Thermoforming
- In a Nutshell

A SPE Tutorial Presentation

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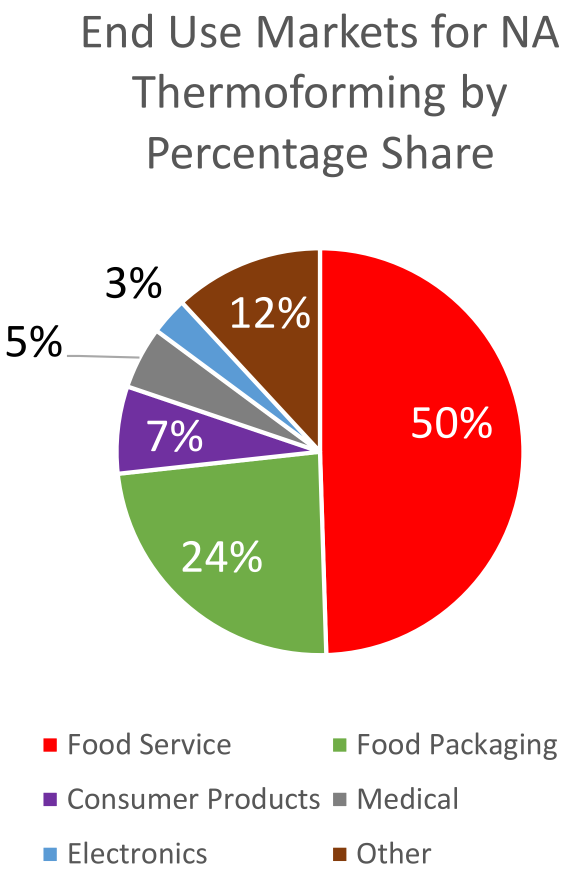
Market size

- Global Market (all Plastics) ~ 8.5 Blbs
- 2012 – 2017 CAG = 4%
- Top 20 NA 2015 Thermoformers Sales = $8.82 Billion
- 2015 Estimated NA HDPE usage= 1.2 B lbs



Source = Plastics News

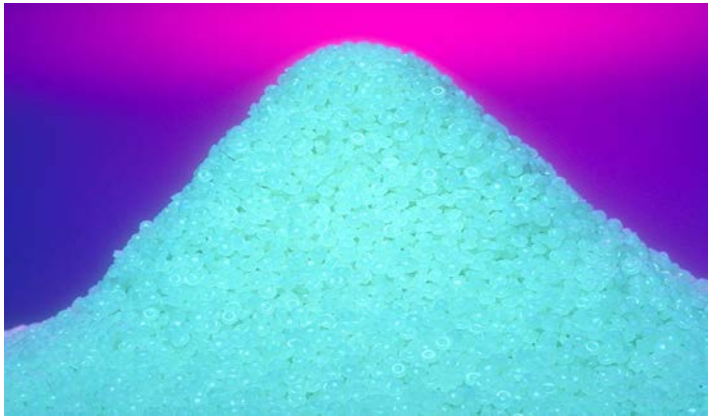
Thermoforming in a Nutshell

- Thermoforming uses heat, vacuum and pressure to form a plastic sheet into a shape determined by a mold.
- Known for its versatility, short lead times and low mold costs, thermoforming is the transformation method of choice for large, semi-complex parts.
- Parts can be assembled using a variety of methods such as snap fits and sonic welding.
- Thermoforming can accommodate a wide variety of plastic materials, sheet thicknesses and part sizes

Thermoforming in a Nutshell

- The thermoforming process consists of
  - Sheet Extrusion
  - Forming
  - Finishing
- Each of these processes will be described and some common problems encountered during the process will be discussed as well.

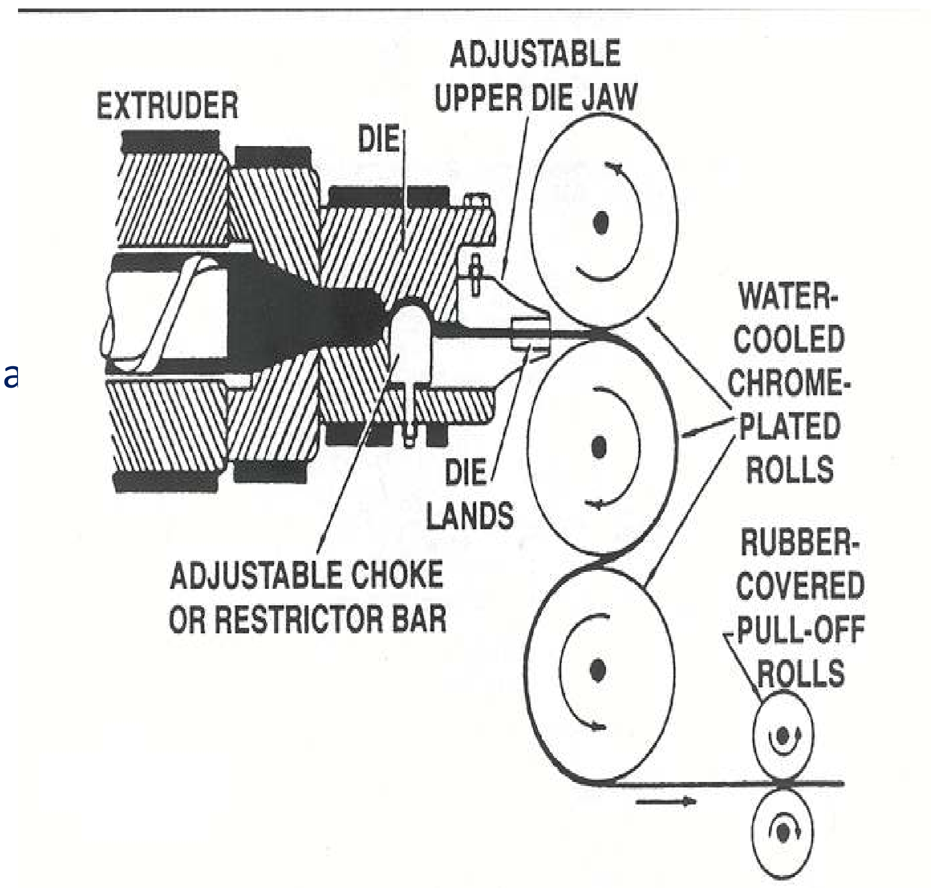
Thermoforming in a Nutshell - Sheet Extrusion



- The purpose of sheet extrusion is to transform thermoplastic resins into roll or sheet stock through a combination of heat and pressure.
- There are 3 primary ways of producing sheet:
  - Extrusion through a flat or coat hanger die onto casting rolls
  - Extrusion through an annular die onto a sizing mandrel followed by slitting and flattening
  - Calendaring

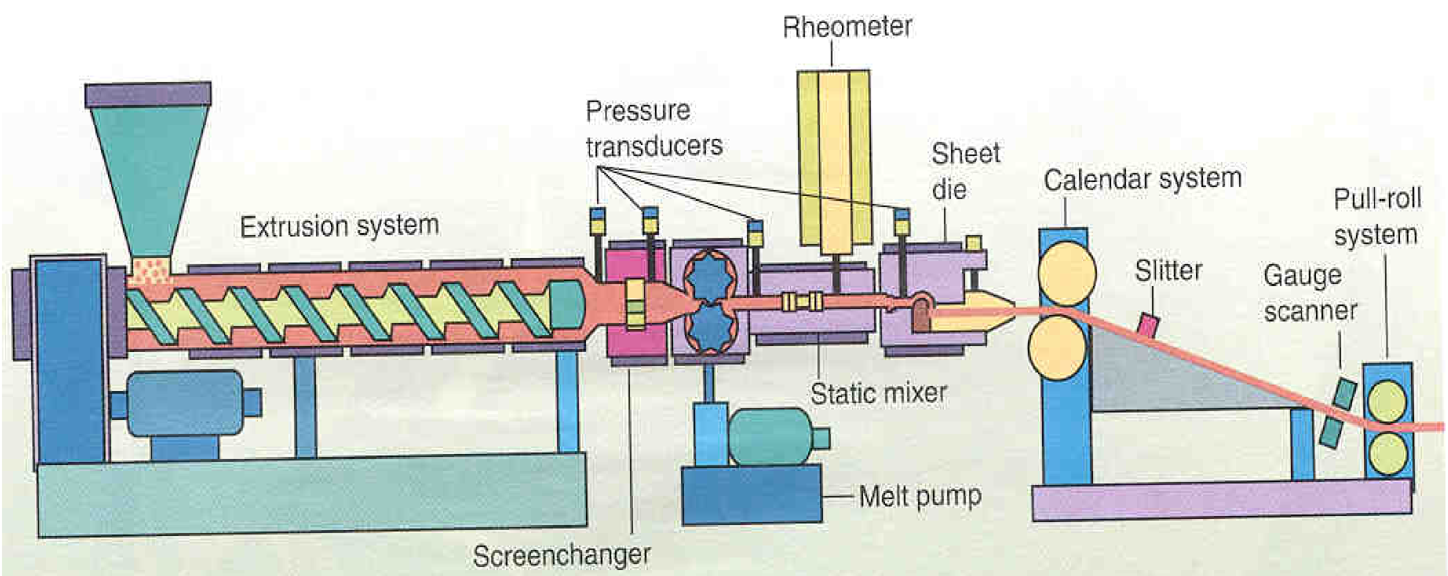
Thermoforming in a Nutshell - Sheet Extrusion

- The most common method of sheet production for thermoforming is the flat die method and this presentation will concentrate on this method.
- This process can be described as follows:
    - Resin is fed into an extruder where it is melted and conveyed to the die
    - The die acts to form the melt into an initia width and thickness
    - The sheet exits the die and is deposited onto a series of rolls to cool. The rolls determine the final sheet thickness and the cooled sheet is slit to the desired width.



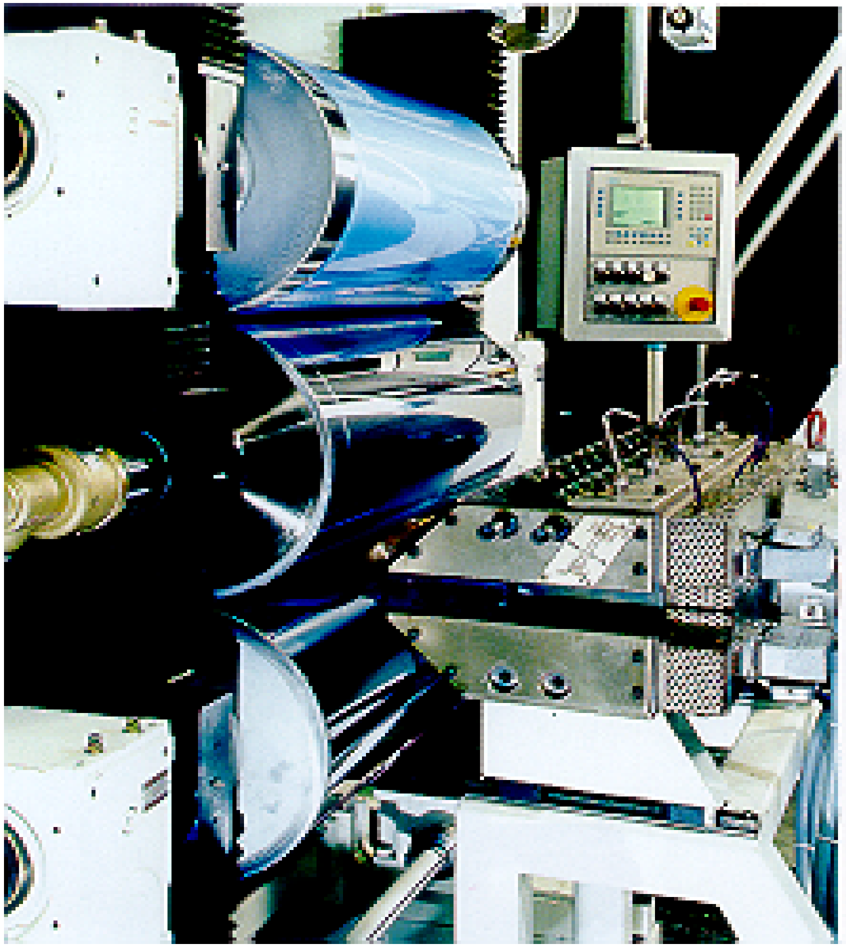
Thermoforming in a Nutshell
- Sheet Extrusion

- Although relatively simple in concept, sheet extrusion is crucial to the thermoforming process.
- Poorly extruded sheet will cause difficulty in the forming process and result in poor quality parts.
- Factors that must be controlled during sheet extrusion are:
  - dimensions (length, width, thickness) -surface orientation
  - Finish - toughness



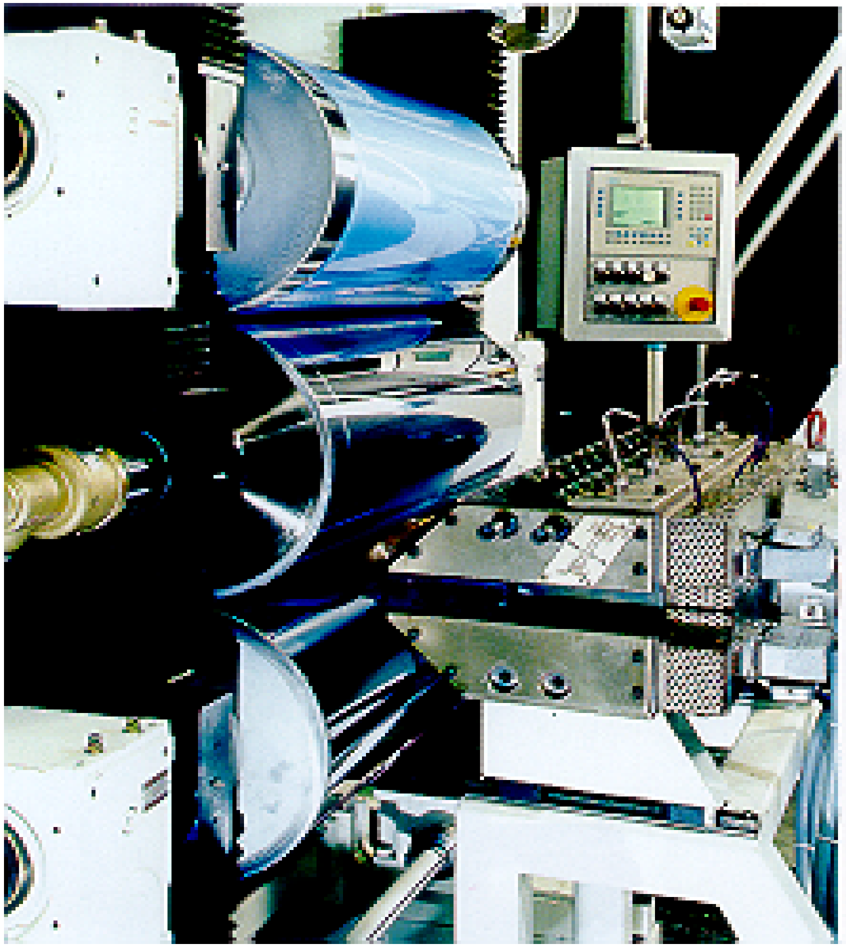
Thermoforming in a Nutshell - Sheet Extrusion

- Dimensions:
  - **Length** is controlled by cutting the cooled sheet using any of a variety of methods and is generally determined by whether the thermoforming process takes place in line or as a secondary process. If thermoforming takes place "in line", then the sheet does not have to be cut until after the forming takes place. If thermoforming takes place as a secondary or "off line" process then the sheet is generally cut to lengths that are determined by the size of the part plus the amount needed to clamp the sheet into the clamping frame.



Thermoforming in a Nutshell - Sheet Extrusion

- **Dimensions (cont'd.)**:
  - **Width** is primarily controlled by the die and the finishing rolls and secondarily by slitting the cooled sheet. Again, allowances must be made for the amount of material needed to hold the sheet in the clamping frame. Many dies have adjustable restrictors or "deckles" that are used to adjust the width of the sheet during the extrusion process. Shrinkage of the sheet in the cross machine direction as it cools can also affect width but can be easily compensated for during the extrusion process.
  - **Thickness** is primarily controlled by the die and secondarily by the finishing rolls.

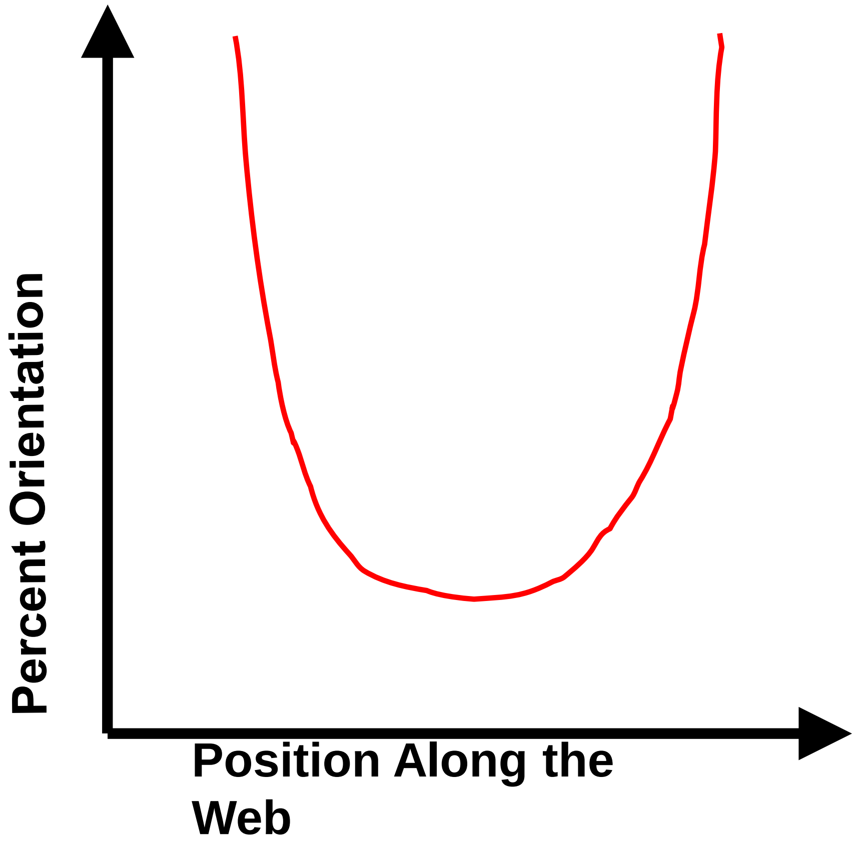


Thermoforming in a Nutshell: Orientation

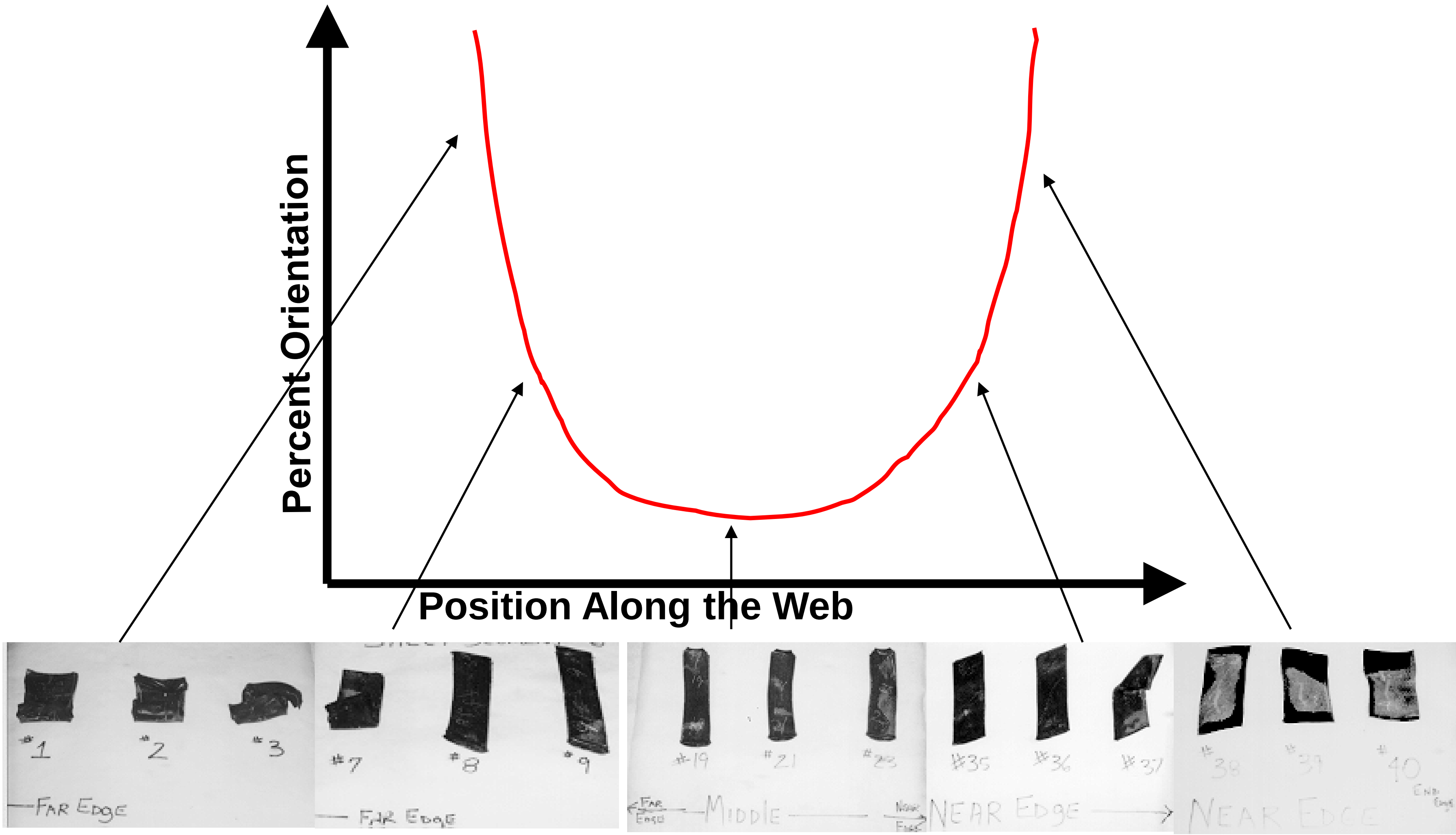
- Orientation is the term used to describe the stresses introduced into a thermoplastic sheet during the extrusion process. These stresses are caused when the resin is stretched during the extrusion process, causing the polymer molecules to line up or "orient" mostly in the extrusion or "machine" direction. Some orientation in the transverse or "cross-machine" direction is also introduced during the extrusion process.
- Since orientation can lead to thermoforming problems, it is important to know how much orientation has been introduced during processing.
- Orientation is typically measured by determining the amount of shrinkage experienced by a standard size coupon at a given temperature below the melting point of the polymer.
- The amount of shrinkage in the extrusion (MD) direction is calculated and reported as a percentage.
- Depending on gauge, HMW HDPE sheets can have orientation values between 35 and 70% and the amount of orientation will vary across the web.

Thermoforming in a Nutshell: Orientation

- Orientation across the web is generally describe as having a "smile" profile.
- The highest amount of orientation (greatest % shrinkage) occurs at the edges of the web and decreases to a minimum near the center.
- Most of the time, orientation across the web is fairly symmetrical. However, it does not have to be symmetrical.



Thermoforming in a Nutshell: Orientation



Thermoforming in a Nutshell: Orientation

Why is Orientation Important?

- Highly oriented sheet will:
  - pull free from clamps during the heating process, starting fires in the ovens
  - exhibit different amounts of sag during the heating process, requiring a lot of operator attention
  - exhibit differential shrinkage, causing warping in finished parts
- A high degree of orientation has also been shown to affect the physical properties of the finished part in some cases.

Thermoforming in a Nutshell: Orientation

Where Does Orientation Come From?

- In flat sheet extrusion, orientation is introduced in two main places:
  - the extrusion process
    - resin composition
    - the die
    - thickness
  - The cooling and finishing processes
    - roll stack
    - cooling baths
    - takeoff

Thermoforming in a Nutshell: Orientation

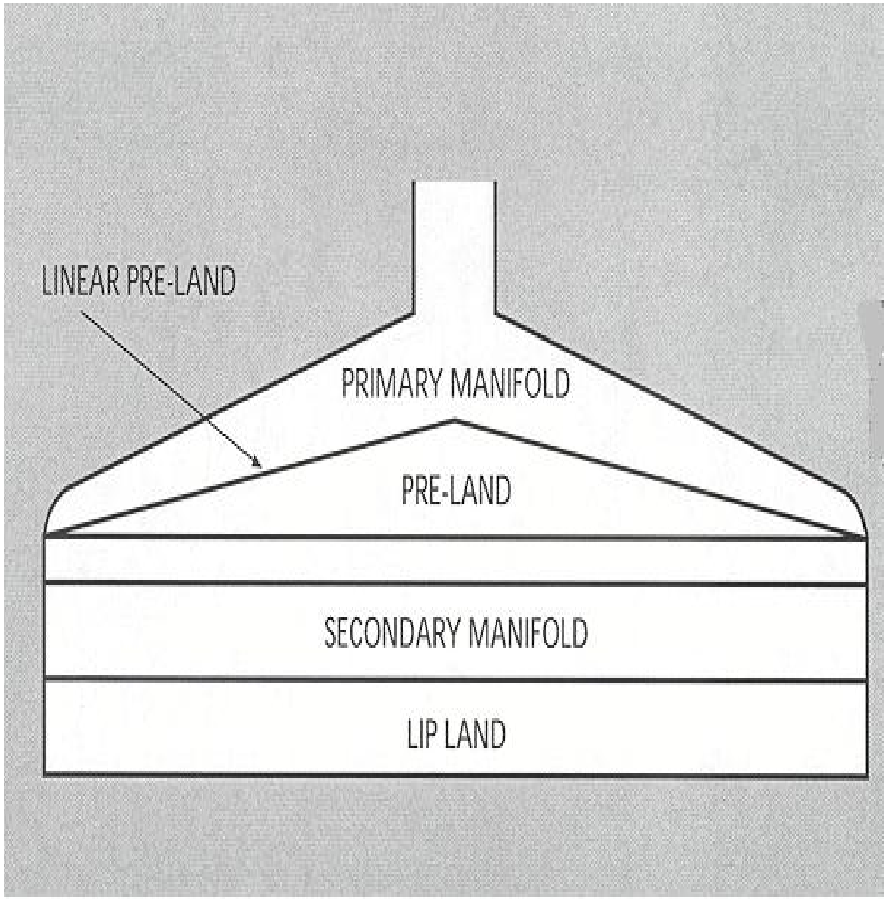
Orientation in the Extruder

- One of the major causes of problems in the sheet extrusion process is the use of non-uniformly mixed material. This is generally caused by trying to use large amounts(>50%) of regrind in the extrusion process and/or by attempting to push the output rates of an extruder. Incomplete mixing will lead to a melt stream with fluctuating viscosity, causing different flows through the die and regions of different composition in the sheet.
- Additionally, regrind begins to loose physical properties and this will also lead to sheet with varying physical properties, including orientation.

Thermoforming in a Nutshell: Orientation

Orientation in the Die

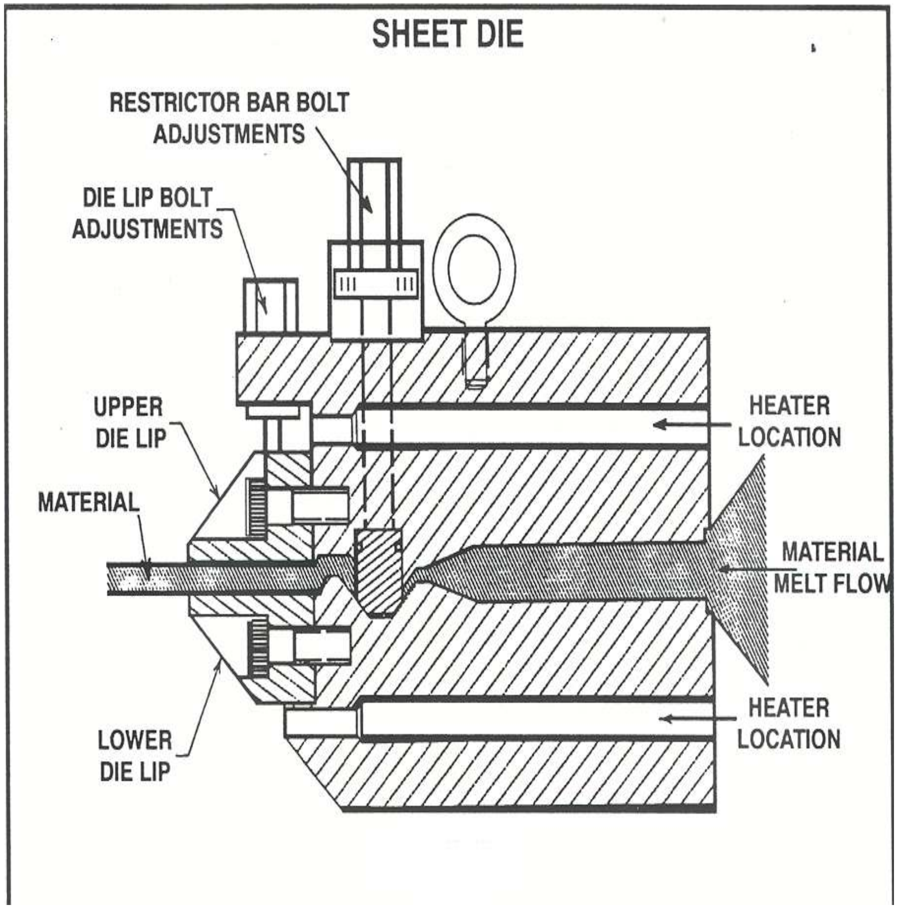
- A sheet die attempts to spread the polymer to predetermined width and thickness values.
- A standard coat hanger die introduces orientation as the polymer is spread out, with the material at the edges of the die experiencing more orientation due to drag effects



Thermoforming in a Nutshell: Orientation

Orientation in the Die

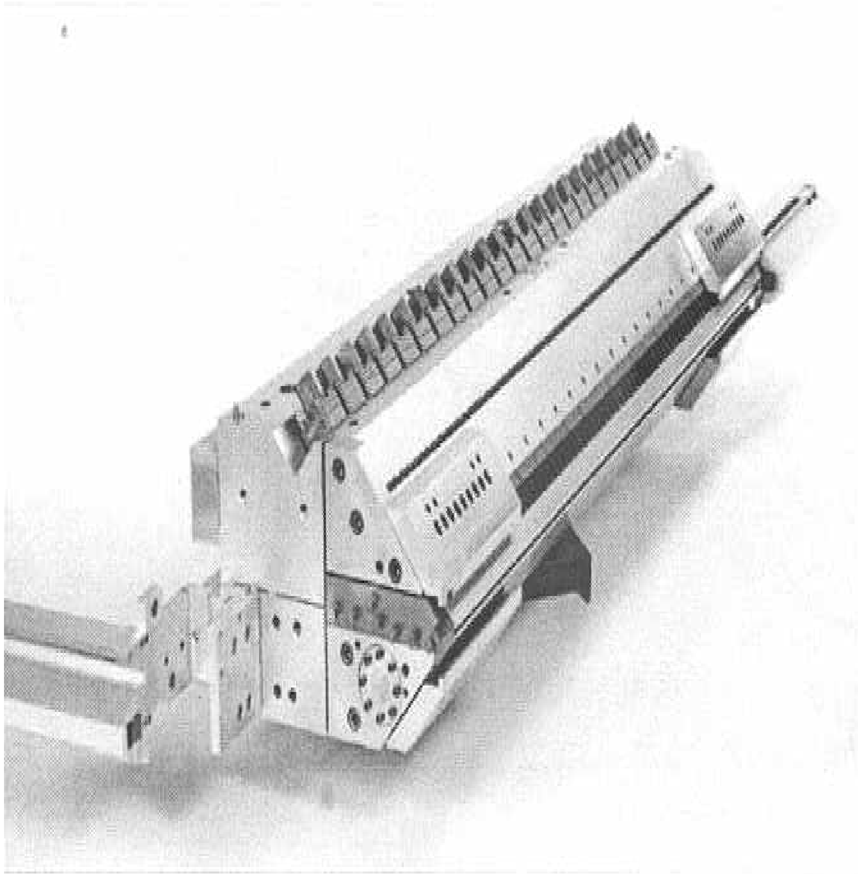
- Restrictor bars can also introduce differing amounts of orientation by changing the volume of flow in one area versus another and drag effects.
- The die gap must be carefully selected and monitored. If it is too large, orientation can occur from draw down effects and if it is too small, it will be difficult to achieve a uniform gauge.



Thermoforming in a Nutshell: Orientation

Orientation in the Die

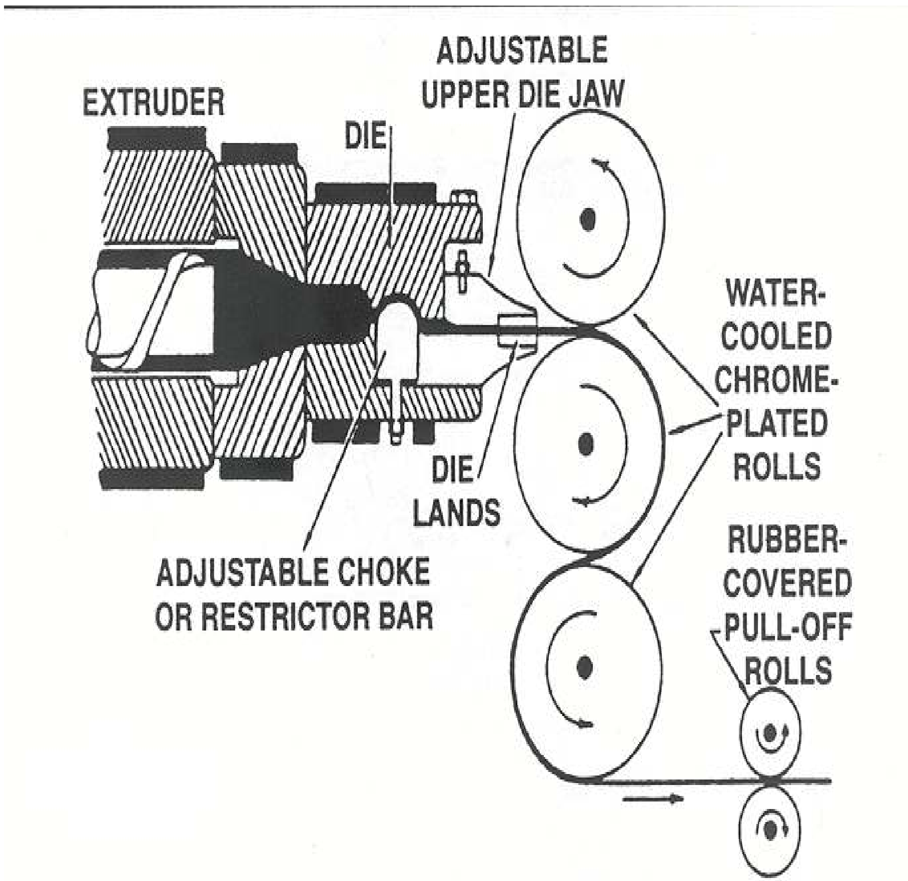
- Gauge should be set using the die and not the roll stack.
- Die gaps should be approximately 1.1 times the desired gauge in order not to starve flow to the rolls.



Thermoforming in a Nutshell: Orientation

Orientation in the Roll Stack

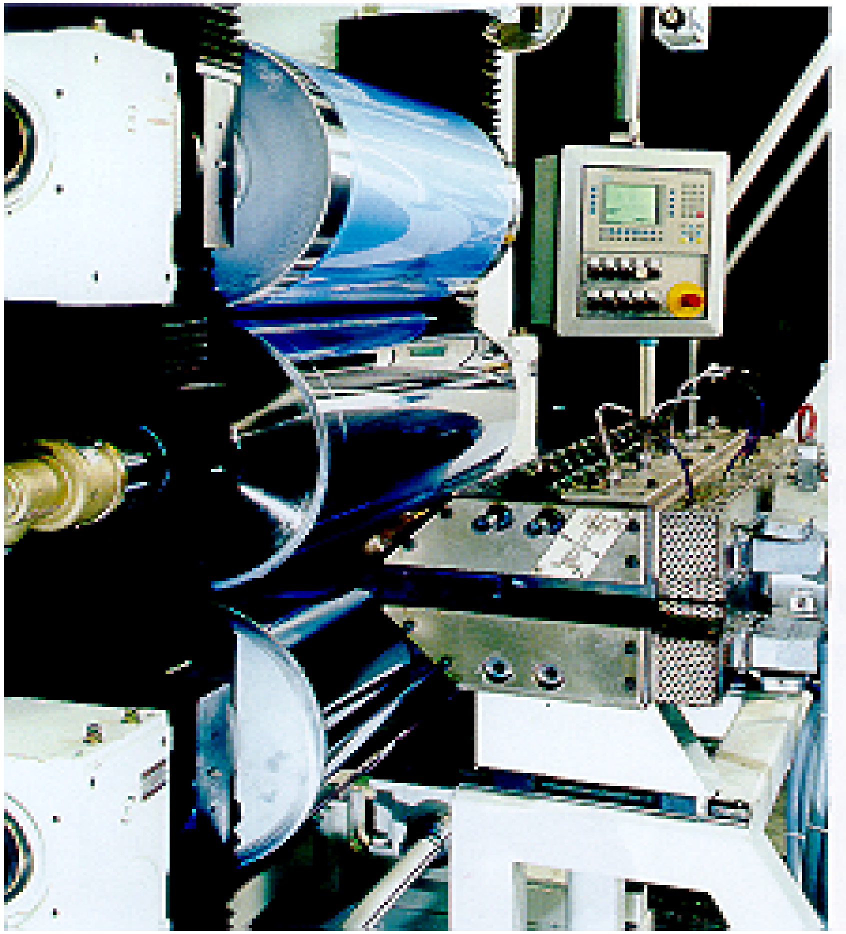
- Molten polymer is fed from the die to the roll stack where it is cooled and the final gauge is set, based on the gap between the rolls.
- A “bank” of polymer is established on the die side of the rolls which then draw the polymer through the rolls, cooling it in the process.
- As it cools, the polymer shrinks and this shrinkage should control the gauge, not the pressure of the rolls.



Thermoforming in a Nutshell: Orientation

Orientation in the Roll Stack

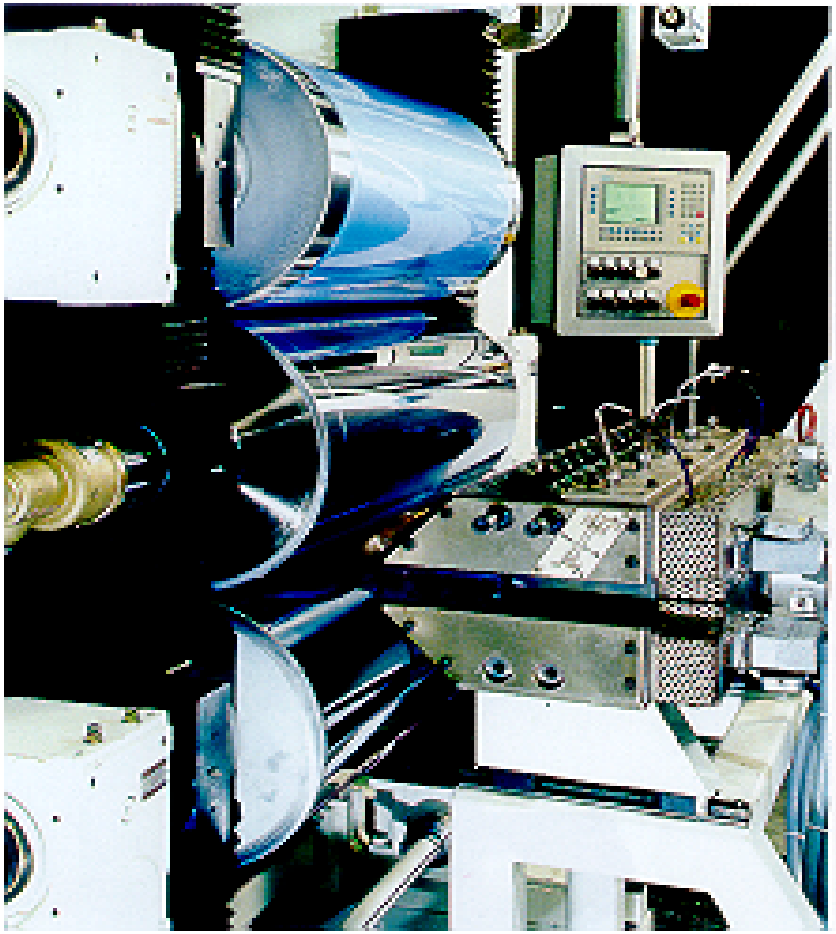
- The amount of bank is critical to the orientation in the sheet.
- Too large or too high of a bank will lead to calendaring which leads to high and variable orientation.
- Too small of a bank leads to high orientation as the polymer is stretched on the rolls.
- The gap across the rolls must be uniform as well.



Thermoforming in a Nutshell: Orientation

Orientation in the Roll Stack

- The rolls must be clean and must have good cooling. Blocked cooling channels can lead to variable orientation across the sheet.
- Roll temperature is an important variable as well. For a melt temperature of 450 F, the initial roll temperature should be around 200 F and the final roll should be around 160 F. This will, however, vary with gauge.



Thermoforming in a Nutshell: Orientation

Orientation After the Rolls

- Although the majority of any orientation is set after the roll stack, the sheet is still cooling and reaching equilibrium. Differential pulling by the take off system can still impart some orientation. It is important to make sure that the take off system is providing constant tension across the web.
- I do not recommend the use of cooling baths after the roll stack. The residence time is generally too short to cool the sheet completely.
- If the core is still warm compared to the outside, differential drawing can occur, introducing orientation.

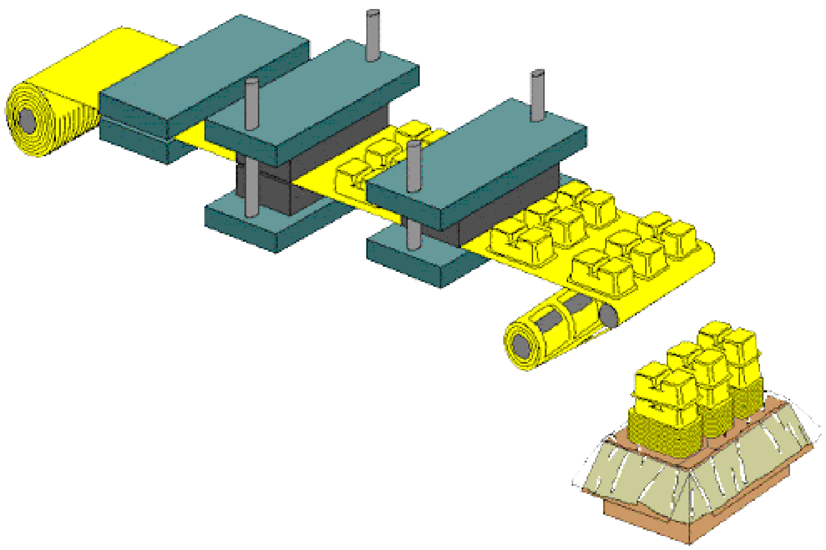
Thermoforming in a Nutshell: Orientation

Removing Orientation by Trimming

- Since the majority of orientation occurs at the edges of the sheet and varies quite a bit over a relatively short distance, one way to greatly reduce orientation is to trim it out.
- This requires the production of sheet that is substantially wider than is required and can lead to high amounts of regrind being generated. Nevertheless, it can be a useful strategy.
- In any event, sheet must be trimmed to remove the edges formed during extrusion and cooling.

Thermoforming in a Nutshell: Forming

- Forming is the process of turning the extruded sheet into the desired end use item.
- The sheet is heated to forming temperature and placed between molds where pressure is used to cause the sheet to stretch and assume the shape of the mold.
- Pressure may be applied by vacuum, compressed gas, plugs or matched molds.



Common Forming Temperatures

Rule of Thumb Starting Parameters for Various Thermoforming Resins (°F)					
Material	**Specific Gravity**	**Mold Temp**	**Lower Processing Temperature**	**Core Temperature**	**Max Processing Temperature**
ABS	1.07	185	260	280	400
Acrylic	1.15	185	300	325	425
Poly Carbonate	1.20	280	335	350	400
HDPE	0.95	180	280	340	430
Polypropylene	0.91	260	280	320	410
Polystyrene	1.06	185	260	275	350

The 10-10-5 Rule For Forming:

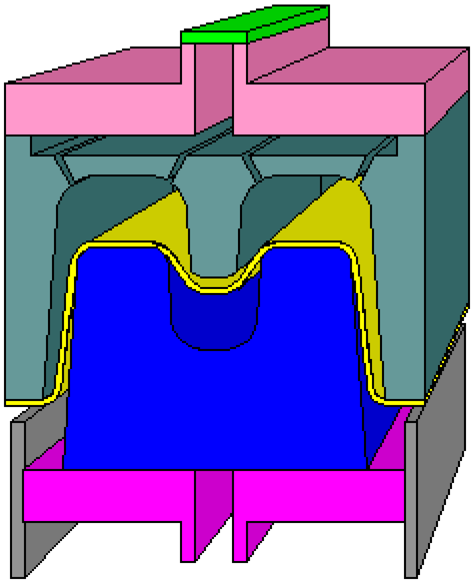
The difference in temperature variance across the sheet should meet the 10-10-5 rule:

- The first 10 applies to the10 locations on the sheet where temperature should be known: the four corners and centers of both sides.
- The next 10 refers to the suggestion that the temperature should not vary by more than 10°F at any of these 10 locations.
- Five (5) refers to the suggestion that the temperature at each location (top and bottom) should not vary by more than ±5°F.

For optimal forming, this conditions should be held throughout the heating, forming and cooling process.

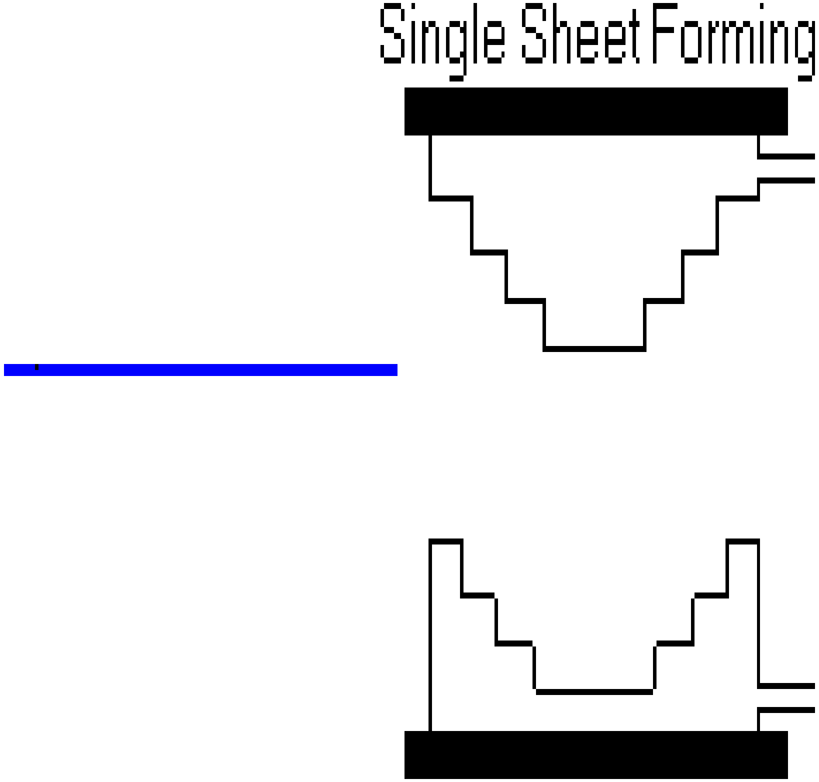
Thermoforming in a Nutshell: Forming

- There are 2 methods of thermoforming:
  - **Basic thermoforming** in which the heated sheet is formed in one operation
  - **Advanced thermoforming** in which the heated sheet is stretched prior to forming
- The advantages and disadvantages associated with each method are beyond the scope of this presentation.



Thermoforming in a Nutshell: Forming

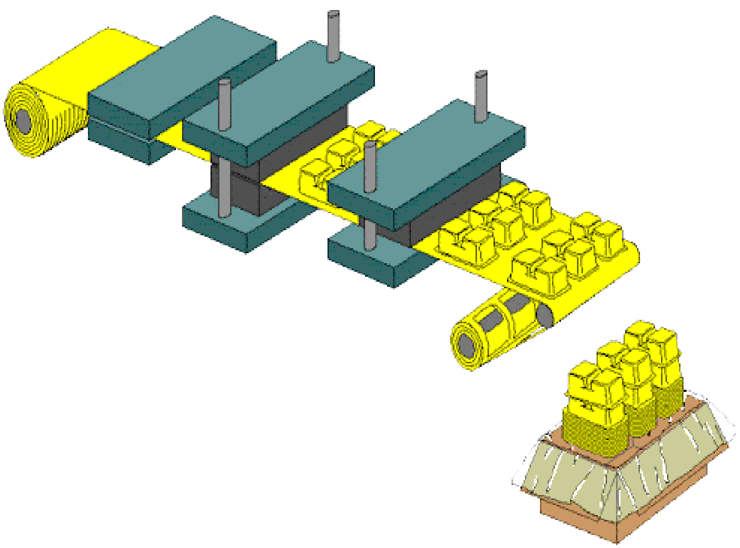
Matched Mold Forming uses a set of matched male and female molds to compression mold the heated sheet. Vacuum assist is not generally necessary



Thermoforming in a Nutshell: Forming

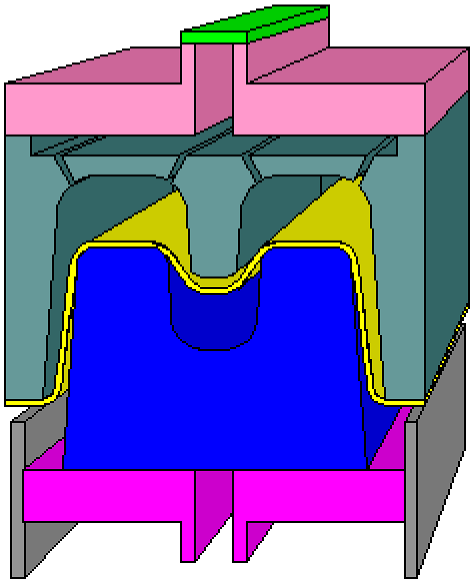
Advanced Thermoforming methods:

- Plug-Assist Forming
- Vacuum Snap-Back Forming
- Slip-Ring Forming
- Twin Sheet Forming



Thermoforming in a Nutshell: Forming

- **Plug Assist Forming** – the sheet is clamped to a mold and a plug forces the sheet part way into the mold, vacuum is then applied to draw the sheet into contact with the mold.
- **Vacuum Snap Back Forming**– the sheet is clamped to the mold, a partial vacuum is applied to stretch the sheet and then the sheet is forced back onto the mold by releasing the vacuum on one side and applying a vacuum to the other side of the mold.

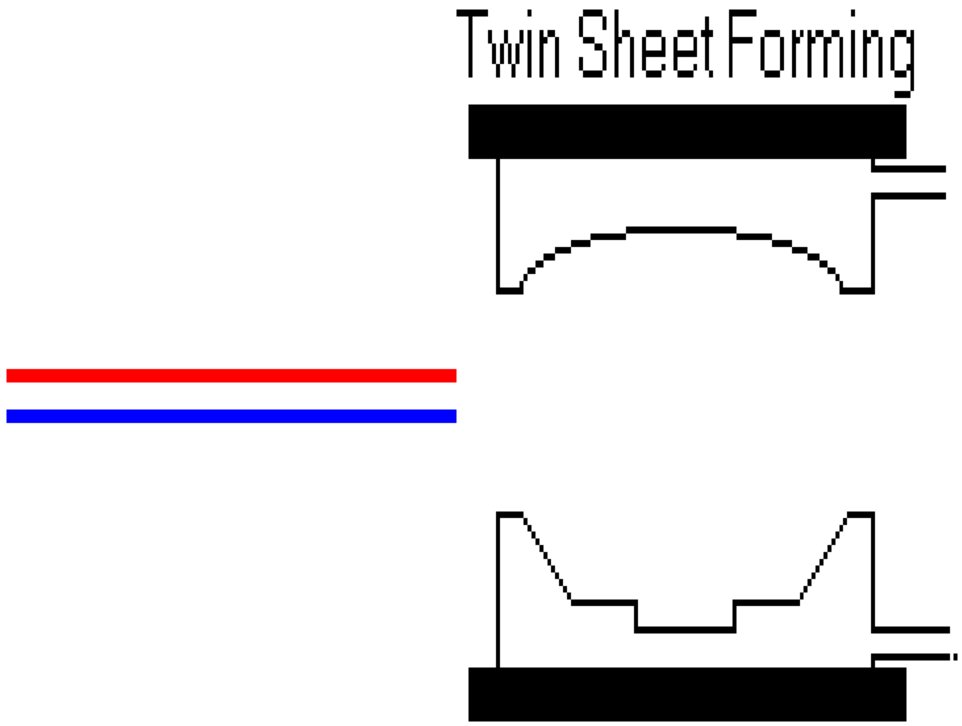


Thermoforming in a Nutshell: Forming

- **Straight Vacuum Forming** consists of placing the heated sheet on a female mold with a vacuum removing the air between the sheet and the mold.
- **Drape Forming** consists of placing the heated sheet on a mold, a vacuum is applied to remove the air from the mold and a gas is used to push the sheet into the mold and hold it until it cools
- **Pressure Forming** – the sheet is forced into the mold using a high pressure gas. Vacuum may be used to remove air from the opposite side of the mold or the mold may be vented.
- **Free Draw Forming** uses gas pressure or vacuum to form a simple part with out a mold.
- **Slip-Ring Forming** – the heated sheet is clamped to a spring loaded ring that is drawn over the mold, the sheet is stretched to approximate the shape of the mold and vacuum is applied to finish the process.

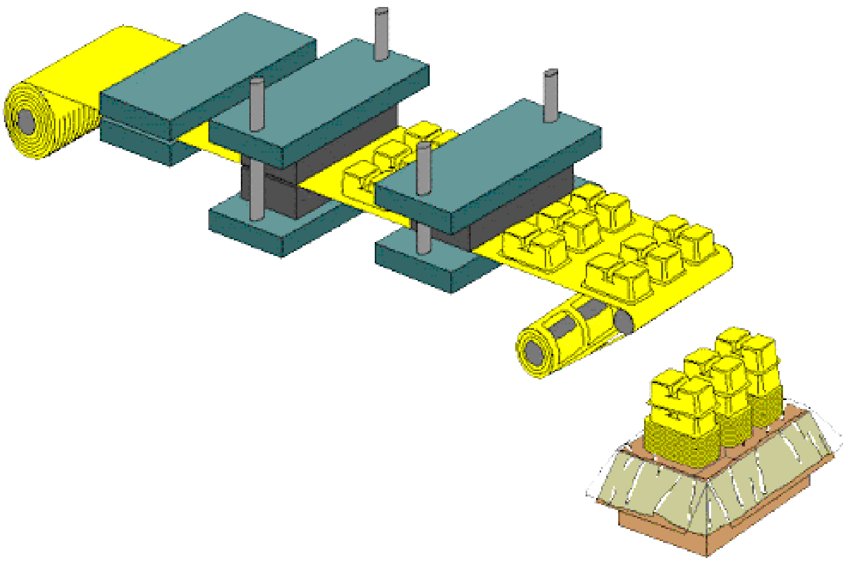
Thermoforming in a Nutshell: Forming

- **Twin Sheet Forming** – used to produce double-walled parts, hollow parts or structural parts requiring rigidity. Two heated sheets are held in a clamping frame, two female molds are used and vacuum is applied to the molds at the same time as gas pressure is applied between the sheets.



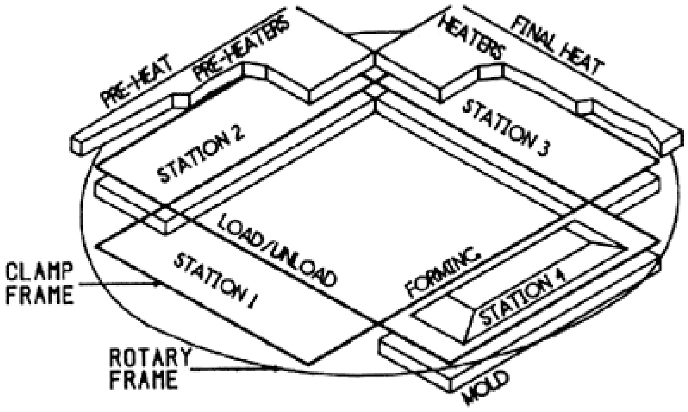
Thermoforming in a Nutshell: Forming

- Thermoformers can be fed in two ways:
  - **Offline** – where it is fed by cut sheet or rolls
  - **In-line** – where the former is fed from the extruder



Thermoforming in a Nutshell: Forming

- In offline processing, the sheet is extruded as a separate operation, surface finished and cooled on a three roll stack.
- The sheet is slit to remove edge beads and to achieve the desired width.
- It is then either wound into rolls and stored or cut into flat sheets that are stacked prior to storage.
- The thermoformer is then fed using either the sheets or from a roll that is unwound in a controlled fashion.



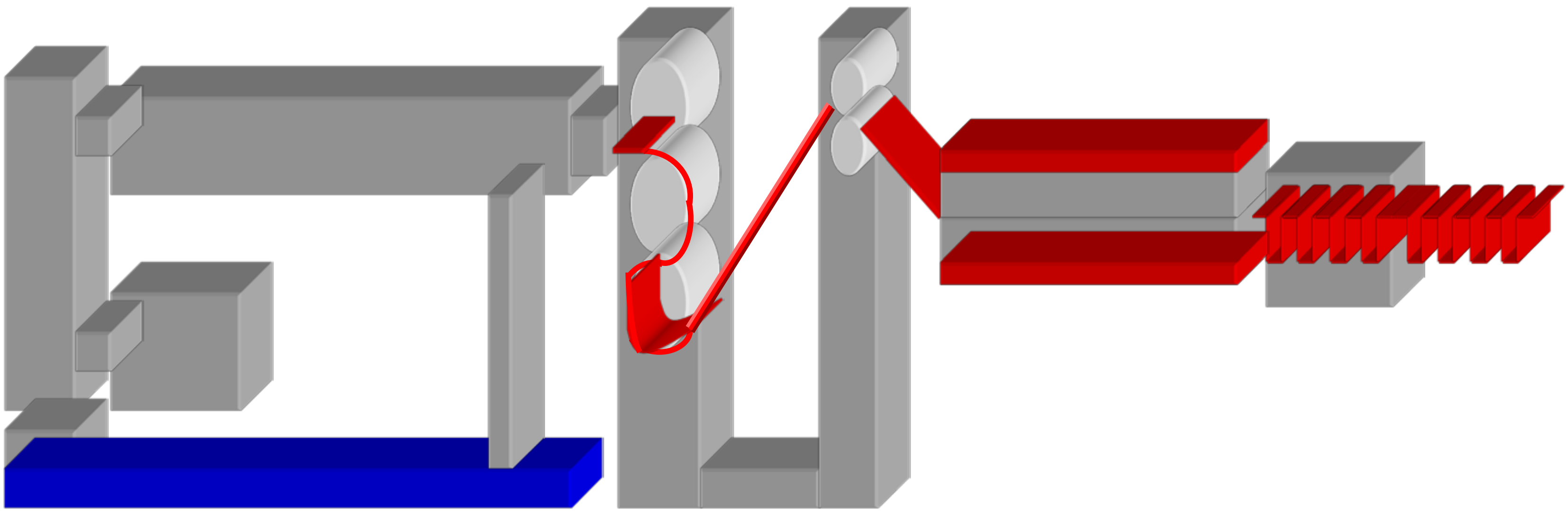
Thermoforming in a Nutshell: Forming

- There are basically three types of in-line thermoforming systems:
  - Tandem In-line systems
  - Hot In-line systems
  - Rotary In -line systems

- The advantages and disadvantages associated with each system are beyond the scope of this presentation.

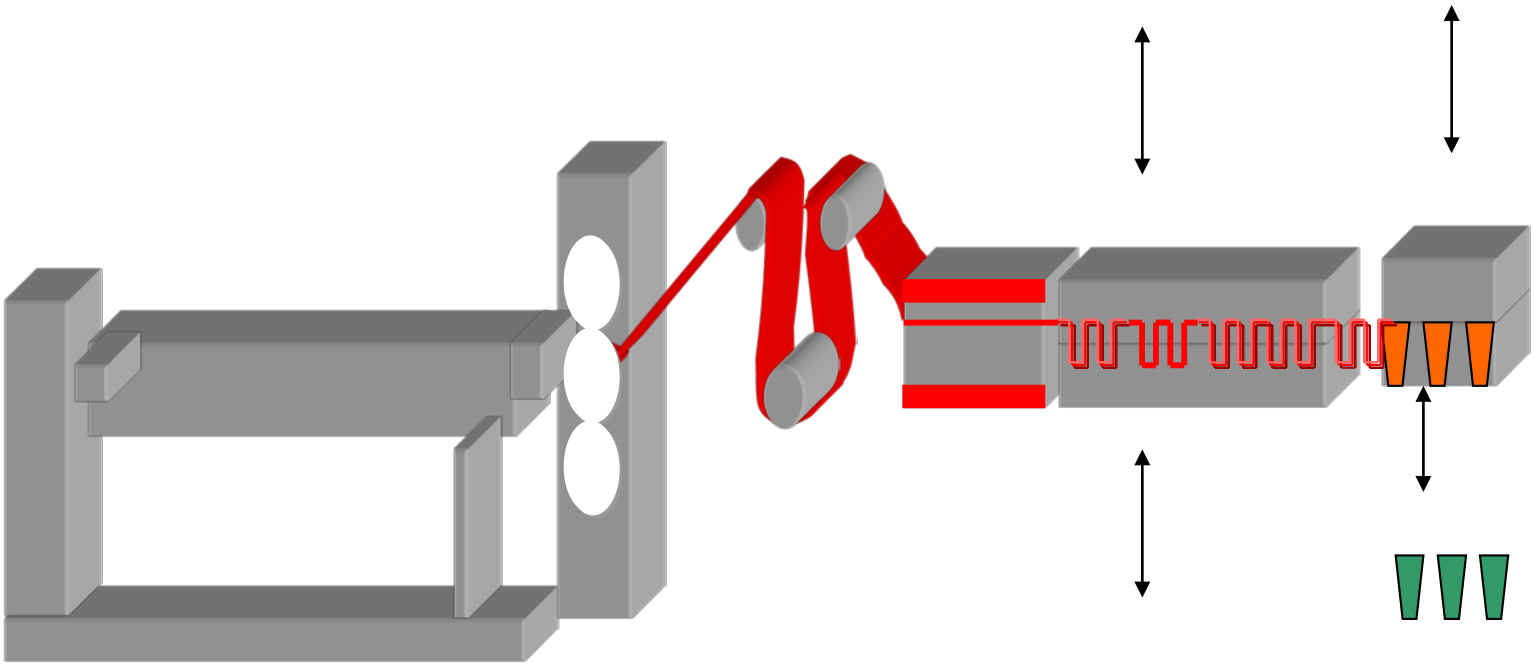
Thermoforming in a Nutshell: Forming

Tandem in line systems combine a sheet line minus an edge trimmer and a winder system with a thermoforming system.



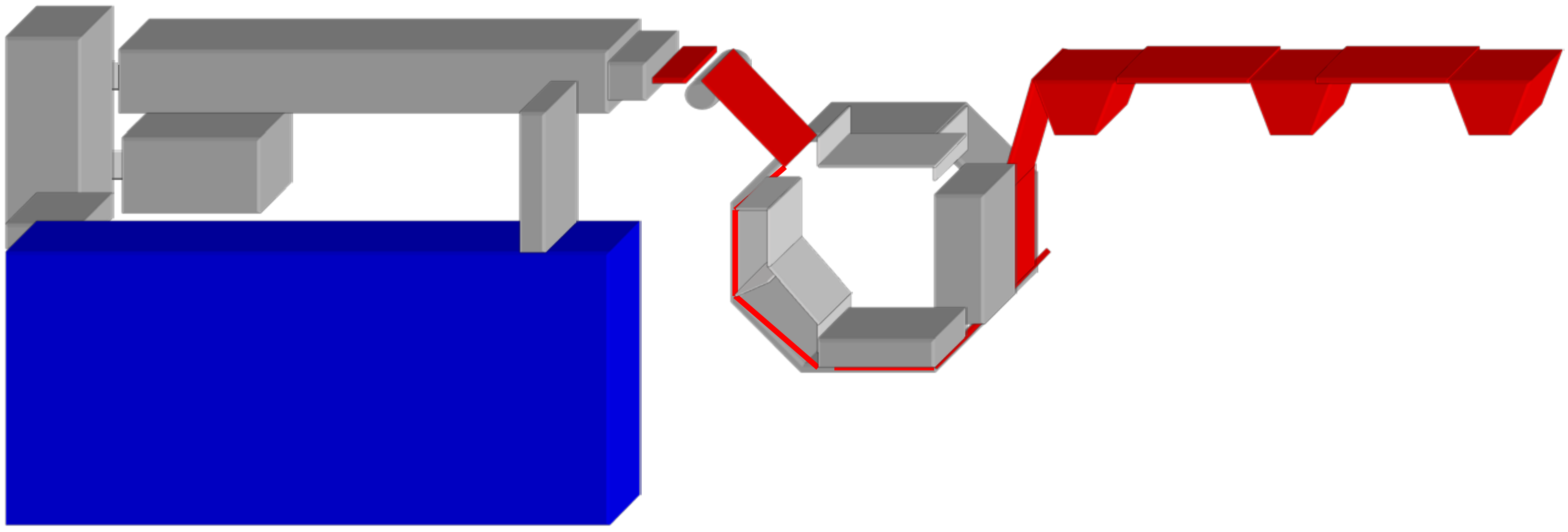
Thermoforming in a Nutshell: Forming

Hot in line systems combine a sheet line minus an edge trimmer and winder with an in line heating system and thermoformer



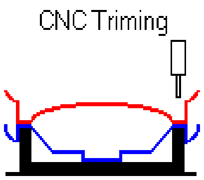
Thermoforming in a Nutshell: Forming

Rotary in line systems extrude the sheet directly onto a cooled vacuum forming drum. Good for shallow draw parts.



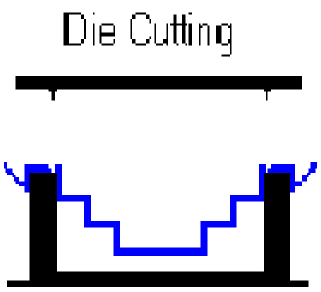
Thermoforming in a Nutshell: Trimming / Finishing

- Once the part has been formed, it generally needs to be removed from the web or have excess material removed from the edges.
- This process is referred to as trimming.
- Trimming can be accomplished manually or automatically.



Thermoforming in a Nutshell: Trimming / Finishing

- Alternatively, parts can be die cut cut in order to remove excess material or to achieve a desired size.
- This is the quickest and easiest method and for simple parts, is the method of choice.



Thermoforming in a Nutshell: Trimming / Finishing

- Parts may also be trimmed using a toothed tool such as a circular saw or they may be cut with an abrasive wheel.
- Of the two, the abrasive wheel generally gives smoother edges and avoids cracks and chips in the finished part.
- A number of other methods for trimming exist as well. Some of these are:
  - Nibble cutting
  - Hot jet gas cutting
  - Laser cutting
  - Water jet cutting
  - Hot wire cutting
- All have their advantages and disadvantages.
- Finally, the finished part may be drilled, painted or plated or a decal or other decoration may be applied.