Understanding Thermoforming

2nd Edition
James L. Throne

Understanding Thermoforming
Understanding Thermoforming

2nd Edition
Foreword to the Second Edition

The first edition of this modest work was designed as an introduction and supplement to my larger effort, “Technology of Thermoforming”, also published by Hanser. It presented a general overview of this rapidly growing field, without extensive details or equations.

Although the basic elements of thermoforming have not changed in the near-decade since the publication of the first edition, the industry is maturing and more details of the inner workings of the process are needed. Thermoforming is not just about machinery, molds, plastics, and making parts. It is also about process monitoring and control, quality assurance, safety and competitiveness with other processes. I’ve made an effort to broaden the work to include many of these aspects.

Two disparate areas for product development have become important recently. Thermoforming has been used in transportation for many years, primarily to produce low-volume parts. Truck and aircraft interiors and bus and train toilet interiors are examples. The development of paint film technology has spurred an interest in thermoformed paint-free exterior panels for domestic vehicles. Another developing area is bio-devices. Biotechnology is arguably the most rapidly growing science worldwide. Of course, there are many thermoforming applications already. A recent development, where 25-micron thick film is thermoformed into 350-micron hemispheres as containers for cell cultures, emphasizes microthermoforming.

The intent of the work has not changed. It remains a primer. I’ve rearranged the chapters to focus on the mechanics of the process first, then to consider the nature of the polymers. I’ve also added a short chapter on comparing thermoforming – technically and economically – with other technologies such as blow molding, rotational molding, and injection molding.

One caveat, though. In the first edition, there were no equations. In this edition, there are equations, but only simple ones, for illustration only.

Jim Throne
1797 Santa Barbara Drive
Dunedin, Florida, 34698-3347, USA
Contents

Foreword to the Second Edition ............................................. V

1 Introduction to Thermoforming ............................................. 1
  1.1 Brief History .......................................................... 1
  1.2 General Markets ..................................................... 3
  1.3 Terminology ........................................................... 5
  1.4 General Characteristics of Thermoformed Products .......... 6

2 General Forming Concepts ................................................. 9
  2.1 Heating and Bending .................................................. 9
  2.2 Simple Heating and Stretching ................................... 11
  2.3 One-Step Forming .................................................... 11
    2.3.1 Drape Forming ................................................. 11
    2.3.2 Vacuum Forming .............................................. 12
    2.3.3 Free Forming .................................................. 12
    2.3.4 Non-Uniform Heating ....................................... 13
    2.3.5 Matched Mold Forming ................................... 13
  2.4 Other One-Step Forming Processes ................................ 14
    2.4.1 Autoclave Forming .......................................... 14
    2.4.2 Diaphragm Forming ........................................ 14
  2.5 Two-Step Forming .................................................... 15
    2.5.1 Pneumatic Preforming ...................................... 15
    2.5.2 Plug Assisted or Mechanical Preforming ............... 17
    2.5.3 Pressure Forming ........................................... 19
    2.5.4 Coining ..................................................... 19
  2.6 Three-Step Forming .................................................. 19
  2.7 Twin-Sheet Forming .................................................. 20
    2.7.1 Heavy-Gauge Twin-Sheet Forming ....................... 20
    2.7.2 Light-Gauge Twin-Sheet Forming ....................... 22
  2.8 Contact Forming ..................................................... 24
  2.9 Thermoforming as a Portion of the Overall Manufacturing Process .... 25

3 Part Design ................................................................. 27
  3.1 Part Design Philosophy ............................................. 27
    3.1.1 Design Protocol .............................................. 28
    3.1.2 Project Protocol ........................................... 29
  3.2 Should This Part Be Thermoformed? ............................... 30
  3.3 General Parameters Affecting Part Design ...................... 31
    3.3.1 Shrinkage ................................................... 31
  3.4 General Product Design ........................................... 34
    3.4.1 Corner versus Chamfer .................................. 35
## Contents

3.4.2 Draft Angles ...................................................... 35
3.4.3 Thermal Expansion ............................................... 36
3.4.4 Dimensional Tolerance ............................................ 37
3.4.5 Improving Dimensional Tolerance .................................. 39
3.5 Part Surface Quality ...................................................... 40
3.6 Trim Line Location ....................................................... 41
3.7 In-Mold Decorating and Labeling .......................................... 42
3.8 Seal Designs on Twin-Sheet Thermoformed Parts ............................ 43
3.9 Some Guidelines to Successful Part Design .................................. 44

4 Machinery for the Thick-Gauge Forming Process ........................... 49
   4.1 Shuttle Press ............................................................. 49
   4.1.1 Two-Oven Shuttle Press ........................................... 50
   4.2 Cabinet Press ............................................................. 51
   4.3 Rotary Thermoforming Press .............................................. 51
   4.4 The Elements of Heavy-Gauge Machinery ............................ 53
       4.4.1 Sheet Handling ................................................... 54
       4.4.2 Sheet Clamping ................................................... 54
       4.4.3 Sheet Shuttle or Rotation .......................................... 54
       4.4.4 Oven(s) .......................................................... 54
       4.4.5 The Forming Press ................................................ 55
       4.4.6 Pneumatic Prestretching ........................................... 56
       4.4.7 Plug Assist Prestretching ........................................... 56
       4.4.8 Load/Unload Elements ............................................ 57
       4.4.9 Vacuum Box and Vacuum System ................................... 57
       4.4.10 Pressure Box and Pressurization System ............................. 58
       4.4.11 Condition Monitors and Process Control ............................ 59
       4.4.12 Safety Elements ................................................... 61

5 Machinery for the Light-Gauge Forming Process .......................... 63
   5.1 Standard Roll-Fed Machine ................................................ 63
   5.2 Contact Heater Machines .................................................. 65
   5.3 Form-Fill-Seal Operation .................................................. 65
   5.4 Elements of Light-Gauge Machinery ........................................ 67
       5.4.1 Sheet Take-off or Unwind Station ................................... 67
       5.4.2 Pin-Chain and Pin-Chain Rail ...................................... 67
       5.4.3 Oven(s) .......................................................... 68
       5.4.4 The Forming Press ................................................ 69
       5.4.5 Plug Assist Prestretching Devices ................................... 71
       5.4.6 Trim Means ...................................................... 71
       5.4.7 In-Machine Stacking Means ........................................... 72
       5.4.8 Vacuum Box and Vacuum System ................................... 72
       5.4.9 Pressure Box and Pressurization System ............................. 73
       5.4.10 Trim or Web Take-up Station ....................................... 74
       5.4.11 Condition Monitors and Process Control ............................ 74
       5.4.12 Safety Features ................................................... 76
6 Machines for Other Applications ........................................... 77
6.1 Extrusion-Forming Lines .................................................. 77
6.1.1 Advantages of Extrusion-Forming Lines for Heavy-Gauge Forming .... 77
6.1.2 Advantages of Extrusion-Forming Lines for Light-Gauge Forming .... 78
6.1.3 Disadvantages of Extrusion-Forming Lines for Heavy-Gauge Forming . . 78
6.1.4 Disadvantages of Extrusion-Forming Lines for Light-Gauge Forming . . . 78
6.1.5 Important Extruder Characteristics in In-Line Forming ............... 79
6.2 Matched Mold Forming Machines .......................................... 79
6.2.1 Foamed Polymer Machines ........................................ 80
6.2.2 Composite and Composite Laminate Machines ...................... 80
6.3 Wheel Machines .......................................................... 81
6.4 Custom Machines ........................................................ 82
6.5 Twin-Sheet Forming Machines ............................................. 83

7 Molds and Mold Design ....................................................... 85
7.1 Production Mold Materials ................................................ 85
7.1.1 Cast Aluminum ................................................... 85
7.1.2 Machined Aluminum ............................................. 87
7.1.3 Other Production Mold Materials .................................. 87
7.2 Prototype Mold Materials ................................................. 88
7.2.1 Hardwoods .................................................................. 88
7.2.2 Plaster ........................................................................ 88
7.2.3 Medium-Density Fiberboard ....................................... 89
7.2.4 Syntactic Foam ....................................................... 89
7.2.5 Thermoset Plastics ................................................... 90
7.2.6 Sprayed Metal ....................................................... 90
7.3 Mold Design Elements ..................................................... 90
7.3.1 Cooling ....................................................................... 90
7.3.2 Venting ....................................................................... 91
7.3.3 Undercuts ................................................................... 92
7.3.4 Mold Surface Texture ................................................ 93
7.3.5 Textured Mold or Textured Sheet? .................................. 94
7.4 Plug Assist Materials and Designs .......................................... 94
7.5 Other Mold Features ......................................................... 97
7.5.1 Cavity Isolators or Grids and Perimeter Clamps ...................... 97
7.5.2 Pressure Box .......................................................... 97
7.5.3 Draw Box ................................................................... 98
7.5.4 Coining ....................................................................... 98
7.5.5 Web Breakers and Chasers ......................................... 98
7.5.6 Rapid Tool Change .................................................... 99
7.6 Molds for Matched Mold Forming ......................................... 100
7.7 Molds for Twin-Sheet Forming ........................................... 100

8 Methods of Heating Sheet ..................................................... 101
8.1 General Heating Concepts .................................................. 101
8.1.1 Conduction .................................................................. 101
8.1.2 Convection ...................................................... 103
8.1.3 Radiation ....................................................... 104
8.1.3.1 Radiant Efficiency ......................................... 105
8.2 Common Thermoforming Heaters ........................................ 106
8.2.1 Convection or Hot Fluid Heating .................................. 106
8.2.1.1 Hot Air Heating ........................................... 106
8.2.1.2 Combustion Gas Heating ................................... 107
8.2.1.3 Hot Liquid Heating ........................................ 107
8.2.2 Electric Heaters .................................................. 107
8.2.2.1 Round or Rod Heaters ..................................... 108
8.2.2.2 Flat Panel Heaters ......................................... 109
8.2.3 Combustion Heating ............................................. 110
8.2.4 Contact Heating ................................................. 112
8.3 Selecting the Proper Heater ........................................... 113
8.4 A Comparison of Widely Used Heaters ..................................... 115
8.5 Heating Cycle Time ...................................................... 117
8.5.1 Forming Temperature Range ...................................... 117
8.5.2 Energy Uptake ................................................... 118
8.5.3 Polymer Characteristics .......................................... 119
8.5.4 Geometric Factors ............................................... 120
8.5.5 The Issue of Sheet Sag ............................................ 121
8.5.6 Heating Composites, Laminates, and Other Plastics ............... 122
8.5.7 Pattern or Zonal Heating ......................................... 123
8.5.8 One-Sided versus Two-Sided Heating .............................. 124
8.5.9 Heating Cycle Time Prediction .................................... 126
8.5.10 Equilibration .................................................... 126

9 Sheet Stretching and Cooling ................................................ 129
9.1 Modulus and Stiffness.................................................... 129
9.2 The Concept of Viscoelasticity .......................................... 130
9.2.1 Elasticity ........................................................ 130
9.2.2 Viscosity ........................................................ 130
9.2.3 Viscoelasticity ................................................... 131
9.2.4 Measuring Viscoelastic Properties of Polymers ...................... 132
9.3 The Concepts of Stress and Strain ..................................... 133
9.3.1 The Forming Window ............................................ 134
9.3.2 Forming Area Diagram ......................................... 135
9.4 Prestretching ............................................................ 136
9.5 Pressure Forming ........................................................ 137
9.6 The Effect of Sheet Cooling ............................................ 138
9.6.1 Forming Area Diagrams for Laminates and Composites .......... 138
9.6.2 Differential Stretching against a Mold Surface .................... 138
9.7 Draw Ratios ............................................................. 139
9.7.1 The Usefulness of Draw Ratios .................................... 140
9.7.2 Wall Thickness Reduction in Laminates ........................... 140
9.8 Part Wall Thickness Prediction ........................................ 142
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.8.1</td>
<td>Finite Element Analysis</td>
<td>142</td>
</tr>
<tr>
<td>9.8.2</td>
<td>FEA Data Input</td>
<td>143</td>
</tr>
<tr>
<td>9.8.3</td>
<td>Model Verification</td>
<td>144</td>
</tr>
<tr>
<td>9.9</td>
<td>Sheet Sag and Sag Rate</td>
<td>145</td>
</tr>
<tr>
<td>9.10</td>
<td>Cooling Against a Mold Surface</td>
<td>146</td>
</tr>
<tr>
<td>9.10.1</td>
<td>Light-Gauge Cooling Criteria</td>
<td>147</td>
</tr>
<tr>
<td>9.10.2</td>
<td>Heavy-Gauge Cooling Criteria</td>
<td>147</td>
</tr>
<tr>
<td>9.10.3</td>
<td>Cooling and Residual Stress</td>
<td>147</td>
</tr>
<tr>
<td>9.10.4</td>
<td>Coolant Characteristics</td>
<td>147</td>
</tr>
<tr>
<td>9.10.5</td>
<td>Coolant Flow Rate and Temperature Control</td>
<td>148</td>
</tr>
<tr>
<td>9.11</td>
<td>Cooling Against the Plug</td>
<td>149</td>
</tr>
<tr>
<td>9.12</td>
<td>Heat Removal by Mold and Coolant</td>
<td>149</td>
</tr>
<tr>
<td>9.13</td>
<td>Forming Times</td>
<td>150</td>
</tr>
<tr>
<td>10.1</td>
<td>The Mechanics of Trimming</td>
<td>154</td>
</tr>
<tr>
<td>10.2</td>
<td>Light-Gauge Trimming</td>
<td>155</td>
</tr>
<tr>
<td>10.2.1</td>
<td>In-Mold Trimming</td>
<td>155</td>
</tr>
<tr>
<td>10.2.2</td>
<td>In-Machine Trimming</td>
<td>158</td>
</tr>
<tr>
<td>10.2.3</td>
<td>In-Line Trimming</td>
<td>158</td>
</tr>
<tr>
<td>10.2.3.1</td>
<td>Canopy or Horizontal Trimming</td>
<td>159</td>
</tr>
<tr>
<td>10.2.3.2</td>
<td>Flatbed or Vertical Trimming</td>
<td>160</td>
</tr>
<tr>
<td>10.2.4</td>
<td>Two-Step Trimming</td>
<td>160</td>
</tr>
<tr>
<td>10.3</td>
<td>Prototype Trimming</td>
<td>161</td>
</tr>
<tr>
<td>10.4</td>
<td>Heavy-Gauge Trimming</td>
<td>162</td>
</tr>
<tr>
<td>10.4.1</td>
<td>In-Plane Trimming</td>
<td>162</td>
</tr>
<tr>
<td>10.4.2</td>
<td>Hand Power Tool Trimming</td>
<td>164</td>
</tr>
<tr>
<td>10.4.3</td>
<td>Milling or 3-Axis Machines</td>
<td>164</td>
</tr>
<tr>
<td>10.4.4</td>
<td>Multi-Axis Routers</td>
<td>165</td>
</tr>
<tr>
<td>10.4.5</td>
<td>Robotic Trimmers</td>
<td>165</td>
</tr>
<tr>
<td>10.5</td>
<td>The Importance of the Trim Fixture</td>
<td>166</td>
</tr>
<tr>
<td>10.5.1</td>
<td>Cutter Design</td>
<td>166</td>
</tr>
<tr>
<td>10.6</td>
<td>Trim Tolerance</td>
<td>167</td>
</tr>
<tr>
<td>10.7</td>
<td>Other Trimming Concepts</td>
<td>168</td>
</tr>
<tr>
<td>10.7.1</td>
<td>Water Jet Cutting</td>
<td>168</td>
</tr>
<tr>
<td>10.7.2</td>
<td>Laser Cutting</td>
<td>169</td>
</tr>
<tr>
<td>10.7.3</td>
<td>Trimming Foam</td>
<td>169</td>
</tr>
<tr>
<td>11.1</td>
<td>Polymer Characterization</td>
<td>171</td>
</tr>
<tr>
<td>11.1.1</td>
<td>Plastic vs. Polymer</td>
<td>171</td>
</tr>
<tr>
<td>11.1.2</td>
<td>Thermoset and Thermoplastic Definitions</td>
<td>172</td>
</tr>
<tr>
<td>11.1.3</td>
<td>Crystalline and Amorphous Definitions</td>
<td>172</td>
</tr>
<tr>
<td>11.1.4</td>
<td>Homopolymers, Copolymers, Terpolymers, and Blends</td>
<td>173</td>
</tr>
<tr>
<td>11.1.5</td>
<td>Additives, Fillers and Reinforcements</td>
<td>173</td>
</tr>
<tr>
<td>11.2</td>
<td>The Thermoforming Window</td>
<td>175</td>
</tr>
</tbody>
</table>
11.3 Thermoformable Polymers ............................................... 176
  11.3.1 Polystyrene and Other Styrenics ................................... 176
  11.3.2 Polyvinyl Chloride and Other Vinlys ............................... 177
  11.3.3 Acrylics ......................................................... 178
  11.3.4 Cellulosics ...................................................... 179
  11.3.5 Polycarbonate ................................................... 179
  11.3.6 Polyesters ....................................................... 180
  11.3.7 Polyethylene ..................................................... 182
  11.3.8 Polypropylene ................................................... 183
  11.3.9 Other Polyolefins ............................................... 187
  11.3.10 Formable Biopolymers ........................................... 189
  11.3.11 Other Formable Polymers ........................................ 191
  11.4 Multilayer Polymers. ................................................ 193
  11.5 Foamed Plastics ......................................................... 194
    11.5.1 High-Density Foams ............................................. 194
    11.5.2 Low-Density Foams .............................................. 196
  11.6 Thermal Properties ...................................................... 198
    11.6.1 Heat Capacity ................................................... 199
    11.6.2 Thermal Conductivity ............................................ 199
    11.6.3 Polymer Density ................................................. 200
    11.6.4 Thermal Diffusivity .............................................. 200
    11.6.5 Thermal Coefficient of Expansion ................................. 200
    11.6.6 Thermal Properties of Multilayer Structures, 
      and Filled and Reinforced Polymers ................................ 201
  11.7 Infrared Energy Absorption for Specific Polymers ................. 201

12 Issues of Quality Control .................................................... 205
  12.1 Incoming Sheet Quality .................................................. 205
    12.1.1 What the Thermoformer Needs to Know About the Extrusion 
      Process ............................................................. 205
    12.1.2 What the Thermoformer Needs to Know About Quality ............. 210
    12.1.3 What the Thermoformer Needs to Know About Regrind ............. 215
  12.2 The Role of the Purchase Order ........................................... 217
    12.2.1 Incoming Sheet Quality Evaluation ................................ 218
  12.3 Production Monitoring .................................................. 218
    12.3.1 Monitoring Temperature .......................................... 218
    12.3.2 Sheet Formability ............................................... 219
    12.3.3 Cutting Surfaces – Microfracture Concerns .......................... 221
    12.3.4 Finished Part Performance ....................................... 221

13 Comparison with Other Technologies [47, 48] ........................... 223
  13.1 Classification of Plastics Molding Technologies ........................ 225
  13.2 Polymer Material Choices ............................................... 226
  13.3 Other Processing Concerns ............................................... 226
14 Pragmatic Aspects of Thermoforming .......................................................... 229
  14.1 Safety ........................................................................................................... 229
  14.2 Thermoforming Machine Set-Up ............................................................... 232
    14.2.1 Set-Up for a New Machine ................................................................. 232
    14.2.2 Set-Up for a Used Machine .................................................................. 233
  14.3 Mold Set-Up ................................................................................................ 234
    14.3.1 New Mold Set-Up ................................................................................ 234
    14.3.2 Existing Mold Set-Up .......................................................................... 234
  14.4 Trim Set-Up ................................................................................................ 235
    14.4.1 Heavy-Gauge Trim Set-Up .................................................................. 235
    14.4.2 Light-Gauge Trim Set-Up .................................................................... 236
  14.5 Maintenance ............................................................................................... 236
    14.5.1 Emergency Maintenance ..................................................................... 236
    14.5.2 Preventative Maintenance ................................................................... 237
  14.6 Troubleshooting Tips .................................................................................. 239
    14.6.1 Non-Crisis Troubleshooting ................................................................. 239
    14.6.2 The Crisis Situation ............................................................................ 241

References ............................................................................................................ 243

Recommendations for Further Reading .............................................................. 247
  Books .................................................................................................................. 247
  Other Sources .................................................................................................... 247
  Historical Reading ............................................................................................. 248

Appendix: Glossary of Thermoforming Terms .................................................. 249

Subject Index ....................................................................................................... 257
Annual plastics consumption in North America (USA) has reached approximately 100,000 million pounds (45,000 million kg), which is approximately a third of the world consumption. Plastics are converted from polymers and additives to products in many ways. Injection molding and extrusion are primary conversion technologies. Compared with these technologies, thermoforming is a minor conversion technology, as is blow molding, rotational molding and many other processes. Further, thermoforming is considered a secondary conversion technology, because it requires another conversion technology, extrusion, to provide its input material, extruded sheet and film.

This chapter gives a brief history of thermoforming. Then general markets are reviewed, and the general definitions used in this book are presented. A glossary of terms and some general references are provided at the end of the book.

### 1.1 Brief History

In thermoforming, plastic products are shaped from softened plastic sheet. The plastic sheet is heated to a temperature range where it is soft or supple. It is then stretched against a cool mold surface. When the sheet has cooled to the point where it retains the shape of the mold, the sheet and the formed part are removed from the mold and the excess plastic is trimmed from the part. The portion of the sheet that is trimmed away is usually recycled to produce additional sheet.

Thermoforming is a generic term for a group of processes that include vacuum forming, drape forming, billow or free bubble forming, mechanical bending, matched-mold forming, and the newer processes of pressure forming and twin-sheet forming.

Thermoforming is considered as one of the oldest methods of forming useful articles of plastic. In the 1870s in the USA, John Wesley Hyatt, considered the father of modern plastics processing, and his mechanical engineering colleague, Charles Burroughs, rolled thin, skived sheets of celluloid or cellulose nitrate into tubes, inserted the tubes into steel molds that contained the desired shapes, and heated the sheets with steam under pressure. The steam softened the celluloid sheets and forced it against the mold shapes. The molds were then cooled in water, rigidifying the plastic. The molds were opened and the parts trimmed to size. Typical products included small, shaped bottles, baby rattles, and mirror cases, see Fig. 1.1. Table 1.1 provides highlights of other advances in thermoforming.
Table 1.1: Highlights in Thermoforming History

<table>
<thead>
<tr>
<th>Time</th>
<th>Place</th>
<th>Thermoforming Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prehistory</td>
<td>Egypt and Micronesia</td>
<td>Tortoise sheet (keratin) is heated in hot oil and shaped to produce food containers</td>
</tr>
<tr>
<td>Prehistory</td>
<td>Americas and Micronesia</td>
<td>Tree bark (natural cellulosics) is heated in hot water and shaped into bowls and canoes</td>
</tr>
<tr>
<td>1870s</td>
<td>England</td>
<td>Parkes, Spill experiment with nitrocellulose</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>Hyatt develops moldable camphorated cellulose nitrate</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>Hydraulic planar developed for cutting thin sheets of Celluloid, Charles Burroughs Co., NJ</td>
</tr>
<tr>
<td>1910</td>
<td>England</td>
<td>Sharps piano keys drapeformed over captive wooden cores</td>
</tr>
<tr>
<td>1930</td>
<td>USA</td>
<td>Bottle formed from two thermoformed halves by Fernplas Corp.</td>
</tr>
<tr>
<td>1930s</td>
<td>USA</td>
<td>Relief maps thermoformed for US Coast &amp; Geodetic Survey, Washington, DC</td>
</tr>
<tr>
<td>1933</td>
<td>Europe</td>
<td>Formed rigid polyvinyl chloride (PVC) used in Phillips refrigerator</td>
</tr>
<tr>
<td>1935</td>
<td>USA</td>
<td>Cellulose acetate ping-pong balls twin-sheet formed by E. I. DuPont de Nemours Co., Inc., Wilmington, DE</td>
</tr>
<tr>
<td>1938</td>
<td>USA</td>
<td>Blister pack of cellulose nitrate</td>
</tr>
<tr>
<td>1938</td>
<td>USA</td>
<td>Automatic thin-sheet roll-fed thermoformer developed by Klaus B. Strauch Co.</td>
</tr>
<tr>
<td>1942</td>
<td>USA, England</td>
<td>Cast acrylic (PMMA) thermoformed for fighter, bomber windows, gun closures, windscreens</td>
</tr>
<tr>
<td>1943</td>
<td>USA, England</td>
<td>Cellulose acetate thermoformed for glider windows</td>
</tr>
<tr>
<td>1948</td>
<td>England</td>
<td>Cast acrylic (PMMA) bathtubs thermoformed by Troman Brothers</td>
</tr>
<tr>
<td>1954</td>
<td>USA</td>
<td>Skin-packaged products shown at Hardware Manufacturers Association trade show, Chicago</td>
</tr>
<tr>
<td>1970</td>
<td>USA</td>
<td>Thermoformed ABS concept car automobile body by Borg-Warner, Inc.</td>
</tr>
<tr>
<td>1985</td>
<td>USA</td>
<td>Crystallizing polyethylene terephthalate (CPET) introduced for food reheat use by Viking Products</td>
</tr>
</tbody>
</table>
1.2 General Markets

Thermoforming products are usually categorized either as disposable products or as permanent or industrial products. The majority of disposable products is used in rigid packaging. Permanent or industrial products are made of relatively thick plastic sheet and the process is often referred to as heavy-gauge or thick-gauge thermoforming. Disposable products are made of relatively thin plastic sheet and the process is often referred to as light-gauge or thin-gauge thermoforming. These two categories will be further defined later in this chapter.

For several decades now, more than two-thirds of all thermoforming products have been disposable products. Typical disposable products include blister packs, point-of-purchase containers, bubble packs, slip sleeve containers, audio/video cassette and diskette holders, cosmetic cases, meat and poultry containers, unit serving containers, convertible-oven food serving trays, wide-mouth jars, vending machine hot and cold drink cups, egg cartons, produce and wine bottle separators, medicinal unit dose portion containers, and rigid form-fill-and-seal containers for foodstuffs, hardware supplies, medicines, and medicinal supplies.

In a recent economic review it was estimated that there are about 500 companies engaged in thermoformed packaging in North America. They operate about 700 plants, run 5,000 machines, and employ 35,000 people.

Permanent or industrial products are not dominated by a single product application. Instead, the products include equipment cabinets for medical and electronic equipment, tote bins, rigid packaging – heavy-gauge

Disposable products – light gauge

Figure 1.1: “Celluloid baby rattles show the intricate detail that could be molded into decorative and functional articles. These doll-like figures, precursors of the famed Kewpie doll, were among the first plastic products (circa 1890) to be made by the Hyatt blow molding technique”[1]

1 In the first edition of this book, thin-gauge and heavy-gauge were used to define these two general categories. Correctly, the terms should either relate to the sheet thickness as thin-gauge and thick-gauge or to the sheet weight as light-gauge and heavy-gauge. Light-gauge and heavy-gauge are the terms used in this edition.
single and double deck pallets, other dunnage applications, transport trays, automotive inner-liners, headliners, shelves and instrument panel skins, aircraft cabin wall panels, overhead compartment doors, snowmobile and motorcycle shrouds, farings and windshields, marine seating, lockers and windshields, golf carts, tractor and RV shrouds, skylights, shutters, bath and tub surrounds and lavs, storage modules, exterior signs, swimming and wading pools, landscaping pond shells, luggage, gun and golf club cases, boat hulls, animal carriers, and seating of all types.

In a recent economic review, it was estimated that there were about 250 companies engaged in industrial product thermoforming [3] in North America. They operate about 300 plants, run 2,800 machines and employ 14,000 people. Thus, in North America, there are about 750 companies, operating about 1,000 plants, running nearly 8,000 machines and employing nearly 40,000 people.

Although the North American industrial thermoforming industry suffered a substantial recession in the early part of the millennium, it has rebounded to pre-2000 growth. The North American light-gauge thermoforming industry did not suffer as severely and has continued to grow on average about 4% per year. In general, in North America, the sustained growth of the thermoforming industry has been somewhat greater than the sustained growth of the polymer industry in general. That the growth rate is slowing may be a measure of the maturation of the industry. Globalization is also slowing North American growth, with many companies seeing increased offshore competition. In a recent survey on globalization, more than two-thirds of the companies interviewed reported losing business to foreign competition [4]. Many companies seeking lower labor, mold, and machinery costs are setting up operations abroad. Others are partnering with manufacturers in foreign countries. China is considered the major manufacturing competitor, with lower labor costs, a strong work ethic, pro-industry financial support, and technically trained workers. India, Thailand, Malaysia, Brazil, Russia, and Eastern Europe are expected to be major influences on worldwide manufacturing in general and plastics in particular.

It is estimated that in 2007, the North American thermoforming market exceeds 6,000 million pounds (2,700 million kg), with an estimated value of about US$ 13,000 million². Approximately 20% of this market is identified as “industrial products”, or products that have some permanent application. The top five industrial product markets are transportation, recreation, electrical/electronic, medical, and storage and dunnage. Eighty percent of the market is identified as “packaging products”, or products that have short lives. The top five packaging product markets are food packaging, consumer products, medical and pharmaceutical, electronics, and personal care and hygiene.

² In Plastics News, February 12, 2007 issue, it was determined that the 270 respondents to their 2007 survey of North American thermoformers had sales of $ 8,180 million and that 18.4% of sales or about $ 1,500 million were in industrial products. In 2004, Dr. Mooney estimated that the total North American industrial market in 2003 was around $ 2,300 million and about 1,000 million pounds. If it is assumed that the industrial market has grown approximately 3% APR, it is estimated that the total North American industrial market is now about $ 2,500 million and about 1,100 million pounds. Again, assuming that the ratio of industrial to packaging product sales is about the same, the total North American industrial market is now about $ 13,500 million. If the unit value ($/lb) of packaging products is relatively the same as that for industrial products ($ 2.30/lb), then the total 2007 North American conversion is approximately 6,000 million pounds (2,700 million kg).
It is estimated that the European thermoforming market is about 60% of that of the North American market. The Asian market is about 40%. The South American market is about 20%, and the rest of the world market is about 20%. From this, it is estimated that the size of the world thermoforming market – both industrial and light-gauge products – is about 15,000 million pounds (7,000 million kg), with an estimated market value of about US$ 30,000 million.

1.3 Terminology

In essentially all types of thermoforming, there are identifiable processing steps. First, the sheet is mechanically clamped. It is then heated without mechanical manipulation. When the sheet is hot enough, it is shaped without further heating. The initial shaping may be pre-shaping, by air pressure or mechanical means. The sheet is then brought in contact with a mold. The mold is usually single-sided. This means that only one side of the sheet contacts the shaping surface. The other side is open to the environment. When the sheet is cool enough to retain the shape of the mold, it is removed. The product is then trimmed from the excess sheet around it. The trim is then reprocessed into new sheet.

The thermoforming process is often subdivided according to the thickness or gauge of the sheet. If the sheet thickness is less than 0.060 in (1.5 mm), the process is called thin-gauge or light-gauge thermoforming. If the sheet thickness is less than about 0.010 in (0.25 mm), it is often called film or foil. Heating and forming film often requires non-conventional equipment.

If the sheet thickness is greater than about 0.120 in (3 mm), the process is called heavy-gauge or heavy-gauge thermoforming. If the sheet thickness is greater than about 0.500 in (13 mm), it is often referred to as plate. Heating and forming plate often requires unconventional equipment.

Another way of classifying the thermoforming process is by the way in which the sheet is presented to the thermoforming press. If the sheet is thin, it is usually extruded into rolls. The roll diameters may be 40 to 60 in (1 to 1.5 m), may weigh as much as 4000 pounds (1800 kg), and may contain as much as 10,000 feet (3000 m) of sheet. This sheet is fed continuously into thermoformers called roll-fed machines.

If the sheet is too thick to be rolled without the sheet taking a set or permanent curl, it is guillotined into discrete pieces that are stacked on pallets. These sheets are then fed, either manually or automatically, into thermoformers called cut-sheet machines.

Sheet in the thickness range of 0.060 to 0.120 in (1.5 to 3 mm) is often too expensive to be used to produce disposable products and is often too thin to have structural characteristics. However, there is growing interest in this middle-gauge sheet thickness for large-volume, deep-draw drink cups and for certain under-the-hood automotive applications. Because the sheet is usually too thick to roll without inducing permanent curl, cut-sheet thermoforming is the typical way of producing these products. The exception to this is low-density foam sheet of polystyrene (PS) or polyolefin (PO), which is produced on rolls in thicknesses greater than 0.120 in (3 mm). A comparison of the general characteristics of light-gauge and heavy-gauge thermoforming is given in Table 1.2.
1.4 General Characteristics of Thermoformed Products

There are many reasons why thermoformed parts compete well with parts manufactured by other processes. Thermoforming is a low-temperature, low-pressure process. It usually requires relatively inexpensive mold materials and usually uses single-surface molds. Molds are often fabricated in relatively short times. Heavy-gauge thermoforming is often used to produce prototypes of products to be manufactured by other processes. Heavy-gauge thermoforming is often used to fabricate a limited number of production parts at costs below those produced by other processes.

Table 1.2: Characteristics of Light-Gauge and Heavy-Gauge Thermoforming

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Light-Gauge</th>
<th>Heavy-Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sheet thickness</td>
<td>&lt; 0.060 in (&lt; 1.5 mm)</td>
<td>&gt; 0.120 in (&gt; 3 mm)</td>
</tr>
<tr>
<td>Dominant products</td>
<td>Packaging, disposables</td>
<td>Cabinetry, industrial</td>
</tr>
<tr>
<td>Sheet handling</td>
<td>Roll-fed</td>
<td>Palletized cut sheet</td>
</tr>
<tr>
<td>Typical machine type</td>
<td>Pin-chain linear start-stop</td>
<td>Shuttle or rotary press</td>
</tr>
<tr>
<td>Machine control aspects</td>
<td>Automated</td>
<td>Automated to manual</td>
</tr>
<tr>
<td>Controlling aspect – heating</td>
<td>Heater output W/in(^2) (kW/m(^2))</td>
<td>Conduction into sheet</td>
</tr>
<tr>
<td>Pattern heating</td>
<td>Usually not done</td>
<td>Common</td>
</tr>
<tr>
<td>Part size tendency</td>
<td>Small</td>
<td>Medium to very large</td>
</tr>
<tr>
<td>Number of mold cavities</td>
<td>Many</td>
<td>Usually one or two</td>
</tr>
<tr>
<td>Mechanical assist</td>
<td>Plug</td>
<td>Plug, billow, vacuum box</td>
</tr>
<tr>
<td>Mold type</td>
<td>Female (negative) usually</td>
<td>Male (positive), female (negative), mixed</td>
</tr>
<tr>
<td>Mold materials</td>
<td>Machined aluminum</td>
<td>Cast aluminum (production), wood, plaster, syntactic foam, white metal</td>
</tr>
<tr>
<td>Mold cooling</td>
<td>Actively controlled</td>
<td>Active to none for prototype</td>
</tr>
<tr>
<td>Free surface cooling</td>
<td>Usually ambient</td>
<td>Forced air, mist, fog</td>
</tr>
<tr>
<td>Trimming aspects</td>
<td>Punch-and-die, steel rule die, forged die, rim rolling</td>
<td>Multi-axis routing</td>
</tr>
<tr>
<td>Non-product trim level</td>
<td>About 50%</td>
<td>Less than about 30%</td>
</tr>
<tr>
<td>Wall thickness tolerance, normal</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Wall thickness tolerance, tight</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Pressure forming application</td>
<td>Deep draw, formed rim</td>
<td>Textured surfaces, deep draw</td>
</tr>
</tbody>
</table>
Light-gauge thermoformed parts traditionally have surface area-to-thickness ratios as large as 100,000 : 1. No other process can produce similar results. Light-gauge thermoforming is often used to fabricate millions of production parts at costs below those produced by other processes.

Thermoforming has several disadvantages. The incoming material is extruded sheet. The extrusion process may add 20% to 50% or more to the cost of the as-formed product. Because the sheet must be held in a fixture during heating, forming, and trimming, that portion of the sheet that is not product should be reground and re-extruded. This incurs additional extrusion cost.

Because thermoforming is a differential stretching process, the product wall thickness is non-uniform, as shown in schematic in Fig. 1.2. Some improvement in wall thickness uniformity can be achieved by mechanical or pneumatic stretching of the heated sheet prior to bringing it in contact with the mold surface. However, wall thickness tolerance is typically 10% to 20%. Because local areas of formed parts are typically designed to minimum critical thicknesses, many portions of the formed parts contain more plastic than required for performance. Only one side of the formed part replicates the mold surface. Because thermoforming is a relatively low-pressure process, the majority of the plastics formed are unfilled or unreinforced. Because thermoforming is a process in which a plastic sheet is primarily stretched in an elastic manner, formed products are under substantial residual stress. To minimize product distortion in use, care must be taken to minimize exposure to elevated temperatures.

Plastic part design is considered in detail in Chapter 3. Thermoforming is compared and contrasted with other forming processes in Chapter 14.
2 General Forming Concepts

The simplest thermoforming process consists of heating a sheet of plastic to its forming temperature and mechanically forcing it against a cooled solid shape called a mold. There are many variations and improvements of this simple process. Many more variations are employed in heavy-gauge thermoforming than in light-gauge thermoforming. The primary reason for this is that thicker sheet retains its formable temperature longer. This allows for more manipulation of the hot sheet before it is forced against the mold surface. Heat is lost very quickly from thin sheet. As a result, thin sheet must be formed quicker.

This chapter highlights some of the major methods employed in contemporary thermoforming. The subject is presented in increasing levels of complexity.

2.1 Heating and Bending

Some of the earliest plastics applications, such as picture frames and jewelry, were made by simply heating and bending plastic sheets, see Fig. 2.1.

Three general heating methods are used:

- An electric strip heater to produce a sharp linear bend in the sheet
- A hot air gun if the sheet is to be deformed in a general region
- A hot air oven is used if the sheet is to be deformed throughout its surface

When the local area of the sheet is hot, the bending fixture is activated and the sheet is allowed to cool in its final, bent form.

As an example, barrel skylights, characterized as partial cylinders, are often made by fixturing one edge of the sheet into one edge of a cylindrical fixture and heating the sheet until it sags against the surface of the fixture. The free end of the sheet is then captured in the other edge of the fixture and held until the sheet cools and retains the shape of the fixture. Care must be taken to ensure that the plastic is adequately heated, otherwise some spring-back may occur and the initially molded angle may gradually open.

Although the heating and bending technique harkens back to the very early days of plastics processing, even today prototype parts are fabricated by machine cutting shapes from plastic sheet, heating and manually or mechanically bending portions of the shapes, then thermally welding or solvent soldering the shapes into the desired products, see Fig. 2.2.
Figure 2.1: Examples of simple heating and bending [5]

Figure 2.2: An example of a modern product made by router cutting, heating, bending, and solvent welding [6]
2.2 Simple Heating and Stretching

Thermoforming consists of differential stretching of a heated sheet. Only the sheet free of the mold surface stretches. When the sheet touches the mold surface, it is chilled and stops stretching. As stretching continues, the sheet free of the mold surface gets thinner and thinner. The portion of the product that is formed last is the thinnest, most oriented, and weakest. As a result, the final thermoformed part has non-uniform wall thickness. As seen in Fig. 1.2 for forming into a female or negative mold, the thinnest portion is in the bottom corner of the product.

2.3 One-Step Forming

Differential air pressure is used to differentially stretch a formable sheet. This is achieved by drawing the air from between the sheet or by inflating the sheet. One-step forming is defined as simply forming the heated sheet without previous manipulation. There are three general one-step forming methods and one variation used primarily for heavy-gauge forming.

2.3.1 Drape Forming

Some of the earliest thermoformed products were produced by simply heating sheet until it is soft, then manually draping the sheet over a simple form. Drape forming over a male or positive mold yields a part that is thinner along its sidewalls, rim, and corners than at its bottom. This is shown in Fig. 2.3. Although the air between the mold and the draping sheet can be expressed manually, it is usually removed by applying vacuum. The inside of the formed part contacts and replicates the mold surface. Drape forming is used to make heavy-gauge products such as exterior signage and refrigerator liners. It is used to make light-gauge products where the mating surfaces must have high tolerance such as lidded containers.

![Figure 2.3: Drape forming](image-url)
2.3.2 Vacuum Forming

The commercialization of vacuum forming in the early part of the 20th century followed the development of simple electrically driven vacuum systems. As seen in Fig. 1.2, the sheet forms the desired part as the volume between the heated sheet and the female cavity or negative mold is evacuated. As a result, the outside of the formed part contacts and replicates the mold surface. Vacuum forming into a female cavity yields a part that is thick at its rim, progressively thinner along its sidewalls, and very thin at its bottom and corners as shown in Fig. 2.4. Note that this non-uniformity in part wall thickness is in direct contrast to that for drape formed parts. Vacuum forming is used to make heavy-gauge products such as equipment cabinets and spas. It is used to make most light-gauge products such as point-of-purchase containers, picnic plates and cups, and unit dosage pharmaceutical containers.

Both vacuum forming and drape forming yield parts with highly uneven wall thicknesses. Both techniques are commercially used today, primarily for shallow-draw parts, or where wall thickness variation is not critical to the functioning of the product.

2.3.3 Free Forming

Free forming, also called billow or free bubble forming, is shown schematically in Fig. 2.5. Unlike all other forms of thermoforming, free forming requires no mold. The sheet is often clamped against the rim of an enclosure. It is then heated from one side only. When the sheet reaches its forming temperature, air pressure of less than 10 psi (0.07 MPa) and typically no more than 2 to 4 psi (0.014 to 0.028 MPa) is applied against the sheet surface, causing the sheet to expand. As the sheet expands, the crown may touch a microswitch or the sheet may intersect a light beam. The inflation pressure is then controlled to maintain the bubble size as the bubble cools in the ambient air. Because the softened plastic bubble never contacts a solid surface, it remains mar-free. Typically, the bubble is quite uniform in thickness except in the clamping region.

Heavy-gauge, free-formed shapes are used in skylights and aircraft windscreens. Light-gauge, free-formed shapes have been used to produce blister packages. Cellulosics, amorphous
polyethylene terephthalate (APET), polyvinyl chloride (PVC), oriented polystyrene (OPS), polymethyl methacrylate (PMMA), polycarbonate (PC), and other transparent plastics are most often used for these applications.

### 2.3.4 Non-Uniform Heating

Often when forming heavy-gauge parts, local wall thickness can be somewhat adjusted by adjusting the local heater temperature. Non-uniform heating, also called pattern heating, zoned heating, or zonal heating, produces a sheet that is hotter in certain areas than in others. Hotter sheet stretches more easily than cooler sheet. As a result, regions of the formed part that are too thick can be thinned by increasing the energy to the sheet in those regions. In contrast, regions of the part that are too thin are not drawn as much by decreasing the energy to the sheet in those regions. In free forming, for example, the expanding bubble can be altered from its traditional hemispherical shape by judicious local temperature control. The methods of local temperature control will be discussed in more detail in Chapter 8.

Non-uniform heating is rarely used in light-gauge thermoforming primarily because the sizes of the formed parts are often small when compared to the size of the heater elements.

### 2.3.5 Matched Mold Forming

Matched mold forming, or two-sided forming, is shown schematically in Fig. 2.6. Matched mold forming is employed whenever the sheet is too stiff at its forming temperature to be vacuum formed.

Because low-density foam sheet cannot be heated to traditional polymer forming temperatures without extensive foam cell rupture, the majority is thermoformed using matched tooling. Pressures of about 45 psi (0.3 MPa) are used. Highly filled sheet is normally too stiff to be vacuum- or pressure-formed at the polymer forming temperature. It is usually formed at pressures up to 150 psi (1 MPa) using matched tooling. Short-glass reinforced sheet is also

---

**Figure 2.5:** Free-blowing
too stiff to be formed using single-sided molds. Pressures up to 150 psi (1 MPa) are used with matched tooling to achieve the desired shapes. Matched tooling and higher pressures, approaching compression molding pressures of 1500 psi (10 MPa), are needed to shape long-glass and continuous glass fiber-reinforced polymers.

2.4 Other One-Step Forming Processes

2.4.1 Autoclave Forming

Recent work involving one-sided molds and pressure bladders over the free surfaces of the forming sheet, similar to thermoset wet-composite forming, holds promise for forming marginally stiff polymer sheet. Often, this technique is carried out in a pressure autoclave.

2.4.2 Diaphragm Forming

Diaphragm molding entails laying the thermoformable sheet against a warm diaphragm, then pneumatically or hydraulically inflating the diaphragm against a one-sided mold, see Fig. 2.7.