Plastics Topics – Failure of plastics

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Contents

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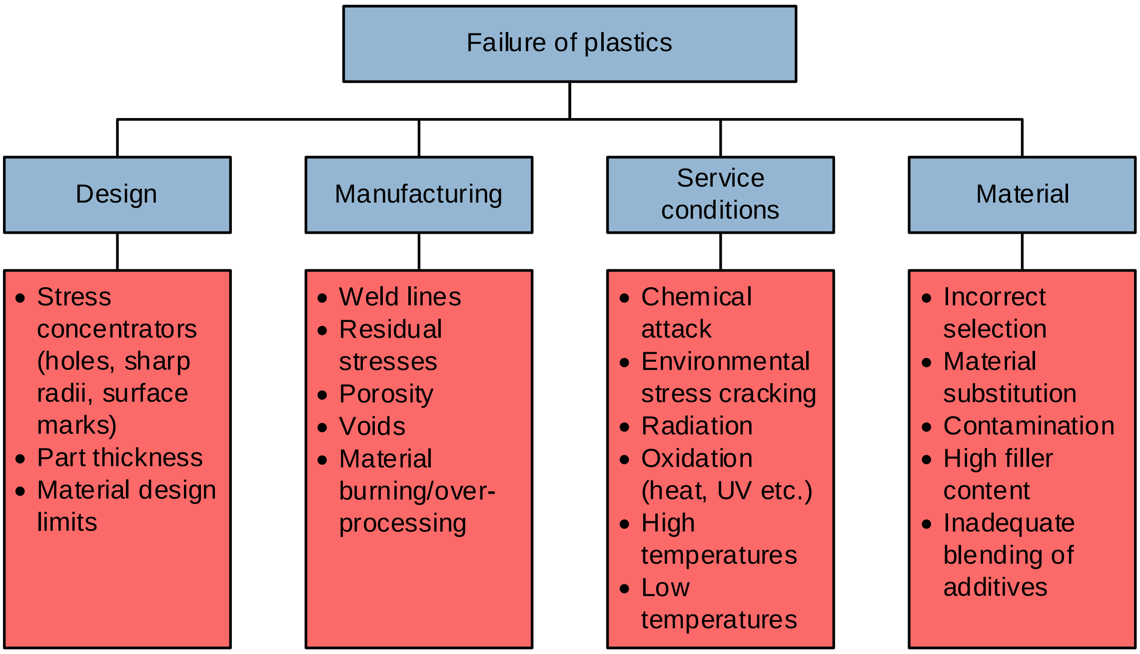
1. Introduction

In many of previous Plastics Topics we have discussed the limitations of plastics in terms of high and low temperatures, chemical resistance and other factors. The case of failure is the ultimate limitation; failure is any event where a part no longer performs the intended function. In some cases, the failure can be ‘graceful’ with progressive loss of function but more serious is ‘catastrophic failure’ where the loss of function is rapid and dramatic. Catastrophic failure can lead to events such as the loss of the Challenger Space Shuttle through the failure of an O-ring at low temperatures and the costs and results of catastrophic failure often far outweigh the cost of the part that failed. Catastrophic failure has massive costs for companies and society as a whole.

Failure of plastics is a broad area and the reason for failure can be assigned to a variety of categories. The diagram (below) shows the broad categories and some of the possible detailed concerns within each major category:



An atlas of reasons for failure

In practice, it is rare that failure is related simply to one of the major categories, a typical failure will result from a combination of these, e.g., incorrect materials selection for a low temperature service condition. Whichever reason (or group of reasons) is assigned as the cause of failure, the result is generally seen as a mechanical failure and the part breaks.

In this Plastics Topic we will look at the modes and types of mechanical failure, some of the factors affecting it and some of the available methods to reduce mechanical failure.

2. Loading conditions

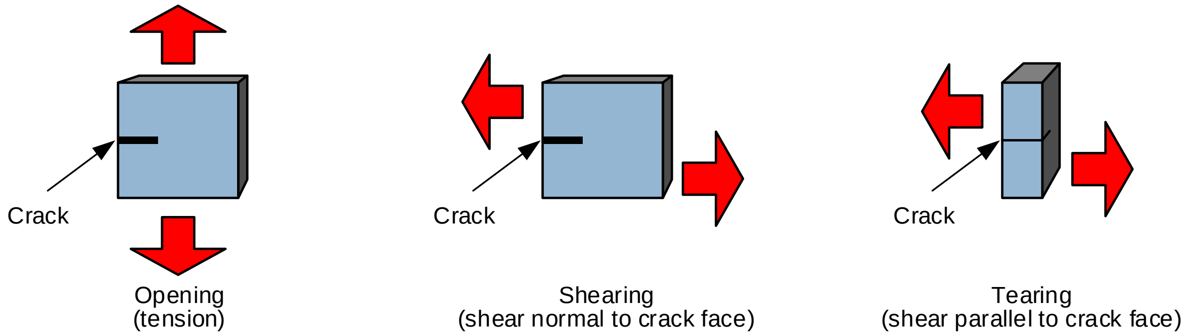
The loading condition, both the direction and the duration are critical aspects of mechanical failure.

Loading direction

The diagram (below) shows various loading directions for a crack in an idealized block of material. Loads can be applied to directly open a crack in tension (tension normal to the faces of the crack), to shear open a crack (shear at right angles to the leading edge of the crack) or to tear open a crack (shear parallel to the leading edge of the crack).

To make things simple for this Plastics Topic we will only consider the pure tension loading direction. In real life, nothing is as simple as this and real loading directions are generally a mixture of these three cases.

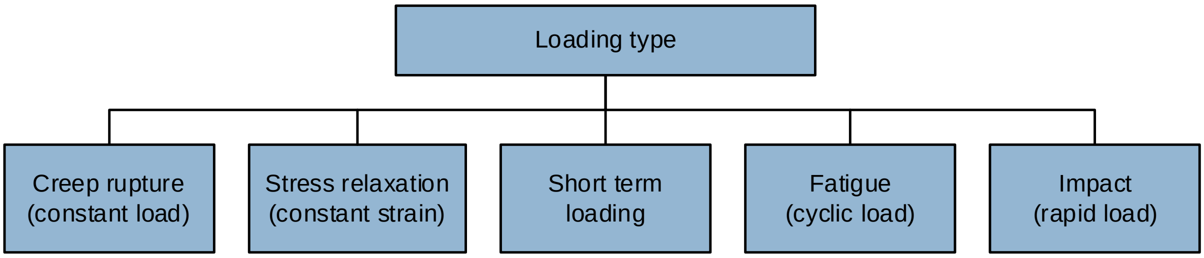
Plastics Topics – Failure of plastics



Loading directions for mechanical failure

Loading duration

The load duration is also important in mechanical failure and the diagram (below) shows the various durations of load that need to be considered.



Loading durations for mechanical failure

Creep rupture

Creep rupture is the final result of the creep process (where a polymer extends slowly under a constant load). Creep rupture is the point of failure where the polymer chains can no longer hold the applied load, the stress reaches levels high enough for microcracks to form and the product fails.

Stress relaxation

Stress relaxation is similar to creep but in this case the deformation is constant and movement of the polymer chains reduces the force necessary for a given deformation. Stress relaxation rarely results in mechanical failure but can lead to a part losing functionality.

Short-term loading

Short-term loading is a most general type of loading where the load is high enough to cause failure in either the brittle or the ductile mode.

Fatigue

Fatigue is caused by a cyclic load that is generally much lower than the load necessary to cause failure under short-term loading. It has been estimated that 90% of the engineering failures in materials relate in some way to fatigue loads.

In fatigue a small pre-existing crack can grow under the low applied cyclic load until it is large enough to cause failure under the low applied load. The time for fatigue failure depends on:

- The number and size of pre-existing cracks in the product.
- The size of the product.
- The frequency and magnitude of the applied cyclic load (particularly how much of the load is applied in tension).

With some polymers, fatigue at high frequencies can lead to significant heat generation as a result of the viscoelastic properties of the polymer and failure through creep of the product rather than through the more traditional fatigue failure mechanism.

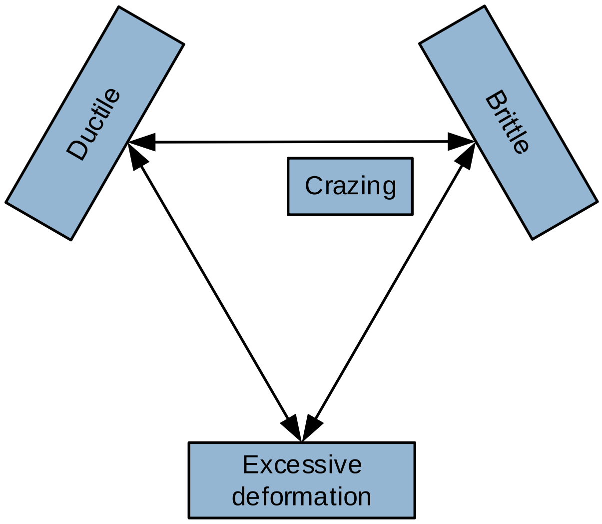
Impact

Impact failure is the result of an extremely short-term load, i.e., a rapid blow. Impact is very important in the failure of plastics because of the time-temperature equivalence of plastics.

To make things simple, we will only consider the general short-term loading duration. Again, in real life, the load durations may be a mixture of these cases.

3. The modes of mechanical failure

The result of an excessive combination of load direction and load duration will be final mechanical failure and this generally occurs through ductile failure, brittle failure or excessive deformation. For glassy polymers crazing may also occur before mechanical failure. These modes of failure are shown in the diagram (below):



The modes of mechanical failure

Ductile failure

Ductile failure occurs when substantial plastic deformation (or yielding) occurs before fracture and the yield point should always be regarded as the limit for practical design. Above this limit plastics that fail in a ductile mode will yield, draw and eventually fail at the Ultimate Tensile Strength. Ductile failure is slow and uses a lot of energy in the failure, any cracks present grow slowly, the extension (strain) at final fracture is high and the fracture surfaces tend to have a fibrous appearance. As a failure mode, ductile failure tends to be more graceful and the loss of function is more gradual than brittle failure.

Brittle failure

Brittle failure[1] is the most dangerous type of mechanical failure because it occurs without warning at low strains and before any significant yielding has taken place. Brittle failure is catastrophic, rapid and uses relatively low amounts of energy: the loss of function tends to be instantaneous and total. The fracture surfaces after brittle failure tend to be smooth and clean due to the rapid crack growth.

Brittle failure is strongly affected by the presence of stress concentrations and impurities and design for brittle failure must be more conservative than design for ductile failure. A particular trap for designers is the 'ductile-brittle transition temperature': products above this temperature can fail gracefully in a ductile manner but reducing the temperature below the transition point leads to catastrophic brittle failure.

[1] To bring us all back to a sense of reality here, the word 'brittle' can be linked to the old English word 'brytel' meaning 'frail' or 'easily shattered' - it is alleged that this can also be linked to the word 'brothel' as a 'house for frail women'. Scientists and engineers should always remember their roots and not get too pretentious.

Plastics Topics – Failure of plastics

More than one design has been fatally flawed by poor materials selection and the ductile-brittle transition temperature. In World War II, the loss of many Liberty ships in the Atlantic was due to cold weather operations at temperatures below the ductile-brittle transition temperature for the steels used. This led to rapid and catastrophic failure of welds – the ships literally split in half from brittle failure, sometimes even whilst sitting at the docks!

The transition from ductile to brittle behaviour is also affected by the speed of crack growth in the material, slow moving cracks can speed up and make the transition from ductile failure (using high amounts of energy) to brittle failure (using low amounts of energy): the rate of crack growth after a ductile-brittle transition can literally be explosive and fatal. This has happened with plastic gas pipes where slow crack growth has accelerated and created pipe bursts of several kilometres.

Brittle failure is perhaps the most commonly seen type of failure for plastics products because it is hard to predict and is so damaging in terms of product functionality and possible fatalities (in the case of gas pipe failures).

Excessive deformation

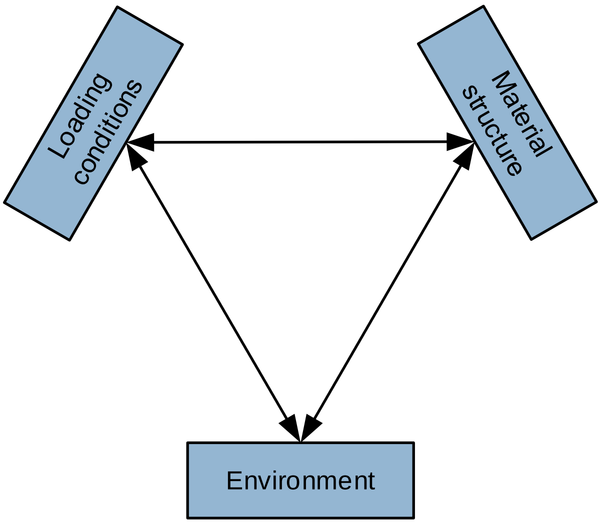
The final mode of mechanical failure is excessive deformation and whilst not a failure mode that results in fracture, it can lead to a loss of function. A product that has excessively deformed may not suffer from ductile or brittle failure but if it is unusable in service it is considered to have failed.

Crazing

Crazing is sometimes seen in glassy polymers before yielding and before brittle fracture but is not catastrophic. Most readers will be familiar with crazes in a plastic ruler that has been bent too much; they are the light reflecting areas in the centre of the ruler. Crazes are not cracks but are areas of low-density polymer where the polymer chains are highly oriented across the craze. Crazes can continue to be load bearing, but a craze can degenerate into a crack if the load is maintained or increased. They can be regarded as crack precursors and are about the only early warning sign available before brittle fracture in glassy polymers.

4. Factors affecting the ductile-brittle transition

A range of factors can encourage ductile-brittle transition and the main factors are shown in the diagram (below):



Factors affecting the ductile-brittle transition

Loading conditions

The loading conditions, particularly the load duration, will affect the ductile-brittle transition. A rapid loading rate will increase the possibility of brittle fracture and impact fractures are almost always brittle failures. This is yet another case of the equivalence of time and temperature for plastics. Plastics react to high loading rates at moderate temperatures in the same way as they react to moderate loading rates at low temperatures, i.e., below the ductile-brittle transition temperature.

The load direction also affects the behaviour and plastics that would fail in a brittle manner in tension will often fail in a ductile manner if placed in compression.

Particularly damaging for many materials is development of triaxial stresses; these are stresses that develop in directions other than that of the main applied stress, when these develop around existing cracks then brittle failure can occur.

Material structure

If the material structure has particles or elements that can act as ‘stress concentrators’ then these will encourage brittle failure. For plastics the ‘stress concentrators’ can be:

- Additives that have not been mixed properly.
- Large areas of crystallinity.
- Crazes formed from previous loading.
- Brittle areas of modified polymer structure on the surface (particularly from environmental effects).

For most plastics the molecular weight is also an important factor because the toughness of a polymer generally increases with the molecular weight of the polymer.

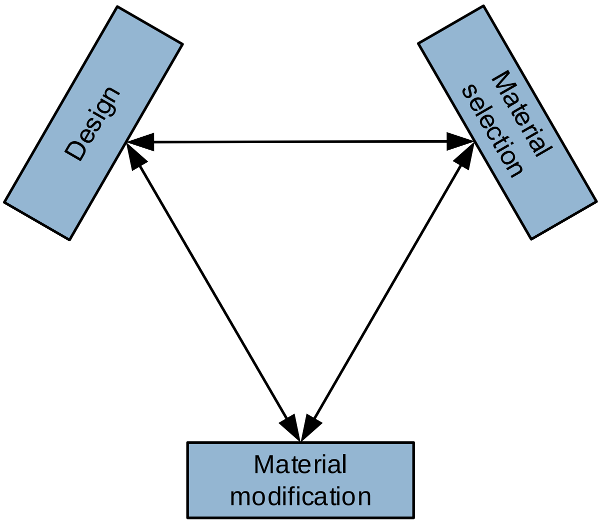
Environment

Environmental factors seriously affect the ductile-brittle transition and the phenomenon of ‘environmental stress cracking’ is one of the major causes of failure of plastics products. Typical environmental effects are:

- Low temperatures increase the possibility of brittle failure particularly if below ductile-brittle transition temperature. For most polymers this transition is generally around the Tg (glass transition temperature) of the polymer.
- Exposure to heat, light, oxygen, UV, ozone or other weathering / degradation processes will lead to surface degradation and the formation of small cracks in a harder surface - the ideal conditions for brittle failure.
- Environmental stress cracking (ESC) is one of the most insidious methods of promoting brittle failure and it is estimated that ESC is the cause of over 30% of plastics product failures. A plastic may be ductile when loaded in air and may also be resistant to a particular liquid when unstressed but when both loaded and in contact with the liquid the plastic will fail rapidly in a brittle manner. The mechanism is thought to be that the loading opens up crazes or microcracks, which then fill with the liquid and swell the surrounding polymer to act as ‘micro-wedges’ that precipitate brittle failure. An example of ESC is polycarbonate (PC) and chloroform – PC is normally tough but when loaded in the presence of chloroform can suffer brittle failure at very low load levels. Unfortunately, most chemical resistance charts do not give data on ESC with the result that plastics that are nominally resistant to a specific chemical can be specified and fail rapidly under very low loads.

5. Reducing brittle failure

Reducing brittle failure is a key aim for any plastics product designer and this requires using both good design principles and selecting materials that are tough and ductile. Failing to follow some simple rules can lead to catastrophic brittle failure and potentially disastrous results. Brittle failure is not simply a failure of the product; it is a failure of the whole product design process. The designer has several possibilities for reducing brittle failure and these are shown in the diagram (below):



Reducing brittle failure

Design

Product designers can play a large part in avoiding brittle failure by following best practice in design such as:

- Avoid stress concentrators such as square or sharp corners that can act to initiate cracks and brittle failure. The Comet airplane disasters of the 1950's were due to square corners on the windows – these acted as stress concentrators for initial fatigue crack growth and final catastrophic brittle failure leading to the loss of two aircraft.
- Avoid abrupt changes in section thickness that can also act as stress concentrators.
- Avoid notches and undercuts (or at the very least give them a generous radius) to reduce stress concentration.

One of the keys to understanding design to avoid brittle failure is an understanding of the mechanics of fracture. This involves the use of 'fracture mechanics' to predict the effect of a stress concentrator (a crack or a notch) and the applied stress on the behaviour of a product. One of the significant results of fracture mechanics is that neither the applied stress nor the crack size is the sole determinant of the susceptibility to brittle failure – it is the vital combination of the two that determines if a part will fail. Fracture mechanics is beyond the scope of this document but offers a set of tools and techniques to help designers produce parts that will fail safely rather than catastrophically.

Material selection

Selecting the right material is a key to avoiding brittle failure and selecting a material with a high fracture toughness (K_c) will generally reduce the probability of brittle failure.

If fracture toughness data is not available (it is geometry dependent for most materials) then select materials that tend to fail in a ductile manner, e.g., stiff and strong materials that yield before failure and have a large area underneath the stress-strain curve.

If none of this data is available then select materials that have high impact strength values.

Material modification

Poor material structure will increase the probability of brittle fracture but if the material is suitably modified then it can also reduce it. Polymer blends can be created to reduce the probability of brittle fracture and typical cases are:

- The modification of PVC-U with acrylic additives to give 'impact modified' PVC-U with increased impact strength and reduced possibility of brittle failure.
- The addition of small amounts of rubber to various polymers to toughen the base polymer.
- The use of co-polymers such as ABS (acrylonitrile butadiene styrene) instead of homopolymers

such as PS to incorporate the rubbery phase directly into the polymer and provide improved resistance to brittle failure.

6. Summary

Failure of plastics products is inevitable as there will always be situations where the applied loads exceed the design loads. Despite this, product designers need to understand that good design and materials selection can reduce the possibility of catastrophic brittle failure and encourage ‘graceful’ ductile failure.