TMG News – March, 2012

Welcome to TMG News

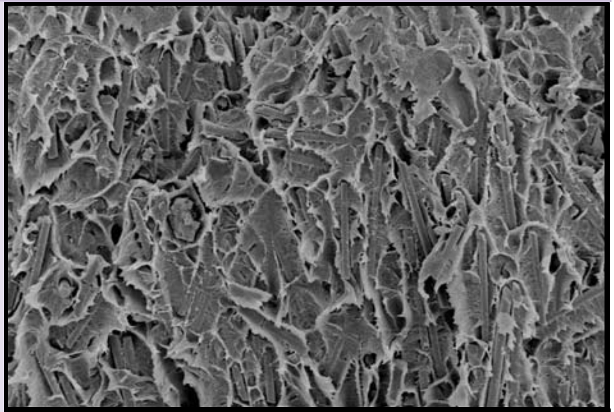
Welcome to TMG News, the newsletter brought to you by The Madison Group. This is a quarterly newsletter that contains plastics-related articles and information regarding educational opportunities. We enjoy working with our clients to help them solve their plastics problems. However, we also believe that it is our responsibility to help educate our clients as well.

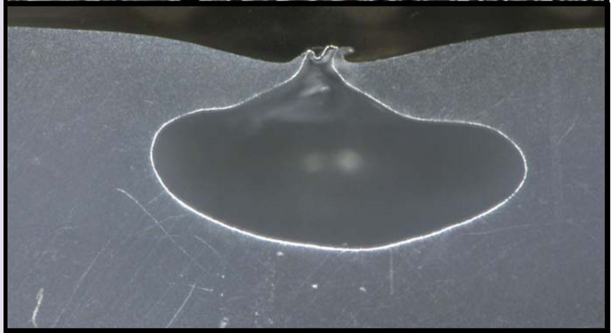
Plastic part performance is dependent on five factors: design, material, fabrication, installation, and service conditions. Parameters of these factors act collectively, contributing to the functionality of the plastic part application. This issue of the newsletter features articles that address different aspects of these factors. The first article covers creep rupture, a leading mechanism of plastic failure. The second article focuses on the optimization of both the plastic injection molding process and molded part quality through cooling, in an attempt to find the balance between economic part production and achieving the needed level of quality.

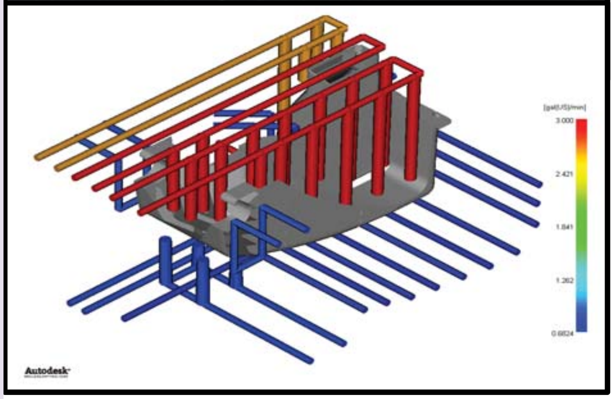
I hope that you find this issue interesting and helpful. I also encourage you to contact me if you have ideas for future issues.

Jeff Jansen

If you do not wish to receive TMG News you can opt out by contacting me at jeff@madisongroup.com.







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Creep Failure of Plastics

Jeffrey A. Jansen

Introduction

Creep is the tendency of a polymeric material to deform permanently under the influence of constant stress, as applied through tensile, compressive, shear, or flexural loading. It occurs as a function of time through extended exposure to levels of stress that are below the yield strength of the material. Creep rupture is the failure within a material as a result of continuously applied stress at a level below the tensile strength. Plastic materials are particularly prone to creep rupture through exposure to static stresses, and a recent study indicates that 22% of plastic failures are associated with creep[1]. Stress relaxation is a phenomenon that is analogous to creep, in which a time-dependent decrease in stress is observed under sustained constant strain.

The relatively high frequency of creep failure is linked to the widespread lack of awareness and understanding of the effects of time on polymeric materials, particularly at the design stage; the unique difference in time dependence between polymeric materials and metals; and the increasing use of plastic materials in diverse applications with longer time demands.

Viscoelastic Mechanism

The disparity in time-dependent properties between polymeric materials and metals is a direct result of the difference in the molecular structure of these two materials. Metals exhibit ionic bonding; while polymeric materials are held together by a combination of covalent bonds forming the polymer structure, and intermolecular forces bonding individual polymer chains. This type of bonding, together with the relatively large molecular weight of polymeric materials, produces both viscous and elastic responses. The viscoelasticity of polymeric materials is often represented using mechanical components, such as springs representing the elastic or restorative properties, and dashpots representing the viscous or damping characteristics. One such model, the Standard Linear Solid (SLS) Model, includes these components in series and in parallel, as illustrated in Figure 1. The SLS is the simplest model that predicts both creep and stress relaxation phenomena. Although this model can be used to generally predict the behavior of the strain-versus-time creep curve, for instantaneously applied loads and static loads over a prolonged period, the model lacks the ability to accurately model material systems numerically.

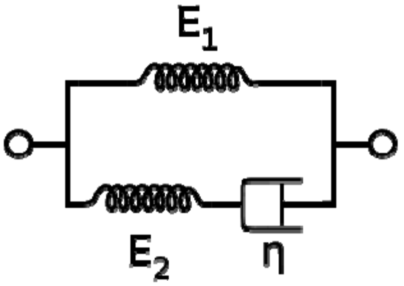

Figure 1 – The spring and dashpot SLS model is shown.

The viscoelastic nature of polymeric materials results in inherent time dependency, such that low to moderate forces exerted on a plastic component over an extended period of time reduce the inherent ductility of the material. This often results in brittle fracture within normally ductile plastics. A key aspect of this time-dependent behavior is that prolonged static stresses lead to a decay in the apparent modulus through localized molecular reorganization of the polymer chains. At stresses below the yield point, molecular reorganization includes disentanglement preferentially, as there is no opportunity for yielding.

When a polymeric material is exposed to constant stress, a continual change is observed in the form of an increasing level of strain, known as creep. Initially, the observed strain will be a function of the modulus of the material. If the stress is continuously applied, the strain will continually increase. Given the relationship between stress, strain, and modulus, as defined by Hooke's Law,

$$E = \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{\sigma}{\varepsilon}$$

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[1] "Failure of Plastics and Rubber Products" by David Wright.

the calculated modulus at a period later in time will appear to have decreased. However, the stiffness of the material is not actually decreasing. The apparent modulus representing the apparent stiffness of the material is a mathematical construct for describing the effect of the constant stress on the plastic material and corresponding increase in strain over time. This response, the decrease in apparent modulus over time, is similar to the response exhibited by material as a function of increasing temperature. Thus, time and temperature act on polymeric materials in the same way. Figure 2 compares the analogous effects of time and temperature on a poly(butylene terephthalate) (PBT) resin.

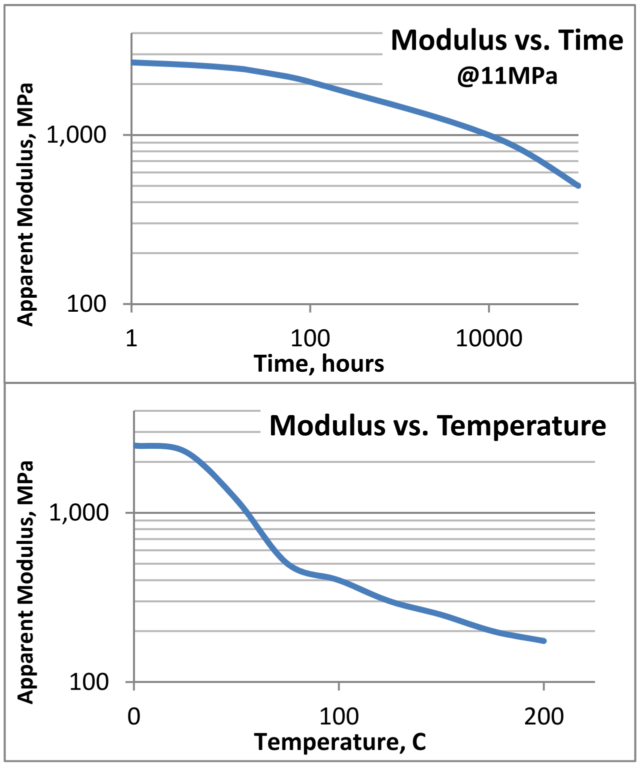

Figure 2 – The equivalency of time and temperature on the modulus of a PBT resin is shown.

Failure

Cracking associated with creep rupture failure occurs as a stress relief mechanism. The brittle fracture mechanism occurs as a localized molecular response where disentanglement is favored over yielding. As with other types of plastic cracking, the covalent polymer backbone bonds are not broken. Instead, failure occurs through a molecular disentanglement mechanism, in which polymer chains slide past one another. The stress on the material, both internal and externally applied, overcomes the intermolecular forces, such as hydrogen bonding and Van der Waal's forces.

The absolute ranking of plastics by type for creep resistance is confounded because of the complex and interrelated nature of the mechanism. The key factors that affect creep and the corresponding apparent embrittlement process within plastics include:

- Material formulation, including the base polymer and additives;
- Temperature;
- Stress concentration;
- Stress type and magnitude;
- Environment.

In spite of the complexities, some generalizations regarding creep and creep rupture, are possible:

- Plastic resins that are impact-modified or contain rubber-like constituents generally offer poor creep resistance.
- Thermoset resins undergo a very low level of creep, if any.
- Elevated temperature results in an increase in the level and rate of creep.
- Features within a molded part that act as stress concentrators will increase the susceptibility of the part to creep failure. Such stress concentrators include sharp corners and notches, molded-in stress, and poorly fused knit lines.
- Chemical exposure and cyclic stresses will accelerate the failure as environmental stress cracking (ESC) and dynamic fatigue, respectively.

A key element in creep failure is the stress level. Modest levels of stress applied over long periods of time induce crazes and cracks within plastics. This is the underlying cause of the long-term transition from ductile-to-brittle behavior within ductile plastics. At relatively high stress levels failure occurs over a relatively short period of time and is generally ductile in nature. Contrastingly, at low stress levels, failure occurs after a substantially longer period of time, generally through brittle fracture. Thus, static stress applied over a period of time acts as a ductile to brittle transition, as illustrated in Figure 3[2].

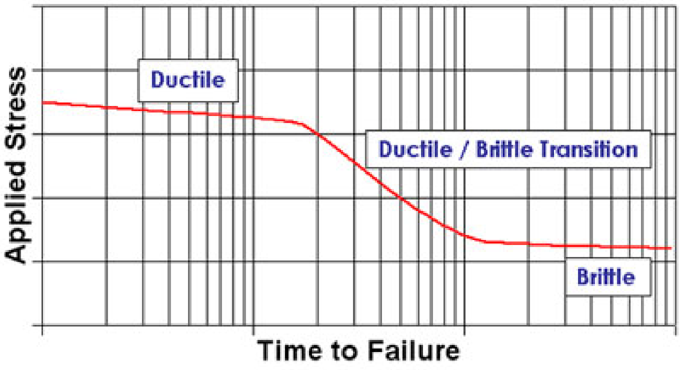

Figure 3 – Graphic illustration of the ductile-to-brittle transition associated with the exertion of constant stress over a period of time.

Creep Testing

Avoiding creep failure begins with a thorough understanding of the concept of time-dependent behavior of plastic materials and requires comprehensive knowledge regarding the service conditions, and insight into the properties of the material being used. Characterizing the creep properties of a plastic material can be accomplished through two different testing programs. The first is the traditional means to assess creep performance, ASTM D2990 - Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics. This method involves hanging weights from test specimens under various controlled conditions of temperature and stress with mechanical testers known as creep stands. Sample deflection is evaluated over time and the time to creep rupture is measured. This allows projections to be made over time. Such experiments are often conducted over 10,000 hours. The second creep assessment method is based on dynamic mechanical analysis (DMA) in combination with time-temperature superposition (TTS). A series of short-term isothermal analyses are conducted, and the testing process generates a master creep curve which shows the apparent modulus of the material over an extended period of time at the temperature of interest. After all of the runs are completed, the reference temperature is selected, which is typically the temperature at which the plastic will be used in service. The master curve is then generated with the data for the temperature of interest and from this - strain over time at a specified load - can be calculated. Based upon this information and data from additional mechanical testing, the time to failure can be projected. The time required for each test takes minutes and a thorough characterization of a material can be completed within a week, not months.

If you would like more information regarding creep, failure analysis, or materials characterization please contact The Madison Group at 608-231-1907, or email at jeff@madisongroup.com.

For further information regarding creep read these papers authored by the staff at The Madison Group.

"Lifetime Prediction of Plastic Parts - Case Studies" authored by Paul J. Gramann, Ph.D., Javier Cruz, Ph.D., and Jeffrey A. Jansen, M.S. published and presented at the Society of Plastics Engineers Annual Technical Conference (ANTEC) 2012. **http://www.madisongroup.com/publications/ANTEC_2012_Lifetime_Prediction.pdf**

"Ductile–to-Brittle Transition of Plastic Materials I and II" authored by Jeffrey A. Jansen published in *Advanced Materials and Processes*, ASM International, February 2006, pg. 39-42 and February 2007, pg. 25-27 **http://www.madisongroup.com/publications/Janse_ASM_Ductile_to_Brittl_Combined.pdf**

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[2] http://www.rapra.net/consultancy/enviromental-testing-enviromental-stress-cracking.asp

TMG Tidbits

Failure Analysis and Prevention - Plastic Parts Seminar

The Madison Group together with the University of Wisconsin - Stout will be offering a seminar entitled "Failure Analysis and Prevention - Plastic Parts." The course will introduce the attendees to the concept of plastic failure and the analytical approach to evaluate failures. The performance of plastic materials can be linked to five factors: material, design, fabrication, installation, and service. The presentation will review these factors, with a particular emphasis on molding, and explain how they relate to failure. The critical concept of *ductile-to-brittle transition* will also be covered. The attendees will come away with a better appreciation of the factors that are responsible for brittle fracture in a normally ductile plastic material. Additionally, the presentation will highlight how structural and processing simulation can be incorporated at any stage of the design process to help prevent or resolve any quality or performance issues. The seminar will highlight key issues with plastics and plastic part design and show how these concepts were used to solve real-life problems.

Location:	University of Wisconsin – Stout; Menomonie, Wisconsin
Date:	Tuesday, May 15, 2012
Time:	9:00 to 12:30 Presentation 12:30 to 1:30 Tour of UW-Stout Plastics Lab
Cost:	Free of charge

The seminar is being presented as an educational outreach between The Madison Group and the UW-Stout SPE Student Chapter. To register or obtain more information contact Jeff Jansen of The Madison Group at 608-231-1907 or jeff@madisongroup.com.

The Madison Group will be Presenting at SPE ANTEC 2012

The Madison Group will be presenting the paper "Lifetime Prediction of Plastic Parts – Case Studies" at the Society of Plastics Engineers Annual Technical Conference (ANTEC), which will be held April 2 – 4 in Orlando, Florida. This paper, coauthored by Paul J. Gramann, Javier Cruz, and Jeffrey A. Jansen, will be presented at 9:00AM on Tuesday, April 3, and will review techniques that can be used to give an understanding on how long a plastic will perform over time. The presentation will include projects that The Madison Group conducted in which life time prediction techniques were used to help understand why the parts were failing and give guidance on correcting the problem. The abstract of the paper:

"Lifetime prediction of plastics is a very difficult proposition, but one that is becoming increasingly important as plastics are used in more demanding and critical applications. The lifetime of a plastic part is influenced greatly by many factors including the type of plastic, stress level, temperature, type of loading, and environmental conditions. All these factors make absolute lifetime prediction a nearly impossible task. However, by understanding how these factors influence plastics over time, one can begin to make educated predictions with some level of accuracy. This paper will discuss techniques that can be used to predict the lifetime of a part. Case studies are given that show the application of lifetime prediction of two industrial applications."

To access a copy of the paper
http://www.madisongroup.com/publications/ANTEC_2012_Lifetime_Prediction.pdf

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The Importance of Cooling on the Injection Molding Process

Erik Foltz

Examining the injection molding process reveals that the majority of the cycle time is dedicated to cooling the part. Often accounting for two-thirds of the overall cycle time, the cooling stage of the process can have a significant influence on part quality. Additionally, it is the most beneficial stage to optimize and improve to reduce the cycle time. Yet, often the cooling layout is one of the last aspects of the mold design to be addressed. Cooling must be designed around mold functionality (slides, lifters, ejection system) and must not compromise the structural integrity of the mold. Simulating the cooling stage can help the designer understand what is happening inside the mold and determine how and if the mold design can be improved.

An injection mold is essentially a heat exchanger. The molten plastic introduces heat into the mold and the coolant extracts the heat out of the mold. The rate at which this heat can be extracted out of the plastic part is dependent several on factors - the plastic resin used, part geometry, mold material, cooling line placement and coolant conditions. These different factors need to be considered collectively in order to understand how to best cool the part and reach an acceptable cycle time.

The goal when designing a cooling layout is to cool the part as uniformly as possible. Most mold designers try and achieve this by concentrating cooling circuits in high-heat load areas, and reducing the number of circuits in low-heat load areas. Mold designers will also incorporate high conductivity inserts in areas where they may feel they cannot get adequate cooling. Table 1 shows that alloys and metals such as Beryllium Copper or Aluminum have a much higher thermal conductivity than traditional tool steels. Using these higher conductivity steels can help maintain a lower mold temperature without requiring concentrated cooling lines. However, drilling cooling lines and incorporating high conductivity inserts costs money. A balance between part performance, optimal cooling, and cost must be obtained. Simulating the cooling stage and entire injection molding process can allow the mold designer to see how a design will perform and how it will influence the dimensional stability of the part.

Table 1

Mold Material Thermal Conductivity	
Metal	Thermal Conductivity
P-20	16.7 Btu/ft*h*F
H-13	17.0 Btu/ft*h*F
A-2	24.2 Btu/ft*h*F
S-7	14.0 Btu/ft*h*F
BeCu (40HRC)	59.9 Btu/ft*h*F
BeCu (30HRC)	74.9 Btu/ft*h*F
Aluminum	109.8 Btu/ft*h*F

How Can Simulation Help?

Once the initial mold design and cooling layout have been established it is important to maximize the heat transfer between the part and the mold. With all other parameters fixed, the most important factor in determining how much heat can be extracted by the coolant is the flow rate through the cooling circuits, Figure 1. In order to maximize this heat transfer the flow rate must be turbulent. Engineers use a dimensionless number called Reynolds number (Re), Eq 1, to help them determine when the flow has transitioned from the laminar regime to the turbulent regime. The Reynolds number is directly proportional to the flow rate, V_{avg}, and density of the coolant, $\rho_{coolant}$, and is inversely proportional to the viscosity of the coolant, υ. If the coolant used and the diameter of the cooling channel, D, are fixed, the only way to increase the Reynolds number and ensure turbulent flow is to increase the flow rate.

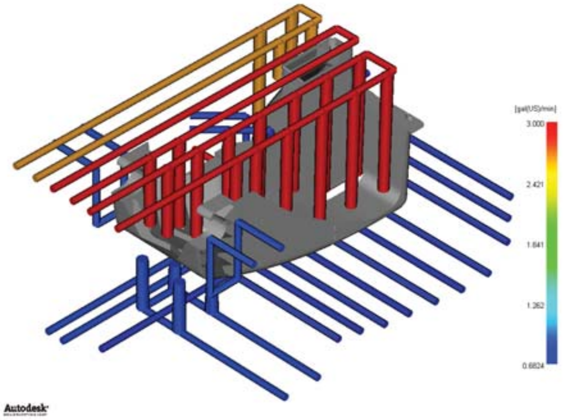


Figure 1: Simulation can help determine the required flow rate to achieve turbulent flow through the cooling circuits.

$$Re = \rho_{coolant} \frac{D * V_{avg}}{\upsilon} \qquad \text{Eq 1.}$$

So what is restricting a molder from simply pushing as much coolant through a mold as possible? The answer is pressure. As the flow rate increases for a cooling circuit, the pressure required to maintain that flow rate also increases, and this requires greater pumping power. Once the flow has become turbulent, increasing the flow rate further provides diminishing returns in heat extraction while increasing the pumping power substantially. This extra energy consumption can reduce profit margins, while providing minimal benefit. Therefore, flow rate and pressure need to be considered together to help determine the optimal coolant conditions.

Even with an optimized cooling layout and mold construction, the geometry and material of the part may not allow for the desired cycle time to be achieved. From basic injection molding theory we know that the cycle time is directly proportional to the square of the part thickness, t_{part}, and is inversely proportional to the thermal diffusivity of the resin, ρ, Eq 2.

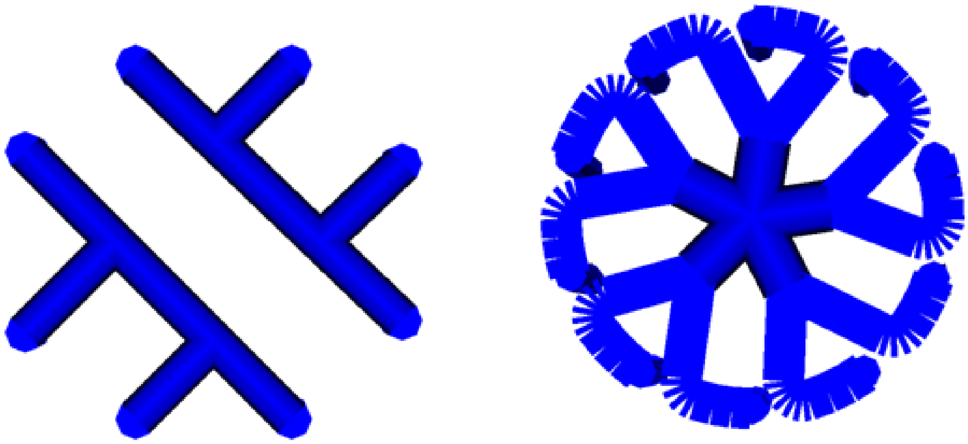
$$t_{Cooling} \propto \frac{{t_{part}}^2}{\rho} \qquad \text{Eq 2.}$$

This means that if the wall thickness of the part is doubled, the expected cycle time would be quadrupled. This also means that the polymer chosen can influence the cycle time. While cycle time is not a high priority when deciding what material is best for the application, there are often several resins that meet the performance requirements. Additives such as talc, glass fibers, or carbon fiber can influence thermal properties of the base resin and allow the resin to cool faster. Awareness of the thermal behavior of the different resins could mean the difference between meeting the quoted cycle time or not.

Case Study

A toolmaker was awarded a job to build a new mold for a plastic container. Part of the project scope was to modify the cooling layout to reduce the cycle time. The toolmaker decided to use simulation to help determine how to achieve this goal. The core side of the mold was designed to incorporate a Moldmax (Beryllium Copper) core cap, Figure 2, which would have two circuits cooling the cap. It was anticipated that using the higher conductivity insert would help remove the heat from the top of the core and cool this area most efficiently. A simulation was run with the proposed design, and revealed that the mold temperature was not reduced significantly enough to reduce the cycle time, Figure 3. Therefore, additional simulations were performed that used a cascading cooling circuit design to cool the core cap. Also, the plastic resin that was injected was changed. The new design increased the surface area of the cooling lines and helped maintain a cooler mold temperature which allowed the cycle time to be reduced. The change of resin further reduced the cycle time to allow the desired cycle time to be achieved. Through the use of simulation, time and money were saved by showing that the resin was limiting the cycle time and that the cooling layout had to be modified from its original design.

Figure 2: Core side of container mold showing Moldmax insert.



Original Cooling Layout Modified Cooling Layout

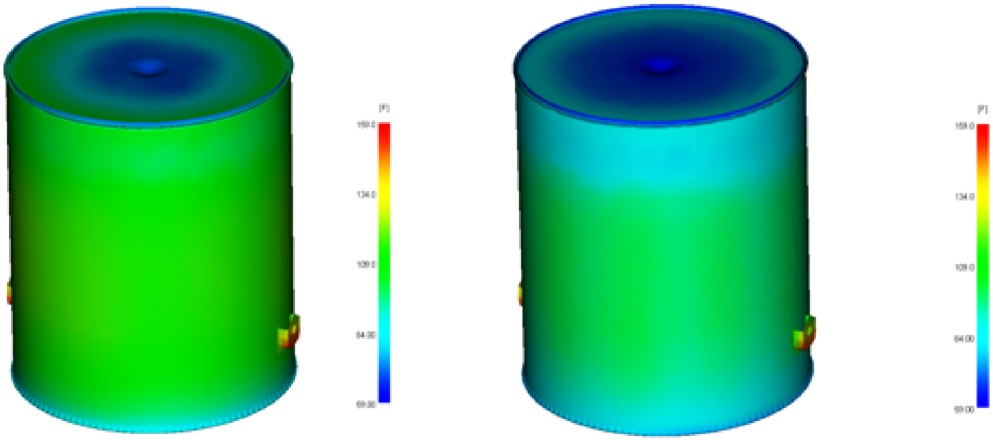


Figure 3: By modifying the cooling layout in the core cap the mold temperature within the core was reduced.

If you would like more information regarding failure analysis please contact The Madison Group at 608-231-1907, or email at *erik@madisongroup.com*.

For further information regarding injection molding and mold design read these publications authored by the staff at The Madison Group.

"Simulate Your Way to a Better Mold" by Erik Foltz published in Moldmaking Technology, August, 2011, pg. 28-31 **http://www.madisongroup.com/publications/Simulate-Your-Way-To-A-Better-Mold.pdf**

"Injection Molding Handbook" edited by Paul Gramann, Tim Osswald, and Tom Turng, Hanser Publications

9 Upcoming Society of Plastics Engineers Webinars

Educational Opportunities - SPE Webinars

Webinars provide a cost effective way to expand knowledge of plastics. The Society of Plastics Engineers (SPE) offers a wide selection of high quality webinars, many of which are taught by experts within The Madison Group. Here are some of the upcoming webinars:

Degradation Failure of Plastics

Jeffrey A. Jansen

May 17, 2012 10:00 AM Central Time

Polymeric materials are susceptible to several molecular degradation mechanisms, including oxidation, hydrolysis, thermal degradation, and UV attack. While diverse in their processes, all forms of degradation result in a reduction in the molecular weight of the base polymer. This molecular reduction is accompanied by a deterioration of physical properties, rendering the plastic part prone to failure. Degradation represents an important failure mechanism for plastics, with a study indicating that 17% of plastic failures are associated with degradation. This webinar will review the various degradation-related failure mechanisms.

Non-Destructive Analysis of Plastic Parts Using CT Imaging

Paul J. Gramann, Ph.D.

June 5, 2012 10:00 AM Central Time

Visual inspection is the most powerful and important method when examining a part. In certain situations, however, the destructive sectioning and disassembly required for a comprehensive visual inspection is not possible. In those cases CT imaging can provide equivalent information. CT imaging is a technique that is relatively new to the non-medical industry that can provide a wealth of information. This webinar will review this powerful technique for analyzing plastic parts. Specifically, how CT imaging works, its advantages and limitations. Several examples of its use with plastic parts will be given.

Plastic Pipe Failure

Jeffrey A. Jansen

July 19, 2012 10:00 AM Central Time

Plastic pipe and tubing are an extremely popular alternative to copper, steel, aluminum and other materials. In fact, it has been projected that 33% of all US pipe production is made with plastic. Plastic pipes, tubing and profiles are used in a wide variety of industries including, building & construction, automotive, consumer goods, lawn & garden, windows & doors, furniture, plumbing, and electrical. Plastics are popular in these industries because of the wide range of properties that can be obtained. In spite of this versatility, instances of premature failure do take place. If you work with plastic piping systems, this webinar will enhance your understanding of the performance considerations and common failure mechanisms. Topics covered include an introduction to plastic piping systems, failure analysis methods for evaluating failed pipes, pipe failure mechanisms including cracking, buckling, weathering, and fatigue. Case studies associated with piping failure will be presented.

Ductile to Brittle Transitions in Plastics Parts 1 and 2

Jeffrey A. Jansen

September 6 and 13, 2012 10:00 AM Central Time

Thermoplastic resins are utilized in many applications because of their unique property set, including their ductile response to applied stress. This ductility is associated with the viscoelastic nature of polymers and is attributed to their unique molecular structure. In spite of that inherent ductility, most plastic components fail through one of the many brittle fracture modes. Experience has shown that most plastics failures occur as brittle fractures of normally ductile materials. Thus, within evaluations of plastic component failures, the focus of the investigation frequently turns to identifying the nature of the ductile to brittle transition.

For more information on SPE webinars contact Barbara Spain at 203-740-5418 or bspain@4SPE.ORG.

TMG Professional Organizational Involvement

The Madison Group is committed to working with professional societies and organizations within the field of plastics. Our employees are extremely active and serve on a number of organizational boards. This allows us to stay at the forefront of technology and help lead this industry. The following are some of the activities that The Madison Group employees are involved in:

Javier Cruz

Board member of the Failure Analysis and Prevention SIG of the Society of Plastics Engineers
ASTM member and reviewer of standards for Section D20 (Plastics)

Bruce Davis

ASTM member and reviewer of standards for Section D20 (Plastics)

Erik Foltz

Board member and Technical Program chair for the Injection Molding Division of the Society of Plastics Engineers

Paul Gramann

Board member and past chair of the Failure Analysis and Prevention SIG of the Society of Plastics Engineers
Past Chair of the Thermoset Division of the Society of Plastics Engineers
ASTM member and reviewer of standards for Section D20 (Plastics)
Editorial board for the Journal of Plastics Technology, Carl Hanser Publishers

Jeffrey Jansen

Board member and past chair of the Failure Analysis and Prevention SIG of the Society of Plastics Engineers
Board member of the Milwaukee Section of the Society of Plastics Engineers

Antoine Rios

Board member and past chair of the Composites Division of the Society of Plastics Engineers
Board member of the Failure Analysis and Prevention SIG of the Society of Plastics Engineers
ASTM member and reviewer of standards for Section F17 (Plastics Piping Systems)