PLEXIGLAS® ACRYLIC RESIN
Processing Manual
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**COMBUSTIBLE DUST**

Acrylic dust, as with most polymeric dusts, can accumulate and coat the walls of conveying systems and may be combustible. Copper wire or conductive bars must be placed across every gasket or mechanical joint in the system to ensure proper mechanical grounding. The copper wires and bars should be uninsulated so that any broken wire or grounding connections are clearly visible.

Follow industry safety best practices, including those described in the following references:

- NFPA 652, Standard on Fundamentals of Combustible Dust
- NFPA 654, Standard on Fundamentals of Combustible Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids
- NFPA 68, Standard on Explosion Protection by Deflagration Venting
- NFPA 69, Standard on Explosion Prevention Systems
- OSHA 29 CFR 1910.22 (a) Housekeeping, Allowable Dust Accumulations

**GROUNDING AND BONDING**

Ensure thorough grounding and bonding throughout all pellet handling systems, including copper wires or grounding bars across every gasket, flange, and mechanical joint. The copper wires and bars should be uninsulated so that any broken wire or grounding connections are clearly visible. Refer to Figures 1 and 2 for examples.

The maximum resistance to ground from any component of the system should have a total resistance of less than five ohms. This should drain off any static electricity, or potential to create a spark. Be certain to individually ground each component (silos, roots blower, motor, etc.) and ensure that all individual parts of the conveying and storage system are bonded to each other by conductive materials. See Figure 3.

Ground all bulk load trucks or railcars before loading or unloading.

**SAFETY DATA SHEETS**

Please consult the safety data sheet for all materials before handling, processing, or storing them. The current SDS for all Plexiglas® resin products can be found in the SDS Section of Plexiglas.com.

**VAPOR CONTROL DURING MELT PROCESSING**

Melt processing of any polymer material, including Plexiglas® resin, has the potential to generate flammable vapors, which may include residual monomer, additives, decomposition products, and other components. Always ensure that considerations for flammable vapors are included in the design of processing and safety equipment as well as in your operating procedures.
**Flanged Connections:** This procedure requires centering the flange on the pipe and securing it by back welding. Also, a male/female flange placement can reduce misalignment.

*Note: When the flange is bolted tight, the pipe is compressed to a metal fit and the \( \frac{3}{8} \)" gasket is compressed to \( \frac{1}{16} \)".*
Careful resin handling is vital for keeping visual rejects to a minimum. Good housekeeping and proper system design, coupled with good filtration of the air used for conveying the resin, is critical to the production of a quality finished product. This section outlines basic guidelines for building and operating a resin handling system that will keep the resin clean and minimize fines.

**CONTAMINATION**

The excellent color, clarity, and cleanliness of Plexiglas® acrylic resins can be jeopardized with poor material handling.

Plexiglas® acrylic resins are sealed in heavy-gauge, moisture-resistant, polyethylene-lined drums or cartons. Slit the liner with a knife to open; tearing the liner may cause contamination with polyethylene particles. When loading hoppers, wipe the lid of the container clean to avoid contamination. Keep the drum or carton covered during the run to prevent dust and dirt from contaminating the contents of the container. Always reseal containers when not in use. Disassemble and clean hopper loaders before loading if previously used for a different color or anything other than acrylic resin. Similarly, vacuum and wipe down hoppers before use. A small amount of polystyrene or other plastic resins can contaminate an entire hopper load. Also note that even residuals from other transparent resins can cause visual defects when mixed with Plexiglas® resin.

Always check dryers for blowing fines and stray particles to avoid contamination.

**DRYING**

Absorbed moisture in Plexiglas® molding resins does not affect the final physical properties of molded parts, except where excessive moisture levels cause porosity/voids. Plexiglas® acrylic resins are packaged in specially constructed containers at low moisture levels and can frequently be used with minimal drying. However, excessive moisture can cause surface defects or bubbles in thick parts. These surface defects are sometimes referred to as splash, splay, or silver streak and can be eliminated by drying the resin in warm air circulating ovens, vacuum dryers, or hopper dryers. If drying trays are used, apply a layer of molding resin no more than one inch deep. Maintain moisture levels of no more than 0.05% or less for demanding jobs. Less sensitive applications may tolerate as much as 0.1% moisture.

Commercially available moisture analyzers are generally suitable for checking moisture levels in Plexiglas® resin, including loss-in-weight and calcium hydride method analyzers. Ensure that the testing cycle used is specifically designed for acrylic resins. Note that the appropriate cycle may depend on the thermal characteristics of the grade being analyzed. We recommend that moisture readings be taken only after the equipment cycles at least 10 minutes, to ensure that moisture inside the pellet has adequate time to diffuse to the pellet surface and escape. If using a standard lab oven to dry pellets for moisture measurement, we recommend a minimum of four hours at 100 °C, although shorter times may be permissible in a vacuum oven.

Use dehumidified or desiccant drying systems for the best possible drying performance. We recommend dew points in these systems of -29 °C to -40 °C [-20 °F to -40 °F]. Dew points above -18 °C [0 °F] are unsatisfactory. We recommend a minimum drying time of four hours for Plexiglas® resins. For thick part molding, including light guides, keep drying times to a maximum of eight hours for optimal optical and color performance. Recommended drying temperatures are listed below:

| TABLE 1: RECOMMENDED DRYING TEMPERATURES FOR PLEXIGLAS® RESINS |
|-----------------|------------------|
| Plexiglas® Resin Grade | Dryer Temp |
| HT121-LPL®       | 100 °C [200 °F] |
| V825, V825T, V826, HT121, V045 | 88 °C [190 °F] |
| V045i, V052i, DR®, MI7, MI7T | 82 °C [180 °F] |
| V920, VM, HFI7, HFI10, SG7 | 77 °C [170 °F] |
| VS, SG10         | 66 °C [150 °F] |

<table>
<thead>
<tr>
<th>TABLE 2: MOISTURE LEVEL TARGET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Applications</td>
</tr>
<tr>
<td>Less Sensitive Applications or Very Well Vented Extruders</td>
</tr>
</tbody>
</table>

**CONVEYING**

**Conveying Blowers and Air Filters**

Rotary lobe blowers (also known as “Roots” blowers) work well for dilute phase (higher volume/higher velocity) transfer. For dilute phase transfer systems, use higher/denser pellet loading, as this will minimize pellet degradation and dust generation. Be careful not to overload the transfer system and plug the transfer lines.

Keep the air used to convey the pellets free from contamination. We recommend two particulate filters, and multi-stage filtration is essential for critical applications. Multi-stage filtration systems consist of progressively finer filters, ideally ending with a HEPA filter (99.97% removal of particles at 0.3 microns).
Vacuum Transfer Systems

Piping and conveying lines for vacuum transfer systems should also be constructed of stainless steel. Avoid aluminum, galvanized steel, and glass because they can be abraded by acrylic pellets, resulting in contamination of molded parts. Use long-radius bends, with a bend radius at least ten times the pipe diameter, to reduce the likelihood of abrasion and to improve conveying efficiency. See Figure 4.

Distributor Boxes

A distributor box on the bottom of the silo outlet can be used to introduce pellets into the air stream. Ensure that distributors or collector boxes have an air-tight connection to the silo and that all conveying air should be filtered, preferably with HEPA filters. We recommend the use of a knife gate valve above the distributor box to facilitate distributor box cleaning and maintenance. Rotary or star valves may also be used.

Star Valves

A rotary star valve can be used to introduce pellets into the conveying line. This type of valve is vented so the pressure or vacuum from the conveying line will be relieved, allowing pellets to flow uniformly into the conveying stream. Ensure that your rotary valves are specifically designed to handle pellets of the appropriate size. This usually means that the rotor ends are closed instead of open, as is common for most powder systems. It is good practice to place a knife gate valve immediately above the rotary valve to allow for emptying and maintenance of the rotary valve. See Figure 5 for a typical arrangement.

Pellet Loaders

We recommend that all material contact surfaces in pellet loaders are constructed of stainless steel. This includes conveying lines, loader liners, and pickup wands. Many loaders use soft or elastomeric seats to seal and pull vacuum. These seats need to be tough and durable, and should never be exposed to pellet flow. Even when used properly, these seats will still wear over time and are a possible cause of foreign particle contamination.

Airborne particles are another source of potential contamination. Most loaders are open to ambient air when they are not loading. Foreign particles can include insects, dirt, dust, metal flakes, and fines from non-compatible resins. These contaminants may cause streaking, clouding, or other undesirable finished part defects. The air entering the loader must be filtered to preserve the cleanliness of the acrylic and reduce reject rates due to contamination.
**Flex Lines**

It is often necessary to use flex lines in a conveying system. In these cases, stainless steel flex lines are recommended. However, polymeric flex lines may be used for short distances or for connecting to charging wands so long as they are properly grounded and bonded to the conveying system. Regularly check the internal condition of any flex lines, especially polymeric lines, as pellets tend to erode them over time. Use of flex lines and connectors should be kept to a minimum to allow for maximum conveying efficiency.

**Silos**

All resin contact areas of the silo should be stainless steel. Exterior supports and brackets may be painted carbon steel. The sides of the outlet cone at the bottom of the silo should have a minimum 60° angle from the horizontal to promote mass flow and assure total emptying of the silo, as shown in Figure 5. If the silo or hopper is square or rectangular, the corner angles should not be less than 60°.

**Silo Accessories**

The silo fill line must enter directly into the center of the silo top, vertically at a right angle. A second nozzle on the top of the tank must be vented to a fan and baghouse or bin vent. A cyclone or decelerator (discussed later) may also be used to top load a silo, with the cyclone vent routed to the baghouse.

The baghouse and fan can be made of carbon steel. They are normally interlocked, operating only when product is transferred into the silo and preventing transfer until both have been powered on.

**Silo Dryers**

Each silo should be connected to a dryer to dry the air above the product. It is common to use a twin-tower design, with one supplying dry air to the silo from one tower while the other is regenerating. Clean the air with fine filtration, preferably HEPA filtration, to prevent any foreign particle contamination. The air then enters on one side of the top of the silo and exits on the other side of the top. Valves should be interlocked to close while the silo is being filled, directing the dry air outside during this operation.

**Cyclones**

A cyclone (constructed from stainless steel) can be used when it is necessary to load the product more gently into a silo or when a vent nozzle to a baghouse is not available. The cyclone will slow the pellet velocity and let the pellets fall by gravity into the silo, bin, or hopper. A top view and a front view of a typical cyclone are shown in Figure 6.

When the air and pellets enter tangentially, the inertia of the pellets causes them to slide into the silo against the outer wall. This slows the product and removes it from the high velocity air, allowing it to drop by gravity into the silo. The air exits out the top center of the silo to a baghouse along with any product fines. If the cyclone is feeding product into an open vessel, or one that cannot contain the pressure or vacuum, a star valve may need to be installed at the bottom of the cyclone.

**Silo Vents**

Each silo should be equipped with an emergency vacuum/pressure relief valve to prevent over-pressure or vacuum damage to the silo. Acrylic dust is potentially explosive so emergency venting is required. Because of space limitation on the roof of the silos, sometimes this emergency vent can be incorporated into a manhole cover.
**Silo Level Indicators**

There are several systems on the market for silo level indication. However, reliability for use on pellets has historically been a problem. The most reliable system has been, and still is, dropping a weighted tape measure in the top manhole and measuring the outage. Care must be taken to ensure that no dirt or foreign particles fall into the silo while the level reading is being taken.

An ultrasonic indicator system works reasonably well so long as each silo has a totally separate system. Another reasonably accurate method of determining the level of material is via the use of load cells.

**All pellet contact surfaces should be stainless steel.**

**REGRIND**

For easier processing, keep regrind usage at or below 10 to 20% of virgin material.

Handle regrind using the same cleanliness, conveying, and drying practices as virgin material, being particularly mindful of potentially higher fines levels in regrind material. Significantly higher percentages of regrind may be used if it is re-pelletized prior to use.

Regrind use typically does not significantly harm the physical properties of the finished product. However, take care to avoid contamination and the development of excessive heat history, which may affect part appearance. Do not allow regrind to accumulate since it will readily absorb moisture and is very difficult to dry adequately. For sensitive molding jobs, it may be necessary to remove the fines in regrind to prevent white spots and streaks in the molded parts.

Plexiglas® acrylic resins can also be blended into other polymers such as ABS or SMA for efficient recycling of sprues, runners, and defective parts. Conduct application-specific testing to determine suitable regrind levels for your individual process.
**INJECTION MOLDING**

**EQUIPMENT**

### Clamp Tonnage

Every square inch of a part’s projected surface area requires 2.5 to 3 imperial tons of clamp pressure. Insufficient clamp pressure tends to produce flashed parts. Excess clamp pressure is typically not detrimental and may be necessary for thin-walled parts that are < 0.100" (< 2.5 mm) thick or other difficult-to-fill parts where high injection pressures are required.

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**Equipment/Screw Design**

Plexiglas® acrylic resins can be molded satisfactorily in reciprocating-screw injection molding machines with general purpose screws for most applications. The screw has three basic parts: the tip, the non-return valve and the helical screw. However, not all screws are well suited to process Plexiglas® resin. For most molding machines with barrel sizes up to 70 mm in diameter, the manufacturer’s general purpose screw is suitable for acrylics. These screws typically have an L:D ratio of 15:1 to 20:1 with a compression ratio of 2:1 to 2.5:1 and a square pitch or helix angle of 17.6°. For injection machines with barrels larger than 70 mm, some manufacturers change the pitch of the screw so that the helix angle is less than 17.6°. This change generally results in an erratic screw recovery which introduces air into the melt, resulting in splay and diesel burning in the molded parts. We therefore strongly recommend that only a square pitch (17.6° helix angle) be used for processing acrylics. To facilitate acrylic melting, large molding machines may require fewer turns in the transition zone than are typically specified for other thermoplastics.

Screw coatings such as chrome plating or ceramic are acceptable but not required. Do not use nitrided steel barrels and screws as they can cause trace contamination. This contamination is especially detrimental when processing clear and translucent colors. Some screw manufacturers offer acrylic-specific screw designs which can be advantageous for extremely demanding jobs.

As for the non-return valve portion of the screw assembly, we recommend using a check ring-type valve, rather than a ball-check, to process acrylics. Ball-check valves provide possible hang-up areas, which can result in thermally degraded material.

Figure 7 illustrates typical screw nomenclature. The nose cone and check valve are not included in the length of the screw since they do not affect the pumping capacity and plasticizing ability of the flighted section; however, they may contribute to improved mixing and greater homogeneity of the melt.

**NOTE:** When comparing various screws, be sure that the length/diameter ratios of the different screws are based on the same definition of length.

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**Nozzle Tips/Extensions**

Acrylics have a stiffer flow and therefore generally require a more open nozzle orifice or free-flow design. Use shot size and cycle time to determine the optimum orifice size. Large parts and long cycles require a larger orifice than small parts with short cycles. Contact both your manifold manufacturer and your Altuglas International technical service representative to assist you in determining the optimal orifice size for your nozzle.
MOLD DESIGN

Two-plate and hot-runner molds are commonly used to mold Plexiglas® resins; three-plate tools can also be used. Careful design of the sprue, runner, and gating system is required to obtain defect-free parts with good physical properties. Plexiglas® molding resins are relatively viscous at molding temperatures, therefore design your mold to minimize heat and pressure losses in the sprue and runner system to ensure proper fluidity when the melt enters the cavity.

Runners

Runners should cause minimal cooling and resistance to flow during injection. To do this, runners should combine a maximized cross section with minimal surface area and be as short as possible. A full round runner meets these requirements better than any other shape but is more difficult to machine because both sides of the mold must be cut individually, and the half rounds in each section must mate properly when the mold is closed. The trapezoidal runner is next best because it approaches the full-round design except it’s in one side of the mold. Half-round or shallow rectangular runners are not desirable because of their high surface-to-volume ratio and restricted flow area.

Full-round runners of the following diameters give optimal performance when molding Plexiglas® acrylic:

<table>
<thead>
<tr>
<th>Runner Length</th>
<th>Runner Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 13 cm [5 in]</td>
<td>6.4 mm [1/4 in]</td>
</tr>
<tr>
<td>&gt; 13 cm [5 in], but &lt; 20 cm [8 in]</td>
<td>8 mm [5/16 in]</td>
</tr>
<tr>
<td>&gt; 20 cm [8 in]</td>
<td>10 mm [3/8 in]</td>
</tr>
</tbody>
</table>

Runners don’t need to be highly polished, but they should be smooth and free of undercuts.

Three-Plate and Hot Runner Molds

Center or sprue gating of multi-cavity molds is an efficient method of gating many Plexiglas® acrylic parts even though it requires a more complex three-plate mold or hot runner mold. Typical specifications for center or sprue gating molds to be used for Plexiglas® acrylic are shown below.

Cavity and Runner Layout

For best results when using a multi-cavity tool, fill all cavities uniformly, continuously, and simultaneously. A balanced H-runner layout uses the same runner length from the sprue to each cavity and contains the same number of equivalent turns and identical gates to help ensure uniform molding conditions in each cavity. A balanced H-runner system requires slightly more material for each shot than an unbalanced runner system, but this typically is offset by improved yield of good parts.

A balanced H-runner layout can be used to fill molds with a total cavity count that is evenly divisible by four (4, 8, 16, etc.). Should a different number of cavities be required, a “spoke” runner system can be used to provide a balanced layout system. As with the balanced H-runner layout, the spoke runner layout uses the same runner length from the sprue to each cavity. Combinations and modifications of the balanced H-system and balanced spoke system can be used to meet specific mold design requirements.

Cavity Support

Place pillar blocks behind each cavity to provide a generous area of support. If the cross-sectional area of the pillar blocks is less than one-half of the projected area of the part, the mold plates may bow, causing a thickness variation up to several thousandths of an inch in the molded parts. Severe lack of support may lead to flash even though the clamping pressure is adequate to prevent it, which can be mitigated by placing support pillars behind the runners as well.
Three-plate molds permit center gating of multi-cavity molds but sprues and runners still need to be removed. This can be avoided by using a hot runner in which heat is applied to the runners to keep the plastic melted, hot, and fluid during the entire molding cycle. Hot runner molds tend to minimize sprue or runner scrap, give shorter cycles, increase the effective plasticizing capacity of the machine, and are adaptable to automatic operation. The most successful are those that are externally heated with cartridge heaters or with a combination of cartridge heaters and heat pipes for even temperature distribution. Insulated runners can be used with Plexiglas® acrylic resins, but their low initial cost is generally not worth the greater operating problems relating to freeze up from cycle interruptions. The internally heated variation of a hot runner is not recommended due to problems associated with flow and overheating of the resin.

The most critical sections of the hot manifold assembly are the secondary nozzles or hot drops. Nozzles that are too hot will cause drooling and possible degradation; those that are too cool will freeze-up. Therefore, nozzles should have individually regulated temperature zones. Externally heated drops tend to work best, but internally heated drops can also be used.

Straight flow, externally heated designs (shown below) work well but leave a short stem that may have to be removed from the molded part. Internally heated types or those with a spreader leave an almost invisible gate vestige. However, these tend to restrict flow and can lead to thermal instability problems. They are also more troublesome to size properly and frequently act to narrow the molding range of the material.

Valve gate designs provide the best combination of unrestricted, easy flow with a wide processing window. Molded parts can have a nearly invisible gate vestige and low stress in the gate area. Consider this style for any multi-cavity hot manifold application.

### Gating

In parts with variable cross-sectional thicknesses, the gate should be located in the thickest section to minimize fill problems. Parts are usually weakest in the region near the gate; therefore, low stress areas should also be considered for gate locations. General specifications for various gate types are shown in Table 5.

Gate transitions from full round and trapezoidal runners are shown in Figure 8. The round runner terminates in a spherical shape, which traps cool material at the outside while passing hot material at the center of the runner. Runners of trapezoidal or other shapes cut into one plate tend to drag cold material into the cavity because of the nonsymmetrical transition shape. A streamlined transition section minimizes this tendency.

![Figure 8: Runner to Gate Transitions](image-url)
<table>
<thead>
<tr>
<th>Type of Gate</th>
<th>Figure</th>
<th>Specifications</th>
<th>Applications and Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tab</strong></td>
<td>![Tab Diagram]</td>
<td>Minimum tab size: 6 mm [1⁄4 in] by three-fourths of the part thickness. Gate depth: 80% of tab thickness. Maximum land length: 1.5 mm [1⁄16 in].</td>
<td>Recommended for relatively flat, thin parts; tab minimizes gate stress and eliminates jetting.</td>
</tr>
<tr>
<td><strong>Edge</strong></td>
<td>![Edge Diagram]</td>
<td>For thick parts; gate thickness may be the same as or greater than the runner thickness.</td>
<td>Suitable for thick as well as thin parts; permits keeping melt under pressure longer during cooling.</td>
</tr>
<tr>
<td><strong>Fan</strong></td>
<td>![Fan Diagram]</td>
<td>Smooth transition from runner to part. Gate should be at least four-fifths of part thickness.</td>
<td>For thick sections and to minimize jetting.</td>
</tr>
<tr>
<td><strong>Flash</strong></td>
<td>![Flash Diagram]</td>
<td>Gate should be 0.75 – 1.5 mm [3⁄32 – 1⁄8 in] thick, no more than one-fourth the length of the part. Maximum land length: 1.5 mm [1⁄16 in].</td>
<td>For thin dials with an uninterrupted straight edge.</td>
</tr>
<tr>
<td><strong>Center</strong></td>
<td>![Center Diagram]</td>
<td>Maximum diameter: 2.5 mm [1⁄8 in]. Maximum land length: 1.5 mm [1⁄16 in].</td>
<td>Recommended for deep circular parts such as bowls, cup shapes.</td>
</tr>
<tr>
<td><strong>Sprue – Conventional</strong></td>
<td>![Sprue Conventional Diagram]</td>
<td>Diameter: 26 mm [1 1⁄32 in] for a long sprue.</td>
<td>Use when it is possible to run the sprue directly into the mold (leaves degating scar).</td>
</tr>
<tr>
<td><strong>Sprue – Short ½&quot; to 1&quot; long</strong></td>
<td>![Sprue Short Diagram]</td>
<td>Diameter: 5.5 mm [3⁄32 in].</td>
<td>Hot sprue bushing eliminates all but a very small degating scar.</td>
</tr>
<tr>
<td><strong>Sprue – Hot</strong></td>
<td>![Sprue Hot Diagram]</td>
<td>Diameter: 2.5 mm [3⁄32 in].</td>
<td></td>
</tr>
<tr>
<td><strong>Submarine</strong></td>
<td>![Submarine Diagram]</td>
<td>Oval shape: 1.52 mm × 2.54 mm [0.06 in × 0.1 in] minimum.</td>
<td>Parts degate automatically when the mold opens.</td>
</tr>
<tr>
<td><strong>Submarine – Plug</strong></td>
<td>![Submarine Plug Diagram]</td>
<td>Plug diameter approximately equal to the wall thickness of the part. Diameter of approximately 3 mm [¼ in] is adequate (knockout pin cut-off). Gate: 1.5 – 1.95 mm [⅛ – ⅜ in]. Note: larger plugs will cause sinks while smaller plugs may cause jetting and surface defects.</td>
<td>Parts degate automatically when the mold opens, leaving the plug to be removed from the part.</td>
</tr>
<tr>
<td><strong>Diaphragm</strong></td>
<td>![Diaphragm Diagram]</td>
<td>Diaphragm thickness may vary from 3 – 4.75 mm [¼ – ⅜ in] and may be used as a 360° flash gate or may be open to the full thickness of the part.</td>
<td>For cylindrical shapes or parts requiring a large cut-out.</td>
</tr>
<tr>
<td><strong>Ring</strong></td>
<td>![Ring Diagram]</td>
<td>3 – 4.75 mm [¼ – ⅜ in] diameter ring with short land of 0.8 – 1.6 mm [⅛ – ⅜ in] thickness.</td>
<td>For hollow cylindrical parts such as tubes, pen barrels, etc.</td>
</tr>
<tr>
<td><strong>Spoke</strong></td>
<td>![Spoke Diagram]</td>
<td>Gate dimensions can vary from very large to pin-point depending on whether the material flows directly into an open area or impinges on the mold.</td>
<td>Same application as diaphragm gate; produces less scrap.</td>
</tr>
</tbody>
</table>
Tunnel or Submarine Gates

This type of gate can be one of two types, short or long. When a short submarine gate is used, a 15° angle from the vertical axis is preferred, which results in very little gate debris. To further minimize debris, a warm mold, 66 – 93 °C [150 – 200 °F] is recommended. When the design of the part or mold dictates that a long submarine gate be used, the entrance angle should not exceed 30° from the vertical axis, to ensure gate sheering. Keep the size of the gate as small as possible for easy degating during ejection but large enough to fill the part. The included tunnel angle should be between 10° to 20°.

Degating

Submarine-gated parts are automatically degated when the mold opens; heated valve gates do not leave a gate vestige or runner. Other gates normally require a degating operation after the part is removed from the mold. Clippers are often used but they may cause fracturing of Plexiglas® acrylic parts in the gate area, especially if the parts are allowed to fully cool. It helps to heat the cutters to about 135 °C [275 °F].

Other tools used to degate and remove tabs or plugs from molded parts are steel slitting saws, band saws, and hot knives. A steel slitting saw with 10 to 25 teeth/inch, without rake or set, and operating at 8,000 to 12,000 surface feet per minute, will degate a tab gate with a smooth and notch-free finish. Conventional metal-cutting or friction-type band saw blades are convenient for degating flash-gated parts.

A hot knife for degating Plexiglas® acrylic parts should be flat on one side and ground to a 10° angle on the other side. The temperature of the blade should be controlled to about 135 °C [275 °F]. Very thick gates may be cut on a circular saw if straight and on a band saw if curved; a skim router or a polishing operation may be used to improve final appearance of the sawed gate.

Polishing

Plexiglas® resins can replicate almost any surface texture (high or low gloss) given the appropriate processing conditions. To obtain optimum clarity and luster in parts molded of Plexiglas® acrylic, the mold cavity surfaces should be ground to eliminate all tool marks and polished to a high luster. Draw polishing in the direction of ejection of parts should minimize any tendency for the parts to stick in the mold or to obtain scuff marks.

Draft and Radius

Minimum draft of 1° to 2° should be provided wherever possible but some draft should be provided in all cases. Generous radii should be designed into all corners to avoid sharp changes in geometry which can lead to stress-concentrated areas prone to failure. This relationship is shown in Figure 9. In addition, there should be a minimum radius of 0.75 mm [0.030 in] on all corners of the parts to avoid cracking the parts during ejection from the mold.

Deep parts with little to no taper on the sides can be removed best if they are pushed from the mold rather than drawn from it. This is accomplished by placing the knockouts around the base of the part as shown below. A disadvantage of this knockout placement is that air entering around the pins does not help break the vacuum formed as the part is separated from the mold. An example design of this is shown in Figure 10.

Inability to admit air between the mold and the molded part during ejection may cause trouble with large-area flat parts as well as with deep parts. If a small scar due to the metal joint can be tolerated, a spring-loaded poppet valve installed in the mold can correct this condition. It is also possible to apply low-pressure, compressed air through such a valve and use the entire area of the part rather than local spots. This provides a uniform, non-distorting knockout.

Stripper plates are often used in place of pins on molds for parts such as tumblers, boxes, etc., where there is a thin, plane edge. Stripper plates have an advantage over pins because of the continuous surface contact and lack of marring. They have the disadvantage of requiring an extremely close fit to the parting line if flashing is to be avoided. Certain parts such as lenses cannot tolerate the scars caused by knockouts on the part itself. Such parts may be removed by knockouts in the runners if the gates are sufficiently strong, and if there is adequate draft on the part. Tab-gated parts have been successfully ejected with a single knockout in the tab. This eliminates the dependence on the gate to lift the part from the cavity. In a similar manner, knockouts in bleeder tabs can be used.
**Venting**

Many molds have sufficient clearance around the knockout pins and at the parting line to serve as vents; however, if voids or burned areas are encountered in the part, increase clearance for venting. The continuous venting technique ensures adequate venting and, since it’s incorporated into the initial design of the mold, may cut down the time required to put the mold into production. To obtain continuous venting, cut a groove into the mold or around the inserts as shown below. This permits air to pass quickly out of the mold through the short lands and large grooves. Examples of continuous venting are shown in Figure 11.

Another method of venting is to cut vents up to 0.05 mm [0.002 in] deep and 10 mm [⅜ in] wide in a sunburst pattern around the mold; however, this provides a more localized type of venting. Additional clearance may be provided around the knockout pins to allow localized venting in the cavities.

**Dimensional Tolerance and Mold Shrinkage**

Parts molded from Plexiglas® acrylic resins can be held to close dimensional tolerances provided that the injection molding process is closely controlled. Varying temperature, pressures, or cycle times can result in parts of varying quality and size. One prerequisite for critical molding jobs is optimum temperature control of both the plasticizing system and the mold.

---

**Figure 10: Knockout Placement on Deep Parts**

- **Advantage**
  - Pins push the part from the force

- **Disadvantage**
  - Air does not enter

- **Advantage**
  - Air can enter

- **Disadvantage**
  - The pins draw the part tighter against the force

---

**Figure 11: Continuous Venting**

- **⅝” Half-Round Groove**
- **⅛” Land (Relieve if necessary, 0.001”)**
- **Vent Gap Between the Two Halves of the Mold**
- **Clearance Around Knockout**
Cold-mold to cold-piece shrinkage (or simply mold shrinkage) is the difference between the dimensions of the molded part and the corresponding dimensions of the mold cavity, both measured at room temperature. The magnitude of mold shrinkage varies appreciably with the part shape, mold design, direction of flow and molding conditions. The typical expected mold shrinkage for Plexiglas® acrylic is approximately 0.4% but under extreme conditions, it may be as low as 0.2% or as high as 0.7%. Table 6 lists the changes in operating variables that can increase or decrease mold shrinkage. The mold shrinkage generally increases as the part thickness is increased.

Gate size may influence mold shrinkage. A gate that is too small freezes quickly, which can reduce the effectiveness of packing. A larger gate will transmit pressure to the part and minimize shrinkage. However, an oversize gate requiring extended hold times may cause other molding defects.

Molded parts exposed to high temperatures may show additional shrinkage due to relief of molding stresses. Minimize molding stresses to achieve the best high temperature dimensional stability.

Humidity Correction

Molded parts will undergo further dimensional changes as they absorb moisture from the atmosphere, and they may take more than 30 days to reach equilibrium dimensions at a given relative humidity. To eliminate the need for waiting for humidity equilibrium, the parts may be cooled to service temperature in a desiccated atmosphere and a correction factor added to the part size based on the humidity conditions the parts will encounter in service. The table below lists the correction factors for various relative humidity levels.

<table>
<thead>
<tr>
<th>Relative Humidity to which parts will be exposed in service at 23 °C [73 °F]</th>
<th>Correction Factor to be added to parts measured after cooling to 23 °C [73 °F] in a dry atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>0.1%</td>
</tr>
<tr>
<td>65%</td>
<td>0.2%</td>
</tr>
<tr>
<td>80%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Coring

Molds are cored for the circulation of a liquid, usually water, to control mold temperature. Dimensions and spacing for cored cooling are shown in Figure 12. Good mold temperature control is important for uniform cooling of the part, for minimizing stresses, and for shortening the molding cycle. Mold temperature control is considered “good” when the mold surface returns to the same temperature at the beginning of each cycle and the temperature differentials across the mold surface served by the cooling are kept to a minimum.

Immersion thermometers can be installed in both the inlet and outlet lines to measure the temperature rise of coolant flowing through the mold. The temperature of the outlet water should be no more than 3 °C [5 °F] different from the inlet water and the temperature differential between the mold surface and the cooling water should be kept to a minimum; otherwise, excessive cooling of the mold will take place during any interruption in molding and several shots will be required to get back on cycle.

Pressure losses in the circulation system should be minimized for efficient heat transfer and maximum flow. To accomplish this, hoses should be as short as possible and have a minimum inner diameter of 10 –13 mm [3⁄8 – 1⁄2 in]. Fittings and coring should be of the largest practical diameter. Large molds can accommodate 17 mm [5⁄8 in] diameter coring; a minimum coring diameter of 13 mm [1⁄2 in] is recommended for all other molds.

Coring should be located as shown in Figure 12.
**Ejection**

In some molds, the sprue puller alone will not assure that the molded part remains on the movable half of the mold so it can be ejected by the knockout pins or lifters. Undercuts on the runners or on the part itself will often correct this problem. If the gate is too weak to pull the part from the stationary mold half, and if the part cannot tolerate an undercut, use modified knockout pins to improve part pull. This strategy is shown in Figure 13. Well-placed knockouts will help to remove the part evenly and without undue local stress. Several knockout pins can be modified as shown in Figure 13. The depth of grinding should be less than the knockout throw so that in the fully ejected position the small tabs, when molded against the pins, will be completely free of the mold. These tabs can be clipped from the part. Clipping causes a scar that is a little more noticeable than the mark left by the pin itself.

**Ribs**

Properly designed ribs can increase strength, permit a decrease in wall thickness, and increase part stiffness. Excessive rib thickness may result in sink or part warpage. Proper part design for ribs is shown in Figure 14.

---

**Figure 13: Modified Ejector or Knockout Pins**

- Minimum thickness for sufficient strength to pull part and minimize scarring of part
- Section ground away to provide a “Z” puller system
- Ejector or knockout pin in extended position

**Figure 14: Proper Rib Design**

- Stress Concentration
- Sink
- Good Design
- Poor Design

Clearance for venting
Physical Attachment and Welding Features

Parts molded of Plexiglas® resin can be mechanically attached to other components via the use of screw bosses and snap fits. These techniques are commonly used for applications requiring nondestructive disassembly or rapid assembly with low capital investment. Plexiglas® acrylic resins may be joined to themselves or other materials providing appropriate design considerations have been taken.

Screw Bosses

When designing screw bosses, avoid accumulation of material in walls, joints, and corners by coring out. Good practice aims at minimizing risk of sink marks, voids and deformation in the design process. Suggested dimensions and considerations for screw boss design can be found in Table 8 and Figure 15.

Snap-fits

Snap-fit assemblies must be designed within the elastic limitations of the materials taken into consideration. The following formulas may be used to estimate the percent deformation of Plexiglas® acrylic resin for a given design. Design considerations are shown in Figure 16.

- Cantilever: \( e = \frac{d}{0.67 \times \left| \frac{l}{h} \right|^2} \)
- Bush Fit: \( e = \frac{(d_1-d_2)}{d_1} \times 100 \)
  - \( \beta \) angle range for a dismountable system = 40 – 50°
  - \( \beta \) angle range for a non-dismountable system ≥ 50°
  - \( \alpha \) angle should be between 20° and 30°

<table>
<thead>
<tr>
<th>TABLE 8: RECOMMENDED SCREW BOSS DESIGN PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-Series and HT121</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Pilot Hole (d)</td>
</tr>
<tr>
<td>Boss Diameter (D)</td>
</tr>
<tr>
<td>Screw Guide (p)</td>
</tr>
<tr>
<td>Base Radius (r)</td>
</tr>
<tr>
<td>Preferred Screw Type</td>
</tr>
<tr>
<td>Permissible Deformation (e)</td>
</tr>
</tbody>
</table>
Thermal/Mechanical Welding
Please see the Finishing Operations section of this document for details on ultrasonic, vibration, and hot plate welding along with information.

PROCESSING

Computer Analysis Data
Many engineers are using computer software packages to model the injection molding process, including determining whether a mold can be filled at a given wall thickness, the clamping force required, gate locations and sizes, potential warpage of the part, cycle time required, and other mold design parameters. Most Plexiglas® acrylic resins have properties data packaged in the Moldflow software data format (.udb files). Please contact Plexiglas® Resins Technical Service for more information.

Purging/Material Changeover
A material changeover from one grade of clear Plexiglas® acrylic resin to another can be accomplished quickly and only requires running the screw dry and performing several air shots with the new material. After several air shots, molding can be resumed. Colors will require a longer purging cycle to clean the screw, check-ring, nozzle, and hot manifold system (if used).

Non-acrylic materials must be completely purged from the equipment to prevent contamination. Normally this involves running the screw dry of the old resin and then purging the system with Plexiglas® acrylic. When possible, purge using the most viscous acrylic available. Acrylic regrind or non-dried acrylic resin processed at cylinder temperatures of 232 – 260 °C [450 – 500 °F] can be used for this purpose. A complete cleaning procedure includes cleaning of the hopper and feed throat.

In more difficult cases, non-chemical type purging compounds may be used. After using a purge compound, it is recommended to follow the regularly recommended acrylic purging procedure to reintroduce acrylic to the equipment system. In some cases, the screw may need to be removed from the barrel for a more thorough cleaning.

Typical Processing Conditions
Starting conditions depend on the grade of Plexiglas® resin used. Typical cylinder and mold temperatures are listed in Table 9. The high end of the mold temperature range tends to produce parts with minimized molded-in stress, but at the cost of longer cycle times. Temperatures lower than those suggested should be avoided for thick parts, as higher molded-in stress can generate “crazes” or micro cracks just below the part surface.

Melt temperature can be varied to suit the part or process. With proper drying and reasonable residence time, melt temperatures up to 271 °C [520 °F] can be tolerated. At this temperature, flow is maximized, stress is minimized, but cycles are longer.
<table>
<thead>
<tr>
<th></th>
<th>Temperatures</th>
<th>Other Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt Temp Range</strong></td>
<td><strong>°C [°F]</strong></td>
<td><strong>Mold Temp Range</strong></td>
</tr>
</tbody>
</table>
**Shot Size**
Ideally, the shot size should be about 50% of the cylinder capacity. Using a shot size smaller than 20% of the barrel capacity should be avoided as it results in increased residence times. In extreme cases, this can produce thermal stability issues, poor screw recovery, and unpredictable injection speeds. Shot sizes using more than 80% of the barrel capacity should also be avoided because they tend to yield poor melt temperature uniformity.

**Back Pressure**
Normal back pressure for Plexiglas® acrylic resins is 3.5 – 103 bar [500 – 1500 psi] measured via plastic pressure. Higher levels of up to 240 – 345 bar [3500 – 5000 psi] can be used to raise melt temperature.

**Injection Pressure**
The injection pressure required to fill a mold depends on the shape and size of the part. With large or very thin parts, high injection pressures may be needed. When hydraulic pressures are higher than about 103 bar [1500 psi], some effort should be made to either raise melt temperature or enlarge gates, runners and the sprue.

**Screw Speed**
Screw speed (recovery RPM) should be selected so the screw recovers a few seconds prior to the mold opening. Long recovery times are preferred provided the recovery profile is smooth, consistent, and repeatable. Higher speeds will usually will not harm Plexiglas® acrylic but are not needed except to raise melt temperature.

**Injection Speed**
Moderate to fast injection speeds are preferred for most parts, because this minimizes orientation and molded-in stress. Light guides, reflex lenses, thick parts, or parts featuring small optical elements may require slower fill speeds to minimize flow lines, fishhooks, and defects associated with melt turbulence. Shear rates over 40,000 s⁻¹ should be avoided to reduce risk of shear degradation.

**Cycle Time**
Required cycle times depend on part thickness and the resin selected. The effect of part thickness on cycle time is shown in Figure 17.

**Shutdown/Standby Procedures**
For delays of less than five minutes, retract the carriage and bring the screw into the forward position; i.e. bottomed out.

For long delays, retract the carriage, close the feed slide, and empty the material from the screw and cylinder. If the delay will be longer than 30 minutes, turn down the temperature of the cylinder heaters to 204 °C [400 °F]. For overnight shutdowns, empty the cylinder, and turn down the heaters to 150 °C [300 °F].
### Table 10: Injection Molding Troubleshooting Guide

<table>
<thead>
<tr>
<th>Machine Defects</th>
<th>Part Defects</th>
<th>Machine Variables</th>
<th>Mold Variables</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excessive Flash</td>
<td>Under sized Part</td>
<td>Back Pressure</td>
<td>4↑ 5↓ 3↓ 6↑ 5↓</td>
<td>8↑ 7↑ 1↑ 7↑ 6↑ 8↑ 5↑</td>
</tr>
<tr>
<td>Oversized Part</td>
<td>Oversized Part</td>
<td>Clamp Pressure</td>
<td>3↑</td>
<td>8↑</td>
</tr>
<tr>
<td>Part/Sprue Sticking</td>
<td>Oversized Part</td>
<td>Melt Temperature</td>
<td>6↓ 6$ 5$ 4↓ 4↑ 3↑ 1↑ 6↓ 5$ 5$ 5$ 2↑</td>
<td></td>
</tr>
<tr>
<td>Short Shot</td>
<td>Oversized Part</td>
<td>Holding Pressure</td>
<td>5↓ 4↑ 2↑ 3↑ 3$ 4↑ 2↑ 4$ 3↑ 3$ 6↓</td>
<td></td>
</tr>
<tr>
<td>Choppy Screw Recovery</td>
<td>Oversized Part</td>
<td>Injection Pressure</td>
<td>2↓ 1↑ 1$</td>
<td>3↓ 4↓</td>
</tr>
<tr>
<td>Black Specks</td>
<td>Oversized Part</td>
<td>Injection Speed</td>
<td>5↑ 4$ 4$</td>
<td>8↓</td>
</tr>
<tr>
<td>Burn Marks</td>
<td>Oversized Part</td>
<td>Shot Size</td>
<td>7↓ 7$ 6$</td>
<td>6$ 6$ 7$ 3$</td>
</tr>
<tr>
<td>Cracking on Ejection</td>
<td>Oversized Part</td>
<td>Cool Time</td>
<td>3↓ 4$ 4$</td>
<td>8↓</td>
</tr>
<tr>
<td>Delamination (Multi-shot)</td>
<td>Oversized Part</td>
<td>Mold Temperature</td>
<td>5↑ 5$ 5$</td>
<td>8↓</td>
</tr>
<tr>
<td>Jetting</td>
<td>Oversized Part</td>
<td>Rear Zone Temperature(s)</td>
<td>6$ 2$ 6$ 1$</td>
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</tr>
<tr>
<td>Splay/Silver Streaks</td>
<td>Oversized Part</td>
<td>Hold Time</td>
<td>5$ 5$ 7$ 7$</td>
<td></td>
</tr>
<tr>
<td>Sinks</td>
<td>Oversized Part</td>
<td>Screw Decompression</td>
<td>3$ 3$ 2$</td>
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<tr>
<td>Cooling Voids</td>
<td>Oversized Part</td>
<td>Screw Speed (RPM)</td>
<td>3$ 6$ 5$ 7$ 7$</td>
<td></td>
</tr>
<tr>
<td>Warping</td>
<td>Oversized Part</td>
<td>Gate Locations</td>
<td>4 4 7 4</td>
<td>1↑ 7↑ 6$ 8$ 5$ 8$</td>
</tr>
<tr>
<td>Record Grooves</td>
<td>Oversized Part</td>
<td>Size of Gate</td>
<td>5$ 1</td>
<td>4↑</td>
</tr>
<tr>
<td>White/Cloudy Streaks</td>
<td>Oversized Part</td>
<td>Size of Sprue/Runner</td>
<td>8$ 1</td>
<td>4↑</td>
</tr>
<tr>
<td>Number indicates recommended order of corrective actions</td>
<td></td>
<td>Check Draft/Radii</td>
<td>1 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check Tool Finish</td>
<td>7 3 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Size of Vent</td>
<td>6$ 7$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check Parting Line on Tool</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clean Vents</td>
<td>8 5 6 6 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry Material Hotter and/or Longer</td>
<td>1 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check for Worn Screw/Barrel Components</td>
<td>2 8 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check Screw Design</td>
<td>2 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Purge/Clean Screw and Barrel</td>
<td>3 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check for Contamination</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

**Machine Variables**
- 3$ 6$ 5$ 7$ 7$: Back Pressure
- 6$ 6$ 5$ 4$ 4$ 3$ 1$ 6$ 5$ 5$ 5$ 2$ $: Clamp Pressure
- 5$ 5$ 5$ 2$ $: Melt Temperature
- 4$ 4$ 3$ 2$ $: Holding Pressure
- 4$ 4$ 2$ $: Injection Pressure
- 3$ 3$ 2$ $: Injection Speed
- 2$ 1$ 1$: Shot Size
- 5$ 4$ 4$ $: Cool Time
- 7$ 6$ 5$ 5$: Mold Temperature
- 6$ 2$ 6$ 1$: Rear Zone Temperature(s)
- 5$ 5$: Hold Time
- 4$ 3$ 2$: Screw Decompression
- 3$ 6$: Screw Speed (RPM)

**Mold Variables**
- 8$ 7$: Gate Locations
- 7$: Size of Gate
- 6$: Size of Sprue/Runner
- 5$: Check Draft/Radii
- 4$: Check Tool Finish
- 3$: Size of Vent
- 2$: Check Parting Line on Tool
- 1$: Clean Vents

**Others**
- 1 3 7: Dry Material Hotter and/or Longer
- 2 7 3: Check for Worn Screw/Barrel Components
- 1: Check Screw Design
- 2: Purge/Clean Screw and Barrel
- 1: Check for Contamination
EXTRUSION
**EQUIPMENT**

**Barrel and Screw**

Avoid nitrided steel barrels and screws as they can generate trace contamination through abrasion, which may be visible in transparent applications. Xaloy barrels and hard-tipped (Stellite or flame-hardened) flight lands are recommended.

Chrome plating of screws is recommended, but not required, for satisfactory processing because it makes cleaning the screw easier and provides corrosion and abrasion-resistant surfaces.

The screw is normally operated without internal cooling, i.e. in the “neutral” condition. The neutral condition is the simplest, and usually preferred, method of operation. Water, or other temperature-controlled coolants, should never be circulated through the entire length of the screw. In some cases, applying liquid cooling to a limited section in the feed end may be advantageous. Since limiting the range of circulation is difficult when a screw is already bored through most of its length, the cooling bore, when feasible, should be limited to a distance four times the screw diameter downstream from the start of the helix.

The need for limited screw cooling is usually apparent when an obvious decrease occurs in the rate of feed intake to the screw over time (if this can be observed) and the motor load and machine output rate drop substantially as the run progresses. Such behavior results from polymer adhering to the screw channel surface to form a blockage that rotates with the screw and prevents or slows the rate of transport. The blockage usually occurs within the first few turns of the helix, downstream from the feed opening.

Zoned screw cooling should not be applied when a serious block occurs, because the blockage may then be reinforced. If an evident need for zoned cooling exists, the flow of cooling water should begin before machine startup while the channel is open, provided that the length of cooling is limited to the distance stipulated above. Using a moderate flow rate for the coolant should keep the exit temperature of the water around 38 °C [100 °F].

**Screw Design**

A wide variety of screw designs may be used to process Plexiglas® resins. A plasticizing extruder is required to receive and transport discreet solid particles of resin, heat and melt them into a viscoelastic melt, and pressurize the melt to force it through an attached die. It is not surprising, therefore, that screw design can be important in imposing limits on the process and its efficiency and productivity. Some general statements can provide an understanding of how screw design affects productivity:

Successful operation requires the screw to provide constant melt temperature and melt pressure at the delivery end. Constancy of the melt conditions strongly affects the uniformity of the flow rate and consequently the dimensional uniformity of the sheet or profile shape.

The maximum achievable production rate will depend on many factors, but it is generally better to not push to the most extreme possible rates as this often leads to more process variation, more variation in the extruded part, and more operator interventions. A breakdown in uniformity most often appears as a variation in melt temperature exceeding acceptable limits, but reliable information on changes in melt temperature is difficult to obtain in commercial machinery because the melt thermocouple probe is easily damaged.

It is often difficult to predict the rate-limiting parameter in a given extrusion system. Real-world trials are usually necessary to determine the maximum achievable production rate. Larger screw diameters allow higher throughput, but can be limited by available motor speed and horsepower.

Screw design has an effect on maximum output rate provided the process is not otherwise limited. Generally, short screws (low L/D ratio) and screws with shallow metering channels provide lower output rates. Long screws and screws with relatively deep metering channels provide higher output. In addition to variations in screw length and channel depth in the metering section, options of adding shearing or mixing devices and of using two or more stages can also be adopted to extend output capacities. These changes in design can be considered steps toward improving the uniformity of plastification achieved in the extruder.

Before selecting or modifying a screw design, consideration should be given to the possible effects on the melt temperature in a particular process. When making rods or other products having a heavy section, in which cooling the extrudate is a major concern, design changes that increase the melt temperature should be avoided. In making complicated profiles, the increased productivity must more than compensate for the losses in yield that arise from difficulties in sizing and in cooling a less viscous extrudate. A favorable climate for improving productivity by modifying screw design is afforded by the production of flat sheet and similar applications in which simple dies and setup and improved handling techniques can better cope with the effects of increases in temperature and rate.

The above comments indicate that no single design is appropriate for all processes and applications and explain why a variety of screw designs have been used in extruding Plexiglas® resins.
Figure 18 presents typical screw designs for single-stage and two-stage machines in some commonly used diameters. The designs utilize a pitch equal to the diameter of the screw. These designs are intended only to be guides; minor changes in design can be made without causing difficulties, but excessively long or shallow metering zones increase the shear exerted by the screw and increase the melt temperature. Two-stage screws often allow for better venting, however a proper balance must be maintained between the first- and second-stage metering sections to prevent flooding the vent.

**Static Mixers**

Static mixers are frequently inserted between the extruder and the die to provide uniform melt temperature and improved mixing. Static mixers can be used to distribute color concentrates in Plexiglas® resins. They also promote greater uniformity in the melt temperature of the extrudate presented to the die and may conceivably permit higher output rates without instability. When properly designed, installed, and temperature-controlled, these units produce only a small drop in pressure. A static mixer should run the same temperature as the stock. A static mixer should neither heat nor cool the melt.
**Breaker Plates and Screens**

For transparent applications, breaker plates with medium screens (100 or 200 mesh) are commonly used, with 80-mesh being the minimum recommended. For other applications, nominal screening (20/40 or 20/40/60 mesh packs) are commonly used. It is also common to include an additional 20-mesh or other coarse screen on the downstream side to act as a support for the finer screens. Additional screens can be helpful when the die offers low resistance to flow and the screw has limited mixing or homogenizing ability. The use of breaker plates can also help reduce the amount of “gels” or contaminants in the final product. The back pressure of a melt screen will increase over time as particulates and other material catches on the screen, so it is important to continuously monitor the back pressure. Excessive back pressure can cause the screen to bend or tear, allowing impurities to pass into the final product.

Plexiglas® resins exhibit good thermal stability, particularly in areas from which air is excluded. Degradation in slow flow areas should be of little concern in most applications.

**Melt Pumps**

Melt pumps are used to give more stable output, which can improve yield and product quality. They can also increase output rates. We recommend the use of a melt pump when fine melt filtration is required (greater than approximately 100 mesh), as is common in transparent applications. Sometimes a coarse melt screen is placed at the inlet of a melt pump to protect the pump from damage due to foreign materials in the polymer stream. Insertion of a melt pump may enable an extruder to run with a lower head pressure since the extruder would only need to convey the melt to the melt pump, instead of all the way through the die. Melt pumps can be difficult to purge and therefore may extend product changeover times and startup scrap rates, especially when the polymer grades are very different (such as different colors).

**Drive Horsepower**

The estimated horsepower required for extruding Plexiglas® resins can be obtained from the following relationship: **H.P. = 0.14*Q**

Where \( Q \) is the actual or expected output rate in lb/h. The constant 0.14 in the equation is a conservative value that covers most cases of high productivity in which relatively high melt temperatures develop and the screw supplies most of the total power requirement. In estimating cases with low productivity, the constant can be set at 0.10.

It is important to understand that the value of horsepower derived from the equation is the power delivered to the screw and is not necessarily the rated horsepower of the drive motor. When the equation indicates that the rated power of the drive motor should be adequate but excessive motor current loads are nevertheless noted during operation, the problem arises from the type of speed control device in use and from the percentage of shaft speed at full output at which the machine is running. With any speed control device having constant torque characteristics, the rated motor horsepower can appear at the output shaft only when the machine runs at full speed. At reduced speed when the drive motor is drawing the full rated motor current, the percentage of rated power available at the output shaft is the percentage of full speed at which the shaft is turning. In such a case, if the power requirement exceeds the amount available, the drive motor exceeds its rated current draw.

When the above problems occur with constant torque systems and marginal limitations cannot be resolved by adjusting the operating conditions, consider a change in the speed control system, allowing the unit to operate closer to its maximum output speed. The gear ratio in the extruder gear reducer can be changed if gear change options are available. Before making such a change, however, it should be recognized that the gear reducer may become overloaded if adequate safety factors have not been provided in the original specifications of the equipment.

**Dies**

Many different commercial sheet dies have been used successfully to extrude Plexiglas® resins. These include the “straight manifold” types, often termed T dies, and a variety of “coat hanger style” modifications of the T die. Both typically have adjustable die lip openings and may also have adjustable choke bars.

It is essential to provide dies with an effective and properly balanced heating system having adequate, sensitive controls, especially when the die is divided into heat zones as in the usual sheet die.

To minimize die lines, maintain a high-quality finish on the die lip, particularly in the area at and just ahead of the point where the melt leaves the lip surface. Irregularities in the die lip surfaces, whether caused by mechanical imperfections or corrosion damage, can produce die lines and inconsistent thicknesses.

Rapid corrosion can occur at the die lip discharge if the lips are low-grade steel, and especially if moisture has not been effectively removed from the melt and escapes at this point. A high-quality grade of alloy tool steel is preferable when the die must produce good quality extrudate over a prolonged period. Although chrome plating of the die flow surfaces is not necessary, this practice offers several benefits:

- Plating promotes the release of polymer deposits in cleanup operations and makes physical damage less likely.
- Inspecting and judging the condition of the land areas become easier.
- Plating provides some protection against corrosion.
Streamlining the interior flow surfaces of dies has a favorable effect on the ease of purging when changes are made in grade or color. Because Plexiglas® resins possess excellent thermal stability under the conditions normally occurring in dies, streamlining to prevent polymer degradation is not necessary. This stability also permits deckling of sheet dies in producing sheet narrower than the die. Excessive deckling should not be used, however, since it may form a heavy bead on the edge of the sheet.

**Profile Design**

In profile extrusion, the process stability and output rate are the primary factors for maintaining the shape and giving close dimensional tolerances. Optimum extrusion conditions must be established early in the extrusion procedure and held constant while various modifications in the die are made.

Figure 19 shows the design of a typical profile. The die construction of Figure 20 is a three-part assembly that provides consideration for low-cost machining, operation, and additional modifications. Nominal streamlining is provided on the internal flow channels with 1/16-inch minimum radii on corners and breaking of all sharp edges. The internal surfaces should have an extremely smooth machine finish and the die lands a ground and polished finish. Conventional strip heaters are mounted on the exterior of the die body with electrical connection.
Figure 21: Profile Modifications

Example Sequence for the ‘Try and Cut’ Design Methodology to Achieve Target Dimensions for an Extruded Profile

<table>
<thead>
<tr>
<th>TRIAL NO.</th>
<th>DIE PLATE CONTOUR</th>
<th>BASIC DESIGN AND PROCESS DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>5% oversize on thickness dimensions 10% oversize on linear dimensions 12:1 land-to-opening ratio Melt Temp. 229 - 243 °C (445 - 470 °F) Die Temp. 210 - 232 °C (410 - 450 °F)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2 - 10% oversize on thickness dimensions 10 - 30% oversize on linear dimensions 10:1 land-to-opening ratio Span 0.023” H Output 32 - 57 kg/h (70 - 125 lb/h) @ 30 - 50 RPM Melt Temp. 229 - 241 °C (445 - 465 °F) Die Temp. 216 - 227 °C (420 - 440 °F)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2 - 15% oversize on thickness dimensions 10 - 30% oversize on linear dimensions 10:1 land-to-opening ratio Curvature #8 (parabolic) 2.5” Span 0.010” H Parallel Prisms 60 0.065” W x 0.056” H Output 50 kg/h (110 lb/h) @ 40 RPM Melt Temp. 235 °C (455 °F) Die Temp. 216 - 224 °C (420 - 435 °F)</td>
</tr>
</tbody>
</table>

Figure 21 gives a schematic representation of a typical embossing pattern on a profile surface. The extrudate is fed through a horizontal straight-through take-off for nip roll engagement. The overhanging extremities of the hot extrudates are supported on cooled sizing fixtures. To achieve the optimum embossed quality, uniform flow distribution must be provided with a full rolling bank, on the order of 1.6 - 3.2 mm (1/16 - 1/8 in). To maintain good pattern alignment and definition, careful regulation and close synchronization of the line speeds between the embosser and the pull units are required.

Figure 22 also shows the essentials of techniques used in cooling and sizing profiles. After it leaves the embossing roll nip, the warm extrudate can be post-shaped by means of a series of plate fixtures conduction-cooled with water and sized to the contour and dimensions of the finished part. The movable plate fixtures are mounted on an adjustable bed assembly and often spaced 7.5 - 13 cm (3 - 5 in) apart along a bed length of 2 m (6 ft). In cooling extrudates from 220 °C (430 °F) to below 93 °C (200 °F) at line speeds up to 1.2 m/min (4 ft/min), bed lengths of 1.2 - 1.8 m (4 - 6 ft) are usually required with an additional equivalent length for air cooling on a roller conveyor prior to puller and cutting operations. If the extrudate temperatures or line speeds are higher than these, longer beds and closer spacing of the cooling fixtures should be provided with adjustable assembly fixtures. Figure 22 illustrates the fold-down method for shaping the extrudate and shaping it downward and below the mating fixtures. This sort of post-shaping starts at the nip of the rolls and is completed within two or three successive sets of angled features.
Final shaping and cooling complete the production of the part. To give support during the fold-down, set up adjustable external fixtures outside of the extrudate in the same plan as the internal sizing plate. This procedure maintains the shape closely.

**Take-off, Cooling, and Sizing Systems**

The usual system for handling and cooling extruded acrylic sheet as it leaves the die is a three-roll polishing stack. Three-roll stacks can produce high-gloss flat and embossed sheet. For flat sheet, the rolls should have a mirror-like chrome finish. The center roll is held in a fixed position, and the movable top and bottom rolls are held against adjustable stops by means of pressurized cylinders. Pressures of at least 45 kg [100 lb] per lineal inch should be available.

The polishing stack must be level and pull the extrudate straight from the die lips. The rolls should be as close to the die lips as possible to minimize sagging of the melt. Rolls should be kept clean and care must be taken never to mar the surfaces, because an imperfection on the rolls would appear as a defect on the finished sheet. Each roll must be equipped with its own temperature control. The center roll should be about 6 °C [10 °F] below the temperature at which the sheet begins to stick to the metal. Roll surface temperatures above 104 °C [220 °F] may cause sticking.

Typical roll temperatures for smooth flat sheet range from 71 – 104 °C [160 – 220 °F]. The most downstream roll should be the hottest. Higher temperatures on the top roll “polish” the sheet resulting in excellent surface finish.

Excessive temperatures on the last roll, which may be on the bottom or the top depending upon stack orientation, may allow the pull rolls to stretch the sheet and produce severe orientation. The rubber pull rolls must exert constant tension on the sheet. The tension should be kept at the lowest level required to ensure the proper travel of the sheet through the take-off system. Excessive tension, which is the main cause of excessive orientation in the machine direction, should not be used to control the thickness or width of the sheet. Speed control for the polishing and pull rolls should be applied by separate synchronized controls and a variable differential.

Embossed or patterned sheet can be made on a three-roll stack by replacing a smooth roll with an embossing roll. The operation is otherwise identical to that used for flat sheet. A three-roll stack is superior to a two-roll stack for embossing, because it gives patterns with better definition. The three-roll stack also provides greater cooling and thereby can hold the pattern straight in both directions more easily, an important factor for producing patterns with good optical quality. Roll stacks can be configured in either an up or down orientation, where the extrudate first passes between the gaps of the lower two rolls, or the upper two rolls respectively. A two-roll stack usually requires additional cooling to freeze the pattern onto the sheet.

The temperatures of embossing rolls must be controlled precisely to ensure control of the cooling operation. The temperatures for embossing are slightly lower than for polished sheet. They are set in the range of 38 – 88 °C [100 – 190 °F] for three-roll stacks and 32 – 66 °C [90 – 150 °F] for two-roll operation. The actual temperatures depend to some extent on the nature of the pattern.

The extrudate may be cut to length with a traveling saw, or a shear cutter can be used for thinner sheets. The width of the sheet can be sized with slitting knives or trim saws or by scoring the sheet near the three-roll stack and breaking off the edges at the end of the line. Mask or interleaf finished sheet with tissue or polymer film as soon as possible to reduce the possibility of scratching during handling. Polymer masking can be applied on the line just before the pull rolls.
**Pressure Control**

Head pressure, usually defined as the melt pressure at the screw tip, can be regulated in several ways, including 1) adjusting a valve installed between the extruder and the die, 2) adjusting the speed or suction pressure of a melt pump, or 3) changing the mesh size or geometry of melt screens. The head pressure can significantly influence the melt temperature developed by the screw. Pressure control can, therefore, be used to raise the melt temperature or to maintain a constant melt temperature (or head pressure) when other factors, such as screen clogging, may affect the head pressure.

Valving devices are usually helpful or beneficial when high productivity is feasible and required. A valve is particularly advantageous in a two-stage vented extruder to control the inventory of melt in the second stage. Adequate inventory in the second stage improves output stability. Valving should not be attempted unless operable, dependable pressure gauges are used to register the head pressure. The valve is often in a highly restricted position and its adjustment is quite sensitive. The temperatures of the valve element and the die have an effect on the head pressure and should be measured accurately and controlled to help maintain process stability. All polymer flow valves should be fully opened before shutting down, to avoid potential severe damage during the next startup.

Process elements that separate and rejoin the polymer flow, including some types of plug valves and screen changers, can make the flow less consistent and more difficult to control.

**PROCESSING**

**Drying**

Plexiglas® acrylic resins are packaged at low moisture levels in specially constructed containers and can frequently be used with minimal drying. Absorbed moisture in Plexiglas® molding resins does not affect the physical properties of extruded sheet/profiles, however excessive moisture can cause surface defects such as die lines or tick marks. These defects can be avoided by drying the resin in warm air circulating ovens, vacuum dryers, or hopper dryers. Moisture levels should be 0.05% or less for the most sensitive applications. Some applications may tolerate as much as 0.1% moisture, especially when using a vented extruder. Please see Table 1 in the Material Handling section of this guide for recommended drying conditions for Plexiglas® resin grades.

A two-stage, vented extruder can remove a moderate amount of water from a feed of undried resins and leave no evidence of moisture defects. In the range of moisture contents that this type of machine can handle, however, the behavior of the polymer in the extruder may vary with the moisture content enough to alter flow characteristics through the die. Profiles and sheet extruded from feed materials exposed to humid conditions will almost certainly have unacceptable appearance and performance. Drying equipment is usually still required with two-stage vented processing, even though the drying requirements may be less strict than in corresponding single-stage operations. Extruders with more vents, larger vent surface areas, and deeper vent vacuum will be more effective at removing moisture and, in some cases, may eliminate the need to pre-dry the resin.

**Start-up Procedures**

Before startup, set the temperature controls for each zone to the predetermined temperatures and thoroughly heat the extruder and die. At the end of the preheating period, start the screw at slow speed while making sure to feed material slowly from the hopper. Never run the screw dry.

Continue running the screw at slow speed until a uniform extrusion is obtained at the die. If the pressure becomes too great, immediately stop the feed and lower screw speed until pressure is reduced. Then determine the cause of the difficulty and correct the faulty condition. When the flow of extrudate is satisfactory, increase the screw speed gradually and adjust the temperature settings to operating conditions. We recommend the installation of a rupture disc or other relief system to reduce the likelihood of equipment damage from excessively high pressures.

In starting a partially loaded extruder that has cooled, the preheating or “heat soak” period should be long enough to soften the plastic in the barrel and die so that it can flow and permit rotation of the screw without excessive resistance.

**Typical Processing Conditions**

Extruder barrel zone temperature settings vary with circumstances, machines, and screw designs. Table 1 lists ranges of temperatures applicable to commonly used Plexiglas® V-Series resin formulations. When suitable operating temperatures have been established for a particular formulation, the changes suitable for another formulation can be approximated from the relative differences shown in Table 1.

The most important temperature, and the one usually most difficult to establish without actual experience with the equipment, is the rear zone. Because this temperature affects the frictional forces in the feed area, it has a strong influence on the dry solids conveying rate and is therefore important in determining the motor load and process rate. The temperature setting for the rear zone must be kept in a range in keeping with the melting, transport, and pumping functions of later zones. Within these limits (and the input power limits), a consistent relationship exists whereby reducing the rear zone temperature increases the motor load and process rate [output/rpm] and vice versa. Note that screw speed (rpm) is the primary determining factor for process rate and that regulating the rear zone temperature has
only a contributory effect on the screw speed at which a given output is obtained. This setting can influence motor overload in constant torque drives, as discussed above. Give primary attention to the temperature of the rear zone, particularly on a first run, and adjust to provide a permissible steady motor load and minimum variation on head pressure. Temperature profile is also a factor in venting effectiveness.

TABLE 11: PLEXIGLAS® RESINS TYPICAL EXTRUSION PROCESSING CONDITIONS

<table>
<thead>
<tr>
<th>Grades</th>
<th>Feed Barrel Temp</th>
<th>Middle Barrel Temp</th>
<th>End Barrel Temp</th>
<th>Die Temp</th>
<th>Melt/Stock Temp</th>
<th>Head Pressure</th>
<th>Polishing Roll Temp</th>
<th>Screw Speed</th>
</tr>
</thead>
</table>

**Die Temperatures**

As with most thermoplastics, Plexiglas® resin extrudates tend to exhibit increased gloss with increasing die temperatures. With formulations having melt flow rate values greater than four, the variation in gloss is relatively small over the usual operating range. As a result, the die temperatures can be chosen to provide the best compromise between any of the following objectives:

1. To optimize the flow distribution from the die, a worthwhile aim with “non-adjustable” profile dies.
2. To regulate or influence the head pressure.
3. To suppress surface defects.

**Melt Temperatures**

In operating extruders at relatively low productivity, a direct correlation can be expected between the melt temperature developed at the screw discharge and the barrel temperatures in the equipment, especially in machines of small diameter. Because of the effects of the screw design factors discussed in the previous Screw Design section, the influence of the barrel temperatures on melt temperature decreases with increasing productivity. Other factors, such as screw speed, head pressure, and polymer viscosity assume the major role in determining the melt temperature. Melt temperatures in general, approach the listed nominal front barrel temperatures in cases of low productivity and reach values 28 – 42 °C [50 – 75 °F] higher at higher productivities.

**Pellet Handling**

Though extruders vary in their sensitivity to changes in input feed temperatures, some reaction to such changes should be anticipated with any machine. In the case of Plexiglas® resins, a rise in feed temperature increases the output rate under a given set of operating conditions. A constant output rate requires a constant feed temperature.

Problems caused by variations in processing conditions are more likely to occur when hot dried resins are fed to a large uninsulated and unheated feed hopper or when the material is not loaded automatically by a level sensing device. In such cases, when the hopper is likely to become filled completely with hot feed and then left to run low before refilling, an obvious condition for promoting changes in feed temperature develops. The ideal feed hopper should be small with quite steep walls to minimize adsorption of moisture and changes in feed temperature.
Vacuum loaders and compressed air loaders utilize the movement of air to fluidize and transport resins from one station to another. Vacuum loaders have the advantage of conveying under negative pressure with respect to the surroundings, thereby reducing the possibility of fine particles escaping into the surrounding area. This resistance to escape is particularly beneficial in maintaining cleanliness with a feed of regrind. Using compressed air presents the risk of contaminating the feed with oil unless special oil-free compressors are employed.

Though aluminum tubing is often used to convey plastic resins, it should be restricted to straight runs only. Curved sections should have sweep bend curvature and be made of stainless steel to prevent contamination. In very demanding applications, the exclusive use of stainless steel tubing is well advised.

Mechanical transfer devices, such as screw or helical conveyors, are sometimes used. The design and materials of construction of such devices must be considered carefully with regard to the possibility of abrasion.

Whatever transfer device is selected, it should permit convenient adjustment to maintain the required feed levels at the various stations. In charging a hopper dryer, holding the level constant stabilizes the drying time. When transfer devices are used to unload a dryer and feed an extruder hopper, they should provide a relatively constant level in the hopper. This is necessary for a stable output rate and minimum variation in feed temperature.

Hopper dryers are sometimes mounted directly on the extruder to provide gravity flow of the hot feed into the extruder feed throat and to remove the need for a transfer device. Direct mounting often causes difficulties, however, because the volatile materials given off from the back of the screw cannot vent. Material fed by gravity from the hopper dryer should proceed through a small open hopper to allow venting of the feed area. A more convenient arrangement, frequently needed because of limited head room, is to mount the hopper dryer on the floor, and use a transfer device to feed the extruder hopper. Separation of the hopper dryer from an extruder can increase the efficiency of scheduling and carrying out cleanup operations on the dryer and the extruder. This separation also provides flexibility in supplying several extruders from a single dryer if the drying capacity is adequate.

**Shutdown Procedures**

If the operation is stopped for any length of time, shut off the feed and immediately reduce the screw speed to a minimum. Run the screw at slow speed until material stops flowing out of the die. Then turn off the extruder and die heaters. When processing polymers that resist degradation, the extruder can be left in this condition for the next startup if a cleanout is not needed.

It is important to recognize that the “static” temperatures established at the barrel walls, screw surface, adapter, and die melt passages during heat up can be altered substantially by the shearing forces and frictional heat developed under “dynamic” operation. With the possible exception of the surface temperatures at the front and rear ends of the screw, these temperatures tend to increase as the machine enters its operating mode. A reduction in motor load and operating stresses in the equipment usually occurs as the machine approaches dynamic equilibrium, but care must be exercised to prevent overloading and severe stressing of the equipment during startup. If no previous information on the process is available, it is advisable to start with barrel temperatures set near the upper end of the ranges listed in Table 12.
<table>
<thead>
<tr>
<th>TABLE 12: EXTRUSION TROUBLESHOOTING GUIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Die Lines</strong></td>
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<tr>
<td>6↓</td>
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<td>7</td>
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<td>9</td>
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<td>7</td>
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<td>1</td>
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<td>9↑</td>
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<td>2</td>
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<td>4</td>
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</tbody>
</table>
HEATING

The objective during the heating process is to raise the sheet surface and core to the correct thermoforming temperature without burning or blistering the sheet surfaces. The key to good thermoforming is to make sure that the cross section of the sheet is sufficiently heated to allow the entire sheet, surface and core, the ability to elongate during the forming process. Conduction of heat from the sheet surface to the core requires a long heat soak. The time required for heat to soak into the core (center) of the sheet increases with the square of the sheet thickness. The heat capacity and thermal conductivity for the materials involved will influence the rate of conduction in multi-layer, multi-material sheets.

Either one-sided or two-sided heating can be used to thermoform sheets constructed with Plexiglas® resins. We recommend two-sided heating for any heavy-gauge application to maximize control and minimize time necessary to elevate the core to proper forming temperatures. Radiant heating is the best heat source:

- Heating source of 260 – 925 °C [500 – 1700 °F]
- Ceramic heaters radiate heat energy more efficiently than quartz or Calrod heat sources
- Other substrates may absorb different amounts of radiant energy than Plexiglas® acrylic; thus, surface temperatures may increase at different rates
- Care should be taken to maintain the surface temperature at 163 – 182 °C [325 – 360 °F] to avoid surface defects such as blistering, burning, and color/gloss shift

IMPORTANT: Forming temperature is affected by:

- Sheet thickness; this is the primary factor
- Heat capacity and thermal conductivity of the sheet; the type of substrate and level of regrind
- Intensity of heat source, efficiency, and absorption characteristics of the sheet

Forming too cold adversely affects material distribution, can lead to surface defects, and dramatically increases the level of residual stress from the forming cycle.

For heavy-gauge sheet thicker than 5.5 mm [0.225 in], it is recommended that only two-sided heating is used. This prevents long cycles, cold forming, and possible overheating of the sheet surface.
The key to minimizing stress in thermoforming is to have the proper temperature in the interior of the sheet, not just the top and bottom surfaces. As the sheet thickness increases, the conduction of heat through the plastic becomes the limiting factor.

The process of heating the core can be accelerated by moving from a single-sided oven to two-sided heating, but not by increasing the amount of time the heaters are on. Thermal conductivity from the sheet substrate to the sheet core controls the core heating time.

While two-sided ovens are preferred, if a single-sided oven is used, we recommend preheating the sheet for two to three hours in a hot air circulating oven at 71 – 82 °C [160 – 180 °F]. Dehumidified heating air is beneficial. Preheating helps to prevent overheating of the sheet surface, to prevent surface defects related to volatiles being driven off rapidly (bubbling), and to minimize the likelihood of cold forming.

Heat transfer from air to sheet is improved by increasing the air velocity in an enclosed oven. Remember, this only raises the surface temperature. Do not overheat the surface. Allow adequate time for the heat to soak into the core.

Steps should be taken to shield the oven from drafts to prevent thermal shock of the sheet during the heating and forming steps.

**Cooling**

All things being equal, thin sections cool faster than thick sections. The side of the sheet that is exposed to the air cools by convection. The side in contact with the thermoforming tool cools by heat conduction through the tool material. The tool material will influence the rate of conduction. Tools made of insulating materials, like wood, will have a lower conduction rate than thermally conductive materials, like aluminum.

Differential cooling rates produce stresses in the thermoformed part. These residual stresses will result in reduced performance of the final part. The aim is to minimize this effect by standardizing the cooling rates.

- Molds should be heated/temperature controlled for even cooling of the formed shell
- Thermal stress results from plastic sheet coming in contact with a cold mold
- Cold mold + uneven cooling = risk of poor part performance
- Prevent quick cooling of thin sections by insulating the thin sections and limiting differential cooling
- Check the mold and part surface temperature with a pyrometer or hand-held infrared thermometer
- The forming vacuum should be released when the material freezes; this will prevent the substrate from contracting in the mold, which can result in an increase in internal stresses in certain areas
- Remove the part from the tool after sufficient cooling

While the part may be in its finished form at this point, there still may exist a thermal gradient through the sheet. Large parts that are formed from thick sheet can continue to cool for up to 30 minutes after ejection from the forming tool. To reduce the chance of part warp or excessive internal stresses, while maintaining good cycle time, these parts can be placed in a separate “cooling fixture” that supports the part, but allows for convection cooling on both sides of the formed part.
**TABLE 13: THERMOFORMING TROUBLESHOOTING GUIDE**

<table>
<thead>
<tr>
<th>Blistering or Surface Deformation During Forming</th>
<th>Uniform Bubbles Within Sheet During Forming</th>
<th>Blistering/Bubbling After Forming</th>
<th>Corners too Thin in Deep Draws</th>
<th>Yellowing or Color Degradation</th>
<th>Whitening of Surface or Decreased Opacity</th>
<th>Poor Wall Thickness Distribution</th>
<th>Crazing or Cracking of Part in Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Variables</td>
<td>Machine Variables</td>
<td>Machine Variables</td>
<td>Machine Variables</td>
<td>Machine Variables</td>
<td>Machine Variables</td>
<td>Machine Variables</td>
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<td>2↓ 2↑ 2</td>
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<td>2↓ 2↑ 2</td>
<td>2↓ 2↑ 2</td>
<td>2↓ 2↑ 2</td>
</tr>
<tr>
<td>Adjust heating rate</td>
<td>Adjust cooling rate</td>
<td>Ensure even heating/improve control</td>
<td>Adjust heater intensity</td>
<td>Adjust sheet forming temperature</td>
<td>Adjust corner radii</td>
<td>Ensure even adhesion between layers</td>
<td>Adjust mold temperature</td>
</tr>
<tr>
<td>4 2 3 3 1</td>
<td>4 1 3 3 1</td>
<td>4 1 3 3 1</td>
<td>4 1 3 3 1</td>
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<td>4 1 3 3 1</td>
<td>4 1 3 3 1</td>
<td>4 1 3 3 1</td>
</tr>
<tr>
<td>Change forming technique</td>
<td>Dry sheet before forming</td>
<td>Wrap stored sheet with moisture barrier</td>
<td>Minimize sheet storage time</td>
<td>Preheat sheet</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5 5 5 4</td>
<td>3 1</td>
<td>4 2</td>
<td>5 3</td>
<td>6 4</td>
<td></td>
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</tr>
</tbody>
</table>

Number indicates recommended order of corrective actions.

Ambient conditions dictate maximum storage time after pre-drying.
FINISHING OPERATIONS
ANNEALING

We recommend annealing to ensure optimum quality and maximum useful service life from parts molded or extruded from Plexiglas® acrylic resin. The primary benefits of annealing Plexiglas® parts are improved resistance to external stresses (mechanical or chemical) and greater dimensional stability at elevated service temperatures.

Annealing is the process of heating a molded part for a period of time and at a temperature near, but below, its softening point. This heating followed by slow, uniform cooling will cause stress relaxation without distortion of shape. The goal of annealing is to redistribute and reduce the stresses in the part generated by the molding/forming process. Annealing does not completely eliminate molded-in stresses in a well-molded part and can only partly relieve the internal stresses in a poorly-molded one.

**Selecting an Optimal Annealing Cycle**

This procedure is only intended to establish a suitable temperature and time period for annealing your parts. To achieve the maximum benefits from annealing, follow these suggestions:

1. Place several carefully measured, as-molded parts in the annealing oven at the higher temperature from Table 14 for the specific grade from which the parts were molded.

2. Heat-treat them for the length of time indicated for the maximum applicable part thickness.

3. Allow the parts/oven to cool no faster than the suggested cooling rate listed in Table 14 based on the maximum part thickness. Exposing heated parts to ambient air temperature can re-introduce cooling stress at the part surface.

4. Remove the parts from the oven and let them cool for several hours at room temperature before remeasuring their dimensions.

5. If the dimensional change following this heat treatment proves no greater than 1%, or the maximum permissible change for your specific application, the parts may be properly annealed with these conditions. In certain cases, even additional heating time may be required to further relieve internal stresses.

6. If the dimensional change exceeds 1% (or maximum permissible), repeat the test at the lower temperature and time indicated in Table 14. If unacceptable dimensional changes continue to occur, this is positive evidence the part is poorly molded and requires improvement of molding conditions.

<table>
<thead>
<tr>
<th>Part Thickness mm (in)</th>
<th>HT121</th>
<th>V825, V825T, V826, V052i, V045, M17</th>
<th>V045i, V920, M17, DR®</th>
<th>HFI7, SG7, HFI10, VM</th>
<th>VS, SG10</th>
<th>Max Cooling Rate °C [°F]/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 – 3.8 mm [0.060 – 0.150 in]</td>
<td>2.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>3.9 – 9.5 mm [0.151 – 0.375 in]</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>9.6 – 19 mm [0.376 – 0.750 in]</td>
<td>4</td>
<td>9</td>
<td>4</td>
<td>9</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>19.1 – 28 mm [0.751 – 1.125 in]</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>29 – 38 mm [1.126 – 1.500 in]</td>
<td>8</td>
<td>13</td>
<td>8</td>
<td>13</td>
<td>13</td>
<td>7</td>
</tr>
</tbody>
</table>
FABRICATING AND BONDING

Parts made of Plexiglas® acrylic resin can successfully be fabricated using a variety of techniques. These include cutting, routing, scribing, machining, turning, drilling, threading, tapping, sanding, polishing, and buffing. Parts may also be bonded via mechanical or chemical methods. For more in-depth information on all of these techniques, please see the Plexiglas® Fabrication Manual, which can be found in the Sheet Literature section of Plexiglas.com

Thermal/Mechanical Welding

Parts molded of Plexiglas® resin can be thermally welded using hot plate, vibrational, ultrasonic, or laser techniques to create leak-proof, permanent, attractive, contamination-free, high-strength bonds. Welds result from frictional or conductive heating of the polymers under applied pressure such that a melt bond occurs between the components. Common welding techniques include ultrasonic, vibration, and hot plate. These techniques are best suited to polymers with similar melt characteristics. The broad melting range of Plexiglas® acrylic resins make them compatible with a number of common amorphous thermoplastic polymers. The following guidelines may be used as reference points when welding Plexiglas® acrylic resins. Optimum conditions will vary with application depending on part size, geometry, and materials employed.

### TABLE 15: RECOMMENDED WELDING PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>Ultrasonic (20 KH)</th>
<th>Vibration</th>
<th>Hot Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>40 – 70 μm</td>
<td>0.75 – 1.75 mm [0.030 – 0.070 in]</td>
<td>N/A</td>
</tr>
<tr>
<td>Pressure</td>
<td>200 – 415 kPa [30 – 60 psi]</td>
<td>1375 – 3450 kPa [200 – 500 psi]</td>
<td>N/A</td>
</tr>
<tr>
<td>Temperature</td>
<td>N/A</td>
<td>N/A</td>
<td>315 – 425 °C [600 – 800 °F]</td>
</tr>
<tr>
<td>Melt Depth</td>
<td>N/A</td>
<td>N/A</td>
<td>0.75 – 1 mm [0.030 – 0.040 in]</td>
</tr>
<tr>
<td>Seal Depth</td>
<td>N/A</td>
<td>N/A</td>
<td>0.25 – 0.50 mm [0.010 – 0.020 in]</td>
</tr>
</tbody>
</table>

**Ultrasonic Welding**

The use of an energy director is recommended for ultrasonic welding of Plexiglas® acrylic resins. The director, shown in Figure 25, concentrates energy to speed softening and melting of the joint. When welding different polymers, the energy director should be incorporated in the higher modulus material.

**Plexiglas® acrylic resins may be heat staked for assembly to materials that cannot be welded, e.g. metals and crystalline polymers. Staking is readily accomplished using heat or ultrasonic energy. Heat stake design considerations are shown in Figure 26.**

General weld compatibility to various other polymers is shown in Table 16.

---

**Figure 25: Energy Director Design**

**Figure 26: Heat Stake Design**
TABLE 16: WELD COMPATIBILITY

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Plexiglas® V-Series</th>
<th>Plexiglas® MI-7</th>
<th>Plexiglas® DR®</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultrasonic</td>
<td>Vibration</td>
<td>Hot Plate</td>
</tr>
<tr>
<td>PMMA</td>
<td>G</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>ABS</td>
<td>G</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>ABS/PC</td>
<td>G</td>
<td>VG</td>
<td>VG</td>
</tr>
<tr>
<td>PC</td>
<td>G</td>
<td>VG</td>
<td>VG</td>
</tr>
</tbody>
</table>

Weld Rating

<table>
<thead>
<tr>
<th>% of Polymer Strength* Attainable</th>
<th>Excellent</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld Rating</td>
<td>90 – 100%</td>
<td>70 – 90%</td>
<td>50 – 70%</td>
<td>25 – 50%</td>
<td>0 – 25%</td>
</tr>
</tbody>
</table>

* Tensile strength of weaker material

CHEMICAL RESISTANCE

Plexiglas® V-series and impact resistant acrylic resins have good resistance to a variety of common cleaners and application environments. The chemical resistance of Plexiglas® V-series acrylic resins will vary with the stress level, temperature, reagent, duration of exposure and resin grade. Altuglas International recommends that parts made from Plexiglas® resins be tested with all reagents under appropriate conditions for the end-use application.

For a detailed list of chemical compatibility, please see the Plexiglas® Resins Chemical Compatibility Guide, which can be found in the Resin Literature section of Plexiglas.com
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December 2020