process is often used for transparent parts, where good optics are required. The process works best with high-hot-strength materials such as cast acrylic and butyrate; however, polycarbonate and ABS have been successfully formed. Applications include display cases, windows, and light lenses (see Fig. 8-1).

Stretch forming. In this process, the sheet is heated to forming temperature, moved to the mold surface, and then, by pulling on the sheet edges, stretched over the male mold surface. It is then clamped in place for cooling. Acrylic or polycarbonate transparencies are frequently formed by this process. The method is also used when wrapping plastic around a mandrel to form a “U” or coiled shape (see Fig. 8-2).

Matched molds. This process uses two molds with matched or mated surfaces that compress the hot sheet between them. Depending on the material’s elongation, platen press forces are 5–60 psi (34–414 kPa). Some fiber-reinforced materials may require higher pressures. Tooling costs in this process are higher, with longer lead times, because two mold surfaces are needed. Furthermore, the higher operating pressures demand stronger molds. However, with this process, details are molded on both part surfaces, and with properly temperature-controlled aluminum molds, the parts cool more quickly and with fewer residual stresses. Foams and fiber-reinforced materials are typically formed by this process (see Fig. 8-3).

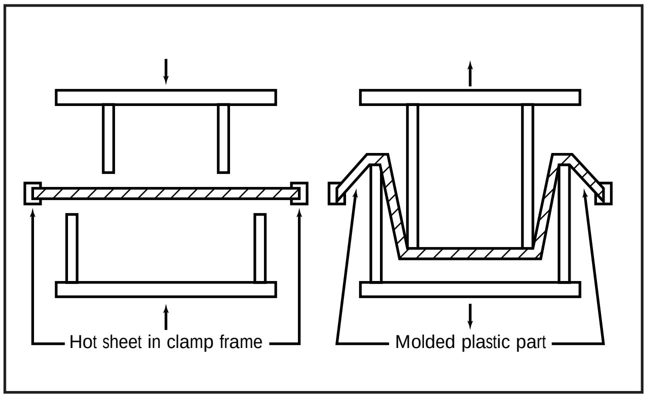

Fig. 8-1 Ridge forming.

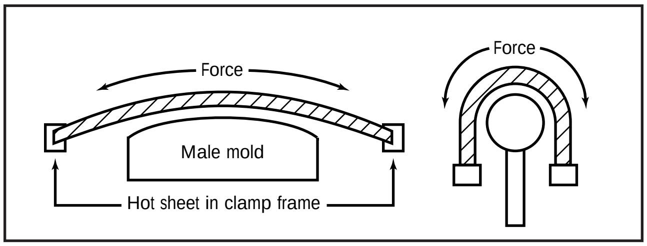

Fig. 8-2 Stretch forming.

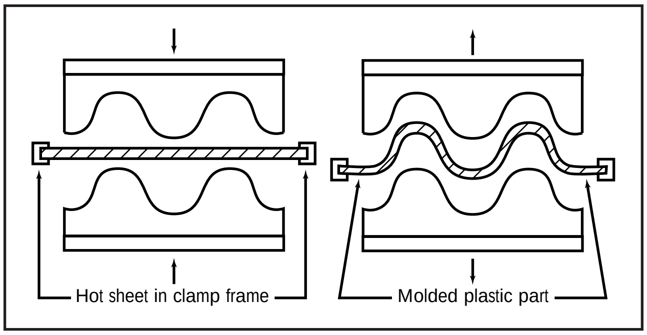

Fig. 8-3 Matched molds.

Strip heating. Strip heating is widely used to make single-plane bends in sheet thermoplastic. A tubular heater or coiled nickel-chrome resistance wire (approximately 0.025 in. [0.64 mm] in diameter) is inserted into a slot in the surface of a large platen. The plastic sheet, laid on the platen surface, is warmed in only the narrow straight line of the heater. The sheet is then bent and placed in a jig to hold its shape while cooling. Additional heaters can be aligned in the platen to create multiple bends in the part. For high-production requirements, multiple heater platens and jigs are used to maintain production speed (see Fig. 8-4).

For materials greater than 0.125 in. (3.18 mm) thick, applying heat from both sides of the part eliminates surface blistering. One side is heated for 35–45% of the cycle, the part is flipped for an additional 45–55%, and the first side is again heated for the balance of the cycle. Alignment blocks are fixtured on the platen to ensure accurate location of the sheet over the heater strips.

Straighter, sharper bends are created in thick materials if a 90° V-groove, for right angles, is machined on the inside surface of the sheet prior to heating (see Fig. 8-5).

Vacuum Forming

Drape vacuum forming. The most common thermoforming method is drape vacuum forming. A male or female mold is moved into the hot sheet, and a vacuum is used to remove the resistant air trapped between the sheet and the mold. Atmospheric pressure (14.7 psi [101 kPa]) is used to move the heated sheet into contact

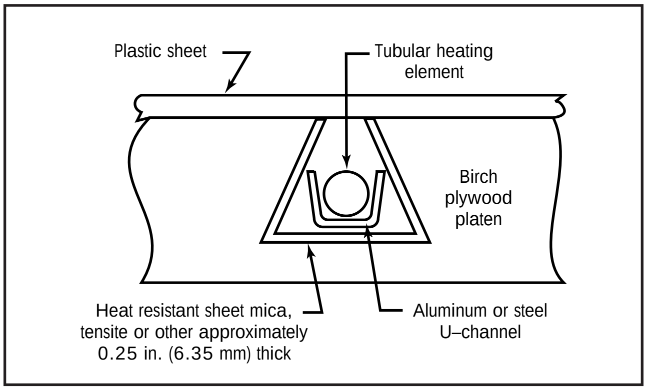

Fig. 8-4 Strip heating.

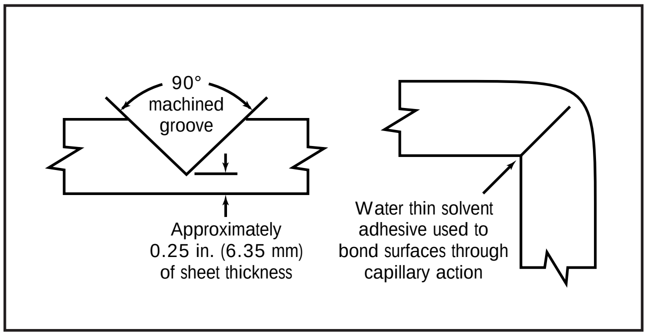

Fig. 8-5 V-groove for sharper bends.

with the mold, and holds the sheet until it cools below the heat distortion temperature.

In this process, good material distribution, or equal thinning, depends on the following variables:

- Uniform sheet heating.
- Mold temperature.
- Material type.
- Rate of air evacuation (vacuum and/or compressor air).
- Prestretching of the sheet.

By maintaining the mold temperature approximately 10° F (6° C) below the heat deflection temperature of the material, and by using a fast air evacuation (vacuum and/or pressure), the best material distribution is attained. A temperature-controlled mold enhances part quality.

In drape vacuum forming, as the hot sheet comes in contact with any portion of the mold, that area of the sheet cools faster than the untouched area. Hot strength increases where the sheet touches the mold. This causes most of the sheet stretching (and thinning) to come from the untouched area.

There are a variety of methods for prestretching the sheet to ensure uniform material distribution.

Male mold—snap back. This is a common process because the assist box can be made quickly and inexpensively. The assist box is moved into the hot sheet, causing a seal around its perimeter. A vacuum is introduced into the box, drawing the still-hot material into a bowl shape in the box. A photoelectric eye is often used to control the depth of the bowl or bubble. The mold is then pushed into the bubble, allowing the platen on which the male mold is mounted to seal the hot material to the edge of the box. At this time, the vacuum is reversed from the prestretch box to the mold, causing the material to snap back to the mold surface. The box is then moved away from the part to eliminate interference with the cooling fans (see Fig. 8-6).

Male mold—billow plug. This setup is similar to that of the snap back except the box is pressurized, causing the hot material to billow out from the box in a bubble shape. The billow height, about 75% of the mold height, is adjusted with the first few sheets of formed material. The mold is moved into the bubble of material, which wraps itself around the mold until the platen has sealed the material to the box edge. The vacuum is then applied to the mold, drawing the material into contact with the complete mold and platen surface. This process produces a more uniform wall thickness than the snap back but is more difficult to adjust for proper production. Pressure in the box must be controlled by relief valves as the mold is forced into it (see Fig. 8-7).

Female mold—plug assist. When prestretching the material into a female mold, a plug assist is used. The plug is built from wood or syntactic foam, materials with low-heat transfer properties, to the approximate shape of the mold cavity. A clearance of about 0.50 in. (13 mm) is provided between the plug and mold surfaces. The female mold is mounted above the sheet frame to provide a seal around the perimeter of the mold without allowing the sagging sheet to touch the mold surface. The plug is then moved into the hot

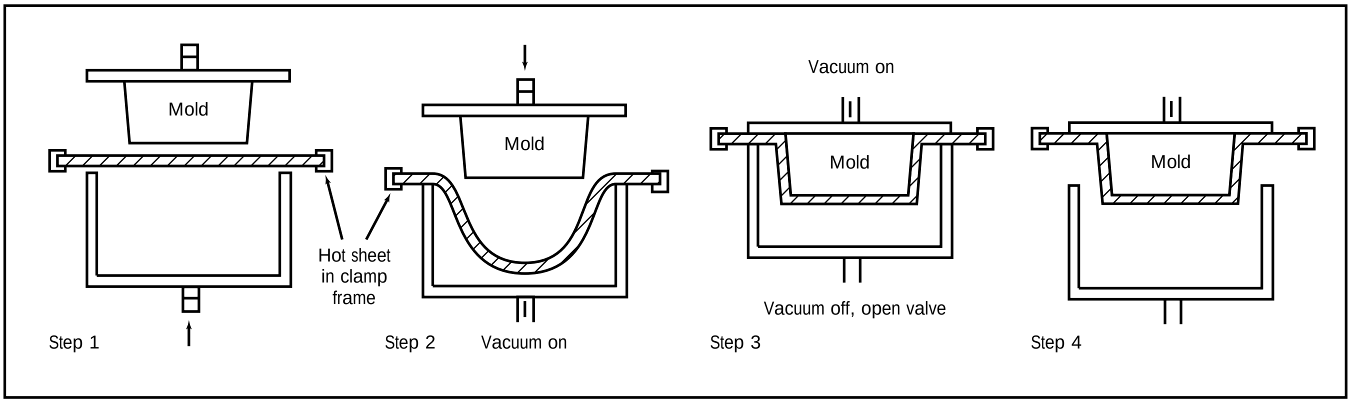

Fig. 8-6 Male mold—snap back.

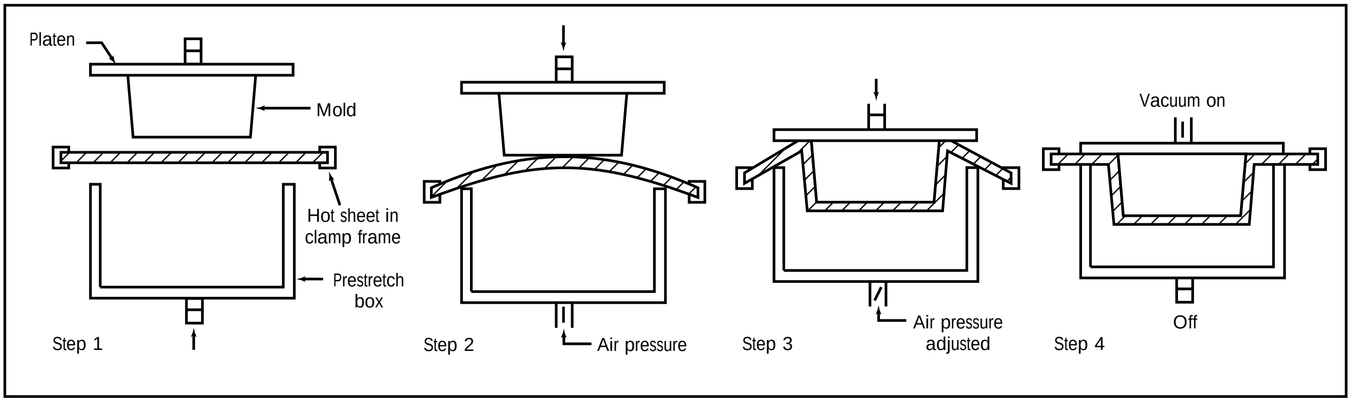

Fig. 8-7 Male mold—billow plug.

sheet, pushing it into the mold cavity. Air that is trapped in the mold causes the sheet to billow around the plug as it is compressed. When the plug has pushed into the mold, stopping just short of touching the bottom of the cavity, vacuum is rapidly applied in the mold, transferring the sheet from the plug to the mold (see Fig. 8-8).

Female mold—billow snap back. When it is impractical to use a plug assist, some prestretching can be achieved by introducing pressurized air into the mold after a seal is made with the hot sheet, creating a bubble away from the mold. A bubble that is about 75% of the cavity depth is recommended. The air pressure is then reversed to pull a vacuum, and the prestretched hot material snaps back into the cavity of the mold. This process adds thickness to the bottom of the part (see Fig. 8-9).

Female mold—billow plug assist. This process is a combination of the previous two methods. It is the best way to achieve reasonably uniform wall thickness in large, deep parts. However, it is often difficult to coordinate all the elements of this procedure to effect a perfect draw of the material. The plug assist should travel into the hot bubble fast enough so that the compressed air in the mold keeps the material against the plug until it has completed its movement. At the same time, the compressed air must be bled from the cavity to prevent "blow outs."

Free-draw vacuum forming. Free-draw vacuum forming is used when the best optics or surface finish is required. The portion of the sheet that does not touch the forming frame yields optics equivalent to those of the original sheet. In this process, a vacuum box is built with the top opening in the shape of the formed part's flange or open side. The box is moved into the hot sheet, and a vacuum is introduced in the box. The ambient air pressure pushes the material into the box in a spherical bubble; the deeper the vacuum, the greater the bubble. Only the material in the clamp frame and on the perimeter of the vacuum box touches a mold surface; therefore, the entire bubble remains free of "mold markoff" or distortion. A photoelectric eye is often used to control the vacuum and thus the depth of the part (see Fig. 8-10).

This process is widely used to produce skylights, windscreens, viewing windows, and other industrial parts. Close-tolerance dimensions are not possible with this vacuum-forming technique.

Twin-sheet forming. This process is used to form hollow parts. It is competitive to blow molding in forming large, heavy-wall parts. Typical twin-sheet-formed parts are pallets, dunnage containers, double-walled parts that require great rigidity (such as large machine housing walls or platform floors), and air plenums or ducts. For extra rigidity, twin-sheet parts can be filled with rigid foam, or, in some cases, have metal or wood inserts placed in the part during forming.

In twin-sheet forming, two hot sheets are moved between two opposing cavity or female molds and vacuum formed into their respective molds. The molds are then pressed together with the hot-formed sheets between them. The pressure of the two molds squeezing the sheets together effects an excellent bond similar to that achieved by thermowelding. Twin-sheet molds are designed to create a bonded surface around the perimeter of the part, and at various selected areas throughout the part, as required for strength and appearance. The sheet surface must be at forming temperature when the bonding occurs.

Successful twin sheeting relies on the following mold design and construction considerations:

- Blow pins are required, to introduce and remove compressed air from the interior of the part to facilitate interior cooling.
- All mating perimeter and interior surfaces must be parallel and of the proper width to allow material movement during the squeezing process.
- Some molds require electric heating strips behind the mating surfaces to maintain this area of the mold at higher temperatures and effect an acceptable bond.

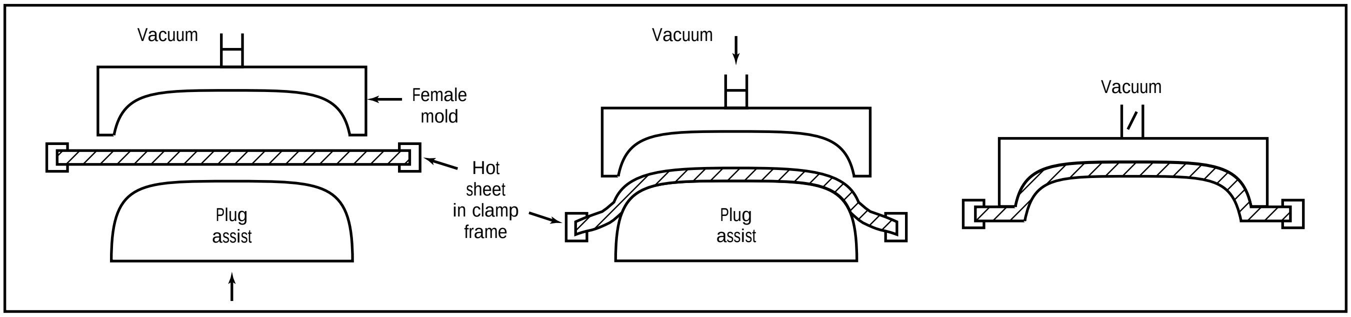

Fig. 8-8 Female mold—plug assist.

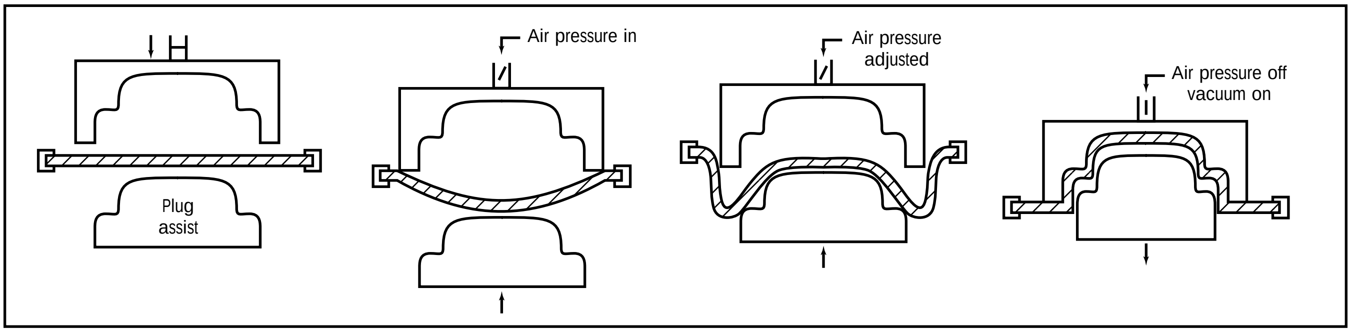

Fig. 8-9 Female mold—billow snap back.

Twin-sheet forming can be done with light-gage materials (0.010–0.060 in. [0.25–1.52 mm] thick) on continuous roll-fed machinery (see Fig. 8-11) and with two other methods on three machinery designs using heavy-gage materials.

Single-station/single-oven forming machine. In this process, two sheets of material, each not exceeding 0.100 in. (2.54 mm) thick, are clamped together in a single frame with a flat air nozzle projecting between the sheets. The sheets then enter the oven, consisting of upper and lower heaters, and each sheet is heated from one side only. During the heating and forming cycle, hot air is blown through the nozzle between the sheets. This is done to introduce heat to the back side of the sheets, to prevent them from sticking together, and to introduce ambient air to the back side of the sheets during the subsequent forming and sealing sequences (see Fig. 8-12).

When the frame removes the sheets from the oven, molds press into the sheets from opposing sides, vacuum draws the sheets into the molds, and the pressure of the joining molds effects the seal. This is the least desirable method of twin-sheet forming, because the sheets are heated from the sides opposite to the surfaces that require critical bonding temperatures.

Double-ended ovens on a single-station forming machine. This machine has a single forming station with two sets of clamp

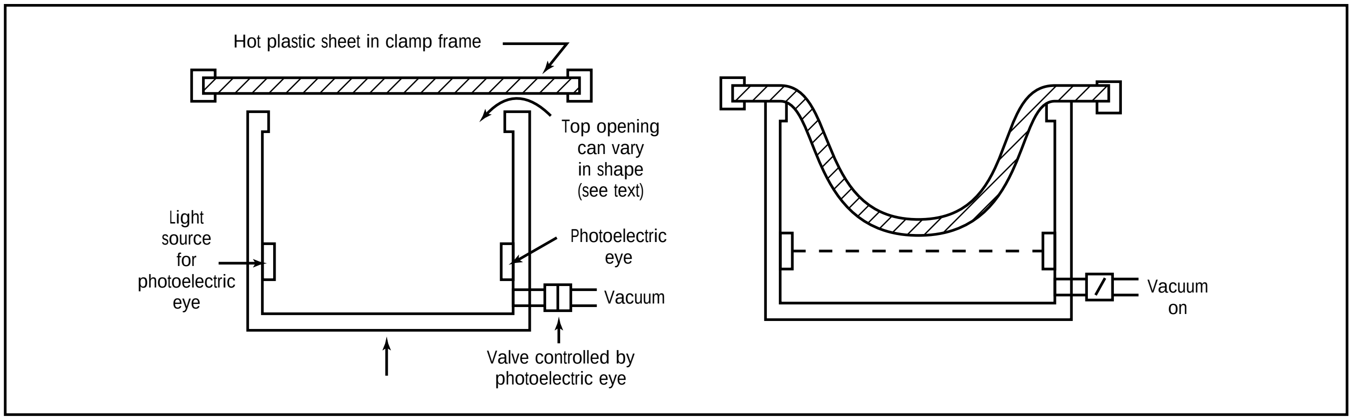

Fig. 8-10 Free-draw vacuum forming.

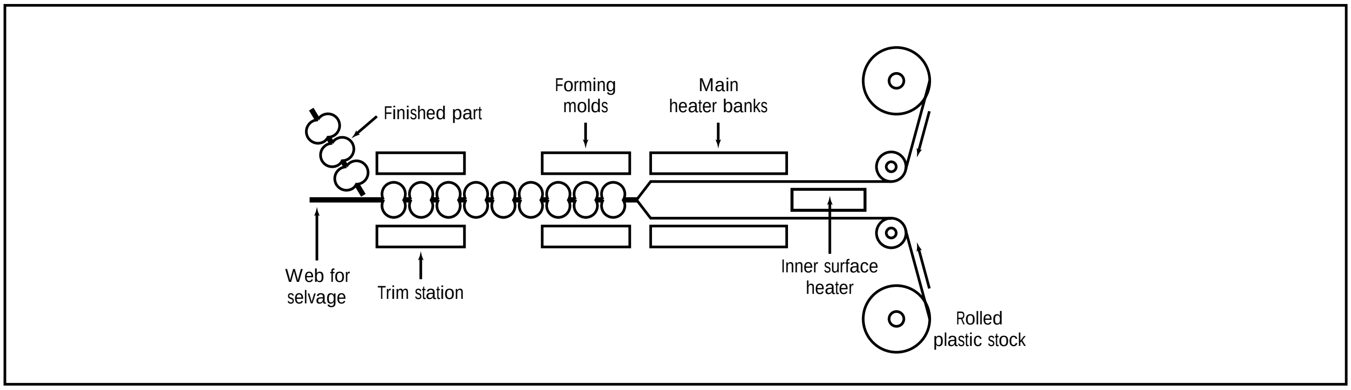

Fig. 8-11 Twin-sheet forming on continuous roll-fed machinery.

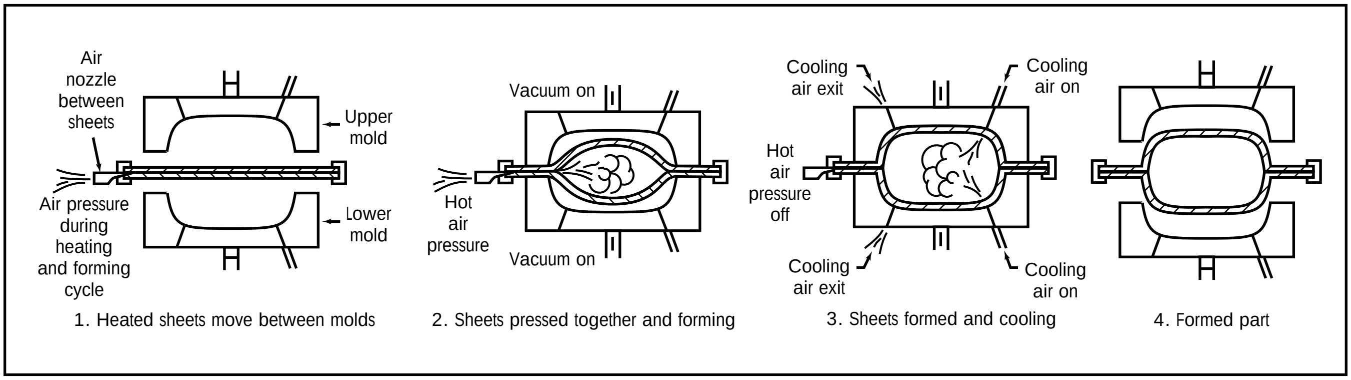

Fig. 8-12 Single-station/single-oven forming machine.

frames, one above the other, approximately 6 in. (152 mm) apart. The frames carry the sheets, one to the right and the other to the left, into two ovens, with top and bottom heaters in each oven.

Again, one mold is mounted above and one below the sheets in the center or forming station. When the hot sheets return to the forming station, the molds move into the sheets, and a vacuum draws the sheets into the molds. The molds then continue into the hot sheets, pressing together to effect the seal. This machine gives more efficient heating and greater control of the bonding surfaces than the single-station/single-oven unit, with approximately the same production rates (see Fig. 8-13).

Four-station rotary forming machine. This machine has a large horizontal wheel with four material clamp frames arranged in a block shape. The wheel rotates the material into the stations in the following order (see Fig. 8-14):

- Station 1: Load and unload.
- Station 2: First-heat oven—top and bottom heaters.
- Station 3: Second-heat oven—top and bottom heaters.
- Station 4: Form station—upper and lower molds.

This machine gives the most efficient heating and greatest control of the bonding surfaces. It also provides simultaneous and continuous use of all stations. More than double the productivity of a single-station machine is attained with no increase in the required number of molds.

Because of the 12–15-second dwell time between heating and bonding the sheets (Stations 2 and 3), engineering thermoplastic grades, such as polycarbonate and polysulphone, are not recommended for four-station forming. The materials cool too fast during the open time before heating and bonding. The process, however, is ideal for polyethylene and works well with polystyrene and ABS.

During the short dwell time of the second sheet, while the first sheet is formed into the lower mold and the mold is lowered awaiting the next hot sheet, robotic arms can reach into Station 4 and insert wood, metal, or other plastic “orphan parts” into cavity areas. These parts, captured between the two formed sheets, are made a part of the final article. The orphan parts can be reinforcing or strengthening sections, or threaded inserts for later use in assembly.

Slip forming. This process works in both match mold and vacuum forming. An oversized sheet is removed from the oven and laid on a mold. When the vacuum is applied or when the opposite match mold presses, the loose sheet is drawn into the mold area and formed (see Fig. 8-15). Slip forming is an excellent method of forming materials that have restricted stretch or elongation, such as polyethylene-backed carpet and fabrics and fiber-reinforced thermoplastics.

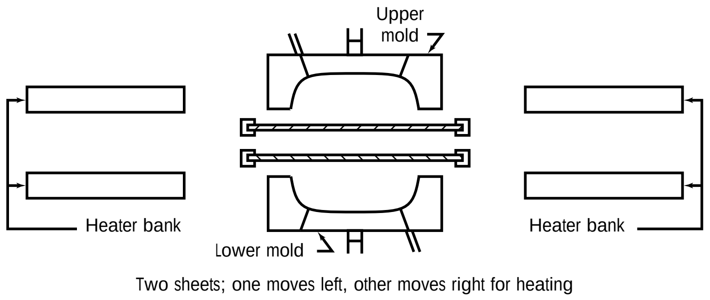

Fig. 8-13 Double-ended ovens on a single-station forming machine.

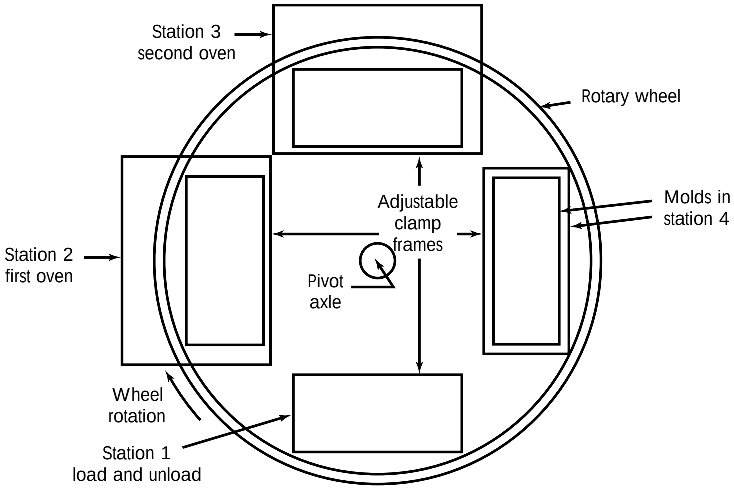

Fig. 8-14 Four-station rotary forming machine.