THE ROLES OF MULTIPLE FACTOR CONCURRENCY AND STATISTICAL DISTRIBUTION IN PLASTIC PART FAILURE

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Abstract

When a plastic part fails, a tough question is often asked, “Why are a limited number of parts failing?”. This is particularly true with seemingly random failures at significant, but low, failure rates. Two aspects are generally linked to such low failure rates, multiple factor concurrency and the statistical nature of plastic failures. Failure often only takes place when two or more factors take effect concurrently. Absent one of these factors, failure will not occur. Plastic resins and the associated forming processes produce parts with a statistical distribution of performance properties, such as strength and ductility. Likewise, environmental conditions, including stress and temperature, to which the resin is exposed through its life cycle is also a statistical distribution. Failure occurs when a portion of the distribution of stress on the parts exceeds a portion of the distribution of strength of the parts. This paper will review how the combination of multiple factor concurrency and the inherent statistical nature of plastic materials can result in seemingly random failures.

Background

Failure within a plastic part can be defined in several ways. A useful definition for the purpose of understanding failure is an undesirable event or condition that results in the inability of a component to function properly or perform its intended function safely, reliably, and economically. In many cases failure is catastrophic and results in a component that is completely inoperable. In other cases, however, the part may be partially operable, but not fully functional; or simply may be compromised to the point that it is deemed that further use is unreliable or unsafe.[1]

Failure within plastic components can take many forms, including:

- Deformation / Distortion
- Esthetic Alteration
- Degradation
- Wear
- Fracture

This paper focuses on failure through fracture in illustrating the role of multiple factors in plastic part performance and the statistical nature of plastic part failure. However, it is important to note that the same principles apply to the other types of failure as well.

The mechanism of cracking within a plastic material principally occurs through disentanglement, whereby polymer chains slide past one another. The applied stresses, both internal formed-in and assembled-in together with those from external sources overcome inter-molecular forces, such as Van der Waals forces, London dispersion forces, hydrogen bonding, and dipole interactions. The mechanism is the same regardless whether the polymer is amorphous or semi-crystalline. Generally, the stresses responsible for cracking are insufficient to produce breakage within the covalent bonds of the polymer backbone.

Failure in Plastics

While it might seem complex, it is important to remember that cracking is simply a response to stress. Fracture takes place as a stress relief mechanism. Ductile fracture is a bulk molecular response that occurs through yielding, a macro molecular rearrangement, followed by disentanglement. Conversely, brittle fracture is a micro molecular response where disentanglement is favored over yielding. The most common failure mechanisms of plastic components are:

Short-Term Overload

Overload of a plastic occurs primarily as a ductile fracture, when short-term applied stresses exceed the load-bearing capacity of the material. This stress results in bulk deformation yielding followed by disentanglement, leading to failure. Overload is modeled by the response of the material to testing per ASTM D638.

Impact

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. Crack initiation occurs when the minimum energy is exceeded, and the crack propagates when the applied load exceeds the required initiation energy. Impact failure of plastic requires amounts of energy lower than required to produce failure given a slower strain rate.

Creep Rupture

Creep rupture is the formation of cracks that occur as a function of time through extended exposure to levels of constant stress, tensile, compressive, shear, or flexural, that are below the yield strength of the material. Prolonged exposure to constant stress leads to a decay in the apparent modulus through localized molecular reorganization of polymer chains. Because the stress level is below the yield point, molecular reorganization takes place exclusively through disentanglement, as there is no opportunity for yielding. The exertion of low to moderate stress over an extended time leads to apparently lower ductility within the plastic. Thus, creep can result in brittle fracture in normally ductile plastic materials. The inherent viscoelastic nature of polymers leads to this time dependency.

Fatigue

Fatigue is the progressive and localized structural damage to a polymeric material that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the yield strength and tensile strength of the material. Fatigue occurs when a material is subjected to repeated loading and unloading. If sufficient loading occurs, microscopic cracks will begin to form at the surface via disentanglement. Eventually, a crack will reach critical size, and the structure will suddenly fracture. Like creep, fatigue produces an apparent decay in strength over time / cycles.

Environmental Stress Cracking

Environmental stress cracking (ESC) is the premature embrittlement and subsequent cracking of a plastic due to the simultaneous and synergistic action of stress and contact with a chemical agent. No chemical reaction takes place between the polymer and the chemical agent, and there is no molecular degradation. The plastic would undergo stress cracking in air given sufficient time, and the presence of the chemical accelerates the stress cracking. The chemical agent permeates into the molecular structure and interferes with the inter-molecular forces bonding the polymer chains. This reduces the energy required for disentanglement to occur, producing a shift in the preferred mechanism from yielding.

Molecular Degradation

Molecular degradation within plastics represents a chemical reaction that reduces the molecular weight of the polymer, resulting in decreased material strength and ductility. The energy required for polymeric disentanglement is reduced with the associated shortening of the polymer chains. This degradation can occur through several mechanisms including:

- Oxidation
- Ultraviolet Radiation (UV)
- Hydrolysis
- Chain Scission
- Side Chain Alteration

Molecular degradation can take place throughout the product life cycle through exposure to extreme or inappropriate conditions during molding, installation, or service.

Why are a limited number of parts failing? – Statistical Distribution Considerations

The answer to this question can be complex. However, a simplistic approach is to interpret the in-service conditions (stresses, etc) and material properties (strength, etc) on the part as statistical distributions. When the plastic part is designed, it is typical to review the material's property datasheet provided by the material supplier and use this data as an input to the design. However, the value in the datasheet is usually an average and no information is typically given in regards to the standard deviation of that value. In reality, the mechanical properties of the material follow a statistical distribution. Actually, some of the most common mechanical tests regulated by ASTM or ISO require reporting the average value and standard deviation of the measured property. A few ASTM standards such as D256 (impact resistance), D638 (tensile properties) and D790 (flexural properties), go as far as reporting the standard deviation results of properties measured within the same laboratory and between various laboratories.

Details on the type of statistical distribution of properties are beyond the scope of this paper, but the distribution can take the form of a normal distribution, beta distribution or skewed normal distribution [2, 3]. The statistical distribution of a property is important because if the distribution tail of such property overlaps that of the in-service conditions failure could occur. As the material properties fall within a statistical distribution, the same occurs with the stresses, temperature and conditions existing during the service life of a part. Figure 1 shows a distribution of in-service expected stresses and a distribution of part strength. In this case, the separation between the two distributions is related to the design safety factor. However, the stresses and strength of the part can vary due to unforeseen factors causing these two distributions to overlap (Figure 2). The overlap region of both distributions represents a small portion of the parts that would lead to failure. Here, for simplicity, failure is considered to occur when the stress on the part is greater than the strength of the part.

The distributions can shift due to one factor or multiple factors. If the shift is greater than the safety factor then there is an increased probability for failure to occur. The distribution can be affected not only by a shift, but also by changes that make it broader. Common effects as adding reclaimed material or molecular degradation during molding would broaden the distribution (Figure 3). DeRudder, et.al. [3] show that the distribution broadens and shifts due to the addition of recycled material.

The probability of failure can also exist due to broadening of the distribution with no shift. An example would be when a material is substituted. It is not uncommon to specify materials by a property or a group of properties. A material can have the same datasheet property value, but a different property distribution. This could be a problem if the tail of the distribution is too broad that it overlaps the distribution of the in-service conditions. Therefore, as with any material substitution the proper due diligence is extremely important.

Equally important is the variability introduced when measuring properties. As ASTM D638 for tensile properties shows, there would be differences in the measured average between testing laboratories. For example, the tensile break strength of LDPE shows a standard deviation of up to 5.9% of the reported average, 6.2% for LLDPE, 8.3% for acrylic and 2.9% for glass-reinforced nylon [4]. Therefore, it is paramount to include this variation as part of the safety factor. Of note is that ASTM D638 shows a standard deviation of 55% for tensile strength at break for polypropylene. This shows a substantial distribution of values for polypropylene due to the inconsistency of necking of the tensile bars [4].

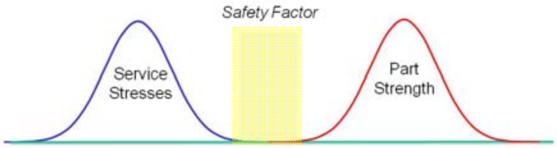

Figure 1: stress and strength distribution separated by a design safety factor

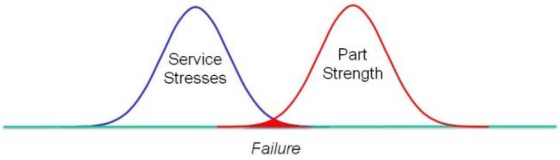

Figure 2: stress and strength distributions overlapping leading to a failure probability

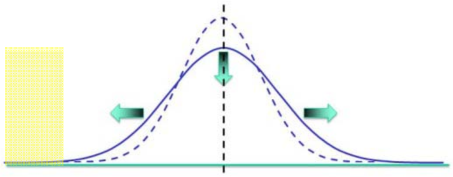

Figure 3: broadening of statistical distribution

Why are a limited number of parts failing? – Concurrent Factors Considerations

The influences that affect the performance of a plastic component can be separated into five different factors covering the lifecycle of the part:

- Material
- Design
- Processing
- Installation
- Service

These factors do not act independently, but instead act concurrently to determine the functionality of a plastic component. In many cases, a single cause of failure cannot be determined because multiple factors are contributory. Some of the factors, by their nature, affect the material properties (strength, etc.) of the part, while others contribute to the applied in-service conditions (stress, etc.).

Material

The material considerations related to a plastic include both the molecular structure of the polymer and the entirety of the material composition of the plastic. A key aspect of polymer structure that directly determines the strength of the material is the average molecular weight. More than any other single characteristic of the material, molecular weight will determine the attributes of the plastic resin. Other structural attributes that affect the strength of the plastic are molecular weight distribution, and degree of branching. Because polymers are produced via a chemical reaction their imprecise control can result in inherent variation, particularly in regards to average molecular weight and molecular weight distribution.

Intended or unintended formulation constituents can greatly influence the performance of a plastic component. The presence or absence of additives such as reinforcing fillers, impact modifiers, and anti-degradants will significantly alter the performance. Finally, the presence of contaminants may substantially reduce the strength of the material, rendering it susceptible to premature failure. Examples:

- Changes associated with lot-to-lot variation within the polymer structure, such as average molecular weight and molecular weight distribution, can significantly alter position and shape of the strength distribution;
- An improper level of anti-oxidant, reducing the thermal stability of the material during processing and service, thus shifting the strength distribution downward;
- Contamination present with the molding resin causing discontinuities, lowering the strength distribution.

Design

The design of a plastic component can have a substantial impact on its performance and is critical to success or failure. Design refers to not only the configuration of the part itself, but also the corresponding tooling. Some critical design features include:

- Material Selection
- Wall Thickness
- Ribs
- Bosses
- Threads
- Holes
- Snap Fits
- Inserts
- Plastic Flow
- Gating
- Cooling
- Venting

While the design of a part is fixed and is not generally subject to a distribution, the design will certainly determine the level of applied stress and the strength of the part. Thus, a superior design will make the part more robust, and a suboptimal design can render the part prone to premature failure. Examples:

- Material selected is not suitable for the service conditions of temperature, chemical contact, or stress shifting the strength of the part downward;
- Inadequate corner radius or poor thread design resulting in severe stress concentration or non-uniform wall thickness producing a high level of molded-in residual stress shifting the stress upward;
- Improper gating design producing knit lines in high stress areas, thus shifting the strength distribution downward.

Processing

Processing the material into the final part configuration, whether through compounding the resin, injection molding, extrusion, machining, joining, plating, and other operations, results in exposure of the material to a wide range of stressful conditions including high shear, elevated temperature, and chemical exposure. Proper processing is essential to produce a part that is optimized to withstand the stresses imparted during service. Examples:

- Exposure to elevated temperature for prolonged periods of time or improper drying resulting in molecular degradation that produces a downward shift and broadening in the strength distribution;
- Excessively cold mold temperatures that reduce the crystallinity of a semi-crystalline resin, which shifts the strength distribution downward, and/or results in molded-in residual stress that shifts the stress distribution upward;
- Inadequate molding parameters resulting in poor dispersion, inhomogeneities, contamination, or voids, resulting in a downward shift and broadening of the strength distribution as well as an upward shift in the stress distribution through stress concentration.

Installation

The installation of the plastic component represents the final step before placing the part into service. Similar to processing, the material can be exposed to a variety of stresses that can affect the performance of the part. Examples:

- The part can be damaged through mishandling that results in a downward shift in the strength distribution;
- The part is installed misaligned or aggressively tightened in a way that increases the applied loading, thus an upward shift and broadening in the stress distribution.

Service

Once the part, consisting of the material formed into the design, is installed and placed into service there are a limited number of external effects, as illustrated in Figure 4, that can influence the performance. Essentially, these stresses can be categorized as mechanical stress, temperature, exposure, and time. However, these stresses often combine synergistically in a way that is multiplicative, not additive. Examples:

- Exposure to deleterious chemical agents, temperature, or UV radiation that results in molecular degradation, resulting in a downward shift and broadening of the strength distribution;
- The part is placed under conditions of dynamic or continuous stress, such as fatigue or creep loading, that produce a reduction in the apparent ductility and a downward shift of the strength distribution,
- The part is cleaned with an unexpected chemical that acts as an ESC agent effectively producing a downward shift of the strength distribution.

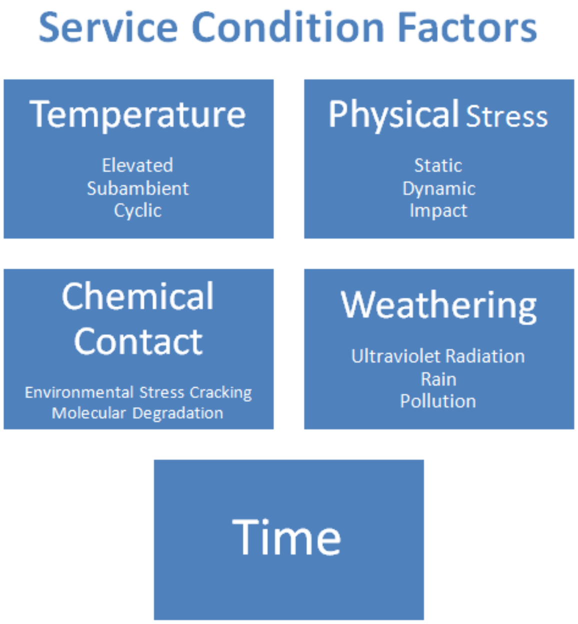

Figure 4: The factors that can act upon a part in service are represented.

Summary

The cause of failure in plastic parts is not typically trivial. Parts can fail as the result of various factors concurrently reducing the expected strength and/or increasing the expected in-service stresses of the part. The number of factors affecting part performance produces a broad statistical distribution of the material properties and service conditions. The overlap of these two statistical distributions leads to sporadic and seemingly random failures. When working to identify the cause of component failure, it is important to consider the interaction between the various factors and the inherent statistical distribution of the performance and service conditions.

Case Illustrations

Case 1 – Retaining Tab

A number of retaining tab components, injection molded from an unfilled grade of poly(butylene terephthalate) (PBT), failed during installation. It was indicated that previous production lots of the retaining tabs had failed at rate of approximately 1 in 5,000. The current failure rate was 1 in 1,000, a statistically significant increase.

A comprehensive failure analysis was conducted on the retaining tabs, and it was concluded that the parts failed via brittle fracture through a rapid crack propagation mechanism, consistent with the high strain rate resulting from the snap fit insertion of the tabs. The location of the failures corresponded to a relatively high stress area, as indicated by finite element analysis (FEA). The cracking within the failed tabs initiated at molded-in inclusions, within the parts (Figure 5). The presence of the inclusions produced significant stress concentration and a localized reduction in the mechanical integrity of the molded part. The inclusions were identified as poly(phenylene sulfide)

(PPS), a material having a substantially higher melting point compared with the (PBT) tab material. A significant factor in the failure was molecular degradation of the tab material associated with the injection molding process, as presented in Table 1. The molecular degradation rendered the material more brittle and diminished the mechanical integrity of the molded part. The combination of the high strain rate snap fit insertion, the presence of the inclusion, and the molecular degradation caused the inherently ductile material to undergo a ductile-to-brittle transition and ultimately fail. The inclusion acted to lower the strength distribution and increase the stress through stress concentration. Concurrently, the molecular degradation lowered and broadened the strength distribution. It was opined that failures occurred when the molded parts were sufficiently degraded and an inclusion was present within the high stress area of the retaining tab. It was thought that the required concurrence of these factors was responsible for the relatively low failure rate.

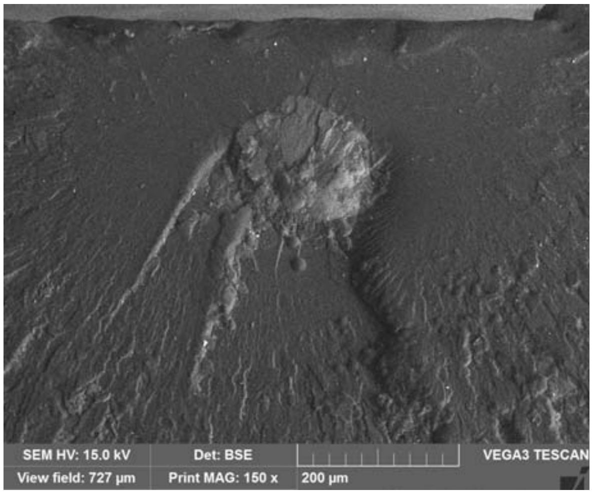

Figure 5: An inclusion was present within the retaining tab at the high stress location, and was evident on the fracture surface.

Table 1
Melt Flow Rate Test Results
(g/10 min.)

Molding Resin	Previous Lot	Current Lot
23.9	32.5	37.0

Case 2 – Fiber Reinforced Polypropylene Cover

Another example of a multiple factor failure is the common misconception that because the datasheet strength of a fiber reinforced plastic is higher, then it would be a better option. Two factors often ignored are the fiber alignment and the weldline strength. The strength of the fiber reinforced material reported in the datasheet would be much higher than the strength measured transverse to the fibers. For a 30% fiber reinforced polypropylene, the part strength can be expected to be 34% below the datasheet value [5]. Therefore, the statistical distribution of the strength would be much broader, which should be considered during design. Additionally, the strength reduction at the weldline is more drastic than in unreinforced materials. The reported reduction in weldline strength of a non-reinforced polypropylene is 14% [6]. In contrast the reduction in weldline strength for a 30% glass-fiber-reinforced polypropylene can be up to 66% [6]. Concurrently, if the mold design and processing parameters are not ideal, the surface finish of the part could be rough, especially at the weldline (Figure 6). A rough surface finish or a weldline showing an indentation facilitates the effect from chemical agents either via degradation or ESC. If the fibers at the surface are not properly coated with the resin this problem can be further exacerbated. This is a common example where multiple design, material and processing factors affect the strength of the part and the surface finish to cause part failure.

Figure 6: Rough surface finish caused by fibers on the surface of the part

Acknowledgements

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Keywords

Failure, Statistical Distribution, Concurrent Factors, Multiple Causes