CHEMCAST®

The all purpose cell-cast acrylic sheet

Technical Manual

THERMOFORMING

UNIGEL

CHEMCAST®
The all purpose cell-cast acrylic sheet

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History of the thermoforming industry

Thermoforming principles

Since the early twentieth century some plate forming techniques have been known, with materials such as metal, glass and natural fibers. The true principles of thermoforming occurred with the development of thermoplastic materials, which was during the Second World War. The postwar years brought large volumes of marketing and the rapid development of equipment and machinery capable of adapting to modern manufacturing methods, to produce more useful and profitable products.

During the fifties, the production volumes of thermoplastic materials and products made from them reached impressive figures. The decade of the 60s was an era that laid the foundations for the future development of the thermoforming industry. In the 70s, large consumers and product competition demanded high-speed and productivity machines. Equipment producers met these needs with machines capable of producing about one hundred thousand thermoformed individual containers per hour. There was also need for more sophisticated controls.

Since the 80s to date, thermoformers have gained such confidence in their process, that they have gone beyond their expectations and have established solid lines capable of producing finished thermoformed articles no longer from sheet, but from the resin pellet; besides recycling its waste with minimal control. Equipment has now computerized and today allow self-monitoring and diagnostic functions. Currently, very complicated equipment do not require more than one person for their handling and control due to advances in electronics. Therefore, it is believed that the labor market for the thermoforming industry will experience a shortage of trained and experienced technical staff, as trad itional knowledge would no longer be sufficient; therefore, conferences, seminars, courses, etc., would serve to increase the general knowledge of the thermoformer, and give greater maturity to this well-established industry.

Products manufactured by thermoforming

Many thermoformed products in use today have been made to replace their original use forms; this situation has occurred so quickly that it has almost been forgotten what they were; for example, it is not easy to remember that hamburgers were packed before single-piece polystyrene packaging or with what material the interior of the refrigerators were covered.

The list provided below starts with the product with the largest number of thermoformed parts produced and is in descending order to that with the lowest production.

Packaging industry

Since the beginning of the thermoforming process, the packaging industry has been the most benefited due to the high productivity and advantages offered by cost-benefit.

Currently, most of the packaging equipment (blister) are high speed automatic feeding. These devices are called ''form-fill-seal'' and are used for packing cosmetics, cold meats, soft drinks, candy, stationery, etc.

Takeaway industry

In the growing "takeaway" industry, there is a large number of thermoformed products used, ranging from complete food containers (containers with partitions) to the packaging for hamburgers, sandwiches, soft drinks, etc.

Generally, this industry requires a print on the thermoformed packages. This print may be performed before or after thermoforming; examples of these products include trays, cups, sandwich containers, hamburgers, hot dogs, etc.

Food packaging industry

Supermarkets are the largest users of thermoformed containers. The materials used are inexpensive thermoplastics. These containers are designed to be stacked or arranged in different ways. Examples: containers for meat, fruit, eggs, vegetables.

Transport

Public and private transport such as the bus, train, subway, plane, car, etc., has numerous parts of thermoformed plastics among its equipment; most of these are used for interior finishing or external parts that are not structural: Among others: seats, backs, armrests, door sidings, service tables, windshields, instrumentation protection, guards, spoilers, etc.

Signs and advertisements

They are usually made of acrylic and can be in one single piece and of large size. In these advertisements or signs, transparent acrylic (glass) is usually used and the color is painted on the inside with acrylic based paints.

The use of acrylic makes outdoor ads weather -resistant and virtually maintenance free, in addition to withstanding extreme conditions of heat or cold. As examples of these there are outdoor and interior illuminated advertising, signs in public places, offices, etc.

Household items

There are a number of household items that have thermoformed parts; in fact, they are high-volume productions. They are found, for example, in cabinets, washing machines, dishwashers, dryers, refrigerators, window air conditioners, humidifiers, television and radio cabinets, etc.

Food industry

One of the oldest and largest consumers of thermoformed products is the food industry. The use of trays and other accessories have the potential for higher consumption since, in addition to large users such as hospitals, kindergartens, schools, fairs and others, the military sector and international aid organizations are added. Examples: trays, cups and plates.

Medical Industry

The medical industry requires a variety of st erilized products and packaging for hospitals, clinics and doctors' offices. The specifications of these products are usually very strict and the use of recycled materials is unacceptable.

The use of acrylic, as a physiologically harmless material is incr easing day by day. Examples: surgical equipment, syringes and needles, surgical tables, cabinets, incubators, dental chairs and exercise platforms, etc.

Agriculture and horticulture

The marketing of ornamental plants in supermarkets and specialty stores has generated, since a long time, the need to manufacture pots and small containers, even with multiple cavities for exhibition and sale. These types of containers are made from recycled plastics and inexpensively. The following can be cited as examples: pots, containers of different sizes with one or more cavities, small greenhouses, seed growing trays, sowing containers, etc.

Construction and housing

The construction industry has employed thermoformed products for several years, with their popularity rapidly accelerating. There are a lot of products that have been easily replaced by thermoformed parts; in fact, there are products that could not otherwise be made, such as domes or arc tubes. Acrylic is widely used in this sector due to its resistance prop erties for weathering and thermoformability.

Examples of these are: domes, arc tubes, whirlpool tubs, bathroom modules, sinks, bathroom screens, tables, chairs, bases for lamps, kitchenware, watches, facades, ladders, partitions, window frames, aquariums, etc.

Luggage

Some luggage manufacturers, are opting to use the thermoforming process since it has advantages over injection products, as being an effort -free molding, the chances of fractures in thermoformed part equipment are reduced. Examples: suitcase s of all kinds, briefcases, etc.

Photographic equipment

One of the oldest products in thermoforming are developing trays, in addition to flash cubes (the metallic reflector) and the magazine for floor cameras, even when their production requires a precision thermoforming technique.

Suitable polymers for thermoforming

Basically, all thermoplastic polymers are suitable for the thermoforming process. Such materials, when subjected to heating present a variation in their modulus for elasticity, hardness and resilience under load. With a temperature increase exceeding the HDT, the behavior of the material will tend to become a rubberized state, with the critical value being the tempering temperature of the thermoplastic polymer. This can be observed in the rap id buckling of the heated sheet, when the force of gravity is sufficient to cause this deformation.

POLYMERS	HEAT DEFLECTION TEMPERATURE			THERMOFORMING TEMPERATURE		
	A 264 PSI (°C)	A 66 PSI (°C)	W/OUT LOAD (°C)	SHEET TEMP. 8°C)	MOLD TEMP. (°C)	HELP TEMP (°C)
Extruded acrylic	94	98		135-175	65-75	
Cellcast acrylic	96	110		160-180	65-75	
Cellulose acetate butyrate	65-75	75-80	120-150	140-160		
High density Polyethylene		60-80	100	145-190	95	170
Polypropylene	55-65	110-115	140	145-200		
Polystyrene	70-95	70-100	100	140-170	45-65	90
High impact polystyrene	85-95	90-95	120	170-180	45-65	90
SAN	100	105		220-230		
ABS	75-115	80-120	95	120-180	70-85	90
Polyvinyl chloride (PVC)	70	75	110	135-175	45	80
Polycarbonate	130	140	160	180-230	95-120	140

Table No. 1 contains the appropriate and most common polymers for thermoforming, as well as their forming temperature.

Thermal properties

One aspect that is taken less into account in the practice of thermoforming is the thermal properties of polymers, this being one of most relevant and critical aspects of the process. The understanding of these factors will reduce the risk of long pre - production runs or poor adaptation of the product to the environment.

When talking about thermal properties it is essential to establish the concepts related to this topic. First we must remember that energy is often dissipated through friction and so appears as heat or internal heat energy of a body. Of course a substance's heat is sometimes deliberately increased to change i ts temperature or to alter its shape.

The specific heat and thermal conductivity are two of the physical properties of polymers that are extensively used in thermoforming.

Temperature

In the discussion of the thermal phenomenon it is essential to include some terms and concepts. The first of these thermal properties is temperature. Temperature is a measure of the degree of "hot" or "cold" of an object. The properties of water was taken as a parameter being indispensable to establish a temperature scale, in particular the melting point of ice and boiling point of water. There are three scales to measure the temperature of a substance, scale in degrees Celsius (°C), Fahrenheit (°F) and Kelvin (°K), and the first two being the most used.

Measurement of heat

Heat is just one form of energy and therefore the appropriate physical unit for measuring heat is the same as for mechanical energy and this is the joule. As in the same case of temperature scales, water is used as a substance parameter for defining the heat unit. The amount of heat required to raise the temperature of 1 kg. of water one degree (now taken as 14.5 °C to 15.5 °C) is defined as 1 calorie (cal.).

Specific heat

When 1 calorie is supplied to 1kg. of water, the water temperature will be increased 1 degree, for example, if the same amount of heat is supplied to the same mass of methyl alcohol, the temperature will increase by approximately 1.7 degrees, or if 1 cal. is supplied to 1kg. of aluminum, the metal temperature will increase about 5 degrees. In fact each substance will respond in different degrees when subjected to heat. The amount of heat required to raise 1 kg. of a substance by one degree is called specific heat of that substance. Water serves as a parameter and it has been determined as 1 cal. /Kg., taking it as a basis for comparison with all materials. With the exception of water, most materials have a lower specific heat than plastics.

Thermal Conductivity

Thermal conductivity is one of three ways by which heat energy can be transferred from one place to another; it occurs as a result of molecular motion and therefore requires the presence of matter. Heat energy is transferred by collisions where the rapid motion of atoms and molecules of the hotter object passes some energy to the cooler object or with slower movement of atoms and molecules. When a substance is heated it expands, heat causes the volume of a substance to increase and its density to decrease. Acrylic thermal conductivity is 5 x 10 -4 cal./sec. cm2.

Thermal Expansión

Thermal expansion is the result of increasing the temperature of a substance, and consequently the latter expands, in fact; almost all substances, solids, liquids or gases have the property of increasing their size, when their temperature rises. Regarding thermoforming, when a polymer is heated the mobility of the molecule chains is increased, therefore they tend to separate with respect to each other, increasing the volume and area ofthe polymer. This property is important especially in thermoformed pieces which are exposed to sudden temperature changes or weathering. In thermoforming the plastic sheet expands faster than the metal frame, causing wrinkles near the frame, these wrinkles disappear when the sheet shrinks. The numerical values of the coefficients for he ating and cooling are identical; this means that it takes the same time to heat than to cool. It must be taken into account that there can be problems when the thermoformed parts must be within a very tight dimensional tolerance, other problems may occur when the shrinkage occurs in a male mold, making it difficult to demold the part. The thermal expansion coefficient of acrylic is 9x10-5 cm./cm./°C.

Acrylic sheet

General purpose acrylic sheet

Characteristics

The methyl methacrylate th ermoplastic polymer has a molecular structure of linear and amorphous type that does not form crosslinks. Acrylic is a thermoplastic material used in applications where stability in the open, high light transmission, light weight, resistance to certain che mical agents and color stability are required.

Availability

PLASTIGLAS acrylic sheet is manufactured by the casting process in molds (cell - cast), being the most common and flexible method for a wide range of sheets of varying degrees, thicknesses, sizes and colors.

PLASTIGLAS acrylic sheet is manufactured for general use applications, for indoor and outdoor use, sheet for deep forming with superior properties regarding thermoformability, chemical resistance and wear, in addition to the ImpactaMR acrylic sheet with impact properties superior to any impact acrylic of the market.

PLASTIGLAS products are available in a range of more than eighty colors such as transparent, translucent, opaque, marbled, fluorescent, pearlescent and matte finish.

Physical properties of acrylic sheet

PROPERTY*	ASTM TEST METHOD	UNIT	VALUE	UNIT	VALUE
OPTICAL					
Specific weight	D792-64T		1.19		1.19
Dispersing power			0.0174		0.0174
Retraction index	D542-50	ND	1.49	ND	1.49
Light Trans. (Glass)	D1003-61	%	92	%	92
UV light Trans. 320 mu		%	5	%	5
Haze	D1003-61	%	3	%	3
MECHANICAL					
Resistance to tension	D638-64T				
Breakage		Kg/cm_2	700-760	PSI	10,000-11,000
Modulus of elasticity		Kg/cm_2	28,000-30,000	PSI	400,000-425,000
Elongation at break		%	4.5	%	4.5
Resistance to flexion	D790-63				
Breakage		Kg/cm_2	1,050-1,125	PSI	15,000-16,000
Modulus of elasticity		Kg/cm_2	28,000	PSI	400,000
Resistance to compression	D780-63T	Kg/cm_2	1,260	PSI	18,000
Resistance to cutting Stress	D732-46	Kg/cm_2	630-700	PSI	9,000-10,000
Resistance to impact	D256-56				
Charpy		Kg/m	0.48	Ft./lbs.	35
Izod		Kg-cm/cm	$3 \times 10_4$	Ft. lbs./in.	0.4-0.5
Hardness (Rockwell)	D785-62		M-100		M-100

THERMAL					
Forming Temperature		°C	140-180	°F	280-360
Expansion coefficient	D696-44	Cm/cm/°C	$9 \times 10_{-5}$	in/in/°F	$4 \times 10_{-5}$
Expansion coefficient		°C	$2.7 \times 10_{-4}$		
X Volume					
Max. service temp		Cal/sec. cm_2	80	°F	176
Thermal Conductivity		Cm/min.	$5 \times 10_{-4}$	BTU/hr. ft_2	14
Flammability	D-635	Cal/°C deg	3	ft/min.	1.2
Specific heat			0.35	BTU/lb. °F	0.35

ELECTRICAL					
Dielectric resistance	D149-61	K volt/mm	20	volt/mil	500
Dielectric resistance	D150-59T				
60 cycles			4		4
10_2 cycles			4		4
10_6 cycles			3		3
Arc resistance	D495-61		Without imprint		Without imprint
Resistance (volume)	D257-66	ohm-cm	$1.6 \times 10_{16}$	ohm-cm	$1.6 \times 10_{16}$
Resistivity (surface)	D257-66	ohm	$1.9 \times 10_{15}$	ohm	$1.9 \times 10_{15}$
Water absorption 0.2 to 0.3% by weight after 24 hr. immersion					

**Determination with samples of 3.0 mm thickness*
These values are typical and informative and do not represent any specification.

Chemical properties of acrylic sheet

CHEMICAL SUBSTANCE	KEY	CHEMICAL	KEY
Acetic acid (10%)	R	Hydrogen	R
Acetic acid Acetone	L	peroxide	RL
Ammonium chloride	N	Isopropyl alcohol	R
Ammonium hydroxide	R	Kerosene	N
Benzene	R	Thinner	RL
Calcium chloride	N	Methyl alcohol	N
Carbon tetrachloride	R	(30%) Methyl	N
Chloroform	RL	alcohol (100%)	N
Chromic acid (10%)	N	Methyl ethyl	R
Chromic acid	RL	ketone	N
(concentrated) Ether	N	Methylene	N
Dioctyl phthalate	N	chloride Nitric	R
Ethyl acetate Ethyl	RL	acid (10%)	R
alcohol (30%) Ethyl	N	Nitric acid	R
alcohol (95%)	RL	(100%) Phenol	R
Dichloroethylene	N	(5%)	R
Ethylene glycol	N	Sodium chloride	N
Gasoline	R	Sodium hydroxide	N
Glycerin	RL	(10%) Sodium	N
Hexane	R	hydroxide (60%)	R
			R

Table No.4

The key is used to describe chemical resistance as follows:

R = Resistant

The cell cast acrylic resists this substance for long periods and at a temperature of up to 49˚C (120˚F).

LR= Limited resistance

The cell cast acrylic resists the action of this substance only for short periods at room temperature.

N = Not resistant

The cell cast acrylic does not resist this substance. It can swell, dissolve, be attacked or damaged in some way.

These values are typical and informative and do not represent any specification.

Protections

For protection, ease of handling and according to the needs of machining of the PLASTIGLAS acrylic sheet, we offer four different types of protection:

Kraft type paper

This protection is applied on both sides of the sheet to protect it from damage it may suffer during transport, handling, storage and transformation. Because of its high resistance such protection is recommended for very long transformation processes. It also allows drawing with marker, pencil or crayon.

Antis tatic film

This is a protection less resistant than paper, based on a transparent antistatic plastic film which is applied on both sides of the sheet to protect it from damage it may suffer during transport, handling, storage and machining.

Adhesive plas tic film

This transparent plastic protection is recommended for long machining processes as due to its high strength it allows the sheet to be protected during the various manufacturing processes, presenting a resistance to transport, handling and storage similar to the kraft protection.

Thermoformable film

This thermoformable plastic protection (transparent) is applied on one side of the sheet; it is ideal for the manufacture of thermoformed products with great depth (bathtubs), it allows protection during transport, handling, storage and transformation similar to the adhesive plastic film. Its use is recommended in gas ovens with forced air circulation and temperatures between 180°C – 200°C.

PLASTIGLAS acrylic sheet is available in Mexico with static p rotection on both sides without additional cost in thicknesses of 1.5 to 6.0mm and with kraft paper protection in thicknesses from 8.0 to 32.0mm. however you can choose another kind of protection for an additional charge and on request.

Characteristics

Sensacryl FPMR is a methyl methacrylate thermoplastic polymer, partially reticulated with excellent thermoforming properties, chemical resistance to solvents, resistance to wear and staining, which makes it a material with greater possibilities in the design and manufacture of bathroom furniture, spas, automotive parts and general applications where the thermoformed part is reinforced with fiberglass.

Sensacryl FPMR acrylic sheet has superior thermoforming properties than general use and indoor use acrylic sheet. Among the advantages that this material exhibits that which it can be formed more easily stands out, requiring less labor, it achieves higher stretch without tearing, it has a higher temperature resistance allowing greater flexibility in operation.

Table No. 6 Chemical resistance of Sensacryl FPMR deep molding acrylic sheet

CHEMICAL SUBSTANCE	
Naphtha	Hydrogen peroxide (3%)
Ethyl alcohol	Sodium hypochlorite (conc.)
Amyl acetate	Phenol (5% in water)
Ammonia solution (10%)	Toluene
Citric acid solution (10%)	Ethyl acetate
Urea (6.0%)	Acetone

Table No.7 Properties Sensacryl FPMR deep molding sheet

	PROPERTIES	VALUE	UNIT	METHOD
General	Size	180 x 120	cm.	
		180 x 180	cm.	
	Thickness 180 x 120 cm.	4 + -0.4	mm.	PG 60POE-03-02B
	180 x 180 cm.	4 + -0.8	mm.	PG 60POE-03-02B
Mechanical	Tensile strength (min.)	9200	psi	ASTM D638
	Elongation at break (min.)	4	%	ASTM D638
	Barcol Hardness (min.	48	No. Barcol	ASTM D2538
	Izod impact grooving	0.44	lb-ft./in$_2$	ASTM D256
Thermal	Forming temperature	180-200	°C	
	Low deformation temperature load a 264 PSI (°C)	87	°C	ASTM D648
	Thermal conductivity	1.4	BTU/hr. ft$_2$	
	Thermal stability (two hours at 180°C)	No evidence of degradation		P MIL-8184
	Flammability index	0.6	in/min.	ASTM D635
	Degree of flammability	94	HB	UL-94
Various	Chemical resistance	Passes test		ANSI Z 124.1
	Cigarette resistance	Passes test		ANSI Z 124.1
	UV light resistance (thousand hours, carbon arc)	No degradation		ANSI Z 124.1
	Retention of impact (720 hours carbon arc)	100	%	UL 1563
	Water Absorption	0.33	%	ASTM 570
	Resistance to staining	Passes test		ANSI Z 124.1

All values are referred to 3.0 mm acrylic sheet.

These values are typical and informative and do not represent any specification.

Physical properties

Sensacryl FPMR acrylic sheet has excellent mechanical and flame retarding properties, considering that the general purpose acrylic sheet has a horizontal burn rate test (ASTM-D635) of 25-30.4 mm/min; Sensacryl FPMR acrylic sheet has 15.2 mm/min.

Table No.6 summarizes the typical properties of this material.

Chemical properties

Sensacryl FPMR acrylic sheet, besides resisting chemicals that are listed in the table No.4; meets standard ANSI-2124.2.1980.

Handling and protection

For the protection and handling of Sensacryl FPMR, Plastiglas deep molding sheet, it is presented with three types of protection:

PJ Type: Kraft type paper protector, bonded to both sides of the sheet. Protects from damage it may suffer during transport, handling, storage and machining. This paper allows drawing on with a marker, pencil or crayon, thus facilitating subsequent operations.

PP Type: It is a less durable protection than paper, based on a static plastic film, which also resists the damages the material may suffer during transportation, handling, storage and machining.

PF Type: Thermoformable plastic film (colorless on one side), upon request, ideal for thermoformed products, with a resistance to transport, handling, storage and transformation equal to PJ type. Due to its characteristics, it is ideal for the manufacture of thermoformed parts with depth (bathtubs). Its use is recommended in gas ovens with forced air circulation and temperatures between 180° C and 200° C.

Material Certification

Sensacryl FPMR acrylic sheet has been subjected to quality certification tests in specialized laboratories in the United States, according to ANSI-Z 124.2.1980 standards for bathtubs made of plastic materials, and UL-94; passing the cigarette and wear resistance tests. After one thousand hours of exposure in a carbon arc intemperometer, the sheet did not present and change in appearance or color, maintaining its impact resistance by 100%.

Thermoforming cycles

In the thermoforming process of acrylic sheet, the temperature is the most important factor; so this should be monitored carefully. Low temperatures cause excessive internal stresses in the formed part, reducing its resistance and becoming susceptible to deformation and cracking.

High temperatures can cause the material to blister (boil), reducing its resistance to scraping during forming, mold marks may also occur.

The appropriate temperature range for thermoforming Sensacryl FPMR, is between 180° C and 200° C. The time the material must be subjected to heating depends on the thickness of the sheet, heating equipment and type of forming employed. The heating equipment recommended for thermoforming Sensacryl FPMR sheet is in an oven with forced air circulation, gas or electrical resistors can be used, and good temperature and time monitoring. Considering this material has a thickness of 3.2 mm. it is suggested that it remains in the oven at the indicated temperature for a period of eight to ten minutes to obtain the right softening. If the material is hung vertically in the oven, the heating will be more homogeneous and therefore the forming more detailed. A better distribution of thickness should not be expected, which can only be controlled using mechanical assistance or screens that allow the controlled distribution of temperature by areas. The best forming cycle, temperatures, times and techniques for each type of part, must be determined in each particular equipment, checking the sheet until thoroughly softened, this can be determined when the sheet is stirred and uniform wrinkling form along the surface.

Heating of plastics

Heat transfer: conduction, convection and radiation

In the thermoforming process, the heating operation is one of the steps that takes longer and which may present the greatest difficulties, causing the poor utilization of human and material resources. That is why this chapter is dedicated to heat transfer, aiming to try to clarify the phenomena that occur in the plastics heating operation.

Although scientists have divided heat transfer in three different phenomena: conduction, convection and radiation, in practice the three are concurrent.

Conduction

It is the transfer of heat from one part of a body to another of the same body, or from one body to another that is in physical contact with it, with no significant movement of the particles of the body.

Convection

It is the transfer of heat from one point to another within a fluid, gas or liquid (by mixing a portion of one fluid with another). In natural convection, fluid motion is entirely due to differences in density as a result of temperature differences. In forced convection, which is what interests us, the movement is produced by mechanical means. When the velocity is relatively low, it should be understood that free convection factors, such as differences in temperature and density, can have an important influence.

Radiation

It is the transfer of heat from one body to another that is not in contact with it through the wave motion through space.

For purposes of the thermoforming process, three means for transmitting heat are considered, these are:

a) Contact with a hot solid, liquid or gas.

b) Infrared radiation.

c) Internal or microwave excitation.

The first two are widely used in the thermoforming of plastics and for several of them the temperature range is between 120° C and 205° C (250° F and 400° F)

Thermal properties of plastics

Plastics are poor heat conductors; therefore, very thick sheets require a considerably long heating time. Table No. 8 lists some thermal properties of some materials for comparing. In the thermoforming of plastics it is important to consider the choice of method for heating and the heating equipment size.
Heating the sheet on both sides (sandwich type heating) helps reduce the time spent on this operation. In some cases, the heating time can be reduced if the sheet is preheated and maintained at an intermediate temperature; however, this is rarely used in materials 6 mm. thick.
Additionally, the proportion of heat required to raise the temperature in plastics is high, compared with any other materials; water is the exception. To estimate the heat required in a sheet, this can be calculated using the following formula:

Heat required =
Length x Width x Thickness x Material Density x (Specific heat x Temperature difference + Melting heat)

Table No.8 Thermal properties of some materials

MATERIALS	SPECIFIC GRAVITY g/cm$_3$	SPECIFIC HEAT Btu/ lb °F	MELTING HEAT Btu/lb	THERMAL CONDUCTIVITY Btu sq ft hr. °F	THERMAL COEFFICIENT OF LINEAR EXP. in/in °F 10$_{-5}$
Air	0.0012	0.24		0.014	
Water	1	1	144	0.343	
Ice	0.92	0.5	144	1.26	2.8
Soft wood	0.5	0.4		0.052	1.5
Hard wood	0.7	0.4		0.094	1.5
Phenolic R.	1.5	0.3		0.2	3-5
Epoxy R.	1.6-2.1	0.3		0.1-0.8	1.5-2.8
Polyethylene	0.96	0.37	55	0.28	7
Acrylic	1.19	0.35		0.108	3.5
Polycarbonate	1.2	0.30		0.112	3.7
Graphite	1.5	0.20		87	0.44
Glass	2.5	0.20		0.59	0.5
Quartz	2.8	0.20		4 and 8	0.4 and 0.7
Aluminum	2.7	0.23		90	1.35
Steel	7.8	0.10	171	27	0.84
Copper	8.8	0.092	171	227	0.92
			88		

Heat transmission

Means

For practical purposes we will divide the heat transfer media into four types which are:

Heating by contact

The fastest heating method is to place the plastic sheet in close contact with a hot metal plate. It is used especially for mass production of smaller and thinner items.

Heating by immersion

This method consists of immersing the sheet in a liquid that transfers heat as evenly and quickly as possible, but its use is restricted to molding of parts with very large or very thick sheets, as the handling and cleaning of the piece is difficult.

Heating by convection

The air convection ovens are widely used, because it provides even heating and some materials that have certain moisture content can, to some degree, be dried. These ovens provide a large safety margin with respect to variations in thermoforming cycle times.

Important note:

All heating means mentioned above require considerable equipment preheating time.

Heating by infrared radiation

This method can provide instant heat and therefore its exposure cycles are very short, sometimes just a few seconds are enough. The main sources that provide this type of energy are:

- Quartz lamps emitting in the visible and near infrared.

- Ceramic or metal resistors that emit more energy in the far infrared.

The Surface of these radiation heaters may be between 315° C to 705° C. It should be noted that at higher temperatures, the mass of the radiation occurs at lower wavelengths. In contrast, at lower temperatures, the radiation is spread over longer wavelengths; and this is extremely important, since each plastic absorbs infrared radiation in different regions. Only the absorbed radiation is used to heat the plastic directly.

Internal heating

This method has not had enough application in thermoforming, because the equipment is very expensive. Moreover, it is not applicable to all thermoplastics and cooling times are too long, being applicable to forming processes where localized heating in a specific area ofthe material is required, for example, the forming of material edges having a high loss factor, such as PVC In certain applications, thermoformed products have nonuniform wall sections, even when the sheet has been heated uniformly. The heterogeneous shrinkage of the sheet is due to the part's own design. In these special cases, controlling the heating by sections will provide more uniform wall regions. This procedure is called shading or screening, and consists of placing a nonflammable filter that regulates the heat (a wire mesh, asbestos, etc.) between the sheet and the heat source, with this heat flow to certain areas of the material will decrease and avoid excessive stretching of that area.

In more sophisticated equipment today, there are electronic controls and parabolic ceramic elements that allow heating different areas of the sheet with variability.

Forming temperatures and cycles

a) Demolding temperature

b) Lower limit of operation

c) Normal forming temperature

d) Upper limit of operation

Demolding temperature

Temperature at which the piece can be removed from the mold without distorting. Sometimes it can be removed at higher temperatures when cooling devices are used.

Lower limit of operation

This represents the lowest temperature at which the material can be formed without creating internal stresses. This means that the plastic sheet must touch each corner of the mold before it reaches its lowest limit. The material being processed below this limit will present internal stresses which subsequently cause distortions, loss of gloss, cracking or other physical changes in the finished product.

Forming normal temperature

It is the temperature at which the sheet must be formed in a normal operation. This temperature must be reached throughout the sheet. Low depth thermoformed products using air or vacuum will allow handling slightly lower temperatures and results in shorter cycles; but, on the other hand, high temperatures are required to for deep formed products or pre-stretching operations, details or intricate radio.

Lower limit of operation

It is the temperature at which the thermoplastic sheet begins to degrade, it also becomes too fluid and cannot be manipulated. These temperatures may be exceeded, but only with modified formulations that improve the physical properties of the sheet. Injection and extrusion molding in fact uses much higher temperatures, but only for very short periods of time.

General recommendations

a) The characteristics of the finished product will be determined by the type of thermoforming technique applied.

b) The material must be heated uniformly to the tempering and forming point, before it cools below its molding temperature.

c) The acrylic should be slowly and uniformly cooled while in the mold.

d) The formed piece must be cooled before applying any finish, such as spray painting or screen printing.

e) The design of the piece should consider a 2% shrinkage in both directions and a 4% increase in thickness, as well as a 0.6% shrinkage upon cooling.

Forming temperatures and cycles

As already mentioned earlier, one of the most important steps in the thermoforming process is determining the correct temperature in the material. In acrylic, proper selection of the tempering temperature or normal forming temperature will prevent that:

At low temperatures:

Internal stresses are concentrated in the thermoformed piece that subsequently, with sudden changes in the environment temperature are revealed in the form of fissures or cracking.

At high temperatures:

Bubbles and mold marks occur in the piece due to excessive heating.

Table No. 9 defines the temperature ranges for the general use Plastiglas acrylic sheet and Sensacryl FPMR deep molding sheet.

Table No.9

TYPE OF MATERIAL	TEMPERATURE RANGE	
	LOWER LIMIT (°C)	UPPER LIMIT (°C)
PLASTIGLAS acrylic sheet (General purpose)	160	180
Sensacryl acrylic sheet (Deep molding)	180	200

In Mexico, due to the high cost of electricity, it is more common to use a convection oven with forced air circulation by means of gas for which a practical formula is useful to determine the permanence time of an acrylic sheet, taking into account the previously adjusted tempering temperature range.

Formula: 2.1 x E (mm) = **T** (minutes)
Where: 2.1 =Factor, E =Material thickness in millimeters, **T** =Time in minutes

This formula applies to thin Plastiglas sheets (1 to 6 mm). For greater thicknesses it is necessary to change the factor, as follows:

Formula: 3 x E (mm) = **T** (minutes)

And as mentioned above, there are variables that can modify these formulas, such as room temperature where the oven is located, the time of year (especially in extreme climates), the fluctuation in the thickness of the material and equipment conditions among others.

Forming temperatures

All thermoplastic materials have a specific process temperature. These ranges apply regardless of how the material will be processed. Below are listed the most commonly used materials compared with acrylic:

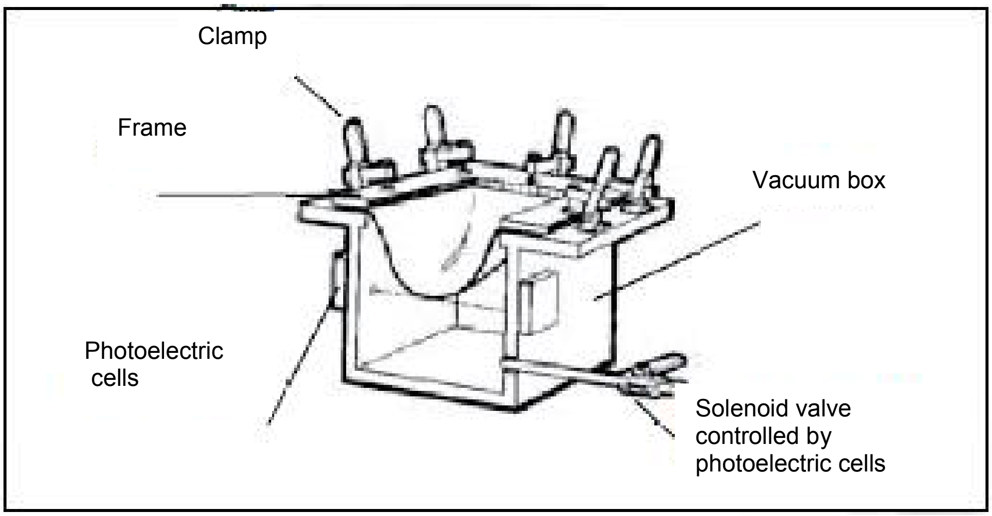
Table No. 10 Forming temperature ranges

MATERIAL	SHEET TEMP. (°C)	LOWER LIMIT (°C)	NORMAL (°C)	UPPER LIMIT (°C)	DEMOLDING TEMP. (°C)	MOLD TEMP. (°C)	MECH. AID TEMP. (°C)
PLASTIGLAS	160-180	160	170	180	120	65-75	
Acrylic Sensacryl	180-200	180	190	200	130	70-80	
FP Acrylic ABS	125-180	125	165	180	85	70-85	100
Polycarbonate	200-250	200	235	250	140	90-120	140
Polyethylene AD	160-220	160	190	220	85	90-100	170

Determination of correct temperature in the material

Another important factor in the thermoforming process is determining the correct temperature in the plastic material. It should be considered that, regardless of the means of heat transfer, the sheet should be heated to the recommended temperature range (tempering range), plus the sheet must have uniform heating.

In practice, it is not easy to precisely establish the temperature of the sheet, even with contact thermometers; therefore, the determination is based on the behavior of the sheet. The gradual change in which the sheet yields during the heating process (tempering point), is one of the signs used to establish a suitable temperature. Some controls have been developed for thermoforming equipment by infrared radiation, wherein the sheet is held horizontally, and that use the "sagging" or "bulging" phenomenon and control the time and/or heating temperature using photoelectric cells.



However, this criterion cannot be applied indiscriminately to all plastics, as some materials may overheat before starting to sag or bulge. Even when a temperature range is set, the expected sheet temperature result may not be obtained; this can be caused by:

a) Fluctuations in material thickness.

b) Changes in temperature of the equipment and/or environment.

c) Minimum line voltage fluctuations (for infrared heating equipment).

d) Probably the regulator for the gas equipment with forced air circulation is not adequate, there is not enough gas pressure; it is not the right burner or the latter is covered with soot, etc.

There are cone-shaped pyrometers, tablets for heating by infrared radiation or gas (hot air), which can provide a more accurate measurement. Although possibly the best way to measure the sheet temperature is by an infrared gun, which measures it by area; even though this equipment is expensive, it is the only one that accurately and reliably measures the sheet temperature.

Thermoforming equipment

Originally, convection ovens were the first devices for heating plastic sheets for thermoforming and even today this preference for heating sheets of different thicknesses and a uniform temperature distribution is maintained.

Heating can be supplied by means of gas or electrical resistor units. Forced air recirculation and baffles to achieve air circulation from 4,500 to 6,100 cm3/min (150 to 200 ft3/min), are crucial for obtaining a homogeneous temperature. The oven temperature must adjust to the plastic forming temperature.

Heating by infrared radiation, compared with oil immersion or contact heating (the last two very limited in practices), is extremely fast. For example, the heating time by infrared radiation in a sheet of 3.0 mm. can be achieved in one minute at 10 watts/in2 approximately.

Because the infrared radiation heating time is extremely short, the heat energy absorbed by the sheet can cause overheating that will even impact on the material degradation (bubbles or burns) if left unchecked. It is important to consider that in long runs, it is necessary to gradually decrease the oven temperature.

In some cases, where the product has intricate or very deep sections, the risk is run of a considerable thinning of the material thickness; here the use of screens is required (they can be made with perforated or unfolded sheet metal) to prevent overheating.

Infrared radiation elements can be acquired in a very wide range of designs, in order of importance they are:

1. Tungsten filaments in quartz tubes or lamps (temperature of 2,200° C).
2. Nichrome spring-type resistor in refractory ceramic bases.
3. Nichrome resistors protected by tubular sheet or stainless steel.

There are manufacturers of infrared radiation thermoforming machines in a variety of sizes, capacity, degree of automation and versatility.

The specifications for the acquisition of a thermoforming machine vary depending on the finished product to be obtained and therefore it is necessary to consider:

Voltage, wattage, amperage, forming useful area, number of heaters (lower and upper), controls for temperature regulation by areas, degree of automation, capacity to accept mechanical aids, sheet holding type (mechanical clamps, tires, etc.), fans for cooling of the piece, overall dimensions, production capacity, cost-benefit.

Gas ovens with forced air circulation

This provides uniform heat and constant temperature with the minimal risk of overheating the acrylic sheet. Electric fans should be used to force the hot air to be circulated over the acrylic sheet at a speed of 4,500 to 6,100 cm3/min., and devices to distribute the air to all areas of the oven.

Gas ovens require heat exchangers to prevent the accumulation of soot caused by the gas flow, as well as controls to interrupt the passage of gas if necessary.

Electric ovens can be heated using resistor groups of 1000 watts. In the case of using a oven with a capacity of 10m3, approximately 25,000 watts of power will be consumed and half of it will be used to compensate heat loss through leakage, isolation transmission and by the use of doors. It is suggested that the insulation thickness is at least 2" and that the oven doors are as narrow as possible, to minimize loss of temperature.

Automatic devices should be used for strict temperature control between 0° C and 250° C. For a more uniform heating of the sheet it is important to hang it vertically and this can be achieved by having a system that holds the material along its length with clasps or channels with springs and that these move by means of runners that slide on closet-type rails.

Basic criteria for the construction of a gas oven with forced air circulation

The best suggestion that can be made regarding this is to request any manufacturer of industrial ovens for the construction of one with the features already mentioned above, since the construction especially of the heating system and startup is very risky for anyone with superficial knowledge of the subject.

This type of equipment must be approved by specialists in gas installations and must be registered with the appropriate authorities.

It is also important to note that the information provided here is only depending on the metal structure and fastening system for the acrylic sheet. The oven construction can be divided into the following subsystems:

a) Structure

b) Fastening of acrylic sheet

c) Electrical System

d) Gas installation

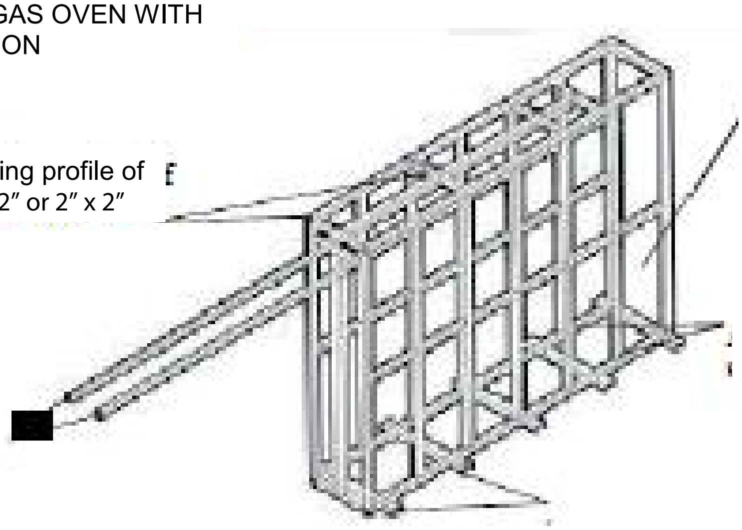
e) Controls

Recommendations for the manufacture of the oven

Manufacture of the structure with commercial iron tubing of 1 1/2" x 1 1/2" or 2" x 2".

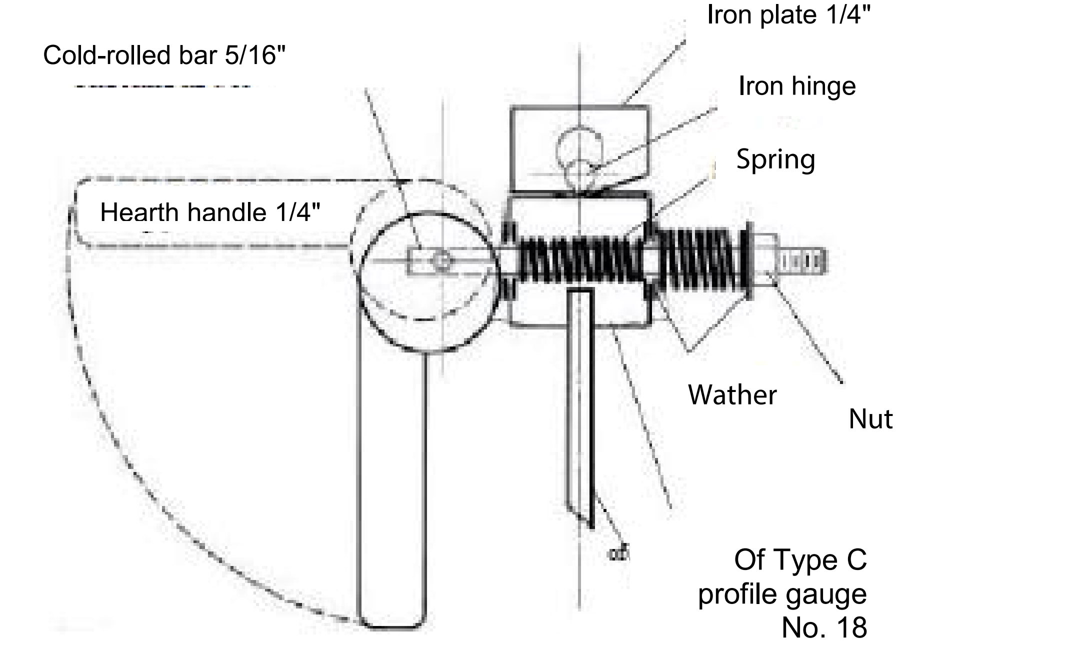
a) Cut the tubing to size, as per the design adapted to needs.
b) Weld the side walls.
c) Weld the top, bottom and rear wall; to join them with the side walls and thus have the complete structure.
d) Line the inside of the structure with black sheet gauge 18, riveted with "pop" or dotted with electric welding.
e) Cover the gaps (thickness of tubing) with rigid fiberglass plate for thermal insulation key RF-4100, or similar.
f) Line the inside of the structure with black sheet gauge 18 and rivet with "pop" or weld.
g) Making the doors of PTR tubing structure 1" X 1" and make in the same way as the other walls; these should be shorter so the guides can pass.
h) Place the doors on the oven by means of hinges.
i) Place closet-type guides on the oven, these must be twice as long as the oven. They will be fixed by screws on the upper wall of the oven. Once fixed to the oven and already in the place where it will be fixed, the guidelines will be fixed by means of supports to the roof or structure of the premises.

STRUCTURE OF GAS OVEN WITH
AIR RECIRCULATION

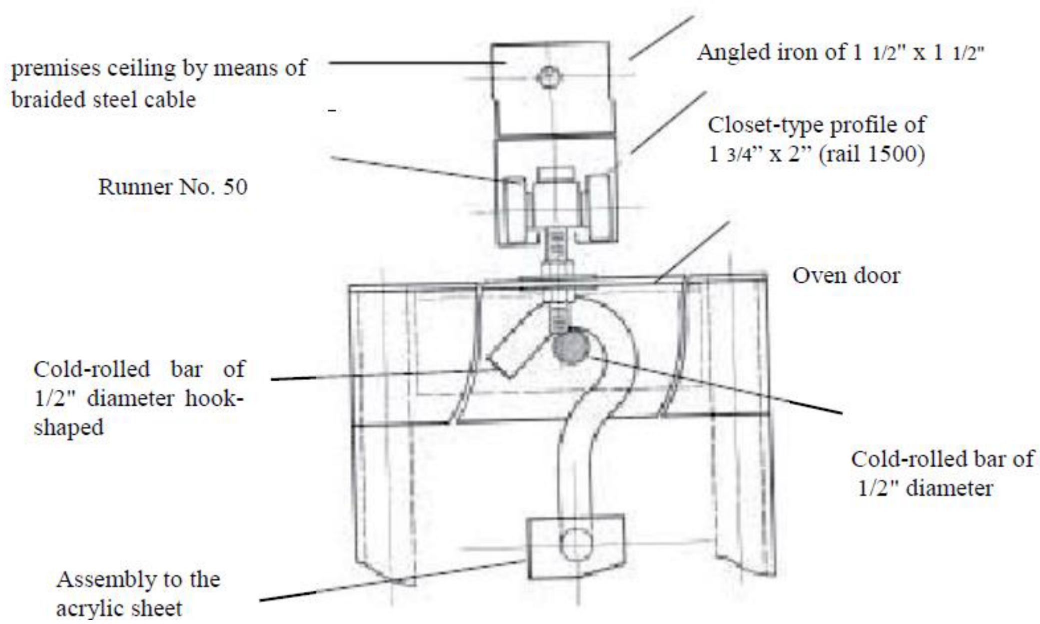


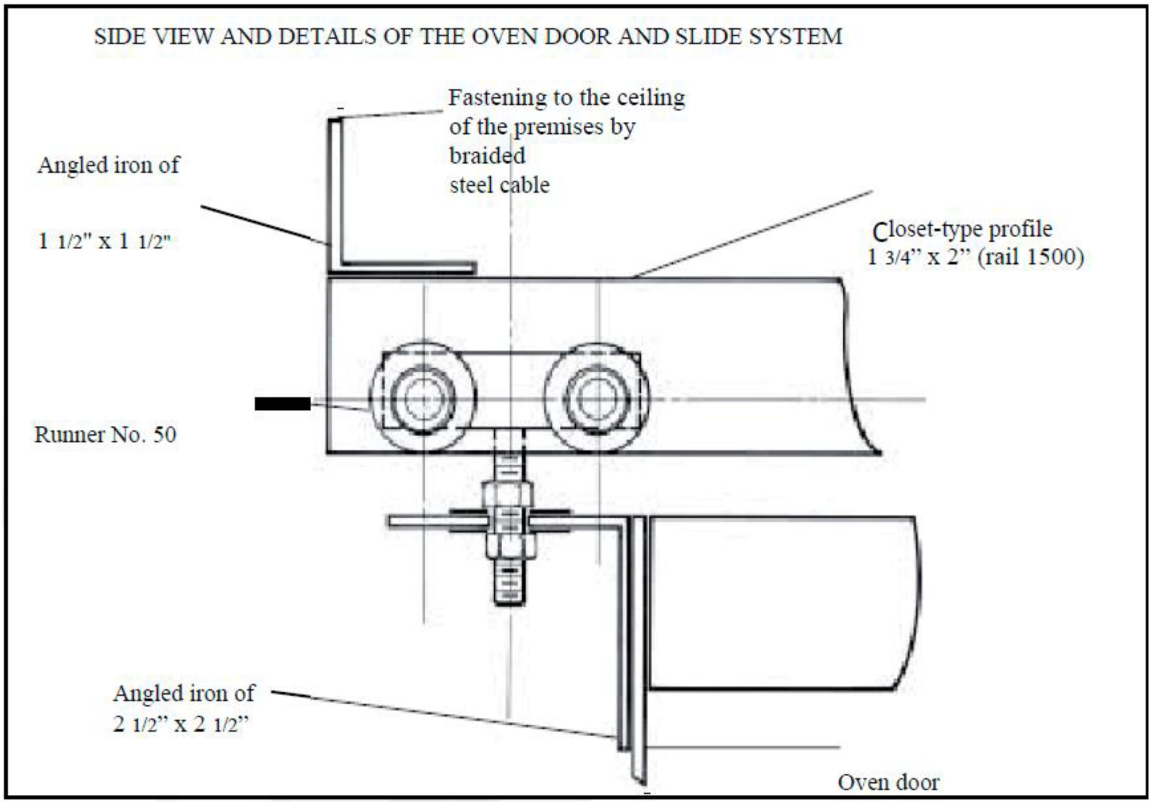
1/4" "U" plate supports

ACRYLIC SHEET FASTENING SYTEM



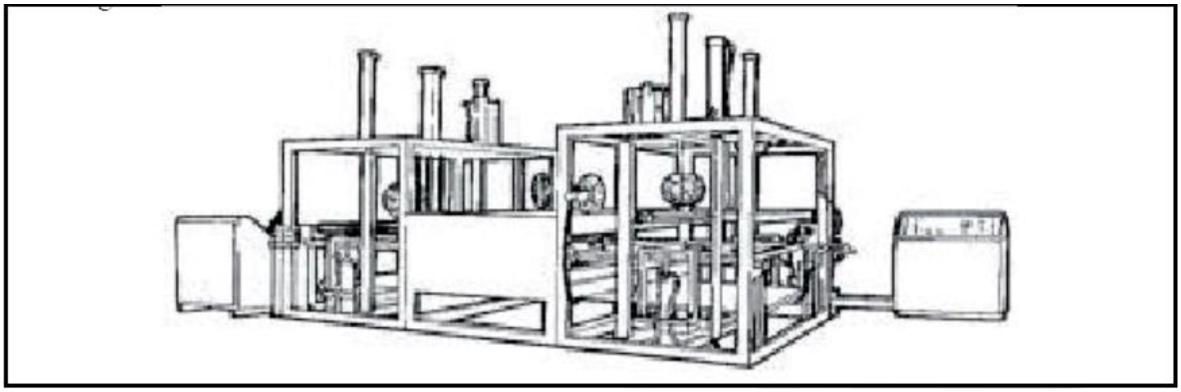
FRONTAL VIEW AND DETAILS OF THE OVEN DOOR AND SLIDING SYSTEM Fastening to the





Infrared heating oven

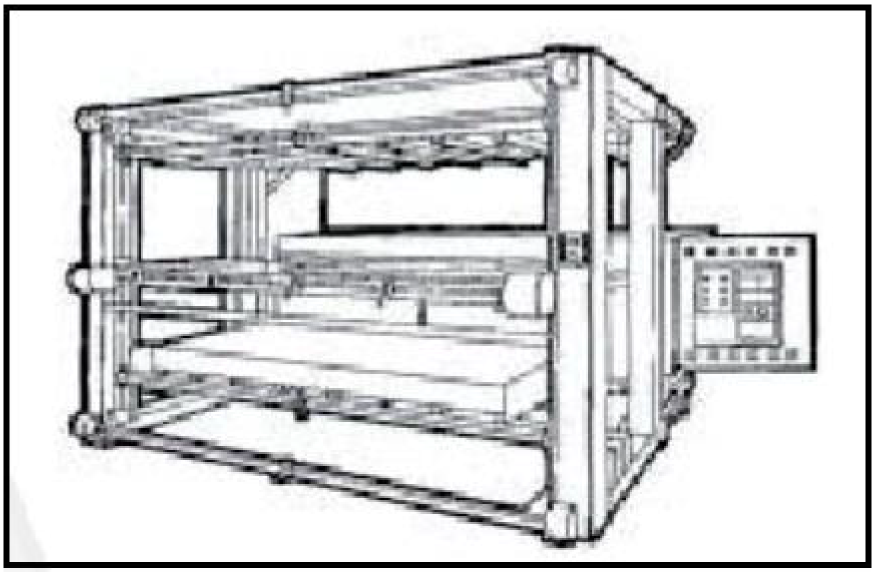
It is commonly used in automatic thermoforming machines, heating the sheet by means of radiation at a speed of 3 to 10 times faster than in an oven with forced air circulation, thus providing very short heating cycles, it should be emphasized that the temperature-time ratio becomes critical and it is more difficult to obtain a uniform heating of the material.



Infrared energy is absorbed by the exposed acrylic surface, quickly reaching temperatures above 180° C to then be transmitted to the center of the material by temperature conduction.

Heating by infrared radiation can be obtained using metal tubing elements, spiral (spring type) electrical resistors, or grouping infrared lamps. To achieve a more uniform heating distribution, a net or wire mesh may be mounted between the heating elements and the material that functions as temperature diffuser. It is also appropriate to place the infrared heating plate about 30 cm. from the material and the lower plate at about 50 cm.

To regulate the power input to the equipment, it is recommended to use devices such as variable transformers or percentage meters that help to control the temperature. It is also advisable to make a plan of power loads, high capacity equipment, an electricity substation will even be needed.

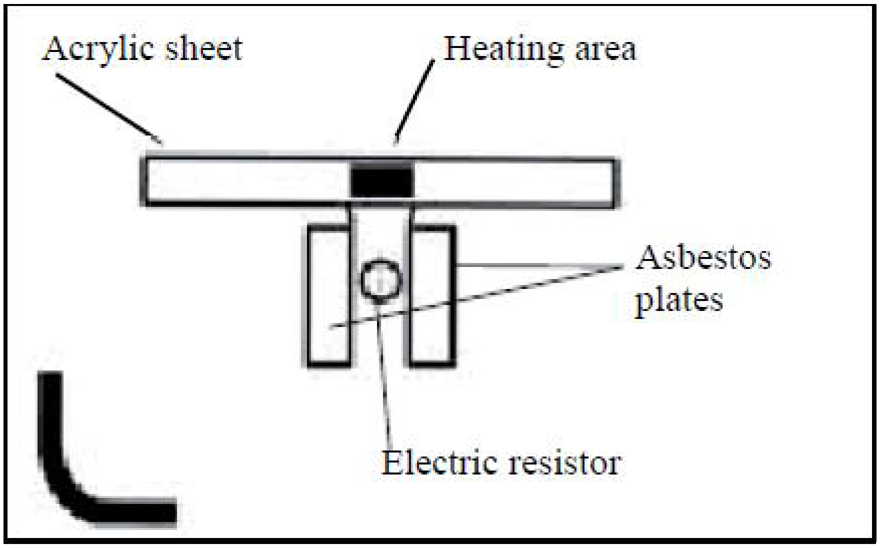


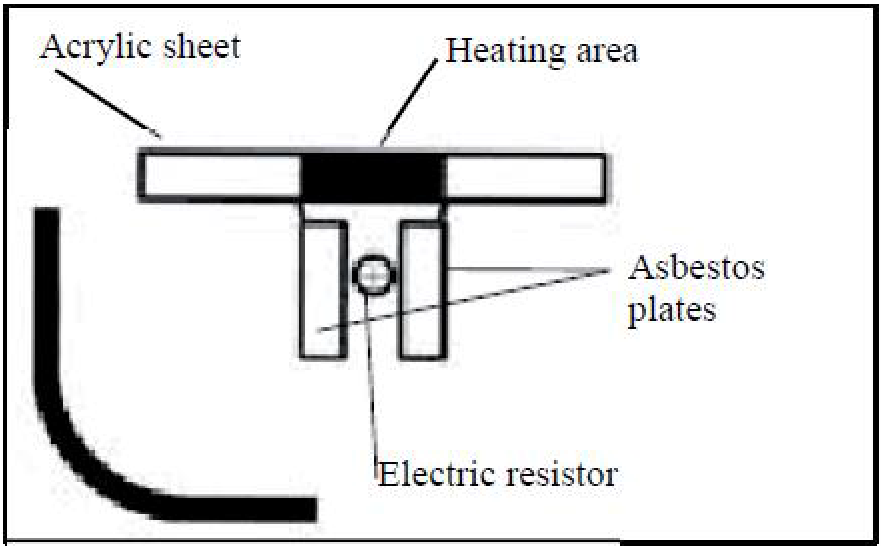
Electric linear heating resistors

An electrical resistor can be used only to form folds in a straight line; for this it is necessary to have a spring-type electrical resistor (No. 20) or the reinforced type (about 1 Kw. X 1.2 Mts.).

Linear resistors are made of wire encased in Pyrex ceramic tubes. The material must not come into contact with the tube to avoid marks on the surface. A distance of 6 mm is recommended from the tube to the material to achieve uniform heating in thin material.

When material over 3.0 mm. thick is to be heated by this procedure, it is advisable to place resistors on both sides thereof. In the illustration below, it is exemplified how a folder with asbestos plates at the beginning of production will provide a suitable fold, but as production progresses the heating area is amplified resulting in a larger radius fold, this is why a recirculating water resistor is much more convenient for the folding of acrylic.





Basic criteria for the construction of a linear heating electrical resistor

The two-dimensional thermoforming or linear folding can be performed with a spring-type resistor or tubing resistor. The construction of these devices shall be conditioned on the thickness, type of fold and volume to produce. Generally, a resistor of 1.2 m. long is the most common, although one of 60 cm. is also acceptable, specifications for this resistor will be 1 Kw. for every 1.2 meters and with a rule of three it is possible to deduce consumption either for a resistor of greater or lesser length.

The most common acrylic folders are constructed with asbestos plates as side walls, they are appropriate provided a high volume is not required to be produced, because asbestos plates, when subjected to the same infrared radiation, will tend to heat up and thus the heating area will increase, with the consequent deviation from standards of production of a piece. That is, at the start of production, there will be small radii and, as production progresses, the heating area will be wider, causing a larger radius.

An electrical resistance folder with recirculating water will be more effective and pieces with better folding quality will be produced. This equipment requires tubing profiles that enable recirculation of water, which will keep the surface cold and only allow a uniform heating zone. Below the materials required for the construction of these folders are listed.

The incorporation of a rheostat to control the temperature intensity of the acrylic sheet is important, as it will provide a suitable production rate and, obviously, a reduction in the cost of electricity.

FOLDER WITH ASBESTOS PLATES	FOLDER WITH WATER RECIRCULATION
• Spring-type, tubular or nichrome tape resistor.	• Spring-type, tubular or nichrome tape resistor.
• No.16 or 18 cable with fiberglass insulation.	• No.16 or 18 cable with fiberglass insulation.
• Terminals.	• Terminals.
• Heavy duty cable 2 x 14.	• Heavy duty cable 2 x 14.
• Plug.	• Plug.
• Dimmer 500, 1000, 2000 or 3000 watts.	• Dimmer 500, 1000, 2000 or 3000 watts.
• Asbestos plate 1/8", 3/16" or 1/4".	• Tubular aluminum profile 3/4" x 3/4".
	• Hose, 6 meters.
	• Clamps.
	• Storage tank 10 to 20 lts. approx.
	• Garden water pump.

Auxiliary equipment: vacuum, air pressure and mechanical forces

The thermoforming process consists of heating and softening a sheet of any thermoplastic material and subjecting it to adopt the configuration of the corresponding mold to thus obtain a nearly finished product with a particular morphology.

Sometimes it will be necessary to use an external force to shape a flat sheet in a different shape and force it to copy the outline and details of the mold. The level of energy or expense of this force should be adjustable so that the plastic sheet can be easily forced to adopt another shape.

The forming forces more commonly used in the thermoforming process are: vacuum or air pressure, mechanical forces and the combination of these three. Selecting a forming force in the forming process is generally subject to the product size, volume to produce and speed of forming cycles.

In addition to these criteria, the factors mentioned below should also be considered, as any of these can make a difference in the selection of the forming force:

a) The intrinsic limitations of each thermoplastic material.

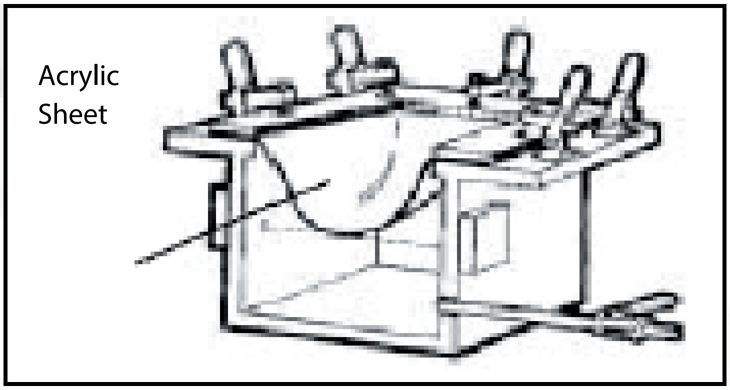
b) Mold construction and material.

c) Thermoforming equipment available.

Vacuum forming

The oldest method to form a sheet of plastic on a utilitarian piece is vacuum forming. The original description for the thermoforming process was precisely that of "vacuum forming".

The basic principle of the vacuum forming process is to have a softened thermoplastic sheet in a perfectly sealed mold and where the trapped air will be evacuated by vacuum force or suction. As air is evacuated from the mold, it causes a negative pressure on the surface of the sheet and therefore, natural atmospheric pressure will yield to force the heated sheet to fill the empty spaces, as can be seen in this illustration.



Vacuum Equipment

There are a variety of vacuum pumps: reciprocating piston, diaphragm, vane, eccentric rotor, etc. All these provide a good vacuum, but are not able to evacuate a large volume of air at high speed; therefore it is necessary to connect a storage tank that serves as a "vacuum accumulator". Moreover, there are compressors that can displace a large volume of air but are limited in vacuum strength.

A suitable vacuum system requires a pump capable of moving from 710 to 735 mm. Hg. (28 to 29 Inch. Hg or from 0.5 to 1 psi absolute) in the storage tank prior to forming cycle.

The line, duct or pipe between the storage tank and the mold must be as short as possible and with a minimum of elbows. It is important to eliminate air leaks damaged pipe, perforated hoses, couples or loose nipples, as well as unnecessary valves. It is recommended to use quick-acting or ball valves. Vacuum pumps are available in one or two steps. A two-step vacuum pump can evacuate pressures below 10 psi; the ability to move or evacuate of a one-step pump is reduced by half. Table No.11 shows the typical capacities for vacuum pumps.

Table No. 11 Typical specifications for vacuum pumps

SPECIFICATIONS			THEORETICAL VACUUM CAPACITY				
No. OF CYLINDERS	DIAMETER (mm)	STROKE (mm)	ONE-STEP (M_3/MIN)	TWO-STEP (M_3/MIN)	SPEED (RPM)	REQUIRED POWER (Kw)	PIPELINE OUTLET DIAM.
1	76	70	0,255	----	800	0.56	19
2	76	70	0,510	0,255	800	0.74	25
2	102	70	0,906	0,453	800	1.48	32
2	127	80	1.70	0,850	750	2.2/3.7	38
2	140	102	2.80	1.40	900	3.7	52
3	140	102	4.22	2.80	900	5.6	52

Vacuum tanks

Except for some vacuum equipment, most are supplied with a storage tank. Considering that the working pressure is about 10 psi (about 21 in. Hg / 530 mm. Hg) vacuum, then the volume of the storage tank should be 2.5 times the volume comprised between the mold, the vacuum box and the piping. Doubling the volume of the storage tank (and other similar conditions) will enable increasing the pressure by 15% (11.5 psi), as established; the theoretical limit for the vacuum forming process is only 14.7 psi.

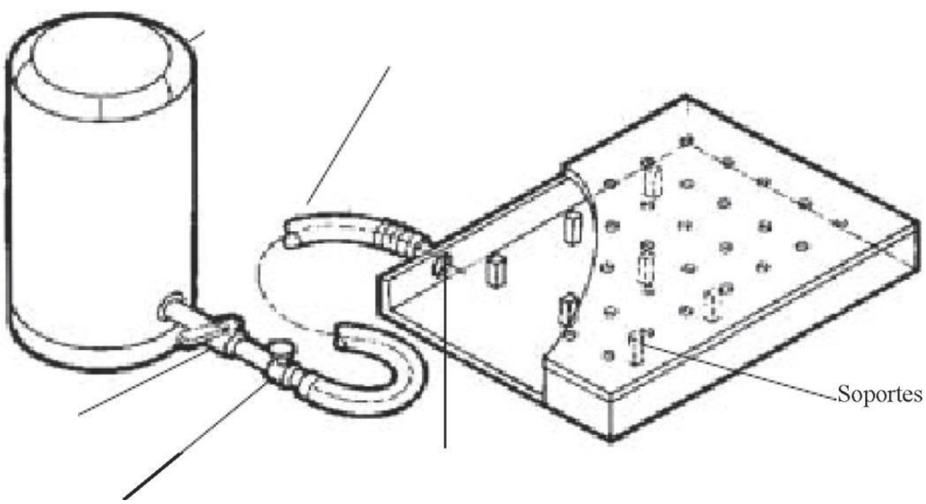
In many cases a rapid vacuum displacement is of great importance. This can only be done by locating the vacuum tank as close to the mold and reducing friction on the pipe as much as possible, this can be achieved by means of:

a) A larger diameter of the pipe.

b) Having generous curves in the pipe, avoiding 90° elbows.

c) Changes in the cross section of the pipe (diameter changes).

Many devices that are offered on the market violate these rules. Generally, a diameter of 1 inch is required in the pipe to move 1 ft3 of air, for large pieces a diameter of 2 or 3 in. will be suitable. It is also advisable to have a flexible internally reinforced plastic hose with a wire or other material core that does not allow it to collapse; it is convenient to connect it between the mold and the pipe, as shown in the following illustration:



Application of vacuum forces

Generally, pumps operate continuously to maintain the vacuum in the storage tank, with a variation in the vacuum gauge reading with each cycle. The vacuum generated in the formed part must be maintained sufficient time to cool down and resist the internal force of the material that will tend to retain the original shape, causing ripples and buckling.

As a rule, the faster the vacuum is, the appearance of the piece will be better, occasionally a slow forming speed is desirable for very deep pieces or intricate sections. When a female mold is very deep and where the configuration becomes a problem, a slow vacuum can give the plastic more time to shrink in the cross section, thus a poor configuration can be eliminated.

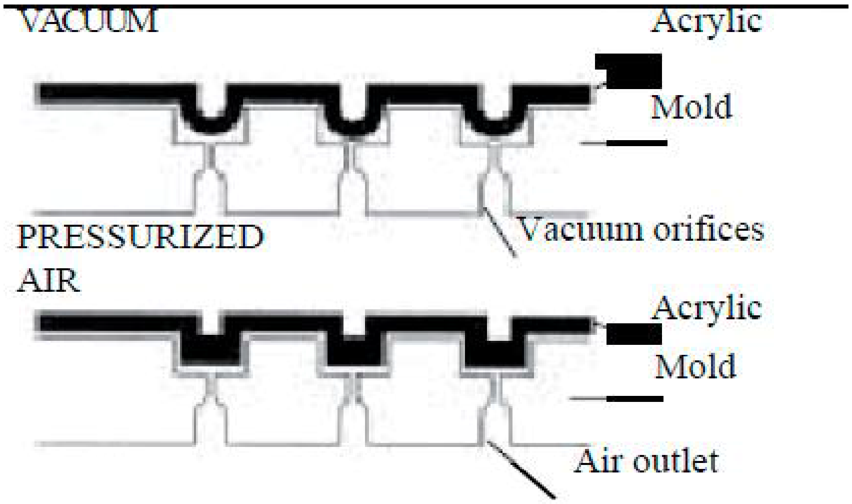
Forming with Pressurized air

In operations where the vacuum force is replaced by pressurized air, it must be considered that it is more difficult to obtain a satisfactory sealing of the mold. The forming force can easily be multiplied up to 10 times if the air pressure is at 100 psi. However molds can rarely resist such pressure.

For air pressure forming it is necessary to take all possible precautions. A regular size mold eventually requires a closing pressure of several tons, which a common press (type "C") naturally cannot resist. It is desirable to then use a series of "clamps" or quick action fasteners that are very suitable for this use. A poor construction mold with the pressure that is exerted may act as a bomb and explode. A machined aluminum or metal mold is a good choice; molds made of wood or resins should not be used unless they are reinforced with metal.

Pressure forming equipment must be stronger than the vacuum forming equipment. It must also have a similar tank for the compressor. The pipeline does not require strict specifications as the pressure drop is negligible. If in a pipeline the pressure drop is 5 psi, the pressure loss in the vacuum system will be 10 psi, 50% of the pressure, but if the pressure system is 100 psi, then it will be 5%. It is also advisable to install a pressure reduction valve and a manometer, as well as a baffle or filter at the inlet of the mold, so that the cool air is never in direct contact with the hot sheet. Sometimes it will be necessary to incorporate heaters in the air system that will help in large blows, that will remain hot until the part is formed in the mold.

If possible, it is also necessary to have filters to remove water that tends to condense in the system and can eventually corrode the equipment; including that combined with particles they may clog air vents in the molds. Regular maintenance of the equipment is essential.



The mold, when required, must have holes for ventilation of trapped air and thus prevent wrinkles or deficient formings.

Forming with air pressure has become popular especially in small pieces. The advantages of this method are: improved dimensional tolerances, forming speed can be considerably increased, as well as improved definition of fine details.

Mechanical forming

The thermoforming process is not limited to pneumatic techniques; there are several mechanical forces that can be applied. The simplest form of mechanical forming is used in two-dimensional forming, in this case the heated sheet is placed on the surface of a curved mold that usually has a smooth surface and gravity is enough to curve the sheet; it is necessary that the edge of the sheet is fastened to keep it in position until the part cools. This is the case of the manufacture of the arc tube where the ends are firmly fastened and there is no variation in thickness.

Male-female mold mechanical forming

Male-female molding is used among other things, for forming of complicated pieces. In this molding technique a heated sheet is formed between two molds opposed to each other but with similar contours (male-female). When the molds are joined together, the edges will force the sheet to take an identical form between the space created between the two molds. Any bulge on the male mold will mechanically force the plastic on the counterpart (female mold). For medium or high production mechanical equipment for closing the molds are used; in other cases the movement is produced by servomotors. If both molds have a controlled temperature, a reduction can be achieved in the cooling time.

There are three basic criteria for a good performance in thermoforming using this technique:

The first is that the force applied, whatever the source (pneumatic, hydraulic or mechanical) must be strong enough to induce the plastic to deform, naturally a very large surface or a very intricate mold require greater pressure force.
The second refers to adequate ventilation of trapped air. The pressure exerted between the molds causes air to be trapped between them the sheet that must be removed for proper configuration of the piece. This can be accomplished by drilling one or both molds in the areas where the abnormality is detected.
The third is related to the maximum depth of stretch, which results from the forces employed in the process. It is easily understandable that a máximum stretch is only

successful when the mold has exit angles greater than 5° and very large and smoothed curvature radii, angles very close to 90° may actually decrease the stretch and even tear the plastic material.
This sophisticated thermoforming method should not be used in all of the mold configuration, its use being limited to only some parts of the mold.

Combined techniques

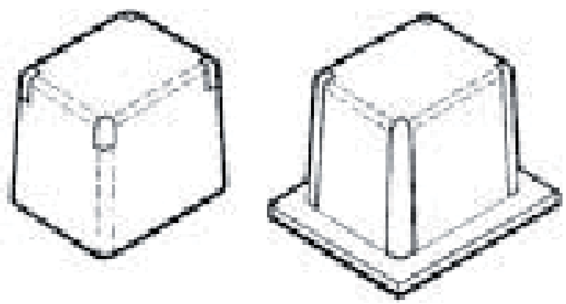
Male-female mold mechanical forming depends not only on the forces that are used; usually this kind of forming can be combined with vacuum, compressed air or both at the same time. Consequently, the male-female mold does not have to match exactly; the male mold may be relatively smaller in dimensions and substantially different in shape to the female mold.
When done in this manner they can act as "pushers" in the plastic sheet. Such assistance is called mechanical aid, because the softened material is pressed into the female mold. The purpose of this aid is to pre-stretch the material so that the final form is achieved in combination with vacuum and/or air pressure.
Using mechanical aids in the process has the advantage of a better distribution of material thickness, over any other process. With the combination of these techniques many variations in the process can be obtained. Such variants may be changes in vacuum pressure, the application time of vacuum or pressure, the closing speed of the molds, or the forming cycles.

Design of mechanical aids

Usually mechanical aids are made of wood. Hard or tropical woods are the most used in manufacturing aids. In some cases it is possible to incorporate inserts of other plastic materials such as nylon, rigid polyurethane, acrylamides, and aluminum or steel which are easily machinable.

In cases where the volume to produce so requires, it is possible to incorporate a cooling and/or heating system. The decision to heat and/or cool the aid must be taken into account from the design as later it will be very difficult if not impossible to try to condition a heating element, which is why the machining required for the incorporation of the system must be made.
When the aid is very cold, the sheet will surely cool over it. The cooling usually occurs between points comprising the aid and the sheet and between the sheet and the mold. In extreme cases, the sheet may shrink over the aid during forming.
If mechanical aid is very hot, the sheet will slide over the edge of the aid, in this case the aid will simply press on the sheet. Stretching may occur in the sheet between the area comprising the aid and the edge of the mold.

The shape of the aid will have a decisive influence on the wall or thickness of the final piece. In the illustration below three different types of aid can be seen.



Flat surface type aid and blunt edges

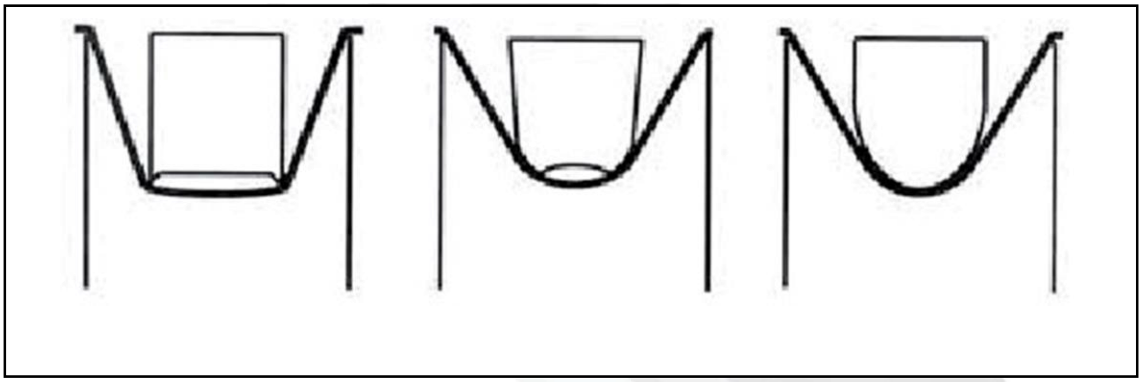
This allows the sheet to stretch between the aid and the edge of the mold and meanwhile the sheet will present cooling in the part in contact with the tip or edge of the aid. A piece formed by this method will have a thick bottom and thin walls.

Tin can type aid

In this second alternative, the sheet enters into contact and rapidly cools only in the small perimeter area of theaid. The stretching is similar to the flat aid type, but the central area in the aid allows further stretching.

Spherical type aid

On the other hand, in this type only a small area enters into contact with the aid. It may happen that there is significant stretching in this case as the aid advances, therefore the perimetral area between the edge and the aid will decrease.



Flat surface type aid and blunt edges

Tin can type aid

Spherical type aid

Thermoforming molds

Choice of thermoforming technique

One of the most important aspects to be taken into account for the thermoforming of pieces is the thermoforming technique to be used, because if for product characteristics an improper technique is used, it is likely that problems will arise before obtaining a piece with the specifications determined from the start and in many cases there may be a failure with the consequent loss of time, money and resources. Therefore, prior to making a mold we must consider the following:

1. The shape and dimensions of the piece.

2. The desired appearance.

3. The thermoforming technique.

Based on these factors, possible defects of the pieces can be planned and anticipated. This chapter analyzes all the variables that occur when it is required to manufacture a thermoforming mold.

Criteria for the design of thermoformed products

It should be mentioned that although the thermoforming technique is versatile and flexible, it differs in appearance and features compared to the products manufactured by injection molding. In the following comparison chart their basic differences may be analyzed. In conclusion, for the design of thermoformed pieces it is necessary to establish the following criteria:

1. Thinning in the material thickness should be considered, this will depend above all on the shape, size and technique used (Chapter 8). In general terms it can be considered that the thinning in the thickness of the material is directly proportional to the height of the piece.

2. A molding exit angle of between 3° and 5° must be considered.

3. A shrinkage of the piece of 0.6% on cooling should be considered.

4. Usually, the surface of the thermoformed piece will be smooth, although there may be some textures.

5. In the design of the piece it is appropriate to include large radii; it is possible to obtain edges, but they may cause tears in the material.

Table No.12 Basic Differences between the Injection and Thermoforming Process

VARIABLES	PROCESS	
	INJECTION	THERMOFORMING
Thickness.	Constant	Variable.
Exit angles of the mold.	0.5° to 1°	3°- 5°.
Molding temperature.	200° C - 240° C.	160° C - 180°C
Dimensional tolerance.	Excellent	Relatively good, not for precision pieces.
Inserts	The insertion of elements in other materials is possible.	The mold surface can be prepared to support inserts.
Surface finish	Smooth surfaces or surfaces with any texture can be achieved.	Only smooth surfaces and some not very deep textures.
Production	High production, hundreds or thousands of pieces daily.	Half production several dozen pieces daily
Mold	Of steel with high cost alloys or treatments, complex design, male female mold.	Variety of materials, relatively low cost, simple design, male or female mold can be used.
Possibility of ribs, holes of all kinds, threads, etc.	Yes.	No.
Scrap.	Very little.	Depends on the shape of the piece, approximately 25% waste
Waste material.	It is recoverable.	and it is recoverable.
Radii	It is necessary to round the edges, approximately 1.5 of the material thickness.	Comparatively larger radii are required, from 1 cm. to 5 cm. depending on the shape and depth.
Development time of the piece (from the design, mold and testing).	From 3 to 6 months.	1 month maximum.
Subsequent treatment and finishes.	Any treatment or finish can be applied (painted, hot-stamping, metallic, screen printing, etc.).	Any treatment or finish can be applied (painted, hot-stamping, metallic, screen printing, etc.).

The criteria presented below are the key success factors for the production of thermoformed pieces. These are the core point for any development that is intended to be manufactured, but is also of vital importance to deepen these concepts, considerations in the design of molds will be discussed later in detail. Therefore these basic criteria and considerations in mold design are the basic parameters for the construction of thermoforming molds, regardless of the complexity that they may have. It must be mentioned also that evaluation of the following items is required in the construction of molds:

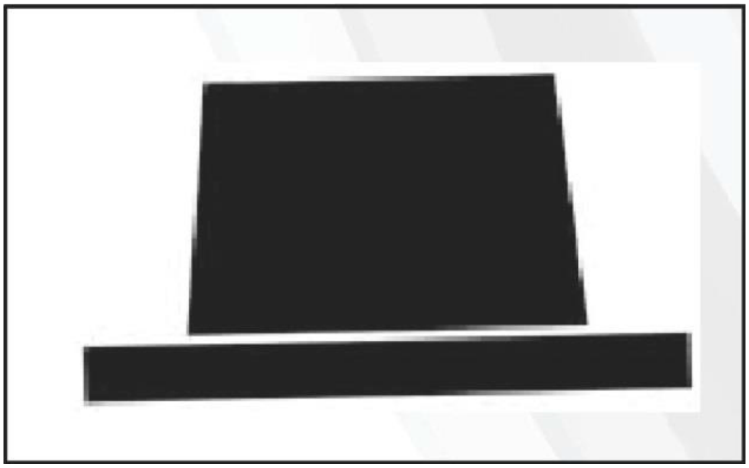
1. Shape and dimensions of the piece.

2. Appearance of the piece.

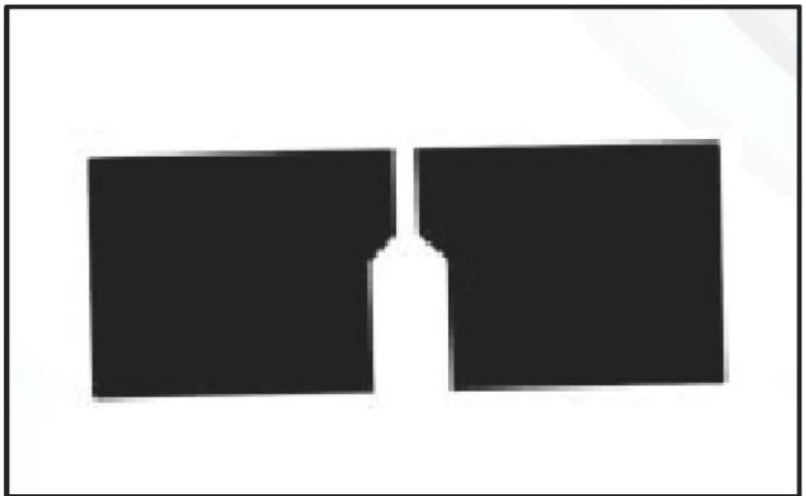
3. Estimated manufacturing volume.

Pondering over these concepts, perhaps the most important is the estimated volume of production, since on this will depend the definition of the type of mold, material, finish, thermoforming technique, etc. The criteria for mold design will be presented below:

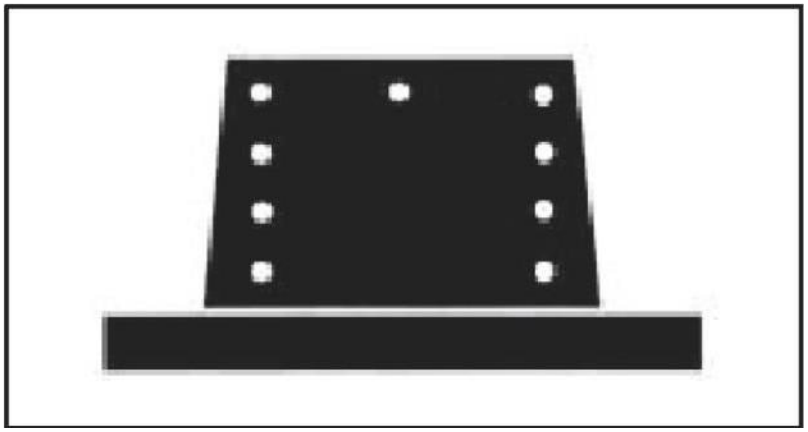
I. A male mold is easier to use, less expensive and is the most suitable for forming deep pieces. A female mold generally should not be used to form parts that require a depth greater than half the width of the piece. The female mold will be used when the finished piece requires that the concave face has no contact with the mold.



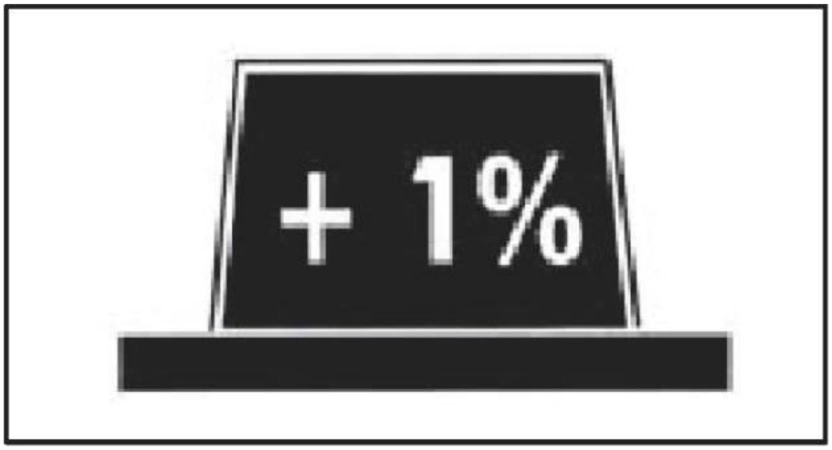
2. The molds must have sufficient vacuum holes so the tempered sheet can conform to the critical parts of the mold, the vacuum holes must be made in the deeper parts and in areas where air can be trapped, they must be sufficiently small not to cause marks (1/32 "to 1/8" diameter). A more effective vacuum can be achieved if the hole is enlarged from the inside.



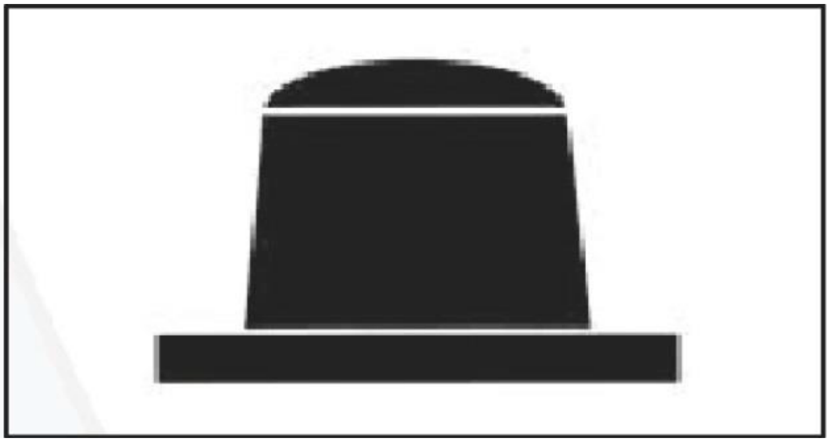
3. Ducts to allow circulation of water or oil through the mold must be provided when its temperature control is required.



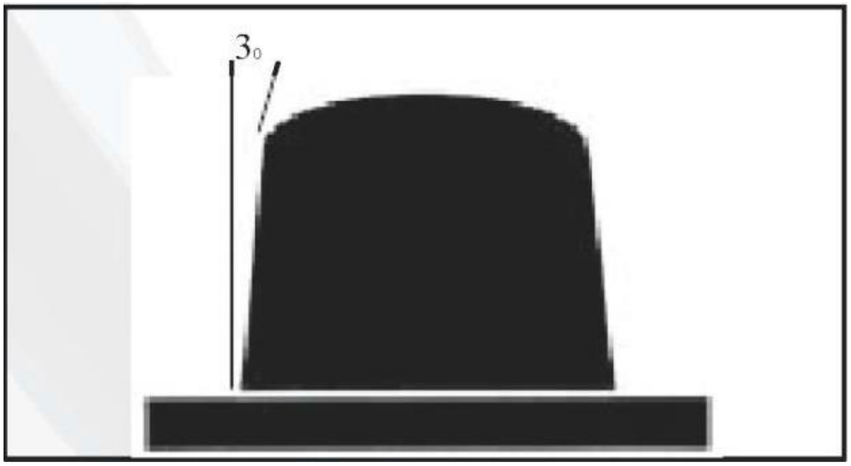
4. When the dimensions of the formed piece are critical, molds must be constructed in larger sizes to compensate for shrinkage of the material. Shrinkage to be expected from the molding temperature to ambient temperature is 1% maximum.



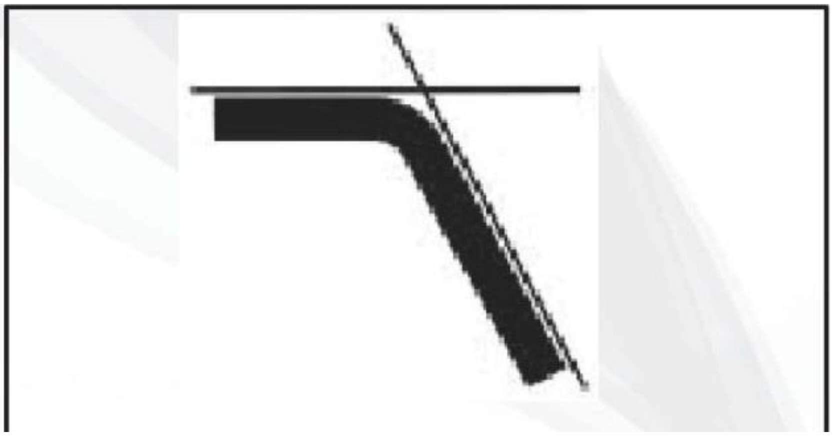
5. A slight curvature of the mold in the flat parts of large areas, will allow flat areas to be obtained when cooling the material.



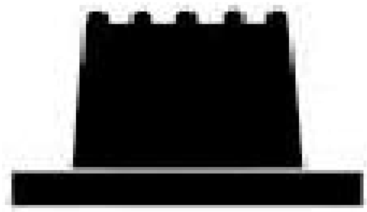
6. Pieces with walls at 90° cannot be obtained, the mold should have an exit angle of at least 3°



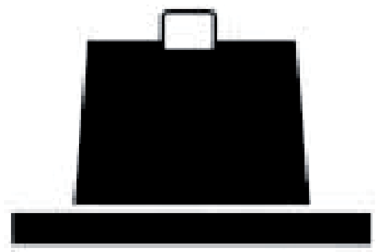
7. It is advisable to round the corners, since vertex forming accumulates internal stresses. The strength of the piece will be greater by designing rounded sides, corners and edges.



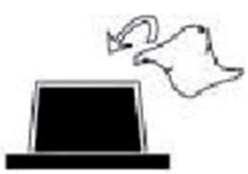
8. Thin or weaker parts can be strengthened with reinforcing ribs. The ribs will also reinforce large size flat areas.



9. If necessary to mold embedding a permanent insert, the difference in the expansion coefficient for different materials must be considered, otherwise it may fail because of a forced insert, due the difference in expansions and contractions of the materials in contact.



10. Mold surfaces may be lined with cotton flannel, felt, velvet, suede or other materials to reduce mold marks. The most common is to use cotton flannel.



One of the great advantages of the thermoforming process is the diversity and types of molds that can be manufactured at a very low cost and relatively short time, having great acceptance in various applications over other processes.

Generally and unlike injection molds, only half of the mold is needed and depends on the product shape, the desired appearance and the technique selected (it can be a male or female mold).

The choice of which is the right one becomes more important when the piece to be thermoformed is deeper. When the pieces are shallow, small profiles or when the thinning of the material thickness is negligible, then the choice will depend on the appearance of the piece. If the detail of the mold is important, then the side of the plastic sheet that touches the mold surface must be the view of the piece.

Sometimes a greater radius or smooth appearance is desirable or if the material sheet has a pleasant surface, then in these cases the side not touching the mold surface will be the view of the piece, in addition to a more closed dimensional control with the mold surface being obtained.

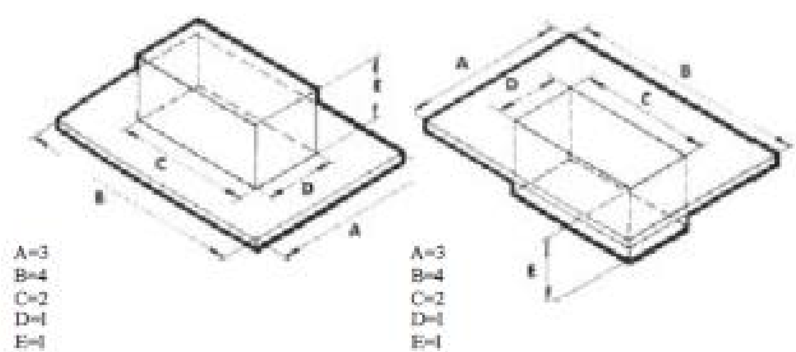
Thinning in the material thickness

Under all thermoforming conditions where the pieces are formed by a sheet of plastic, the surface area will become longer, there will be a stretch and therefore the material thickness will become thinner.

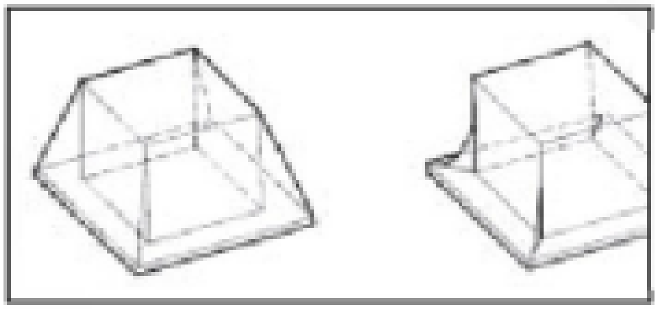
One of the decisive factors for this thinning is the radius, usually defined as the maximum depth or height radius with the minimum space through the opening. To estimate this thinning, one must determine the area of the sheet available for thermoforming and divide it by the area of the final piece, including the waste. It is always desirable that the molds and thermoformed pieces have generous curvature radii. Theoretically, there is a formula to determine the percentage of material thinning, considering the material is uniformly tempered and stretched.

% of thinning=	Material thickness origin al thickness of the material	Available area of the total sheet area of the formed piece

$$\frac{A \times B}{A \times B \times E\ (2C + 2D)}$$



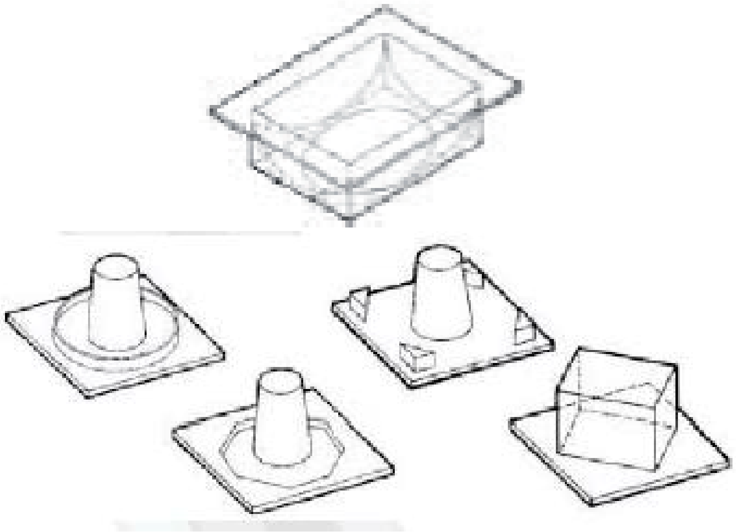
In practice, with a micrometer or caliper the thickness can be determined directly on the thermoformed piece, by cutting small pieces in different sections; other methods are using translucent sheets and correlating the color intensity against thinning of the sheet. The thickness can also be determined by gridding the sheet with an oil marker before thermoforming it and observing the stretching of the material.



One consideration that should be taken into account is the possibility of wrinkling in a critical area or in the lower part of a male or female mold. If the tempered sheet is unable to shrink from the dimension A to E, the excess material will form wrinkles.

In the case of a female mold the opposite occurs, the sheet will lengthen to the four corners of the mold surface, becoming extremely thin. This effect can be observed in most thermoformed tubs.

Below some techniques are shown to prevent wrinkles.



When a low molding temperature is used, the sheet will retain a higher toughness and elasticity. For large pieces, it is recommended to increase the molding time or temperature with areas difficult to thermoform and thereby minimizing this kind of defect. For a deep molding sheet, having a partially crosslinked structure (cross-linking) it tends to minimize the wrinkle defect. When there are multiple molds sufficient space should be provided to prevent wrinkles, a distance of 1.75 times the height of the piece will be adequate.

Shrinkage and dimensional tolerances

Shrinkage and dimensional tolerances in thermoforming are different for pieces formed in the male mold and those formed in female mold. In a male mold shrinkage can be reduced if the piece is cooled for most time in the mold. If cooling takes place to ambient temperature in the mold, shrinkage will be minimal. This will result in that the internal dimension of the piece will be very close to the dimension of the mold, but with a quite unproductive operation cycle.

The fact is, however, that in male molds the piece must be demolded when still hot, otherwise demolding will be difficult. Thermal shrinkage precisely refers to this, which is the proportional difference between the ambient temperature and the temperature at the time of demolding. This way, to preserve the specified dimension of the piece will require that the model is slightly larger.

Compared with the female mold, the formed piece will begin to shrink as soon as the material temperature is below the molding temperature. To maintain a continuously closed tolerance, the mold dimension must be significantly increased and vacuum pressure maintained during the entire operating time.

As a guide it can be assumed that shrinkage in male molds will be .127 mm/mm (0.005 in/in) and in female molds it will be higher. For acrylic, polycarbonate, polystyrene thermoplastic and oriented polyester approximately .203 mm/mm (0.008 in/in) can be considered. However, these valuesshould be taken with caution as the following conditions may make them vary significantly:

1.- Mold temperature: with a difference of 10 °C (15 °F), shrinkage may change upwards of .0254 mm/mm (0.001 in/in).

2. Size and thickness: It concerns the exit angle limited by the mold and the effect of a greater thickness with respect to the temperature profile.

3. Final use temperature: Due to the expansion and contraction proportional to the linear expansion coefficient, the thermoformed piece will continuously vary with changes in ambient temperature.

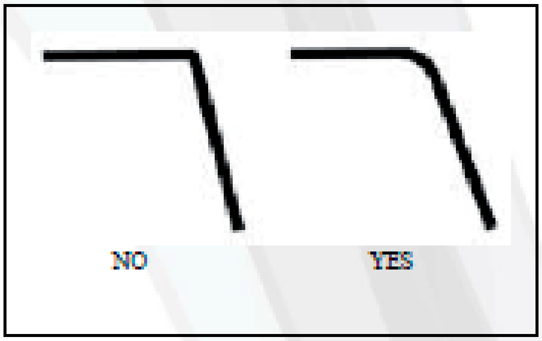
4. Extreme use conditions: The shrinkage can reach top values after the first exposure to the highest temperature of use.

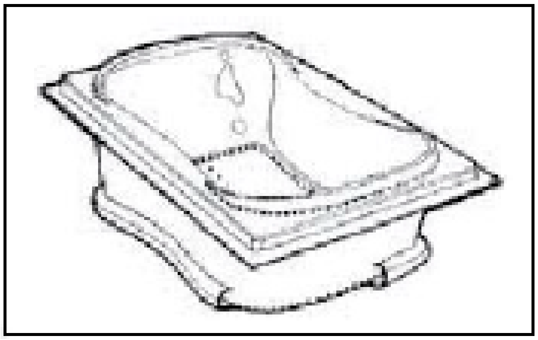
5. Molecular orientation: There may be higher shrinkage with regard to the molecular orientation of the material.

Sometimes it will be necessary to prevent distortion and shrinkage, having cooling templates until the piece is completely at ambient temperature. Furthermore, pieces that are thermoformed at a temperature below those specified, tend to return to their original state due to the plastic memory of the material. It is recommended that shrinkage and deformation should be monitored during the course of production.

Appearance of the mold

It should be clarified that the surfaces obtained by injection and extrusion processes cannot be reproduced in conventional thermoforming techniques. Even highly glossy materials can lose their gloss in the process, in addition to tending to emphasize marks and undulations by contact of a cold mold and changes in the thickness of the material. The change in material thickness will cause small distortions, thereby cleaning of the work area is indispensable. It is recommended that all contours are well rounded, in fact a mold with large radii will benefit the thermoforming operation since the material will tend to stretch better.





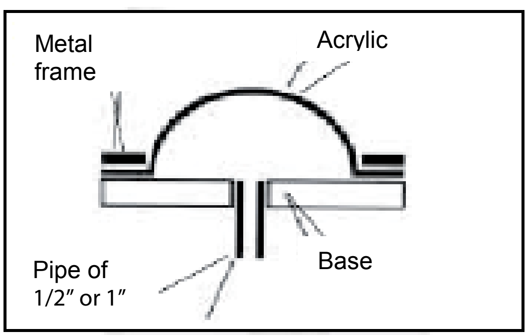
If the sheet is required to copy mold details such as anti-skid textures or similar, these must be at least three times greater than the material thickness, it is actually better to have a less smooth molding surface, as this will not copy mold errors to the piece. It can even be sandblasted with glass beads or abrasive materials. With this trapped air can be eliminated allowing the movement of air between the mold and the piece. Sometimes it is desirable to scratch the surface of the mold with coarse sandpaper, this helps in the demolding stage to break the vacuum between the mold and the piece.

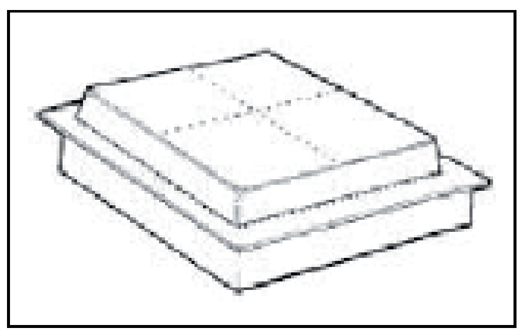
Smooth, well polished surface

Rough surface

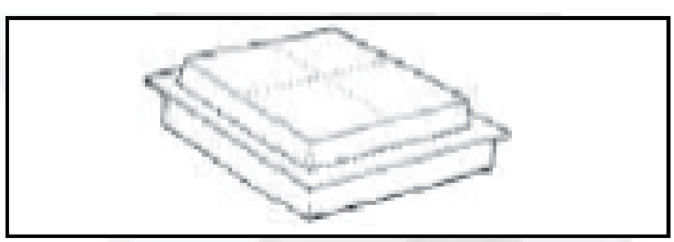
Vacuum drill holes

When thermoforming with vacuum or air pressure techniques are used, it is very important to move the largest volume of air between the mold and the sheet in a minimum of time. Depending on the type of mold, an orifice of 1/2" or 1" can be used, as in the case of dome thermoforming, up to a homogeneous distribution in all corners of the mold.

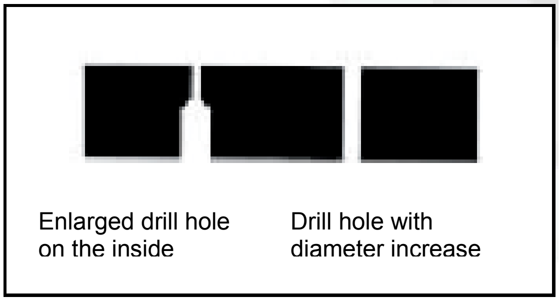


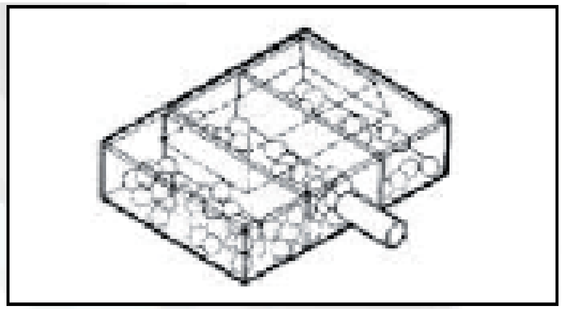


The drawings show the distribution of the vacuum or air pressure drill holes typical of molds for free press forming, male mold and female mold.



In general, the diameter of the vacuum drill holes should be slightly smaller than the material thickness. As a starting point, the vacuum drill holes will have a diameter equivalent to the final thickness of the thermoformed piece for cases in which the material is very thin or thick, or if it does not matter whether these holes are marked, then this rule does not apply. We can consider that an appropriate range is between 1/32" to 1/8" diameter. If necessary, to displace a large volume of air, some holes may be drilled at 1/8"or 1/4" in diameter. Depending on the mold construction, the drill holes may be extended on the inside of the mold as shown in the drawing. To reduce the time of displacement of air volume in the periphery of the softened sheet and in the vacuum box, the space may be filled with styrofoam balls or pieces of polyurethane.



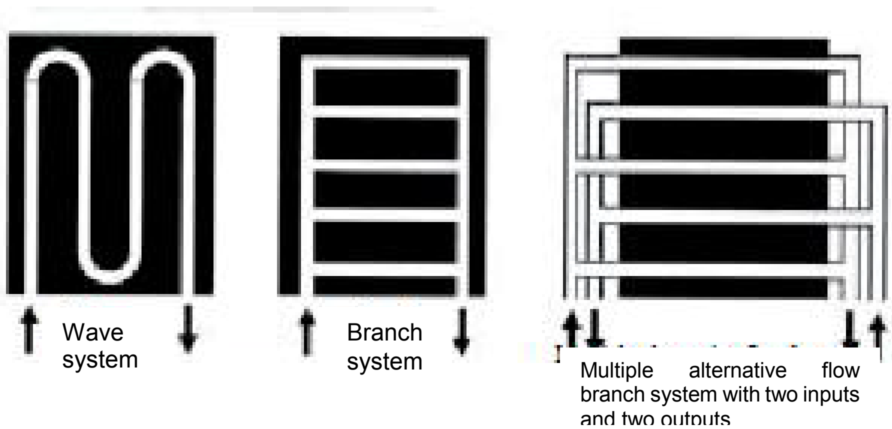


Another function of the mold is to contribute together with the frame to stabilize the position of the sheet and support a good seal around the entire periphery of the mold, in some cases it is convenient to make a channel around the piece, precisely on the outside area of the cutting line.

Cooling of the mold

In many cases when production runs are very long, it is desirable that the mold has a cooling system, usually copper tube is used and this should be properly located with sufficient capacity to carry a large volume of water or refrigerant. There should be a relationship between the temperature of the sheet and the mold so that the material does not cool in excess and does not thermoform below the lower limit of the molding temperature.

There are different methods for cooling a mold, for example, when there are critical areas of molding, nylon or polytetrafluoroethylene plastic inserts can be incorporated. In some cases a plastic coating can applied to reduce thermal conductivity, or can even be injected after thermoforming through openings or vacuum or pressurized air drill holes. The following illustration shows three cooling systems: the first is a wave cooling system, the second is a branch system and the third is a multiple external alternative flow system with two inputs and two outputs.



Molding aids

As we have mentioned above, when a piece is thermoformed there will always be thinning in the material thickness. Molding aids are used to obtain a better distribution of material in the thermoformed piece. The purpose of this is stretching the softened sheet, acting as a preform. This technique is very important especially when you have pieces of great depth. In general, molding aids can be constructed of the same materials used in the molds. There are three different categories of molding aids:

Metal aids

Usually made of iron or aluminum, they should be very smooth and with radii at the edges. The temperature range is considered at 10 to 15° C (40° F) below the material temperature, if its temperature is too high it will stick to the sheet.

Thermal material aids

Aids made of wood, plastic or metal are built on the principle of a good thermal insulator. The surface may be smooth wood, plastics such as nylon, or another thermoset, synthetic foam or any other material including soft flannel.

Skeleton type aids

Skeleton or outline type aids are just round welded bars forming the edges of the piece, they must be fully rounded to avoid tears in the material.

The dimensions of the aids are based on the measurements of the part, as these have a great influence on the distribution of the material thickness. It should be noted that in some cases, by only changing the depth of penetration of the same aid (75% of the depth of the piece), the material thickness between the faces and surface can be controlled. Therefore the equipment must have the ability to adjust the depth, penetration force and speed needed.

Materials used in the manufacture of thermoforming molds

Materials used

In contrast to other plastic molding processes, such as injection or compression, thermoforming has the advantage of using relatively low pressure and temperature, for this reason it can be used a variety of materials. We can usually use wooden molds, they are ideal for low production and as wood has low thermal conductivity, it favors the tempered sheet not to quickly cool on contact, but when there is a medium or high production target wooden molds are inadequate. The construction of molds with phenolic laminates is better because they are not greatly affected by heat or humidity.

There are also molds made with mineral or metallic fillers and polyester or epoxy resin or rigid polyurethane. These have the ease to be emptied from a mold and even having a multiple cavities mold. The thermal properties of epoxy or polyester resins make them suitable for medium production runs, even copper tubing can be embedded as a cooling system to better control the temperature of the mold, but it is still insufficient for high production.

Aluminum molds are best for high production, but the thermal conductivity of aluminum will make it necessary to preheat the mold by means of hot water circulating through the cooling/heating system or radiating heat with electrical resistors or even heating the mold with the same material to be thermoformed. For long runs it will be necessary to incorporate a thermostat to ensure that there is less temperature variation in the mold surface, thus avoiding overcooling. The use properties of aluminum may be improved by applying polytetrafluoroethylene.

In short, there are four groups for the construction of thermoforming molds:

1) Wood

2) Minerals

3) Plastic resins

4) Metals

Table No.13. Use of materials in Thermoforming molds

GROUP	MATERIALS USED	PRODUCTION VOLUME	ADVANTAGES AND DISADVANTAGES
Woods	Pine Mahogany Cedar Maple Plywood Chipboard	Low	These molds are characterized by their low cost, short construction time and good surface finish, although in some cases the wood grain leaves molding marks. The wood must be kiln dried and if a better finish and avoiding dimensional changes due to moisture are desired, the molds should be sealed with casein, phenolic varnish or epoxy resin diluted in methyl ethyl ketone. To achieve a better finish the wood grain must be parallel to the length of the mold. Molds made of plywood or chipboard last longer. The duration of the mold can be extended considerably by strengthening with metal edges.

GROUP	MATERIALS USED	PRODUCTION VOLUME	ADVANTAGES AND DISADVANTAGES
Minerals	Plaster (calcium carbonate) Sodium fluosilicate	Low Medium	Plaster molds last longer than those of wood and can be emptied of a plaster compound of low shrinkage, high strength and internally reinforced with metal mesh, fiberglass or other materialsthat do not absorb moisture. The plaster is emptied over the model and must be allowed to cure for about 5 to 7 days at ambient temperature. If the surface of the model is good, a subsequent finishing will not be required. Polyester resin, epoxy or phenolic coatings provide a more durable surface. Extreme care must be taken not to chip the plaster when making the vacuum holes. Can sometimes the perforations can be eliminated, if previously inserted pieces of wire are left in place which are removed after setting..
Plastic reams	Polyester ream, Epoxy ream, Phenolic ream, Plastic laminates, Nylon	Medium	Plastic ream molds are more expensive and elaborate than those of plaster or wood, but are longer lasting, have smoother surfaces and better dimensional stability. Polyester, epoxy or phenolic resins can be filled with aluminum powder, which provides a more uniform temperature of the mold or, with kaolin, fiberglass and other fillers. The vacuum system can be incorporated to these molds, embedding half-round cardboard in the back of the mold.
Metal	Aluminum, Copper-beryllium, Iron	High	They are ideal for large production runs, high pressures or mechanical forming. Casting molds of aluminum, bronze or any other low melting point alloy can be used, and machined steel, brass or bronze. They are more expensive, construction time is longer, and they have better surface finish, low maintenance cost and better dimensional stability. A cooling system must be used, as well as preventing rapid cooling in the piece.

Recommendations for thermoforming molds

1. For wooden molds the best demolding agent is baby powder or flour.
2. For metal or plastic resin molds, demolding waxes are recommended.
3. In very sensitive materials such as polystyrene, foamed PVC or acrylic, soft woods should not be used because they would make molding marks.
4. For long production runs wood must not be used, due to the slow cooling that will cause the mold to expand, causing the joints to open.
5. For plastic or metal resin molds aerosol demolding agents can also be used.
6. For molds of sinks, bathtubs, bathroom modules, it is possible to obtain a porcelain gloss by sandblasting the mold surface; the roughness will cause a finish with these features.

Thermoforming techniques

Thermoforming is the most simple and general process to transform the acrylic sheet. Being a thermoplastic material it softens and is easily handled being able to take any form when it has been heated to the right temperature and time.

Upon cooling it recovers its rigidity and retains the shape to which it was subjected. The cost of equipment and molds is relatively low and can be obtained in two or three dimensional forms by a wide variety of processes.

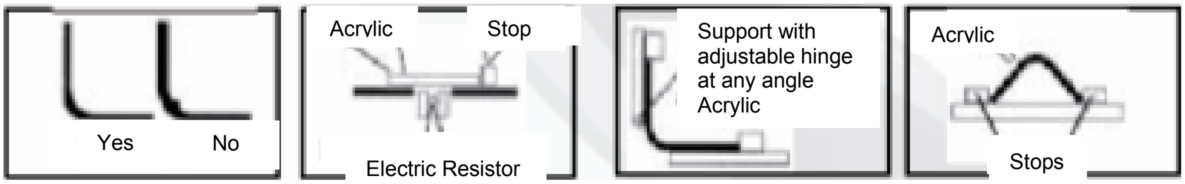
Bidimensional thermoforming

Bidimensional thermoforming is a folding process that can be achieved by two methods:

Linear heating folding

On a linear resistor Plastiglas acrylic sheet is heated, folding it to the desired angle. To proceed to the folding, remove the protective paper from the fold line (the rest of the paper can be left to protect the areas where work will not be done), then place the sheet on the supports with the line to fold directly over the heat line, making the fold on the heated side. The heating time varies depending on sheet thickness. To fold acrylic sheet thicker than 4.0 mm it is advisable to heat it on both sides for proper folding. Heat the sheet until it begins to soften in the fold area. Do not try to fold the sheet before it is well heated, this can cause irregular or folded corners.

Heat carefully; uneven heating may cause arcing in the fold line. Sometimes this is difficult to avoid, especially in pieces of lengths greater than 60 cm. Arcing can be reduced by fastening the newly formed material with pliers or a template until it cools. Templates can be made of wood, fixed or adjustable.



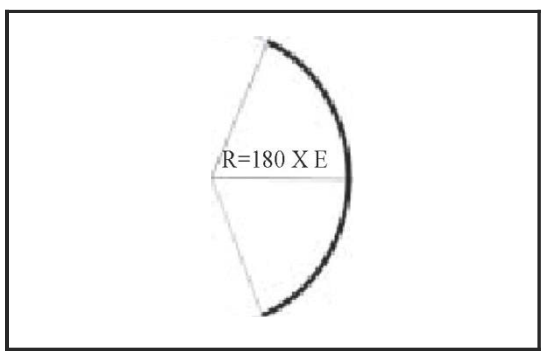
With proper heating clean and bright corners will be obtained.

Place the sheet on the supports with the line to be folded directly over the heat line.

Use fixed or adjustable templates to keep the workpiece at the desired angle.

Cold-forming

PLASTIGLAS acrylic sheet can be cold formed in curved frames, provided that the curvature radius is 180 times greater than the thickness of the material used. Formula: R (radius) = 180 x E (material thickness in mm.)

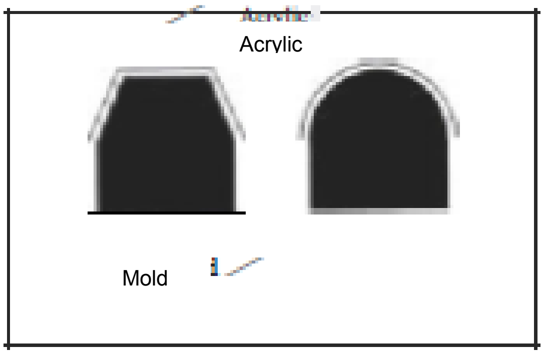


Three-dimensional thermoforming (with molds)

The procedures for three-dimensional forming generally require the use of vacuum equipment, pressurized or mechanical air, or a combination of these to mold the PLASTIGLAS acrylic sheet into the desired shape. These techniques are described below:

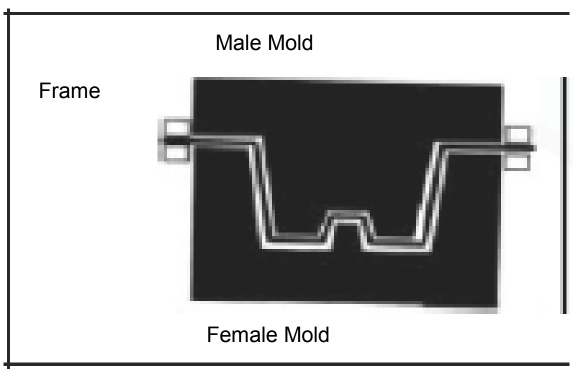
Free or gravity forming

This method is the simplest of all, because the sheet, once the material has softened, is placed over the mold and by the material's own weight it adopts the figure. The edges of the material can be fastened to the mold to prevent the ripples that tend to form during cooling.

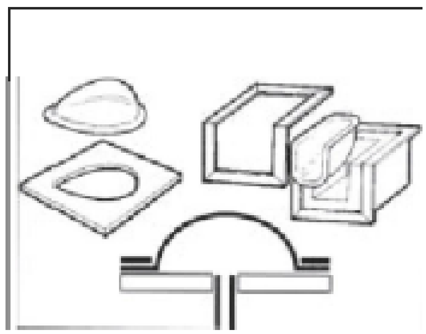


Mechanic forming with female and male **mold**

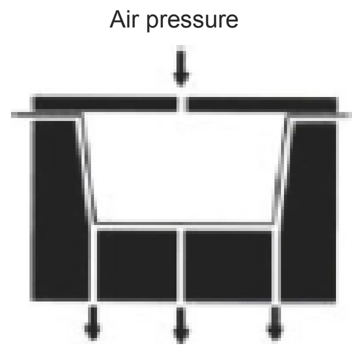
PLASTIGLAS acrylic sheet can be formed by pressing the tempered material between the male and female molds, to produce pieces of very precise dimensions. This procedure requires an excellent finish of the molds to minimize marks thereof.



Air pressure or vacuum free forming Parts requiring optical clarity such as domes, helicopter cabins, etc. can be formed without a mold, it is sufficient to form the PLASTIGLAS acrylic by vacuum or air pressure. The shape of the finished part will be given by the shape and size of the rim fastening it to the frame and by height given; however, these shapes are limited to spherical contours or freely formed bubbles. For this type of forming the use of vacuum should be preferred, or pressure if greater than one atmosphere.

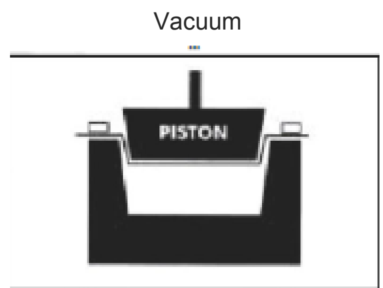


Forming under vacuum and pressure, female mold This procedure allows forming in molds pieces whose shape requires more precision than those obtained by vacuum. However the high pressures will cause mold marks on the piece. As high pressures are required, the molds must be made of metal, epoxy resins or other materials that withstand high pressures without deforming. The good finish of the molds is imperative to achieve quality parts.



Piston-aided pressure forming, female mold

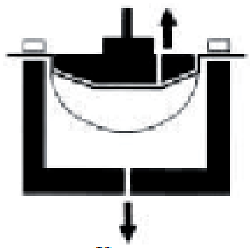
The piston aid technique is used to reduce the thinning at the bottom of the formed pieces. The piston stretches the material before pressure is applied. A piston speed of 6 m/min. is required, it can damage the material in its initial contact. Molding pressure of 2.8 Kg/cm2.



Vacuum forming with return and male mold

This technique is valuable for forming pieces requiring uniform wall thickness and the smallest number of molding marks. The tempered sheet is stretched in a vacuum box until it reaches the necessary depth to accommodate the mold; once the mold has penetrated, the vacuum is gradually released so that the acrylic can return to its original shape meeting it. More defined shapes can be achieved if vacuum is applied to the male mold on the return.

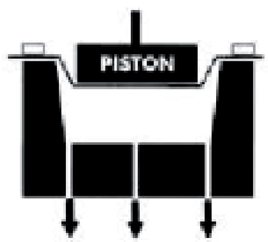
Vacuum



Vacuum

Piston-aided pressure forming, female mold and vacuum

This method is the most sophisticated of all, since it is a combination of almost all the above, it is generally used for very deep thermoformed pieces where more controlled thicknesses are required and there is the problem of rupture due to excessive molding depth.

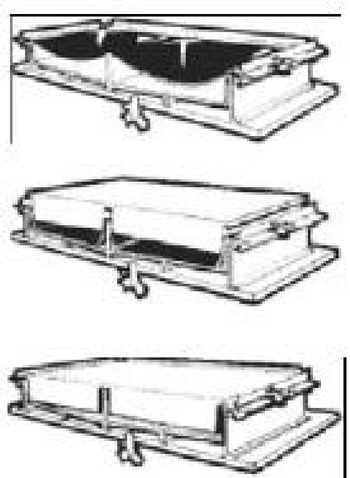


Vacuum

Molding techniques in infrared heating oven

This section will try to expand on the techniques described above. Although these examples are designed for infrared heating equipment, it is possible to apply these to conventional molding systems used in Mexico.

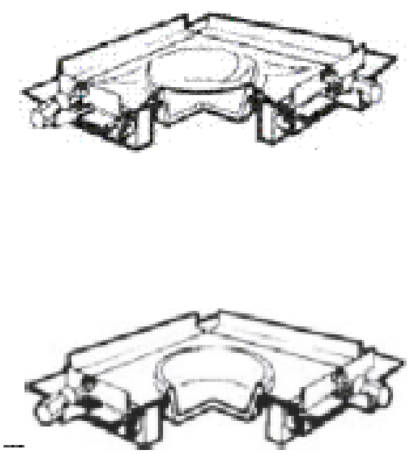
Vacuum forming, female mold
and mechanical aid



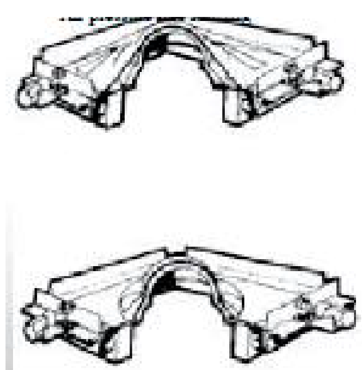
Pre-stretching at more pressure,
mechanical aid and vacuum

Vacuum forming, female mold
and mechanical aid

Vacuum forming, female mold

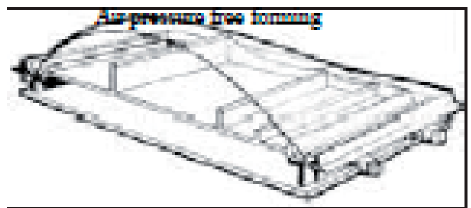


Vacuum forming, female mold



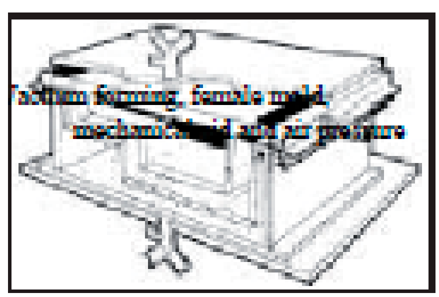
Pre-stretching under air pressure, mechanical aid and vacuum

Air pressure free forming



Pre-stretching under air pressure, female mold, mechanical aid and vacuum

Vacuum forming, female mold, mechanical aid and air pressure



Cooling of thermoformed pieces

The cooling of a thermoformed piece is as important as the heating, but in some cases it may take more time than heating. It is therefore important to select the most appropriate method. Sometimes when very thick pieces are formed that tolerate a lower internal stress is formed, it is advisable to delay the normal cooling, covering the piece with a soft cloth or flannel. If the piece is fastened with clamps, the clamping force will gradually loosen during the cooling and shrinkage will present that will reveal the high stresses of this process.

Most of the heating absorbed during the heating cycle must be dissipated from the plastic before the mold is removed, otherwise distortions and warping can occur on the piece. If the piece is formed in a male mold, will, must be demolded before shrinkage presents and it is difficult to demold.

Conventional cooling

Conduction and convection are virtually the only methods to dissipate heat, given that thermal conductivity in plastics is low, a long cooling will be presented in pieces that are more than 2.0 mm in thickness. The most common is to use electric fans to cool the piece; This method has the advantage that the piece can be cooled in the mold, the disadvantage is that the air current will not be sufficient to cool the mold during each cycle therefore this will exceed in heat, interfering with the normal heating cycle.

The cooling of a piece in contact with the mold is very efficient if it is metal and has cooling duets with recirculating water. It is recommended that in these cases a sufficient volume of coolant is used to keep the mold temperature uniform. If the cooling water is maintained at a certain temperature, the formation of marks on the piece (usually known as ripples on its surface) due to having a cold mold can be minimized. Aluminum or epoxy and/or polyester resin molds are very suitable if it is intended to include a cooling system. Wooden molds are not very suitable for long runs because they do not rapidly dissipate heat.

Non conventional methods of cooling

There are very rapid cooling methods using a spray or fine curtain of deionized water or liquid carbon dioxide, which rapidly cools the surface of a thermoformed piece. This method is not commonly used because of its cost; either of the two can be justified, especially if applied locally to prevent thermal tears in deep pieces, remembering that an irregular and fast cooling of the formed piece is induced to generate stresses affecting durability.

Cutting of thermoformed pieces

After the forming cycle is completed, the pieces should be cut to remove excess material, rarely the final piece does not require cutting, as in the case of illuminated advertising. Most of the thermoformed products require some kind of cutting.
The appropriate equipment and technology must be selected; in any case there are some factors that determine the selection, as in the case of the sheet size, size and depth of the piece, the acceptable level of roughness of the cutting surface, the dimensional tolerance required and the cutting speed among others.

Cutting equipment

There are several types of equipment for cutting thermoformed pieces:

Electric tools

Circular saw

The circular saw must have straight teeth to promote cooling and not softening the material. Tungsten carbide teeth provide an excellent cut and longer life between sharpening. The cut feed should be slow to avoid the material heating or stellation. The saw should be operated at relatively high speeds and before starting the cut, make sure it has reached its maximum speed. The greater the thickness of the material to be cut, the greater must be the saw diameter be and the lower the number of teeth per centimeter (minimum 2 teeth per cm.). When a hand circular saw is used, it is necessary to firmly support the sheet and feed with steady pressure and speed to avoid stellation.

Table No. 14 Specifications for circular, traveling or radial saw cutting

SHEET thickness (mm)	DISC		
	DIAMETER (inches)	THICKNESS (inches)	No. TEETH (*)
1.5-3	8	1/16-1/32	96
3-4	10	3/32-1/8	82-96
5-10	10	1/8	82-96
12-15	12	1/8	82-96
18-21	12	1/8	48-52
25-52	12-14	1/8-5/32	48-52

*Teeth with tungsten carbide pads, tooth with straight face to the center, combined or alternate.

This method provides a highly uniform cut and serves both to shape and make large diameter holes. The router fixed to a table can be used with a copying guide for intricate designs.

The cutting tool on a circular saw or router can eventually be changed for a normal abrasive or even a diamond disc; this type of disc is desirable to use especially when the formed acrylic piece is reinforced with fiber glass, as with tubs, basins, telephone booths, etc.

Automatic equipment

This type of cutting equipment is used when a high level of automation is required; usually this equipment has a specialized computer system and software, such as CAD-CAM-CAE, with which the cutting pattern is designed for subsequently sending the information to a peripheral, which in this case can be routers of 1 to 5 heads, pressurized water system or laser. The cutting capacity is not limited to one direction or plane, almost any type of cut or drill can be made.

Pressurized water cutting

The abrasive pressurized water cutting system eliminates many of the problems associated with conventional machinery and cutting operations. A very fine water jet is concentrated under 50,000 psi pressure, at a speed of about 3 m/min. and with an accuracy of +/- 1 mm.

Using a combination of highly pressurized water and abrasive materials such as silica dust, the water jet can cut all materials without producing heating and leaving a unique finish on the cut surface.

The advantages of this cutting system in acrylic are the elimination of distortion by heating, any cutting angle can be performed due to its multidirectional type integrated to computer systems, it eliminates secondary operations such as sanding and reduces waste material by having a very small cutting area.

Laser cutting

Laser cutting is a technique already used by other industries for several years and its main features are:

• High precision cutting

• Flexible manufacturing

• Costs reduction

An advantage of the laser cutting system is the versatility of application, as in addition to its direct use in cutting of acrylic sheets it provides the possibility of processing in many other types of materials.

With the laser device it is possible to cut, weld and grind surfaces up to 30 mm. thick, because the laser energy is concentrated on one single point and heat generation can be restricted to a minimum area whereby there is no heat deformation or structural changes in the material. Fine cuts with precise edges are also obtained, which is highly recommended for acrylic pieces with very intricate shapes. Holes from 0.1 mm. in diameter can be made, at a rate of up to 150,000 perforations per hour. A laser machine can cut up to 1/2" acrylic at a speed of 30 cm/min.

Swage

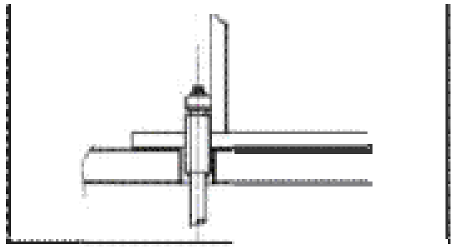
This technique is not widely used because it has limitations; in acrylic it is only possible to swage thermoformed pieces when they are still warm and have thicknesses not greater than 2.0 mm, and it is recommended that the blades are at a temperature between 40 and 60° C. Even so the cutting quality is not very good. This type of cutting technique works best on plastics such as acetate, polystyrene and foamed PVC.

Techniques cutting

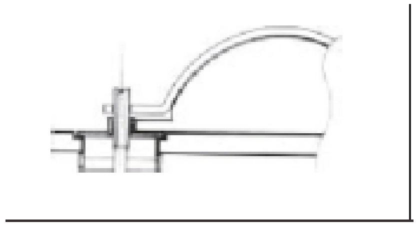
Although there are non conventional and high automation cutting techniques, its practical application is far from being seen, due to the high cost of investment and maintenance in relation to traditional techniques such as circular saw and router cutting.

The following illustrations show various alternatives for cutting thermoformed pieces. Whenever possible, it is desirable to construct a cutting template as support of the thermoformed piece, this way variations in the piece will be avoided and production standardized.

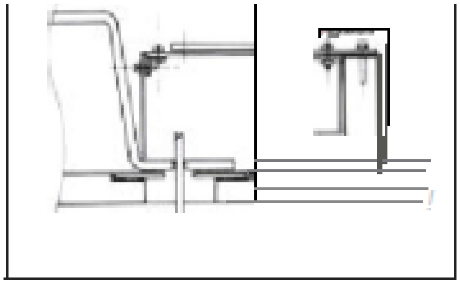
Cutting with router and bearing bit



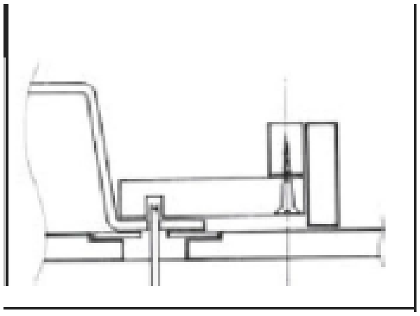
Cutting with router, straight bit and cutting guide



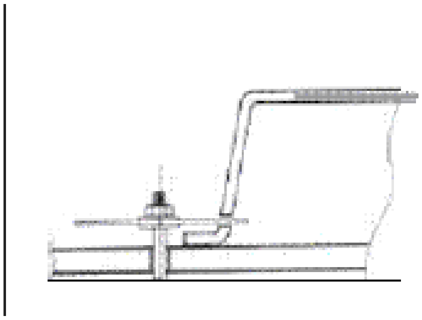
Cutting with bench saw and iron or aluminum stop angles



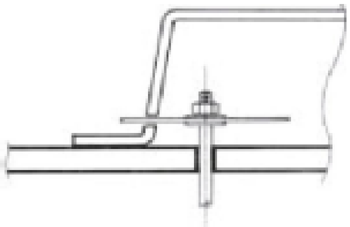
Cutting with bench saw and wooden stop



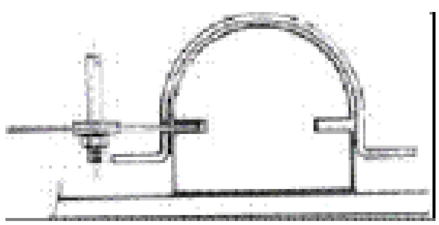
Cutting with router and biscuit cutter or abrasive disc on the outside



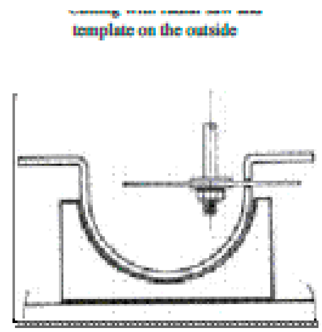
Cutting with router and biscuit cutter or abrasive disc on the inside



Cutting with radial saw and template on the outside



Cutting with radial saw and template on the outside



Thermoforming variables

There are variables in the thermoforming process that may affect the appearance, quality, size and distribution of the material in a formed piece. Knowledge of these variables can often solve difficult production problems in the thermoforming process. Below are the variables that are presented most often as deviations in the thermoforming process.

Material variables

Sheet thickness

When heating is used based on electrical resistors or infrared radiation, the decalibration in the material thickness can cause uneven heating and as a result have variations in the formed part. In a pre-stretching or deep forming, closed dimensional tolerances are required to prevent the material from breaking in very thin areas by the vacuum or air pressure exerted. In very deep parts there will be a variation in the thickness of the material, this will depend on the thickness used, the area and the maximum depth of the piece. In cases where there is a variation in thickness between sheet and sheet, the heating temperature should be reduced to prevent further softening in the material. If the temperature of the sheet is homogeneous, even with thin areas it is very likely to achieve a satisfactory piece.

Sheet pigmentation

In the case of radiation heating (electric resistors), different colors of the same material can make the temperature and heating cycles vary. In a convection oven (hot air recirculation) this variable does not apply.

Sheet size

In order to obtain a better distribution of the material in a very deep piece, it is cheaper to increase the size of the sheet instead of the material thickness.

Uniformity of the sheet temperature

When the temperature of any material is increased, tensile strength is reduced and therefore the sheet becomes more malleable. The best results in thermoforming are obtained with simple or deep forming made at the lower range of the tempering temperature.

Uniformity of the sheet temperature

For high quality pieces, it is important that the sheet is evenly heated to the tempering point across the material. Sheets that do not have a uniform heating will have a poor forming: the stretching in normal temperature areas will be higher than in those where softening was not achieved.

Mold variables

Vacuum holes or boreholes

The vacuum speed is directly proportional to the quality of the piece. A slow vacuum causes the part of the sheet where the first contact with the mold occurs to cool faster than the rest. The result is obtaining very thin sections of the wall or incomplete pieces. For fast air displacement, using vacuum holes measuring between 1/8" and 1/4" is recommended. When possible, it is convenient to have vacuum channels or duets because they displace a higher volume of air.

Mold surface

A sheet of thermoplastic material when it is formed will tend to take the appearance of the mold; a matte finish in the mold, will give an opaque finish in the material; a highly polished finish (mirror finish) will consequently give a bright piece.

Mold Temperature

The temperature on the mold surface directly influences a better appearance of the formed part, in the duration of forming cycles and the size of the formed piece. The final shrinkage of a thermoformed piece will depend on the approximate temperature of the mold being similar to the thermal expansion coefficient of the material.

Temperature of mechanical aids

To prevent the sheet of material from cooling during a pre-stretching operation causing "cooling marks" and poorly formed parts, the mechanical aid must be heated to a temperature above the point of distortion.

Pre-stretching variables

Vacuum box

In return vacuum and free forming it is very efficient to use a vacuum box which is 8 to 12 cm. longer than the total depth of the bubble formed to prevent cooling of the perimeter of the sheet with the mold. Before the bubble can be formed, the sheet must seal tightly against the mold. In a vacuum return operation, the maximum thinning will occur at the bottom of the bubble formed. For thicker walls, it is necessary to have a two-step edge in the vacuum box that will cool the upper area and create a more thickness.

Air temperature

It is often desirable that the system air is preheated; the air temperature in an environment that is introduced to the system may cause the sheet to cool, affecting the size and shape of the piece. In thin materials, the cooling problem is more severe. With preheated air, the temperature should be about 10% below the temperature of the sheet. It is recommended to install a baffle or air diffuser at the inlet of the mold because it can prevent a sharp cooling in certain areas of the material.

Mechanical aids

Variables

Shape of the mechanical aid

The aid must adapt closely to the shape of the mold cavity, but it must be 10 to 20% smaller in length and width (or diameter). When these dimensions are 12 cm. or more, smaller aids must allow at least 1/4" clearance between the end part and the aid to prevent irregularities in the thickness of the material as much as possible.
When the mold is in the shape of channels (corrugated sheet) with abrupt changes from planes to tight areas, it is important that the aid be made with inserts that fit into the mold channels. These inserts will help to deposit more material with which the thickness is increased in a particular area. For boxes in the mold, the same aid projection must be applied. In the case of deep depressions in the mold walls it is desirable to incorporate an auxiliary mechanism for carrying more material in that area; all corners will be smoothed with generous radii.

Aid materials

For good results the mechanical aid must have excellent qualities of heat transfer and continuous and prolonged resistance to high temperatures. Aluminum is one of the best. For short runs or prototypes a hardwood will be better and to keep the wood from drying out too much without cracking with the heat, the surface must be greased often.

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Temperature of the aid

The temperature of the aid should be kept just below the forming temperature of the sheet. There may be low working temperatures in the aid, in any case if the temperature drops, the cooling marks will become more visible.
As a strict control of the mold temperature is not so critical, in the aid an even heating of up to 10° C should be kept unchanged. With proper regulation of temperature, molding marks are usually completely eliminated.

Surface of the aid

A smooth surface with well polished and dust and debris free radii will produce good pieces.

Height of the aid

An effective mechanical aid is one that is longer than the depth of the mold cavity, as in this way its adjustment may be regulated.

Vacuum speed in aid

The increase in speed of the aid increases the compressed air capacity in the mold cavity. The capacity of the vacuum system and its duration in relation to the run of the aid affects the pressure in the mold cavity. Normally the vacuum in the cycle must begin at the same time at which the aid touches the material.

Action depth of the aid

The best results are obtained with a penetration of the aid in 70 or 80% of the mold cavity. This relationship results in the best combination between thickness at the bottom and the walls of the piece.

Material variables in forming with aids

The type of plastic material used will affect the amount of pressure required to maintain proper contact of the material around the aid. The high strength materials such as acrylic and ABS require air pressures between 15 and 50 psi.

Problems and Solutions Guide

DEFECT	POSSIBLE CAUSE	SUGGESTED SOLUTION
• Bubble or blister in the sheet	• Excessive humidity	• Pre-dry the sheet. • Heat both sides of the sheet at 60° C (140° F).
	• Heating too fast	• Reduce oven temperature. • Increase the distance between the sheet and the heater.
	• Uneven heating	• Check and fix the oven. • Check heating elements.
• Details and incomplete shapes	• Insufficient vacuum	• Remove obstructions from the vacuum system. • Increase number of perforations. • Increase diameter of holes.
	• Slow vacuum displacement	• Greater capacity of tanks and vacuum pump. • Line leakage. • Check the vacuum system for possible leaks. • Use vacuum channels in potential areas.
	•Insufficient heating of the sheet	• Increase temperature or heating time.
	• Overheating	• Reduce heating time.
• Change in color of the sheet	•Low mold temperature	• Reduce temperature of the oven. • Heat mold.

DEFECT	POSSIBLE CAUSE	SUGGESTED SOLUTION
• Change in color of the sheet	• Low temperature of mechanical aid. • The sheet thins too much . • Cooling of the sheet before completing its shape. • Inadequate mold design. • Unsuitable material.	• Heat mechanical aid. • Increase thickness of the sheet. • Place the sheet faster in the mold. • Increase vacuum speed. • Heat the mold and mechanical aid. • Decrease depth of the mold. • Improve vacuum airflow. • Use larger curvature radii. • Material change.
• Excessive warpage or buckling of the sheet	• Sheet very hot. • Sheet too large in area	• Reduce heating ime. • Reduce temperature of the oven. • If possible, reduce the size of the sheet. • Use screens, mainly in the center of the sheet (with infrared heating oven only).
• Marks due to cooling in the formed piece	• Sheet too hot. • Mechanical aid with insufficient temperature •Low mold temperature (shrinkage ceases when it makes contact with the cold mold or	•Reduce the mold temperature. • Reduce heating time. • Increase temperature of the aid. • Use felt or soft flannel on surface of the aid. • Raise mold and/or aid temperature, without exceeding the temperature ranges. • Smooth and/or round the mold in critical areas.

DEFECT	POSSIBLE CAUSE	SUGGESTED SOLUTION
• Small wrinkles or circular marks.	• Sheet very hot. • Vacuum drill holes too large.	• Reduce the mold temperature. • Reduce heating time. • Refill and drill again to a smaller diameter.
• Variation in buckling of the sheet.	• No temperature uniformity in the sheet.	• Check the oven for any drafts, it is necessary to incorporate affles.
• Wrinkles during forming	• Excessive heating of the sheet. • Excessive buckling of the sheet. • Insufficient vacuum.	• Reduce the oven te mperature • Reduce heating time. • To the extent possible, increase the distance between the heaters and sheet (only for infrared heating ovens). • Reduce the range of the molding temperature. • Check the vacuum system. • Increase vacuum holes or channels. • Use screens to reduce heat in the area.
• Very bright lines or areas.	• Sheet overheated in area of brightness.	• To the extent possible, increase the distance between heaters and the sheet (only for infrared radiation heating ovens). • Reduce heating time. • Sandblast the mold surface.
• Poor surface appearance of the piece.	• Defect caused by trapped air on the smooth surface of the mold. • Insufficient vacuum.	• Increase number of vacuum holes. • If the marks appear isolated, increase the number of vacuum holes in the affected area.

DEFECT	POSSIBLE CAUSE	SUGGESTED SOLUTION
• Poor surface appearance of the piece.	• Excessive mold temperature. • Insufficient temperature of the mold. • Mold surface too	• Reduce the mold temperature. • Increase temperature of the mold. • Smooth the mold surface. • Make another mold with another material.
•Excessive distortion or shrinkage after demolding the piece. .	• Piece demolded too fast.	• Extend the cooling cycle. • Move the piece to a cooling template. • Use a coolant. • Use spray steam to lower the temperature of the piece. • Use electric fans to cool the piece inside the mold.
• Excessive thinning of the piece wall thickness.	• Improper forming technique. • Variation in the material thickness. • Uneven heating of the sheet. • The sheet is at an excessive temperature • Cold mold. • The sheet is not held securely in the frame.	• Use a different forming technique: vacuum with return, air pressure and mechanical aid, air pressure and return with vacuum • Check that the material is within quality standards and/or request material claim. • Check the oven preparation. • Reduce the oven temperature. • Reduce heating time. • Heat the mold. • Increase closing pressure. Check possible variation in thickness of the sheet.

DEFECT	POSSIBLE CAUSE	SUGGESTED SOLUTION
• Twisting of the pieces..	• Piece not properly cooled. • Uneven distribution of wall thickness. • Inadequate mold design. • Inadequate design of the piece.	• Adjust cooling cycle. • Use mechanical or technical aid to pre-stretch. • Possible uneven heating of the sheet. • Increase vacuum holes. • Modify mold. • To the extent possible, modify the flat areas with a small curvature. • Increase temperature of the mold
•Shrinkage marks in the corners.	• Mold surface too smooth. • Insufficient vacuum.	• Sandblast the mold surface. • Check the vacuum system. • Add more vacuum holes.
• Pre-stretch of the bubble uneven.	• Insufficient sheet temperature. • Uneven thickness of the sheet. • Insufficient air pressure.	• Check the oven operation condition. • Use cooling screens (Only in infrared radiation heating ovens). • Longer heating time at a lower temperature. • Incorporate a system of air distribution with baffles.
• Thin corners in deep formings.	• Improper forming technique. • Thin sheet thickness. • Uneven heating of the sheet. • Inadequate heating of the mold.	• Switch to another forming technique. • Increase thickness of the sheet. • Check the oven operation. • Use screens to change the distribution of heat. • Change the temperature of the mold.

DEFECT	POSSIBLE	SUGGESTED SOLUTION
• The piece sticks to the mechanical aid.	• Mechanical aid (wood). • Mechanical aid (metal).	• • Apply a demolding agent. Cover with felt or soft cloth. • Apply a demolding agent. • Lower temperature of the aid. • Cover with felt or cloth.
• The piece sticks to the mold	• High temperature of the piece. • The exit angle of the mold is insufficient. • Mold built in wood.	• Extend the cooling time. • Reduce temperature of the Mold. • Give angle between 1 and 3.° • Change to female mold. • Apply a demolding agent
•The corners of the formed piece crack when in service. .	• Inadequate design of the piece. • Concentration o stresses in the piece	• Redesign the piece. • Increase the radius of curvature of the mold. • Increase thermoforming temperature. • Ensure that the piece has been completely formed before it cools below the molding temperature

APPENDIX
Glossary of terms

ABSORBENCY

The fraction of radiant energy that is retained by the sheet.

CAVITY

Depression of a mold made by vacuum, machining or the combination thereof. Depending on the number of depressions, it can be a cavity or multicavity.

CYCLE

Repetitive complete sequence in the thermoforming process, comprising: heating, shaping, cooling and demolding.

HEAT TRANSFER COEFFICIENT

The measure of the effectiveness of the energy transported between a fluid stream and a solid surface.

CONDUCTION

Energy transferred by direct contact of a solid.

CONVECTION

Energy transferred by the movement of a fluid stream.

COPOLYMER

Polymer composed of two different types of monomers.

THERMAL DIFFUSIVITY

Index of transmission of heat energy in a material.

ENTHALPY

Internal energy of a system.

DIMENSIONAL STABILITY

The ability of a piece to maintain the precise shape and dimensions of the mold used.

AIR PRESSURE FORMING

Pressure difference which exceeds two atmospheres (30 psi).

HOMOPOLYMER

Polymer formed from a single type of monomer.

INFRARED

Part of the electromagnetic spectrum between the visible light range and the range of radio waves. The radiant heating is the range where infrared heaters are used to heat the sheet. The wavelength is 2.0 to 10.0 mm.

COOLING MARKS

Marks caused by incorrect temperature of the plastic sheet, resulting from inadequate heating.

RADIATION

It is the transfer or exchange of electromagnetic energy.

REFLECTANCE

The fraction of radiant energy that is reflected by the sheet surface.

RESIN

Another name used to refer to a plastic polymer or material.

VACUUM TANK

The tank between the vacuum pump and the mold, which allows a uniform application of pressure during forming.

TRANSMITANCE

The fraction of energy that is transmitted through the sheet.

MELT TEMPERATURE

The temperature range in which a crystalline polymer changes from solid rubberized state to a viscoelastic fluid.

MOLDING TEMPERATURE

The temperature of the piece when it can be demolded without deformation.

TENSION

External load applied to a defined area.

TERPOLYMER

Polymer formed by three different types of monomers.

SCRAP

Excess material that is not part of the final piece.

Plastic reinforced with fiberglass

Introduction

Reinforced plastics are those thermoplastic or thermoset materials in whose molding process a reinforcing material is used that enhances the mechanical characteristics of the product. This reinforcing material may be continuous or discontinuous. Examples of the former are fibrous materials: sisal, jute, hemp, rayon, etc., but the most used is fiberglass.

Polyester resin and reinforced plastic

A polyester is formed by reacting a polybasic acid and a polyhydric alcohol at temperatures above 100° C to obtain a polyester and water. According to the type of acids and alcohols used and of the modifications made, the following types of products will be obtained.

Unsaturated polyesters

They are linear polyester resins obtained by reacting dibasic acids and polyhydric alcohols, which are capable of polymerizing in a crosslinked manner ("crosslinking") with vinyl monomers to form a thermoset plastic.

Alkyd polyesters

They are oil-modified polyesters which are used for decorative and/or protective coatings, for example, paints, varnishes, printing inks, etc.

Polyester plasticizers

Fully saturated polyesters which are used to "soften" other plastics, are also known as polymeric plasticizers; they are used in the manufacture of vinyl with or without reinforcement, e.g., that used in manufacturing of car seat covers, wall hangings, etc.

Fibers and films

They are high molecular weight polyesters, molecularly oriented and for which specific alcohols and acids are employed. Example: polyethylene, polypropylene, etc.

Polyester foams

They are polyesters with a high number of hydroxyl groups that react with crosslinked chains with isocyanate groups to form foams, elastomers, coatings, etc.

According to the above classification "polyesters" are a variety of compounds or chemicals, however it is commonly used to name the compounds which are defined as unsaturated polyesters, so unless otherwise indicated, this denomination will be adopted.

Polyester resins are used in a wide range of applications in various industries, e.g., molding with reinforcement materials (reinforced plastic), encapsulation, protective coatings, decorative items, buttons, etc. The reinforced plastic industry is the one with the highest consumption of polyester.

The growing demand and application of reinforced plastic items is mainly due to its properties and features, among which we can mention:

1) Ease of handling of the components (the polyester resin is applied in liquid form).

2) Fast curing and ease of use.

3) Excellent dimensional stability in the final product.

4) Good dielectric properties.

5) Excellent physical and mechanical properties. A reinforced plastic sheet, equal to three thicknesses of a steel sheet, has mechanical resistance to tension, it weighs about half and has more elasticity.

6) Resistance to corrosion and many chemical agents.

7) Ease of finish (colored, painted, machining, etc.).

In order to obtain optimal characteristics in the reinforced plastic, it is necessary that the reinforcing material has the best mechanical and chemical properties, therefore below the most used reinforcements will be described.

Reinforcing materials

Reinforcing materials are a group of generally fibrous materials that when combined with resins, whether thermosetting or thermoplastic, improve their mechanical and physical characteristics.

The main reinforcing materials are:

1. Cellulose fibers
   Alpha cellulose
   Cotton
   Jute
   Sisal
   Rayon

2. Synthetic fibers
   Polyamides (Nylon)
   Polyester (Dacron)
   Polyacrylonitrile
   Polyvinyl alcohol fibers

3. Asbestos fibers

4. Special fibers
   Carbon and graphite fibers
   Boron and tungsten fibers
   Ceramic fibers

5. Reinforcing loads

6. Fiberglass

Fiberglass

In the reinforced plastics industry, the most commonly used material is fiberglass, this preference is due to its characteristics:

1. High tensile strength.

2. Incombustible
3. Biologically inert
4. Excellent resistance to weathering and many chemicals.
5. Excellent dimensional stability
6. Low thermal conductivity

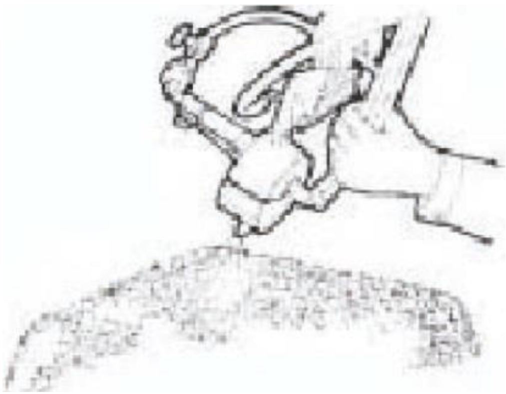
The main forms of use of fiberglass reinforcement are:

Roving Mat	(Roving)
Woven roving	(Mat)
Surfacing	(Surfacing mat)
Chopped stand	(Chopped stand)

Below the production processes and characteristics of these materials are briefly described.

Roving

The "roving" is a wick or rope is one of the forms of fiberglass which is used most frequently and is indispensable when reinforced plastic goods are manufactured by spray, directed filament and hot molding (preform manufacturing). The "roving" is presented wound in reels and generally consists of 60 strands.



Mat

This is the most popular and well known form or presentation of fiberglass in the reinforced plastic industry and is composed of monofilament fiber, whose length is approximately 5 cm. Because the filaments forming the mat are not placed in an orderly manner, this material has the ability to spread the loads and mechanical stresses in all directions (isotropically).

Woven roving

This form of presentation of fiberglass consists in "roving" strands woven in crosslinked form and at angles of 90° to their longitudinal axes. Combined with mat, it is used as secondary reinforcement in the manufacture of boats and large structures.

Surfacing mat

This material consists of fiberglass sections similar to the mat, albeit with a lower weight/area unit. The surfacing mat is mainly used to improve the finishing of reinforced plastic and increase resistance to weathering characteristics, as being placed on the reinforcing material, generally mat, it does not allow the fiber to "draw out" in addition to absorbing resin, that increases the smoothness of the finish.

Chopped strand

This is a little used presentation of fiberglass and is obtained from the mat forming machine. The size of this material ranges from 1.25 to 5.0 cm. in length (1/2" to 2") and its main application is in the forming of items by the premix method.

According to the classification of reinforcing materials, there is another type of production used in the manufacture of reinforced plastics, the most important being:

Asbestos

Sisal, jute, hemp Synthetic fibers Ceramic fibers

Polyvinyl alcohol fibers

Special reinforcements

To increase the efficiency and application of reinforced plastics, various reinforcing elements have been developed, whose main feature is a high elasticity module, so that the mechanical strength of the laminate is notably increased. This property is of particular interest in specialized areas such as aerospace vehicles, submarines, etc. Among the reinforcements included in this line are:

Boron tungsten filaments Carbon and graphite fibers Metallic filaments

Reinforcing loads (whiskers) Adhesion promoting agents Hybrid reinforcements

Metallic reinforcements

The mechanical strength of a plastic/reinforcement composite is originated in the binding, generally mechanical, of the system components. This binding, satisfactory in most cases, can decrease with aging of the compound or product and by humidity when systems with fiberglass reinforcement are used, because the fiber is hydrophilic and tends to absorb water, which weakens or destroys the plastic binding.

To prevent this situation, silane type chemical compounds are employed which are added to the inorganic load, to the resin or to the reinforcing material, they acting by providing a chemical bond at the interface of the bonding, improving and maintaining the mechanical properties of the compounds, apart from improving the dielectric characteristics of the system.

Manufacturing of reinforced plastic molds

To manufacture a mold a model or original of the piece to be obtained is required. When one only has specifications and drawings, the model can be made of plaster, wood or epoxy paste, depending on the degree of difficulty of the piece and skill of the operators. Sometimes the model can be made by combining polyurethane foam or polystyrene plates coated with a thin layer of plaster or epoxy paste.

When the model is finished its harshness should be reduced with water sandpaper and then apply a sealer to eliminate the porosity of the material. This sealant is in most cases a nitrocellulose lacquer which is applied by spraying or a solution of shellac in alcohol. After polishing the model, an application of a demolding agent material is made whose specific function is to avoid adherence of the resin to the mold. The demolding agents can be classified into three types:

Solutions

Generally aqueous polyvinyl alcohol, methyl cellulose, etc.; these types of separators must be applied in each molding operation.

Waxes and wax emulsions

This demolding agent is applied with a cloth or flannel, and proceeded to polish manually.

Internal demolders

This type of separating agents are mixed with the gel-coat. When these demolders are mixed with the mold gel-coat (tooling gel-coat) the demolding characteristics increase, thereby facilitating molding.

After selecting the demolding agent, it is proceeded to "paint" the mold with a resin preparation known as gel-coat or topcoat.

Finishing film (gel-coat)

Consists of a formulation based on resin that provides a film whose characteristics are:

- Forming a smooth surface
- Preventing reinforcing material coming to the surf ace
- Improving the properties of weatherability

In some cases it is suggested to place a "veil" of fiberglass to reinforce the gel-coat, thus ensuring a resin-rich layer and preventing the reinforcing material to draw out. Usually the gel-coat is applied by spraying, but it can also be applied by brush; it suggested that the amounts of accelerator/catalyst are less than those required in the immersion formulation.

The finishing film thicknesses are determined by the use and characteristics of the piece to be obtained and measured with a wet film gauge.

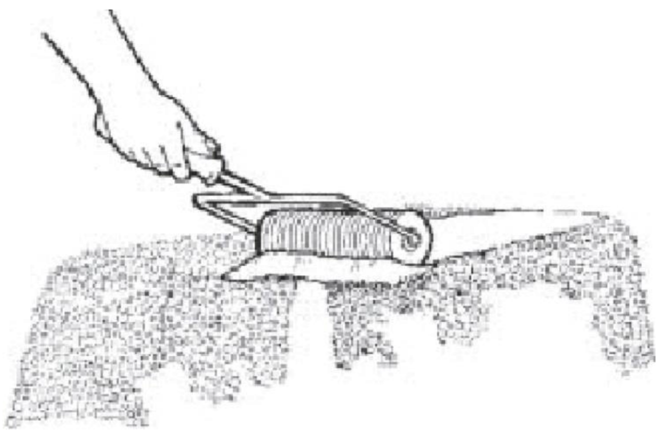
Manual or chopping process

This method is often used because it does not require the use of specialized equipment. Its process is explained below:

The prepared mold with demolding agent (wax, separating film or both) is given a finishing layer with a brush or spraying equipment whose thickness varies according to the use of pieces and as specified by the supplier. Once the gel-coat thickness is determined and once it has cured, the fiberglass mat is placed on the mold. Then, with a brush and vertical movements, the resin is applied to the plane of the mold whose formulation consists of styrene monomers, methyl methacrylate or both, as well as an accelerator, loads and/or thixotropic agents, color concentrate, catalyst, etc.

After this, and before the resin gels, it is "rolled", that is passing a plastic or metal roller, usually grooved with diameter ranging from 9.0 to 25 mm. and a length of 5 to 20 cm., as appropriate.

This roller when rotating in various directions and with uniform pressure, helps remove air trapped in the resin and reinforcing material, as well as achieving good adhesion with the gel-coat. It is advisable when dealing with large pieces that the chopping and rolling is done in sections not greater than 1 m2.



Often the commercial measurements of mat and woven roving (which is always applied to this procedure) are not sufficient to cover the mold in its entirety, therefore it is necessary to join by fiberglass sections. The suggested procedure consists in "overlapping" the mat or woven roving so that the overlap is approximately 5 cm., it is advisable that the resin used to impregnate these sections contains the least amount of accelerator and catalyst to avoid problems caused by contraction of the material. These contractions come from the existence of a larger amount of resin, which in turn decreases the curing time and increases the exothermic temperature.

It is sometimes necessary to use one or more layers of woven roving as reinforcement, the material must be placed between two sections of mat or better still as a final layer and never in direct contact with the gel-coat as if there is a bad application of the finishing layer, the woven roving will be visible, which can give a bad appearance to the product.

The brushes or rollers used must be washed intermittently with a mixture of solvents such as acetone, ethyl acetate, methyl ethyl ketone, etc., as the resin hardens upon curing and can result in loss of the tool. Often it is enough to place these implements in a container with the listed solvents or a mixture of monomers.

Reinforced plastic machining

The manufacture of reinforced plastic often includes operations in the machining process or adjusting of items obtained, which although not highly specialized should be done carefully in order to get good results. Among the operations grouped under the name of "machining" are cutting, drilling, bonding, etc. The most important are listed below:

Cut in the mold

Also known as "trimming" it is the cutting of the material (fiberglass and resin) that protrudes from the mold or manufactured piece. This operation is done with steel blades, following the contour of the mold of the piece when the resin is gelled and still has not achieved full curing. In the case of items manufactured by means of pressure and temperature, the material cutting should be done immediately after removing the piece from the mold; otherwise the operation will be more laborious.

Cutting with equipment

This operation is done in fully finished products and it is advisable to use abrasive discs, as metal discs are not as fast, accurate and ergonomic as those suggested. In this operation the use of water is recommended at the time of the cut; in this way the water acts as a coolant and lubricant helping to eliminate dust from the reinforced plastic and also the cut obtained is cleaner.

Reinforced plastic bonding

It is often necessary to join two or more sections of reinforced plastic for the end piece; commonly used systems are as follows:

Bonding with glue

Although two forms are used in such unions, union by the edges or by overlapped joints, the latter is the most recommended, as the contact surface is greater. The adhesives used are generally polyester resin (modified with flexible resin) or epoxy resin that provides excellent adhesion. The adhesive material can be placed directly onto the plastic surfaces, although it is suggested to be applied to a layer of reinforcing material, placing the latter between the surfaces to be joined, then pressing to achieve uniformity in the joint.

Rivets

The use of rivets is rare in this industry, but if necessary the use of aluminum or brass rivets is recommended, and diameters greater than 4.5 mm (3/16") should not be used. The minimum distance from the edge of the laminate where the rivet must be placed, is equivalent to 3 times its diameter; in addition the use of flat washers it is suggested to reduce the tendency of the rivet to penetrate the laminate.

Use of screws

The use of screws is the most common for bonding reinforced plastic pieces, except for adhesive bonding. In this group we can mention the use of self-tapping screws, but this type is not advisable. The use of screws with nut has advantages such as ease of installation, adjustment, and availability. In order to achieve maximum efficiency for placement of screws the following rules must be observed:

- The distance from the center of the screw to the edge of the laminate should be at least equal to 3 times its diameter.

- The distance between the center of a screw with respect to the following must be equivalent to 2.5 times the hole diameter.

- The use of flat washers is suggested on both sides of the laminate, in this way the load and mechanical stress is more evenly distributed.

- Perforations should be perpendicular to the reinforcing layer, in addition to perfectly tightening the screw (the hole and screw diameter must match).

- The use of screws allows applying adhesives, with which a better quality bond and greater strength will be obtained.

Unit Conversion Table

Specific Gravity:	$1 \ \frac{g}{cm^3} = 62.4 \ \frac{lb}{cu\ ft}$
Specific Heat:	$1 \ \frac{Btu}{lb°\ F} = 1 \ \frac{cal}{g°\ C}$
Melting Heat:	$1 \ \frac{Btu\ ft}{sq\ hr°\ F} = 12 \ \frac{Btu\ in}{sq\ ft\ hr°\ F} = 0.00413 \ \frac{cal\ cm}{cm_2\ sec\ °C} = 0.0173 \ \frac{W\ cm}{cm_2\ °C}$
Thermal Conductivity:	$1 \ \frac{in}{in°\ F} = 1.80 \ \frac{cm}{cm°\ C}$

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Conversion table for temperature scales

°F	°C	°F	°F
50	10	275	135
55	12.8	280	137.8
60	15.6	285	140.6
65	18.3	290	143.3
70	21.1	295	146.1
75	23.9	300	148.9
80	26.7	305	151.7
85	29.4	310	154.4
90	32.2	315	157.2
95	35.0	320	160.0
100	37.8	325	162.8
105	40.6	330	165.6
110	43.3	335	168.3
115	46.1	340	171.1
120	48.9	345	173.9
125	51.7	350	176.7
130	54.4	355	179.4
135	57.2	360	182.2
140	60.0	365	185.0
145	62.8	370	187.8
150	65.6	375	190.6
155	68.3	380	193.3
160	71.1	385	196.1
165	73.9	390	198.9
170	76.7	395	201.7
175	79.4	400	204.4
180	82.2	405	207.2
185	85.0	410	210.0
190	87.8	415	212.8
195	90.6	420	215.6
200	93.3	425	218.3
205	96.1	430	221.1
210	98.9	435	223.9
215	101.7	440	226.7
220	104.4	445	229.4
225	107.2	450	232.2
230	110.0	455	235.0
235	112.8	460	237.8
240	115.6	465	240.6
245	118.3	470	243.3
250	121.1	475	246.1
255	123.9	480	248.9
260	126.7	485	251.7
265	129.4	490	254.4
270	132.2	495	257.2
		500	260.0

Conversion formulas for temperature scales
°F = °C X 1.8 + 32
°C = °F- 32/1.8

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