Thermoforming Quarterly®

A JOURNAL OF THE THERMOFORMING DIVISION OF THE SOCIETY OF PLASTIC ENGINEERS

THIRD QUARTER 2011 ■ VOLUME 30 ■ NUMBER 3

Conference Edition

MADE IN AMERICA

Big Ideas Loom Large in U.S. Manufacturing

INSIDE . . .

Thermoforming Quarterly®

THIRD QUARTER 2011
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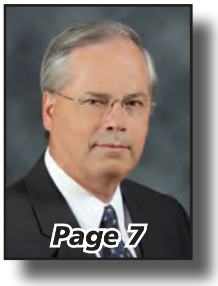

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Thermoforming Quarterly®

A JOURNAL PUBLISHED EACH CALENDAR QUARTER BY THE THERMOFORMING DIVISION OF THE SOCIETY OF PLASTICS ENGINEERS

Editor
Conor Carlin
(617) 771-3321
cpcarlin@gmail.com

Sponsorships
Laura Pichon
(847) 829-8124
Fax (815) 678-4248
lpichon@extechplastics.com

Conference Coordinator
Gwen Mathis
(706) 235-9298
Fax (706) 295-4276
gmathis224@aol.com

Cover Photo courtesy of Jeff Miller/University of Wisconsin-Madison

Chairman's Corner

Ken Griep

Being Prepared to Meet Future Opportunities

On behalf of the SPE, I would like to welcome you to our annual conference in Schaumburg, Illinois, September 17th – September 20th, 2011. More than ever, the purpose of this conference is to provide a forum to encourage, help and inspire you to continue developing your business strategies.

While sitting on my deck writing this article, I have noticed a cool breeze offering a pleasant change from the recent heat wave most of us have endured. Along with the summer heat, we experienced the failure of our government to positively handle the debt crisis and then we watched as S&P downgraded our AAA credit rating. Similar to the heat, the wasteful spending practices are oppressive. Each of us needs to communicate with our elected officials, on all levels, to let them know that the current practices are hindering the future expansion and success of our businesses.

Now we are watching a major shakeup in the stock market with a roller-coaster ride of ups and downs. We seem to be facing new challenges every day and undoubtedly we will see more in our future. We are all in this together. Therefore, we feel that this year's conference, **"Being Prepared to Meet Future Opportunities,"** has a very timely message.

With the 2011 Conference, we will celebrate 20 years of delivering highly technical and informative sessions to the thermoforming industry. During this time, we have seen many friends come and go from the industry. However, over the past two decades, we have also seen our industry grow and expand into areas that were once considered almost impossible when we started.

The Board of the Thermoforming Division would like to thank each and every one of you who have attended over the years and who continue to provide your support. Our biggest thanks are reserved for our exhibitors. Their involvement and dedication have provided the foundation for innovative displays of machinery, tooling and materials as well as offering a deep well of technical information. They also play an important role in recruiting experts from various end markets to join us and share their specific knowledge. This exchange of ideas is what gives attendees new and cutting edge information in order to maintain and keep a competitive edge over other processes.

The 2011 conference will present a major change to the format. In order to provide more opportunity for communication, the layout will allow both the exhibitor and the attendee to have more exposure time on the floor. This will allow more events and technical sessions to be held in a single location. This efficiency will provide greater opportunities for you to network, meet customers and suppliers and still benefit from the technical sessions.

I would also like to extend a special thank you to our **volunteer** conference team. This team has spent many hours away from their families and businesses in order to make this event a success.

Just as a cool breeze is a pleasant change from the heat, we must look to the future for positive changes. We are navigating unusual economic storms that require us to tack and change course frequently. Do not lower your standards to gain work. We need each other for support to keep a strong industry. Remember that manufacturing is the backbone of our nation.

Thank you for your continued support and get the word out: "Do Thermoforming"!

If you would like to share your views or comments, please feel free to contact me. I would like to hear from you.

Ken@pcmwi.com

Ken Griep

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Made in Wisconsin:

Vessel to contain cosmic force takes shape

By Terry Devitt, University of Wisconsin - Madison
July 20, 2011

At the heart of most celestial objects is a dynamo. The Earth's dynamo, spun to life in the molten metal core of our planet, generates a magnetic field that helps us find north and, perhaps more critically, shields us from solar winds that would otherwise singe our planet.

Stars and other planets have dynamos, and so do galaxies and clusters of galaxies.

And soon, Wisconsin will have the closest thing this side of the solar system to a cosmic dynamo.

With support from the U.S. National Science Foundation (NSF) and the specialized talents of four Wisconsin companies, the finishing touches are now being put to a 3-meter diameter, hollow aluminum sphere designed to hold in a vacuum a dynamo-generating 200,000-degree Fahrenheit plasma.

PHOTO: JEFF MILLER

After pouring more than 7,000 pounds of molten aluminum on June 16, 2011, workers at Portage Casting and Mold Inc. in Portage, Wisconsin, open a five-section-mold that formed one of two nine-meter-diameter hemispheres needed for the main vacuum vessel of the Plasma Dynamo Facility being installed at Sterling Hallon campus.

The vessel now being constructed will be at the heart of a new University of Wisconsin-Madison laboratory and promises researchers their best opportunity to put cosmic dynamos under a microscope.

Until now, scientists, generations of whom have labored to tease out the secrets of cosmic dynamos, have been relegated to studying the phenomena from vast, usually astronomical distances.

"The project itself is to study how magnetic fields are generated in planets and stars," explains Cary Forest, a UW-Madison professor of physics who will direct the effort formally known as the Madison Plasma Dynamo Experiment.

To do that, Forest and his colleagues required a specialized vessel to contain the types of high-temperature plasmas observed in space. Sometimes referred to as the fourth state of matter, plasmas are superheated gases where the atoms that make up the gas have been stripped of their electrons, leaving a conducting, highly electrified collection of atomic nuclei and free electrons.

After a nationwide search for a company to cast the hollow, thick-walled aluminum sphere that will contain the plasma at the core of the experiment, Forest's team settled on Portage Casting & Mold (PCM), a company less than an hour from Madison. The company specializes in fabricating large cast and fully machined molds, patterns and core boxes for plastic companies and foundries nationally.

PCM, according to the company's director of tooling Dan Griep, was excited to land the project, which was funded primarily through a $2.4 million grant awarded through NSF's Major Research Instrumentation Program to build and operate the experiment.

"This relationship is more important than ever," explains Griep. "There are a lot of funds flowing through the state of Wisconsin in these projects. If we can capture even half of the new UW business, it would have a huge impact on not only employment,

PHOTO: JEFF MILLER

Using $2.4 million in stimulus funding from the National Science Foundation (NSF), the experiment is a continuation of research studying the origin of magnetic fields in the universe and exploring the self-generation of magnetic fields in a plasma dynamo as a potential energy source.

but enhance our ability to identify new business and understand where we should focus in the future to support programs that are cutting edge across the UW System."

The opportunity to participate in building the apparatus for the dynamo experiment, says Griep, will help the Wisconsin company compete nationally and internationally for similar projects simply through exposure.

"The foundry-tooling industry in Wisconsin is alive and well and we are definitely open for this business," says Griep.

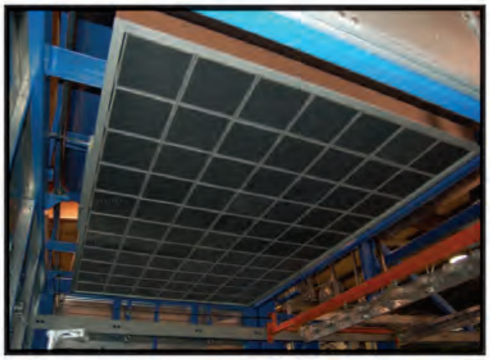
For the university, according to UW-Madison project engineer John Wallace, casting the plasma containment vessel and other work done in close proximity to Madison provides an opportunity for physics students to see first-hand how complex experimental equipment is fabricated, experience that will help them in future work. The aluminum sphere will be cast in halves and, after machining, will weigh in at about 10,000 pounds. Prior to final machining, the vessel will be subjected to an X-ray analysis by Lafayette Testing Services, a Milwaukee firm, to ensure that the cast sphere is free of voids.

The halves will then be shipped to D&S Machine Service in Luxemburg, Wisconsin, for sizing after which they will be returned to PCM for machining on large, five-axis milling machines capable of sculpting the sphere into its final form. When the machining process is finished, the sphere will be cleaned and tested for vacuum integrity at PCM's test facility in Portage. When complete, the inside of the chamber will be coated with alumina, a ceramic material that can hold up to the high plasma temperatures. Two Wisconsin companies, says Forest, are bidding to perform that work.

"It is an enormous advantage to actually talk to the people making the object and to work with them when we are designing the experiments," Forest says.

When the chamber is finished, it will be moved to a newly refurbished laboratory in Sterling Hall. The device is expected to be delivered in the fall and the first plasmas will be generated early in 2012, according to Wallace. The fact that the central, critical element of the Madison Plasma Dynamo Experiment could be built in Wisconsin is gratifying, says Forest.

"We are particularly proud of this aspect of the project," he notes. "That, after a national search, we found we could do this in our backyard, with Wisconsin companies and local expertise, is exciting." |



PROSPECTIVE AUTHORS

Thermoforming Quarterly® is an "equal opportunity" publisher! You will notice that we have several departments and feature articles. If you have a technical article or other articles you would like to submit, please send to Conor Carlin, Editor. Please send in .doc format. All graphs and photos should be of sufficient size and contrast to provide a sharp printed image.

2011 Thermoformer of the Year

Steve Murrill
Owner/President
Profile Plastics, Inc.
Lake Bluff, IL

Stephen R. Murrill is owner and President of Profile Plastics, Inc. of Lake Bluff, IL. Profile Plastics is a heavy gauge thermoforming company specializing in vacuum, pressure and twin-sheet processes. Steve has a BSChE from Purdue University and a MBA from the University of Chicago. Prior to the purchase of Profile Plastics in 1987, Steve worked for Signode Corporation in Glenview, IL as a New Ventures Manager in the Business Development and Acquisitions Department. Prior to Signode, he held several positions at Exxon Chemical Co. USA, Houston, TX.

Steve was exposed to plastics at an early age. Steve's father, Randy Murrill, worked at Dupont for 39 years. They lived in Orange, TX; Parkersburg, WV; and Wilmington, DE. Randy was involved making Teflon, Delrin, and Lucite which went into such products as fishing line, brushy fibers, and glazing.

In high school, Steve belonged to Junior Achievement and was president of a company called JASAP, which was sponsored by Marbon Chemical. Named the 1967 JA Company of the Year, the venture produced and sold a unique playing card holder and score card keeper.

Steve earned his BS ChE from Purdue University where he was the editor of the *Purdue Engineer*. During college he was a summer intern with Kodak and Exxon.

After receiving his degree, Steve went to work for Exxon spending time in Houston before moving to Chicago. He then went to work for Signode Corporation originally in their palode division (plastic pallet strapping). Steve moved into Signode's New Venture Group where he first learned about of Profile Plastics.

In 1987, Steve purchased Profile Plastics from John Grundy. Profile Plastics was started in 1960 in a garage and grew to be one of the leaders in the industry, particularly with the development of pressure forming. Under Steve's ownership and direction, Profile Plastics continues to be at the forefront of thermoforming in both technology and business operations. Steve has been a long-time proponent of molded-in color and texture and has led many of Profile's customers away from injection molding or painted structural foam, especially for those products requiring large, highly cosmetic covers in low to medium volumes.

In 1995 Profile Plastics moved to a new 100,000 sq. ft. facility. In 2003 Steve bought the assets of cross-town competitor Arrem Plastics in Addison, IL and actively led the transition of hundreds of molds in the Lake Bluff facility. In 2008, Steve made another acquisition and purchased Pullman Industries of Rochester, NY, further expanding Profile's customer base and sales volume. Twenty-four years since his purchase of Profile Plastics, Steve is still deeply involved in every facet of the business – even running the weekly production meetings. Currently using 13 state-of-the-art formers and 15 state-of-the-art 5- and 6-axis CNC routers and robots, Profile continues its record sales growth through Steve's leadership.

He has been a member of SPE since 1976, served on the Thermoforming Division Board of Directors since 1987, and served as its Chairman for two years. He has been active in every annual SPE Thermoforming Conference since its inception and was the Chairman for the 1992 Thermoforming Conference held in Midland, MI. He has been a speaker, moderator and program chairman for the Thermoforming Conference and many other SPE Conferences and RETECs held by other Divisions and Sections. He received the "Lifetime Achievement Award" from the Thermoforming Division in 2001.

Steve holds strongly to the late John Griep's vision that if the thermoforming industry to grow, it must have a vehicle for the free discourse for those who work in the business. To that end, he has put much of his energy into the SPE Thermoforming Division. People who have met Steve will attest to his openness in discussing what many consider to be the "secrets" of our business. It is that willingness to share knowledge which has helped us all to grow thermoforming into the dynamic plastic process that it is today.

Thermoforming vs. Injection Molding

By Art Buckel, McConnell Company

Many thermoformers have been asked, "What advantage is there in comparing thermoforming to injection molding for my parts requirements?" If the immediate answer is, "Our molds are cheaper and quicker to build," the respondent has missed an opportunity to extol the benefits of our process.

In this article, I am going to document ten advantages and four disadvantages of thermoforming when compared to injection molding. All four disadvantages relate to part costs. I will also examine two cases of heavy gage parts development where thermoforming was preferred to injection molding.

Advantages

1. *Better physical properties in finished parts*

Let us begin by taking one of the most important and often overlooked advantages of thermoforming: residual stress in the part. When you next take a commercial flight, check your empty, clear plastic cup. If you squeeze the cup and it immediately splits, you can bet there will be an injection port stub on the bottom center. If you squeeze the cup and it collapses without breaking, and then allows you to push it back to original shape, it is thermoformed.

The difference here is the high residual stress of the injection molded part which greatly reduces the impact strength of the finished product. This is especially true in heavy gage forming. Before forming, the heated sheet is virtually stress-free. When properly formed, the sheet is almost completely stretched at the forming temperature before it is shaped and cooled against the mold. This sets up a minimum of internal stress in the finished part. Additionally, the starting resin for extrusion and blow molding will be of a lower, more viscous melt flow which generally has better physical properties than the higher melt flow (melt index) resin required by the injection molding process.

In injection molding, the melted material must flow rapidly through very restrictive mold entries and between close-set mold walls. Injection molding requires that the molten material flowing into and through the mold cavities be slowed down. The material cools faster where the material is in contact with the mold wall and slower in the center of the material flow. Thus, within a molded wall the material has been cooling and setting at various rates, setting up high internal stress.

2. *Relatively low mold costs*

Because most thermoforming is accomplished with a single surface mold, it stands to reason that the molds will be less expensive than injection molds. However, the differences in pressure requirements also contribute to lower thermoforming mold costs. Injection molds require fine steel materials for long use, with low mold wear. The best material for thermoforming is aluminum, cast or machined from block or plate. This creates a great difference in material cost as well as lower machining. The thermoforming process creates no abrasion to the mold surface so the aluminum mold works well for millions of parts.

3. *Lower cost machinery*

Generally speaking, thermoforming machines are less expensive than injection molding machines. This allows more thermoforming production with lower machinery amortization which helps thermoforming to hold down costs and be more competitive.

4. *Thermoforming allows production of very large parts*

In today's thermoforming factories it is not uncommon to see very large parts in high volume production. Parts measuring up to 14' wide and 22' long are possible in many plants in the USA. This is not even conceivable for injection molding machines.

5. *Multiple layer sheet material*

The co-extrusion process allows many layers of various materials to be produced for thermoforming, both continuous thin- and heavy-gage sheet forming. Nine to 11 layers of material are not uncommon today.

6. *Pre-decoration of sheet*

There is a vibrant packaging business today where pre-printed rolled material is used in continuous or roll-fed thermoforming. Pre-printed sheet is also used with normal patterns and with distortion printing for registration forming. Extrusion can also laminate top layers of wood grain, marble, and many other designs to be thermoformed with no further decorating of the parts required.

7. Thin walled parts of various sizes

Small packaging parts of less than .015" are thermoformed by the millions in mold set-ups of 150 to 200 parts per shot. Many larger parts such as cake covers are larger, deep draws from thin materials.

8. Thermoforming foam sheet

Foam sheet, from thin to heavy gage, is readily thermoformed. Products such as egg cartons and other food packaging, auto side panels, athletic pads, shoe sections, and industrial packaging are all in production using the thermoforming process.

9. High strength reinforced composites

Sheet thermoplastics with continuous fibers or rovings of graphite, glass, and carbon are being thermoformed today in North America and Europe. Processors are using matched aluminum molds on modern pressure forming machines and/or high pressure presses.

10. Pressure forming

High pressure thermoforming (30 to 130 psi) of thermoplastic sheets produces high quality parts with great detail on one surface. These parts have the high-resolution appearance of injection molded parts with much better quality in molded size control and physical properties.

Disadvantages

1. Cost of sheet production

Most competing processes start with resin in pellet form, and go straight to the molding of the finished part. Thermoforming must start with sheet or film. Consequently, the expense of producing the sheet or film has to be added to the price.

2. Trimming material

There is no way to thermoform parts without clamping the sheet outside of the mold and part area. Therefore, the material in the clamping area and where any apertures are required, must be trimmed away after forming leaving a part that uses only a portion of the required sheet weight. That trimmed scrap material must go into the part cost. Scrap can vary from 15% to 60% of the original sheet.

3. Trimming labor

Labor to trim the scrap and apertures from the formed part adds cost to the part.

4. Reverse side details

Because thermoforming is usually done with a single sided mold, any details required (standoffs, stiffeners, ribs, etc.) on the reverse side must be added. This additional labor increases the part cost.

Case Study 1

The front and rear fascias (bumper covers) on all new automobiles are injection molded because of lower parts cost, despite the high cost of the mold ($1-1.5MM per mold). In 1999, The Renault Automobile Company of France planned to begin assembly of some new models, in South America. However, there was limited production (9,000 per year) planned which made amortization of the molds prohibitively expensive. Because of the shape the parts could not be shipped from Europe at an acceptable cost. The parts were required to have no visible mold marks, accurate size, and a very uniform wall thickness.

Renault approached a company, well-established in thermoforming parts for the South American automobile assembly plants, and inquired about the possibility of thermoforming the fascias.

The company, Thermoform Ltd., was a long-time client of the author. They asked if it was possible to thermoform the fascia considering very large undercuts at each end. After a study of drawings and photos of the required part, I determined that it could be done. I did a basic mold design and obtained a budgetary quote of mold costs, specified the TPO material, sheet size, thickness and approximate forming and trimming time for each part. The thermoformer quoted the budgetary mold and parts costs and received a contract to prototype and prove the viability of thermoforming as an acceptable manufacturing process.

In their Bogota, Colombia plant, we built a prototype mold with moving ends to facilitate part removal from the undercuts. Remarkably good prototype parts were delivered to Renault for approval. In the final proposal, based on what we learned in the prototyping stage, Thermoform Ltd. stated that the physical properties of the production parts would exceed those of the injection molded parts being used in Europe. Renault issued a contract for mold and production parts.

The mold design was finalized and was built at Borke Mold Specialists in Hamilton, Ohio. Upon mold completion, the first parts were formed there and delivered to Renault to be shipped to their technical center in Paris for final evaluation and approval.

(continued on next page)

One of the most rewarding elements of this experience, in my opinion, was reading the approval report from Renault which stated, “Although we do not understand why, these parts have demonstrably better physical properties than our standard parts.” The success of the thermoforming process has led to additional fascia production for other auto manufacturers (including GM) in South America.

One such part won the “Best Automotive Part” award at the 2002 SPE Thermoforming Conference.

Case Study 2

I am sure that almost everyone reading this article is familiar with a famous TV advertisement run by a popular luggage manufacturer where apes are bouncing hard-sided luggage off the stone walls of a zoo compound, exhibiting the durability of the product.

A major competitor to this luggage manufacturer made a decision to use high pressure thermoforming of ABS to create a top tier line of hard side luggage. The decision was based on the higher impact strength and other physical properties of the product when thermoformed, despite the higher costs when compared to injection molding.

The molds were built by Portage Casting and Mold in Portage, Wisconsin and consisted of two halves, each undercut around the entire perimeter, fully textured, and temperature controlled. The parts met all customer requirements and went into a long and successful production. ❙

Need help with your technical school or college expenses?

If you or someone you know is working towards a career in the plastic industry, let the SPE Thermoforming Division help support those education goals.

Within this past year alone, our organization has awarded multiple scholarships! Get involved and take advantage of available support from your plastic industry!

Here is a partial list of schools and colleges whose students have benefited from the Thermoforming Division Scholarship Program:

- UMASS Lowell
- San Jose State
- Pittsburg State
- Penn State Erie
- University of Wisconsin
- Michigan State
- Ferris State
- Madison Technical College
- Clemson University
- Illinois State
- Penn College

Start by completing the application forms at www.thermoformingdivision.com or at www.4spe.com.

Thermo Forming Division

Thermoforming Index – A New Test for Sheet

By Donald Hylton, McConnell Company and Clark Atlanta University

A new test has been developed that may change the way in which extruded sheet is evaluated and graded before shipping to thermoformers. Generally a high percentage of the problems thermoformers encounters are somehow sheet related.(1) Specific causes of the problems have been difficult for them to pinpoint since the general practice is to tweak the processing parameters in an effort to make the sheet run. If tweaking fails, as a last resort the sheet supplier is consulted. The sheet supplier will make amends by replacing the shipment if they conclude that it is indeed a sheet problem. This process is costly and time consuming. In the end, a significant amount of manufacturing time, material and – most importantly – money (in the form of costs) has been lost. Unfortunately, this is the state-of-the-art in the industry. This is true for both heavy gauge and roll fed operations.

The sheet extruder depends on feedback from the thermoformer on the quality of their sheet. The thermoformer has to run the machine before he can determine sheet quality. In essence the manufacturing process has become the Quality Control Lab. Why is this case? The answer is simple. There is not a test procedure commonly used today that can determine the formability of production sheet ***before*** it is shipped to the thermoformer. This article is introducing to the industry a new test that is capable of accurately evaluating sheet formability before shipping. The test gives a result called the “Thermoformability Index” (TFI). The “Thermoformability Index” can show how well sheet will thermoform before it is shipped. This is the breakthrough.

The thermoformability index is measure of how sheet behaves in the oven and how well the sheet thermoforms. What it actually measures is the flow of the sheet (simulating sag in the oven) and resistance to sag or “hot strength” (elastic property). These properties are directly related to the material’s molecular attributes up and are indicative of behavior in the process. The test is run on a commercial instrument called a rheometer. The sample is a 1 inch (25mm) disk cut or punched from the sheet. The disk can be punched from a location that does not interfere with forming. Tests are conducted at speeds, forces and temperatures simulating thermoforming. It takes less than 30 minutes to run a test. This technology was first introduced at ANTEC 1991(2) and explained at ANTEC 1998.(3)

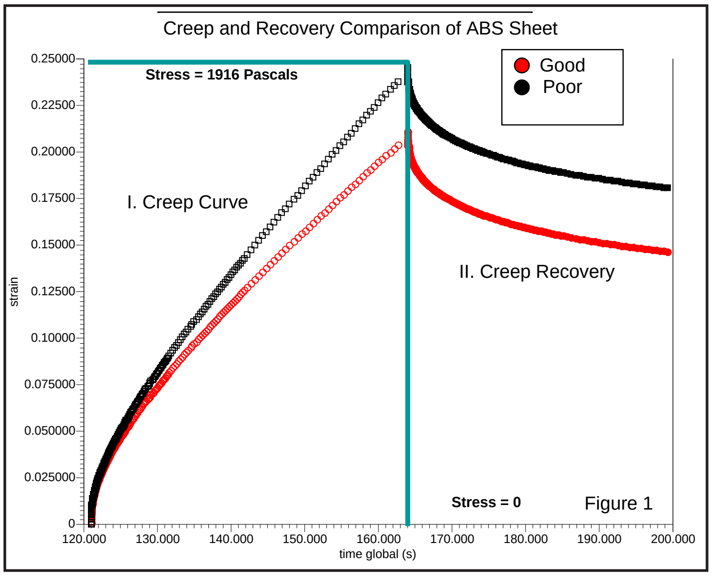
The thermoformability index, like the melt index, measures material characteristics that are related to processing behavior and molecular characteristics. The melt index is used to classify materials and can indicate how well it will extrude into sheet. The concern is that the melt index listed on data and on spec sheets is based on pellets before sheet production and is not an accurate indicator of forming behavior. The formability index has been shown through actual case histories that it can do for sheet what the melt index does for pellets.

What is the Thermoformability Index?

This test uses a science called Rheology. Rheology is the study of how materials flow. Since the thermoforming operation causes materials to flow when sagging in the oven and when the material conforms to the mold to make the final part, it makes sense that a Rheology test can be used to evaluate materials in the process.

Simplistically, the TFI is a measure of the viscoelastic properties of a material under stress, time and temperature conditions experienced in thermoforming.(4) Plastics have dual properties, viscous and elastic (viscoelasticity). These properties exist no matter the state of the material. Depending on the temperature and speed of the process one property can become dominate. In thermoforming an ideal balance of the two properties are necessary. That is, the material needs a viscous component to facilitate flow and an elastic component for self-support. These properties are directly related to the material’s make-up and are indicators of behavior in the process. The test is run on a commercial instrument called a rheometer. Tests are conducted at speeds, forces and temperatures simulating thermoforming. The force (stress) simulating gravity is applied the heated sheet sample for at least 10 seconds. During this time the sample flows or creeps. This is viscous flow. From the speed of the flow component one can calculate a viscosity.

After 10 seconds the force is instantly relieved to zero and held at zero for 30 seconds. During this period the sample will spring back and recover. This is the elastic component. The amount of "spring-back" is used to calculate a quantity called recoverable compliance. The compliance coupled with the viscosity yields a relaxation time. This relaxation time is the TFI. Figure 1 is a graphical illustration of the data. The first portion of the curve represents the creep or flow portion of the curve. The y-axis is strain or the extent the material flows while under stress. The second portion represents the period when the sample is under zero stress. As you can see the strain reduces with time. This is the recoverable portion of the curve. The calculations are as follows:



1) Viscosity = stress/slope of the strain curve (Pascal-Seconds)
2) Recoverable compliance = extent of the strain recovery/stress (1/Pascals)
3) TFI = viscosity **x** recoverable compliance (Seconds)

Typically good thermoforming materials such as forming grades of ABS, Acrylic and Polystyrene will have forming index numbers greater than 20 seconds. TFI values between 10 and 20 will thermoform but require tighter controls on material and processing conditions as the material is not as forgiving the lower the TFI becomes. Polyolefin materials such as Polypropylene and TPO may have values less than 10. In this case the material requires precise temperature and processing conditions as the forming window is very narrow. Table 1 is a comparison of the TFI for ABS, a profile extrusion grade ABS and a forming grade of TPO.

Table 1

Material	TFI (seconds)
Forming Grade ABS	23.7
Pipe Extrusion Grade ABS	15.06
Forming Grade TPO	9.12

The TFI is useful for troubleshooting production issues:

A sheet extruder shipped two lots of ABS sheet to a thermoforming customer. Both lots met all of the specifications applied to each shipment. The process was lined out and was running well with Lot number 1. When Lot number 2 was placed in the process, forming difficulties were experienced immediately. Rather than tweak the processing conditions the customer replaced lot 2 with remnants from lot 1. The forming problems disappeared indicating it was exclusively a sheet issue. The extruder had to return the lot and replace it with another shipment that it hoped would resolve the problem.

In an effort to prevent the problem from reoccurring, the extruder submitted samples to our laboratory at Clark Atlanta University for evaluation. TFI tests confirmed that the two lots were different and that they should behave differently in the process. Table 2 shows the TFI values for the two lots.

Table 2

Sample	TFI (s)	Processing Behavior
Lot 1	17.410	Good
Lot 2	14.785	Excessive Sag – Freeze lines

The sheet supplier was able to determine the cause of the differences in the lots and is now capable of producing sheet with consistent TFI values using TFI prior to shipping.

TFI is Useful for Grade Development and Competitive Analysis:

It is a common practice in industry to have more than one source for a raw material. In this case, two grades of TPO were submitted to a thermoformer for evaluation in a transportation application. Data sheets from the two grades indicated that there were no apparent differences in the grades and they should perform similarly. However,

(continued on next page)

a subsequent trial run showed that the two grades thermoformed differently. The grades evaluated for their TFI at Clark Atlanta University were found to have different TFI values. Grade A had a TFI of 9.12 while Grade B had a TFI of 8.66. The forming behavior of the two was consistent with their respective TFI's.

In this case, use of the TFI could have prevented the use of thousands of pounds of material, extrusion and thermoforming time. Data sheets usually show information from injection molded specimen and pellets before sheet production. There normally is not any relevant information on the data sheet that directly relates to thermoforming. For accuracy and usefulness the data sheet should reflect sheet physical and processing properties including TFI.

TFI and QA/QC:

Perhaps the most significant use for TFI is in Quality Control. The TFI test is a linear viscoelastic test. This means that the fundamental laws such as Newton's Law of viscosity and Hooke's Law for elasticity are obeyed:

1) Newton's Law - Viscosity = stress/strain rate
2) Hooke's Law - Modulus = stress/strain
3) Compliance = 1/modulus

As a result, the data is directly related to material attributes. The TFI is very sensitive to variations in material properties. It is a measure of the influence of molecular weight, molecular weight distribution, regrind, blend components and blend ratios on the forming behavior of materials. This is extremely important for maintaining consistency in manufacturing. Table 4 lists the TFI for a typical production run illustrating the influence of processing conditions on TFI.

Table 4. Effect of Melt Temperature

Processing Conditions	TFI
Pellets Before Processing	15.43
420 F melt	14.98
480 F melt	14.26

Reproducibility is extremely important for any Quality Control test. The TFI, because it obeys fundamental laws, is a highly reproducible test. For example 16 tests were conducted on a single sample. The average value was 15.06 with a standard deviation of +/- 0.5006 (3.3%).

Summary

A new test, the Thermoformability Index, has been developed that can effectively evaluate the thermoforming characteristics of sheet before it is shipped to the thermoformer. This represents opportunities for significant cost savings for sheet extruders and thermoformers. Below is a list of the advantages and uses of thermoformability index from actual cases.

1. Screening of thermoforming grades without the necessity of costly production trials
2. Distinguishes the differences between sheet that form differently in the process
3. Distinguishes lot-to-lot variation in sheet production
4. Shows why sheet from different vendors formed differently
5. Shows the influence of regrind on forming behavior
6. Shows the influence of heat histories on forming behavior
7. Shows the influence of blend components on forming behavior
8. It is easily adaptable as a quality control tool for sheet extrusion operation (TFI is currently in use as a QC tool)
9. Replaces lengthy and expensive thermoforming trials saving thousands of pounds of sheet
10. The test can be run on sheet without destroying the sheet. |

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Optimization of molding conditions of plug-assisted thermoformed thin containers in a high speed and volume production context

Michel Labonte and Charles Dubois, CREPEC, Ecole Polytechnique de Montreal, Montreal, Quebec, Canada

Abstract

For an industrial thermoformer, thermoforming plastic thin containers using a plug involved technological knowledge on material behavior, plug material and process variables. Technical papers on the subject exist and are well documented but not with reference to the optimization of process conditions on high speed and high volume lines. Design of Experiments (DOE) approach like the Taguchi method can be used to refine the process and to minimize rejects. In this paper, a case study on thermoforming of PET single use containers on a high output industrial machine using a single criteria based on the Taguchi method for the optimization of wall thickness distribution is discussed.

Introduction

Thermoforming studies have been conducted on different aspects of the process. Modelization simulators of the process have been developed over the years. Process conditions and plug materials in plug-assist thermoforming have been investigated [1, 2]. Dynamic characteristics of the plug using rheological model has been developed for understanding the effect of descent speed and pressure from the plug [3]. Although some studies have modeled infrared sheet-roll heating [4], none have investigated the process with regard to the period (less than 10 s) and with transparent materials. Furthermore little considerations have been given to the effect on the process of different types of heaters and the variety of heaters configurations. Considering that the typical thermoforming of single-use thin containers is done using multi-cavities molds for high outputs and cadences of less than three seconds (with or without a plug-assisted system). The Taguchi approach becomes highly relevant under these conditions because it can be used to optimize the quality of containers by fine tuning its thermoforming process through the production equipment.

This paper will present a case study of thermoforming PET single use containers with a high output industrial machine using single criteria method based on the Taguchi approach for the optimization of wall thickness distribution.

The Taguchi method

Taguchi method is a design of experiments (DOE) method. It is designed to optimize a single characteristic and to yield a set of process parameters. It has been applied to many plastics processes and products [5-7] but has never been exploited to the thermoforming transparent of thin containers at high production cadence.

Times, pressures or vacuum, temperatures, speeds and displacements are the process variables of interest. Some variables have more importance than others and some show important interdependence with others. A deep understanding of the process is essential prior to conducting the experiments in order to obtain robust results.

Originally, Genichi Taguchi presented the method for quality control purposes. It was intended to minimize the loss factor due to non-quality in products. He considered that any deviation from a nominal value target result in a lowering of quality of the product and a loss not only for the manufacturer but also for the society. Taguchi approximated the loss by a quadratic function[1] and noise factors[2] in the process, between products and from external variables. This method provides a robust combination of process variables and identifies precisely the variables that need to be closely monitored for an optimum quality and minimum deviation from target values.

There are three distinct steps in the method: preparation of the trials, realization of the trials and analysis of results. In the preparation, the characteristic (response) to be analyzed is specified. Through group discussions, the most important process variables are identified and fixed levels are determined. Then appropriate orthogonal array table is chosen and using linear or triangular graphs, variables are assigned to the right columns for the determined interactions between variables. According to the table chosen and with appropriate combination of process variables, the trials are run and results for the targeted characteristic (response) are compiled off line. Finally, results are analyzed using adapted averages calculations, classical variance analysis and signal over noise (S/N) ratios. The use of graphics

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[1] Identified as "loss function" in Taguchi's literature

[2] Borrowed from the acoustic field, Signal/Noise (S/N) ratio in db

enables a better comprehension of results. Variables are analyzed with regard to sensibility to variation or drift. An optimal combination of different variables at the appropriate level is obtained. A final trial is run using this optimal combination for validation.

The process variables for the containers

In this case, the equipment used is a continuous thermoforming machine having a combined molding and cutting area with a maximum of 48 cm X 36 cm and an oven of approximately 1.5 meters in length. The 500 ml (16 oz) container is made from roll stock of *a*PET 530 µm (21 mils) thick, including a thin barrier and a PE layer for heat sealing for an additional 50 µm (2 mils). Two aluminum molds of six cavities are mounted on the machine with swinging arms[3]. Cavities are organized as three in a row, two rows in each mold and all cavities are numbered. Molding is plug-assisted: six plugs are used simultaneously. High speed robotic stackers complete the machine. Hourly production output is more than 15 000 containers.

The main quality specifications (response) are minimum wall thickness: bottom (355 µm), sides (255 µm) and corners (225 µm).

Figure 1: The container and the specifications for wall thickness

After discussions as well as previous evaluations, it was decided that the optimization study would consider the effect of four important process variables on quality specifications. Each variable will be tested at three different levels. Selected variables and levels are listed in Table 1: oven temperature (A), forming time (B), plug lowering time (C) and plug lowering speed (D).

Table 1: Process variables and their levels

		Levels		
Process variables	**Letter**	**L1**	**L2**	**L3**
Oven temperature (ºC)	**A**	565	555	570
Forming time (s)	**B**	0.6	0.5	0.8
Plug lowering time (s)	**C**	0.11	0.06	0.16
Plug lowering speed (-)	**D**	Med	Slow	Fast

Note: Heating time of the sheet is approximately 3.25 X the cycle time according to the oven's length and the incremental advance of the sheet at each cycle.

L_9 (3^4) is the appropriate orthogonal array table to be used. This table can accommodate 4 variables at 3 different levels and require a total of nine different trials. Combination of variables for each trial is indicated in Table 2.

The nine trials were run one after the other for approximately 10 minutes of production for each trial. During each trial, four molding shoots, i.e. containers of each cavity for a total of 48 were sampled for thickness evaluation. Wall thickness of the bottom, the sides and the corners were measured for each sample. These several measurements highlight the limitation of the Taguchi method. In fact, only one criteria or specifications at the time can be evaluated for optimization [8]. The set of optimal combination of the different variables (A to D) for the bottom thickness is not necessarily the same one for other criteria like the sides and the corners thickness. In this study, only the criteria for the bottom thickness will be investigated and taken into consideration.

Table 2: Orthogonal array table L_9 (3^4) for combination of variables and levels.

Trial no.	**A**	**B**	**C**	**D**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The results for a single characteristic: the bottom thickness

The results for average bottom thickness are compiled as follow:

$$\mathrm{A}i = \left[\sum_{n=1}^{48} y_{ij} \right] \Big/ 3n \qquad (1)$$

$$\mathrm{A1} = \left[\sum y_{11} + \sum y_{12} + \sum y_{13} \right] / \, 3n \qquad (1a)$$

$$\mathrm{A1} = [315 + 320 + \ldots + 305] \,/\, (3 \times 48)$$

$$= 400\ \mu\mathrm{m} \qquad (1b)$$

Where n is sample size (4 containers x 12 cavities), y is the thickness, i is for the result y where variable at level 1, 2 or 3 and j is the trial number (1 to 9) as per orthogonal array table (see Table 2).

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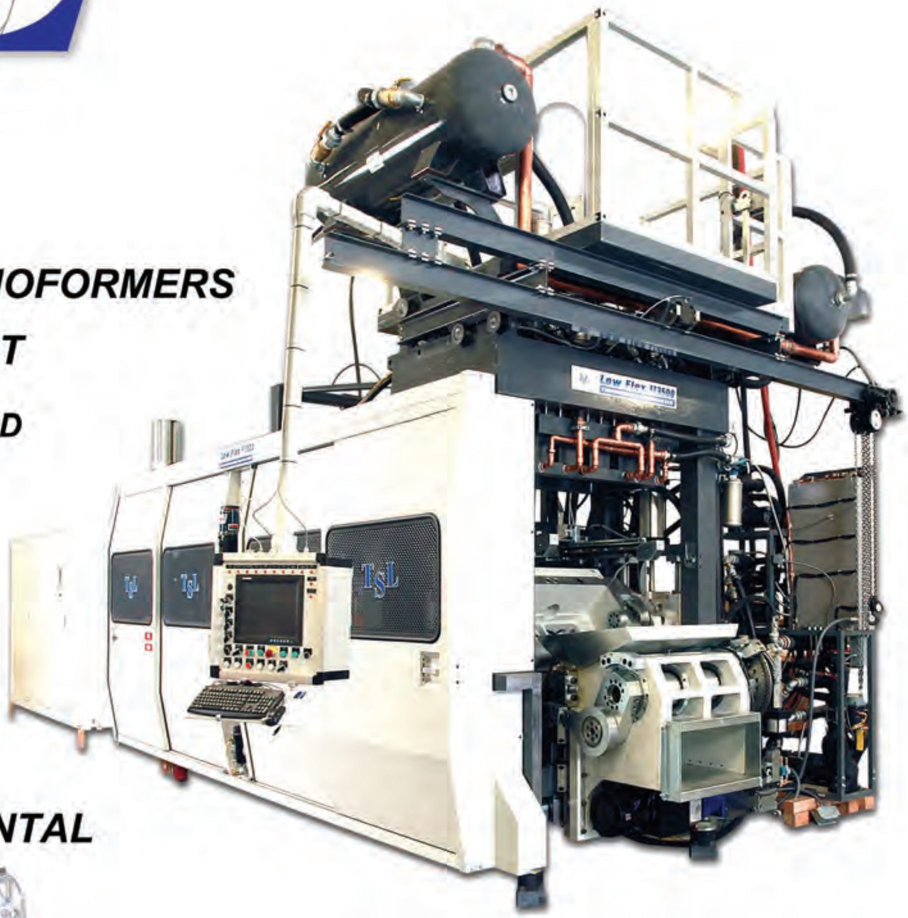
[3] Technical characteristic of this specific equipment.

(continued on page 20)



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$$Ci = \left[\sum_{n=1}^{48} y_{ij} \right] \Big/ 3n \qquad (2)$$

$$C3 = [\sum y_{33} + \sum y_{35} + \sum y_{37}] \,/\, 3n \qquad (2a)$$

$$C3 = [220 + 225 + \ldots + 305] \,/\, (3 \times 48)$$

$$= 395 \ \mu m \qquad (2b$$

The maximization of the bottom thickness (assuming corners and sides thickness are adequate[4]) is the focus of this optimization process using the Taguchi method.

Results from equations (1) and (2) are shown in Figure 2. Based on the <*maximum is the better*>, the optimum combination of variables is A1B3C2D3. This combination overcomes the requested specifications of 355 µm minimum. Oven temperature (A) and forming time (B) seems to be not sensitive for this thickness variation probably due to the short time of the heat cycle (approximately 10 sec) of the sheet's portion to be thermoformed into containers. Plug lowering speed (D) and plug lowering time (C) seem more sensitive to variation. In fact, they are the critical variables in plug actions. The plug stretches the plastic sheet to disperse more uniformly the thickness and push the material to the bottom just before being vacuumed. But this push of material to the bottom negatively affects the distribution of material to the sides and the corners.

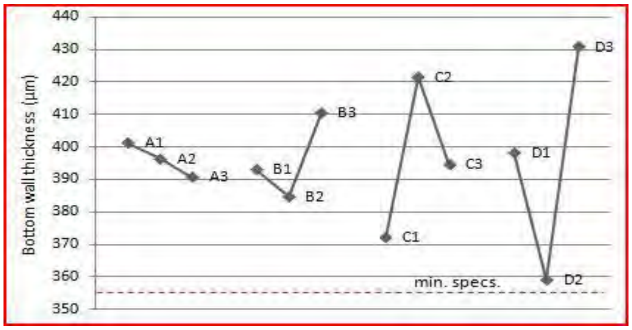

Figure 2: Results for average wall thickness at the bottom of the container.

In this compilation, the signal to noise ratio (S/N) is the value of the response signal over the variation of the signal due to noise [8, 9]. Maximization of the ratio brings minimum noise to the target characteristic. The S/N ratio derived from the loss function of <*maximum is the best*> can be used in this analysis. Usually, analysis of signal over noise ratios allows evaluation of variability of response within a trial, i.e. factors combination.

$$[S/N] = -10\, log_{10} \left[\frac{1}{r} \sum_{j=1}^{r} \frac{1}{y_{ij}^2} \right] \qquad (3)$$

Where y_{ij}^2 is the squared measured bottom thickness for each measurement, *i* is for the result *y* where variable at level 1, 2 or 3 in each trial, *j* is the trial number and *r* is number of repetitions of measurement, i.e. 4 X 12 molds.

Results from equations (3) are shown in Table 3 and in Figure 3. Note that results for S / N ratios look similar to the wall thickness. In fact, only a linear change of scale is brought by the equation (3) used in the <*maximum is the best*> situation. If situations like <*nominal is best*>, <*signed target*> or <*smaller is better*> were selected, results outcomes would have been different due to the different equation used.

Table 3: Average thickness and S/N ratio obtained on trial for bottom measurements.

Trial No.	**Bottom Thickness**				
	(µm)	**S/N**		**(µm)**	**S/N**
A1	400	23.84	**C1**	370	23.28
A2	395	23.74	**C2**	420	24.24
A3	390	23.63	**C3**	395	23.69
B1	390	23.68	**D1**	400	23.79
B2	385	23.52	**D2**	360	23.95
B3	410	24.00	**D3**	430	24.46

Note: bottom thickness measured in mils and rounded for µm equivalents. (1 mil = 0,001 inche = 25.4 µm)

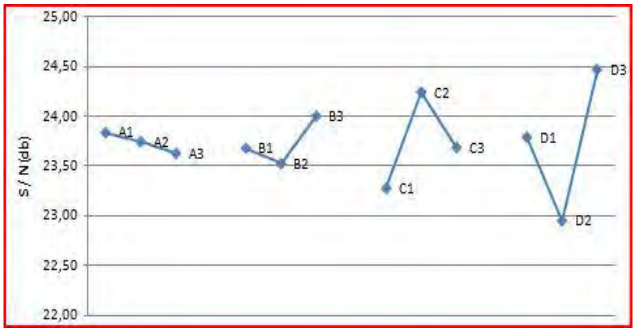

Figure 3: Results for S / N ratios for the bottom thickness.

Significant variables

In the Taguchi method, a standard analysis of variance (ANOVA) is also performed. It is either performed on the actual values or on the S / N ratios. In this case, it was done on the actual values for more significance of the results as per Figure 2. Results of the ANOVA are in Table 4. The variance ratio as noted by *F* is the ratio of the variance due to the variable and the variance of residual error. The variance is the relationship between sum of squares and the degree of freedom

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[4] See Figure 3 and Figure 4 and the section on results for other characteristics: sides and corners thickness

(DOF). The larger the *F* value is, the more important is the effect of this variable. Values of the F factor are tabulated in Table 4.

Based on results from Table 4, the relative significance of each variable is in order: the plug lowering speed (D) at *F* = 7.25, the plug lowering time (C) at *F* = 2.93 and with much less significance the forming time (B) at *F* = 0.16 and the oven temperature (A) at *F* = 0.06. For the variables chosen in this study, the plug speed down was found to be the most significant. Results also show that the faster the plug lowering speed (D3) is the more important bottom thickness becomes. The faster the plug goes lower then less time is required to stretch the plastic film thus limiting slip on the plug. Almost a linear function of the phenomena is observed between D1, D2 and D3 as per Figure 2. Unfortunately, this variable is controlled on the equipment by the aid of a pneumatic flow valve with full opening in 10 turns. Given the specifications of major pneumatic flow valves, it makes it difficult to carefully control opening and therefore the air flow to the piston for lowering plugs. Pneumatic servo valves are not as available as hydraulic ones.

Variable	DOF	Sum of squares	Vari-ance	*F*	rho %
A	2	5.30	2.66	0.08	0.32
B	2	11.53	5.77	0.16	0.69
C	2	205.45	102.67	2.93	12.24
D	2	508.61	254.31	7.25	30.30
Error	27	946.87	35.07		56.40
Total	35	1667.72			100.0

Table 4: ANOVA table for the multiple results from bottom wall thickness.

The second most relevant variable is the time the plug is in the lower position (C) prior to activation of the vacuum. Variations in the test are quite low from 0.6 s to 0.16 s, but it appears that the optimum is the lowest (C2).

The forming time (B) varies from 0.5 s to 0.8 s with a slight effect on the thickness distribution. The optimum seems to be at 0.8 s (B3). Finally the oven temperature (A) shows almost no effect on the thickness distribution, although the optimum seems to be the lowest value (A1). The optimum combination of variables for the <*maximum is the better*> is A1B3C2D3 based on the maximum bottom wall thickness; minimum specification to be at 355 µm.

The results for other characteristics: the sides and corners thickness

Although the Taguchi method is based on the optimization of only one specification or characteristic at the time, similar thickness evaluations were done for the sides and for corners of the containers. Based on <*maximum is the better*>, optimum combination for the sides is A3B2C1D2 and optimum combination for corners is A2B3C2D3. Results are shown on the Figure 4 and Figure 5.

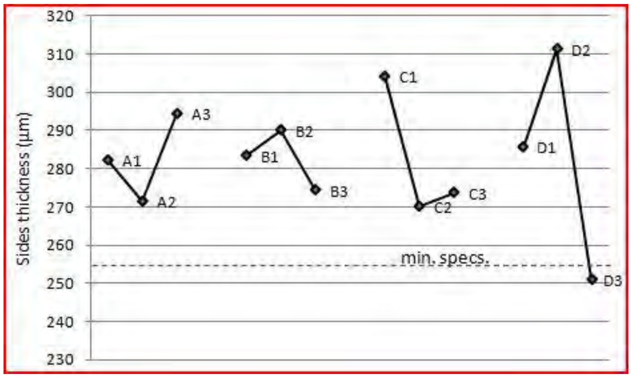

Figure 4: Results for average wall thickness at the sides of the container.

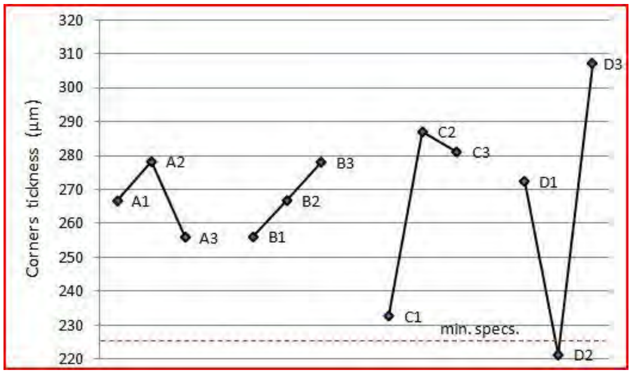

Figure 5: Results for average wall thickness at the corners of the container.

The optimum combination obtained for the bottom thickness, i.e. A1B3C2D3 seems to meet the requirements for sides and corners except for the condition D3 which miss the minimum thickness target of sides by approximately 5 µm.

Conclusions

A Taguchi method was used to refine a plug-assisted and high speed thermoforming operation and define the optimum combination of process variables for the product of interest. This method is a simple and efficient approach that can be performed on an industrial production site if needed. It required short production times, less than 90 minutes in this case, and yields a satisfactory quality process. The experiment must be well prepared. In fact, much more time is required in the planning process and in the analysis of results than in the "test itself". A well prepared test will bring relevant and useful results for technical and economic production.

(continued on next page)

Unfortunately, the Taguchi method is limited to the optimization of only one characteristic at the time. It is the Achilles' heel of the method but additional works are presently being carried out. Studies are currently investigating multi characteristics and others effects like the side and the sagging effects of high speed thermoforming of single use containers. The concept of utility, issued from economic sciences and sometimes used in sciences, will also be used in these studies to give them the appropriate weight to each of these characteristics and effects.

Acknowledgements

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Key words

Thermoforming, plug-assisted, design of experiments, Taguchi method, process optimization, wall thickness distribution.

***ANTEC 2011* / 2519**

SPE Thermoforming Division Names Art Buckel Director Emeritus

Members of the Thermoforming Board of Directors honored Art Buckel with a plaque recognizing his status as the first Director Emeritus of the Board.

This new designation was created as a way to honor those who have actively served on the Thermoforming Board of Directors and have faithfully supported the thermoforming industry. Directors emeritus will have lifetime terms and may continue to participate in all Division work. They are not required to attend Board meetings nor do they have voting responsibilities.

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From the Editor

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Thermal Radiant Absorption in Thin Semi-Transparent Plastics[1]

By Jim Throne, Dunedin, FL

Abstract

Infrared absorption characteristics of three thin semi-transparent plastics are examined, using their Fourier Transform Infrared scans. Their heating characteristics are analyzed using the transient one-dimensional lumped parameter mathematical model.

Introduction

Thermoforming is the process by which shaped parts are made by heating and stretching plastic sheet. Thin plastic sheet, being sheet 0.060 inch or 1.5 mm in thickness or less, is usually heated with radiant energy. Transparency is required for many thin-gauge parts such as rigid packaging. As noted below, most packaging plastics are semi-transparent, meaning they appear transparent in the visible wavelength range of 0.4 μm to 0.7 μm, but are semi-transparent in the far infrared region where radiant heating occurs. "Semi-Transparent" implies that, in addition to the sheet absorbing a portion of the inbound radiant energy, a portion of the energy is reflected from the sheet surface, and a portion is transmitted completely through the sheet.

In this note, the effect of plastic sheet material characteristics on the extent of radiant energy absorbed by the sheet is examined.

Radiation Concepts

Radiation input to a substance is usually written as the sum of three characteristics – absorptivity, α, being the amount of energy that is absorbed by the substance, transmissivity, τ, being the amount of energy that passes completely through the substance, and reflectivity[2], ρ, being the amount of energy that is reflected back toward the radiant source.

Author's Note: Energy input to plastic sheet is usually through a combination of radiant and convective sources. The model that is often used to predict the rate at which a specific plastic of a specific thickness heats is called the transient one-dimensional heat conduction model (7). For thick-gauge sheet (greater than 0.120 inch or 3.0 mm in thickness), the standard model assumes that the sheet is radiopaque, meaning that all the inbound energy is absorbed on the surface of the sheet. The conduction of this energy into the sheet from the surface is the controlling heat transfer factor. For thin-gauge sheet, conduction is no longer as major a factor. Instead, the ability for the sheet to absorb the inbound energy becomes significant. This series of papers focus on energy uptake of thin-gauge semitransparent sheet.

$$1 = \alpha_T + \rho_T + \tau_T \qquad (1)$$

Where the subscript T means the total amount of energy. Symbols without the subscript mean the local values of energy.

For a radiopaque plastic, transmissivity is zero [$\tau = 0$]. Reflectivity, ρ, is given in terms of the index of refraction of the substance, as:

$$\rho = \left[\frac{n_1 - n_2}{n_1 + n_2} \right]^2 \qquad (2)$$

Where n_1 is the index of refraction of the medium through which the radiant energy is passing and n_2 is the index of refraction of the substance. For common glass in air, $n_1 = 1$ and $n_2 = 1.5$. Thus about 4% of light is reflected, or $\rho \sim 0.04$. The nature of the reflected energy in a radiopaque plastic only depends on the specularity of the surface of the plastic. In this note, specularity will not be considered as a technical issue.

The mathematics for radiant heating of radiopaque solids is well-known and will not be discussed here. [1-4].

Semi-Transparent Radiation Concepts

For semi-transparent solids such as optically transparent plastics – PVC, PS, PMMA, PC, PET, and others –

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[1] This paper is in two parts. The second part will be published later.

[2] Please note that the symbol ρ is used herein for both local reflectivity and material density. These are not to be confused.

transmissivity must be considered. For the first part of the discussion that follows, transmissivity is considered to be independent of wavelength, λ. There are two general methods for including transmissivity in radiant heating mathematics.

The ray-tracing method has been used extensively to describe the effect of transmission and reflection within a semi-transparent solid [5].

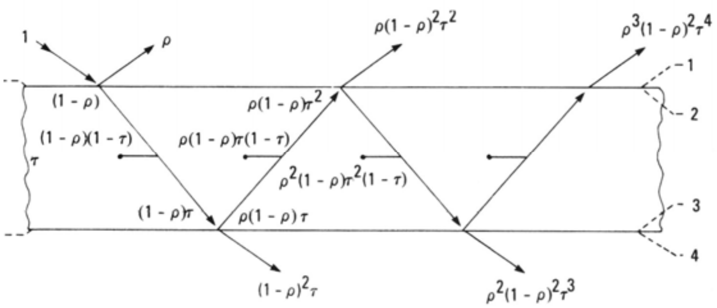


Figure 1. Ray-Tracing Method in a Semi-Transparent Solid [5, Fig. 18-2, p. 780].

Note that both inner and outer surfaces of the solid reflect radiant energy. The energy transmitted through point 1 is given as the inbound energy unit minus the reflectivity, or $\tau=1-\rho$. The amount of that energy that is absorbed by the solid is given as the one minus the transmitted energy. But the transmitted energy is given as $\tau=1-\rho$. Therefore $\alpha=\tau(1-\tau)$ or $\alpha=(1-\rho)(1-\tau)$. That portion not absorbed, $\tau(1-\rho)$, reaches the rear surface of the solid where a portion of that is reflected, viz, $\rho(1-\rho)\tau$, and the rest, $(1-\rho)(1-\rho)\tau$, passes through the rear surface to the environment.

The fraction of the unit of unit inbound energy that is reflected is simply a progressive sum of the reflective energy from each bounce off the inner surfaces of the solid:

$$\rho_T = \rho[1+(1-\rho)^2\tau^2(1+\rho^2\tau^2 + \rho^4\tau^4 + \rho^6\tau^6 + \ldots)] \quad (3a)$$

$$\rho_T = \rho\left[1+\frac{(1-\rho)^2\tau^2}{1-\rho^2\tau^2}\right] \quad (3b)$$

The fraction of the energy transmitted is the progressive sum of all the energy rays that exited through the rear surface of the solid:

$$\tau_T = \tau\left[\frac{(1-\rho)^2}{1-\rho^2\tau^2}\right] \quad (4)$$

And finally, the most important term in the heating of the semi-transparent solid, the fraction of the energy absorbed:

$$\alpha_T = 1 - \tau_T - \rho_T \quad (5a)$$

$$\alpha_T = \frac{(1-\rho)(1-\tau)}{1-\rho\tau} \quad (5b)$$

An alternate model, known as the net-radiation or heat flux model [5, pp. 780-781] yields the same results.

As an example of the relationship between these three elements, consider the air-water arithmetic given above. If $\rho = 0.04$, then

$$\alpha_T = (1-0.04)\frac{1-\tau}{1-0.04\tau} = 0.96\frac{1-\tau}{1-0.04\tau} \quad (5c)$$

If the sheet is rather thick, the fraction of energy transmitted through the sheet will be small. As a result, the fraction of energy absorbed by the sheet will be:

$$\alpha_T \cong (1-\tau) \quad (5d)$$

In other words, reflectivity for the air-water combination is essentially nil.

Radiation in Semi-Transparent Plastics

What about plastics? In Table 1 are tabulated the refractive indices of many plastics. The common semi-transparent ones are highlighted.

Table 1.
Refractive Indices of Plastics

Fluorcarbon (FEP)	1.34 -
Polytetrafluoro--Ethylene (TFE)	1.35
Chlorotrifiuoro--Ethylene (CTFE)	1.42 -
Cellulose Propionate	1.46 -
Cellulose Acetate Butyrate	1.46 - 1.49
Cellulose Acetate	1.46 - 1.50
Methylpentene Polymer	1.485 -
Ethyl Cellulose	1.47 -
Acetal Homopolymer	1.48 -
Acrylics	1.49 -
Cellulose Nitrate	1.49 - 1.51
Polypropylene (Unmodified)	1.49 -
Polyallomer	1.492 -
Polybutylene	1.50 -
Ionomers	1.51 -
Polyethylene (Low Density)	1.51
Nylons (PA) Type II	1.52 -
Acrylics Multipolymer	1.52 -
Polyethylene (Medium Density)	1.52. -
Styrene Butadiene Thermoplastic	1.52 - 1.55
Polyethylene Terephthalate (PET)	1.58
PVC (Rigid)	1.52. - 1.55
Nylons (Polyamide) Type 6/6	1.53 -
Urea Formaldehyde	1.54 - 1.58
Polyethylene (High Density)	1.54 -
Styrene Acrylonitrile Copolymer	1 .56 - 1.57
Polystyrene (Heat & Chemical)	1.57- 1.60
Polycarbonate (Unfilled)	1.586 -
Polystyrene (General Purpose)	1.59
Polysulfone	1 .633

(continued on next page)

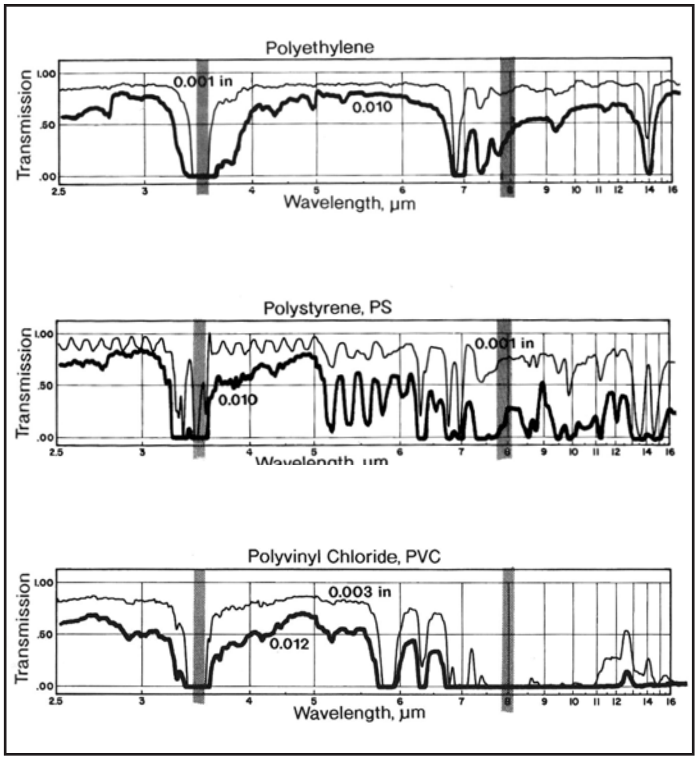
For the polymers listed in Table 1, the reflectivity range is 0.021 to 0.057. Although reflectivity is very small for plastics, it is considered in the analysis that follows.

Consider now transmissivity of semi-transparent plastics. It is generally accepted that the Beer-Lambert law holds for semi-transparent solids[3]:

$$\tau_T(\lambda)=e^{-\alpha(\lambda)l} \qquad (6)$$

Where λ is the wavelength, τ_T is the wavelength-dependent transmissivity, α is the wavelength-dependent absorption coefficient of the solid, and l is the thickness of the solid.

Radiant heating of most semi-transparent plastic solids occurs in the far infrared wavelength range of 2.5 µm to perhaps 10 µm. The primary range for thermoforming is about 2.5 µm to about 7 µm. This range corresponds to a temperature range of 350°F to about 1600°F. The Fourier Transform Infrar or FTIR device is ideal for determining the wavelength-dependnt transmissivity of semi-transparent plastic solids. Several FTIR plots are shown in Figures 2-4. Note that the wavelength-dependent transmissivity is shown for two film thicknesses.



Figures 2-4. Infrared traces for three semi-transparent plastics.

As is apparent from these plots, energy transmission, and therefore energy uptake, is highly wavelength-dependent. As an example, the plastics shown absorb 100% of inbound radiant energy in the 3.2 µm to 3.7 µm wavelength range. This is the fingerprint for all plastics having carbon-hydrogen bonds [C-H]. Certain plastics such as PVC absorb 100% of the inbound radiant energy around a wavelength of about 8 µm, as well. This is not the case for others such as PE.

As noted earlier, the arithmetic was proposed for radiant properties that are independent of wavelength. As an example, average transmissivity values are shown in Table 2 for the two thicknesses of the three plastics shown in Figures 2-4. Keep in mind that the transmissivity values represent τ_T.

Table 2.
Average Transmissivity Values (3-7 µm)

Plastic	Transmissivity for thin film	Transmissivity for thicker film
PE	~0.88 @ 0.001 in	~0.56 @ 0.010 in
PS	~0.76 @ 0.001 in	~0.35 @ 0.010 in
PVC	~0.62 @ 0.003 in	~0.44 @ 0.012 in

Average and Mean Transmissivities

Because τ and l are known, local absorption coefficient values can be calculated from equation (6). And because these values are known for the three thicknesses of these plastics, the average absorption coefficient values, (thin + thick)/2, can be considered:

Table 3.
Absorption Coefficient Values from Table 2

Plastic	Absorption Coefficient, in^{-1} for thin film	Absorption Coefficient, in^{-1} for thicker film	Mean Absorption Coefficient	Average Absorption Coefficient
PE	128	58	86	93
PS	274	105	203	190
PVC	159	68	104	114

The mean absorption coefficient values can also be determined, from (thin x thick)$^{1/2}$. Table 4 (shown on next page) compares the average transmissivity values of Table 2 with those calculated using the mean and average absorption coefficient values of Table 3.

As is apparent in Figure 5 (shown on next page), the absorption coefficient values calculated using the Beer-Lambert law, decrease with increasing sheet thickness for these three plastics. Although this effect has been observed

---

[3] Although this theory was discovered by Pierre Boughuer, it is often attributed to Johann Lambert who rediscovered it, and August Beer, who extended it to other materials, including atmospheric gases.

for essentially all plastics for which there are infrared scans, there is no apparent reason for this anomaly[4].

Transmissivity Values for Thin-Gauge Plastic Sheet

Thermoformers rarely radiantly heat plastic films of thicknesses less than 0.010 inches or 250 µm. Therefore, the transmissivity values for the thicker films of Table 3 are considered valid in further calculations. In addition, the Beer-Lambert law is assumed to be valid for all calculations for films thicker than 0.010 inches or 250 µm.

Table 5 (shown on page 26) presents calculated values for absorptivity and reflectivity for the three plastics in Table 2 for original thick films and for sheets of 0.020 inches or 0.5 mm, 0.030 inches or 0.75 mm, and 0.040 inches or 1.00 mm in thickness.

Note that even at 0.030 inch or 0.75 mm, PE and PVC still absorb only about 80% of the incident radiant energy. Figures 6 (show on page 28) and Figure 7 (shown on page 29) illustrate the effect of sheet thickness on transmissivity and absorptivity values for these three semi-transparent plastics.

Table 4.

Comparison of Table 2 Average Transmissivity Values with Mean and Average Calculated Values

Thin Film

Plastic	Table 2 value	Mean Calc'd Value	Mean Pct Error	Avg Calc'd Value	Avg Pct Error
PE	0.88	0.93	+ 5.7	0.91	+ 3.5
PS	0.76	0.82	+ 7.9	0.83	+ 8.8
PVC	0.62	0.73	+17.7	0.71	+14.6

Thick Film

Plastic	Table 2 Value	Mean Calc'd Value	Mean Pct Error	Avg Calc'd Value	Avg Pct Error
PE	0.56	0.42	-25.0	0.40	-28.6
PS	0.35	0.13	-63.0	0.15	-57.3
PVC	0.44	0.29	-34.1	0.26	-40.9

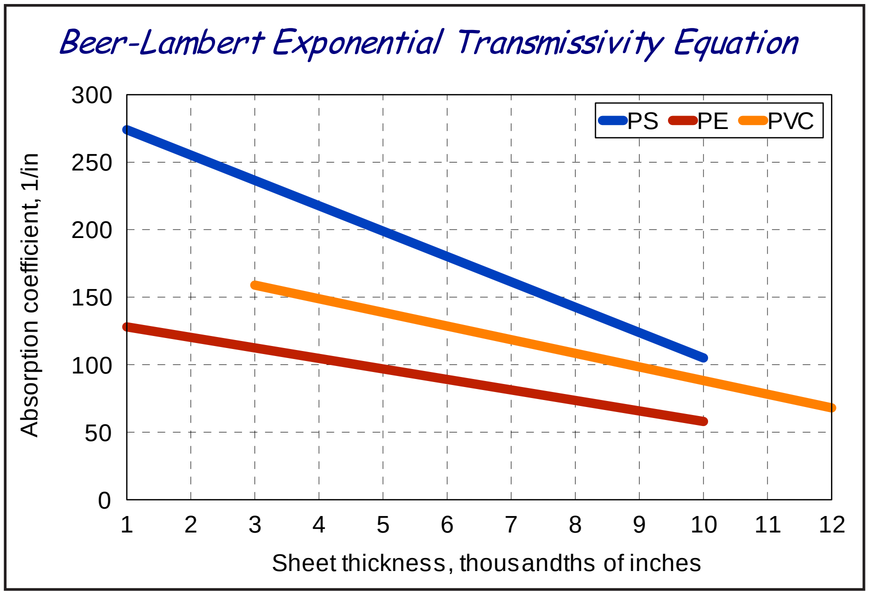


Figure 5. Calculated average absorption coefficient values for three semi-transparent plastics, noting the disparity between very thin films of 0.001 in and very thin thermoformable sheet.

---

[4] According to the literature on spectroscopy, for liquids, solutions that are not homogeneous can show deviations from the Beer-Lambert law because of the phenomenon of absorption flattening. The deviations will be most noticeable under conditions of low concentration and high absorbance. The deviations so noted tend to be minor, to a few percent, and not on the order of magnitude seen here. There seems to be no equivalent concept for plastic solids. There is also a strong indication that inclusions of different indices of refraction may act to alter the transmission of radiation through the solid (6).

(continued on next page)

Table 5.
Calculated Absorptive and Reflectivity Values

Thick Films of Table 2

Plastic	Absorption Coefficient, in^{-1}	Avg Trans. τ_T	Calc'd trans, τ	Calc'd Reflec., ρ,ρ_T		Calc'd Absorb., α_T
PE	58	0.56 @ 0.010 in	0.61	0.045	0.062	0.395
PS	105	0.34 @ 0.010 in	0.38	0.052	0.059	0.608
PVC	68	0.44 @ 0.012 in	0.48	0.047	0.057	0.513

0.020 inch (0.5 mm) thick sheet

Plastic	Avg Trans.τ_T	Calc'd trans, τ	Calc'd Reflec., ρ,ρ_T		Calc'd Absorb, α_T
PE	0.31	0.34	0.045	0.050	0.645
PS	0.12	0.136	0.052	0.053	0.828
PVC	0.26	0.283	0.047	0.050	0.693

0.030 inch (0.75 mm) thick sheet

Plastic	Avg Trans, τ_T	Calc'd trans, τ	Calc'd Reflec., ρ,ρ_T		Calc'd Absorb, α_T
PE	0.176	0.193	0.045	0.047	0.778
PS	0.043	0.048	0.052	0.052	0.905
PVC	0.130	0.143	0.047	0.048	0.822

0.040 inch (1.00 mm) thick sheet

Plastic	Avg Trans, τ_T	Calc'd trans, τ	Calc'd Reflec., ρ,ρ_T		Calc'd Absorb, α_T
PE	0.106	0.115	0.045	0.046	0.848
PS	0.015	0.017	0.052	0.052	0.933
PVC	0.066	0.073	0.047	0.047	0.887

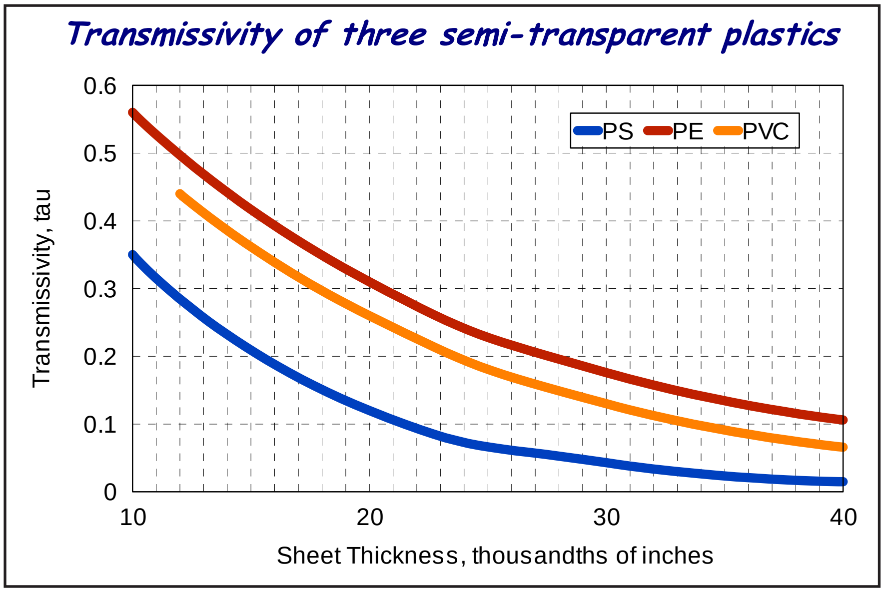


Figure 6. Thickness-dependent transmissivity values for three semi-transparent plastics (assuming Beer-Lambert values for thicker FTIR films).

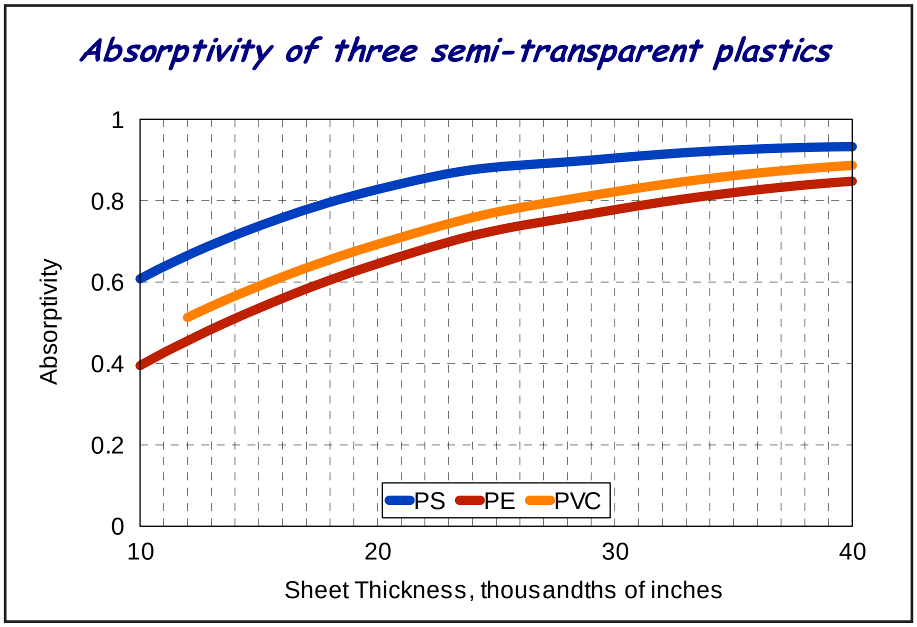


Figure 7. Thickness-dependent absorptivity values for three semi-transparent plastics (assuming Beer-Lambert values for thicker FTIR films).

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Brian is a senior at the University of Wisconsin - Stout where he is pursuing a double major in Plastics Engineering and Mechanical Engineering. He is a member of the Stout Academic Honor Society and serves as Vice President of the SPE Student Chapter at Stout.

Brian has held two internships at Scientific Molding Corporation where he was involved in many aspects of manufacturing, including the design of inspection gages, cost reduction projects, research and secondary process development. As a UW-Stout Plastics Lab Assistant, he wrote lab manuals and process sheets for newly acquired lab equipment. Brian hopes to work in the polymer medical device industry after graduation. |

MARTHA M. BRUNDAGE

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Martha is a sophomore at the University of Akron, where she is pursuing a degree in Mechanical Polymer Engineering. She received Associate degrees in Plastics Processing and Coloring of Plastics from Terra Community College, where she served as President of the SPE Student Chapter. She was also featured in television promotions for Terra and visited area high schools on recruiting trips.

After gaining three years of experience as a color development engineer, mechanical lab tester and quality assurance technician at Washington Penn Plastics Co., she chose to continue her education at the University of Akron. A motivated, dedicated student, she hopes to one day make an impact on the plastic industry. |

KEVIN W. RUDY

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Kevin is a senior at Ferris State University pursuing a double major in Plastic Engineering Technology and Rubber Engineering Technology. He served as President of the SPE Student Chapter at Ferris and Vice President of the Ferris State Rubber Group.

Kevin has held internships at Advanced Molding Solution and Trelleborg Automotive, furthering his knowledge of molding both plastics and rubber. He most recently served as a tutor for the freshman class at Ferris, assisting them on thermoforming, extrusion, blow molding and injection molding. Sharing his insights on his educational experiences at Ferris and as an intern in industry has been very rewarding to Kevin. |

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SECRETARY

Mike Sirotnak
Solar Products
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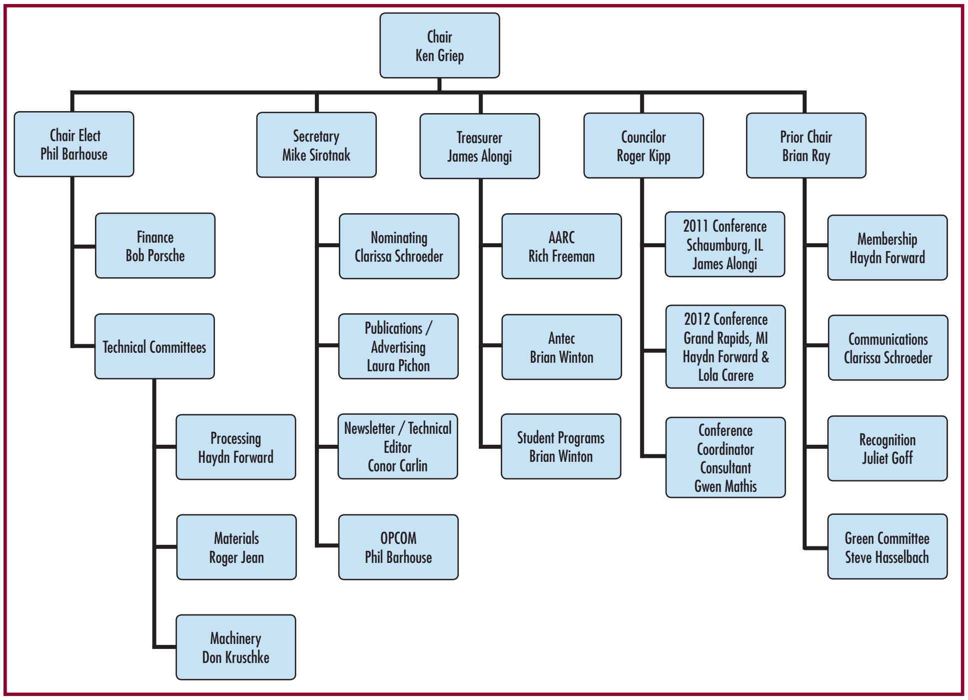

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MAAC Machinery
590 Tower Blvd.
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T: 630.665.1700
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jalongi@maacmachinery.com

Roger Fox
The Foxmor Group
373 S. Country Farm Road
Suite 202
Wheaton, IL 60187
T: 630.653.2200
F: 630.653.1474
rfox@foxmor.com

Hal Gilham
Productive Plastics, Inc.
103 West Park Drive
Mt. Laurel, NJ 08045
T: 856.778.4300
F: 856.234.3310
halg@productiveplastics.com

Don Kruschke (Chair)
TME
31875 Solon Road
Solon, OH 44139
T: 440.498.4000
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donk@allthingsthermoforming.com

Mike Sirotnak
Solar Products
228 Wanaque Avenue
Pompton Lakes, NJ 07442
T: 973.248.9370
F: 973.835.7856
msirotnak@solarproducts.com

Brian Ray
Ray Products
1700 Chablis Drive
Ontario, CA 91761
T: 909.390.9906
F: 909.390.9984
brianr@rayplastics.com

Brian Winton
Lyle Industries, Inc.
4144 W. Lyle Road
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T: 989-435-7714 x 32
F: 989-435-7250
bwinton@lyleindustries.com

MATERIALS COMMITTEE

Jim Armor
Armor & Associates
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F: 714.846.7001
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Phil Barhouse
Spartech Packaging Technologies
100 Creative Way
PO Box 128
Ripon, WI 54971
T: 920.748.1119
F: 920.748.9466
phil.barhouse@spartech.com

Lola Carere
Premier Material Concepts
100 N. Park Road, Apt. 1432
Wyomissing, PA 19610
T: 567.245.5253
lcarere@rowmark.com

Juliet Goff
Kal Plastics, Inc.
2050 East 48th Street
Vernon, CA 90058-2022
T: 323.581.6194
Juliet@kal-plastics.com

Donald Hylton
McConnell Company
646 Holyfield Highway
Fairburn, GA 30213
T: 678.772.5008
don@thermoformingmc.com

Roger P. Jean (Chair)
Rowmark/PMC
PO Box 1605
2040 Industrial Drive
Findlay, OH 45840
T: 567.208.9758
rjean@rowmark.com

Laura Pichon
Ex-Tech Plastics
PO Box 576
11413 Burlington Road
Richmond, IL 60071
T: 847.829.8124
F: 815.678.4248
lpichon@extechplastics.com

Robert G. Porsche
General Plastics
2609 West Mill Road
Milwaukee, WI 53209
T: 414-351-1000
F: 414-351-1284
bob@genplas.com

Clarissa Schroeder
Auriga Polymers
1551 Dewberry Road
Spartanburg, SC 29307
T: 864.579.5047
F: 864.579.5288
clarissa.schroeder@us.indorama.net

Eric Short
Premier Material Concepts
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Holly, Michigan 48442
T: 248.705.2830
eshort@rowmark.com

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Richard Freeman
Freetech Plastics
2211 Warm Springs Court
Fremont, CA 94539
T: 510.651.9996
F: 510.651.9917
rfree@freetechplastics.com

Ken Griep
Portage Casting & Mold
2901 Portage Road
Portage, WI 53901
T: 608.742.7137
F: 608.742.2199
ken@pcmwi.com

Steve Hasselbach
CMI Plastics
222 Pepsi Way
Ayden, NC 28416
T: 252.746.2171
F: 252.746.2172
steve@cmiplastics.com

Roger Kipp
McClarin Plastics
15 Industrial Drive
PO Box 486
Hanover, PA 17331
T: 717.637.2241
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Bret Joslyn
Joslyn Manufacturing
9400 Valley View Road
Macedonia, OH 44056
T: 330.467.8111
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Stephen Murrill
Profile Plastics
65 S. Waukegan
Lake Bluff, IL 60044
T: 847.604.5100 x29
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Dennis Northrop
Akzo Nobel
1872 Highway 5 Bypass
Lancaster, NC 29720
T: 803.287.5535
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Mark Strachan
Global Thermoforming Technologies
1550 SW 24th Avenue
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Jay Waddell
Plastics Concepts & Innovations
1127 Queensborough Road
Suite 102
Mt. Pleasant, SC 29464
T: 843.971.7833
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Art Buckel
McConnell Company
3452 Bayonne Drive
San Diego, CA 92109
T: 858.273.9620
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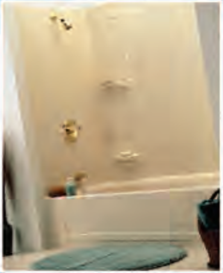

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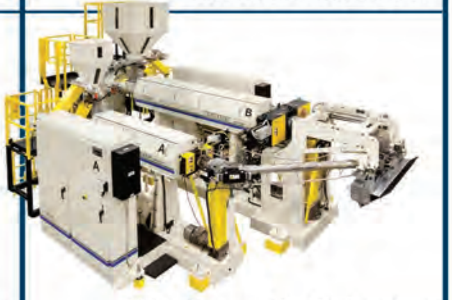

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