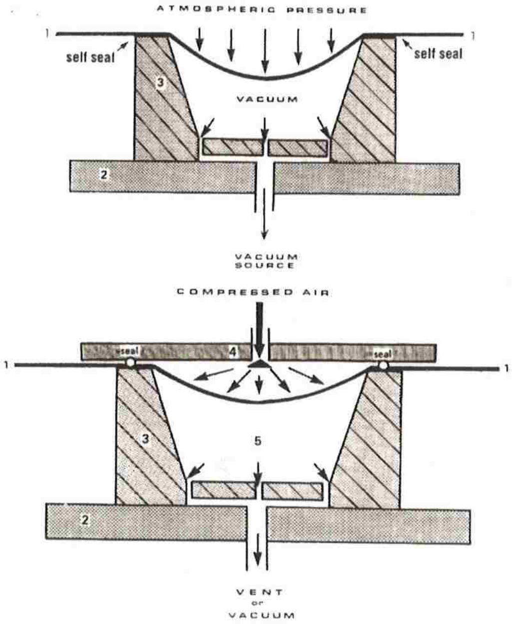
PRACTICAL THERMOFORMING

PRINCIPLES AND APPLICATIONS

SECOND EDITION, REVISED AND EXPANDED



JOHN FLORIAN

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PRACTICAL THERMOFORMING

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SECOND EDITION, REVISED AND EXPANDED

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Preface to the Second Edition

The rapid and accelerated growth of the thermoforming industry has not slowed despite the economic recession of the late 1980s and early 1990s. The economic downturn and environmental issues caused havoc, and unfortunately both entered into the business picture at the same time, which had a devastating effect on some packaging manufacturers and suppliers. Among the hardest hit were thermoform product suppliers catering to high-volume product lines for fast-food packaging. Investment for new equipment for the first time in many years experienced some weakness as well. Despite the setbacks, the thermoforming industry has remained one of the fastest growing due to its low initial investment requirements, superior cycle repeatability, and adaptability to various product configurations.

The temporary setback in product losses in the fast-food areas were quickly replaced with other equally high-volume products. Such abrupt changes in the packaging field may have caused some temporary oversupply and marketing territory takeovers; however, soon competitive forces leveled off. The heavy-gauge thermoforming processors were not affected equally by the environmental concerns or the general recession, which were regional, touching some areas of the country more than others.

The current outlook is bright; there is plenty of opportunity for growth for all thermoformers. In my opinion, thermoforming manufacturing methods have not yet reached 50% of their growth potential. What was thought impossible to make in the past can easily be made today. We can only wonder what we will be able to produce in the future.

The first edition of this book has been most successful. It is found on many thermoformers' desks and is the foundation of my seminar programs. The entire field of thermoforming, including supportive and peripheral areas, is laid out for the reader. To date, there is no book on this subject comparable in quality or detail. The few books that have been written on this subject either concentrate on a specific topic or give overwhelmingly complicated explanations of the technical concepts and include theoretical formulas that often do not produce real-life results.

This second edition has been revised to update information that has changed since the first edition was published and expanded to incorporate subject areas that have come about since and those that will be of greatest interest in the future. For example, I have covered the issue of plastics recycling, which in recent years has come into the spotlight. Recycling concerns must be addressed as they will remain with us due to environmental and legislative influences. They will affect all thermoformers as well as the end users of their products.

The goal of the second edition remains the same: to provide the best and most detailed information, references, and guidance for the thermoformer. The uniqueness of my book is that it is written in a simple, easily comprehensible style and meets the needs of the widest range of people involved in the thermoforming industry. It is especially recommended for owners, managers, and design engineers, as they are the decision makers, as well as for newcomers to the industry. It could be used as a reference guide by practicing engineers, technicians, quality control and customer service personnel, equipment designers and builders, thermoplastic suppliers, sales and purchasing agents, and even thermoforming machine operating personnel.

The illustrations and tables in this book are prepared to emphasize only the concepts discussed. To achieve that, the figures of equipment and molds exclude all nonessential components not directly involved with the specific explanation. Including all the necessary supporting, safety, and actuating mechanisms actually present would have made the illustrations difficult to understand. The tables are also prepared with easy reading and referencing in mind.

Over thirty-five years of involvement with the thermoforming process and its products has provided me with valuable knowledge and understanding of this manufacturing business. Working with many large and small firms throughout North America, from Puerto Rico to Hawaii and Canada to Mexico, I have encountered many different manufacturing conditions, equipment variations, and technical challenges. In the last sixteen years I have been involved with education—teaching the thermoforming process in various private classes and seminars and at the University of Wisconsin—Madison. This wide range of experience has given me the opportunity to gain insight into the most pertinent and practical information on the thermoforming molding process. This book covers it all, from the basic concepts to the latest innovations. The process methods described constitute fundamental techniques that suggest numerous variations and combinations for the practical application of the thermoformer. The book also contains comprehensive explanations and possible causes of problems occurring during thermoforming.

In this book, I left untouched the information that has not changed as well as the basic rules of the thermoforming process. I chose not to include brand and trade names to avoid any commercialization. I mentioned a trade name only when a specific item is known solely by that name. I am confident that most makers and users of the materials and equipment will recognize their specific products, materials, equipment, and machinery, by either concept or function.

One more time, I would like to take this opportunity to thank my wife, Judy, for her many years of understanding and support throughout my career. Patiently giving up her personal time, she not only typed the manuscript but also helped shape the text to provide the clearest possible explanations that would be understandable to everyone, even those unfamiliar with the subject area. With God's gracious help, we have accomplished this once again for the second edition.

John Florian

Preface to the First Edition

The thermoforming process has become one of the fastest growing plastics manufacturing methods since the commercialization of thermoplastic materials due to its superior adaptability, low initial investment, and excellent repeating qualities. In just four decades, thermoformed goods have become part of many existing product lines. Thermoforming has completely replaced other processing techniques for some product lines and has even created new plastic product lines. Every year rapid developments and clever implementations of this manufacturing method allow it to compete with more established methods and to penetrate many new product categories. The possibilities for this industry are extensive and the business opportunities within it are enormous.

The rapid growth of the thermoforming industry and the keen competitiveness among thermoforming processors has kept many of the technical details and developments and the practical know-how in secrecy. In recent years, with the crossover of personnel between companies, the flow of information has increased. The literature on thermoforming, however, still lags behind the industry's projected boom, which has created the need for more education, training, and documentation.

The thermoforming process can be used for material from the thinnest (thin-gauge) to the thickest (heavy-gauge) material to manufacture products from the smallest to the largest possible size and to produce anywhere from just a few pieces to an enormous quantity. Covering all the possible process principles within a single work is therefore not an easy task. But, of course, the similarities and overlapping process behaviors within these variations form an essential body of knowledge that will be of interest to all working in this field.

The goal of this book is to provide information, references, and guidance on the thermoforming of thermoplastics in a simple and easily understood format. The book is intended to meet the needs of a wide range of people involved in thermoforming: business owners and managers, new and experienced engineers, product designers, quality control engineers and customer service personnel, equipment designers and builders, material and machinery suppliers, sales and purchasing agents, and the actual operating technicians.

The illustrations and tables for this book have been prepared to emphasize the basics. The illustrations generally exclude all components that are not directly involved with the specific explanation in order to emphasize the particular thermoforming or equipment functions. Under actual working conditions, with all supportive, safety and actuating mechanisms, these principles would not be so clearly illustrated. The tables are also prepared with easy reading and referencing in mind.

Through my many years of involvement with the thermoforming process, working closely with many highly knowledgeable and skilled colleagues, I have gathered the knowledge and understanding of this process that have enabled me to complete this book. I would like to thank the many equipment and material suppliers who contributed information on their own products, machinery, and instrumentation. Although specific brand and trade names have been avoided throughout this book in order to minimize commercialization, their product concepts and functions are thoroughly represented and explained here. I would like to thank Gerald Sitser for his help in editing and for filtering out my native language influences from this writing.

Last but certainly not least, I thank my devoted wife, Judy, for her long, full understanding and total support throughout my career and for her tireless hours typing, proofreading, and reviewing this entire project, which took up all of our extra time but, with God's help, we were finally able to complete. I also would like to thank the editors of Marcel Dekker, Inc., for their interest, encouragement, and patience in working with me.

John Florian

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Introduction

I. THE BASIC CONCEPT OF THERMOFORMING

The thermoforming process is only one of many manufacturing methods that converts plastic resin material into numerous products. Yet in our modern life-style, we are coming to rely more and more on the benefits of thermoforming and make extensive use of plastic products produced by this process.

Thermoforming is the amalgamated description of the various thermoplastic sheet-forming techniques, such as vacuum forming, pressure forming, matched mold forming, and their combinations. All of these forming techniques require a premanufactured thermoplastic sheet, which is clamped, heated, and shaped into or over a mold. Products made by this process are generally finished after the trimming operation and are ready to be used. However, some thermoformed products are designed as components of larger items, such as boats, aircraft, automobiles, or even smaller items such as product display trays. These parts may require additional work after trimming, such as painting, printing, heat sealing, and gluing.

The thermoforming process offers fast and uniform forming and therefore lends itself to automation and long-term production runs. With its relatively fast molding cycles and comparatively inexpensive mold costs, the thermoforming process is often chosen as the most cost-effective manufacturing method over all the other processes. The scrap created by the normal edge

3

Thermoforming Methods

I. BASIC FORMING TECHNIQUES

A. Preforming Sheet Behavior

To form a thermoplastic sheet into a final product shape, the sheet has to be held by all four sides. The captured thermoplastic sheet is then exposed to heat, softening it and making it stretchable for the shaping. The actual forming of the thermoplastic sheet is almost always made by subjecting the heated sheet to the forming forces. After the forming, residual heat is removed from the formed part, setting it into a permanent shape. With these steps, the forming cycle is considered complete.

The heating cycle begins as the secured thermoplastic sheet is exposed to the heating apparatus discussed previously. There is no difference in the reaction to heating between the precut sheet or rolled material forms. The plastic material will react the same way in both cases, provided that the material source and thickness and exposed sheet panel sizes match. Naturally, sheet materials from different sources can be compared only if their raw resin type and sheet manufacturing techniques are the same. A calendered sheet will not react the same way as extruded or cast sheet materials even if they are made of the same resins. On the other hand, resins having the same chemical composition but different manufacturing sources and different polymerizations may not behave in the same way. Theoretically, the same thermoplastic materials produced in the same manner into sheet form should provide identical behavior in the heating and forming process. Such similarities or slight differences can only be pinpointed by experts. In all cases, a comparative study must be made and analyzed for choosing the most ideal thermoforming condition. A thermoplastic sheet placed into a thermoforming machine will provide a consistent sequence of clues as to its behavior in the heating process. Most thermoforming practitioners fail to observe the behavior changes that take place in a sheet as it is being heated but before an actual sag is noticed. Between the time of the cold sheet exposure and the resulting sag, there are changes in the sheet that can be observed. Such changes are not necessarily slow and obvious; often, they occur in just a fraction of a second. The rapid changes could take place so quickly, in fact, that even with the best skills of observation, they may pass unnoticed. That is the reason that for most thermoformers, the first clue to the change is sagging of the sheet. The sheet's response to heat is most likely to follow the sequence shown in Figure 36.

1. The cold thermoplastic sheet is placed into a sheet-holding apparatus and its exposure to heat begins.

2. As soon as the plastic is exposed to the heat, various temperature levels are created within the plastic and the first changes can be observed. Due to a higher temperature on its surface than in its inner core and possible temperature variations on the surface itself, the partially heated plastic will go through a wavelike movement. This movement closely resembles a ripple spreading across the surface of a body of water. The reaction of the plastic sheet to the heat may come in such pronounced levels that the sheet shows an immediate but temporary sag. The sag rapidly disappears with further heating. This temporary condition should not be confused with materials displaying an immediate and permanent sag condition, which are discussed in a later section. It is possible that thermoplastic sheet materials will react only minimally to heat. In reacting to heat, some thermoplastic sheets never display anything as defined as a ripple-like expansion movement; they may show only a slight color or surface sheen change. Some plastics provide such subtle clues as gaining more clarity or getting either shinier or duller. Either way, a change will take place that can be observed and recognized.

3. As the sheet is further exposed to the heat, its normal reaction causes it to tighten up. This tightening gives the sheet the appearance of well-stretched-out material, almost like the skin surface of a drum. In this state, knowledge of the changing temperature conditions is vital to successful heating.

4. During the heating cycle a definite sag will appear in the heated sheet. At this point, the plastic will be heated and softened to the point where its self-supportiveness is reduced and the sheet will yield to gravity. Actually, the softened plastic can no longer support its own weight and will stretch out of its original shape, creating a sag. The sag is a well-defined change in plastic behavior, and being so noticeable, most people recognize it as the first reaction to heat. With many plastics, this is somewhat true. If the plastic sheet does not have any orientation—or even if it does but its weight, due to its gauge or panel size, cannot hold itself up—a sag will develop. This may be the first observable reaction in the sheet when exposed to heat. Many thermoformers automatically use sag as the indicator for readiness of the thermoforming process, although this is not a completely reliable method. Some thermoforming equipment builders even offer an electric-eye sensing device which will trigger an automatic forming cycle as soon as sag interrupts the light signals.

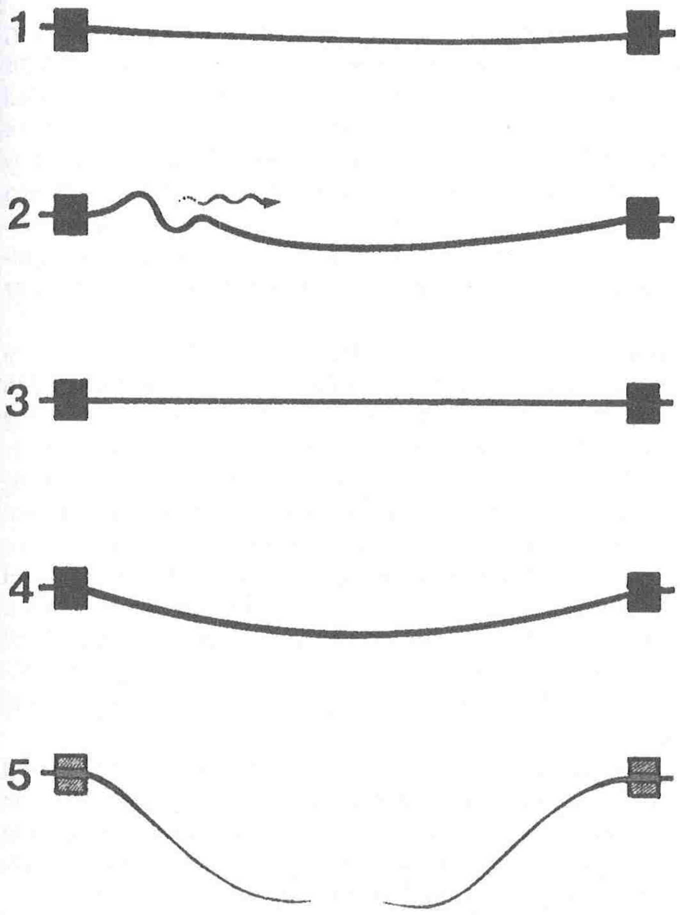


Figure 36 Thermoplastic sheet behavior in heating: (1) clamped cold sheet; (2) rippling reaction to heat; (3) heat-tightening sheet; (4) sagging sheet; (5) overheated sheet.

A heated sheet that develops sag is not necessarily unusable. However, in most instances, sag should be avoided if possible. Using sag as an indicator of readiness for thermoforming is only slightly better than using measured time. The development of sag in the heated sheet will obviously be a more accurate indicator than the use of timers, which are completely unaffected by ambient and sheet temperature changes. For example, a manufacturing area could have wide temperature variations between the early morning and afternoon hours and even greater temperature changes between the day- and night-shift hours. If this is the situation, it is easy to see why sag would be a better indicator than timer units.

Developing sag in a sheet and using it for prestretching of the sheet is also acceptable. This is a common practice in moldless thermoforming or when deeper, well-tapered cavity shapes are formed. In fact, the use of developing sag will help to achieve better wall thickness distributions than its nonuse. Controlling the development and size of the sag is not an easy task. Allowing sag to develop in the heated thermoplastic sheet for thermoforming may not prove to be advantageous at all. Creating a predetermined sag size, no more and no less, is one of the most difficult procedures. Since the sag is produced by the weight of the plastic sheet, it is an ongoing, continuous process. At the point where the sag is judged to be of correct size, it is still expanding and will rapidly stretch out of control. At the same time, the plastic may not be stretching evenly, resulting in a nonidentical bulge shape, hindering uniformity in the shot-to-shot process.

More important, and to the dismay of thermoformers, the developing sag in the plastic sheet alters the distance between the heated sheet and the heater units. Such a change in a given distance, especially when the sagging sheet drops closer to its center to the bottom heater element, will prove to be detrimental. This could cause runaway heating of the plastic, and the overheating will accelerate greatly as the sheet comes closer and closer to the heater units. It is easy to see that a fraction of a moment on the timing controls may mean the difference between forming success and forming failure. In more cases, a sagging plastic sheet will be hotter than is necessary for forming and shaping.

5. Of course, the plastic sheet can be so neglected that it will reach the point where the sag radically overdevelops and the sheet melts and flows apart, making it no longer useful for thermoforming. At this point, not only is the thermoplastic sheet lost in the overheating, but the molten plastic can fall into the heater elements and result in fire. By no means should neglect of the heated sheet continue this long. Most thermoplastic materials derived from petrochemical and fossil-fuel sources, when exposed to extreme heat, will constitute a potential fire hazard. Precautions should be incorporated in thermoforming equipment which enables it to prevent ignition of the plastic material, or even to put out the resultant fire. More important, these precautions should include good control of the sag and perhaps even its complete elimination.

Thermoplastic sheet materials used in the thermoforming process to make various products are produced from different types of resins and in a multitude of gauges and sheet sizes. Their reaction to heat is just as wide ranging as their sources and forms. Some materials demand the most precise control range in which to perform and not get ruined, while others are especially "lenient" regarding overheating. Such differences, shown in Figure 37, should be recognized and, when known, well respected. For example, biaxially oriented polystyrene sheets display one of the most narrow heat ranges between the formability temperature and the loss of orientation, which comes about at the slightest overheating points. When high-impact polystyrenes (HIPS) and acrylonitrile-butadiene styrene (ABS) plastic sheets are heated, substantial overheating is possible without damage to the plastic. Working continuously with the various materials, thermoforming practitioners will soon discover the specific sensitivity and "criteria windows" of the individual plastic sheets, as well as their behavior under different heat ranges. Knowing where the data may fall on the chart will help to achieve the most advantageous forming conditions. Each time a change is encountered in thickness, color, resin material, heaters, or even ambient temperature, the reaction to heat will be altered.

B. Moldless Forming

Thermoforming a bowl or dome shape can be accomplished quite easily. In fact, such shapes can be obtained easily without the use of a mold. There are two basic ways to form the plastic moldlessly. The first and less complicated way consists of producing a sag in the clamped sheet. When a bowllike shape is approaching the desired size, it should immediately be removed from the heat source, for cooling. This allows the weight of the heated plastic sheet to form and stretch it. With this method, producing a bowl shape will take the longest time and the shape produced will never have a uniform curvature. Since the bowl shape is the result of a sag that may produce uneven stretching of the sheet, the curvature of the bowl shape may result in inconsistent placement of the center point. These variations in shape are easily found from one part to the next, giving the product a poor nesting quality.

The second way to produce bowl- or dome-shaped configurations without molds is to build equipment that resembles a pressure box. One of the walls of the box is actually formed by the clamped and heated plastic sheet. When the plastic sheet starts to show some softening, the box should be internally pressurized. The pressure will force the softened sheet to bulge upward to form a dome shape. At low levels of pressure, the softened plastic can be kept from sagging and thus held straight and flat. As the pressure level is increased, bulging

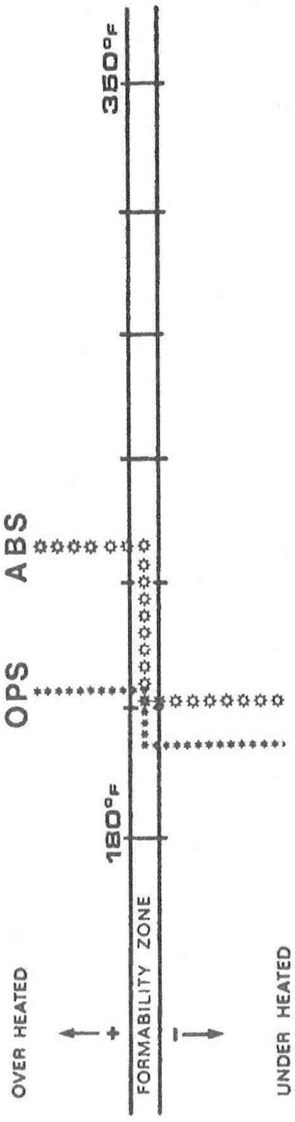


Figure 37 Thermoformability heat range chart. Note the narrow formability range of OPS and the wider formability range of ABS.

will appear; as the pressure is increased further, the size of the bulge will increase accordingly. With the force from the air pressure, the plastic will stretch and form into a domelike shape. When the desired shape is reached, further heating and any increase in pressurization must cease. Consequent cooling will take place or, if desired, fan-forced cooling can be introduced to set the newly acquired shape into a permanent form. Forming domes with this method of pressurized air is much more rapid than producing them by sag, and the comparative shapes are more uniform. It is well known that this type of forming, despite improved qualities, will never produce as uniform a shape as would a mold. However, for the purpose of specific products, this type of forming technique is well accepted and routinely used. Most skylight windows and window fixtures are produced in this manner, for example.

C. Basic Female Forming

Thermoforming a heated plastic sheet with a female mold is one of the simplest methods of forming. Using a preshaped female cavity as a mold makes this thermoforming possible. As soon as the properly preheated plastic sheet is positioned over the mold, the forming cycle is ready to begin. The entire forming procedure takes only a moment to complete. To fully understand and appreciate the intricacy of this brief forming procedure, it is necessary to break this short time span into even smaller segments. As if using stop-action photography, the rapidly created forming can be broken down into six major time segments for examination. Each time segment will have well-defined actions that individually can affect the overall forming procedure. The time segments occur consecutively and always in the same order. The forming procedure, however, can stop short of completion of all the forming segments, thereby causing incomplete forming. The forming procedure can easily be divided into six segments, as shown in Figure 38.

a. The properly held (clamped) sheet heated to a correct temperature level. The well-prepared sheet is positioned above the female mold cavity. The mold and the sheet will move toward one another. Any vacuum force actuated prematurely will be useless. In fact, vacuum actuation may be harmful since due to the heavy loss of high vacuum energy, the forming may not receive its maximum force. In addition, the heated sheet may be chilled by the movement of air sucked through vacuum holes.

b. At the point where the sheet and the upper horizontal surface of the female mold make contact, the vacuum should be activated. The softened plastic sheet, having made contact with the mold's upper surface, provides outstanding self-sealing action. Naturally, the vacuum introduced to the cavity will pull this seal even more airtight. At this point it should be clear that the sheet and the mold together create an enclosure, with the sheet stretched over

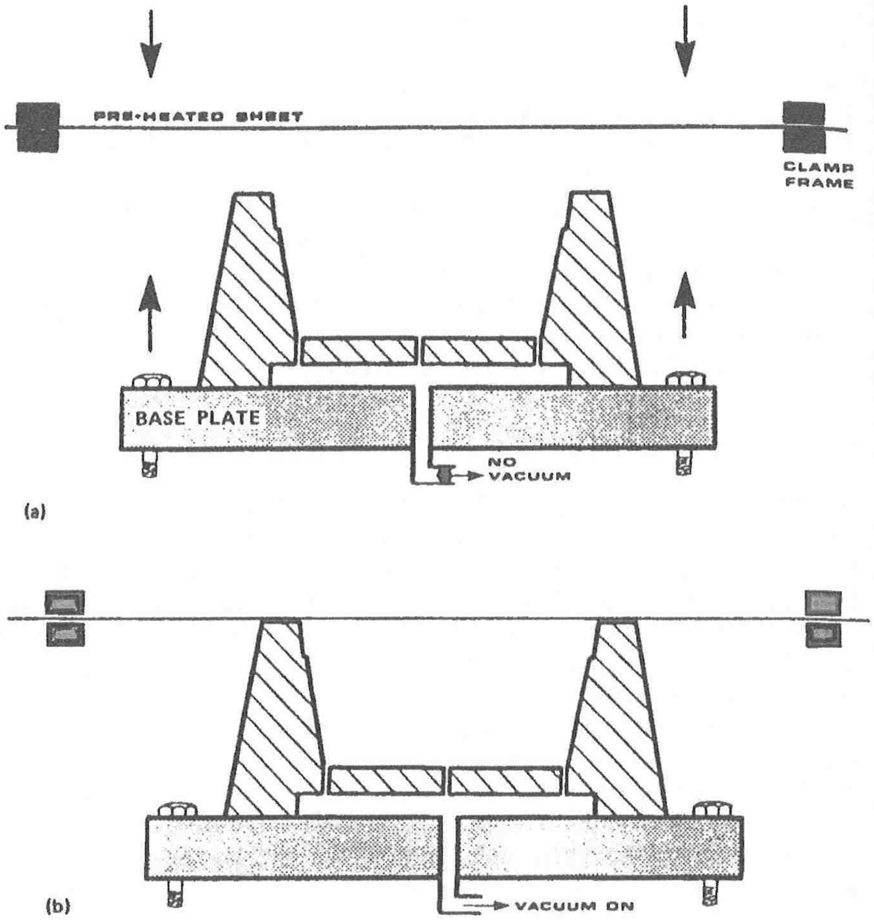


Figure 38 Female molding.

its opening acting as a flexible membrane. The softened sheet will have no resistance against the vacuum force, which will pull it into the cavity.

c. As the membranelike softened sheet is pulled into the cavity, its thickness will be reduced by the stretching. There will be extremely little stretching where the sheet and the upper mold surfaces are joined to create the sealing effect. Most of the stretching and thinning of the material will occur at the membranelike portions of the sheet. If the sheet should not receive sufficient heat to provide the necessary softening for the thermoforming, its chances of

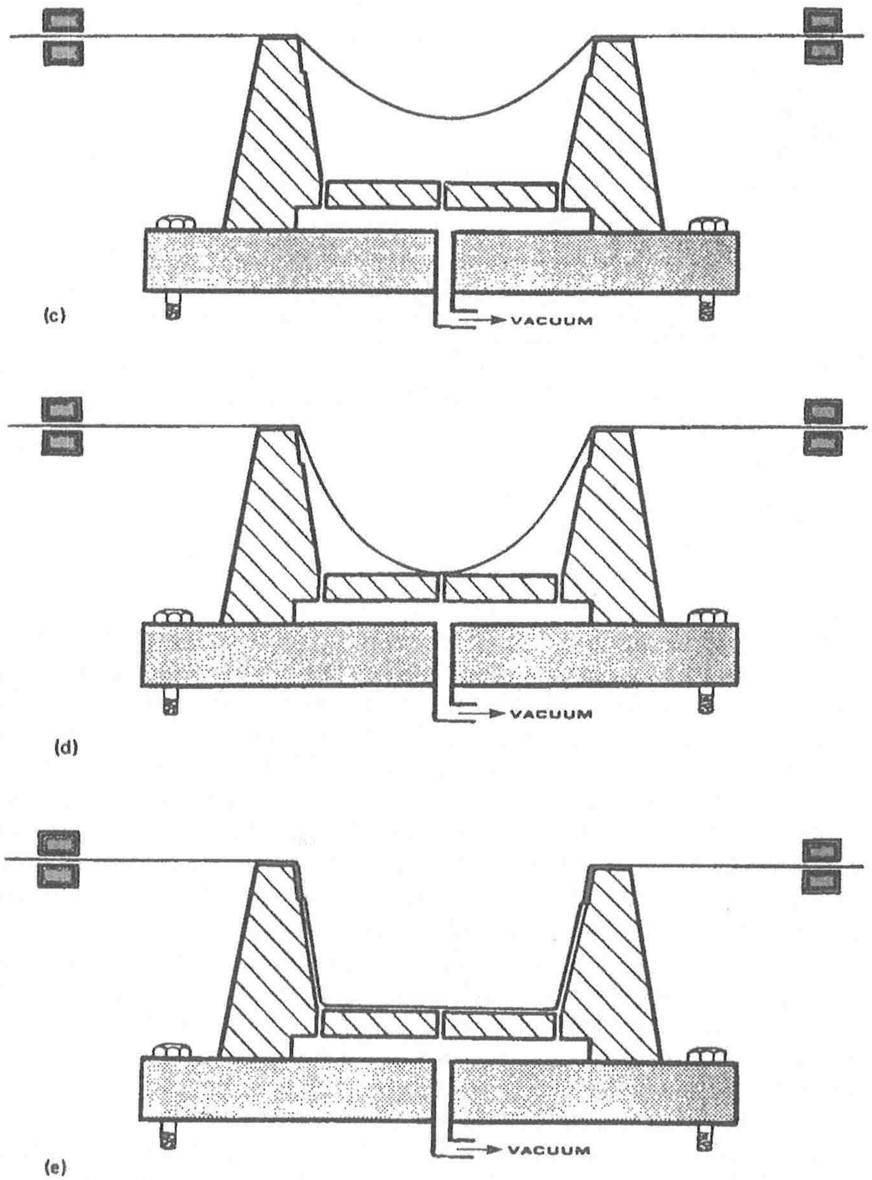


Figure 38 (continued)

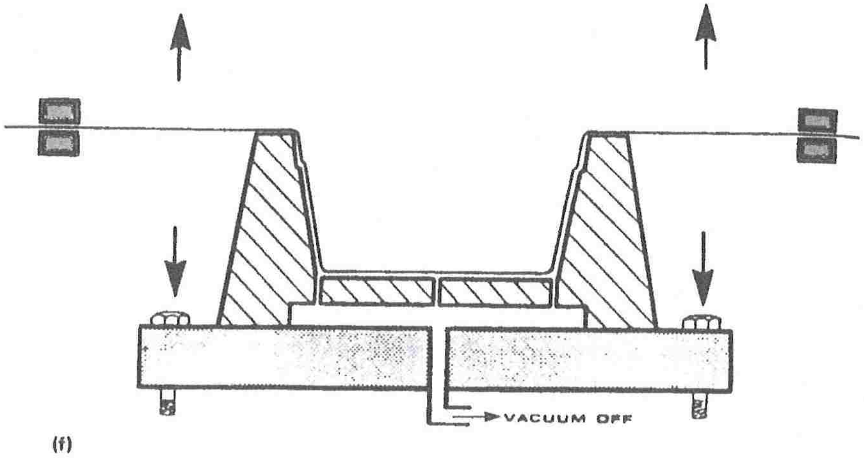


Figure 38 (continued)

stretching will be curtailed. The sheet material will firm up before full detailed forming can be accomplished. Depending on the sheet's preheated temperature, the incompleteness of forming can be either extensive or slight. In the most severe cases, the forming is so incomplete that the plastic sheet only develops a bulge. On the one hand, the forming will stop just short of completion and full detail obtainment. Recognition and determination of the cause of this condition are confusing and difficult. The slight loss of detail may indeed be caused by the underheated sheet, but other culprits—lack of vacuum forces and an overly chilled mold, to name two—could result in the same symptoms.

d. The location of the vacuum holes is also critical in forming of the plastic. When the vacuum channeling holes are placed too centrally in the cavity, the partially formed plastic can lean against the holes and plug them up, rendering further forming impossible. Air pockets will be trapped in the cavity. Properly distributed vacuum holes places in the deepest corners of the mold cavity can eliminate air pockets.

e. When the thermoplastic temperatures are at their proper levels, sufficient forming forces are being applied and fully detailed forming will take place. Reduction of the sheet thickness from its original gauge is a normal physical reaction. To create a three-dimensional shape out of a flat plastic sheet, its surface area must be increased and stretched. To estimate the amount of gauge reduction in the material in order to choose the proper gauge material for the end product, the intended mold surface area must be established and its ratio to the original sheet dimensions correlated. The established increase

in surface area provides a good averaging estimation of the reduction in gauge thickness. Of course, this estimation is only good for approximating the material thinning. In the actual thermoforming, substantial variations can be realized based on the particular thermoformed part configurations. The reduction in gauge could be so severe that certain areas of the formed part will display undesirable thinning. if this is the case, many possible alterations can be implemented in the overall thermoforming procedure before such parts are deemed impossible to make. The programmed heating method previously discussed is one of the options available to remedy this thermoforming situation. Other improvements may become more obvious in later segments.

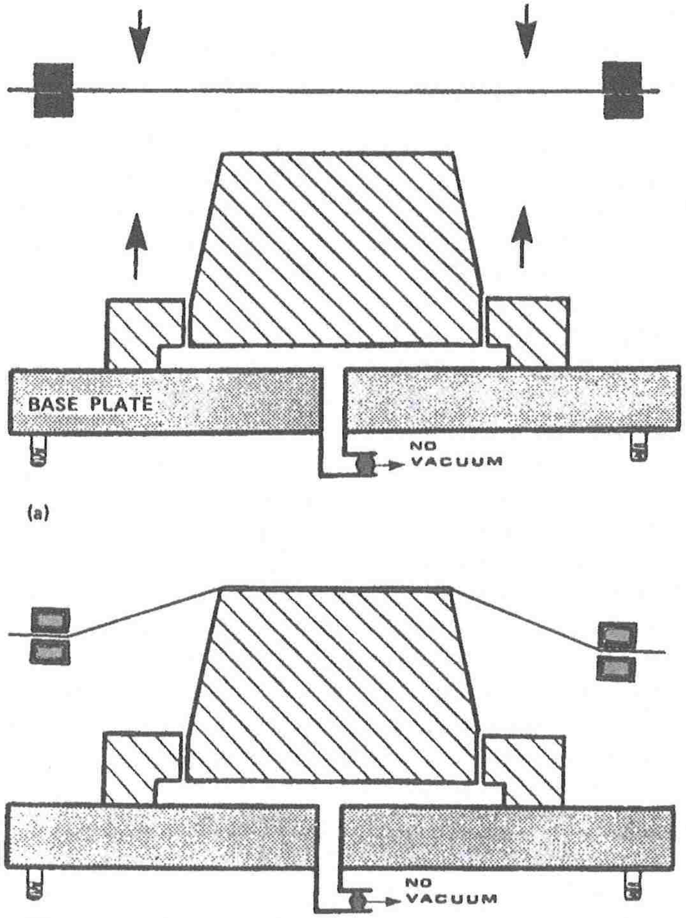
f. If and when the thermoforming is made with all the proper conditions and its outcome is satisfactory, the formed plastic will be in full contact with the inner mold surface. At this point, the mold's cooling effect takes place. The mold, being cooler than the forming plastic sheet, will extract heat out of the plastic through surface contact. The cooling of the formed part not only sets its shape into permanent form but results in a normal shrinkage in size. This shrinkage will cause the part to pull away from the mold surface, facilitating easy removal. Natural shrinkage is a welcome phenomenon with female molds and happens with all plastic material. The shrinkage rates may, however, differ from one plastic type to another. The establishment of shrinkage rates is usually worked out in a range from the lowest to the highest point. The range for a family of plastic will be representative of all members of that family. Substantial variations in shrinkage can be found from one plastic family to another, allowing no substitution of materials if final product dimensions are critical.

D. Basic Male Forming

Thermoforming a heated plastic sheet with a male mold follows closely the "stop-action" sequence of female forming. The same criteria will hold for each sequence. However, certain aspects of the outcome may result in some variations. The actual steps of this sequence are shown in Figure 39.

a. The preheated plastic sheet is placed over the male mold and the two elements are brought together. The clamping mechanism holding the sheet will provide the necessary holding—or even draping—action that is needed when male molds are used in the thermoforming. The particular thermoforming is often referred to as "drape forming" because the heated plastic sheet is actually draped over the mold. The results of the forming will be the same provided that only the clamped sheet moves to drape the plastic over the mold, rather than the mold moving against the sheet or both moving toward each other simultaneously.

b. Unlike the case of the female mold, the vacuum system should not be actuated at the moment when the heated sheet comes in contact with the mold



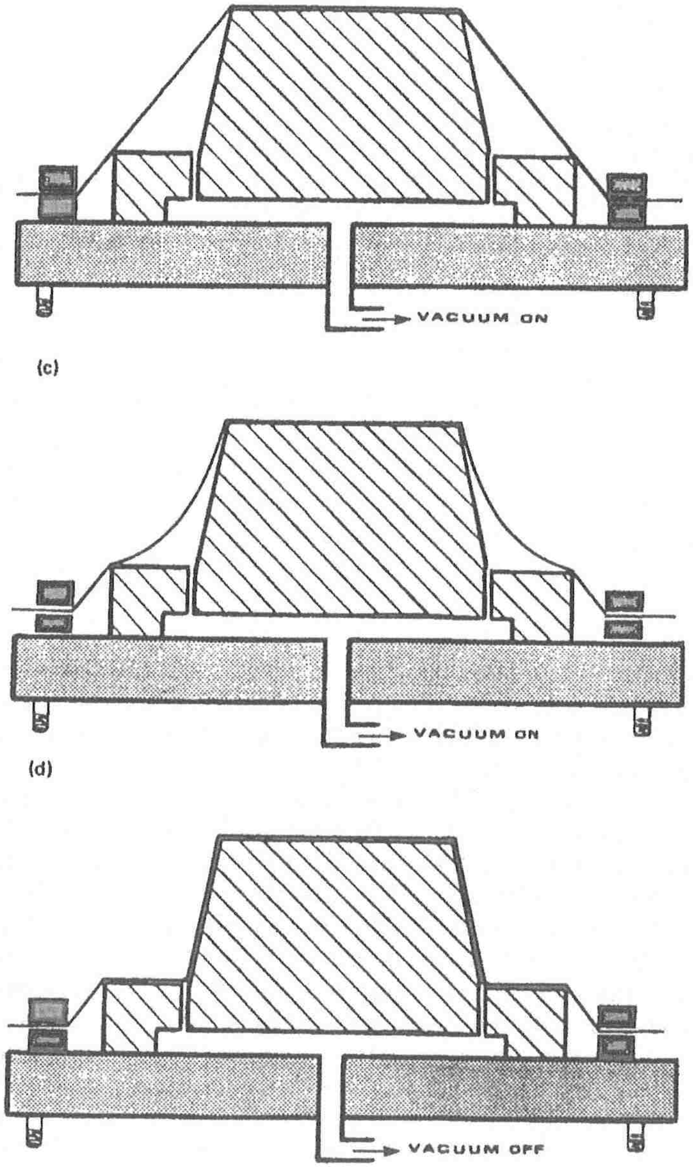
(a)

(b)

Figure 39 Male molding.

surface. At this stage, the thermoforming sequence is not timed to match the female mold condition. Vacuum actuation at this point is premature. If the vacuum is actuated, there will be no plastic forming. When the mold is much colder than the forming plastic sheet, the mold will chill the plastic upon contact. If this cooling is extensive, the contacted material will be unable to stretch for the forming.

c. The clamp mechanism and the male mold surfaces must close further upon each other to create a sealing effect at the lower surface edges of the



(c)

(d)

(e)

Figure 39 (continued)

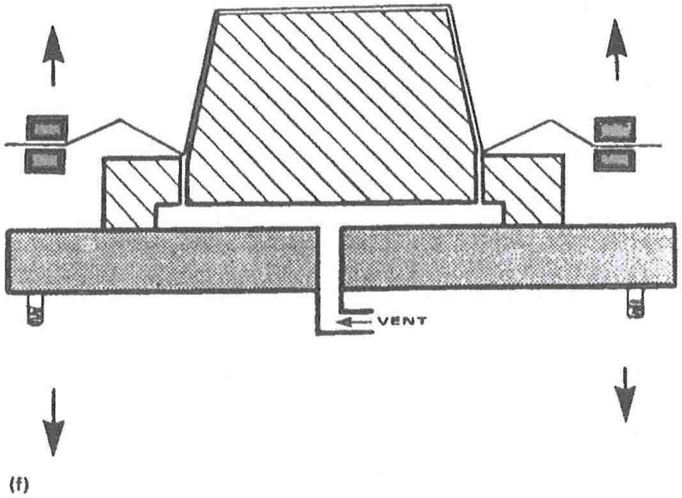


Figure 39 (continued)

mold. As soon as a seal is created between the plastic sheet and the outer surface corners, actuation of the vacuum forces will finish the forming procedure. If the natural sealing effect is incomplete due to the loss in vacuum, the overall forming of the plastic will be affected.

d. When a good seal is achieved between the softened plastic and the mold surface, the forming forces of the vacuum will enhance the sealing qualities. At this stage, the process of forming with the male mold will mimic many characteristics of female mold forming. The softened and draped plastic sheet will trap air between it and the mold. This air is evacuated by the vacuum. This will force the membranelike plastic directly against the mold surface. Another similarity of male forming to female forming is that when the plastic sheet does not receive sufficient heating for softening, the forming may not be fully produced. If the vacuum holes are not placed in the deepest parts of the mold configuration, the sheet will cover and plug them up as the sheet is stretched, leaving air pockets and stopping the forming short of full detail. Underdetailed forming can be caused by any of the conditions noted above as well as with low levels of vacuum forces. Such a variety of problem-causing conditions necessitates a careful examination. Their elimination one by one will ensure the success of thermoforming.

e. When all the elements of forming are successfully achieved, the thermoplastic should be fully formed over the male mold. The heat of the plastic sheet will be absorbed by the mold throughout its entire surface, resulting in a permanent shape being set in the plastic. At this point, the vacuum forces must be turned off.

f. As the cooling of the formed part is accomplished through contact with the cooler mold, the formed plastic should shrink, just as it does with female forming. Since the mold is male, the shrinkage of the formed material, with its normal reduction in size, will tighten it onto the mold. The general shrinkage of the formed plastic part over the mold may not present an overwhelming problem. However, there are occasions when the formed part and tooling do not have sufficiently tapered angles. In addition, ribs and ridges may be present on the sides of the part, or extreme depth-of-draw ratios may be insisted upon. In such cases the shrinkage on a male mold easily proves to be a problem. The formed part will be difficult to remove from the mold. As shown in Figure 39, the components do have sufficient draft angles and the drawn flange area distortion is exaggerated. However, with substantially smaller tapered angles, at mold separation, part removal will cause the flanges and even part of the sidewalls to distort. In the most extreme cases, the shrinkage and grabbing by design-related flaws can be so severe that part separation from the mold is nearly impossible; to attempt it can result in damage or rupture of the formed part.

When the designs of a part do contain slightly tapered angles, which would cause part removal difficulties with its shrinkage, it is always best to choose the female molding method over the male. The choice of female molds versus male molds should be guided by the ease of forming and by the material and wall thickness distribution factors. Female mold forming tends to stretch material in different locations and proportions than an identically shaped male mold. The thermoforming practitioner has the option to choose whichever forming method will produce the best result.

E. Basic Matched Mold Forming

Thermoforming of a heated thermoplastic sheet can also be accomplished with only male and female mold stamping forces. In this type of thermoforming, the male counterpart of the female mold will push the heated sheet into the female cavity. In most instances, this stamping force will act similarly to compression molding techniques. The limitations of this type of matched mold forming are the dependence of the mold configuration and the thermoplastic material stretching and flowing characteristics. Using the matched mold method to force material into the contours of the gap left between the male and female molds is not an easy task. With limited taper designs and substantial depth-of-draw ratios, the heated thermoplastic sheet can only form up to its limits of stretching; after that, it will develop tears and holes. Some materials have greater tear resistance than others. The two limiting factors—mold configuration and thermoplastic material features—are so intertwined and interacting that their specific limits must be tested under actual working conditions. Due to the unknown factors present here, you can only judge the approximate failure limits of specific combinations. This condition is aggravated even further by design patterns containing elaborate configuration combinations, such as male and female elements existing within each mold. Mold configurations that display an open, well-tapered design with smooth surfaces and clean lines are good candidates for matched mold forming. In fact, all thermoplastic foam materials are formed using the matched mold forming technique. Using a matched mold, whether on completely or partially matching contours, is the only way to produce satisfactory details on both sides of the thermoformed product. Matched molds, as they close together, will squeeze the softened thermoplastic foam sheet between their surfaces, forcing it to flow and fill the predetermined mold gap. For example, examination of an egg carton cross section will demonstrate such foam forming results. At the hinge line between the cover and the base, the foam material is squeezed into a solid plastic to allow it to hinge. The egg-holding cells, on the other hand, are produced with a much larger mold gap, giving the foam a softer, cushiony effect. The foam thickness variation is evident throughout the entire egg carton design and gives us a clue that it is thermoformed using a partially matched contoured mold.

There are two basic variations to thermoforming with a matched mold:

1. Having the male mold mounted above the female mold and forming the softened thermoplastic sheet downward into the female. In this case the actual act of forming can be combined with a purposely produced sag. The sag may provide prestretching, promoting better material distribution and resulting in a more uniform wall thickness of the formed part. In this particular case, the not-so-desirable sag can be justified, because it will both improve the forming and benefit the thermoformer. It should be emphasized that developing sag in a sheet does create a slightly overheated condition and therefore extra cooling time will be required.
2. Affixing the male mold to the bottom platen for pushing the heated thermoplastic sheet upward into the female. With this method, the male mold can prestretch the heated plastic sheet by moving upward, causing a tentlike stretch in the sheet. Normally in this process, the male mold's travel is curtailed, as it should be limited to satisfy only the prestretching purposes. Excessive stretching may be more damaging than helpful. Overstretched material may develop wrinkles when the female mold closes onto the male. As the material, overstretched through lack of control, develops more surface area than the mold surface requires, it will be forced to fold over itself as a bona fide wrinkle. To eliminate this unwanted flaw, the thermoformer has only to limit the prestretching and the wrinkle will disappear.

In both types of thermoforming with a matched mold, the forming success is highly dependent on the flow characteristics of the particular thermoplastic material. These characteristics, in turn, are highly contingent on the sheet temperature, which softens the sheet and ultimately allows the forming. With some of the more sensitive thermoplastic materials, just a few degrees' decrease in heat levels could result in major forming difficulties. Individual testing and understanding of a specific material's limitations are very important to success in thermoforming. The particular temperature sensitivity and forming criteria are discussed further in Section II.H.

Matched mold forming is not limited to the use of molds that are closely matched in size. In modern thermoforming processes, using male portions of the mold to facilitate forcing the sheet into the female mold is a common practice. Such "plug-assist" forming, which could qualify as a type of matched-mold thermoforming, is discussed in the following section.

II. THERMOFORMING METHODS

The thermoforming process need not rely solely on the three basic mold types and their simplest forming methods. In many instances, the actual forming of the plastic sheet needs to be managed with some variation of the methods discussed previously. These variations tend not to change the basic thermoforming concept; rather, they improve either the forming technique or the finished product. In some cases, a specific deviation from the basic forming method makes it possible to thermoform an otherwise unformable plastic sheet, or at least to provide better control of its shaping. Some of the ultrasensitive thermoplastic materials cannot even be considered thermoformable without implementation of specialized thermoforming techniques. The main purpose of carrying out any thermoforming method is to improve the outcome of the forming and to achieve the best possible material distribution and stretching. This is accomplished when the finished thermoformed article has been produced with an even wall thickness and excessive thinning is not permitted at any location. Product weakness and failure always take place at the thinnest areas of a product.

Variations in and combinations of forming methods are attainable in numerous ways. Some variations are chosen strictly for their obvious benefits and may serve a specific purpose. On the other hand, some thermoforming methods are implemented to satisfy the inventiveness of the processor rather than for their usefulness. The methods should be examined individually and broken down into segments to be judged for appropriateness. We discuss in detail below the most common thermoforming methods in use today: trapped sheet, plug assist, form and trim in place, pressure bubble plug assist, pressure bubble snapback, snapback vacuum, trapped air assist, solid-phase pressure, and twin-sheet forming. There are other, less popular variations or combinations that can be used successfully. As the industry pursues better results, additional variations will be developed, and there is no limit to the inventiveness that we should see in the future.

Variations in thermoforming methods usually begin with one of the basic methods and then proceed to combine methods borrowed from other styles. Other variations include the altering of forming force levels, changing platen speeds and sequencing, incorporating clamping mechanisms, and resetting vacuum and air-pressure switching and timing.

A. Trapped Sheet Forming

The trapped sheet thermoforming method should be viewed as a specialized type of thermoforming. However, the technique has the simplest components of any of the forming procedures. Since the thermoforming is carried out on a captured and trapped area of the sheet, the method is called "trapped sheet forming." At the same time, because the three basic sequences of the thermoforming (heating, forming, and trimming) all occur at the same location, this type of thermoforming can also be called "heat-form-trim-in-place" thermoforming. The first is more correct because trapping of the sheet is the dominant factor in the process. To understand the inner workings and motion sequences within the thermoforming cycle, Figure 40 should be followed. The thermoforming cycle in this forming method always begins with the unheated sheet and can easily be broken down into four basic segments. There are easily identifiable advantages and shortcomings to the use of this process. The shortcomings will be discussed first because these provide the factors that limit the opportunities and applications of this method. The two major limiting factors relate to thermoplastic sheet heating and exclusive female mold use.

To implement thermoforming by the trapped sheet method, the thermoplastic sheet is heated by a contact heater. Contact heaters provide excellent heat-level controls but slow down the heating procedure because contact can only be made with the underside of the sheet. This sheet heating method limits the use of this process to the lighter-gauge sheets. More than a 25-mil material thickness requires prolonged contact heating, making the heavier or thicker materials uneconomical to run.

The second major shortcoming of the process lies in its restriction to the use of strictly female molds. Typical female mold use curtails the depth-of-draw ratios to 1:1, and parts with the maximum draws will suffer from substantial material thinning. From a product manufacturing standpoint, trapped sheet

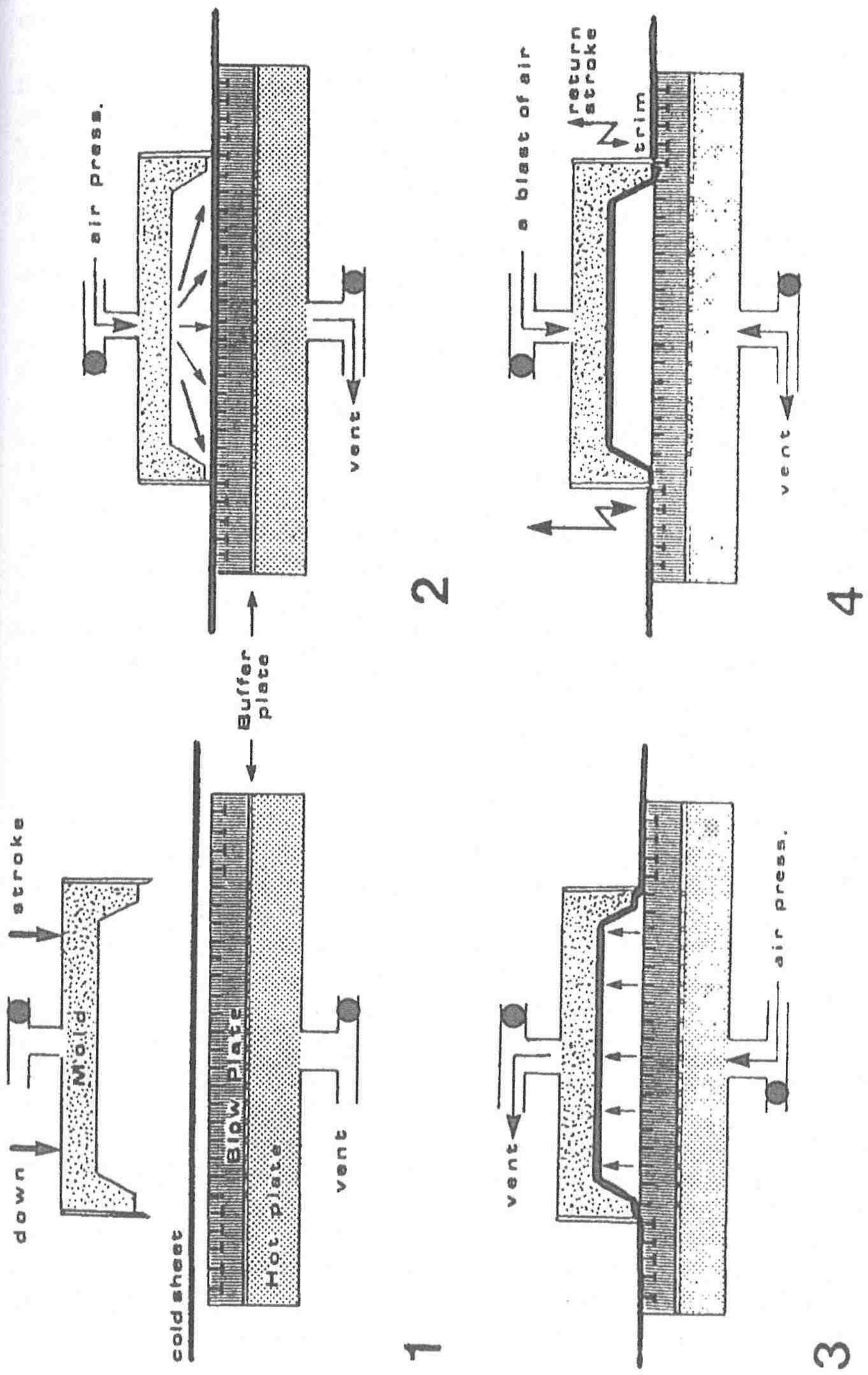


Figure 40 Trapped sheet, contact heat/pressure forming: (1) sheet clamping; (2) sheet heating; (3) forming; (4) trimming and stripping.

forming should be limited to products that have shallow part designs and do not have critical specifications for even wall thickness.

There are definite advantages to the use of this process which make it ideally suited to high-volume production. The simplicity of the process makes it so easy to carry out that many products fall well within the limits. The use of contact heating, with its bulky heating plate, is not only easy to control but is not subjected to temperature fluctuation. In fact, this type of heating is not vulnerable to ambient temperature changes or drafts.

Finally, and most important, the type of mold used, with its own wraparound cutting knives, makes this style of tooling complete and comparatively inexpensive. New tooling, tooling changes, and reknifing can be made reasonably cost-effective. Most production tooling for this type of thermoforming is made by using a heavy 1¼- to 2-in.-thick surface-ground stress-relieved base plate. The mold cavities are sand-casted aluminum bodies with a machined back surface and the surrounding cutting knives are either wrapped around steel-rule knife blades or are one-piece forged knives. When a change in the thermoformed product is to be implemented, an alteration in tooling can also usually be made, thereby avoiding purchasing a new tool. Of course, this alteration of tooling does have limits, and major changes can be accommodated only by building a new tool. This type of thermoforming process does not place stress conditions on the molds, and the only part of the tooling that will wear out is the cutting knife edge.

The four-process sequence shown in Figure 40 illustrates how this thermoforming method works.

1. The unheated sheet is trapped by the cutting knife edges. In this type of thermoforming, the knife has a double duty to perform. Through most of the operation, the knife edge acts like a clamp frame, capturing a predetermined area of the sheet and firmly securing it around each mold's circumference. Naturally, the final duty of the knife remains the trimming of the formed part. In the trapped sheet thermoforming process, each mold cavity is completely surrounded by its own knife. Consequently, each forming is made from its own captured sheet area. The upper platen moves downward with the mold and the knife forces the unheated plastic sheet against the heated cutting plate. The cutting plate is mounted on a stationary platen and is made out of a hardened surface-ground plate, which has built-in blowholes at 1-in. increments. The blow plate is mounted on the heat plate, which is usually heated by embedded cartridge heater units and thermostatically controlled. Between the heat plate and the blow plate, a thin buffer blow plate is placed. This plate carries the same hole pattern as that of the mold's outline configuration. The purpose of the buffer flow plate is to plug those blow-holes that fall outside the mold's knife area, leaving only the inside ones active. All three plates are sandwiched together and connected to a two-way valve system, which is capable of either delivering air pressure or opening itself to the atmosphere for venting.

2. As the mold closes on the sheet, its knife edges dig slightly into the plastic sheet, providing a sealing action and simultaneously holding the sheet in a trapped position, just as a clamp frame would. A valve opens and sends air pressure through the mold, squeezing the sheet against the heated cutting plate. All the trapped air underneath the sheet is vented out, providing absolute contact between the sheet and plate. The heat of the plate transfers to the plastic sheet, making it thermoformable. The heating cycle is regulated by timers that repeat accurately from cycle to cycle.

3. As the sheet is heated to ideal forming conditions, the valves change flow direction and air pressure is provided through the blow plate. At the same time, air pressure on the mold side is cut off and the valve opens to its venting mode. The switching of air pressure will force the now-heated plastic sheet to form against the mold cavity. As the plastic is shaped and formed up against the mold cavity, it not only receives its new shape but will be chilled by the cavity's colder temperatures, setting the newly acquired shape into permanent form.

4. At this stage of the thermoforming cycle, the upper platen will move downward with sufficient power to force the knife edges against the cutting plate and shear the plastic sheet between them. Cutting against a heated plate makes the cutting less difficult. As soon as the cut is made, the upper platen will move upward with the mold and a blast of air will be introduced via the mold. This will provide the necessary stripping forces to get the formed article out of the mold cavity.

To avoid having the formed part drop back onto the heated cutting plate and to facilitate orderly removal from the molding area, the continuity of the cutting edge is interrupted by making several notches in it. The strategically placed notching on the knife edge will leave uncut tabs between the thermoformed part and its surrounding scrap. When the scrap is advanced out of the molding area, it will carry the formed part out with it. At this point, scrap and part separation can be made without interference. The formed part needs only a slight lateral movement for the narrow tabs to break away. Close examination of light-gauge thermoformed parts often provides a clue that this type of thermoforming has been used—fine barblike projections on the trimmed lips made by the broken tabs.

When this type of trapped sheet thermoforming is produced on a continuous basis and the thermoplastic sheet material is fed from roll stock, the scrap advancement not only helps to remove the formed part from the molding area but expedites movement of new sheet material into the forming area. Formed part removal and stacking can be implemented manually or in a more sophisticated manner using automatic stacker units. These units are capable of sliding or pushing each trimmed part into a magazine rack and even automatically counting the number of parts in the nested part stacks.

The tooling for this type of thermoforming is not limited to single-cavity format but can be made into a multicavity format. The number of "ups" is determined by the thermoforming machine platen size. Smaller machines come in 10 in. by 12 in. platen sizes, while larger equipment may have platens as large as 42 in. by 48 in. The number of thermoformed products that can be formed out of a specific platen area—with proper allowance for minimum spacing and edge trim requirements—is the guiding criterion for the number of "ups" for proper tooling format. In the production of rectangular or square products, it is not unfeasible to build the tooling with common knives between them. This method eliminates the spacing between the individual thermoformed parts. The elimination of spacing reduces the combined width of the overall sheet, allowing the use of narrower sheet widths. This, in turn, reduces the final material cost.

Products produced by this thermoforming method are used mostly for packaging, particularly for food-handling purposes. Most cookie trays and food service trays are produced in this manner. The combined advantage of cost savings for cheaper tools and lighter-gauge material and the limited depth-of-draw ratio required makes this process one of the most ideal thermoforming methods for these types of products. At the same time, the process is under constant scrutiny with regard to both quality and economics by manufacturers using other methods of thermoforming, who may be capable of improving both material distribution and cycle times using their methods, thus creating strong competition. The trapped sheet thermoforming method does run slower cycles, making it vulnerable to competition. A 6- to 15-second cycle run is normal for this process. In the past, economic pressure has been so intensive for this process that most of the original machinery suppliers have phased out their new machine lines. However, there is much machinery still operating in various plants. In fact, when a trapped sheet thermoforming machine is placed on the market, it is not only sold rapidly but carries a high price tag.

B. Plug-Assist Forming

Plug-assist thermoforming is the most widely used technique at present. The majority of deep-drawn containers are thermoformed by this method. The assist is used to help stretch and push the heated thermoplastic sheet into the female mold. With the use of an assist, a draw ratio deeper than 1:1 is possible. If all available technological innovations are implemented, a 1:5 draw ratio can be realized and even extended to 1:7 ratios. Forming with plug-assist tooling is basically a type of matched tool forming, which should be categorized in the partially matching contoured tool classification. The plug assist is somewhat similar in configuration to the female mold, but is much smaller. The assist may be only seven-eighths or even three-fourths of the size of the female mold. This size difference results in a pluglike appearance of the assist in relation to the female cavity—hence the name "plug assist."

The use of a plug assist in the thermoforming process offers definite advantages in addition to providing deeper draws. It can provide clearly visible material distribution improvements. The material distribution can be made so precise with the help of the assist that hardly any measurable difference in wall thickness can be found in the thermoformed container. The key to successful use of a plug assist lies in two of its basic characteristic features: (1) assist shape, and (2) assist temperature. Both features can be altered and made to fit a specific thermoforming condition that, in turn, will result in an improved product. By not understanding the inner workings of plug assists, the thermoforming practitioner can actually negate its benefits and make it work against the process. The assist shape and temperature both require careful consideration and some preplanning in order to benefit the process. For the purpose of better wall thickness distribution, the plug assist's single duty is to provide suitable prestretching. Inadequate prestretching results in a nonuniform thickness of the walls of a thermoformed part. To examine the plug assist's inner workings, we can break down the complete cycle into four individual segments, shown in Figure 41.

1. The properly preheated plastic sheet is carried between the two opposing mold halves by a clamp frame or a chain sheet transport. The two opposing molds are mounted such that their alignment is properly maintainable and their centerlines are matching. Mounting can be made with the plug assist facing either downward or upward, as discussed earlier in the section on matched molding. The mold halves can travel against each other at a same time, or one can remain stationary while the other moves; it is best when the plug assist does the traveling, but the generally preferred method is to have both move toward the sheet. The thermoforming practitioner must choose the particular setup and platen travel speeds to accommodate the particular thermoforming process.

The preheated plastic sheet can be clamped and captured by either the plug assist's base plate or an independent clamp mechanism, as shown in Figures 13 and 14. This independent clamp mechanism can be activated prior to the plug assist's motion in order to capture a predetermined area of the heated thermoplastic sheet. Independently operable clamps are very important in continuous roll-fed thermoforming operations. The clamps should eliminate any sheet "pull-in" from stretching by the plug assist upon the already formed or subsequently heated areas adjacent to the forming. The plug assist can exert so much stretching force on a thermoplastic sheet that the two opposing surfaces of the molds or clamps cannot hold the sheet securely. If such is the case,

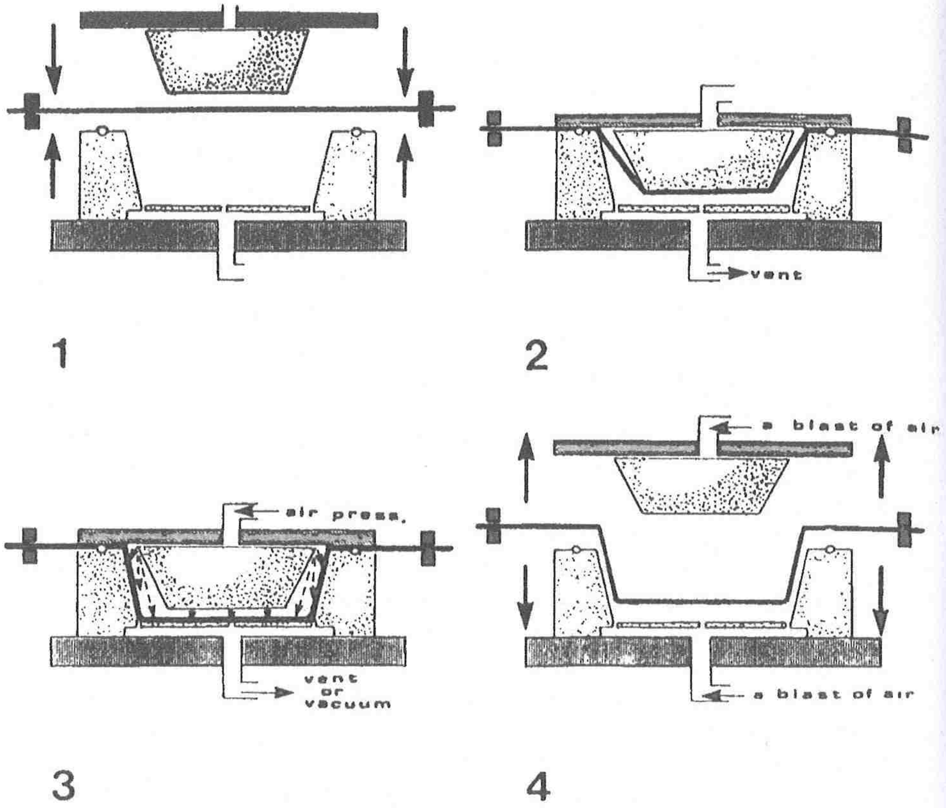


Figure 41 Plug assist thermoforming: (1) sheet clamping; (2) prestretching; (3) forming; (4) mold opening and stripping.

a machined V-groove pattern must be placed into the two opposing surfaces in such a way that the mold side will carry a V-groove while the clamp side will be made into a bladelike V shape. This will pinch and crimp the sheet material between the two V-shaped mating surfaces and will not allow pull-in or sheet slippage.

2. In this stage of plug-assisted forming, the heated thermoplastic sheet is stretched and pushed into the female mold. The plug assist does the actual stretching; it is easy to recognize that the size of the plug assist is influential in the amount of prestretching. Larger plug assists will provide more prestretching of the sheet, and with steeper or milder angles and different-sized radii on its leading edges, the plug can produce variable results in the subsequent stretch.

It is at this point in the forming procedure that the actual size and shape of the assist become critical. The shape and size of an assist can make the difference between satisfactory and poor results in the evenness of wall thickness distribution. Poor assist designs can also interfere with the attainment of full detail transfers.

The temperature of the plug assist can also cause variations in the forming. With the normal escape of heat into the equipment, the plug assist will usually have lower temperatures than that of the preheated plastic sheet. Due to its lower temperature at the moment when contact is made, the plug assist will absorb heat from the sheet at the converging area. At the same time, the female mold's lips, together with the plug-assist base plate or clamp bars, have the same sheet-cooling effect. When enough heat is taken from the preheated sheet at either location, the sheet becomes less stretchable. Where no contact is made with the sheet by the sides of the plug assist, the sheet will retain its heat and will remain easily stretchable. The use of cold mold lips and a cold plug assist will force all stretching to be made out of this narrow and limited area. This will result in a thermoformed product that will display the properties of a much heavier flange and bottom areas and probably, surprisingly thin, weak sidewalls. The results of this thermoforming failure can often be observed on thermoformed soft-drink cups or sour cream and cottage cheese tubs that display an extra-strong and heavy bottom area with extremely thin sidewalls. Poor material distribution will render products unusable in the most severe cases. Better uniformity in material thickness will reduce container failure rates and improve the overall strength of the container.

To minimize or completely eliminate the plug assist's chilling effects, the plug's temperature must be elevated. For the best results, the ideal temperature of a plug assist should match that of the softened thermoplastic sheet. When a plug assist has the same temperature as the sheet, the sheet's stretchable state cannot be affected. In fact, as the plug assist pushes and stretches the sheet, it will allow material stretching along the area where it makes contact. As the mold and plug assist close together, the sheet material can be stretched evenly within the captured area.

Bringing the plug-assist temperature up to match the preheated sheet temperature is one thing; keeping it there is quite another. The plug assist can be heated with electric power, using cartridge heaters and incorporating thermostatic controls. With this type of heating system, the temperature, just as with the heater units, will fluctuate quite frantically. This fluctuation will render unwanted temperatures for even stretching of the sheet. To provide better temperature control for the plug assist and to match the temperature of the sheet, the thermoforming practitioner has two options. First, a mold temperature controller can be used. This unit controls the temperature of a reservoir of fluid that is circulated and pumped through a plumbing system coupled to the plus assist. The reservoir fluid temperature is easily managed and will, in turn, provide good temperature control to the plug assist. The second way to provide outstanding elevated temperature control is to make the plug assist out of an insulating material. The idea behind this approach is very simple. The insulating material can, by nature, pick up and maintain exposed temperatures. By repeated contact with the heated sheet, the plug-assist's temperature will be identical to that of the sheet. The thermoforming practitioner has already made an effort to heat the thermoplastic sheet within a well-controlled temperature zone. The same temperature will be transferred automatically, without deviation, to the plug assist. To heat the plug-assist insulating materials, several thermoforming cycles are required. Through these cycles, contact between the heated sheet and the plug assist will bring the temperature of the plug assist to the same level as that of the sheet. Until the temperature of the plug assist has reached the levels of the sheet, the products will be improperly formed and probably unusable. The number of discarded products and necessary nonproducing cycles is dependent on the composition and insulating abilities of the material from which the plug assists are made. A densely made material requires more repeated cycles and contact with the heated sheet before reaching the same level of temperature than does a less dense material. In today's sophisticated thermoforming, we have adopted a material to use for that very purpose. Called syntactic foam, it gives the needed temperature control to the plug assist. Syntactic foam materials are discussed further in Section III. This material gives exactly what is needed at this stage of the forming and can be made into a variety of shapes. A plug assist made entirely from this material can be formed into almost any shape. If required, syntactic foam can be added to a metallic plug-assist body as inserted pieces or full layers. When the plug assist is made out of differently composed materials within the same mold body, varying face temperatures can be achieved, bringing more sophistication to the technique. As we have already learned, programmed heating is obtainable in the sheet-heating process; with pieces inserted in the plug assist, we can manipulate different temperature zones within the same mold.

In most plug-assist thermoforming practices, the use of rigid plug assists dominates. The rigid materials offer superior dimensional stability and therefore greater accuracy in the forming. The unsuccessful cooling efforts of such plug assists are also well recognized, and metallic material is often substituted.

The use of flexible, cushiony foams for a plug-assist body is not unacceptable and is occasionally useful when everything else fails. In the thermoforming process, there is often a need for some type of mechanical pushing force, a force that could, almost like magic fingers, squeeze the formable plastic into every corner of the mold. Use of a block or large piece of flexible foam material, such as a urethane foam block, may provide the solution. The foam must be larger than the actual female cavity so that it is capable of ramming the heated plastic sheet into the female mold. Since the foam possesses a cushionlike resiliency, it will conform to the female cavity shape and push the forming plastic into very corner and crevice of the mold. With the foam material, the harmful effects of cooling will not be present. As an assist, the foam material has to be selected carefully and replaced frequently. Foam materials under high levels of heat and repeated compression tend to break down and lose their resiliency. Through continuous cycles, the material recovery rate will slow down and forming efficiency will quickly be lost.

Using large blocks of foam (or ideally positioned smaller foam pieces) as an assist can provide outstanding results in thermoforming. Such use of a foam assist should not be considered an inferior method. The best opportunities for adopting foam assist use can be found in smaller-volume runs and those of larger articles. Use of this material will provide surprisingly favorable results.

3. In this segment of plug-assisted thermoforming, the actual forming takes place. Within the female cavity, the plug assist will be fully stretching the preheated sheet. As the two mold halves are closed together, a circumferential seal is created. At this moment, the forming force should be activated. The forming force may consist of a vacuum force, air pressure alone, or both forming forces can be activated at the same time. Using just a vacuum force results in slower forming of the plastic than that obtained using air pressure. Pressure forming will not only improve the speed but will provide more power to the forming, resulting in a more precisely detailed transfer from the mold to the plastic. Depending on how strong the air pressure is on the plug-assist side, it will either gently push or blow the softened thermoplastic sheet against the female mold surfaces. Of course, the air underneath the sheet must be ejected. The air pocket is forcibly ejected by the incoming sheet, which acts almost like a plunger. The trapped air must find a sufficient escape route and provide room for the incoming pressure-forced sheet that will take over its space. The trapped air can be squeezed to vent to the atmosphere, or for more forceful evacuation can be sucked out with vacuum forces. Adding suction in the air-pocket-removal procedures ensures prompt but thorough evacuation, ultimately giving outstanding definition to the thermoforming results. Both vented and vacuum air-pocket removal require plumbing of sufficient size and a multitude of connecting holes in the female mold. Insufficient openings anywhere in the system can cause restrictions in the air-flow that can interfere with and slow the forming. If lack of definition in the thermoforming dictates increased pressure forces and these do not bring an improvement, the cause may be restricted air escape from the female mold. In the most severe cases, the pressure-induced forming is so intense that the formed sheet can trap and push some of the air up against the flared sides of the female mold. This unwanted thermoforming error is caused by improper air evacuation. To remedy this situation,

the forming pressure may be reduced and/or the air evacuation rate increased by adding extra holes. This problem was discussed in Section V.B of Chapter 2.

As the heated plastic is formed and forced against the female mold surface, the mold will extract its heat, causing it to cool and firm up. To remove the heat from the formed part requires some time and is dependent on the part's original temperature, type of plastic composition, and material thickness. To obtain best cooling results, not only can the plastic be held in the mold longer but the forming forces can also be left on longer. Leaving the pressure and vacuum on will hold the formed plastic part firmly against the mold surface, creating an uninterrupted heat sink. As cooling takes place, the plastic part will shrink. At this point, a slight pressure force leakage and weakening will take place. This is a good indication that the forming forces should be turned off.

4. In the preceding step, the forming forces were no longer activated, the plastic part was properly cooled, and shrinkage took place. The mold and the platens should not be separated. To ensure proper stripping, a blast of air is introduced at both sides. The mold will be opened in the same manner as in the mold-closing mode. Ideally, both halves should be opened to allow the formed part to exit the forming area. The opening of the mold must have sufficient "daylight" to allow the formed part to be removed freely. For the most ideal thermoforming conditions, the mold opening should not be made any larger than is required by the formed part for ease of removal. If the opening of the mold halves is allowed to be larger than that required by the thermoformed article, it will not have harmful effects on the stripping and part removal but can impair both the actual forming and timing of the cycle. The extra travel time of the platens in closing and opening will require a longer travel time and will increase the timing of the overall cycle. The increased size of the mold opening will expose the carefully preheated sheet to uncontrollable temperature conditions and result in unwanted cooling by draft. Good thermoforming practices demand accurate platen travel controls. The travel should be altered and adjusted according to the thermoformed product height. For example, forming of a $^1/_2$-in.-deep part does not require, and should not make use of, the maximum daylight opening of the thermoforming machine platens. Thermoforming equipment that does not offer such options must be modernized and equipped with platen travel restrictors.

C. Form-and-Trim-in-Place Forming

Form-and-trim-in-place thermoforming is a natural extension of the plug-assist method. Actually, the initial four sequences of this technique follow plug-assist forming exactly. To fully understand all the motions of this type of thermoforming, the following step-by-step sequence should be studied, in

conjunction with Figure 42. The first four steps are simply a repetition of the plug-assist thermoforming (Section II.B).

1. At the beginning of forming, the preheated thermoplastic sheet is transferred into the forming area by a clamp frame or a chain-rail sheet transport system. In this operation, both sides of the mold (female and plug assist) are equipped with an independently movable and closely fitting frame system. Tooling made in a round configuration must have a ringlike frame surrounding the mold; square and rectangular molds have frames matching their shape. These surrounding frames have two functions, which are carried out in the second and fifth steps.

2. As the mold is ready to close onto the sheet, this special frame will move into place first and act as an independent clamping mechanism. There are instances when both sides of this clamping mechanism will be activated simultaneously, in an attempt to capture a predetermined area of the sheet. For best results, the female mold side should accompany the clamp frame, to simplify the operation. The purpose and results are the same in both cases. Capturing the sheet will not only ensure a uniform area for forming, but in cases of multi-up mold use, will prevent material robbing between adjacent forming areas.

3. Moments after the sheet clamping is accomplished with the tightly fitting frame mechanism, the plug assist will move in and complete prestretching of the heated sheet. Since the independently movable frame mechanism performed its sheet-capturing function prior to this move, stretching will only occur inside the trapped area.

4. With the mold closure and the maximum prestretching of the sheet accomplished, the forming forces are activated. The forming can be made by vacuum, air pressure, or both. The prestretched sheet will be forced against the female mold surface and as contact is made, cooling of the formed part will take place. At the end of the cooling cycle, the shape of the part will be permanently set.

5. At this stage of the thermoforming cycle, the independently moving frame mechanism will perform its second duty: trimming the thermoformed part away from the surrounding area. In this trimming mode, either the two mold halves or the two opposing clamping-frame mechanisms will move out of their aligned position, rendering a shearing effect on the continuity of the captured plastic flange. Since there are very close tolerances between the outside surface of the mold and the frame mechanism, this offsetting movement will result in a clean-cut edge. To ensure proper cutting, this type of tooling is not only made to close tolerance, but of high-quality hardened tool steel. Most tooling for this type of trim-in-place process will simply have a closely fit insert or ring at its shear line. The inserts and rings are either resharpenable or replaceable. There are some limitations to the maximum thickness for this type

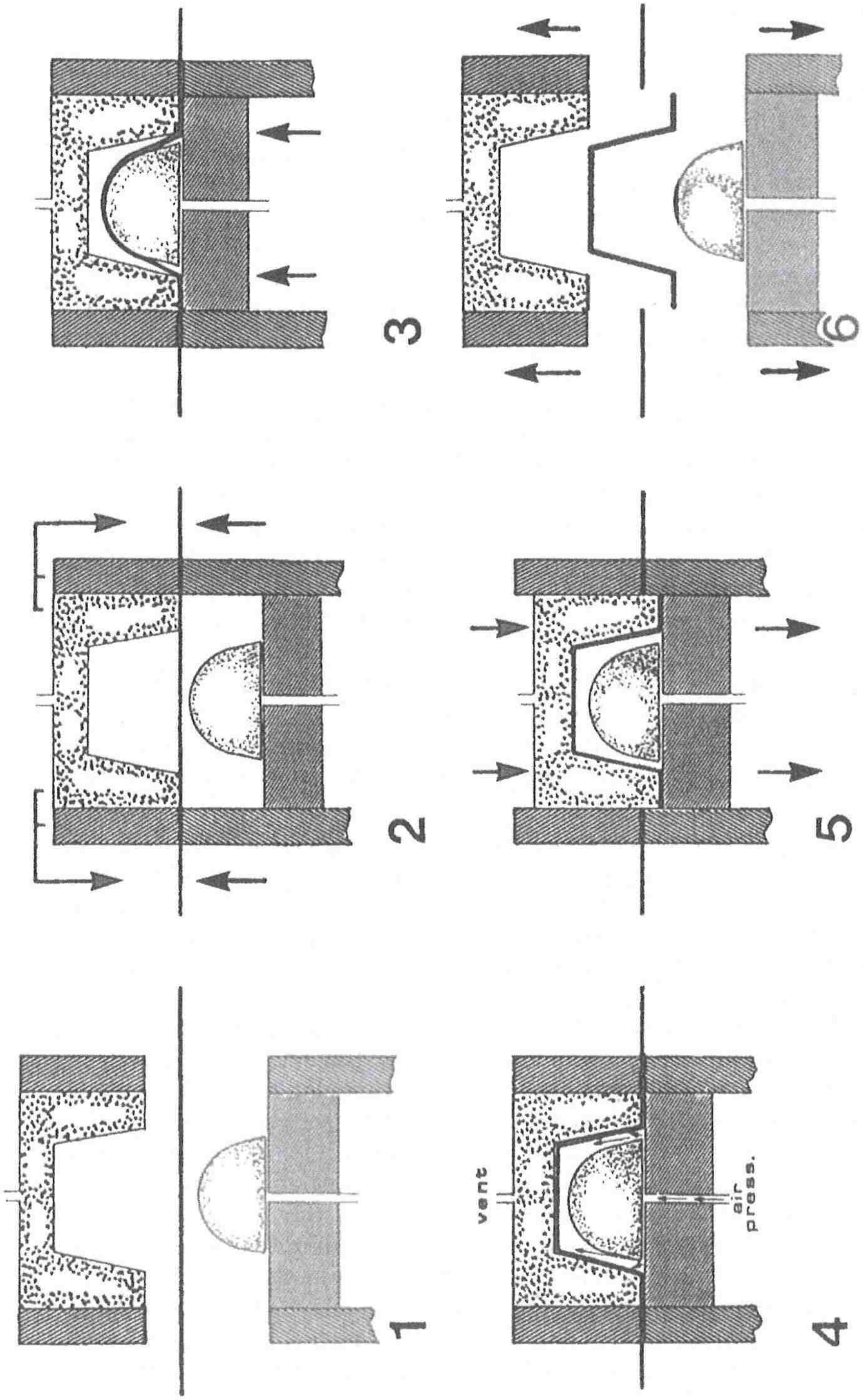


Figure 42 Form-and-trim-in-place forming with plug assist: (1) preheated sheet locating; (2) clamping; (3) prestretching; (4) pressure forming; (5) trimming; (6) mold separation and stripping.

of trimming. However, the upper thickness limits are well within the restraint levels of this process; this is also true of its material handling limits. Some tooling may have a slight shearing angle built into its cutting face, which will lessen the demand for higher cutting-force requirements and make a cleaner cut.

6. After trimming, the thermoforming mold is opened together with its surrounding cutting-frame mechanism. As the mold bodies are moved apart, the completely trimmed part will drop out of the female mold cavity. To aid part ejection, a blast of air is shot through the female mold in unison with an air jet shot from the oven side of the mold. The air jet will help to blow the formed and trimmed parts out toward the front end of the machine. The thermoforming equipment usually has trimmed part-receiving magazines that are built to funnel the blown parts into a stack. The receiving magazine size is dependent on the number of "ups" in the mold, where each cavity will have its own magazine for receiving and stacking the blown-out product.

This type of process is very popular; however, with its benefit limitations, the method can be adapted to only a special segment of the industry. The accuracy of trim-in-place trimming is desirable. Every time a product is both thermoformed and trimmed in the same location, the trim is guaranteed to be made precisely in the same place. For example, round thermoformed parts made with this process always produce an even and concentric trim. Since there are no indexing and reregistration errors, this type of trimming never produces an offset cut. This feature is critical for thermoforming producers who manufacture tightly fitting food and beverage containers and lids. The uniformity of trim results in a trouble-free lid and container mating, the most important feature of this type of product. However, together with the benefits of utmost trim accuracy comes the negative aspect of higher price, a result of the fact that more time is required for the part to pass through the six stages of trim-in-place thermoforming. In-line thermoforming, in contrast, requires only four forming stages to produce a thermoformed product. Trimming, which is usually done in a secondary operation, can be accomplished within the same period as the forming, thereby reducing the cycle time. In the form-and-trim-in-place operation, the extra step (5) does require extra time and increases the overall cycle time. As this operation creates a significant increase in cycle time, and such increases add up in a long continuous production run, thermoforming practitioners should be aware of both the benefits and shortcomings of each method before selecting a process and equipment. Proper analysis of the product specification criteria will help in making the proper choice.

D. Pressure Bubble Plug-Assist Forming

The pressure bubble plug-assist thermoforming technique follows some of the same rules and procedures as those of the two preceding thermoforming methods that we have discussed. The clue to this special forming technique is revealed by its process name: "pressure bubble." This method is used for prestretching a trapped area of the sheet. In utilizing this process, the ultimate goal is to create improved material distribution with maximum uniformity of wall thickness in the finished article. Pressure bubble plug-assist forming is used equally with light- and heavy-gauge materials as well as small or large articles. This technique can also be broken down to four separate forming sequence elements. The four steps are usually produced in a simultaneous motion and combined into a quite rapid cycle. Figure 43 shows the four sequences as a stop-motion study, which allows us to examine each segment individually.

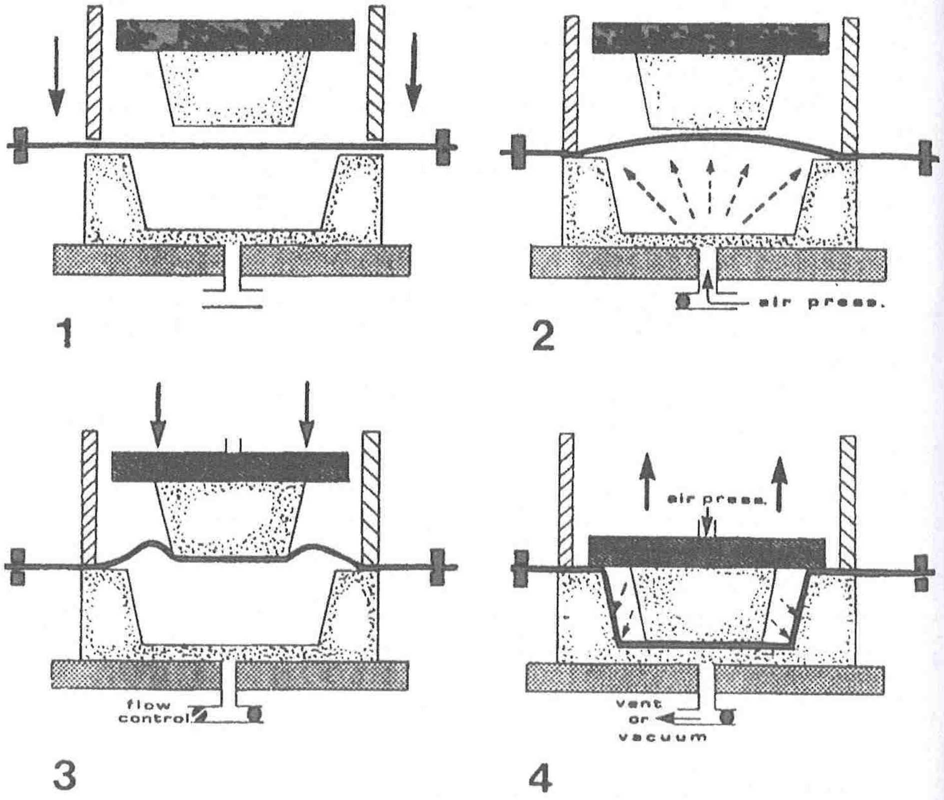


Figure 43 Pressure bubble plug-assist forming: (1) preheated sheet clamping; (2) prestretching of sheet; (3) mold closing; (4) pressure forming into female mold.

1. In this thermoforming method, the process begins with a preheated thermoplastic sheet. An independently actuated clamp mechanism is used to trap the needed area of the sheet for thermoforming. With a small product, particularly in multi-up mold configurations, each mold comes with its own clamping mechanism; with large articles a large circumferential clamp mechanism is employed. In either case, the clamp mechanism will compress the heated sheet against the lip areas of the female mold. The crimp should be made strong enough so that there is no material movement and no escape of pressurized air. As soon as the heated sheet is located in the forming area, the clamp mechanism is activated for capture of the sheet. Pressurization of the bubble can now begin.

2. In this step, air pressure is introduced from the female cavity side. Since the clamp mechanism has created a seal to hold the sheet in this entrapment, the pressure will force the softened sheet into a domelike shape. (The same results can be achieved with vacuum force, also coming from the assist sides, provided that additional sealing is made between the plug assist and the clamp mechanism.) As the domelike bubble is formed, the result will be prestretching of the thermoplastic sheet. The prestretching can be controlled by the size of the bubble: Smaller bubbles will cause less prestretching, larger bubbles will provide the most stretching.

3. As the predetermined stretching is completed, the plug assist will move against the sheet. The bubble will be forced downward against the plug-assist surface. It is easy to recognize how using this method of prestretching will produce better results than those with plug-assist forming alone (Section II.B). A comparison should be made between the second stage of Figure 41 and the third stage of Figure 43. This comparison will provide the necessary understanding of the advantages of bubble prestretching. Some controls should, of course, be incorporated when the prestretched bubbles are produced. An overproduced bubble can, in turn, overstretch the sheet. In fact, the overstretching can be made so extensive that the sheet will bulge around the sides of the plug assist as it plunges into the female mold. This can be caused either by overpressurization of the prestretched bubble or by insufficient relief passages for air to escape and make room for the plug-assist takeover. For both reasons, excessive air entrapment will cause heavy bulging around the circumference of the plug assist. In the most severe case, this bulging can curtail full mold closure or may actually cause the bubble to rupture. In less severe cases, the bulging will produce only a slight overstretching of the sheet. An overstretch will mean that the bubble and the resultant bulge have stretched out over a larger area than that of the entire mold surface. An overly stretched sheet, with its excessive surface, will develop a wrinkle when formed. To eliminate this unwanted wrinkle, all the thermoformer has to do is reduce the size of the bubble. The reduction in the bubble will reduce the prestretch and the wrinkle

will disappear. Fine tuning of the air pressure will curtail the size of the bubble that is formed. Adjusting the travel speed of the plug assist or controlling the outflow of entrapped air will lessen the resulting bulging of the sheet around the plug assist. Limiting the prestretching to an ideal level and providing proper air outflow will make the forming possible.

4. In the last step in this process, air pressure is introduced from the plug-assist side. The pressure will force the softened plastic sheet to form against the female mold surface. As it forces the sheet to form, the air pressure will squeeze the air out from underneath the sheet. For more positive air evacuation and better transfer of detail, the introduction of vacuum forces is recommended. Using a vacuum setup may even improve the forming time.

Following the forming step, all conditions and results match those of the thermoforming techniques discussed earlier. As the forming of the sheet is completed, the mold will cool the plastic, setting its shape into a permanent form. The thermoformed article will shrink and pull away from the mold cavity walls. At this point, the molds are separated and the formed part with its surrounding scrap is removed from the molding area. Products made using this thermoforming method are trimmed in posttrimming operations, which can be implemented either in-line or on separate secondary equipment.

As has been pointed out, in this particular practice, the actual shaping of the sheet is made against the female mold surfaces. Although the actual prestretching method in this technique is capable of providing improvements over straight plug-assist forming, some of the typical female mold characteristics will prevail. The persistence of the desired female forming characteristics should be the main factor to consider in choosing this method of thermoforming.

E. Pressure Bubble Snapback Forming

The pressure bubble snapback thermoforming method proceeds identically to pressure bubble plug-assist forming (Section II.D) except for the fourth stage. The same first three stages form the pressure bubble in order to prestretch the softened plastic sheet. This method also has equal, if not greater, sensitivity to overstretching and the resulting wrinkle.

With this type of thermoforming, the plastic sheet is not formed against the female mold surfaces; rather, it is "snapped back" to be formed against the male mold surface. The male mold not only acts as an assist but actually provides the shape for the plastic and even performs the cooling duties. The female mold acts only as a pressure chamber. The forming sequence is shown in steps 1 to 3 of Figure 44, which are identical to those in Figure 43. But, step 4 differs.

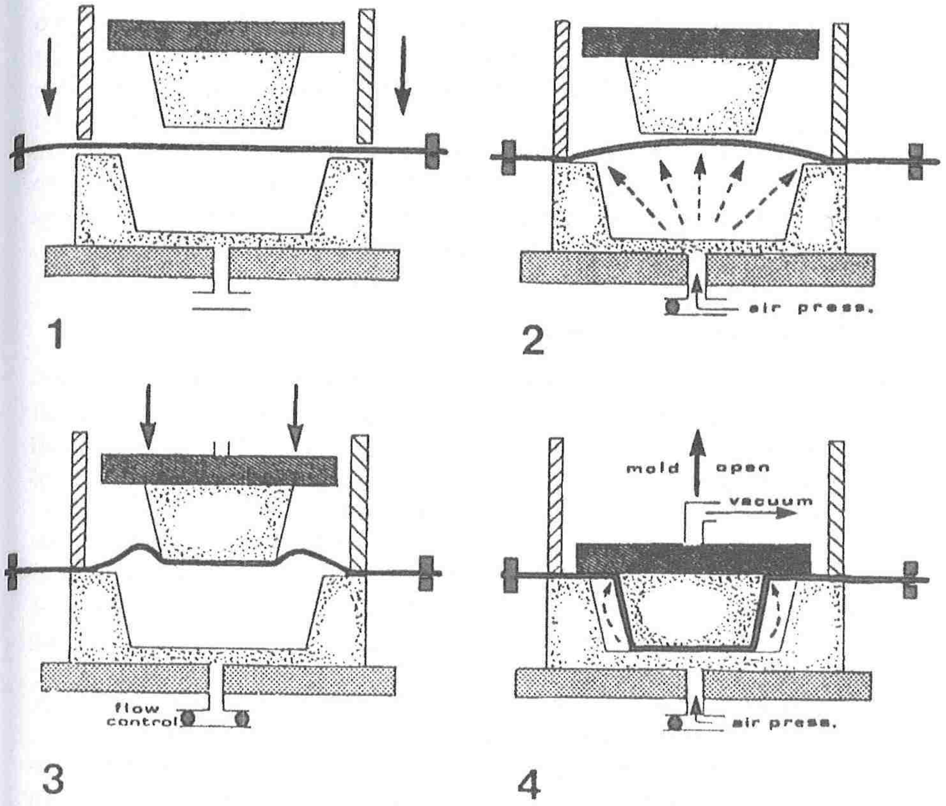


Figure 44 Pressure bubble snapback forming: (1) preheated sheet clamping; (2) prestretching of sheet; (3) mold closing; (4) pressure forming over male mold.

4. As the male mold travels and pushes the softened plastic into the female mold, the air trapped between the plastic sheet and the mold is only partially vented or may not be vented at all. As the two mold halves close together, the pressure that has been built up will increase and force the plastic against the male mold. As the full mold closure is completed, a vacuum is introduced from the male mold side that will snap all the plastic back against itself and complete the forming. Cooling will take effect that will cause shrinkage in the formed article. For each part removal and stripping, the male mold must have sufficient taper angles. This shrinkage onto the male mold is a typical forming result. Since this forming is made with a male mold, most of its adapted features will carry the inherited characteristics of the typical male mold. Although using this type of thermoforming, with its pressure bubble formation for prestretching, will greatly improve material distribution, this forming technique can still carry and display characteristic clues of material shift or thinning typical of male molding.

The thermoforming practitioner has the option of using either of the two bubble forming methods and switching back and forth between the two. With a single mold setup, two different-sized products with varying material distribution can be produced simply by actuating and applying air pressure and vacuum forces to different sides of the mold. Armed with this knowledge, the thermoformer can choose the principal mold sides and forming modes for the product being formed. By making a switch in the forming mode, a secondary product of a different size can be produced without additional tooling cost.

F. Snapback Vacuum Forming

The snapback vacuum forming method is a very simple thermoforming process, well liked and often implemented. Its popularity stems from the fact that its use greatly improves material distribution and can produce improved wall thickness conditions. The snapback thermoforming technique may be one of the oldest and most reliable forming methods for the forming of medium- to heavy-gauge and larger-sized thermoformed products. However, the basic concept can be adapted to any of the thermoforming methods. The simplicity of this forming concept is easily seen in Figure 45, which illustrates its simplest version, in which only a female mold is required. The steps in this forming method can be describes as follows:

1. The preheated plastic sheet is clamped against the female mold lips, creating a trapped air chamber by acting as a cover for the cavity.
2. Controlled levels of air pressure are introduced to this sealed chamber, forcing the heated sheet into a dome shape that will continue to grow with an increase in air pressure. This stretching is the key to obtaining better wall thickness distribution in the final product. The size of the preblown dome will determine the amount of prestretching and will provide some control.
3. When the desired dome size is reached, the air pressure is immediately turned off and vacuum introduced. From the pressurized dome shape, the vacuum will snap the prestretched plastic sheet back into the female mold cavity. This movement finalizes the forming and subjects the plastic to the cooling phase.
4. Now the part is ready to be stripped and removed from the mold. Depending on the shape and sidewall taper angles, removal may be accomplished by simply lifting the part out or may require a slight air blast to assist. In the most difficult cases, stripping may have to be done with mechanical stripper units to push or pull the formed part out.

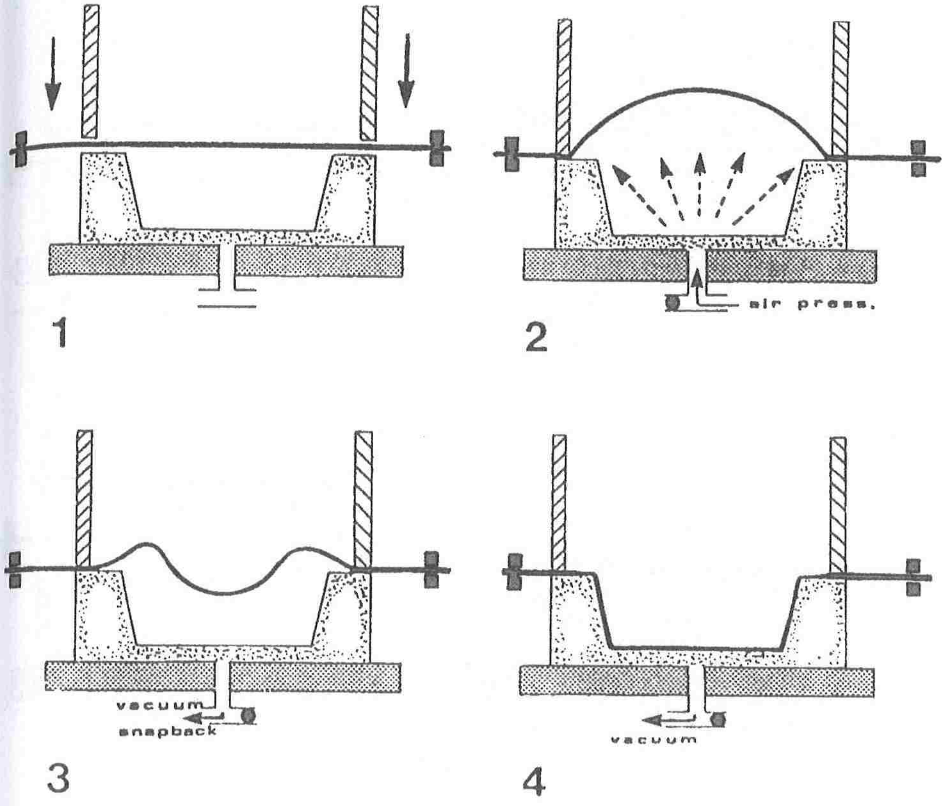


Figure 45 Snapback female vacuum forming: (1) preheated sheet clamping; (2) bubble blowing/sheet prestretching; (3) snapback of sheet; (4) vacuum forming.

There are many variations of snapback vacuum forming that can be adapted for the purpose of better wall thickness distributions; all follow the basic format. One variation is shown in Figure 46. In this drawing, for the purpose of showing a different type of heating method, the heater unit is positioned above the cold thermoplastic sheet, directly in the forming area. This type of heater is built like a drawer, and when proper heat levels are reached in the plastic sheet, the entire unit is slid out of the way. The heater unit is built with rollers and rails or a track assembly. For heating the thermoplastic sheet, this heating method will work as well as any other. The actual selection of different types of heating apparatus is not usually up to the thermoforming operator. The make of the thermoforming equipment and its heater unit design will determine the heating method to be used. In this version of snapback vacuum forming, the actual forming procedure can be broken down to four basic forming steps.

1. The thermoplastic sheet is heated between the opposing mold halves. (With a different type of heater unit, the sheet would be transferred in a pre-

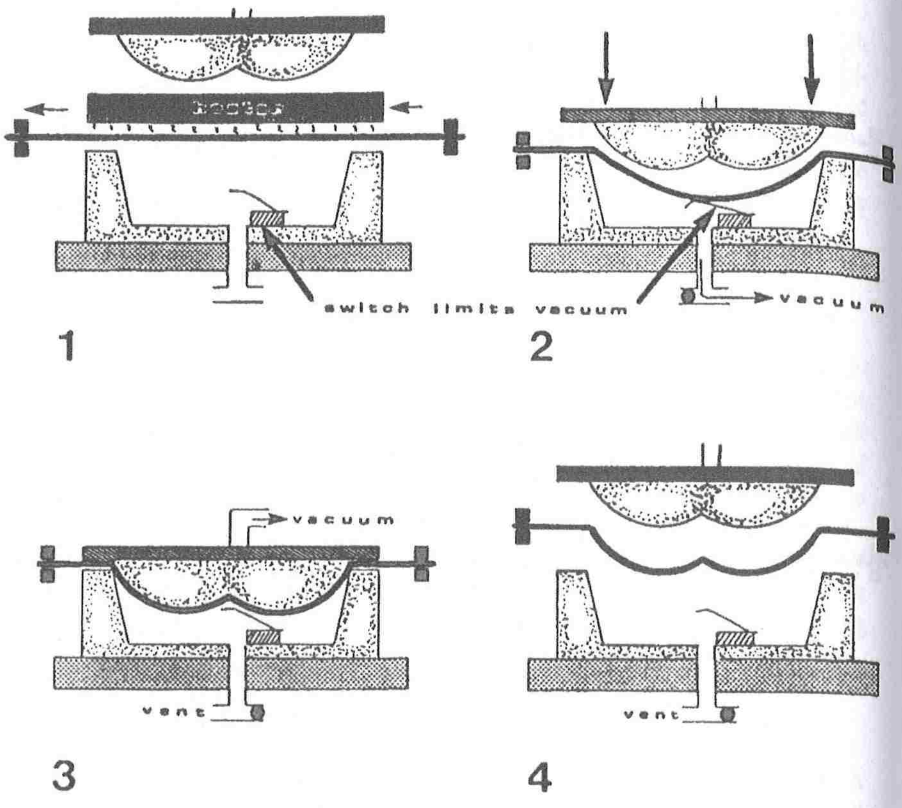


Figure 46 Snapback vacuum forming with a male mold: (1) thermoplastic sheet heating; (2) prestretching of sheet; (3) snapback vacuum forming; (4) mold separation and stripping.

heated condition into place between the mold halves.) At this stage it is easy to recognize that the development of a sag would not be harmful; in fact, sag would simply aid the prestretching effort.

2. The heater unit has been removed to the side so that the two mold faces can move toward the sheet. At the moment contact is made between the female mold upper lips and the sheet, vacuum is introduced through the female cavity. The sheet will self-seal at the contact area and the vacuum can then pull the softened sheet into the cavity. A microswitch is placed on the bottom of the female cavity. This switch is usually equipped with an extension arm to make it ultrasensitive. Additionally, the switch assembly is made to be adjustable in height. As the softened sheet is pulled into a bowllike shape, its bottom will lean on the microswitch arm and trigger it. With the adjustable height of the switch, proper controls can be set for the amount of prestretching that is desired.

3. At the moment of sheet triggering, the microswitch will signal the vacuum valves to switch from vacuum to venting mode on the bottom female side. Simultaneously, the vacuum on the upper mold side will be activated. The rapid change in the direction of the vacuum compels the original bowl-shaped plastic sheet to snap back and form against the upper mold surface. With the full surface contact, the forming is completed and the natural cooling mode will take place.

4. In the final forming step, cooling and shrinkage take place and the molds are separated. The vacuum must be deactivated in both mold halves to facilitate easy mold separation and part stripping. A short blast of air can be introduced to both sides of the mold to aid stripping. However, the use of stripping air pressure must be used with some moderation to avoid distortion or even destruction of the formed article.

Figure 46 shows a male configuration of the upper mold with a female indentation in the center. The same thermoforming procedure can also be accomplished if this mold half is made in a female mold configuration instead of the male. Figure 46 also shows a female bottom mold that in actuality has no function other than to act as a vacuum chamber or vacuum box, one having its upper side covered by the softened sheet. The only contact that has been made between the sheet and this mold side is at the lip seating around the circumference and the centrally located microswitch arm.

G. Trapped-Air-Assist Forming

The trapped-air-assist thermoforming procedure is a questionable on because it is highly dependent on a well-functioning seal created between the clamp mechanism and the assist base plate. This key factor of this seal is so critical that its slightest deterioration will render the entire forming procedure useless. If and when good airtight conditions can be achieved and maintained, the process will function satisfactorily. However, maintenance of the sealing surfaces is usually a difficult task, particularly for large multi-up molds, creating repeated breakdowns and unwanted downtime. Usually, mold configuration and design conditions do not permit the precision necessary to build and maintain sufficient high-quality moving seal surfaces for this type of manufacturing. Since the process is keyed to this single critical factor, its use is highly discouraged. Of course, there are thermoformers who claim success using this method and have proof products of sufficiently good quality made using this system. On the other hand, there is no telling how many breakdowns they encounter while maintaining the seals. Figure 47 shows this thermoforming method broken

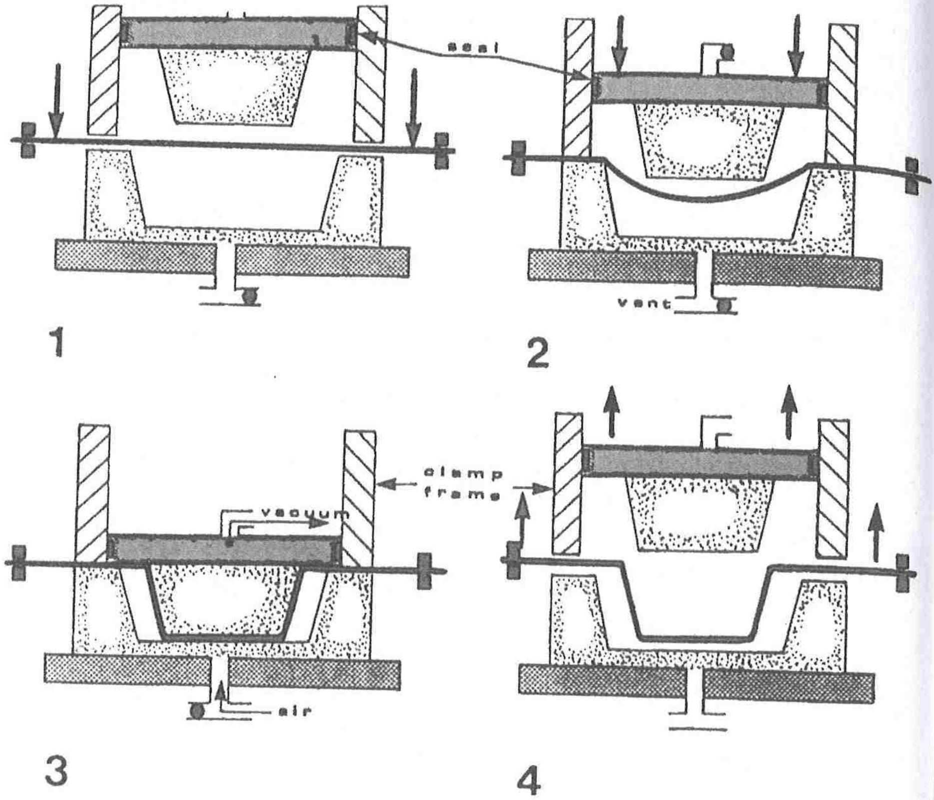


Figure 47 Trapped-air snapback forming: (1) preheated sheet clamping; (2) prestretching with trapped air; (3) snapback vacuum forming; (4) mold opening and stripping.

down into four stages. The following description explains the inner workings of this technique.

1. The preheated thermoplastic sheet is transferred in between the opposing mold halves. The mold arrangement can be made to function by having the female cavity located on either the lower or upper platen. Both arrangements work equally well. In this specific arrangement, the female mold cavity is placed on the lower platen so that the upper platen, with the male plug-assist configuration and clamping mechanism, will close onto it. This move will capture the heated and softened thermoplastic sheet positioned between platens.

2. For prestretching of the sheet, the plug assist will move toward the sheet, and due to the existence of the airtight seal between the clamp mechanism and the plug assist, this travel will condense and pressurize the trapped air. As the plug assist moves downward, just like a plunger, it will push and bow the softened plastic sheet ahead of it. With continued travel, the air compression exerts more pressure on the sheet. Regulation of the amount of prestretching in the sequence is determined basically by the plungerlike actions of the plug assist. If more prestretching is required, increased "head space" is given for the plug assist by starting it from a higher initial position to increase the air volume beneath it. Naturally, the vacuum valve is set in the closed mode in the assist mold side for this trapped-air utilization.

3. The prestretched sheet can be formed against either side of the mold. If vacuum is introduced through the female mold at this stage, the plastic will form against the female mold sides. This forming can be accelerated by air pressure introduction from the male mold side.

If preferred, vacuum can be introduced from the male mold side, with pressurized air then squeezing in from the female mold side, as illustrated. By this arrangement, the forming will be made against the male mold surfaces. Naturally, the change from one mold side to the other could not possibly produce equal-sized products unless the mold dimensions and configurations are matched with a proper mold gap. If there is a substantial size difference between the female and male molds, the differences will be duplicated on the formed plastic.

In the last sequence (as shown in the figure), the formed plastic part is cooled off by the respective mold surface. The customary shrinkage will take effect and mold separation and stripping can be done. The mold halves are separated and the part is removed.

H. Solid-Phase Pressure Forming

The process of solid-phase pressure forming (SPPF) should not be categorized as a separate thermoforming method. However, recent years of heavy publicity have generated enough interest to justify devoting the time to cover this thermoforming practice.

The clue to this type of thermoforming is contained in its name: "solid-phase pressure forming." The thermoforming procedure is made with pressure forces alone shaping the plastic from a sheet form into its final configuration. The key factor in this process is the heated status of the sheet. In this type of thermoforming, the thermoplastic sheet is not heated to normal levels where the sheet is softened to be almost flowing and in a formable state. The plastic sheet is heated, but only to levels that keep it in a solid state. Basically, any underheated plastic sheet being thermoformed could be categorized as being in solid-phase forming. However, the nature of most thermoplastic materials will not permit stretching or forming in the solid state. Most common thermoplastics will tear or rupture in the slightly heated and still solid state. They will accept shaping and forming only when they reach the proper softening temperatures. Exceptions are found only in a very limited number of plastics, one of which is polypropylene.

Polypropylene thermoplastic material has a unique stretchable quality unmatched by that of any of the other popularly priced plastic materials. In fact, polypropylene is distinctly qualified for solid-phase pressure forming. Polypropylene can be shaped quite well into a form by thermoforming just below its crystalline melting point without tearing or rupture. Since the forming is made at a temperature too low to allow material flow, the results of the thermoforming will be high molecular orientation within each thermoformed part. The resulting products will display a high degree of transparency and strength, and due to the nature of the polypropylene material, exceptionally outstanding chemical and physical toughness. In addition to these useful qualities, polypropylene has good fracture resistance and can withstand repeated flexing and comparatively low moisture-transmission rates. All of these advantages, combined with FDA approval, make this type of thermoformed product desirable for food packaging.

To be successful in solid-phase pressure forming, it is essential that the polypropylene sheet be made of a high-grade resin material and extruded with close-to-zero internal stress within the sheet. Use of improper extruder screw designs that are not made specifically for polypropylene resins may produce some internal stress in the extruded sheet. As polypropylene sheets have internal stress conditions locked in, they do not give visual clues to their conditions. However, when exposed to heat, those locked-in stress conditions will seek release, resulting in a material "wander," or shift, from one location to the other. This condition will result in variations of thickness that not only interfere with stretching and forming but also affect the outcome of the thermoforming. Whether the forming process is plagued by this problem constantly or only occasionally, it will be very aggravating to the thermoformer.

I. Twin-Sheet Forming

Twin-sheet forming is one of the many thermoforming techniques to produce double walled products. This method produces similar and competitive items to blow molded and rotational molded products. It even can replace some products which are fabricated by gluing two separately formed article portions together to create a needed product. Most of the time such products can be made by the usual thermoforming process, and after the two individual halves are produced by the two separately made moldings, then they are united together by some fabrication or gluing method to create a single item. In most cases twin-sheet forming could eliminate the two separate thermoforming moldings and definitely eliminates the secondary gluing fabrication by making everything in a single step. In this twin-sheet forming there are two independent sheets used to make the molding. The two thermoplastic sheets, whether in a precut form or a continuous web can be clamped or treaded into the feed system of a thermoforming machine, right on top of one another. The two sheets can be heated very much like single sheets are heated, preferably in a "sandwich" type of double sided oven. Heating is accomplished from top to bottom; therefore both sheets are equally heated from their respective sides. As the heat penetrates the thermoplastic plastic sheets the sheets will go through the customary heat reactions, and eventually will reach the ideal forming temperature. Just like with any of the single sheet heatings, under- or overheating often could jeopardize the thermoforming results. Careful attention should be paid to obtain optimum heating conditions, not only judging each sheet by itself, but considering that each sheet may interfere or effect the other sheet's heating results. The heating must be made in such a way that both sides of the twin-sheets receive the optimum levels of heat for the ideal forming conditions. The heater output levels must be regulated to compensate for heat output variations, which is often observed, between the top and bottom heaters. These heating differences are even further complicated when different colors or different types of plastic sheets are used in the twin-sheet forming. Naturally both sides of the twin-sheet must be at ideal forming temperature for satisfactory molding results. Special attention should be given to the fact that the twin-sheets inner sides facing each other also should be heated to the desired temperature levels for ideal thermoforming. The thermoformer must be patient in the heating of the twin-sheets, because, in spite of the fact that heating is done from both sides the inner surfaces only receives its heating by conduction from the outer surface of the sheet.

The twin-sheet is usually formed by two opposing molds, set up in such a way that each side has its own respective configurations. The molds are most likely to have a dominant female configuration; however that is not the case all the time. In fact the two sides do not have to have a mirror image of each other either. However, they must have the same outline configurations, because that outline is where the unification or sealing of the two halves will take place. As the molding is made, the two molds will create enough clamping force between the two halves that the two parts, which formed to their respective mold sides, are unified by sealing the two together (just like heat-sealing), at the perimeter of their configuration. The retained heat in the formed plastic should be sufficient to make the sealing complete. By this thermoforming molding technique the twin-sheets are formed against the two molds. Each side will resemble the respective mold sides, those creating a hollow product. Naturally, to achieve such a forming, an air passage must be allowed between the twin-sheets. To allow air movement between the twin-sheets, there must be an opening, a small void between the two crimped circumferences of the parts. Often a syringe-like device is employed for the purpose of providing the entrance for air movement. That syringe can be placed in between the two sheets or can be made to puncture and penetrate the plastic sheet as it is formed on the sides of the mold.

In case the forming technique is the vacuum forming procedure, the two molds receiving the vacuum will pull the respective sides of the twin-sheet against each mold side. In order to accomplish this forming, air must be allowed to enter to displace the space between the sheets.

If pressure forming is attempted the introduction of the pressurized air is also made through the small syringe opening. The syringe will act as an air ejector to pressurize the space in between the twin-sheets, forcing it to conform to the respective mold sides. Application of vacuum to the molds may not be necessary, but would not hurt, as it will most likely help to minimize any chance of trapped air pockets.

Both forming techniques highly mimic the blow-molding process, not only in the resulting product but in the thermoplastic material stretching. The only difference is that the blow-molding starts with a molten parison (a round hollow tube) while the twin-sheet forming uses a two thermoplastic sheet arrangement. The twin-sheet forming technique will offer better results over blow-molding, because the sheet extrusion process provides a more precise quality control in sheet thickness and a wider option of variables in the thermoplastic sheet making.

This twin-sheet forming production method often competes with the above mentioned blow molding or rotational molding procedures. Depending on the product line, it may or may not have a unique advantage over them. Since this process does not necessarily start with the same source of thermoplastic material supply, the twin-sheets can be made of a different color or even different makeup of plastics. This way twin-sheet thermoforming can produce a product which has different appearances from one side to the other side, or have different physical characteristics as long as it does not interfere with the forming procedure. This way, for example, a hollow product can be made with different colors on opposite sides. It may have a smooth finish on one side and a textured finish on the other, can be a clear plastic on one side while the other side is made of opaque plastic material. In case it is needed the two sides can be made of different plastics for accommodating a finished product with a wide range of different criteria or purposes (see Figure 48).

To further enhance the twin-sheet process and allow it to improve cycle time, the two sheets can be clamped separately or, in the web-fed situation, fed in two separate paths. By this method the individual sheets can be heated from both sides. The processor can have two independent clamp frames, top and bottom heaters, and one heater in the middle. The top heater will heat the top side of the top sheet, the bottom heater heats the underside of the bottom sheet. The middle heater unit will heat the top sheet underside and at the same time the top side of the bottom sheet.

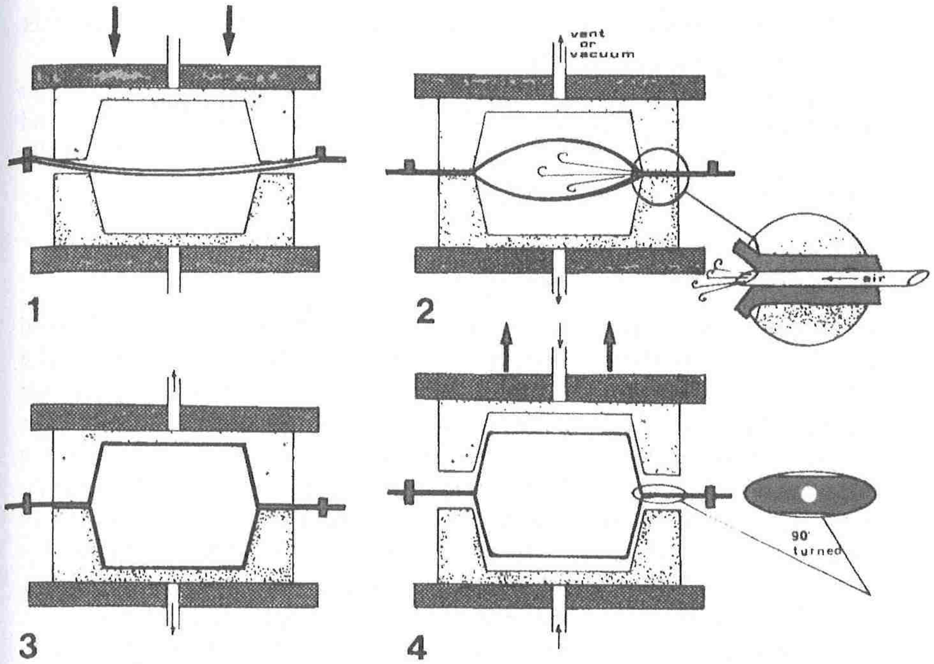


Figure 48 (1) Clamping the twin sheets. (2) Activating the forming forces. If vacuum is applied at the mold, the syringe allows air to enter between the sheets. If pressurized air is used for forming, venting or vacuum is opened to the mold. (3) Full forming and cooling take place. (4) Mold opens and a blast of air through the mold helps the stripping.

Also, the forming of the twin-sheet can be accomplished by an overlapping method using dual rotary equipment, as will be described later in Section III.D of Chapter 4.

Dual-sided heating of twin-sheet also can be accomplished on the web-fed machines. In this case, there are two separate loops of pin chain tacks right above each other. Each chain will carry and index forward with its own sheet supply. There is a triple-decker oven which will heat each sheet on both of its sides. As the two sheets approach the molding area the distance from each other is diminished to almost nil, so that they run on top of each other. This closeness permits thermoforming of the twin-sheet, making it possible to form a product that cannot be produced any other way.

It should be pointed out that there are many more variations and different adaptations that can be produced with the twin-sheet forming technique, and many innovations are currently under investigation which will undoubtedly become general practice in the future.

III. TYPICAL MOLD ARRANGEMENTS

The implementation of various thermoforming techniques begins with mold installation into the thermoforming equipment. Even before installation of the mold, some decisions must be made as to the mold configuration and available equipment choices. These decisions will be tied to the production quantities desired. There are several criteria that will guide the thermoformer, the two most outstanding being product size and product quantity. The remaining criteria may not be as dominant in the decision-making process and might not be considered at all if there are sufficient funds available to deal with them. The factors that limit a thermoformer, such as equipment, type of forming force, or available know-how, can easily be overcome by expedient purchases.

Product size is a strong influence because it can limit the equipment, molds, or even the techniques that are adaptable for a specific thermoforming process. Products of larger dimensions obviously cannot be produced on smaller-format equipment and may require additional specialized installations to support the process. On the other hand, small-configuration products can be produced in multiples at the same time.

The quantity of a product to be made is also a crucial factor in the decision as to what approach the thermoformer should take. When only a few pieces of a specifically configured product are needed, the process certainly will require different planning and arrangements from a large-scale production. The forming technique coupled with the mold arrangement (one-up, multi-up, or family molds) can make the difference between a satisfactory thermoforming operation or merely an acceptable one.

A. One-Up Molds

When a single mold is used in thermoforming, it is often referred to as a "one-up" mold. When the mold consists of a female mold, it can also be called a "single-cavity" mold. There are three independent reasons for using a one-up thermoforming format. The first can be found in the thermoformed article size. Many thermoformed products are so large that the equipment can accommodate only one at a time. The second purpose of thermoforming in single units is that only a limited number of products are needed. Finally, experimentation and testing are implemented most ideally with a one-up mold configuration. Initial mold building and rework are always easier and less costly in a single-mold format. It is possible to find other reasons to use one-up molds; however, their justification should be analyzed carefully before they are accepted. No thermoformer will argue the fact that for oversized parts, due to machine-size limitations, single-unit molding may be the only way to accommodate the forming. Even if more than one part can be formed at once, multi-up molding in a larger size can create interference between the molds that will hamper the outcome.

One-up mold thermoforming is preferable when the manufactured products are not being used or sold in high quantities or when the demand for a larger volume of products is spread over a certain period of time. In either case, the product quantity demand does not justify the purchase of multi-up production molds that will be used only in short production bursts and result in production downtimes between uses. On the other side of the production scale, markets are continuously being supplied by manufacturers sticking to one-up mold equipment long after the product demand has outgrown the single mold's supply capabilities. This can create possible product shortages and invite competition from other suppliers.

All experimental tryouts of new product designs must be made in a one-up mold format. Use of single molds not only keeps the cost down but removes all interfering reactions. Besides the initial mold cost, tooling rework or alteration can be done without a major expenditure. Even if an entirely new mold is suggested, the cost is comparatively moderate. Experimental molds can be produced out of a number of materials that are suitable, inexpensive, and easy to alter or rework and then to reassemble with simple shop tools. Of course, one-up production molds must be made of materials that provide good tool life expectancy and the durability to withstand maximum thermoforming forces.

B. Multi-Up Molds

When product size and demand are not limiting factors, thermoforming producers can install multiples of the same mold in the thermoforming machine, known as "multi-up" molds. Using the same thermoforming procedure, more than one unit of the same product can be produced at the same time. Two or more parts produced in the same cycle will each have its own mold. Multi-up molds come in formats from two-up to any conceivable matrix. Multi-up molds are built with a predetermined, fixed format. The mold arrangement can follow several optional patterns, which are usually guided by the platen size of a machine and the respective sheet panel size. For example, a four-up mold arrangement can consist of four individual molds placed into a single row (1 by

4) or in two rows of two molds (2 by 2). It is not unusual to find molds made into formats as large as 48 up (6 by 8) or even larger.

The tooling for multi-up molds consists of identical individual molds with fixed spacing in between. The molds can be made out of any common block of tooling material or may even be individual molds secured to a common backup plate. This mold arrangement provides a fixed overall dimension to the final mold, which can, in turn, be tied to the thermoplastic sheet dimensions. The overall panel dimensions are determined by the individual thermoformed part dimensions, multiplied by their number in each direction plus the spacing between them and their edge allowances. The calculation and estimation of the proper sheet dimensions is most critical for successful, cost-effective thermoforming. The economic implications of panel size for each cycle are discussed in Section V of Chapter 6.

The spaces between the individual molds in a multi-up mold do not need to be identical or uniform. When two or more moldings are produced in the same cycle it is easy to recognize that molding interference can originate between the neighboring molds. The space allowed between the individual molds may have to be varied according to several factors, including mold configuration, depth of draw, and design patterns. Minimizing the spacing demand between the individual moldings can be accomplished through the use of clamping mechanisms. Such mechanisms were discussed in Section II of Chapter 2 and are illustrated in Figures 13 and 14. In the heating phase for multi-up molds, uniform heating of the thermoplastic sheet is of utmost importance. The thermoplastic sheet that is introduced into the forming cycle must have an identical temperature and soft consistency throughout its entire body. When sheet temperatures and forming conditions are not the same from one molding to another, the thermoforming will suffer. This criterion is as important in two-up mold formats as it is in very large formats. For example, in a large-format mold (that could have as many as 48 up and a panel dimension of 50 in. by 50 in.), the sheet temperature and forming conditions should be identical from one corner area to the other and from the center to the sides. To achieve and maintain temperature uniformity over such a large area is not an easy task, and to provide such uniformity from cycle to cycle requires first-rate equipment controls and thermoforming skills. Understanding the criteria limits of each type of thermoforming can help in the preplanning and final outcome.

It should be noted that relatively thick thermoplastic sheets will be required to form a multiple mold pattern producing several parts using closely placed tooling with a substantial depth-of-draw configuration. From this greater thickness of sheet will be produced an abruptly decreasing wall thickness in the finished thermoformed product. Soft-drink cups, for instance, are usually thermoformed out of 80- to 100-mil-thick thermoplastic sheet and experience a tenfold reduction in their wall thickness. Multi-up thermoforming requires multi-up trimming procedures as well. If the trimming operation does not keep up with the thermoforming speed, it causes a bottleneck in the flow of production. Trimming of multi-up-sized thermoforming can be managed all at once with a matching multi-up trim tool. Such tooling requires some type of registration capability in order to locate the fully formed panel accurately for trimming. With the use of any of the cutting instruments discussed previously, the parts can be trimmed, ejected, and gathered from the trimming apparatus. This type of trimming can be made by both post and in-line operations.

In continuous roll-fed thermoforming operations, the trimming is often accomplished in row formations in a secondary trim press. Basically, this type of trimming of a multi-up molding is made by individual rows, one row at a time. Each row of the thermoformed panel is indexed and registered before trimming. The number of rows produced in the forming determines the number of strokes the trim press must produce to keep up with the thermoforming machine. For example, a mold that displays four rows within its molding format will be four times faster in its trim-press run.

The size of a multi-up mold is often described as much by its numerical array as by the overall numbers of ups. A 48-up mold, for instance, may be eight columns wide by six rows deep, or the other way around. The number of parts in the mold's width and depth give a proper description of a specific multi-up mold arrangement.

C. Family Molds

The family mold is an extension and variation of the multi-up mold arrangement. A family mold is composed of individual molds in a multi-up format that do not share the same configuration. The setup may consist of cavities each made in an entirely different configuration or may contain groups of different mold configurations. The criteria for selecting this type of mold are based on the similarities of the formed parts. Such close dimensional comparability of the finished products allows them to be combined into the same molding. For best results in thermoforming with a family mold, the mold configurations should have the same depth-of-draw ratios. Of course, this criterion is not absolutely necessary, but it can minimize interference between the moldings. It is also best for the parts to be closely matched in at least one of their dimensions. If that is the case, such similarities in size minimize any dimensional misalignments in the combined mold configuration. However, such dimensional differences are also not absolutely essential for success in family mold adaptations.

The strongest argument for successful use of a family mold is an equal product demand on the individual articles. The actual product demand and the resulting sales ratios must match the product output ratios of the family molds. If, for example, a mold has a production ratio of 2:1 between one product item and another, the products should enjoy the same comparative sales opportunities. A constant deviation between the two ratio factors will provide either an overage or a shortage of one of the thermoformed items. Ironically, due to overaggressive merchandising efforts, the item in short supply will be the one to be brought up to its proper level, which results automatically in an oversupply of the other product. This oversupply will generally instigate "creative" marketing ideas, such as price reduction or discounting of the overproduced product, which do not solve the problem. The only way out of this predicament is to replace the family mold with newly built independent molds.

Despite the shortcomings of family molds, many products lend themselves to being good candidates for a family mold setup. Those products may enjoy somewhat similar sales volumes, to the point where an oversupply of one size will not be realized. For example, using family moldings for the production of various sizes of trays for flower pots has had good success.

The family molding technique can also be helpful where a larger area of product is blanked or trimmed out. The specific area that is cut away can be classified as normal scrap. However, with the same effort and energy consumption and a little creativity, a second, smaller product or group of products can be thermoformed out of the blanked area of the first. All that is necessary is to insert smaller molds where the blanking area will occur. The trimming apparatus may be able to handle the trimming of both products, or it is possible that the blanked-out panel may require separate trimming to cut out the smaller items. If there is no further product demand for the smaller units (which have been formed "free" out of the larger product anyway), the blanked sheet portion used for the secondary smaller products can still be scrapped and reclaimed. Opportunistic uses of family molds should not be overlooked. It can often be turned into a profitable supplier of secondary products.

D. Alternating Mold Arrangements

A quite different and innovative mold arrangement came about when high-speed, high-volume operations were demanded for the production of low-cost food containers. At the same time, for several reasons, the polypropylene thermoplastic resins came to be very attractive. Polypropylene can offer several advantages over other resins, as well as favorable costs. However, in the thermoforming process, the material demanded some extra cooling-time allowance. Extending the cooling cycle within the customary thermoforming process lengthened the overall cycle time. Such an increase results in reduced productivity and tends to destroy a large portion of the cost advantage.

To furnish extended cooling cycles for thermoformed articles without increasing cycle times demanded innovative mold arrangements. Such arrangements, which originated in Europe, even involved some reengineering of the thermoforming machines. The thermoforming equipment has been modified for each method and made specifically to implement the respective mold arrangements. Some of these specialized thermoforming methods have proprietary features that are covered by protective patents.

The basic principle of the "alternating" arrangement consists of a single set of male molds that will thermoform against a "team" of recurring female mold cavities. The male side of the mold will perform its normal function of assisting in prestretch of the plastic sheet directly into the female cavities. After the full forming procedure, the molds undergo the customary trim-in-place steps. However, after trimming is completed, the thermoformed parts are not ejected. As the male mold halves are withdrawn from the female cavities, the thermoformed parts are carried away from the molding area and a new set of female mold cavities substituted in their place. The previously thermoformed parts, being retained in the mold cavities throughout the remainder of the cycle, receive the desired extra cooling time. With this innovative method of recurring indexing of female mold cavities, the extra cooling demand is easily met without any sacrifice of thermoforming speed.

There are two basic innovative mold arrangement methods that can accomplish the same task: shuttle molds and revolving molds. Each has its own distinct approach. The results produced by both systems are equally satisfactory. The choice of one system over the other must be made according to criteria other than simply the resultant thermoforming.

1. Shuttle Molds

In the shuttle mold arrangement, the tooling has a double set of female mold cavities opposing a single set of male plug-assist molds. The principle of this method is shown in Figure 49. The female mold cavities will "shuttle" perpendicularly to the sheet advancement motions. The thermoforming is always made in a central location into which an empty and recurring set of mold cavities will index with each cycle. The shuttle movement is made in a horizontal plane, and is repeated cycle after cycle. The previously formed and trimmed parts will remain in the female cavities and will shuttle to the side. The parts will be retained and cooled as long as the center molding is ready to open. As the mold is made to open up, the parts made previously will be simultaneously ejected. As soon as the steps are completed, the mold will shuttle back again and repeat the entire process. It is easy to see that with the shuttle mold arrangement, each set of molds receives twice the usual cooling time of customary thermoforming and does not require more cooling.

2. Revolving Molds

The thermoforming technique using revolving molds follows the same principles and goals as those of the shuttle mold arrangement, but the female mold

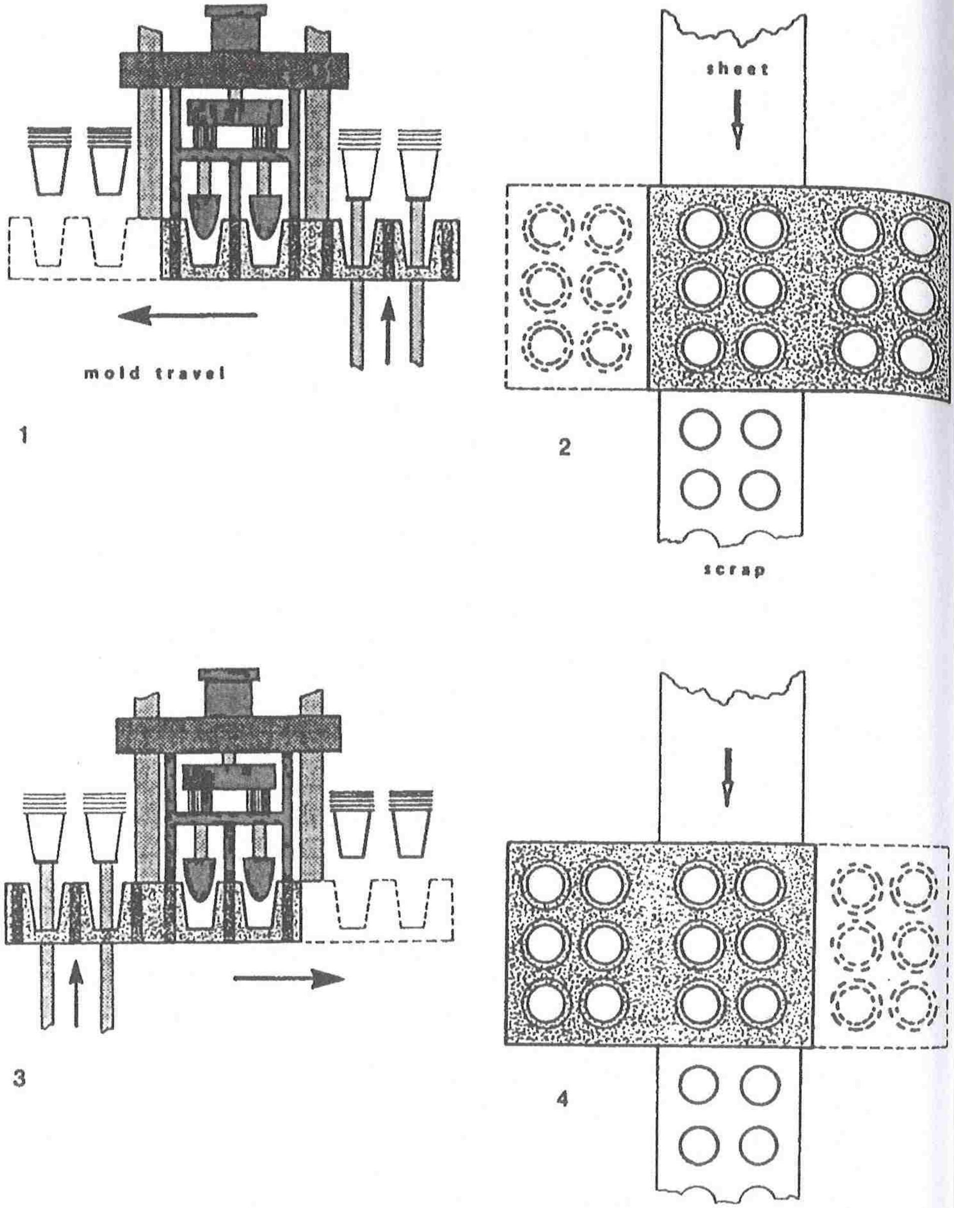


Figure 49 Shuttle mold arrangement: (1) front view, mold on right side, part ejecting to the right stack; (2) upper view, mold shuttles perpendicular to sheet; (3) front view, mold on left side, part ejecting to the left stack; (4) upper view, mold on left side.

cavities are arranged in a horizontally rotating system. This procedure still uses a single set of male plug-assist moldings opposing a four-sided "team" of female cavities. The mold arrangement and its functions are shown in Figure 50. This mold arrangement consists of four horizontally rotating and indexing mold cavity sets. The mold can contain single- or multicavity rows within the revolving mold arrangement. Each rotating index is completed with a quarter turn. The upward-facing female mold cavities are used to implement thermoforming and trimming. The next two indexing locations hold the trimmed parts

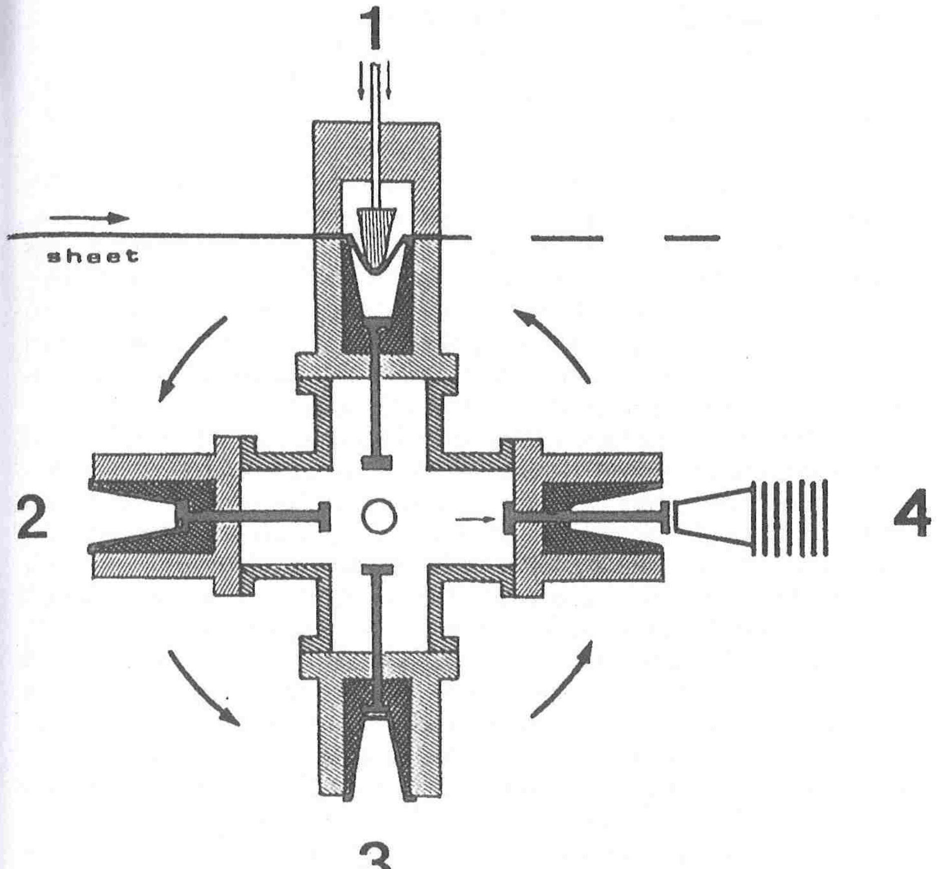


Figure 50 Rotating mold arrangement: (1) forming station; (2) cooling and lip cooling; (3) additional cooling; (4) ejecting and stacking.

within the cavities for extended cooling. In the last indexing location, the parts are horizontally ejected from the mold cavity. In the final rotational indexing, the empty female mold cavities return to the molding area for the thermoforming and trimming cycles. The ejected thermoformed parts are pushed onto a receiving magazine for nesting and stacking. For the nested stack, an automatic counter can be incorporated to help in packaging the thermoformed goods. With this rotating mold arrangement, thermoforming can be managed with 50 or more cycles per minute. At such high rates of thermoforming, it is of utmost importance to make the thermoforming procedure absolutely flawless. If errors should occur, they can easily "hide" within the stacks of finished product and slip unnoticed by all quality control efforts.

E. Rotary Mold Arrangements

In the rotary mold arrangement, a constantly rotating mold arrangement is utilized. The aim of this type of molding is to create continuous movement, resulting from the nonstop rotation of the molds. The principal shortcomings of this type of forming resides in its restriction to one-sided molds. In this type of rotary mold arrangement, it is not feasible to attempt mold-half mating, so female forming methods alone are generally used. Of course, with extended effort, such limitations can be overcome and even plug-assisted thermoforming can be carried out with this type of mold arrangement.

The thermoforming technique using the rotary mold can be approached in three ways, all of which are aimed basically at providing continuous thermoforming and rely on a continuous sheet-fed operation. The simplest version of the rotary mold arrangement has a large rotating wheel setup, somewhat similar to a Ferris wheel. The female mold cavities are placed side by side on the rotating wheel circumference. As the wheel rotates, it picks up the heated thermoplastic sheet and continuously wraps it around the rotating surface. As the sheet makes contact with the rotating mold surface, vacuum is introduced to the particular cavity or cavities. The introduction of vacuum forces will pull the heated plastic sheet into the cavity and force it to form into its own shape. As the rotation continues, succeeding cavities follow the lead of the first, one after the other. The formed parts remain in the cavities until they are stripped off. Next, the vacuum is turned off and venting takes place in the respective cavities. This permits stripping and removal of the formed parts, which remain in the form of a continuous web. The web is then subjected to trimming to separate the individual parts. In this mold arrangement, quite a number of molds can be placed into the large Ferris wheel form to produce the least number of revolutions. The larger-diameter wheels also offer long contact time with the mold after forming, resulting in better cooling.

The second version of the rotary mold arrangement follows the same principles of rotary mold setup. In this thermoforming method, 12 to 18 mold cavities are secured in a turning wheel pattern. Each cavity has a clamshell-type lid fixture that closes to capture the hot sheet between the lid and the mold cavity. This hermetic enclosure of the clamshell lid permits the use of pressure-forming forces. The mechanically closed clamshell lid will be able to hold up to 15 psi pressure and will give better forming details. This molding arrangement can produce up to $2^1/_2$ in. of depth of draw; however, it is most ideal for shallow-depth articles such as container lids. The specialized equipment utilized with this mold arrangement is discussed further in Chapter 4.

The third version of the rotary mold arrangement consists of a continuously moving mold face formed in the surface of a moving belt. The design possibilities of the belt range from a pattern of individual cavities placed next to each other, to one long pattern that concludes with each rotation of the belt, or even one that provides a continuous form. The advantage of using a belted mold system lies in the belt's ability to repeat itself. The mold system must be able to flex enough to complete the belt's rotation. Mold materials must have a rubbery consistency or be segmented in order to follow the belt turns. A single belt with its applied molding surface can be used together with vacuum forces. This type of system must have an efficiently engineered vacuum system and must manage to introduce and hold the vacuum forces when the thermoforming process calls for them. The cancellation of vacuum is also important at the end of belt travel to facilitate stripping the formed article. It is also feasible to use two opposing belt forming systems; each belt having a matched contoured design. Pressures created between the belts will result in a matched mold forming. The two belts squeeze the heated thermoplastic material to form and transmit their surface details on both sides. This method also qualifies as a compression molding technique. Naturally, the mold surface details must have enough venting holes to relieve any air trapped in the design structure. This double-belt mold arrangement works equally well with preheated thermoplastic sheets or with direct extrusion, where the material flows directly between the moving belts.

The mold arrangements discussed so far are not necessarily the only ones that can be implemented in thermoforming. There are combinations and variations that can be developed, and innovations are constantly being introduced. As new mold materials are developed, new uses will be found. Since many inventions like these have been made in the past and will continue to be made, outstanding patents on mold arrangements can limit the adaptation of some of the features. It is the obligation of the thermoformer to select the process that is free of restrictions. Patented mold arrangements are discussed here only to provide the most complete mold arrangement list available, not to promote the concept or imply its unrestricted use.

IV. LIMITATIONS IN THERMOFORMING

The thermoforming process has been very successful in producing a great many useful items. The manufacturing method, with its ideal volume-producing capability, has swept over established product lines, substituting and squeezing out traditional well-accepted manufacturing techniques. The thermoforming industry has not only replaced existing products but has created entirely new products. As the technology of thermoforming has developed and advanced, it has also grown bolder. Equipment capabilities, sophisticated toolings, and forming techniques have made it possible to manufacture products out of a single piece of sheet material where previous products required the assembly of multiple components. The design opportunities are practically unlimited for this manufacturing method. However, in real situations, thermoforming has defined parameters and limitations for which the process cannot offer any solution. It is an advantage to know and understand such limitations before thermoforming attempts are made. Being well acquainted with such limitations can eliminate any unrealistic expectations in respect to both sales and manufacturing. Through the years, many hindrances have been overcome and there is an excellent chance that a few more restrictions will be dismissed. However, some limits to thermoforming will remain constant. In fact, some of the characteristic limitations of the process will forever be inherent in the forming technique. There are shapes and forms that will never lend themselves to production by the thermoforming process. Such impossible situations should be relinquished as a thermoforming goal. There are restrictive boundaries in the thermoforming process which should be learned, respected, and worked with (and not against). Correct knowledge of what a process is capable of doing will save a lot of time, effort, and money. The thermoforming process cannot, by its very nature, be thought of as a total substitute for any other forming process, such as injection, compression, or blow molding. It cannot make products of identical configurations or dimensions or create minutely precise mold duplication. However, in many cases, thermoforming can permit similarly shaped competing products to be substituted. The thermoforming practitioner has the opportunity to design around the particular limiting factors in such a way that it will not affect the function of the product, yet will render a most cost-effective manufacturing method. The three basic limiting factors in thermoforming will remain with the process and under any circumstances, will require some effort to minimize their effects.

A. Detail Loss

In the process of thermoforming, not all conceivable details will be transferred from the mold to the formed part. From a meticulously made mold finish, some loss of detail transfer can be expected. Better transfers will be obtained with higher levels of forming forces, which can be further enhanced with temperature elevation. However, such improved detail transfers can be accomplished only up to a certain level, never 100%. In addition, where only one side of the sheet is in contact with the mold, the opposite side will probably show poor mold details. A thermoformed plastic article may show satisfactory detail transfers on one side, yet exhibit somewhat "washed-out" details on the other side.

A close examination of the forming technique will allow recognition and pinpointing of where and when such fine detail is transferred from a mold surface to the formed part. As the heated and softened thermoplastic sheet is forced against the mold walls, it will take up the contours. Where direct and substantial stretching or strong angular changes appear, higher levels of detail loss can be expected. In stretching and forming, actual material shifts will take effect and work against the obtainment of full detail. Figure 51 shows the two basic types of detail loss where even with the best conditions and the highest levels of forming forces, some lack of detail transfer can occur.

1. With the traditional male taper angles, the mold surface side of the formed article will be best equipped to obtain details. As the soft forming thermoplastic is forced against the mold surface, the mold detail will be closely transferred. The opposite side of the formed plastic article will be somewhat stretched and thinned over the mold radius. The stretching force will reduce

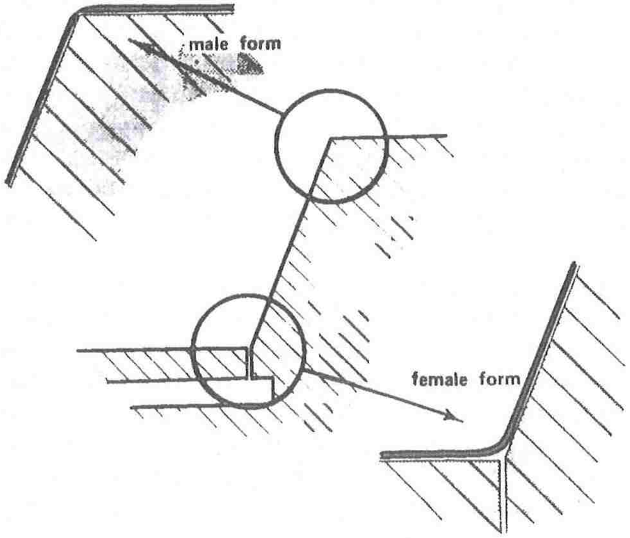


Figure 51 Detail loss in thermoforming.

the resulting radius on the opposite side from the theoretically obtainable parallel curve. As shown in Figure 51, the resulting radius can qualify as a detail loss. For example, when a textured sheet is used in thermoforming and the textured pattern side of the sheet is turned away from the mold, the results of the forming will be a stretching out of the particular textured patterns. The stretching will expand the texture design laterally while reducing its depth of detail. This will give the appearance of a worn and polished surface. In corner areas where at least three surfaces are junctioned together, the resulting stretch and detail loss can be so severe that the texturing will become almost smooth and shiny. This detail loss can be avoided or at least minimized by shunning the use of designs that require small radii. Larger-radius forms usually allow retention of the texture details. This particular sensitivity is most important in products where such loss of detail will diminish the product's attractiveness, as with suitcases, briefcases, and automobile dashboards.

2. With conventional female angles, the forming material will stop short of full corner detail. Even with the most ideal heat conditions and mold temperatures, the forming radius will be limited. This limitation is closely tied to the thermoplastic sheet thickness. Thinner sheet materials tend to form into the radius or corners better than heavier-gauged materials. For all practical purposes, using the sheet material thickness for judging the minimum obtainable radius is a satisfactory method. The thickness of the thermoplastic sheet should be used as the least formable radius in thermoforming.

When trying to obtain a smaller corner radius than the thermoforming can offer, the matched molding method must be used. This permits the mechanical forming forces to become effective and force the plastic to conform and squeeze into smaller radii than can be handled by ordinary thermoforming. Using matching molds, with their compression molding features, is often not feasible. Most thermoforming is made without the possible adaptation of a matched mold, and therefore such radius-forming limitations will often exist. Knowledge of this limitation is most important. It can eliminate overexpectations in the forming results and eliminate the requisition of tooling with unattainable details.

In the case of textured material forming with conventional female angles, the pattern details of the inwardly placed textured sheet finishes (pattern side away from mold) tend to close up. As the thermoforming is accomplished, the curvature of the inside radius will be made smaller than the actual mold radius, depending on the material thickness. This reduction of curvature, together with the tightness of the corners, will tend to compress the texture pattern so that a dulled and wrinkled surface is created. Such compressed textured patterns can be minimized or even eliminated with an increase in corner radius. To maintain ease in forming and to lessen detail loss, the adaptation of larger-radius forms is highly desirable. However, using the larger-radius design patterns can force possible size increases and even diminish product quality. Products thermoformed and made with sharp, strong design angles (smaller radii) will offer superior strength. Products that contain a fair amount of rib design pattern are testimonies to this fact. Products with sharp rib design patterns are far stronger than those with large, less pronounced design patterns. This is only valid, however, when comparing the same thermoplastic sheet materials and thicknesses.

B. Depth-of-Draw-Ratio Limitations

Depth-of-draw limitations involve the process's ability to stretch a given area and thickness material into a three-dimensional product. Certain thermoplastic materials will allow far more stretching than others and, through the stretching, some can resist ruptures much better than others. Some of the materials allow for so much stretching that extreme reduction of gauges will be accomplished without loss of continuity, Products can be thermoformed out of a 100- to 120-mil thermoplastic sheet material and formed into products that display a 10- to 15-mil wall thickness throughout the entire body.

Draw ratios of 1:1 can easily be achieved with any of the simplest methods of thermoforming. This 1:1 ratio means that the smallest entrance distance of an open cavity can be drawn into the same measure of depth. The same limitations pertain to male molds. In cases where multi-up male molds are considered, the spacing between the male molds should be treated the same as a female cavity and the 1:1 ratio limitations must be honored. For example, 2-in.-high male molds must be placed 2 in. apart to be produced by the basic thermoforming methods. If they are placed closer together, serious material thinning will occur. In fact, at some point, depending on the material, the material thinning will be so extensive that the walls will be formed membrane thin and can even rupture. In any type of thermoforming, with either female or male molds, the resulting and unwanted thinning is normally compensated by an increase in sheet gauge. Using a heavier-walled thermoplastic sheet may add material thickness and strength to the radically thinned out areas but, at the same time it will increase material thickness proportionally to all the other areas. So where one problem is being solved, another is being created in areas of exorbitant thickness. Poor material distribution makes a thermoformed part more susceptible to product failures. Most thermoformed products are judged by, and fail at, their weakest areas; no value will be given to the heavier and stronger portions. Most failures occur at the weaker portions of a thermoformed article, making the entire product useless in spite of having portions that display "tank"-like strength.

Increased draw ratios can be achieved through various molding techniques with improved molds and temperature control and planned programming of both. Depth of draw can easily be produced in 1:3 or 1:5 ratios and even 1:7. However, this ultimate draw ratio requires sophisticated process controls and equipment together with specific thermoplastic material. Extending the limits this far cannot be expected using the simplest thermoforming methods and alternating materials. In extending the upper boundaries of this thermoforming criterion, many proprietary methods and process controls are implemented; patented techniques, out-of-the-ordinary equipment, and special materials are used. Where one thermoforming practitioner may be bound by lower depth-of-draw limitations, others will be trying to extend the upper boundaries and may succeed further than is generally known today. Although there will be many advances and much success, there will be always a challenging task ahead.

In any event, the depth-of-draw limitation, even with a well-mastered process, requires constant attention together with proper controls and monitoring. Particular products will demand constant tuning and an ongoing extra effort to maintain production and product quality. At the same time, other products will not be hampered at all by this limitation.

C. Reversed Draft and Undercut Limitations

Producing articles by thermoforming often involves well-proportioned open flair configurations. However, every so often a product design may contain virtually no taper angles, or angles so small that special considerations pertain. It is well accepted that with sufficient taper angles, forming and formed part removal presents no difficulties. With smaller taper angles, the male mold's shape tends to hamper part removal and stripping much earlier than with the female mold. The interference in part removal is caused by the shrinkage, which grabs onto the male mold.

The female mold is less vulnerable to this natural physical phenomenon. The formed part shrinkage on the female mold will work for part removal rather than against it. Formed parts with natural shrinkage and reduction in size are easily removable, even from an absolutely straight walled mold cavity. In fact, parts whose designs contain a limited number of reversed draft angles or undercuts (due to size reduction related to shrinkage) can also be stripped from the mold. Slightly larger undercuts can also be removed and stripped out of the mold but require mechanical stripping assistance. The attempt at removal is affected greatly by the resiliency and deformation recovery quality of the particular thermoplastic material. Mechanical strippers are acceptable for removal of a thermoformed product from a mold, but care should be taken that the stripping force is not damaging to the article. Some materials display a rather rubbery flexibility that permits a deep undercut to be pulled out of a mold. Other materials may rupture and result in permanent damage at the nonreleasing portions of the thermoformed article.

Prior knowledge of the sensitivity of various materials to forced stripping can eliminate unrealistic expectations. It is advisable first to make an oversized drawing of the preferred undercut or reversed taper angle. Such a drawing can easily reveal stripping clearances and mold removal restrictions as well as the desired shrinkage factors. Different materials with different shrinkage rates may not allow direct material substitution without causing removal interference where close tolerances in the undercut are concerned.

Other limitations that exist with most undercuts and reversed draft angles are found in the difficulty of producing them with sharp definitions. The very purpose of producing undercuts and reversed angles is to obtain a fully detailed form. Poorly or incompletely formed undercuts will not provide this function.

Undercuts are used for two reasons. The first is to form a spacing device directly into the thermoformed article. In thinly walled thermoformed products, dense nesting will occur due to the identical configurations of parts and dimensional similarities between the inner and outer surfaces. To overcome the tight and dense nesting results, reversed draft angle protrusions in a ring or lug formation are thermoformed into the plastic product. Because these protrusions are made with reversed draft angles, the nesting articles will be hung up by the tips of their "undercuts." The undercut designs basically create larger nesting dimensions within the parts, which therefore cannot fully slip into one another. The depth of the undercut design will determine how well the stacking feature will work; its location and overall height will regulate how closely the nested part will be spaced when stacked. A typical nesting lug feature is illustrated in Figure 52.

To achieve full details in the forming of an undercut design, the reversed draft cavity must be allowed to evacuate the air trapped within it. To ensure complete forming, it is highly recommended that those critical areas be tied together, with open channels all the way to the main forming force chamber. In this way, when any combination of forming and stripping forces is used, the undercut cavity will be activated. Since undercut designs make formed part removal difficult, the reversed angles are kept at a minimum. The slightest underforming will show up first in detail loss at the undercuts. As little as 3 to 5% loss in detail can cause the production of a nonfunctioning stacking feature.

The second use for undercuts and reversed draft angles is to provide good snap fit between containers and their lids. The undercut designs in this case will give a positive locking feature that is much better than a friction fit. As already pointed out, in the thermoforming process, an undercut feature is the first place where detail will be lost. With even the smallest loss of detail, good, strong snap fits will deteriorate into a weaker snap and eventually to a point where lids will no longer hold onto the container. Lid failure from poor forming and the resulting detail loss are not uncommon. In fact, this is the main culprit of most improper lid and container matings.

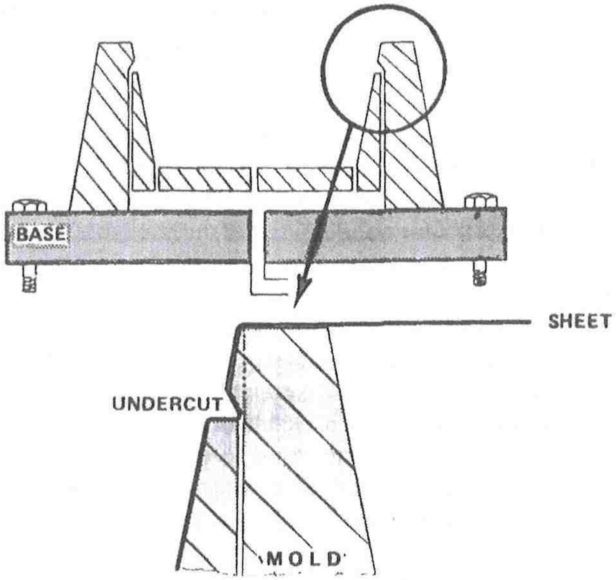


Figure 52 Typical undercut.

Improper fitting of thermoformed parts caused by reduced forming qualities and detail loss should not be confused with those caused by incorrect shrinkage calculations. Although both can cause diminished locking features, the first condition can be remedied, whereas incorrectly estimated shrinkage factors will result in permanently built tooling that has the wrong dimensions.

Occasionally, thermoforming processors must be able to make products containing large reversed draft angles that would not lend themselves to any type of forceful stripping or part removal. These angles cannot be accommodated by any of the common thermoforming molds. Huge undercuts combined with heavy-gauge plastic sheet can be thermoformed, but part removal will be impossible. To work around such an annoying situation, tooling modifications have to be implemented. In cases where one or two—but not many—reversed draft angle undercuts are produced in a given part, it is preferable for the undercut angles to be positioned in the same direction (front to back, left to right, etc.). For these difficult forming tasks, "breakaway" undercut inserts can be placed in the molds. These inserts become part of the mold for the forming and cooling cycle. However, during stripping and removal, those inserts are pulled away together with the formed part. They will thus not interfere with stripping and mold separation. The breakaway mold insert is then replaced in the main mold for use in the next cycle. Thermoforming can also be carried out using several identical pieces of breakaway mold inserts for the maintenance of production flow. Good candidates for this type of breakaway mold insert are such parts as shower and bathtub enclosures. The large soap-dish cavities formed in the sides of the enclosures require an extremely large reverse draft angle and could not be stripped from the mold in any other way.

For large quantities, or grossly oversized undercut shapes, molds can be made with splitting, tilting, or retractable features. Although such molds can be incorporated into the thermoforming process easily enough, their maintenance and airtight characteristics must be made to be repeatable. Accomplishing this will always be an impressive engineering feat.

For the sake of thermoforming expediency, screw caps have been formed using a continuous thread in the form of an undercut which is thermoformed into the caps. The thermoformed caps are removed with rotation (unscrewed) from the mold cavities with a rack-and-pinion device. This proves that there is almost no limit to uses of the thermoforming process. As unsolved process limitations are put to thermoformers, they will usually be able to find ways to overcome them, thanks to the versatility of the process.

D. Layer Reductions in Coextruded Barrier Sheets

The production of thermoformed containers made of coextruded materials has a unique limitation that it is important to understand. Coextruded sheet materials provide exceptional barrier qualities and considerable ability to eliminate chemical migration. The main reasons for using coextruded layers in a sheet for making containers is that some of the individual layers possess these unique barrier properties. When these layers are combined into a multilayered coextruded sheet (or even a laminated sheet), each layer brings its own barrier qualities to the combined sheet. In combination, the sheet layers complement each other and provide an exceptional packaging medium that can substitute for most known metal and glass packaging materials.

Such coextruded barrier material is often formed into containers using the thermoforming process. The thermoforming method is a natural way to produce packaging containers. The coextrusion method is the easiest one for converting the barrier layers into a combined sheet form; each layer thickness is easily controllable. For the best economy, each layer is extruded at the minimum thickness, where its barrier qualities will remain at satisfactory levels. Thermoforming practitioners must realize that the original thickness of a sheet will be reduced in the process of thermoforming. The prestretching and final forming can occasionally cause heavy reduction in the original gauges. This reduction of gauge can easily thin out a specific layer so that its original barrier qualities will be lost. This limitation must be known and planned for.

In addition to this natural overall thickness reduction, thermoforming has another limitation with respect to coextruded sheets. The natural gauge reduction is easy to compensate for with additional increases in layer thickness. However, each layer in the combined sheet composition is produced from different materials. The various layers are used for their different barrier qualities; they may not have similar or even close softening temperature points. In addition, they may also have differing flow characteristics and varying levels of submissiveness to stretching or tear resistance. When coextruded barrier sheets are thermoformed into products for the packaging of any sensitive preparation, such as food or drugs, the results of the thermoforming must undergo thorough testing and scrutiny. The true limitation in the thermoforming of such containers is found in the inability of the process to guarantee even reduction in the forming of the individual layers. Some barrier material layers may reach softening and flowing viscosities before other layer components do, thus creating inconsistent layering. Material may ooze out from between the firmer layers, causing a loss of barrier quality in those areas. Any container that has lost barrier tendencies even over only portions of its surface should be considered useless. It is important to know that thermoforming can cause such diminishing qualities in a barrier layer and that a greater thickness may be needed to compensate for the thinning. It is also important to subject the formed products to proper testing to ensure valid barrier properties. Measuring layer thicknesses in an already formed coextruded sheet or after thermoforming of the product is virtually impossible and cannot be depended upon.

4

Thermoforming Machines

I. INTRODUCTION

As stated earlier, the process of thermoforming easily lends itself to the use of repeated production cycles. Each time the same sequences are repeated, the same production cycle will be performed and identical products made; all conditions must be reproduced as well. When heat and forming force levels plus the timing sequences are duplicated identically, the resulting thermoformed products should be exact replicas of each other. To provide identical forming conditions for every cycle of the process, various types of thermoforming machines are employed. The many possible variations among thermoforming methods, product sizes, and volumes of product will demand an equal variety of thermoforming machinery. It is obvious that widely disparate products, such as a larger hot tub versus a smaller container, will be thermoformed best on thermoforming machines of different sizes and features. In fact, today's highly competitive business environment requires the utmost specialization of equipment, providing specific advantages for a particular thermoforming process to reduce costs and promote quality. Modern thermoforming means that specialized equipment is used for a specific purpose. To carry this specialized practice even further, most thermoformers set parameters on their fields of interest and capabilities. The segregation by a company of their equipment and their selective thermoforming procedure is usually predetermined by various material thickness ranges. Specific thermoforming machines are best suited to tions. A lighter wall-thickness version of this pipe can be used for transferring water or other liquids at low pressure from one place to the other, or even can be used for air conditioning ducts.

Forming corrugations into the plastic tubing or pipes follows the same criteria as the thermoforming process. The size and the number of vacuum holes is just as critical in this process as it is in thermoforming. The oversized holes will show up on the plastic tubing or pipe surfaces as small buttonlike formations. The level of vacuum force is equally important; if there is a leak or not enough vacuum, the corrugations will not form in full detail. In this process the problem or difficulty is greater because the molds are constantly traveling and the chances are more likely to develop an unwanted vacuum leakage through the long path of the mold tunnel.

The task of forming the corrugated pattern into the plastic tubing or pipe configuration is not limited to vacuum forming. It can be accomplished by using pressurized air as well. The only criteria in using pressurized air is to accomplish a good airtight seal. Air pressure introduced at the extrusion through the middle of the extrusion die must be captured by sealing off the previously extruded end of the corrugated tubing or pipe. It is much easier with the smaller sized tubing style. As the smaller tubing is made the beginning of the tubing portion is sealed off promptly and that will block the escape of pressurized air. Then the corrugated tubing is simply wound up in a coil arrangement. When the roll is full a cut is made and the new roll will start with a "pinch-off" seal to continue the process of winding.

The convenience of using pressurized air is currently not available for corrugated pipe making; therefore most manufacturers rely on the vacuum forming method. Unless someone is capable of accomplishing an economically feasible air pressure seal, pipes will continue to be made by the existing vacuum process method.

5

Molds for Thermoforming

I. THE BASIC CONCEPT OF MOLDS

To produce thermoformed articles, some type of tooling implementation is required, regardless of article size or quantity. To carry out most production tasks, complete tooling is needed. Complete tooling can have a wide range of components, including special sheet feed and holding units, trim dies, and related stacking and part-receiving magazines. The two major components of the tooling are the mold and the trim die. In some instances the tooling consists of just a mold. However, it is rare that the thermoformed article does not undergo some type of trimming or finishing after the forming cycles. Most sheet-fed thermoforming operations rely on a secondary trimming method, and such trimming procedures can be produced by any of the tools and techniques described earlier. In some instances the two major components, molding and trimming, are combined into a single piece of tooling that will provide both operating functions. This particular forming and trimming procedure was discussed in Section II.C, Chapter 3.

When these main components of the tooling (mold and trim die) are ordered for a thermoforming job, they are usually engineered and built together as a complete tooling package by the same tool and die shop. In this case, the toolmaker takes full responsibility for the entire tooling; this will include the mechanical fit of components into the specified equipment and their interrelated measurement and function. If the two components are purchased separately, their compatibility becomes the responsibility of the thermoforming practitioner. Tooling obtained either way must function well together to achieve satisfactory thermoforming results.

The mold can easily be considered the heart or main component not only of the tooling but of the entire thermoforming process. The mold forms a heated thermoplastic sheet into a product shape, converting a two-dimensional sheet into three-dimensional formed articles. The mold is the instrument through which the formed plastic will attain its shape. In this shaping of the thermoplastic sheet, the mold must perform well in order to transfer its details as fully as possible and allow the perfectly detailed article to be removed without damage. The mold itself can spell the difference between perfection or imperfection in its own detail transfer and thus between satisfactory results or poor-quality products.

A. Tooling-Up from Idea Stage to Finished Mold

Most product ideas, whatever the source, often begin as humble sketches or drawings. From the sketches, refinements and more details will be developed that will characterize the concept or the shape of the basic thought. Often, when the initial sketches show enough promise, fully developed drawings and possible blueprint designs are produced to provide different viewing angles of the product idea. After the drawings are produced, it is easy to convert them to actual physical shape. Bona fide pattern makers or people who are familiar with pattern-making procedures can easily read the drawings and develop a three-dimensional structure, following the shapes and measurements described. Building a pattern usually follows customary pattern-making procedures and materials. The three-dimensional physical shape is often not made of a single piece or block of pattern material (block of wood) but is assembled from segments or components. In the pattern-making procedure, the maker often dismantles the original form into its conceptual components or segments, which can be produced more easily on pattern-making equipment than a one-piece configuration. The pieces are assembled and fitted with glue or other fastening methods to create the final mold configuration. Pattern-making skills are not extremely difficult to learn. However, some woodworking knowledge is helpful, combined with some understanding of the various configurations and their development. Some people have exceptional talent at visualizing shapes and configurations easily; and can, in no time at all, convert a blueprint into physical form. Pattern shops with highly trained, skillful pattern makers can handle any type of pattern-making endeavor. Smaller, in-house pattern facilities that serve only a single thermoforming plant are limited to the specific types of patterns for which they are set up. Such limited, specialized skills can easily be learned and practiced by internally trained personnel within the shop parameters.

Prior to the initial pattern-making procedures, the pattern maker has to analyze the job as to which form is easiest to create. He must first decide whether it is easier to begin pattern production with a male or a female mold. The intended final configuration of the mold will help determine whether a male or a female mold will be more functional for the thermoforming process. The choice of the best form is usually guided by the forming technique and the quality of material distribution chosen. To make such a decision, the various molding methods and their descriptions in Chapter 3 should be consulted. In addition to the final mold shape choice, the prominent surface or sides of the resulting forming have to be determined. The correct selection is most important because it will decide which side of the formed article has to display the best details and which side will be allowed to carry the expected "detail loss" (also covered in Section IV.A of Chapter 3).

When both determinations have been made for the final mold configurations, the next step is to designate the way the pattern should be made for the particular mold configuration. Although the pattern choice for a mold is set, it is possible that a reversed-shape pattern will be easier to create. For example, when the aim is to produce a female mold with straight cylindrical or tapered cylindrical cavities, instead of trying to carve them accurately out of a block of pattern-making material such as wood, it is easier simply to turn the block on a lathe into a cylindrical shape and then split it into halves, which are then mounted onto a board backing. After gluing and pattern preparation, a reversed pattern can be made from the original pattern work, to create a pattern with the initially intended female configuration.

When dimensional criteria dictate precise measurement of the plastic article, the article must be made on accurately sized molds. This is where the perfect details of the forming results will come into play. To obtain the most accurate details and dimensions on at least one side of the plastic, mold surface contact becomes most important. It is at these contact points along the surface that the plastic will pick up its details, adopting the intended shape. It is of the utmost importance that this criterion be followed throughout the mold-making procedure, all the way back to the original pattern. Allowance for material thickness and correct surface contact must be planned for the final version of the mold.

B. Shrinkage Allowances

Besides correct placement of material thickness in the pattern and tool making, one additional criterion has to be satisfied. To arrive at the intended thermoformed product size, allowance for the natural phenomenon of shrinkage