Go-to-Market Process for New Aerospace Transparencies

By

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B.S.E. Materials Science Engineering, University of Pennsylvania, 2012
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Submitted to the Sloan School of Management and the Department of Aeronautics and Astronautics in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration

And

Master of Science in Aeronautics and Astronautics

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Abstract

One challenge that many manufacturing companies face is the transition from lab-scale product development to full-scale production. Techniques and processes that are used by research and development (R&D) personnel or within a lab may not be suitable for a production environment, and directly applying an R&D process to production may overlook certain capabilities and requirements. This challenge can be made more difficult if there is a development “wall” between R&D and production. R&D personnel are familiar with new products and underlying technologies and have learned important lessons throughout the development process, while production personnel have experience with full-scale production and necessary manufacturing requirements. Getting these two groups to share knowledge and work together can be key to the successful industrialization of a new product or technology.

Texstars is a Texas-based aerospace manufacturer that is currently transitioning a new transparency (optically clear structural material) product based on a polyurethane material technology branded Texeron™, from R&D to production. Texeron™ provides a significant market opportunity to Texstars and its transition requires the development of new equipment and capabilities to reach full-scale production. This thesis examines the industrialization process of Texeron™, including the definition of manufacturing requirements, the selection of equipment, and product-specific tooling design, and provides a working example of how a small company can balance production requirements with cost considerations. Throughout the project, we catalyzed a link between R&D and production personnel at Texstars to enable knowledge transfer. We find that this link could have been established earlier to better anticipate production challenges before production trials began. For future new product introductions, Texstars can initiate coordination between R&D and production and implement a product transition process as soon as a launch customer is identified.

Thesis Supervisor: Brian L. Wardle
Title: Professor of Aeronautics and Astronautics

Thesis Supervisor: Roy Welsch
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Acknowledgements

This thesis would not be possible without the support and contributions of many individuals throughout the last two years.

First and foremost, I’d like to thank my fiancé Lilly for her support throughout the last two years.

I’d like to acknowledge the Leaders for Global Operations (LGO) Program for its support of this work. I’d specifically like to thank my advisors, Dr. Roy Welsch and Dr. Brian Wardle for their continued support during the project and the thesis process that followed. The LGO staff and my brilliant classmates have made this program an exceptional two years, and I can’t imagine doing half of what I’ve done at MIT without them.

Finally, this project would have been impossible without help from all the excellent people I had to opportunity to work with at Texstars. My supervisors, Steve Palagyı and Tony Paolini, offered constant support and guidance throughout my time in Dallas and offered me insight into the operations of a small manufacturer that I will remember throughout my career. The lab research team welcomed me with open arms and continued to answer my questions without hesitation, and special thanks goes to Chuck Ward, Dr. Ron Meline, and David Rollings. The production and tooling teams, including Wilford Womack and Colt Garner, were invaluable in implementing many of the changes throughout this project. I’d like to thank American Industrial Partners, and specifically Danny Davis, for their guidance and for giving me a chance to work with a great company I would not have found otherwise.
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1. Introduction

1.1. Project Motivation

Texstars is a Texas-based manufacturer of transparencies and plastics for the aerospace industry; “transparencies” include windshields, canopies, external and internal lenses, and other transparent windows / components. Texstars has recently developed a new thermoset material technology, Texeron™, designed as an alternative, tunable solution to current materials used to produce certain aerospace transparencies such as glass, acrylics, and coated polycarbonate. Prior to June 2016, small-scale prototype parts using this technology were created largely by R&D personnel using laboratory methods, resources, and equipment at Texstars. The primary motivation for this project is to develop a manufacturing plan, infrastructure, and capability to produce Texeron™ products at scale in a production environment. Initially, Texeron™ will be formed into products for two launch customers as well as being formulated and prototyped for future transparency applications with other customers. Both launch customers are large aerospace original equipment/airframe manufacturers (OEMs) and are working with Texstars to support the development of Texeron™ manufacturing.

1.2. Problem Statement

For the past several years, Texstars has been developing the technology behind Texeron™ using R&D resources, with relatively little involvement from production personnel. By early 2016, the company had secured two launch customers that required application of Texeron™ in two forms: as a laminate thin-sheet layer and as a structural part. This shift to actual commercial use required involving production personnel and resources coupled with time-bounded commitments for end products.

Because Texeron™ is a new material technology for Texstars, prototype parts using the material have been made in the R&D lab, using primarily laboratory personnel and equipment. Due to both practical production requirements and aerospace customer requirements, Texstars must develop a production-led manufacturing system for all commercial applications. This new product introduction process requires the cooperation of several departments across the company, combining the lab personnel knowledge of the material properties and technical
processing ability with the production personnel knowledge of traceability requirements and repetitive, larger-scale manufacturing.

1.3. Thesis Overview

Chapter Two of this thesis will give a brief background on Texstars and review the early-stage development of the Texeron™ material up until mid-2016. Chapter Three will provide details about polyurethane chemistry and processing techniques, highlighting key critical factors when considering a production system. This is especially important because polyurethane manufacturing on the scale required for Texeron™ products was not originally a competency of Texstars, but soon became one through the course of this project. Chapter Four will detail the key requirements of the production system identified at Texstars and focus on detailed development challenges encountered via the two launch customer products.
2. Background

2.1. Texstars Overview

Texstars is a small, 180-employee aerospace manufacturer specializing in plastics and transparencies that has been in operation since 1946. They have two manufacturing facilities located less than 400 meters apart, at the “corner” of Arlington and Grand Prairie, Texas. Texstars is currently a subsidiary of Ascent Aerospace Holdings, which is owned by American Industrial Partners, a private equity firm headquartered in New York City. Despite their small size, Texstars has a full range of capabilities on-site, including production, production support, tooling, quality, and R&D as well as engineering. Their transparency products have contributed to numerous aerospace projects over the decades, including the F-15 Eagle, the Bell 525 helicopter, the E2 Hawkeye, the B-1B Lancer, and most notably, the canopy system for the F-16 Fighting Falcon.

Texstars’ current business lines (or value streams) are split into two main categories, transparencies and plastics. The transparencies value-stream produces canopies, windows, and other products manufactured with glass, acrylic, or polycarbonate. Included in this value-stream are a variety of proprietary coatings used on transparencies to improve performance across a variety of end-uses such as scratch resistance, UV-blocking, P-static discharge, etc. Texstars has developed and continuously improves these coating solutions to stay competitive in the industry. The plastics value-stream produces a wide variety of products such as ducts, glare shields, stand-offs, interior components, etc. and do so using injection molding, vacuum forming, or blow molding technology as well as performing secondary operations such as bonding, hardware attach, and mechanical assembly.

2.2. Texeron™

2.2.1. Early Development

In 2007 and 2008, Texstars partnered with a large aerospace OEM to conduct a study on transparency materials used to manufacture exterior lenses with the goal of improving performance and lowering cost. This study examined a variety of legacy materials that included cast acrylic, stretched acrylic, and coated polycarbonate to set a performance baseline for lenses already in the market. These properties include:
• Tensile strength and modulus: Tension test conducted according to ASTM D638; the specimen is gripped at both ends and elongated until the yield or rupture point. Tensile strength is the maximum tensile stress sustained by the sample material during the test and tensile modulus, or Young’s modulus, is the ratio of stress to strain in the material (ASTM International, ASTM D638-14 Standard Test Method for Tensile Properties of Plastics, 2014)

• Flexural strength: Flexural test conducted according to ASTM D790; the rectangular specimen rests on two supports and is subjected to loading at the midway point. This test fails the material in bending to determine yield or ultimate strength (ASTM International, 2015)

• Hardness: Durometer is used to measure Shore D hardness according to ASTM D2240. This is a relative measure of the sample material’s resistance to deformation (ASTM International, 2015)

• Rain Erosion: Conducted according to ASTM G73; exposes samples to an environment simulating flight through a rain event and observes material removal and damage over fixed periods of time, speed, droplet size, and rate of rain fall (ASTM International, 2010)

• Impact Testing: Gardner Impact test conducted according to ASTM D5420; evaluates the impact resistance of a material by dropping a specified weight from a specified height and observing if the material dimples or cracks (ASTM International, 2016)

• Acetone Resistance: Measures the chemical resistance of the material by exposing the surface to acetone for 30 minutes and observing the damage

• Sand Abrasion: Abrasion resistance test conducted according to ASTM F735. Test provides a measure of how well the material performs in an abrasive environment by comparing the haze of the material before and after abrasion; materials are also polished to test the recovery potential following an abrasion event (ASTM International, 2011)

• QUV accelerated weathering test: Reproduces the damage caused by sun, precipitation, and dew with cycles of UV light and humidity in a closed chamber guided by ASTM D4587; light transmission and yellowness index are recorded as indicators of environmental resistance or susceptibility to UV light (ASTM International, 2011)
An illustration of these baseline properties for legacy materials (acrylics and polycarbonates) is included below in Table 1. All data was collected by Texstars R&D using representative samples of each material.

Table 1: Selection of materials properties used to describe aircraft transparency materials for exterior lenses. All data collected internally by Texstars R&D.

<table>
<thead>
<tr>
<th>Typical Properties</th>
<th>Testing Standard</th>
<th>Cast Acrylic</th>
<th>Stretched Acrylic</th>
<th>Coated Polycarbonate (Coating 1)</th>
<th>Coated Polycarbonate (Coating 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>ASTM D638</td>
<td>77.6</td>
<td>59</td>
<td>59</td>
<td>59</td>
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<td>Tensile Modulus (MPa)</td>
<td>ASTM D638</td>
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<td>2,206.0</td>
<td>2,206.0</td>
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<tr>
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<td>105.1</td>
<td>93</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>Hardness - Shore D</td>
<td>ASTM D2240</td>
<td>90.5</td>
<td>87.2 - 90.5</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Rain Erosion (ASTM G73, 30°, 602mph, 30 min.)</td>
<td>95% removal of coating after 10 minutes</td>
<td>95% removal of coating after 10 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gardner Impact Test [1]</td>
<td>ASTM 5420</td>
<td>Broke at 12 in*lbs</td>
<td>Strong dimpling at 96 in*lbs</td>
<td>Strong dimpling at 96 in*lbs</td>
<td></td>
</tr>
<tr>
<td>Acetone Resistance (30 minutes)</td>
<td>ASTM D2240</td>
<td>Light residue but able to wipe off</td>
<td>No apparent effect</td>
<td>No apparent effect</td>
<td></td>
</tr>
<tr>
<td>Sand Abrasion (600 strokes)</td>
<td>ASTM F735</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ Haze</td>
<td></td>
<td>49.0</td>
<td>58.3</td>
<td>9.2</td>
<td>30.5</td>
</tr>
<tr>
<td>Removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Transmittance</td>
<td>ASTM D1003</td>
<td>92.10%</td>
<td>92.00%</td>
<td>90.70%</td>
<td>89.30%</td>
</tr>
<tr>
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<td>ASTM D1925</td>
<td>0.1</td>
<td>0.4</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Week 1 (168 hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Transmittance</td>
<td>ASTM D1003</td>
<td>91.90%</td>
<td>92.00%</td>
<td>90.80%</td>
<td>89.20%</td>
</tr>
<tr>
<td>Yellowness Index</td>
<td>ASTM D1925</td>
<td>0.7</td>
<td>0.8</td>
<td>3.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Week 2 (336 hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Transmittance</td>
<td>ASTM D1003</td>
<td>91.80%</td>
<td>92.00%</td>
<td>90.80%</td>
<td>88.90%</td>
</tr>
<tr>
<td>Yellowness Index</td>
<td>ASTM D1925</td>
<td>1.2</td>
<td>1.1</td>
<td>3.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Week 3 (504 hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Transmittance</td>
<td>ASTM D1003</td>
<td>91.80%</td>
<td>92.00%</td>
<td>90.90%</td>
<td>86.50%</td>
</tr>
<tr>
<td>Yellowness Index</td>
<td>ASTM D1925</td>
<td>1.8</td>
<td>1.3</td>
<td>3.6</td>
<td>8.9</td>
</tr>
</tbody>
</table>

[1] Tests were completed with 0.25" thick sample coupon of of all materials
[2] UJV accelerated weathering testing runs samples through cycles of UJ light and humidity to reproduce potential damage caused by sunshine, precipitation, or dew in real world environments.

Each legacy material has its set of strengths and weaknesses, but no material performed at a high level across all criteria. Notably, cast acrylic is chemically resistant and performs well in the UJV and rain erosion testing, but has low impact resistance. Coated polycarbonate has a high impact resistance, but the coating is removed under rain erosion testing, exposing the underlying
polycarbonate to environmental damage and making the lens susceptible to chemical erosion and UV exposure (yellowing).

The study then switched to evaluating new coatings, materials, and technologies that could offer a better performance range relative to these properties and provide improved lenses. One goal was to identify a material or technology that could approach the impact resistance of coated polycarbonate without requiring a coating susceptible to failure. An additional benefit would be a material that could be polished to remove abrasion damage. One such material that Texstars developed showed promise: a thermoset polyurethane formulation that would later become Texeron™.

2.2.2. Texeron™ Properties

In developing Texeron™ between 2008 and 2016, R&D personnel at Texstars created 20 to 30 separate formulations, each with different types and ratios of elemental components resulting in different processing characteristics and end-product performance properties (note: a detailed discussion of polyurethane chemistry and processing techniques is included in Chapter Three). By the beginning of the author’s project in 2016, two primary formulations of Texeron™ were selected for use with Texstars two launch customers, Texeron™ 20 and Texeron™ 25, based on the end-use environment and application requirements. A preliminary measure of the baseline properties for these two formulations are included in Table 2. These properties compare favorably to those of the legacy materials evaluated during the first segment of the study, and in many cases, match or outperform them. This is shown in Figure 1, with a solid Harvey ball indicating strongest performance and an empty Harvey ball indicating weakest performance.
Table 2: Baseline properties for Texeron™20 and Texeron™25. All data collected internally by Texstars R&D.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>ASTM D638</td>
<td>59.6</td>
<td>62.5</td>
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<tr>
<td>Tensile Modulus (MPa)</td>
<td>ASTM D638</td>
<td>2,104.3</td>
<td>1,722.3</td>
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<tr>
<td>Flexural Strength (MPa)</td>
<td>ASTM D790</td>
<td>105.2</td>
<td>104.1</td>
</tr>
<tr>
<td>Hardness - Shore D</td>
<td>ASTM D2240</td>
<td>90</td>
<td>89</td>
</tr>
<tr>
<td>Rain Erosion (30°, 602mph, 30 min.)</td>
<td>ASTM G73</td>
<td>Very light pitting, 1% coverage</td>
<td>Very light pitting, 1% coverage</td>
</tr>
<tr>
<td>Gardner Impact Test [2]</td>
<td>ASTM 5420</td>
<td>Broke at 72 in*lbs</td>
<td>Broke at 84 in*lbs</td>
</tr>
<tr>
<td>Acetone Resistance (30 minutes)</td>
<td></td>
<td>Light residue but able to wipe off</td>
<td>Light residue but able to wipe off</td>
</tr>
<tr>
<td>Sand Abrasion (600 strokes)</td>
<td>ASTM F735</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ Haze</td>
<td></td>
<td>68.7</td>
<td>60.6</td>
</tr>
<tr>
<td>Removal</td>
<td>ASTM D4587</td>
<td>Abrasions Polished Out</td>
<td>Abrasions Polished Out</td>
</tr>
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</table>

**QUV Tests**

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Transmittance</td>
<td></td>
<td>92.50%</td>
<td>92.50%</td>
</tr>
<tr>
<td>Yellowness Index</td>
<td>ASTM D1925</td>
<td>1.13</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Week 1 (168 hours)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Transmittance</td>
<td>ASTM D1003</td>
<td>91.30%</td>
<td>90.90%</td>
</tr>
<tr>
<td>Yellowness Index</td>
<td>ASTM D1925</td>
<td>5.16</td>
<td>5.7</td>
</tr>
<tr>
<td><strong>Week 2 (336 hours)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Transmittance</td>
<td>ASTM D1003</td>
<td>91.10%</td>
<td>90.90%</td>
</tr>
<tr>
<td>Yellowness Index</td>
<td>ASTM D1925</td>
<td>5.92</td>
<td>6.48</td>
</tr>
<tr>
<td><strong>Week 3 (504 hours)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Transmittance</td>
<td>ASTM D1003</td>
<td>91.50%</td>
<td>91.90%</td>
</tr>
<tr>
<td>Yellowness Index</td>
<td>ASTM D1925</td>
<td>6.14</td>
<td>6.81</td>
</tr>
</tbody>
</table>

[1] Tests were completed on a sample of base chemistry Texeron™. Additives can improve yellowing performance and provide additional properties.

[2] Tests were completed with 0.125" thick sample coupons of Texeron™.
A major benefit of Texeron™ is the formulation flexibility due to the fact that the resin is mixed in-house and, as such, various elements can be added to enhance performance or add capabilities to best match customer requirements. As discussed in detail below, Texeron™ is a thermoset polyurethane that is formulated by combining several different elemental components into a resin mixture, adding a catalyst, pouring the catalyzed resin into a mold, and allowing the resin cure to the desired hardness factor. Once cured, the thermoset cannot be reheated and reshaped like a thermoplastic material. Because a product made of Texeron™ is mixed together from its base
components, Texstars can add different compounds to strengthen or augment the material properties of the final product. Some examples of this include a UV stabilizer to dampen the effect of weathering, tinting compounds to change the color of product, or a P-Static additive to prevent the build-up of electrical charge on the surface of the transparency. These additives can be mixed directly into the Texeron™ formulation, as opposed to the application of a secondary coating as is currently required for acrylic or polycarbonate parts. Not only does a tunable version of Texeron™ eliminate the need for application-specific coatings discussed above, it also simplifies the production process of any transparency product requiring those type of coatings.

2.3. Initial Production Process

At the start of this project, Texstars production capabilities for Texeron™ were limited entirely to R&D resources – personnel and equipment. All Texeron™ component materials were stored in the lab and all mixing apparatus and mold equipment were contained within the laboratory area. Numerous prototype products had been created using laboratory personnel with some prototype-level support from the tooling department to construct prototype molds. Laboratory personnel were very familiar with the chemistry and mechanics of Texeron™ production, but little of this knowledge had been codified and passed on to the production department.

Building on this initial process, this project aims to define an industrialized production process for Texeron™ that has the capability to handle the demands of full-scale production. This includes developing a dedicated production area within Texstars' manufacturing facilities, identifying key production requirements, defining a specific production process for Texeron™, and conducting production trials with launch customer products. The industrialized production process will set the baseline for the future of Texeron™ manufacturing and enable Texstars to meet current launch customer demand and future expected demand for at least a year or more.
3. Literature Review

Chapter Three will provide an overview of polyurethane chemistry and the processing techniques that are currently used in industry. This information highlights critical factors that must be considered when designing and implementing a polyurethane manufacturing system.

3.1. Polyurethane Chemistry

Polyurethanes are a family of polymers with high molecular weight that can be formulated to provide a wide range of chemical and mechanical properties. Polyurethanes can be thermoplastic, meaning it becomes soft when heated and can be reformed, or thermoset, meaning it cannot be reheated or reformed after initial formation. Because Texeron™ is a thermoset, this thesis will focus primarily on thermoset polyurethanes. Within a polyurethane, the urethane linkage is formed from the reaction of the NCO functional group in the isocyanate with the OH functional group in the polyol (as seen in Figure 2). This reaction can occur at room temperature, but the rate of reaction in manufacturing can be increased through the use of catalysts or accelerants. The type and amount of catalyst will affect how the reaction of the polyurethane proceeds and how fast it occurs. (Szycher, 1999)

\[
\begin{align*}
R'\text{-}N\text{-}C\text{-}O \quad &+ \quad OH\left[\begin{array}{c}
R'\text{-}O\text{-}R\text{-}O^n\end{array}\right]\text{-}H \\
\text{Isocyanate} &\quad \text{Polyether} \\
\end{align*}
\]

\[
R'\text{-}N\text{-}C\text{-}O\quad \text{Isocyanate} \\
\text{Polyurethane}
\]

Figure 2: The urethane unit in a polyurethane is created through the reaction of isocyanate with a polyol (such as polyether) (Sonnenschein, 2015)
If either of the base components used in the reaction, isocyanates and polyols, have three or more functional groups, strong cross-linking between the polymer chains will form and create a three-dimensional network within the polymer. A high degree of chemical cross-links will cause the polyurethane to have increased tensile modulus and hardness, but decreased elongation (the amount of extension a material exhibits under stress before breaking). The exact degree of cross-linking and the effect it has on material properties can be precisely controlled by the types of isocyanates and polyols used in the reaction and the ratio of NCO to OH groups. It is this flexibility that allows polyurethanes to be formulated for numerous applications. (Szycher, 1999)

Cross-linking also occurs because hydrogen bonds form between the polymer chains. This cross-linking also makes the polyurethane a thermoset, meaning that once the resin has cured, it cannot be heated and reshaped like a thermoplastic. This is due to the strength of the chemical bonds created between the polymer chains, which are stronger than the bonds within the polymer chains themselves. Upon heating, the polymer chains will begin to break down before the cross-link bonds. (Clemitson, 2015)

One aspect of polyurethane chemistry that plays an important role to any polyurethane manufacturer is the isocyanate reaction with water. Water has a significant effect, causing voids and foaming if present, on polyurethane systems and contact with the raw materials, mixed resin, and molds must be controlled. When the NCO group in the isocyanate reacts with H₂O, carbon dioxide gas is formed within the system. If controlled and done intentionally, this reaction can create a polyurethane foam because the carbon dioxide gas acts as a bubbling agent. When this reaction is not desired, the resultant polyurethane is typically detrimentally affected by the presence of voids and through the chemical imbalance created because the ratio of isocyanates to polyols that form polymer chains has been changed. (Clemitson, 2015)

3.2. Polyurethane Processing Techniques

Polyurethanes have been commercially studied and manufactured since the 1930s and many resources exist that discuss processing and manufacturing techniques. In the manufacturing of polyurethanes, the resin components are mixed together and cast into the mold before the reaction process progresses too far and the material begins to gel (a term known as “gelation”). Once the resin is injected into the mold, the entire mold may be left to cure at room temperature or placed in an oven for an accelerated cure, depending on the specific process requirements.
After cure, the polyurethane part is removed from the mold and inspected for conformity to the specification; any post-cure processing can then be conducted to finish the part. This chapter will briefly review some key factors that need to be considered and decisions that need to be made when setting up a polyurethane manufacturing process that begins with resin formulation and mixing and ends with a cured, finished part.

**Pot Life**

In polyurethane manufacturing, the working time of the resin before gelation begins is known as the pot life. The pot life is dependent on the processing technique, but is also factor of the exposure temperature and the catalyst used. Too much catalyst or too much heat will cause the reaction to move too quickly and pot life will be short, meaning the manufacturer will not have enough time to cast the resin into the mold before gelation. Too little catalyst or too cold of a temperature, and pot life will be too long, meaning gelation is significantly delayed and the actual molding process is jeopardized. The type and amount of catalyst required for a polyurethane reaction is a control variable, dependent on the type of isocyanate and polyol being used as well as the manufacturing requirements of the system. Similarly, the curing temperature is a control variable. Not only are these important factors in polyurethane formulation, they are a significant input consideration to the manufacturing system. (Oertel, 1993)

**Processing Methods**

The primary processing method that this project investigates is liquid resin casting, where the reactive resin mixture is poured or drawn into the mold then cured at room temperature or under heat to create a solid shape. In general, the resin should be introduced near the bottom of the mold and allowed to flow from bottom to top. This will aid in ensuring a full-formed molded part as well as forcing any gases out of the mold through vents located near the top. Within liquid resin casting approaches, there are multiple techniques available to a manufacturer. (Clemitson, 2015):

- Liquid injection (Figure 3) uses positive pressure (or gravity) to feed the resin into a mold. Vacuum pressure on the opposite side of the mold can be used to assist the resin in flowing across the mold. Air is pushed out through vents in the mold as the resin progresses and fills the mold. Cast parts that have a large surface area for the material to
flow through and materials with low viscosity are ideal for liquid injection. Liquid injection can also lower capital costs associated with the production tools because the molds are not as complex as other casting methods.

![Diagram of liquid injection process](image)

*Figure 3: Example of liquid injection process. The mixed polyurethane resin passes through the transfer pot into the mold by positive pressure from above or a vacuum on the other side of the mold. (Clemisson, 2015)*

- Vacuum casting (Figure 4) utilizes a sealed mold and mixing container that keeps the entire system under vacuum. The resin is drawn into the mold after mixing with positive pressure applied from the container-side or a stronger vacuum pulled from the mold. Vacuum casting is ideal for resins that are sensitive to air and require minimum contact with air before the cure is complete. They also require a resin with a pot-life greater than 5 minutes to allow the resin to flow fully into the mold. Entry-level vacuum casting systems can cost tens of thousands of dollars and the rigorous maintenance required to maintain the integrity of the vacuum seals make them an expensive molding option.
Compression molding (Figure 5) lets the resin begin to gel in an open mold before applying about 2MPa of pressure via a top plate. This conforms the resin to the full shape of the product and air vents are temporarily opened to remove all air from the system. Compression molding produces very little waste material and is ideal for manufacturing processes that utilize expensive resins. However, this type of molding does not always result in a consistent product due to excess material left over from the compression applied, also known as flash.
Rotational casting (Figure 6) involves rotating a cylinder or sphere along one or more axes to form an even layer of polyurethane across the interior surface of the cylinder. Once the polyurethane has cured enough to solidify, it can be removed from the mold and laid flat for the remainder of the cure. This process can create even-wall sizes for a hollow 3D object or flat sheets of consistent thickness if the rotation speed is controlled and the mold is level. Rotational casting is best used with thermoplastic polyurethane that can be melted down from a solid once placed in the rotational mold. The rotational molding process can also take a long time because the mold must be allowed to fully cool prior to removing the finished part.

![Diagram of rotational molding process](image)

*Figure 6: Example of rotational molding: (a) material is loaded into the mold (b) mold is heated and rotated on one or more axes (c) mold is cooled while continuing to rotate (d) finished part is removed. (Harper, 2006)*

As later discussed in Chapter Four, the Texeron™ manufacturing process utilizes liquid injection molding for the two launch customer applications covered in this thesis. This process offers the flexibility and lower tooling development costs that are consistent with the expected scale of early-stage production.

**Mold Construction, Preparation and Release Considerations**

Polyurethane molds can be designed using a variety of different materials that include aluminum, polyurethane, silicone, epoxy, and steel. If the part must be “optically smooth” with a high-
quality surface as is the case for aerospace transparencies, it is important to have a smooth finish, without any scratches or defects, on the mold tool because the polyurethane surface will reflect whatever surface finish is projected from the mold. Steel and aluminum molds are often more expensive and require a longer lead time to prepare, but these hold the shape of the part better as there is less “give” during the forming process, as they are stiffer than the other materials. These molds also require significant rework if design changes occur after the initial tool build. Silicone, epoxy, and polyurethane molds offer additional design flexibility, cost benefits, and a faster lead time, but may not give the same quality of optical finish and tolerance control as metal molds and may degrade more quickly when exposed to the polyurethane. However, as these materials tend to be “consumables”, they allow for easier incorporation of product design changes and can be replaced quickly and relatively inexpensively if damaged. The selection of mold material will differ depending on the stage of product development (e.g., prototype and ideation versus qualification units), volume of production needed, and desired end-part properties.

Another important factor in mold preparation is mold cleaning and selection of mold release agents. Mold release can be used to prevent the polyurethane from bonding with physical structure of the mold and will help with removal of the final polyurethane part once it has cured. Mold release can be in the form of a single-use silicone sprays or a more durable coating that can be used for multiple castings before needing to be re-applied. A key requirement of mold release application is to apply an even layer across the entire mold so the entire surface of the part will demold consistently. Molds must also be thoroughly cleaned in between use to prevent contaminants from building up on the mold surface and being introduced into the resin or reflected on the finished part. This mold cleaning must be done with care to avoid scratching or disfiguring the surface of the mold and introducing optical defects. (Clemislon, 2015) (Szycher, 1999)

Moisture Control

Because the polyurethane reaction is sensitive to moisture, care must be taken throughout material storage, material handling, mold storage and preparation, as well as the actual production processes to eliminate unintended material contact with moisture. This includes controlling the humidity of the storage and work areas, keeping raw materials sealed and
separate from sources of water, and potentially drying materials that have become exposed to moisture. (Szycher, 1999)
4. Texeron™ Manufacturing Process

The first step in transitioning Texeron™ manufacturing from R&D into production is understanding the key material and processing requirements throughout the end-to-end process and how those translate to production requirements. While Texstars’ specific formulations and end-item applications are proprietary, all Texeron™ formulations follow the same principal steps outlined above in Chapter Three. Using an industrial mixing unit or a manual process, Texstars mixes an isocyanate and polyol together in specific ratios until homogenous. The reaction is accelerated with a catalyst and, using liquid resin injection, the resin is cast into a mold specific to the shape of the final part. The mold is then cured in an oven and finally removed from the mold once the polyurethane has hardened to the desired shape and cooled. Where needed, secondary operations such as polishing, fastener installation, or painting, etc. are completed to specification, allowing the customer to receive a part that is ready to install.

Exactly how a manufacturer moves from the basic processes to formulate and form Texeron™ to a functioning production system will be the topic of this chapter. Chapter 4.1 will identify what production requirements are needed for each step in the process and in most cases, how those requirements will be satisfied in the Texeron™ production system. These requirements were gathered through a combination of direct discussions with, and observations of, the Texstars laboratory personnel who have expertise in Texeron™ itself, Texstars production personnel who have expertise in general production methods, and the academic literature cited above. Chapter 4.2 will examine two case studies from this industrialization process in more detail; the casting process for Launch Customer 1 and the tooling and mold development for Launch Customer 2. Chapter 4.3 will detail future process improvement efforts that should be investigated and implemented to further develop the Texeron™ manufacturing capability.

4.1. Process Overview

Texeron™ 20 and Texeron™ 25 consist of several (at least two) base components mixed in differing ratios specific to the end-product performance requirements. When the catalyst is introduced to this mixture, these base components begin to react and polymerize and comprise the resin mixture discussed throughout this chapter. The resin mixture is then cast into the product-specific mold and placed into the oven to cure. Once cured, the product is demolded,
inspected for defects, and sent to post-processing. Figure 7 identifies the high-level process steps and sets the outline for a general Texeron™ product.

![Diagram of Texeron™ production process]

Figure 7: High level Texeron™ production process

4.1.1. Mold Creation and Preparation

A key focus of the development efforts as this project progressed was the design and production testing of the molds for Launch Customer 2. Because of this product’s complex shape and tolerance requirements, its tooling development offers an in-depth case study of future Texeron™ mold designs. The specific development of mold tooling for Launch Customer 2 will be discussed in more detail in Chapter 4.2

Although the molds for each Texeron™ product are unique to the specific customer and application, there are certain requirements that every product’s mold must satisfy, including optical finish, dimensional tolerance, and ease of demold. The optical finish is the number of optical defects present in the transparency per defined area (e.g., square-centimeter, square-inch), where a defect can either be on the surface or within the part. The outer surface of the finished
transparency will reflect exactly the surface of the mold interior, so it is important to keep the mold surface as smooth and clean as possible. Some mold materials are easier to smooth and maintain than others, and a proper release agent can make the smooth surface effective longer. Another consideration, dimensional tolerance, is the amount that the mold material expands or contracts throughout the casting and curing process. Materials such as silicone or epoxy have higher coefficients of thermal expansion compared to metals, and will be less dimensionally stable. For some products, this is less of a concern because the final dimensions are less strict or post-processing will remove variation, but for other products with tight tolerances, allowed dimensional tolerance can limit the mold options available to use. Finally, in a production environment, the Texeron™ product must be relatively easy to demold to make the process quick and efficient but also to prevent the part from being damaged as it is taken out of the mold.

In addition to the general tooling concept, the key factors mentioned in Chapter Three, mold material and release agent, must be determined for every new mold that is designed. The determination of mold material also depends on the stage of development and production that the product is in. Silicone, epoxy, or polyurethane mold materials are generally ideal for early stage design and prototyping, while metal molds are suited for large-scale production where very little change is expected and higher volume, consistent output is required.

For the Texeron™ R&D process, the primary focus was low-cost flexibility. Most early Texeron™ samples tended to be small flat sheets between 0.125” and 0.5” thick. These samples were used for materials property testing as the different Texeron™ formulations where developed. Instead of fixed structures, the development molds for these samples consist of two glass panels held together with metal support bars and clamping pressure. Wax tape or silicone seals are used to create the appropriate thickness for the sample sheet and to create a seal around the glass panel to prevent resin leakage. The top edge of the mold is left open, and the mold is placed upright so the resin can be directly poured into the mold. A known glass release agent, Aquapel® (similar to Rain-X®), is applied to aid the removal of cured Texeron™ from the glass panels to reduce adhesion and prevent damage.

For complex R&D prototypes that were not a flat sheet, silicone molds were cast from a sample of the legacy final product. These molds provided enough structure to test the ability of Texeron™ to form a complex shape, but not enough dimensional stability for a production part.
Release agents for the silicone molds were not needed because the cured Texeron™ does not adhere to the silicone mold surface. Texeron™ resin is poured directly into the mold before it is closed and the mold is clamped together to prevent unintended resin flow prior to gelation. Because these are R&D prototypes, dimensional tolerance is not as crucial as they will be in production.

For full-scale production needs, the focus placed on Texeron™ molds will shift away from the flexibility desired during development and towards a high level of dimensional stability and reliability at volume. As the development cycle of each Texeron™ product transitions from the design and trial phase to full-scale production, molds will be fully machined and polished aluminum that can provide a high-quality, optically smooth surface and maintain that surface for multiple production cycles. Reaching that point requires additional tooling development and production trials, and some of the challenges faced during that process will be detailed in Chapter 4.2.

4.1.2. Raw Material Storage

Raw material storage is important in Texeron™ processing due to two key factors related to product performance susceptibility: moisture and contamination. As discussed above, thermoset polyurethanes are sensitive to moisture as the reaction progresses. If water is present in the resin, carbon dioxide outgassing can occur and cause small voids to form during the cure process that are trapped in the cured part. These voids can cause optical defects and potential structural weaknesses in the final product, potentially leading to rejection by the customer. Therefore, one requirement of the component material storage is to prevent moisture being introduced into the material from the air or other sources. This is especially important for the isocyanate component, as it will absorb moisture from the air over time and which can lead to product failure during cure.

Contaminants in the raw material can also lead to a rejection of the final product, either through optical defects or improper chemical reactions. Small pieces of foreign material can cause imperfections in the optical quality of the final product. Chemical contaminations or the use of an incorrect component can prevent the resin from curing correctly or cause voids and haze throughout the final product.
In the production of Texeron™, these two requirements are satisfied in several ways. First, for long-term storage, the main components are stored in sealed steel drums and blanketed with a layer of nitrogen gas. Because it is inert and heavier than air, the nitrogen provides a buffer layer between the component material and the air to prevent moisture absorption. The bulk of each component remains stored in these drums until shortly before they are used, reducing the amount of time that they are exposed to an environment in which they could be contaminated. Each drum is fitted with a sealed valve that can be opened to transfer some of the bulk material into smaller bottles that hold enough material for 2-3 batches of Texeron™. These bottles are then labeled and color-coded to avoid any confusion of material. The Texeron™ production area, which will be discussed in detail below, was also designed to help control for these requirements.

4.1.3. Formulation Mixing

The mixing process for Texeron™ production consists of three distinct steps; measuring the appropriate amount of each component, mixing the components together, and degassing the resin mixture. In the process diagram, they are represented as one process step because they are closely linked and in larger-scale production could be achieved with a single piece of equipment, but we will discuss each further below in more detail.

Component Measuring

The key requirement for component measuring is ensuring that each batch of Texeron™ has the right components added in the right ratios. This initially sounds like an obvious and trivial requirement, but every product will require a different combination of base formulation (Texeron™ 20 or Texeron™ 25), additive (none, UV stabilizer, tint, etc.), and all scaled relative to overall batch size. In some cases, 0.1g more or less than formulated in a 100g mixture results in a completely different product. Two factors that drive the requirement for exact component measuring are traceability and the nature of Texeron™ as a thermoset polyurethane. An important aspect of aerospace manufacturing is lot traceability throughout the production cycle, and Texstars must ensure that every batch of Texeron™ meets both the correct formulation as defined by the material specification and the correct manufacturing process as defined by Texstars and the customer. Because thermoset polyurethanes cannot be reshaped once cured, each batch must be mixed, cast, and cured individually, and relies on the correct formulation in order to achieve the desired end-product results. In full production, testing 100% of these batches.
will be costly and time consuming and having unintended product failures are costly, so proper production controls are necessary to guarantee the consistency of Texeron™.

One type of control is included in the operator’s instructions, referred to as a Texstars’ “traveler”. The traveler is created by a production engineer and contains detailed process steps to be followed by the operator along with fields to record the activity and outcomes. Operators record task completion and specified process information as a product is made and the traveler remains with each unique product as a means to validate product quality and traceability. For Texeron™, the traveler contains exactly which components, in what amounts, and in what order must be mixed for a given product. Operators will dispense each component into a mixing container that is placed on a scientific scale. This scale is connected to a printer so the exact amount of each component is verified and recorded both by hand and by the scale’s printout, providing another control for process validation. Potential improvements for this method as production volumes increase will be discussed in Chapter 4.3.

A final and important aspect of component measuring is the amount of catalyst. The catalyst represents a very small percentage (less than 1% by mass) of the total mixture and is the last component to be added to the mixture as it begins the gelation process, and has a very significant influence on product quality. The type of catalyst impacts the pot life, mechanical properties, and chemical properties of the polyurethane. The catalyst type is determined by the R&D team and considered static for production. As discussed in Chapter Three, the amount of catalyst has an important effect on the pot life, and although the ratio is set by R&D and amounts are detailed in the traveler, the production operator is directly responsible for measuring the correct amount in each batch. To remove the variability in this step and ensure the right proportion of catalyst to resin, a precision dispensing machine is used by production to measure and dispense the catalyst in terms of micro-grams. Several programs are set on this machine depending on the batch size of the Texeron™ to be mixed, and the operator need only follow the traveler to set the appropriate program and dispense the catalyst.

**Resin Mixing**

In general, Texeron™ mixing consists of three steps; initial mix, catalyst addition, and final mix. The initial mix allows the manufacturer to get a homogenous blend of the isocyanate, polyols, and additives before catalyzing the reaction and starting the clock on the pot life. As discussed
above, pot life can range from minutes to hours depending on the type and amount of catalyst used, but this “timer” on the pot life doesn’t start until the catalyst is added. After the initial mix, the catalyst is added and the resin undergoes its final mix. This introduces the catalyst throughout the entire bulk of the resin to again homogenize the mixture and begin the reaction phase.

The main requirement of the mixing process is creating a homogenous resin, both in composition and temperature. Resin homogeneity is a key factor in obtaining a final part that has high optical quality and consistent mechanical properties. A secondary requirement during mixing is to prevent frictional heating within the resin itself, which shortens the pot life of the resin and leads to processing challenges. Due largely to increased volumes or batch sizes, the Texeron™ mixing process underwent the most significant development and evolution from the R&D process to the production process.

The R&D process of mixing uses an asymmetrical, centrifugal mixer that is run under 2000rpm. This lab-scale piece of equipment mixes the components into a homogenous resin without requiring a blade to contact the material. An illustration of this motion is shown in Figure 8. There are several benefits to mixing the resin with this type of equipment. Because there is no blade contacting the resin, there is no loss of material and no risk of contaminants being introduced. This blade-less, centrifugal equipment also creates a vacuum while in motion, satisfying the degassing requirement that will be discussed below. Finally, the centrifugal mixer has proven very effective in homogenizing a mixture, which satisfies our main requirement at lab-scale.

Figure 8: Illustration of the motion of an asymmetrical, centrifugal mixer. (FlackTek SpeedMixers™, 2017)
Despite these benefits, there are two drawbacks that prevent the lab-scale equipment from being used in production. First, the machine is limited to 350g of material, which worked fine in the lab when only small prototypes were being developed. However, in production, batches of up to 1000g of material are necessary with even larger batch sizes required in the future. While larger centrifugal mixers are available, the step up in cost is not feasible for the early stage of production currently being pursued. Second, the centrifugal mixing process introduces heat as the material moves within the container, which increases with batch size. Because of the high rpm and length of mixing, this heat becomes significant in production batches once the catalyst is introduced and lowers pot life dramatically. In R&D, this problem is solved with a rest period of five to ten minutes during the initial mix and before the catalyst is added. In a production environment, application of the lab-based process with mix-and-rest time intervals adds undesirable variability and down-time.

Therefore, a new mixing solution was required for the Texeron™ production process. This project worked with production and R&D personnel to identify, evaluate, and introduce new mixing equipment. We considered a wide variety of industrial resin mixing systems, ranging in functionality, capacity, complexity, and cost. Large, continuous flow systems can draw component materials directly from steel storage drums and precisely mix them within a single sealed system. Equipment of this nature satisfy all processing requirements from the measuring stage all the way to the casting stage and are an ideal solution for high volume production, however, they are too costly for where Texstars is in the commercialization process. Other mixing systems can be as simple as a hand mixer or a stationary motorized mixing arm. Three specific mixing systems were considered for initial Texeron™ production, and they are evaluated below for functionality, capacity, complexity, and cost (see Figure 9, with a solid Harvey ball indicating strongest performance and an empty Harvey ball indicating weakest performance.).

System 1

System 1 has the most functionality of the three mixing solutions we evaluated, but is also the most complex and most expensive. It has a high degree of accuracy, is customizable, and is the easiest to operate in a production environment to yield consistent results. This system is directly connected to the raw materials and measures each component per defined formulations, mixes them together, and has a dispense unit to fill the mold. Texstars could work with the supplier of
this equipment to program the different formulations of Texeron™ so any product could be made from the same equipment with the “push of a button”. This system keeps the resin under vacuum during mixing to prevent air and moisture exposure, as well as removing any air that has already been introduced. Because System 1 is directly linked to the raw materials source, it can produce any batch size necessary as long as there are enough raw materials available, allowing the production capacity of Texeron™ to grow without having to continuously evolve and change the mixing system. The high degree of available customization also makes this system the most complex and restricts flexibility once built and installed, requiring significant upfront cooperation with the supplier to define the component needs and mixing ratios. Small changes in the formulation components or ratios may require additional setup or programming. Maintenance and repair of this system will require continued involvement from the supplier or specialized training by Texstars’ maintenance technicians. System 1 is also the most expensive, costing an order of magnitude more than the other options and requiring significant upfront investment. This solution is more appropriate to larger scale production, and will be something Texstars looks into over a longer time frame, but is not justified at this point in the product introduction life cycle.

**System 2**

System 2 satisfies many requirements of the measuring, mixing, and casting process, while controlling for cost and complexity. This system draws material from two different holding tanks and mixes them in specific ratios as the material is being dispensed into the mold. The ratios have a high degree of accuracy and, similar to System 1, the operator simply injects the material into the mold while the mixing system measures, mixes, and manages the dispensing operation. System 2 is able to mix different ratios of components stored in the two tanks, but the changeover process is more complicated than simply changing a formulation program. Changeover requires ensuring the two holding tanks have the appropriate resin premix and that the system has been set to the appropriate ratio. Capacity is not a concern for System 2, as the holding tanks can hold up to 10 gallons of resin premix a piece, which is more than enough for future expected product size. Because this system is only drawing material from two tanks instead of all raw materials, it is less complex from an equipment standpoint than System 1. However, a major drawback of System 2 is that it requires the multiple components of
Texeron™ to be pre-mixed into the two holding tanks, adding complexity before the final mixing stage, and increasing the potential for added moisture or exposure to air during the pre-mix operation and tank change-over. These pre-mixed resin components would have to be developed by Texstars R&D and tested to ensure consistency with current Texeron™ samples. Additionally, Texstars would need some methods and controls between material storage and pre-mixing to yield reliable component blends. When factoring in these aspects of System 2, it adds just as much complexity to the process, with reduced functionality, than System 1. The cost of System 2, however, is within the target range for this stage of production.

System 3

System 3 is the least complex and least expensive of the three options, and provides the lowest level of functionality but is more capable than the lab-scale equipment used in R&D. This system consists of a vacuum chamber sealed by an acrylic lid that is integrated with a motorized variable mixing unit. The operator measures each component as described earlier in this section and places the container of resin in the mixing unit. After it is sealed and under vacuum, the operator turns on the mixing unit to a specific rpm for a specific amount of time. Although System 3 has a lower functionality than Systems 1 and 2, it still satisfies all of the process requirements for mixing and degassing to support production. System 3 also has the capability to then draw the material directly from the vacuum chamber into the mold, or the operator could remove the resin and inject using another method. The capacity of System 3 can also handle up to 10 gallons of material, but differs from System 2 in an important way; it is more flexible at lower batch sizes of resin. The vacuum chamber and mixing arm of System 3 can handle small container of 100 grams just as easily as it can handle a 10-gallon container, making it simpler to use for low volume products. System 3 is also the least complex of the potential mixing solutions, meaning it can be set up for production relatively quickly and maintenance can be easily managed by existing Texstars personnel. Finally, System 3 has the lowest cost of the three mixing systems and is within the target range for Texstars’ current level of production.
Mixing Unit Selection

These three options were evaluated with the Texeron™ production team and the final selection implemented for this phase of the project was System 3. System 3 provides the best trade-off between functionality, capacity, complexity, and cost, with the added benefit of production flexibility. The system can handle any single batch size up to 10 gallons, satisfying expected Texeron™ demand for at least a year or more, while representing an appropriate investment for the initial phase of production. It is simple enough that the production team can continue to develop and improve the Texeron™ process without requiring expensive changes or updates.

While System 1 satisfied many requirements of the entire production process, it was too large of an investment for the scale of production expected for the first year. System 1 may be a valid process update once production picks up, but at the initial stage, it represents too high a cost. System 2 presented challenges regarding the pre-mix of materials that could not be solved before Texeron™ production needed to begin. It is also a potential option for future process improvement, but R&D would need to devote resources to develop several two-part mixes for each formulation of Texeron™.

Degassing

The final process step of formulation mixing for Texeron™ is degassing the resin before the mold casting step. The requirement for this step is driven by the need to have as little trapped gas

Figure 9: Comparison of resin mixing systems. A solid Harvey ball indicates the strongest performance and an empty Harvey ball indicates the weakest performance.
as possible trapped in the resin before casting both for optical and physical strength reasons. Air can lead to Texeron™ defects through moisture outgassing, caused by the interaction with water and isocyanate during cure, and through trapped air, which can expand and cause voids or holes that degrade optical clarity. As discussed above, both the R&D and production mixing solutions pull a vacuum during the mix and satisfy this requirement without additional equipment.

4.1.4. Casting

The casting stage of the Texeron™ manufacturing process in use by R&D is a liquid casting system that uses gravity to feed the resin into the mold. Resin is poured into the mold and air is pushed up and out of the open top of the mold as it fills. Casting with this method has proved simple and flexible for the development stage of Texeron™, allowing a single member of the lab to cast a Texeron™ sample. Despite this simplicity, this system is not ideal for production because it does not control the resin’s exposure to air or guarantee air is pushed out of the mold, which can introduce voids, contaminants, and moisture.

For Texeron™ product manufacturing, this project focuses on variations of liquid injection that use gravity, applied pressure, and vacuum to assist the resin in moving through the mold. Although vacuum casting, rotational casting, and compression molding are potential options for future Texeron™ development, they require more complex molds that are not appropriate for the current stage of development. The molds tested for liquid injection are stationary tools that can be prepared and sealed before the Texeron™ resin is mixed, reducing the variability and processing steps required by production. Compared to the other casting methods mentioned above, liquid resin injection is also more flexible to design and process changes. The molds needed for vacuum casting, rotational casting, and compression molding require more upfront time and cost, limiting development opportunities.

The product for Launch Customer 1 requires a laminate thin-sheet layer of Texeron™, which is similar, although longer / wider / and thinner, to the Texeron™ samples that are used during formulation development and testing. A case study in casting develop for Launch Customer 1 is discussed in more detail in Chapter 4.2. This example highlights some of the casting challenges that a manufacturer can experience when trying to shift from an R&D process to an industrialized production process.
4.1.5. Curing

Like the ratio of individual components, the cure cycle for Texeron™ products is determined by R&D as they are developing different formulations and is considered static for production based on Texeron™ formulation and end-product configuration. It is, however, important for the production department at Texstars to understand the different aspects of cure and how it affects the turnaround time for a production tool. Depending on the formulation, a Texeron™ product may need to be cured in an oven for as long as 8 hours, during which time the production tool is unavailable for anything else. Because the production tools represent a large capital investment, using those tools efficiently can reduce the cost of the overall product and improve overall throughput. Going forward, production personnel can work with R&D to optimize the time and temperature of the oven cure as well as the amount of time a Texeron™ product needs to be cured in the oven versus a room temperature cure out of the mold.

4.1.6. Post-Processing and QA

After the Texeron™ product has finished curing, it is inspected for defects before moving into post-processing operations. Post-processing may include drilling holes, bonding with other parts, polishing, or any other process required by the customer. The final product is then sent to the QA department, which inspects the product and the documentation (traveler) relative to the customer’s specifications and validates the product is ready to ship to the customer. Although they are important steps in the process, especially for aerospace products, post-processing and quality assurance were not a focus of this project.

4.1.7. Texeron™ Production Area

Although many production requirements are controlled using processing techniques or properly configured equipment, an important factor in the production of Texeron™ is the production area itself. Utilizing input from several teams at Texstars, this project identified the desired requirements for the production room and then proceeded to build out the room. These requirements include a semi-clean environment with its own temperature and humidity controls, easy access proximity to an oven, enough space to satisfy expected production demand for at least one year, and a controlled storage area for raw materials. We identified two areas of Texstars’ current production facilities that could meet these requirements and were available to
begin setup and support production. Both areas were of comparable size, closed environments, and close proximity to an oven suitable for Texeron™ curing. Because both areas satisfied all necessary requirements, the team collectively conducted a 3P event and walked through each area to factor layout into the decision. The area of the plant that eventually became the Texeron™ Production Area already has a section of the room walled off as an office area. This area would be an ideal location to store the raw materials so they are still contained in and controlled by the Texeron™ Production Area, but out of the way of production personnel. The area also has a large sliding door that facilitates ingress and egress of large equipment and molds, which the group identified as beneficial for future production volumes.

4.2. Launch Customer Development

This chapter will detail the specific challenges faced during one stage of process development for each of the launch customers and provide a case study in transitioning a new technology from R&D to production at a small manufacturer. The product for Launch Customer 1 requires a thin sheet of Texeron™ that will be bonded to another transparency in post-processing. Launch Customer 2’s product is a more complex exterior lens that will be a structural part of the aircraft.

4.2.1. Launch Customer 1 – Casting Process Development

Because Launch Customer 1’s laminate sheet was the first Texeron™ product to be developed, the team at Texstars worked through many aspects of the transition from R&D to production for the first time. As already discussed, the required Texeron™ part for this application is a large, thin sheet of Texeron™ that will be further laminated to other transparent material by Texstars to the final product for customer delivery. This sheet is roughly 1/3rd the thickness of the coupons and 30”x 30” in length and width, making it thinner and larger than any sheet of Texeron™ produced for formulation testing. As it will be laminated and assembled into a transparency window, this Texeron™ sheet must also be optically clear and free of any major defects. The below case study will highlight the evolution of casting process for Launch Customer 1’s thin sheet and how the Texstars team used information from these casting trials to aid other parts of Texeron™ development. It does not propose a singular solution for how to cast this material, but rather documents the challenges that manufacturers may face as they develop a cast resin production process.
Gravity Feed with Open Mold

Based on the initial R&D process, the open mold, gravity feed casting process enables Texstars to better understand the factors that affect the quality of a thin sheet Texeron™. This method of casting is understood by the R&D personnel that use it, but the first goal of production engineers is to identify the key casting and mold parameters that can be optimized and carried forward to other casting techniques. This project aided production engineers to construct their own, scaled-up version of the gravity feed mold that can be used for concept testing. By keeping the general casting method consistent with the known R&D method, the effect of changes in mold material, and casting specifics are more easily understood. While this R&D casting process is not appropriate for full-scale production, it is still valuable to the production development team because it limits the number of variables we are testing. The discussion below will highlight some important lessons that were drawn from these production trials.

Seal Material

Regardless of which casting method Texstars production personnel use for the thin sheet, the mold will need to have an effective seal to prevent resin from leaking out and air from leaking in, which creates voids in the part. The seal material used by R&D for the formulation panels was primarily wax tape of a determined and specific thickness. The tape would be layered along the edges of the glass mold to build up the desired thickness of the test panel and the glass mold would be closed and clamped. While this method is effective for R&D, it is labor and time intensive and does not provide a consistent or accurate thickness for a customer product. Thus, production used the scaled version of the gravity feed concept to test several different seal materials; silicone tape, adhesive silicone gel, fiberglass tape, and Teflon®. Because these materials are all tested under the same conditions and without making significant changes to the casting process, the production development team can be confident that any difference in results is due to the seal material. Through this process, we determined that Teflon® is the best material for the mold seal, because it is both nonreactive and easy to cut and place in the mold.

Resin Flow

The biggest effect that the change in thickness from a 0.125” test panels to the thinner customer panel had on the casting process was getting the material to flow freely through the mold. At
1/3rd the thickness of the test panels, the resin had difficulty filling the mold before gelation, which caused heterogeneity and optical defects in the final product. When trying to use the casting methods described below, the development team was unsure if this problem was due to casting problems, the sheet thickness, or mold design. But using the gravity feed casting method allowed the production team to investigate the problem in isolation and trial solutions with a relatively fast turnaround. One solution entailed heating the mold and the resin to lower the viscosity and increase the rate at which resin enters the mold. This also kept the resin at a homogenous temperature, which is important for an optically consistent sheet of Texeron™. Another proposed solution that was tried using the gravity feed method involved reducing the clamping pressure around some of the mold to increase the thickness and improve resin flow. Although this could be successful, it ultimately added too much variability and inconsistency to be a viable alternative.

**Vacuum Assist**

An alternative casting method to gravity feed is liquid injection with a vacuum assist. This process is similar to the vacuum casting method described in Chapter Three except that the entire process does not need to be done under vacuum. With vacuum assist, the mold is open at two points located at opposite corners of the square, the resin entry point and exit point. A small vacuum is applied to the exit point to draw the resin through the mold, and the mold itself is tilted on two axes so that the entry point is at the bottom and the exit point is at the top. This method guarantees that the resin will fill the entire mold without leaving gaps at the edges.

The development team faced two major challenges when pursuing this casting method: seal integrity and glass deflection. First, the seals at the entry and exit points must be airtight to prevent any air from getting drawn in along with the resin, again potentially causing voids, optical distortion, and weakening the resulting material. These points represent a break in the Teflon® mold seal and are the weakest points in the mold. As the development team began tool trials with this method, weaknesses in the entry and exit seals became quickly apparent as air infiltrated the mold cavity and caused voids and streaking at the corners. Although this seems obvious, it is a small detail that was not an issue for the R&D casting method due to the smaller and thicker sample parts and was not part of the initial knowledge transfer.
Likewise, inward glass deflection was not an issue faced with the gravity feed casting method but became an issue with vacuum-assist for the thinner, larger sheets. Because the surface area of glass tool is so large (roughly 900in²) and the thickness of the desired sheet is so thin, even a small amount of vacuum will cause the two panels of glass in the mold to deflect toward each other in the center and can come in contact. This prevents resin from flowing through much of the mold and creates a large void in the center. Even when the glass panels do not come in contact with each other, any applied vacuum will cause a small amount of deflection, narrows the gap between the glass panels, and results in inconsistent Texeron™ sheet thickness. A proposed solution to this issue is to bond the glass mold panels to an egg-crate like support structure that holds the glass panels equidistant from each other across the face of the mold while under vacuum. This structure will be constructed of a composite material (to match the CTE of the glass) and will provide enough strength to prevent the glass from deflection under vacuum. Although the results of this solution were not available by the conclusion of the project, this example highlights the challenges that need to be overcome in any technology transition process.

4.2.2. Launch Customer 2 – Mold Creation and Tooling

As mentioned above, the product for Launch Customer 2 is an exterior lens with multiple radii of curvature. Texstars has been working directly with Launch Customer 2 to understand the requirements of the lens and develop the tooling concept for a successful launch. A unique feature of the product, identified through discussions with Launch Customer 2, is that it contains an embedded material that must maintain a specific depth profile through the lens. The top and bottom layers, representing the outer and inner surfaces of the lens, are both cast Texeron™. The middle layer is the embedded material which must be located at a specific depth throughout the lens profile within a tolerance of a few tenths on a millimeter (thousandths on an inch). An example of this cross-sectional profile is shown in Figure 10.
The initial prototypes of this product were cast using a mold similar to what was described in Chapter 4.1.1. This mold was a large block of silicone tooling material that was cast in two parts around a sample of the final product. While effective for providing a physical sample of a Texeron™ lens, this prototype mold did not allow for proper inclusion of the embedded material at the required depth, nor did it have the dimensional tolerance to accurately identify design...
flaws and work towards a final tooling solution. This case study will examine two decisions that the Texstars development team made to solve these issues; the proper tooling concept to use in order to satisfy major product requirements and what materials to use for development tooling to balance design flexibility and production trial accuracy.

**Tooling Concept**

The tooling approach for this product focuses on one key decision; how to form the lens to ensure that the embedded material is at the appropriate depth within the lens and maintains the required dimensional tolerances. Texstars needs to devise a tooling concept that is accurate in terms of depth and the associated tight tolerances, consistent, and can demonstrate to Launch Customer 2 that every lens they receive will be within specifications. It must also be a feasible concept for production that does not require too much time or effort to produce, or costs too much relative to rate-based tooling. The development and tooling teams at Texstars identified two basic tooling concepts that are viable options for the exterior lens.

Concept 1 is a single cast concept that directly embeds the material in a single mix of Texeron™. The mold for this tool concept would be designed to hold the embedded material at the correct depth around the edges of the mold before the Texeron™ resin is added. Enough Texeron™ resin is prepared for the full volume of the lens, and the resin is cast into the closed mold and allowed to cure. Ideally, once the product is demolded, the embedded material will be at the correct depth throughout the profile of the lens. Optical measurement or periodic destructive testing would be used to verify that the embedded material is held at the correct depth. The key challenges for this concept are building a mold with a repeatable method of holding the embedded material in place during the casting process and identifying a process to verify the depth of the embedded material.

Concept 2 requires three separate cycles of Texeron™ casting and can be described in three basic steps with three separate mold sections: Final Outer Mold Line ("OML"), Intermediate, Final Inner Mold Line ("IML") (See Figure 11). The first step casts the OML of Texeron™ using the Final OML section and the Intermediate section. This portion of the lens is the thin layer of Texeron™ that will be facing away from the aircraft and be exposed to the elements. The second step secures the embedded material in place at the correct depth and profile. After the OML layer has cured, the Intermediate mold is temporarily removed and the embedded material is placed on
the inner surface of the now cured Texeron™ OML layer. A small amount of Texeron™ resin is brushed onto both sides of the embedded material and the entire mold is cured in the oven to secure the embedded material. The third step is the final cast of the IML surface of the lens. The Intermediate mold half is replaced with the Final IML mold, which has a greater volume for the full lens thickness. Texeron™ resin is injected into the sealed mold and cured to complete the lens. Two key challenges with this method are preventing contamination of the lens by moisture or debris during the various casting steps and ensuring a stable bond between the layers of Texeron™.
Figure 11: Simplified Representation of Concept 2 Casting Process. Gray represents Texeron™ and blue represents the embedded material.
In order for the development team to determine which tooling concept to pursue, we identified the important requirements of the lens by the customer and for production. A key trade-off for Launch Customer 2’s tooling concept is the production simplicity versus the verification of the embedded material depth requirement. Concept 1 necessitates only one cycle of the mixing, casting, and curing process, making it simpler and less time-consuming for production. But because the location of the embedded material can only be controlled at the edges and the material could “float” as the resin is injected into the mold, verifying whether this material is at the right depth is a key quality challenge. For Concept 2, the three-step process adds complexity in the form of three cure cycles, multiple batches of Texeron™, and additional molds, but the depth of the embedded material is more tightly controlled and depth verification is guaranteed as part of the tooling. In a development process, decisions like these have no clear right or wrong answer and the development team must evaluate the importance of process requirements. For Launch Customer 2’s product, the requirement to manage the depth of the embedded material adds to the complexity of the tooling concept, but the ability to control location is worth the additional development cost. Thus, we decided to pursue Concept 2 and develop tooling for a three-step casting process.

**Mold Material Selection**

Another challenge faced by the development team is which materials to use to construct the initial development molds. As mentioned above, a goal of Texeron™ tooling development for Launch Customer 2 is to remain flexible to design or process changes before finalizing production tooling. We want to push expensive development gates as late as possible so we can continue to make changes to the process and molds as we learn more through production trials. Consumable, soft materials, such as silicone, polyurethane, or epoxy, are ideal for this application, but have one important downside; maintaining product tolerances and ensuring the required optical clarity. These materials expand and contract throughout heat and pressure cycles and can lead to dimensional differences from the product drawing, differences that make it difficult to accurately improve the product.

For example, if the product comes out of a cure cycle with a small hole in one section, is it because the mold design and construction prevents resin from flowing correctly or because the mold material expanded to block off that section? If it is the former, design changes need to be
made to improve resin flow. If it is the latter, the problem might be solved with an all metal tool. It is this trade-off between design flexibility using a soft material and trial product accuracy using a harder material that the development team needs to balance as the team evaluates the end-to-end casting process and mold design.

The Texeron™ development team’s solution to this problem is a dual-material tool with hard and soft elements to provide both dimensional stability and design flexibility. A hard aluminum base serves as the structural support for the casting tools, while silicone inserts dictate the specific part geometry and contact surface. These two distinct materials offer enough structural support to limit the amount of expansion and contraction during the cure cycle, but enough flexibility to avoid large up-front costs and quickly iterate design changes. The aluminum base is machined with the general curvature required by each step of the casting process and provides a durable platform that will maintain dimensional tolerance throughout cure. Because of this structure, tooling designers can limit the amount of silicone to 1/4” inserts, which reduce the variability in product dimensions due to heating cycles. These inserts are cast to reflect the exact profile and surface desired at each stage of the casting process. It is cheaper and faster to recast a silicone insert than it is to re-machine an aluminum tool, allowing for a faster cycle of production trials and a lower-cost option to trial design changes without committing to large tooling expenses.

The challenges described above are not the only ones dealt with by the Texeron™ development team for Launch Customer 2’s tooling design, but they are representative of the types of trade-offs that must be made during any development process. Ideally, companies could pursue all design concepts until a final decision is made, but the reality of resource and time constraints require a way to choose a concept and add flexibility where possible. Similarly, development tooling must be stable enough to produce representative products while still able to accommodate future changes that don’t stretch the available resources. Finding sources of low-cost flexibility, both in time and money, is an important aspect of transitioning a product from R&D to full-scale production.

4.3. Process Improvement and Long-term Flexibility

Throughout the development of the Texeron™ production system, this project worked with the team at Texstars to transition many aspects of the R&D process to a production ready system. This included documenting and developing the full production process, creating a separate
production area, with an independently controlled environment, and purchasing of new capital
equipment for storage, mixing, and casting. By the end of this project, production personnel have
the resources and knowledge they need take full ownership of a Texeron™ product from start to
finish. Despite these successes, this is only the beginning of the Texeron™ process development
and there are plenty of future opportunities for process improvement and long-term growth.

*Mold Creation and Preparation*

As demonstrated by the Launch Customer 2 case study, there are many decisions that need to be
made as the trial and production molds are designed for each Texeron™ product. As new
products are introduced and new designs are tested, Texstars will continue to build their
knowledge of how Texeron™ reacts to different mold materials and release agents. A record of
these trial materials and their efficacy is already in progress, and Texstars should continue to
expand this as new products are developed. These lessons can be carried forward to further
reduce development time and lower production costs.

*Formulation Mixing*

The mixing process implemented throughout this project satisfies both the current production
requirements and is designed to allow flexibility in formulations and product portfolio growth.
Future-state mixing systems, such as System 1 and System 2 described above, are a possibility
once production volumes increase and the process is fully understood, but there is still room for
near-term process improvement. The production operators in the implemented system measure
each component individually for each batch of Texeron™ that is mixed. While there are current
controls in place to ensure product quality, process improvement efforts should focus on ways to
reduce sources of variability like kitted component storage, pre-mixed resin components, or an
automatic pumping system.

The mixing profile of Texeron™ resin is another area for continued study. The goal of the
mixing step is to create a homogenous resin that will result in a high-quality polyurethane, while
balancing the pot-life of the resin and production efficiency. The current mixing profile is
effective in creating a homogenous resin, but additional research can be done to reduce the cycle
time while maintaining mix quality.
The biggest benefit of the current formulation mixing process is the long-term flexibility that is built into the system. Other than raw material availability, there are no constraints on what formulations and batch sizes can be mixed. Because Texeron™ is still in the early stages of development as a product line, the development team needed to ensure maximum flexibility and avoid getting locked into a specific production path that will restrict options in the future. If a new formulation is developed by R&D that requires a new component, it can be worked into the current system without disrupting the current production efforts. This allows Texstars to not just grow the volume of current production, but to expand into new products that may not be an option today.

*Texeron™ Production Area*

Like the formulation mixing system, the Texeron™ production area was designed for maximum flexibility. To start, the production area is large enough to encompass expected demand for at least a year or more, and there are areas of the plant adjacent to the current Texeron™ room that can be converted to Texeron™ production in response to increased demand. To allow for future expansion and movement, the development team avoided fixing capital equipment to a specific area of the room. If the production flow needs to be rearranged or the entire production process moved to another area of the plant, it will take relatively little effort by Texstars production.

As the volume of production and the number of individual products grows, process improvement efforts will be crucial in maintaining the efficiency of the Texeron™ area. In the several months of production trials throughout this project, the process flow throughout the production area changed notably from the original design. The experience of running production trials informed us of where the bottlenecks were and what parts of the process require more or less space. Continuing to refine the process flow for current and future products will aid in consistent and efficient performance. Another source of continuous improvement will be refining what consumable resources are available to production operators. Because the Texeron™ products are still undergoing production trials, there are a lot of consumable items currently being used that will become unnecessary once production is finalized (such as different size plastic containers, various types of cleaning cloths, different tubing and seal materials, personal protection equipment pertinent to chemical-based processes, etc.). Maintaining this area to include only the necessary consumable items will reduce the risk that the wrong item is used in production.
5. Conclusions and Recommendations

As a small manufacturer developing a new product, Texstars faced many challenges in transitioning that product from R&D to production, including knowledge transfer and resource allocation. This project worked with all levels of the Texstars organization to tackle these challenges, identify the key decision points, and highlight areas of future improvement. For Texeron™ production and future new product introductions, it is important for Texstars to form and maintain a link between the R&D personnel who have experience with the product and the production personnel who will be responsible for customer delivery. In the development of Texeron™, this link could have been established earlier, enabling the identification of production challenges before they occurred in production trials. For future products, this link should be established as early as possible to allow maximum information exchange and dialogue between parties. Production personnel will have experience and knowledge that can help shape the development of the product and the types of tests that need to be conducted before a product is ready for production.

During the project, this transfer of knowledge and transitioning of responsibilities was done under the backdrop of constrained resources. Each step of the Texeron™ development process, including location decisions, equipment purchases, and process refinements, involved balancing functionality and resource allocation while still satisfying all customer requirements. A key strategy that Texstars can use to improve this process is to find opportunities for low-cost flexibility that can push expensive development gates later in the process, such as versatile equipment or soft molding material. Doing this can allow the company to stretch its resources and quickly change when new information, in the form of new requirements or technological availability, is introduced.

Finally, it is important that Texstars, both with Texeron™ and future new product introductions, undergo this transition process instead of simply copying the R&D process to the production environment. Although the R&D process is effective in producing prototype products and developing new Texeron™ formulations, it does not incorporate the expertise of production personnel. R&D processes may also be “siloed” in development and may ignore certain customer requirements, such as traceability, and certain production limitations, such as cycle time and tooling expense. In the future, as it becomes clear that new development projects will be scaled-
up to full production, Texstars should implement a production development process similar to what was done for Texeron™.
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