactured block form. Some knowledgeable tool shops can manufacture their own custom-shaped syntactic foams by casting them out of a mixture of a fine grade of hollow glass spheres and epoxy resin. The only criterion that need be considered is to obtain absolute uniformity in the syntactic foam density, or the material may separate in the casting. This can easily happen, since the hollow, lightweight, fine glass beads tend to separate out of the heavier, flowing epoxy materials. The two materials will separate as the epoxy is setting up. Any separation of this material results in density variations within the resulting syntactic foam casting. Variations in foam density within a thermoforming mold can interfere directly with the thermoforming results.

The use of syntactic foam materials for creating a warm mold surface is most appropriate with continuous web-fed thermoforming. In web-fed operations, syntactic foam can reach running conditions within three or more forming cycles. If no stoppage is experienced, temperature control will never be needed to maintain the ideal mold temperatures. The few flawed production cycles made at startup cannot be held against this mold-temperature-controlling method. The same temperature-controlling method with syntactic foam mold components can be made to work in a sheet-fed thermoforming operation, but only when the cycles are produced in rapid succession. In a sheet-fed operation it is also necessary that the insulating mold material have an opportunity to receive heat and maintain it from cycle to cycle. If there are extremely long intervals between cycles, the high cost of the thermoforming material sacrificed in the beginning of the process will probably offset the advantages of this mold-heating method in the sheet-fed operation.

C. Programmed Temperature Molds

There are basically two types of programmed temperature thermoforming molds. The first changes temperatures along its entire body. For example, within a single process cycle, a cool mold has to change from cold to hot and back again. Necessary, radical temperature changes can be accomplished in several ways. A mold can have the normal cooling channels with a coolant flowing through them, and simultaneously have electrically powered embedded cartridge heater elements. The heater elements' heat will override the cooling effects of the coolant. When the power is turned on, the mold gets hot; when it is turned off, the flowing cooling fluids take over and cool the mold. For additional efficiency, the coolant fluid can be shut off to gain faster heating times. Either way, when a mold has to change its temperature radically, it will take some time for the change to take effect. Mold temperature reactions will be slower when the molds have higher body mass, since a lighter body mass can accommodate temperature changes much faster. The only sensitivity to be watched for with this changing mold temperature process is that the molds should be constructed of materials that can take the rapid temperature changes without falling apart. Most metal molds are not affected by the usual heat-related expansions and contractions. A minor problem encountered due to the temperature changes is that of loosened screw fittings. However, molds with a nonmetallic or multimaterial makeup can react adversely to rapidly alternating temperatures due to various rates of expansion among the materials. When a mold is constructed from several different types of materials, the second type of programmed temperature thermoforming mold comes into play. This type of construction creates molds that develop different temperatures within the same mold body as they are used. Instead of having a uniform temperature throughout its body, the mold will have areas that are cooled and areas that are either heated by an outside source or remain warm from the contacting thermoplastic sheet. The principle behind these molds lies in the fact that the thermoplastic sheet material will stretch more at the warmer contact points (where no cooling is administered) and at the same time will resist stretching where cooling is applied. This is the purpose of a programmed temperature mold. The warm segments of the mold contacting the heated thermoplastic sheet will not cool these areas and thus allow stretching to occur there. The other sections of the mold will chill the thermoplastic material through the contact; because of the cooling, the colder areas will not stretch as much in comparison and perhaps not at all.

The mold for this programmed temperature setup is constructed within the same configuration as any other mold. However, instead of single-material construction, a second insulating material that is like syntactic foam is added to the particular areas. The syntactic foam mold inserts are fitted into cutaway areas milled out of the original mold body, creating molds that have the intended mold configuration but with different materials incorporated into their body. For example, a male mold can have a "cold" aluminum body, while its four corner areas are made of syntactic foam, which becomes warm. In a reversed arrangement, the mold body is made of syntactic foam material and its corners are segmented out of aluminum. In this arrangement, the aluminum corner inserts are extended down the full height of the mold in order to attain cooling through contact with the mounting plate (Figure 80). Molds like this provide a combination of warm and cool areas, making up the mold structure in a preplanned fashion. Cleverly managed mold structures with preplanned warm and cool areas can prove just as effective a means as preprogrammed heating of the thermoplastic sheet. Between these two advanced heat management techniques—programmed sheet heating and intelligently designed mold temperature variations—the thermoformer can achieve outstanding wall thickness distribution in a thermoformed article. The management of temperature control within the thermoplastic sheet and on the mold surfaces can result in uncompromising quality and success for the thermoformer. Guidelines as to correct placement of the syntactic foam mold inserts are difficult to give because placement is highly dependent on mold configurations and design interactions. In many instances, a trial-and-error method can lead the practitioner to the most ideal mold segmentation. It is highly advisable that before metal cutting or milling is attempted in the mold structure, stick-on tape be placed on the selected cutaway areas for testing purposes. Although the tape's insulating abilities are not suitable for permanent use, the tape will give some indication as to whether the area's shape and size will permit proper functioning. If changes have to be made, it is far easier to try a different tape patch than to rework the mold. The use of tape can be considered a test measure only because the tape will leave its own impressions on the formed article, probably rendering it unusable.

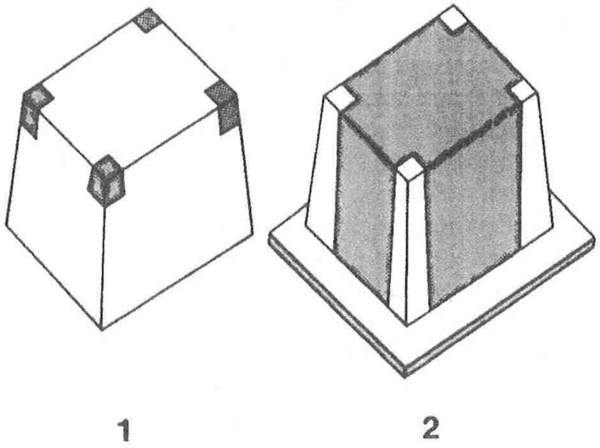


Figure 80 Programmed temperature molds: (1) cool aluminum mold body with warm syntactic foam inserts; (2) warm syntactic foam body with cool aluminum inserts extended all the way to a backup plate.

III. SPECIAL MOLDS

Thermoforming often presents an out-of-the-ordinary challenge where routine thermoforming techniques with customary thermoforming molds cannot provide a specific need. Sometimes, a special mold construction or mold surface treatment is needed that can alter the thermoforming results in the favor of the processor. A special surface treatment or a different mold material can often establish major improvements within the process by making the product more eye appealing or possibly, easier to produce. Either of these benefits obtained through special mold applications will favor the specific or particular specialization. Most thermoforming procedures do not require specialized molds, and the higher costs of such molds can be prohibitive in the manufacture of the thermoformed article. Even though special molds are used only on rare occasions, they are worth mentioning. The knowledge and use of them can prove valuable when their special application is adapted to a mold. The thermoforming practitioner will have to make the final decision as to when and where to apply specialized mold features.

A. Mold Surfaces

When the thermoforming mold does not easily release the formed article, the slow release action may damage the product or hamper production speeds. Difficulty in the release of the part generally stems from deep-drawn, intricate design patterns or nominal sidewall taper angles. The surface binding that often occurs will happen sooner and create more problems with male molds; female mold configurations are less sensitive to release problems. Molds made out of the customary metals and carrying the usual mold surface finishes may not provide the necessary surface slipperiness that some design configurations require. In these instances the mold surfaces can be treated with a special surface coating that will make the surface slippery. There are instances when the mold surface must be made to resist frictional wear or even physical damage from abusive operating practices. Mold surfaces can encounter a harsh chemical environment. Certain chemical coatings or thermoplastic material compound combinations can induce corrosion of the mold surfaces. Some chemical attacks may not be readily noticeable on the mold, but can in a longer period, cause major destruction. Special mold materials or surface coatings can provide ample resistance to chemical damage. There are several sources of physical or chemical destruction that can be encountered in many of the thermoforming processes. When signs of damage to a mold are observed, it is most important that preventive steps be taken to solve the problem. Unfortunately, most problem solving addresses the damage, not the cause of the damage. The sensible way to resolve the problem is to pinpoint the true causes of the problem and then proceed to eliminate them permanently.

1. Release Coatings

Due to the effects of shrinkage, a thermoformed article often will simply not release readily from the mold. Such difficulties are encountered more often with male molds than with female molds. This problem can be further aggravated by a combination of mold configurations where male or female mold structures carry opposing mold configurations within themselves. Release is hampered even further when the mold designs are made with almost no sidewall taper angles. A thermoformer often realizes that all these negative thermoforming aspects will appear to some degree or other during most projects. Before using mechanical force to help remove the formed article during stripping, it is a good idea to apply a slip and release agent. Chemical slip and release agents can usually be applied directly to the plastic sheet. However, these chemical coatings may negatively affect the plastic and further use of the finished products. The chemicals applied to the plastic, for example, must have FDA approval if the thermoformed articles are to come in contact with food. Release agent chemicals could present a problem later in fabrication, gluing, and sealing of a thermoformed article or can even interfere with painting or labeling. Therefore, chemical coatings applied to the thermoplastic sheet or sprayed on the mold surfaces must be used with caution.

Many mold makers choose to use baked-on Teflon coating applied to the mold surface. This is a good method to use to provide slippage to nonslipping mold surfaces. The baked-on Teflon is durable (this is the composition and surface treatment used for "nonstick" cookware) and can provide a functional, long-lasting surface. The permanent Teflon coating, due to its baked-on finish, is applied only to metal molds, especially aluminum molds. In time the abrasiveness of some plastics can wear off the Teflon coating. Wear on the Teflon surface is usually gradual and by no means uniform. In spots where more surface friction is present, more wear will be realized. If enough wear is encountered, the part release becomes a hindrance to production, and the mold must be pulled out of the thermoforming machine. The old, partially worn Teflon coating must be stripped from the mold's surface and a new Teflon coating baked on. The minute thickness of the Teflon coating is normally not a hindrance in the thermoforming procedure. Only in some critical high-speed operations will the Teflon coating interfere by acting as an insulating surface in the cooling phase of the thermoforming. Again, it is up to the thermoforming practitioner when and where to use Teflon coating on a mold surface, and a lack of full analysis of a particular thermoforming situation may produce an incorrect decision. The extra cost of Teflon coating becomes a luxury only when it is completely unnecessary.

2. Damage-Resistant Mold Surfaces

Thermoforming tooling placed in operation can often encounter a rough and potentially damaging environment. The thermoplastic sheet material used in a particular thermoforming process can have abrasive qualities that in the product removal cycles can cause substantial mold surface wear. Design configuration and plastic shrinkage contribute heavily to such mold surface destruction. The surface often experiences only minor wear, resulting simply in a polished surface area and is not significantly damaging. However, when critical portions experience wear, this can prove detrimental to the thermoformed product outcome. For example, the undercut and the stacking lugs can easily be worn away in constantly repeated production. Thermoformed articles containing undercut designs will usually resist removal during stripping from the mold. The thermoplastic material actually has to be forced out of the mold by a mechanical stripping action. Undercut formation stripping will itself increasingly force the plastic against the mold surface at these critical areas. The high pressures between the facing plastic and mold surface, combined with the sliding movement, will create unusually high levels of frictional forces. With softer, rubbery plastics, such stripping actions may not be noticeable at all; however, plastic materials having firmer consistencies or containing material fillers (pigments, stiffeners, or strengthening compounds such as chalk or glass fibers) can have highly abrasive tendencies. An abrasive material on the mold surfaces acts just like fine-grit sandpaper and will rapidly wear down most softer tooling materials.

There are also times when molds are damaged by people. When operating personnel experience difficulties with part stripping and the problem may not be a constant one, instead of resolving the predicament at its source, most operation personnel will resort to temporary measures to cure the problem. Without either consultation or authorization, they will attack the problem with a safety knife or a rigged-up "clawing" tool (a wooden handle with wire or a nail secured to its tip) to gouge out or disengage the stuck article from the mold. This practice is not only damaging to the mold surfaces but is dangerous to the operating personnel. Such practices should be treated as an unsafe act and immediately stopped for safety reasons unless acceptable "equipment lockout" is implemented during dislodging of the article. In most instances, mold surface damage will occur that indicates undesirable operating practices and should send a loud warning signal to supervisory personnel.

The mold damage caused by sharp, damaging tools can easily be resolved by using metals harder than aluminum or treating the aluminum with "hard-coating" anodization. This hard coating of aluminum is a chemical dip treatment that treats only the exposed surfaces of the aluminum mold body. The surface treatment is produced in a minute thickness (about 0.002 in.). Although its hardness is difficult to measure because of its thinness and the softer body backing, the treatment's resultant hardness is comparable to about 60 Rockwell hardness. In spite of its thinness, the hard coating will provide outstanding damage and wear protection for the aluminum mold body. Hard-coating anodization of aluminum mold surfaces should not be considered for all mold constructions; such an expenditure should be made only where a particular condition in thermoforming warrants such a surface.

One last type of mold surface damage worth mentioning is chemical attack. Airborne contaminants—thermoplastic-carried corrosive chemicals combined with the normal "sweat" (condensation) on the mold surface—can have corrosive results on most metal molds. Molds containing steel components will show rusting almost immediately, while those containing aluminum will show some resistance to normal corrosion unless a highly active corrosive residue is encountered. Mold sweat is almost pure distilled water and has the potential of reacting chemically with the aluminum. When antifog agents or other chemical treatments are used on the thermoplastic sheet surfaces, such materials can be deposited onto the mold surfaces to react later with the aluminum. The destruction of the aluminum molds may not be rapid but can be extreme if given enough time. When a corrosive environment is encountered, the thermoforming processor has two options: to flush or spray the mold periodically with a corrosion-neutralizing solution, or to build the mold out of a metal that is less vulnerable to the specific corrosive environment. Such metals would normally be a brass or beryllium alloy which will resist corrosion in any thermoforming situation. The use of these metals can increase basic mold costs at least two- to threefold.

B. High-Quality Mold Materials

Thermoforming molds that require extraordinary construction or materials for specific thermoforming uses, although rare, can have highly desirable benefits.

The use of exotic metal substances with highly specialized surfacing does have its place in thermoforming. These molds are not run-of-the-mill production tools and are produced only for specific needs, and their price tag will reflect this. A highly dimensional-toleranced thermoforming mold made of beryllium cavities and syntactic foam plug assists with trim-in-place hardened tool steel inserts together with all the accompanying manifolds for air, vacuum, and cooling can carry price tags comparable to most injection molds. Yet even with the equally substantial price tag, a thermoforming mold will probably have a greater number of ups within its mold configuration than will an injection mold. In addition, with the higher process cycles, thermoforming offers the advantage of higher output rates. High-quality thermoforming molds can boast accurate and refined details that closely duplicate injection mold tolerance levels. Molds made with this high degree of quality are specifically used when the customer is asking for high levels of detail and uniformity from one article to the next. The thermoforming equipment into which these molds are fit must have equally accurate and precise functions. The slightest deviation in platen movement and registration can cause misalignment between the two mating mold halves. Sloppy alignment can seriously damage the entire mold. When dealing with a precise mold arrangement, extra care must be taken when installing the molds into the machinery. Molds with nominal clearances between their female cavities and their male counterparts must have locating pins fitted into the mating bodies to assure proper mold alignment. The locating pins are removed after the mold is secured to the platens. Setting up a highly accurate mold in a critical thermoforming process should not depend on an "eyeball" method for alignment, as may be done in some general-purpose thermoforming mold alignment.

In an especially demanding thermoforming process when the basic sheet-forming technique incorporates borrowed techniques of compression molding, the common thermoforming limits can be further extended. With the adaptation of compression molding techniques, the two mating mold surfaces squeeze the thermoplastic sheet between them through the mechanical force of the platens. With this method, extra benefits can be gained. First, the thermoplastic sheet can be squeezed into much smaller-radiused corner forms than normal thermoforming methods will allow. Second, surface design patterns of a mold can be squeezed and transferred into the forming plastic, just as in a stamping operation. Third, a perfectly parallel and absolutely flat surface can be squeezed into a plastic sheet by the two opposing mold surfaces. This is most important when a close-to-perfect flange is to be produced on a thermoformed container, one that will offer an acceptable "double-seam" sealing capability with a crimped metal lid. This flat, parallel flange surface and its surface smoothness can be produced satisfactorily by this method only between the two opposing mold surfaces.

The same criteria will exist when the thermoforming goal is to develop an optically distortion-free bottom area on a clear thermoformed receptacle. In this case, the two facing mold portions, which create the specific bottom area, must mate with enough force to squeeze the plastic sheet and provide the distortion-free parallel surface. To provide a flawless impression on the plastic, the mold surfaces can be chrome or nickel plated. In this way, a perfectly smooth mirrorlike mold surface will be squeezed directly onto the plastic. With this compression-type molding technique, any excess material can also be squeezed out under the two mating mold surfaces and pushed into the sidewalls. When the stretching procedure is timed correctly, this squeezed-out excess material can easily be absorbed into the sidewall without any trace. If the stretching is insufficient, the material will show up as a circumferential step or bulge on the sidewalls near the squeezed surface area.

There is one more aspect of high-quality molds that should be discussed here. The best-quality molds and most delicate thermoforming machines are no guarantee of success if the thermoplastic sheet is not administered with equal preciseness throughout the thermoforming process. To satisfy such criteria, a mold-mounted clamping device must be applied. These specific clamping units are either built to surround the entire mold in a framelike fashion, or when individual sheet capture is needed for each mold, the clamping mechanism is built either in a grid pattern or with an independently operating clamp system (see Figures 13 and 14). All of these types of clamping mechanisms incorporated with a thermoforming mold require high levels of engineering, not only for the particular function but for compactness. Internal clamping units must be closely fitted around each mold body without interference from the mold actuations.

C. Special-Purpose Molds

Every so often, a special mold is called into service to be used for a specific product and its adaptation will fit only that situation or product line. Since they cannot be used for any other thermoforming method because of their specialization, some special-purpose molds are tied to specific industries or specific end-user categories. Each special-purpose mold has its own criteria, material makeup, and specialized thermoforming technique. Knowledge of these special-purpose molds and how to use them is most valuable when a thermoforming processor becomes involved with unusual tasks or project developments. Having this knowledge is just one aspect of maintaining a large base of helpful hints upon which to draw when working to solve a newly encountered task.

1. Porous Mold Materials

Thermoforming molds can be produced out of materials—metallic or nonmetallic—that provide a high degree of porosity throughout the mold body. The real advantage of using such porous materials is that the entire mold surface can become activated by the vacuum forces. In ordinary mold cavity air evacuation, where holes are drilled for the introduction of a vacuum, no further pulling of the material will be achieved on the areas between the hole patterns. On the other hand, porous molds present an entire surface of holes for the vacuum. As some pores on the surface become deactivated by the forming plastic, the remaining pores will receive even more of the forming forces. When using porous surface molds, the only criterion to be met is that all the nonessential surfaces, such as the mold's outer surface, be sealed off with a sealant that plugs up the porosity in these nonessential mold surfaces. This will direct all the vacuum forces to the actual forming surface. With this porous mold surface, the vacuum forming force will apply all its power evenly along the surface, creating surface detail transfer so good that even the finest surface patterns of an animal hide can be duplicated perfectly. Since the surface of porous molds contains numerous tiny holes, even the most delicate sewing-thread details can be transferred to the forming plastic. The thermoplastic sheet thickness remains a factor in detail transfer, of course; thinner materials show detail better than do thicker ones.

Porous molds can be produced of metallic materials such as aluminum powder, seizing the fine particles together, or ceramic-type materials that are baked. The main drawback to porous molds is their poor heat transfer ability. Molds made of porous material cannot be used where rapid cycle repetition is mandated. Due to their low cooling abilities, such molds are limited to use in somewhat-low-volume productions.

2. Dual-Function Molds

Some molds serve a dual function. They are first used as thermoforming molds to form a thin skin out of the thermoplastic material. After the forming is completed, the formed sheet is retained in the mold and will index out of the forming station together with the mold. The two will then register into a new station, where the formed body is subjected to a second process. This second process can apply various secondary applications, such as foam filling, coating, adhesive spraying, and flock application. After the secondary application is performed, the combined article is removed from the mold, which then returns to the primary thermoforming stage. This type of mold can be placed into a rotary thermoforming machine format or can be set into a single-station thermoforming setup. In both instances, after completion of the thermoforming process, the mold will either index into a subsequent station or be flipped over to an upward-facing position and subjected to the secondary process. Throughout these secondary operations, the thermoformed article remains in the mold and is subjected to a subsequent process which finalizes the thermoformed product into its finished form. Molds like this are most common in the automotive industry, one of the popular products being the automobile dashboard. First, a thinly skinned surface structure is thermoformed; this is not removed from the mold. The mold, with the formed skin, will index into a foam molding operation. The original mold is closed on another mold half, creating a new foam injection mold. Other product applications can be made just as easily with this type of thermoforming technique.

3. Surrogate Molds

In this specialized thermoforming arrangement, instead of using a permanent mold installation, a previously produced product body is substituted for the mold. The actual forming of the thermoplastic sheet is made right on the surrogate mold form, which after thermoforming actually becomes part of the manufactured article. For each thermoforming cycle a new surrogate mold body is placed or indexed into the forming area. After thermoforming, the combined structure is removed. During thermoforming, both the surrogate mold structure and the thermoplastic sheet that has been formed on it will undergo unification. Actually, due to the heat involved with the forming, a strong bond can develop between the surrogate mold surface and the forming plastic. The bond can be further improved by the use of heat-activated adhesives. This feature of bonding can be judged as both an advantage and an objective for using this type of thermoforming procedure. One of many products produced in this way is car door panels. In making this product, the surrogate mold consists of a composite "substrate" backing material. The material is a wood-particle-based product which by some special process can be formed into the desired configuration. The formed composite substraight panel becomes the mold. Through its porosity or any drilled holes, vacuum can be applied for thermoforming. As the thermoplastic sheet is formed onto the substrate, just like a skin, they bond strongly to each other. Because no mold is involved and the composite material is not an ideal mold cooling medium, only air cooling achieves proper cooling.

There are other products that can be manufactured using the surrogate mold thermoforming techniques, but they are more commonly classified under packaging methods. One such method is "skin packaging," in which the actual packaged goods become the surrogate mold. The plastic film is actually thermoformed right over the to-be-packaged item. The content becomes the mold and the plastic film will enclose it, formed to its contours. The vacuum forces are usually applied through the hole pattern, punched into cardboard stock prior to the application of the film. Through these holes, vacuum is administered which pulls the film against the cardboard and the product to be packaged, creating a finished package.

4. Twin-Sheet-Forming Molds

For simultaneous thermoforming of twin thermoplastic sheet stocks into a single product, two opposing female molds are required. The two molds' cavity configurations do not need to be matching. The only criterion that must be met with these thermoforming molds is that the two molds must have matching cavity lip contours. These mating cavity lips are the key element in this thermoforming process since they form the sealing surface for unification of the two parts. The end results of this process closely duplicate those of a blowmolding process.

The concept of twin-sheet thermoforming is used mainly to produce hollow products from sheets instead of from a molten glob or parison. As in blow molding, these products are made to encapsulate air to provide flotation or for the storage of liquids. For example, small boat hulls, surfboards, motor fuel tanks, chemical shipping containers, and double-sided signs are good candidates for this type of thermoforming and mold construction.

Forming of the twin sheet is made similarly to customary vacuum or pressure forming. The only difference in twin-sheet forming is that airflow must be provided between the two sheets to accomplish the forming. If vacuum forces are used, air from the atmosphere must be allowed to enter between the two forming sheets. With pressure forming, the pressure force should be introduced between the twin sheets without air escape to accomplish full forming. Whether vacuum, air pressure, or a combination is used for the forming, the two molds must be squeezed together immediately to perform the sealing of the two thermoformed halves. There are several variations of this technique, but some are proprietary in nature.

IV. COMMON MOLD ERRORS

Most thermoformers who are closely involved with the production of thermoforming can find themselves in a competitive environment, concerned with the cost of molds and their trouble-free operation. Each concern has specific criteria that must be met to guarantee success. Errors made in thermoform tooling, especially in the mold, can halt most thermoforming efforts. They can not only cause problems for thermoforming producers, but could even affect subsequent product users. Difficulties in a thermoforming process can be caused by many things or by a combination of problems. It is also possible that a suspected fault is not the actual cause of the difficulties; hidden causes are also involved. Inaccurate, hastily made problem detection often misleads the thermoforming processor.

In the thermoforming process many forming difficulties can be traced back to the errors made in the original mold. This is especially true when new mold fixtures are first put into operation. In mold construction not all tool shops are equally familiar with the specific process requirement. Certain tool shops place more emphasis on mold appearance and overly specified dimensions than on proper function. On the other hand, if important mold features are not made up properly, it will cause faulty functions in the thermoforming. Tooling quotations received from various tool shops can often be very different, not only in pricing but in mold quality as well. Thermoforming practitioners must compare tooling costs and evaluate each quotation. Low-priced tooling which later needs rework or modification can in the long run cost more than higher-priced molds which will not need modification or rework.

Please remember that a good mold maker knows where to construct high degrees of tolerance in the mold and at the same time recognizes where less work effort and cost-saving procedures are acceptable. Most mold makers who are acquainted with this critical but generally not followed rule, can provide the best working-quality thermoforming molds without exorbitant cost. Unfortunately, not all tool shops can produce a wide range of mold construction at a competitive price.

The most commonly encountered tooling errors involve vent-hole placement, poor forming force connection, poor mold cooling practice, incorrect mold alignment, unfilled mold gaps, and overly specified molds.

A. Vent-Hole Placement

This is the most common mold-making error. Drilling holes into critical areas in the mold is not only time consuming, but not all areas are readily accessible. The mold's body often has to be tilted to clear the drill chuck in the drilling procedure. It is also possible that the body is not drilled all the way through to create an open channel for the forming force or that the hole size and number are insufficient for thermoforming.

Remedy: Additional holes or enlarged holes should be drilled into the mold body.

B. Poor Forming Force Connection

This could be blamed partially on the mold. The connecting hoses or plumbing lines between the mold and the forming source (vacuum pump or air compressor) are probably at fault. Insufficient line size or connections made with reduced size couplings can also cause poor forming forces. In both cases it will cause a reduction in the forming forces. The reduced airflow could cause the same results if flow reduction is incorporated somewhere inside the mold's body.

Remedy: Plumbing lines, fittings, and connecting couplers of sufficient size should be used to connect the forming source with the vent holes in the mold. The mold's body should be equipped with sufficient branching connections from the plumbing entrance to the venting holes. Adequate cross-section machined-in channeling (milled-in gating) should not cause restricted airflow; however, if any undersized gating is present, it should be enlarged.

It is also worth mentioning that in most thermoforming machine installations and operations the only vacuum gauge is available and installed right at the vacuum pump. Having a vacuum gauge and taking a reading near the pump may not provide an accurate indication as to what the vacuum level is at the mold. Often plumbing restrictions, longer distance between the vacuum pump and the mold, plus a multitude of plumbing turns with elbow installations can reduce the flow and deprive the force of vacuum at the mold. It would be advisable to have another vacuum gauge installed near the mold, that is visible to the operator throughout the entire forming cycle. The gauge next to the mold not only can indicate the maximum levels of vacuum available at the beginning of the forming cycle, but can give additional vital information as to how the vacuum and mold functions are behaving throughout the forming. It can provide knowledge about the mold: whether it has a leak or insufficient sealing is achieved between the thermoplastic sheet and the mold, if the vacuum forming is performed too slowly, and gives comparison to the previous forming speeds. It also can give a good indication to the vacuum system recovery rate for the next forming cycle.

This vacuum gauge when placed next to the mold must be hooked up to the main vacuum line. On a few occasions I have observed that this vacuum gauge next to the mold had a long separate line that is directly connected back to the vacuum pump. In such installations, the gauge is next to the mold, but it is reading the vacuum conditions at the pump. Such a reading cannot and will not provide the information the operator needs. The normal and customary reading of the vacuum gauge should indicate a substantial drop in vacuum levels as the forming is accomplished, but the vacuum level drop should stop at one point and then a recovery or increase in vacuum levels should follow. If the reading on the gauge drops down to zero, it is a good indication that there is a substantial leak in the system that needs to be repaired.

C. Poor Mold Cooling Practice

Most errors in mold cooling are caused by improper coolant flow controls. Time after time, the wrong valve is used to adjust fluid flow. For quick visual identification of the outflowing valve, the valve should be painted bright blue. The second error, an improperly designed cooling channel, is not as common, but its results are serious and far more difficult to resolve. When a mold has a wide range of temperature variations, especially from one area to the next, an

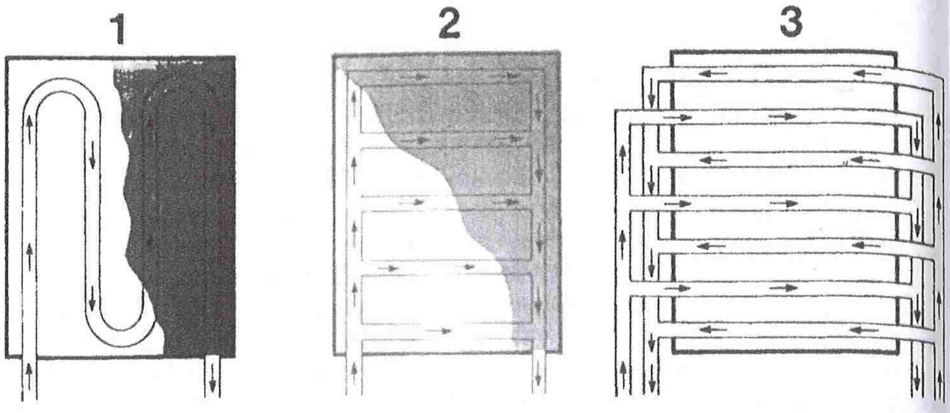


Figure 81 Cooling channel patterns: (1) undulatory cooling pattern; (2) branching cooling pattern; (3) alternating flow pattern with outside manifolds and two inlets and outlets.

incorrect cooling flow pattern is strongly indicated. It is also possible that the mold can absorb more heat at the side facing the oven.

Remedy: All mold cooling channel designs should be preplanned to use an alternating flow pattern with external manifolding (Figure 81). The mold must have sufficient flow rates. In certain molds where extreme heat removal is in demand, flow-turbulent-causing installation should be implemented. Turbulent fluid flow should be created within the mold body to eliminate the slightest coolant fluid stagnation.

D. Incorrect Mold Alignment

This is not a true mold-making error; however, the mold maker can ensure that such an error should not develop. The error is usually encountered when the mold is installed into a thermoforming machine and the two opposing mold halves are not aligned with each other. In an extremely severe case, the two misaligned mold halves, upon closing, can seriously damage each other. The problem is less noticeable if the misalignment is minute; however, it can still cause problems in thermoforming.

Remedy: Installation of locating pins or alignment clamps not only eliminates such misalignment problems but can reduce mold changeover time as well.

E. Unfilled Mold Gaps

This should not be judged as a mold-maker error; however, most of the time the outcome of the forming result will prompt the practitioner to check the

mold or mold setup. This problem will exist only when using a thermoplastic foam material. The thermoplastic foam for thermoforming must be made of closed-cell foam structure. An open-cell foam tends to collapse in foam structure when subjected to heat. For this reason, closed cells or at least a high count of closed-cell-content forms, are adequate only for the thermoforming process. In thermoforming, only closed-cell foam sheet will expand in a thickness ratio of approximately 2:1 when exposed to heat. For example, a $^{1}/_{4}$-in.-thick heated foam sheet is originated from a $^{1}/_{8}$-in. thickness. If the foam material contains higher open-cell counts, or the sheet is subjected to some type of foam destruction prior to thermoforming, its expansion rate (blow-up ratio) will be severely reduced.

Expanded foam material in the thermoforming process is compressed between the two opposing mold halves. If the foam does not expand enough in thickness to fill the mold gap, the formed part wall measurements will be undersized. Undersized wall thickness in the forming is often blamed on moldmaking or setup errors. However, the lack of material thickness is the cause of reduced thickness in the product, after forming, not a faulty mold or poor mold setup.

Remedy: First, the foam material thickness should be gauged. Second, the foam should be subjected to heat to gain its maximum expansion rate, then measured to see if there is any expansion. If the foam does not expand to fill the required mold gap, it should not be expected to thermoform in full detail on both sides of the article. The unfilled mold gap areas will remain unfilled even after the introduction of higher vacuum forces. Such foam material should be replaced with another sheet which has the proper amount of expansion rate or increased gauge thickness. An alternative solution is to reduce the mold gap. However, it will result in diminished strength of the finished article.

F. Overly Specified Molds

Thermoforming molds are often specified to extremely high quality standards. Corners and sidewall/bottom radius are often designed and specified in detail that the particular thermoforming method is unable to produce. Surface finishing could also be specified in a more refined texture than the particular thermoforming method would require. Short-run production molds or experimental molds made of high-grade materials or mold-making materials used in a "lavish" way are unnecessary. It may please the purchaser, but it will not enhance mold performance and can add to the mold's cost. As mentioned earlier, a good mold maker is one who knows how to provide top-quality, accurate molds while offering the best tooling pricing.

about the first edition . . .

"...provides a detailed description of the thermoforming industry."

—*Applied Mechanics Reviews*

about the second edition . . .

Thoroughly updated to reflect the **significant advances** that have occurred since the publication of the previous edition, this timely ***Second Edition*** of a standard day-to-day reference provides **in-depth coverage** of the entire thermoforming molding process *from* market domain and materials options *to* manufacturing methods and peripheral support.

Maintaining the **easy-to-understand style** that sent the first edition into multiple printings, ***Practical Thermoforming, Second Edition*** furnishes **entirely new information** on twin sheet forming, corrugated tubing and pipe manufacturing techniques, plastics recycling, forthcoming equipment, and energy and labor costs...elucidates all possible **thermoforming principles**...**identifies problems** that may be encountered at each stage of the process...offers guidance in selecting **optimal methods** for specific manufacturing requirements...supplies **money-saving** control procedures ...discusses the advantages and disadvantages of every available trimming technique...and much more.

about the author . . .

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