Prevent Failure by Understanding Why Plastic Parts Crack

A variety of factors can contribute to or cause part failure, but understanding the causes can minimize the risks

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Material failures have an overall economic cost of billions of dollars annually, and can have a devastating effect on a product or even an entire company. While the precise definition of failure can be somewhat elusive, a good working description is "a component or process that is not working the way it was intended." Failure is not always catastrophic, but it can be detrimental and have wide-reaching negative implications.

Certainly, manufacturers attempt to avoid failure, but often unanticipated factors result in unexpected problems. The chances for a successful application can be significantly increased through preventative measures, including appropriate material selection, proper mold design and process development through simulation, chemical compatibility screening, environmental testing, and a variety of mechanical evaluations.

Even when preventive actions are taken, failures can still occur. If failure cannot be avoided altogether, then at least it can provide a potential learning opportunity.

In conducting a failure analysis, the focus of the work is to ascertain the nature and cause of the failure. By doing this, information can be obtained to help to avoid future failures. Knowledge of how and why plastics fail is imperative in preventing failure. By avoiding common mistakes it is possible to produce plastic parts that have a greater chance of successful performance.

Failure of an overmolded plastic boss through environmental stress cracking (ESC). The failure was caused by the presence of residual corrosion inhibitors on the brass insert.
Courtesy of The Madison Group

Consideration should be given to determining and measuring the critical performance properties required for a successful product given the application. It is important, however, to understand that whatever performance factor is being measured — such as impact resistance, tensile strength or fatigue lifetime — the property will naturally vary across a distribution due to the inherent variability associated with polymeric materials and their associated manufacturing techniques.

Failure, regardless of the type, occurs when a portion of the stress distribution exceeds the lower tail of the strength attribution. In many cases, a relatively large safety margin is thought to be in place. However, unanticipated factors produce a shift of either the stress or strain distributions that results in premature unexpected failure (see Fig. 1).

Multiple factors affect the performance of plastic components, and these are categorized as:

- Material
- Design
- Processing
- Installation
- Service conditions

These factors do not act independently, and in most cases failure within plastic components is associated with multiple causes. This article addresses five of the most common contributing causes of plastic part failure, in the author's experience.

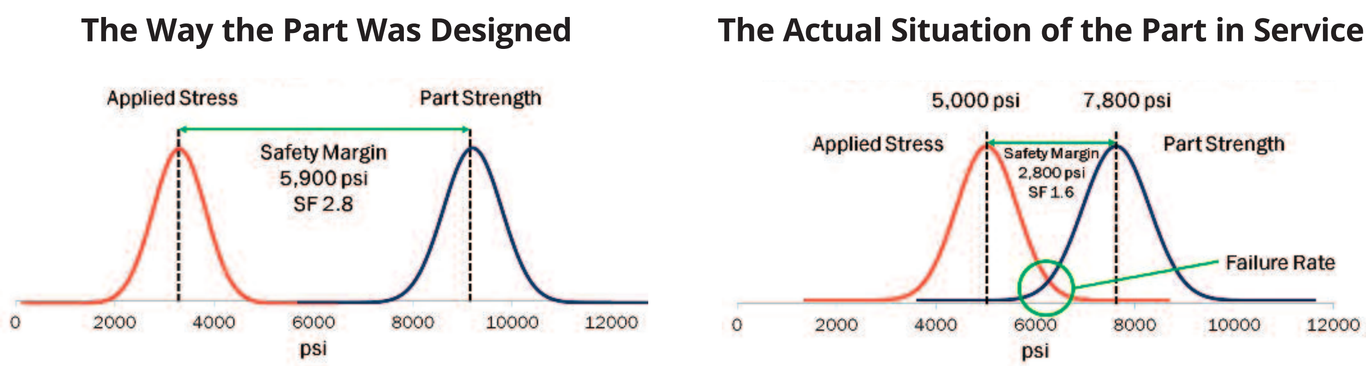

Figure 1. Schematic representation of the anticipated safety margin and the actual overlap of applied stress and part strength of the product while in service. The change is often due to unanticipated factors that result in failure.

Ignoring the effects of time

Thermoplastic materials exhibit viscoelastic properties because of their unique molecular structure, including:

- Relatively long polymer chain length associated with high molecular weight
- Entanglement of the molecular chains
- Chain mobility because the molecules do not share chemical bonds with other molecules, instead held together by intermolecular forces

The viscoelastic nature of plastics leads not only to temperature dependence, but also to reliance on time. Specifically, the mechanical properties of a plastic material will change if the material is under continuous stress. A marked decay in the apparent modulus will be observed for plastics that are under continuous stress at levels below the yield point of the material for an extended period of time.

This reduction in modulus is the result of reorganization of the polymer chains, minimizing localized stress. Given sufficient time, this reorganization will result in disentanglement and subsequently, crack initiation. If the applied stresses are below the yield point of the material, the failure will be manifested as brittle fracture, often referred to as creep rupture (see Fig. 2).

Short-term mechanical properties, such as tensile or flexural strength, are inadequate to predict the long-term load-bearing capabilities of a plastic material. Creep testing, either using a creep stand or dynamic mechanical analysis (DMA), is required to predict the effective life of a continuously loaded component. Taking time into account, and assessing the potential continuous stress placed on a plastic component while in service can be effective in preventing creep rupture failures, particularly at the design and material selection stages.

Chemical contact in service

It is my experience that environmental stress cracking (ESC) is the leading mechanism of plastic component failure. I believe this results from a general widespread lack of awareness and understanding of the interaction between plastic materials and chemicals throughout the plastics supply chain, coupled with the increasing use of plastic materials in diverse, demanding applications.

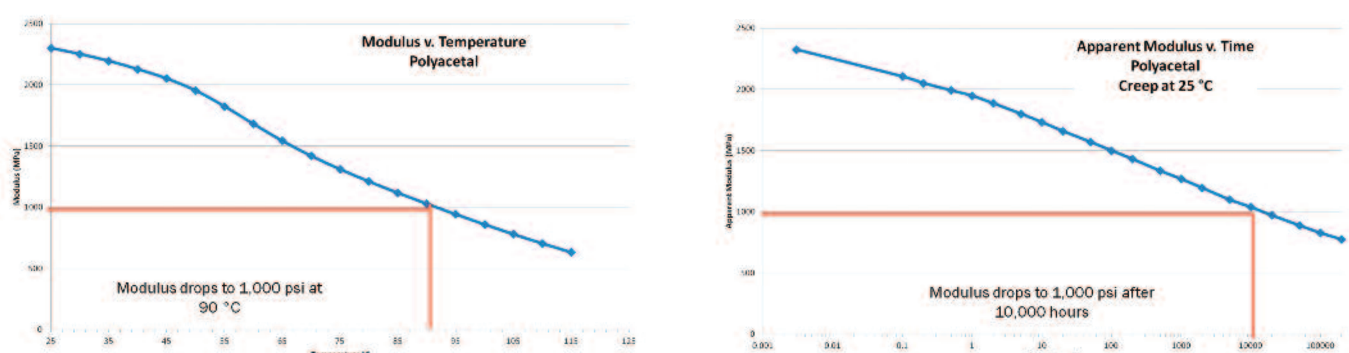

Figure 2. The equivalent effects of temperature and time are illustrated for a polyacetal resin.

Environmental stress cracking is a failure mechanism whereby a plastic material cracks due to contact with an incompatible chemical agent while under tensile stress. It is a solvent-induced failure mode, in which the synergistic effects of the chemical agent and mechanical stresses result in a brittle premature cracking. The contact with the chemical agent does not produce direct chemical attack or molecular degradation.

Conversely, the chemical permeates into the molecular network and interferes with the intermolecular forces binding the polymer chains. This leads to accelerated brittle behavior and premature failure through molecular disentanglement. The ESC failure mechanism is similar to creep rupture, and in many circumstances, the plastic would undergo stress cracking in air given sufficient time. The chemical, and its effect on the intermolecular forces binding the individual molecular chains, accelerates the stress cracking.

Published chemical compatibility tables and general guidelines can be useful in identifying potential problematic plastic and chemical combinations. However, the definitive question of compatibility is addressed through environmental stress crack resistance testing.

Samples are placed under a tensile load and exposed to the chemical of interest for a period of time, while inspected for the presence of cracks. A key aspect in the prevention of ESC failures is the anticipation of chemicals that will contact the plastic part while in production, assembly, installation and service.

Molecular degradation

Molecular degradation is the deleterious alteration of the molecular structure within a polymeric material due to a chemical reaction. There are several molecular degradation mechanisms, including oxidation, hydrolysis, chain scission and destructive crosslinking, all of which involve permanent molecular-weight changes. All these types of degradation can occur throughout any point in the material life cycle, but are particularly harmful if they occur during manufacturing.

Examples of manufacturing-related molecular degradation include:

- Exposure to elevated, shear-induced heating while additives are incorporated into the resin during compounding;
- Exposure to extreme time/temperature profiles during drying;
- Insufficient drying of moisture sensitive resins prior to injection molding;
- Exposure to an elevated temperature for an extended period in the injection molding machine barrel;
- Excessive shear during the injection process;
- Overly aggressive sterilization conditions.

Molded parts in which molecular degradation has taken place can look good and be in dimensional tolerance, but may be inherently brittle and prone to premature failure. The reduction in molecular weight most often associated with molecular degradation reduces the inherent ductility of the plastic material.

The material experiences a decrease in the level of entanglement associated with the shortening of the polymer chains. This reduces the energy required for disentanglement to occur, and shifts the preferred mechanism from yielding to brittle fracture.

Avoiding molecular degradation requires critical attention to manufacturing conditions. This is not limited to molding, but also to preliminary steps, such as compounding and drying. Post-molding activities, including sterilization, machining, plating and welding also should be considered.

Impact loading

Impact is rapid contact between a material of interest and another object. Impact in regards to plastic performance is normally associated with high speeds – high strain rates. The effects of high strain rate stress loading are not insignificant. The viscoelastic nature of polymeric materials imparts strain rate dependency. The application of stress through impact loading results in rapid deformation of the plastic material.

At increasingly elevated strain rates, the polymer molecules that make up the formed plastic component are precluded from having sufficient time to yield and deform, as is normally observed in a mechanical overload condition. The application of stress under conditions of high strain rate within plastic materials directly parallels the performance exhibited at reduced ambient temperature.

The physical response of the polymer chains subjected to impact is preemptive disentanglement. Impact failure of plastic requires amounts of energy lower than required to produce failure given a slower strain rate. Cracking initiates and continues to extend when the applied stress exceeds a minimum energy. Ultimately, the prevention of impact failures requires the anticipation of high strain rate events during a product's design and material selection.

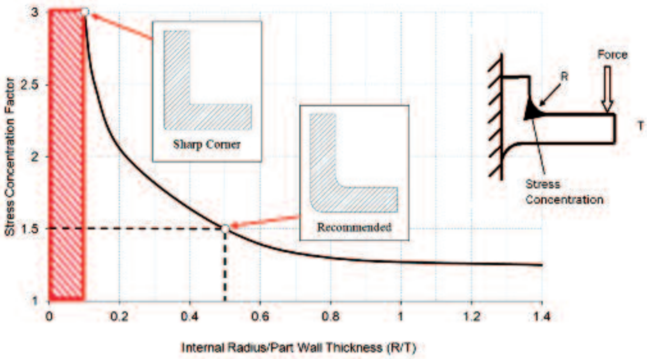

Figure 3. Graphical representation of the stress concentration effects for sharp corners.Data adapted from *The Complete Part Design Handbook for Injection Molding of Thermoplastics*, E. Alfredo Campo, Hanser Publishers

Designs with sharp corners

The design of a plastic component can have a great influence on the ability of the part to tolerate loading, including continuous low levels of stress that can lead to creep rupture; high strain rate loading such as impact; and high levels of stress that can produce mechanical overload. Design aspects that serve as points of stress concentration will increase the apparent brittle response of the material. By focusing the stress, the polymer molecules are prevented from yielding, and cracking through molecular disentanglement is favored. The DuPont Design Guide goes so far as to say that, "Sharp internal corners and notches are perhaps the leading cause of failure of plastic parts".

Most plastics are not sensitive and the increased stress at the notch is called the "Notch Effect." Sharp internal corners in particular can produce stress concentration that inherently reduces the apparent ductility of the material. The lower the notch or corner radius, the greater the magnitude of the ductile-to-brittle transformation (see Fig. 3).

Such stress concentrators include sharp corners, notches, grooves, recesses, holes, and even variable wall thickness and textured surfaces. A thorough review of plastic component designs to ensure rounded edges and the elimination of sharp corners can go a long way to avoiding plastic component failure.

It is not a coincidence that the five causes of plastic component failure reviewed all produce a ductile-to-brittle transition within the material. While these factors may appear to be relatively diverse and seemingly unrelated, they all generate the same molecular-level response within the material. These factors produce a situation in which molecular disentanglement is favored over yielding and deformation. This transition can produce unexpected brittle failure within components expected to exhibit ductile behavior.

By understanding, and even anticipating, how plastic products will fail, it is possible to prevent failure. Information to help avoid failure can be generated in the form of material and prototype testing, and simulation in the early stages of product development, as well as through a thorough investigation of component failures.

Upcoming webinar

The Society of Plastics Engineers will host a webinar given by the author on May 24, titled "Preventing Plastic Component Failure." For more details, contact Scott Marko at smarko@4spe.org.

ABOUT THE AUTHOR

Jeffrey A. Jansen is senior managing engineer and a partner at The Madison Group, an independent plastics engineering and consulting firm in Madison, Wis. He specializes in failure analysis, material identification and selection, as well as compatibility, aging and lifetime prediction studies for thermoplastic materials. He has performed more than 3,350 investigations over the past 23 years. A regular presenter on SPE's webinar series, Jeff is a graduate of Carroll College and the Milwaukee School of Engineering.