



## Accounting for Residual Stress in Injection Molded Parts

Erik Foltz

**Injection molding** has been the dominate process for producing complex, tight tolerance plastic parts. The plastic resin experiences aggressive conditions during the process, which is driven by the need to economically manufacture these components while maintaining the desired tolerances and surface aesthetics. From the shear deformation the polymer molecules experience as they are being melted and injected into the mold, to the rapid cooling of the resin as it comes into contact with the cold mold wall, the orientation and extension of the polymer chains change significantly from its original state. Additionally, the polymer chains cannot always get back into the state they want to be in, which leaves those areas of the part in a non-ideal condition that develops stress from molding. This stress is often referred to as residual stress or molded-in stress. The presence of these stresses is not always obvious, and has been largely ignored in the past due to

the difficulty in quantifying them. However, these stresses can be significant and can lead to performance issues for molded parts such as dimensional stability, optical distortion, cracking, and part brittleness. This article will discuss how these stresses develop and how they can be quantified.

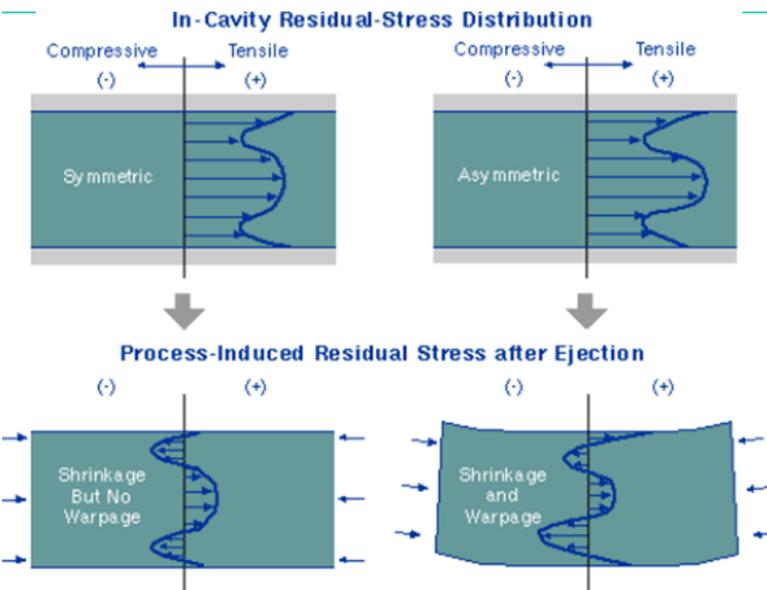


Figure 1: Schematic of Residual Stress Development in Injection Molded Part. Source: Autodesk Moldflow Design Guide.

polymer chain is frozen in this elongated state and a tensile stress is developed in the part, Figure 1. Additionally, the molten plastic continues to flow inside this frozen material, and the polymer chains immediately adjacent to this layer are also placed in a state of tension. The thickness and magnitude of this tensile stress zone are often driven by how fast the mold is filled and the mold surface temperature. These tensile stresses can be further magnified at sharp corners in the part or at core pins, where the polymer chain initially freezes upon initial contact, but then is further stretched as the material continues to flow around the feature.

### How Does the Stress Develop?

During the injection molding process, the molten resin is injected into a mold to form the part. Prior to injection, the long polymer chains are entangled and in a relatively random orientation. However, during injection these same chains are subjected to shear forces that cause them to align and stretch in the direction of flow. While this alignment and elongation have some benefits, such as reducing the viscosity of the polymer melt, it also places the polymer chains in a stressed state. Once the polymer melt touches the cold mold wall, the

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## Accounting for Residual Stress in Injection Molded Parts (Cont.)

**Erik Foltz**

**Stresses continue** to develop in the molten resin during the packing stage. The pressure that is applied during this stage, to compensate for the volumetric shrinkage of the polymer melt as it solidified, restricts the polymers ability to get the chains in their preferred orientation and develop stress. This is a particular problem near the gate, where hot material is continually being introduced into the mold and the injection pressure is highest. These conditions create the most restriction to the polymer mobility, and do not allow the polymer chains to relax into their desired state.

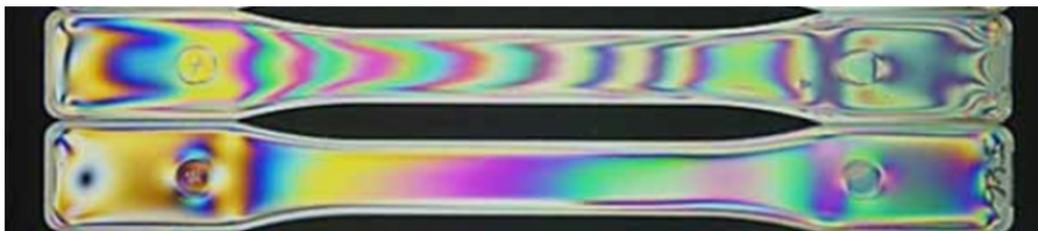
Stress can also be developed in areas remote from the gate, if they cannot be adequately packed out. If pressure cannot be maintained on the polymer melt until it has cooled sufficiently, the polymer will exhibit a greater amount of shrinkage than the surrounding area. This shrinkage gradient will cause stress to develop as the polymer chains are stretched to occupy this volume. Sometimes, there are visible cues such as warpage, sink mark formation or voids. However, other times there is no visual sign that the plastic part is under stress. Regardless of the reason for stress, if the polymer molecules cannot get into their preferred orientation during the molding cycle, they will try to relieve this stress and move into their preferred state after being ejected. If enough movement of the chains occur, cracking and crazing can occur, which can weaken the part. Additionally, these stresses take time to dissipate, and will superimpose on any operational stresses the part experiences while in service. Therefore, the impact and long-term creep performance, as well as the chemical resistance of the product can be adversely affected.

### How to Quantify the Stress?

The combination of more demanding performance criteria, longer service life, and increasing part complexity have forced part designers to better understand the magnitude and distribution of residual stress in their molded parts. Therefore, they must have a method to quantify these stresses. With the ability to quantify the residual stresses, the designer or manufacturer can optimize the part or mold design, and process to yield a better product. There are numerous methods that can be used to help provide an estimate of how much stress exists in the part. A few of these methods are presented below. While the list is not exhaustive, it provides an initial basis for the reader to understand how they might quantify the residual stress in their part.

### Photoelastic Stress Analysis (PSA)

If the component is a relatively simple geometry, and is manufactured from an amorphous resin, photoelastic stress analysis could help provide a measure of the stress present in your molded part. This method relies on measuring the birefringence of polarized light or how the velocity (speed and direction) of the light changes as it passes through the plastic specimen. This birefringence generates a color contour pattern on the part that relates to the amount of stress that exists through the cross-section of the part, **Figure 2**. Often times, this



**Figure 2 Image Highlighting the Birefringence Pattern in Polycarbonate Tensile Specimens using Photoelastic Stress Analysis.**

method is used to qualitatively evaluate the stress state in the molded part. The color generated and the spacing of the different color contours can help identify areas of high stress. While this method can provide directional input on how the residual stress

changes for the part, it cannot easily be used to quantify the stress in the part. Additionally, the color contour provides a composite stress state through the cross-section of the part and does not distinguish between

## Accounting for Residual Stress in Injection Molded Parts (Cont.)

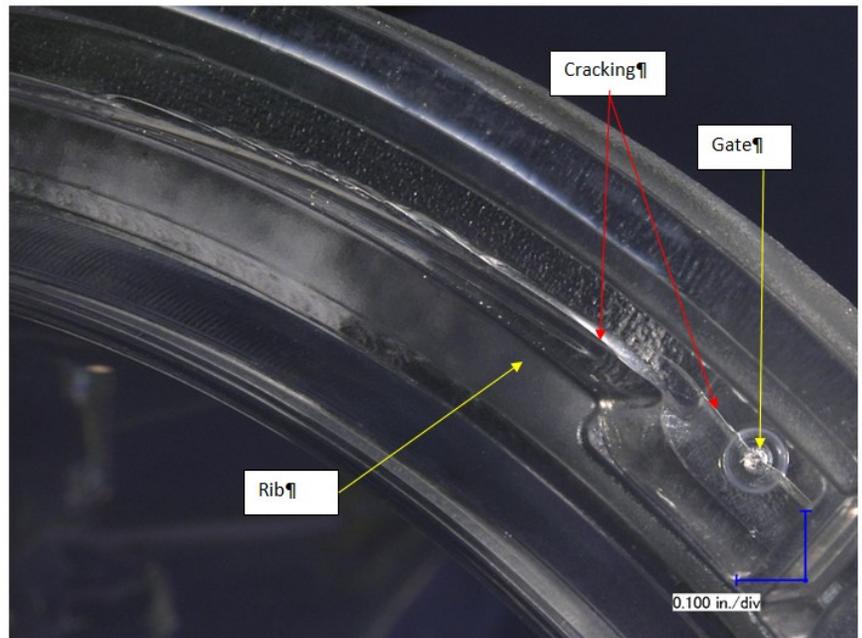
compressive or tensile stresses. This method can be used to provide more quantitative results. However, a sophisticated piece of equipment called a polarimeter is required, and material characterization is required to identify a material constant. This material constant is unique to each material and requires a non-trivial characterization procedure.

While this method can be attractive as a low cost option to qualitatively evaluate the stress state of a physical molded product, there are some limitations. As stated previously, the part geometry has to be a relatively simple, generally plate-like structure, to best use this method. While cylindrical specimens can be accommodated and analyzed, the variable entrant angle of the polarized light and the viewing angle of the specimen reduce this method to a more qualitative evaluation. The specimen must also be manufactured from a transparent material that allows light to pass through it. Therefore, this is not an effective method for filled or semi-crystalline methods. However, this method even has limitations for some amorphous resins, such as acrylic that does not exhibit this birefringence pattern even when stress is present. This can limit the usefulness of this technique to only certain resins.

### Solvent Stress Test

If the designer is more interested in the stress developed at the surface of the part, and the implications it may have on the chemical resistance of the part, an alternative may be to perform a solvent stress test. This test takes the molded specimens and submerges them into different concentrations of solvent mixtures that are known to cause surface cracking at different stress levels, **Figure 3**. The exact solvent and concentrations levels are specific to each resin. However, this test allows for more complex shapes to be tested and can help provide an indication of stresses developed at thickness transitions, ribs and bosses. It can also be an effective method at quantifying stresses near the gate of the part, and how processing may influence the localized stress in these areas.

The ability to quantify the stress state in these more complex parts, make this a nice economical method as compared to the PSA test. The limitations of this method include the fact that such a test has not been developed for every resin or polymer family, and most of the tests used are only for amorphous resins. The reason for this is that the amorphous resins are more likely to exhibit sensitivity to solvents, as compared to semi-crystalline resin. Additionally, from a practical stand point, it is easier to notice the crazing on transparent resins. Therefore, the ability to distinguish crazing at the different solvent concentrations is enhanced. Another limitation is that this method can only provide indications of the stress state at the surface of the part. It cannot directly measure the stress in the core of thick areas that may not be adequately packed out, and may be subjected to high tensile stresses.



**Figure 3: Micrograph Showing Cracking at the Gate and Base of Rib after Exposure to Solvent Stress Test.**

## Accounting for Residual Stress in Injection Molded Parts (Cont.)

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The test can be extended to polymer blends and other amorphous resins that have not been characterized. However, development of these tests require extensive knowledge of the material and specimens at known stress states. The Madison Group's knowledge and experience with this test method allows us to assist in evaluating and developing such test methods.

### Injection Molding Simulation

The previous two methods presented focused on measuring the residual stress on physically molded specimens. Additionally, the test methods have been restricted to unfilled, amorphous resins. The last method uses a proactive approach to mitigating potential areas of high residual stress by using simulation. By using injection molding simulation, the part design and injection molding process can be analyzed and optimized prior to manufacturing any mold or parts. This proactive approach can allow the designer much more freedom or to account for the high-stress state when optimizing the design. Using simulation also allows the stress at both the surface and core of the part to be analyzed, **Figure 4**. Additionally, the stress gradient through the thickness of the part can be examined. This method allows for the high-stress regions in the core of the part to be better identified and quantified. Finally, this method allows any resin part combination to be analyzed. It does not matter if the resin is transparent, semi-crystalline, filled or unfilled. As long as the material characterization properly represents the material behavior, any material can be analyzed.

The major limitation of this method is that the stresses predicted are just that, predictions. Depending on the material characterization or the level of detail included in the simulation, the actual stress values and distribution could be different than those simulated. Additionally, the predicted stresses in thick regions that are not adequately packed out will likely overestimate the stress. This overestimation is a result of the solver's inability to create breaks in the mesh where voids may actually form in the part. Even with these limitations, the use of simulation to provide an approximation of the residual stress state in the part allows engineers and designers to make better decisions regarding material selection, part design and processing.

As higher performance demands are being placed on plastic components, designers are forced to push the envelope of best part design and need to account for all potential sources of stress. Finding efficient and effective methods at characterizing the stress created during manufacturing can lead to better material selection, more robust part performance, and lower overall cost due to fewer part failures. While the lists provided here are not exhaustive, it can at least start the discussion on the need for such testing in the future during product validation.

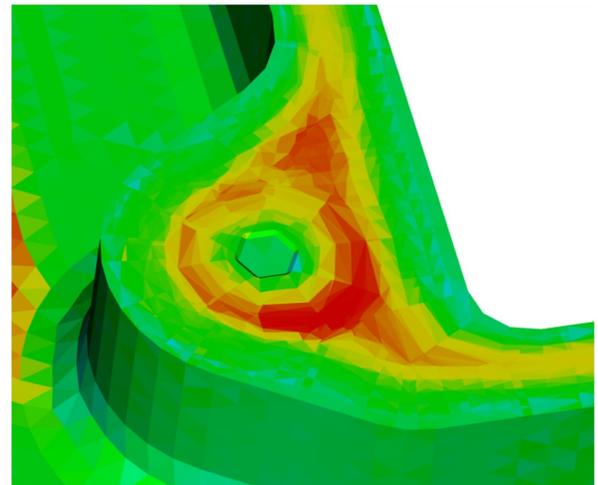
*For further reading about the importance of molding and plastic part performance select the following links, or contact Erik Foltz (Erik@madisongroup.com) or Richie Anfinsen (Richie.Anfinsen@madisongroup.com.)*

MfP: Manufacturing for Performance

[https://www.madisongroup.com/publications/Final\\_NL\\_February\\_2017.pdf](https://www.madisongroup.com/publications/Final_NL_February_2017.pdf)

Plastic Failure through Environmental Stress Cracking

<https://www.madisongroup.com/publications/jansenESC%20Article.pdf>



**Figure 4: Predicted Residual Stress Distribution Through the Thickness of an Injection-Molded Boss Using Simulation.**

## Upcoming Educational Webinar /Presentation

Webinars provide a cost-effective way to expand your knowledge of plastics. Below is a list of the upcoming webinars presented by TMG Engineers:

**Thursday, March 15, 2018** - Jeffrey A. Jansen – SpecialChem

**Time:** 11:00 am (EST)



### **DSC Interpretation Made Easy for Plastics Optimization- Webinar**

• DSC is a very powerful and versatile tool. Insufficient interpretation skills prevent you from taking advantage of the additional information (material condition, properties...) available for efficient optimization of your plastic material and prevention of premature failure. **Join this course to:**

1. Optimize your plastic material and go beyond routine characterization by better extracting, interpreting and using DSC data.
2. Wisely predict performance of your materials by linking it to changes in glass transition temperature, crystallization point, melting point.
3. Save time optimizing your plastics development by getting an expert insight to overcome calibration, sample preparation, contamination issues.

<https://polymer-additives.specialchem.com/online-course/1135-dsc-testing-polymers-plastics-characterization#whyattend>

**Monday, March 19, 2018** - Jeffrey A. Jansen - Society of Plastics Engineers - Carolinas Section

**Time:** 11:30 am – Networking Begins – Lunch/Presentation to Follow

**Polymers Center, 8900 Research Drive, Charlotte, NC**

### **March Technical Live Presentation: Preventing Plastic Part Failures**



The best way to avoid plastic part failure is to understand the most common causes of failure. This presentation will cover topics essential to understanding plastic failure, and present information regarding how and why plastics fail. By avoiding common mistakes, it is possible to produce plastic parts that have a superior chance to perform successfully.

Based on having conducted over 1,550 failure investigations, a number of the most common causes of plastic failure will be reviewed in order to illustrate this point. These include excessive sharp corners, molded-in residual stress, insufficient drying of molding resin, improper material selection, time factors, and chemical contact.

This presentation will focus on practical techniques to avoid future failures. The participants will gain a better understanding why plastic components fail, and how to avoid future failures by applying the knowledge learned.

The event will conclude no later than 2:00pm.

*Please click on the link below for additional information:*

<https://www.eiseverywhere.com/ehome/315321&t=06b78ebc4715836057d99f05b9d21d78>

## Upcoming Educational Webinars (Cont.)

**Wednesday, March 21, 2018** - Jeffrey A. Jansen – Society of Plastics Engineers

**Time:** 11:00 am (EST)

### Environmental Stress Cracking of Plastics – Webinar



If you deal with plastic components, then “Environmental Stress Cracking of Plastics” will provide you with information that will enhance your understanding of the interaction between chemicals and plastic resins, and help prevent premature failure. Environmental stress cracking (ESC) is a phenomenon in which a plastic resin undergoes premature embrittlement and subsequent cracking due to the simultaneous and synergistic action of stress and contact with a chemical agent. ESC is a leading cause of plastic component failure, and a recent study suggests that 25% of plastic part failures are related to ESC.

The webinar will be presented from a practical viewpoint with actual case studies to illustrate the ESC mechanism and explain plastic performance. Topics covered during this session include:

- Introduction to ESC
- How plastics fail
- Explanation of the ESC failure mechanism
- Generalizations related to chemical interaction with plastics
- ESC resistance testing used to evaluate plastic/chemical compatibility
- Case Illustrations of some common solvent-based failure modes

For more information contact Allan Lee [alee@4spe.org](mailto:alee@4spe.org)



**Thursday, March 29th, 2018** - Jeffrey A. Jansen – OnlyTRAININGS

### Webinar

**Polyethylene: Expert Advice on Formulation and Failure Analysis to Achieve Best Performances**

**Time:** 9:00 am (CST) / 3:00 pm (GMT) - CUT

Polyethylene resins are the largest volume plastic material used worldwide; approximately 80 million metric tons. In spite of a rather simple structure, polyethylene is a relatively diverse material used in a wide range of applications. One of the things that make polyethylene unique is the variation in structure, resulting in different classes of polyethylene, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), ultra high molecular weight polyethylene (UHMWPE), and cross-linked polyethylene (XLPE). Polyethylene is classified by a combination of crystallinity/density, chain branching, and molecular weight/melt flow rate.

The various types of polyethylene are utilized in the manufacturing of products in numerous industries:

- **Packaging:** plastic bags, film, bottles, buckets, drums, caps and closures
- **Pipe:** water, natural gas
- **Electrical:** wire insulation
- **Automotive:** fuel tanks
- **Medical:** prosthetics, packaging
- **Industrial:** conveyor systems filtration media, gaskets for recreational
- **Toys**

Part of the diversity of polyethylene is that it can be processed in many different ways, including injection molding, blow molding, extrusion, and thermoforming.

*Please click on the link below for additional information:*

<https://onlytrainings.com/Polyethylene-get-expert-advice-on-formulation-and-failure-analysis-to-achieve-best-performances>

## Upcoming Educational Webinar (Cont.)

**Thursday, April 5, 2018** - Jeffrey A. Jansen – Audio Solutionz

**Time:** 1:00 pm (EST)

### **UV Effects on Plastic Materials – Webinar**



If you work with plastic components that include outdoor exposure, then “Ultraviolet (UV) Effects on Plastic Materials” will provide you with information that will enhance your understanding of the interaction between UV radiation-based weathering and plastic resins, and help prevent premature failure. Topics covered during this session include an introduction to UV degradation and an explanation of the failure mechanism characteristic of UV radiation/plastic interaction. Case studies associated with UV radiation exposure will be presented.

The course will also include a review of the alternatives to protect plastic materials from UV degradation. These include resin additives and protective coatings.

#### **You Will Learn:**

- The mechanism of UV degradation
- The materials susceptible to and most affected by UV degradation
- The effects of UV degradation on plastic materials
- How the use of stabilizers can improve UV resistance of plastic materials
- The role and effectiveness of coatings in the protection of plastic materials
- How testing can be used to determine whether plastic materials are susceptible to UV degradation

Please click on the link below for more information:

<https://www.audiosolutionz.com/chemicals.html>

*Information regarding upcoming educational opportunities can also be found at:*

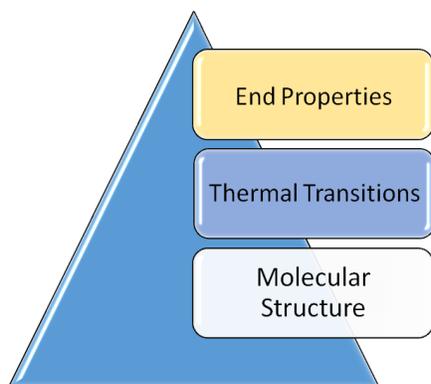
<https://www.madisongroup.com/events.html>

## Problem Solving With Thermal Analysis: Back to the Basics

*Richie Anfinson*

**For the material analyst**, some of the most powerful techniques to evaluate polymeric materials are thermal analysis techniques. Examples of these tests are thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), thermomechanical analysis (TMA), and dynamic mechanical analysis (DMA). The theory behind these testing techniques is to evaluate how the material changes as the temperature is varied. Specifically, the dependent variables in these experiments are weight change, heat flow, dimensional change, and mechanical property change. With this data, one can start to obtain a picture of the material behavior and structure.

When evaluating a problem that arises during design, manufacturing, or end use of a product, there are a seemingly endless number of testing methods used to evaluate and characterize materials. However, in the real world, limitations in sample size, budget, or timeline can affect available testing options for most projects. Unfortunately, these restrictions do not adjust the goal of the project, which is to solve the issue. In



**Figure 1 - The molecular structure is the fundamental building block that dictates how the material behaves when heated and the mechanical properties of the material.**

these cases, the power of thermal analysis becomes evident with the small sample sizes and wealth of data received. This data, when properly analyzed, can be used to investigate the “what” and the “why” of many problems typically encountered in the industry today.

As with anything, the success of analyzing the results of thermal analysis relies on a strong application and understanding of the fundamentals of polymer science/chemistry. The Webster’s dictionary definition of fundamental is an original source; serving as a basis supporting existence; or determining essential function. A more concise set of synonyms for a fundamental would be primary, central, origin, and absolute. In athletics, the fundamentals would be how you move your body in order to throw a ball, hit a pitch, or score a basket.

However, in polymer science, molecular structure is king. The molecular structure dictates the properties of a material. Thus, it is with a strong understanding of molecular structure, the fundamental, that a deep understanding of thermal analysis results is achieved.

Before moving forward let us consider the antonyms of fundamental, which are defined as secondary, consequential, or dependent. Relating to sports, examples of this could be the impact position of the golf club or baseball bat. This impact position is not fundamental in that it will vary based on how you move your body leading up to that moment in time. Thus, in order to fix your “banana slice,” you must focus on the fundamental motion of your body rather than the secondary outcomes. In polymers, the majority of the reported properties of materials are a consequence of the micro-structure of the material. In thermal analysis, the temperature at which numerous different transitions/material changes occur has been tested and catalogued for many known polymers. Examples of these properties would be glass transition, melting temperature, melting enthalpy, decomposition temperature/onset, along with many others. However, when you consider all of these properties you see that these are not absolute, but instead are a consequence of the fundamental structure of the material, **Figure 1**.

Let us consider a single property, glass transition, to understand how this phenomenon applies to the chemical structure. The glass transition temperature is extremely important to both the short-term and the long-term material properties of a polymer. In short, the glass transition is the temperature at which localized molecular freedom of motion is attained. Below the glass transition, the polymer molecular motion is limited

## Problem Solving With Thermal Analysis: Back to the Basics (Cont.)

*Richie Anfinsen*

and thus, the material behaves in a brittle, glassy manner. However, above the glass transition the material has freedom of motion at a local level, which makes the material behave in a rubbery manner. A classical example of these property differences is a racquet ball. At room temperature, the ball will bounce due to the rubbery state of the polymer molecules. However, if the ball is submerged in liquid nitrogen (brought below glass transition) and thrown at the ground, it will shatter.

Factors that will affect the glass transition, from a purely polymeric standpoint, would be the types of bonds (stiffer backbone increases  $T_g$ ), types of side groups (larger molecules increase  $T_g$ ), molecular interaction (polarity and length of chains), and other polymer factors like branching or cross-linking. Having this basic knowledge can help significantly in understanding the thermal transitions observed in the thermal analysis.

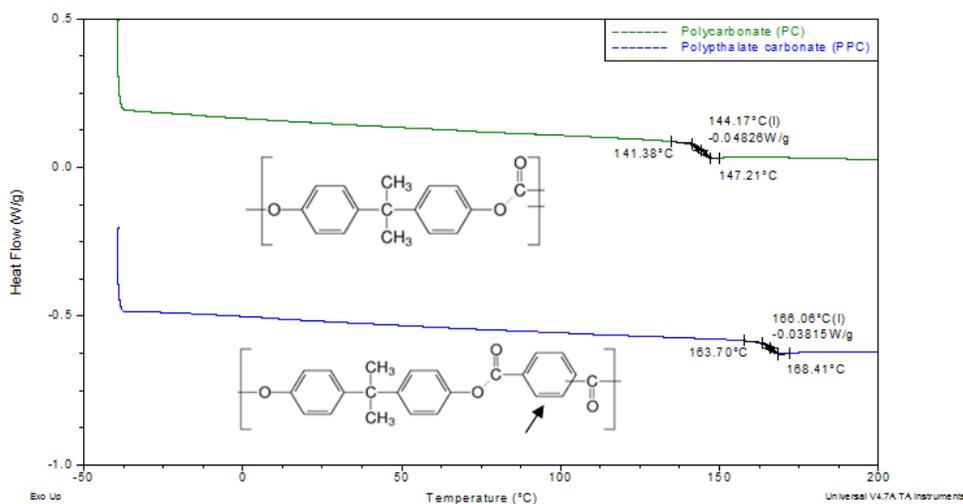
Further, this information will help to piece together why a material shows variations in the thermal transitions. Take for example the difference in glass transition of approximately 20 °C between polycarbonate and poly(phthalate carbonate). The difference in backbone structure includes an additional ring structure that increases the backbone stiffness, **Figure 2**. This difference, in part, results in an increase in the glass transition temperature of the material.

Understanding the fundamentals of what affects

the physical and thermal properties of a polymer requires “dipping your toes” in the world of polymer chemistry. This can be a daunting and terrifying task, at first. However, having knowledge of the basics is an extremely powerful problem solving tool. Like having solid fundamentals in sports, it gives you something to fall back on in order to fix the issues that are being observed on the back end. This bottom-up approach is powerful to solve the most difficult problems we face as we can get to the heart of the matter and work our way up from there.

In order to truly understand the “why” in a problem solving situation, it is important to convert the “secondary” symptoms of the issue to the fundamental. Unfortunately, the problems that arise in the industry are almost always manifested as symptoms. We see failures that occur because the material does not have the correct stiffness, the strength was too low, it cracked over time, etc. It is the job of the problem solver to take a step back and convert the symptoms into the fundamental issues at hand. This technique ensures that you are not just treating the symptoms of the problem, but rather, attacking the underlying cause.

*For more information, please feel free to contact Richie Anfinsen at [Richie.Anfinsen@madisongroup.com](mailto:Richie.Anfinsen@madisongroup.com).*



**Figure 2 – Comparison of DSC thermograms for two polycarbonate-based materials showing how the backbone structure can affect the glass transition.**

## ANTEC Orlando—The Relationship Between Structure and Thermal and Mechanical Properties of Thermoplastic Polyester Materials



**Monday, May 7, 2018**

**Live Presentation at ANTEC Orlando 2018**

**The Plastics Technology Conference**

**Time: 5:00 pm (EST)**

**Session M12**

### **The Relationship Between Structure and Thermal and Mechanical Properties of Thermoplastic Polyester Materials**

**Given By: Engineering Properties and Structure**

**Session: M12: Innovations in Packaging and Plastics**

**When: Monday, May 7, 2018      ANTEC Session: M12      Time: 5:00 pm (EST)**

Three different thermoplastic polyester materials were evaluated to investigate the connection between the structure of the materials and their properties. Three materials representing distinct characteristic structures were selected to contrast the results. The resins evaluated included polycarbonate, with carbonate ester functionality; poly(ethylene -co- 1,4-cyclohexanedimethylene terephthalate), a poly(ethylene terephthalate) copolymer; and poly(ethylene naphthalate), with two condensed aromatic rings. The characteristics tested as part of this work included tensile properties to illustrate the short-term mechanical attributes, glass transition temperatures to represent the thermal response of the materials, and creep modulus to demonstrate the time dependency.

**Click on the link below for more information:**

<https://www.eiseverywhere.com/ehome/252707>

