Thermoforming of Lucite® XL Sheet

Lucite® XL continuous cast cross-linked acrylic sheet is specially formulated for superior thermoforming and chemical and stain resistance properties compared to other acrylic sheet products.

Lucite® XL is used primarily for production of bath ware and spas in which the thermoformed acrylic sheet is reinforced with fiberglass and polyester resins (FRP). In these end uses, Lucite® XL exhibits the excellent processing characteristics and surface quality needed to produce complex parts, which are attractive and durable.

Lucite® XL acrylic sheet can be thermoformed readily using equipment and techniques similar to those described in Bulletin L-1050, "Lucite® L Cast Acrylic Sheet Thermoforming." However, the special formulation of Lucite® XL and other factors which are particularly important to the production of deep-draw FRP reinforced parts merit special consideration. This bulletin provides supplementary information which will help manufacturers consistently produce the best quality parts with Lucite® XL.

Cleaning

Carefully cleaned sheets and molds will minimize irregularities and blemishes and ensure production of a smooth, glossy part. However, acrylic sheet usually carries a static charge and attracts airborne dust, saw chips, and dirt. The best way to control this is to maintain a very clean thermoforming area and try to isolate dirt and dust from the spray-up area.

Once the Lucite® XL sheet is unmasked* it may be cleaned effectively with mild solvents, such as dilute solutions of isopropyl alcohol. That method has the advantage of reducing static and removal of small particles and fibers, sometimes can leach colored dye to the sheet at thermoforming temperatures. A possibly faster, and common method of cleaning is to use an ionized air gun which tends to reduce static charges buildup somewhat versus non-ionized air, as it blows contaminants off the sheet. Numerous other static eliminating cleaning agents exist, but none of these methods is more effective than a scrupulously clean thermoforming area.

* In some cases, manufacturers may choose to thermoform the sheet with the film masking intact, in which case certain precautions are necessary. For details, see the Temporary Protective Film Masking section towards the end of this document.

Thermoforming Cycle

Lucite® XL acrylic sheet should be thermoformed with two important objectives in mind. These are: (1) to heat the sheet to appropriate forming temperatures, and (2) to draw the sheet uniformly into the mold at a rate and manner, which balances accurate mold reproduction, adequate part thickness, and minimized stress in the thermo-formed parts. If the sheet is insufficiently heated or if it loses too much heat during forming, it will draw unevenly and yield parts containing high residual stress. This stress can cause cracking and warping during the reinforcing process or over a longer period of time, after the part has been produced and sold.

For optimum thermoforming performance, the sheet core temperature should be between 320°F and 360°F (160°C and 182°C). Although the core temperature is impractical to measure, corresponding recommended sheet surface temperatures are listed by product type in Table I, below.

Temperatures can be verified using thermolabels or a non-contact IR pyrometer.

Typical Thermo-forming Temperatures*** (°F) Pattern Heating*			
Grade/type sheet	Perimeter area °F	Areas of excessive thinning °F	Maximum Lucite® surface temperature, °F (1)
	Top: 380 - 400	Top: >= 350	400 °F
XL Bath/Gemstones	Bottom: 330 - 360 Xtra (ABS) 320 - 340	Bottom: >= 300 Xtra (ABS) 300 - 320	
Granites: Natural,Celestial, Lustre	Top: 390 - 410**	Top: >= 360	410 °F
	Bottom: 340 - 360** Xtra (ABS) 320 - 340	Bottom: >= 310 Xtra (ABS) 300 - 320	
Lustres and Lustre Marbles	Top: 410 - 430 Top (Xtra): 390 - 420	Top: >= 360	430 °F
	Bottom: 350 - 400 Xtra (ABS) 320 - 340	Bottom: >= 300 Xtra (ABS) 300 - 320	

Notes:
* pattern heating: involves non-uniform heating of the sheet to improve material distribution, ie. part thickness.
- perimeter location: approximately 6-8 inches in from clamping frame, either on top or bottom sheet surface.
- thinning location: sheet area, which corresponds to the location in final part of lowest thickness, eg. footwells, drain end corners, etc.
** Sheet temperatures on warm end, coupled with stretching, provide the highest level of texture.
*** Temperatures in the table are based on our understanding of typical manufacturer's conditions. Each thermo-forming process has its own unique characteristics (2), and those parameters, together with variables in a manufacturer's reinforcement process, will determine the suitability of the thermoforming conditions. Each user must establish suitability of their own process conditions to insure the quality of their finished product.
(1) For properly stored sheet -- moisture absorption reduces the peak temperature of the sheet at which blistering may occur.
(2) Variables include 1 versus 2-sided heating; heating rate; sheet thickness; mold design, material of construction and if heated; pattern heating; evacuation flow, controls and vacuum level.

Above these temperatures, blistering due to vaporization of absorbed moisture or at higher temperatures, polymer degradation may occur. Insufficiently heated sheet or excessive cooling prior to, or during part formation may lead to problems caused by induced stress in the sheet. The optimum heating cycle required to reach forming temperatures depends upon the sheet thickness as well as the type and settings of equipment used and the ambient conditions of the forming area. Such variables make process controls vital in thermoforming. A quick-response pyrometer effectively measures sheet surface temperature and should be used to establish cycle times. Once a heating cycle is established, temperature-sensitive tapes can be used to confirm that the process is in control and sheet surface temperatures are being reproduced consistently. A pyrometer should be used occasionally to check sheet surface temperature and can indicate potential stress problems due to insufficient heating below the surface of the sheet.

An effective method for experimentally establishing and checking heating and draw uniformity is to mark the sheet in 6 inch squares and measure variations in temperature and in draw uniformity across the sheet. This information is very useful in determining how to adjust the heating controls or strategically screen the heating elements with wire mesh (window screen) to prevent overheating and control part thickness in deep-draw areas. Plating or painting of the clamp frame and oven interior to produce reflective surfaces should be considered. This action results in increased oven efficiency and improved temperature uniformity within the sheet. Once the heating controls and cycle have been established, various control mechanisms can be used to reproduce the cycle, for instance, a photoelectric cell which monitors sheet sag during heating, a top-mounted pyrometer to monitor sheet temperature while linked to heater controls, or a timing mechanism may be used.

After the sheet is heated, the vacuum draw should proceed in a smooth and timely fashion. Because the thickness of Lucite® XL is consistent throughout the sheet, proper control of the heating and forming of parts will lead to reproducibility in part thickness on similar points in each part, and on a part-to-part basis. Variations in heating or draw rate, resulting in forming at lower temperatures, could create structural weaknesses caused by induced stress.

Equipment

Ovens - The best way to ensure uniform heating is to heat the sheet from both sides. Ideally, this would be done in a closed air-circulating oven, but these prove to be impractical for production purposes. A semi-automated thermoforming machine usually provides top and bottom radiant heating for sheet held in a movable metal clamp frame. Ovens that heat sheet from the top only run the risk of blistering the top surface of the sheet with too much heat or inducing stress through uneven or inadequate heating. Several heating techniques are currently in use for production of spas or sanitary ware:

(1) Ceramic or quartz panels: This is the best type of unit for uniform heating and longevity. The heating element is completely

embedded in a ceramic or quartz panel. Such elements show little deterioration or loss of efficiency with age, and the individual panels offer a good method for individual or zone controlled heating.

(2) Metal-sheathed tubular rods containing heating elements also are common. The rod surface gradually oxidizes, reducing thermal efficiency which may be partially restored by cleaning with steel wool or emery cloth.

(3) Coiled nickel/chrome wire is frequently used and has a quick response time. It also loses thermal efficiency, and it has the shortest life expectancy of all types of heating elements. The loss of efficiency may lead to inconsistent or inadequate performance and, in the long run, higher energy costs.

(4) Gas flame: This method is least recommended due to potential for inconsistency of the heating pattern and high susceptibility to drafts. They do typically offer energy savings over electric.

(5) Quartz tube: Similar to the metal sheathed tubes, these elements have a quartz tube surface. Due to brittleness, they are better suited for upper heating surfaces than on the bottom. They have medium heat-up response time.

(6) Quartz bulbs (sealed): These have a quick heating response time, leading to advantages in feed-back control and patttern heating and allowing rapid heating times.

(7) Gas catalytic panel heaters: these are characterized by potentially low energy costs (depending on energy source costs), less flexibility in zone control due to panel sizes and longer heater response times. Being a reactive system, fluctuations in air (oxygen) flow may cause variation in heating tiimes. Also, lower emitter temperatures may lead to longer heating times.

Molds - Molds may be constructed inexpensively with simple materials, such as wood, plaster, epoxy, or reinforced polyester. The life expectancy of such molds is short, however, and the low heat-transfer coefficient of the construction materials, coupled with the lack of mold temperature control, reduce thermoforming efficiency. Cast aluminum molds with molded-in heat control channels are more efficient and last longer, but require greater initial investment and are costly to modify.

Uniform mold temperature is essential to the production of minimally stressed parts. Typically, this temperature should be in the range of 145°F-155°F. The mold interior must be channeled, and should have enough vacuum holes to allow fast, uniform evacuation during thermoforming. The vacuum holes, usually 0.025” (.635 mm) in diameter, may be slotted to improve air evacuation and minimize mark-off on the acrylic sheet.

In female molds, the acrylic tends to shrink away from the mold as it cools so that part removal is enhanced. It is good practice, however, to use a 2°-3° draft angle in mold designs to supplement this natural occurrence. Uniform cooling is desirable so that design integrity is maintained, warpage is minimized, and residual stress content is minimal and uniform. In some instances, a male plug assist is used to push sheet into the deepest parts of the mold, although the chances of marring the surface of the part are heightened by such use. If a plug assist is used, the plug temperature should be maintained within 50°F (27°C) of the sheet temperature, or be made from a low thermal conductivity material, in order to assure minimal stress or chill marks in the part. The finished acrylic part can usually be removed safely from the mold at a temperature of 170°F. The actual temperature is dependent upon the part geometry and mold complexity; if the design has an undercut, a cam-actuated mold which opens to release the part may allow removal at a higher part temperature.

Vacuum - The basic requirements of vacuum pump, surge tank and required lines are very critical. The application of the vacuum during the cycle should be consistent. The sheet being drawn must contact the mold (and thus begin cooling) uniformly and quickly so that highly stressed thin sections in the part do not occur.

Normally, a vacuum of 29 inches (736mm) of mercury is used, and the reading on the gauge should not drop below 20 inches (508mm) during forming. The size of the surge tank and the number and size of holes in the mold must be designed with those conditions in mind. Optimal tank dimensions can be calculated by use of the formula:

$$\mathbf{V_s\, P_s + V_m\, P_m = V_t P_t}$$

Where:

Where:	V_s	=	volume in surge tank and piping
	V_m	=	volume in mold (including channeling)
	V_t	=	total volume (Vs +Vmm)
	P_m	=	pressure in mold*
	P_s	=	pressure in surge tank**
	P_t	=	desired working pressure

* At sea level = 14.7 PSI Atmospheric (101 kPa).
** 0.5 PSI equivalent to 29 inches (736mm) mercury.

A proper vacuum pump and surge tank must be supported by appropriate piping. Flexible hose (1½ inches or 38.1mm, minimum diameter) should be used; the tank should be located as close to the mold as possible; and tees and elbows or other restrictions in the lines should be eliminated. Valves should be the full-open type and the vacuum gauge should be placed in a location easily visible to the operator.

Troubleshooting

Problem	Possible Causes
Color variation	1. Undrawn sheet caliper too low for mold design 2. Uneven vacuum 3. Uneven draw rate overall or within areas 4. Sheet surface temperature too high in that area 5. Nonuniform sheet pigment dispersion 6. Nonuniform mold temperature
Thin and thick sections	1. Uneven heating (e.g., nonfunctioning heat element) 2. Uneven draw 3. Nonuniform mold temperature
Scattered surface blisters	1. Overheating in oven from excessive temperature or heating time 2. Oven malfunction 3. High moisture from storage
Surface blisters in areas	1. Local overheating 2. Malfunction of heating elements/controller
Incomplete draw	1. Vacuum system problem, leak sheet too cold because of improper control, malfunctioning 2. Heaters, inadequate insulation of oven area, or exposure to drafts
Surface inclusion on sheet	1. Contamination (sawdust, airborne dust) on undrawn sheet or mold poor mold finish or subsurface mold voids 2. Water droplets on surface - cool area stays thicker
Torn part	1. Sheet incompletely or nonuniformly heated 2. Sheet too thin for mold design 3. Defect within the undrawn sheet 4. Vacuum insufficient, draw too slow 5. Mold surface temperature too low or variable because of improper 6. Channeling of heating fluid

Temporary Protective Film Masking
Polyethylene film is used as a temporary protective film on the top surface of the Lucite® XL cast acrylic sheet. In most cases, it may be left on the sheet during thermoforming and subsequent fabrication to help avoid minor defects to the part surface*. After fabricating the bath, it is recommended to remove the film prior to shipment for sale or prolonged storage. This helps to avoid degradation of the film by heat or sunlight, which can make the film hard to remove.

In some cases, damage to the film may make it desirable to remove the film prior to thermoforming. For example, rough handling may scratch, tear or partially dislodge the film. Forming with the film damaged may leave subtle marks on the acrylic surface. If the film is laid back onto the sheet after it is dislodged, air is trapped under the film which then expands during heating and forming which can leave marks.

The film can also absorb and transmit water vapor. At forming temperatures, the trapped moisture vaporizes and can result in blisters in or under the film which may leave an impression in the sheet surface.

If the film is damaged, or the sheet and film have had exposure to high humidity or lengthy open storage, the user is advised to evaluate and compare effectiveness of removal of the film masking prior to forming. The following steps will help to avoid making marks on the sheet during thermoforming and subsequent handling:

Suggested Actions:
- Lower sheet forming temperature to reduce the mark-off impressions.
or,
- Remove the masking prior to forming the sheet.
- After forming the part, use a protective film* with pressure-sensitive adhesive to cover all or part of the part's surface to avoid problems with scratching and fiberglass over-spray.

In addition to the above suggestions, it is always advisable to keep sheet wrapped and to use proper sheet storage techniques to reduce moisture absorption.

* Contacts for suppliers of protective films are available, upon request.