Plastics Topics – Impact and plastics

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Plastics Topics – Impact and plastics

1. Introduction

The impact performance of plastics is one of the key functional performance characteristics but it is also one of the least well understood and the most difficult properties to measure and predict. Impact strength can be defined as 'the ability of a plastic to withstand a rapidly applied load' but as with most things in the plastics world it is not always as simple as that.

Most people will be familiar with plastics that fail in a 'brittle' manner at room temperature, are easy to break and therefore will have a low impact strength, e.g., polystyrene, PMMA, and unplasticized PVC. Equally they will be familiar with plastics that fail in a 'ductile' manner at room temperature, are difficult to break and therefore will have a higher impact strength, e.g., PE, PP and plasticized PVC.

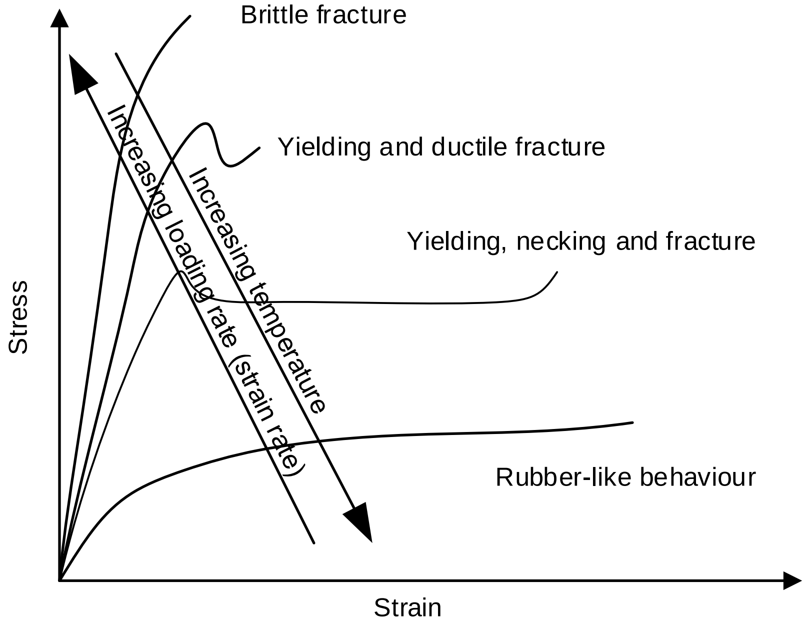
The impact performance of plastics is important for many applications such as:

- Car parts (in collisions and in normal use).
- Aircraft parts.
- Drinks bottles.
- Electronics enclosures and components.
- Storage containers.
- Toys.

Failure under impact is one of the main failure mechanisms for plastics and understanding what happens under impact loads is fundamental to producing products that are fit for purpose.

2. The ductile-brittle transition in plastics

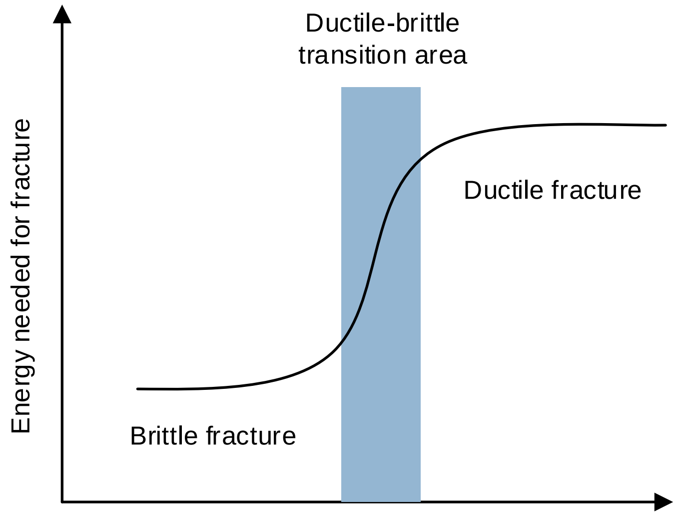
The stress-strain curve for a typical plastic is highly dependent on the temperature at which the material is tested. At low temperatures most plastics behave as brittle materials and there is very little deformation or strain before failure. At high temperatures most plastics behave as ductile materials and there is considerable deformation before failure. This typical behaviour and a range of intermediate responses is shown below:



The effect of temperature and loading rate (strain rate) on the stress-strain curve of a typical plastic material.

The behaviour of plastics shows a 'time-temperature equivalence', i.e., the response of many plastics to loads at high temperatures is the same as the response at slow loading rates. It will come as no surprise that the shape of the stress-strain curve is also affected by the rate of loading (the strain rate) and that increasing the loading rate has much the same effect as decreasing the temperature. At high loading rates most plastics behave as brittle materials and there is very little deformation or strain before failure. At low strain rates most plastics behave as ductile materials and there is considerable deformation before failure.

This fundamental change in failure mode from ductile to brittle failure is called the 'ductile-brittle transition' and is present in many materials (not simply plastics but also many metals). The ductile-brittle transition is perhaps best shown by looking at the amount of energy needed for fracture (the area under the stress-strain curve) and how this varies with temperature and loading rate. A schematic representation of the ductile-brittle transition for many materials is shown below:



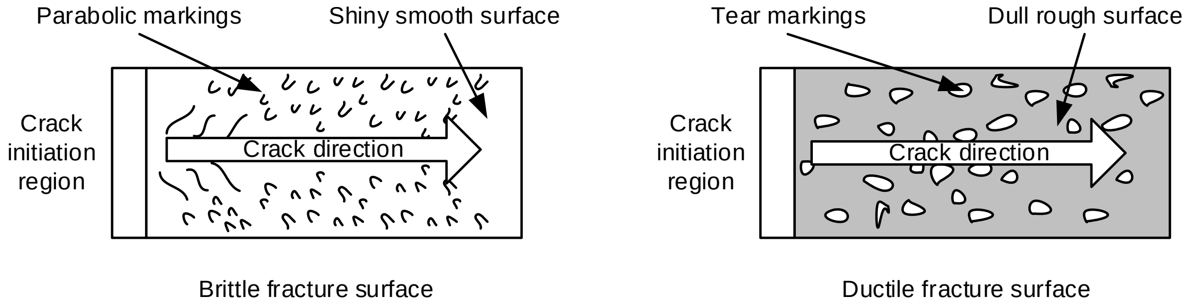
The ductile-brittle transition

Increasing the temperature or decreasing the loading rate eventually changes the fracture mode from brittle to and increases the energy needed for fracture. It is important to note the ductile-brittle transition occurs over a range of temperatures/loading rates and not at a specific temperature/loading rate. There is no single value for the ductile-brittle transition temperature – it occurs over a range of temperatures/loading rates. For most plastics, the ductile-brittle transition occurs in the region of the glass transition temperature (Tg).

The glass transition temperature (Tg) is the temperature at which the polymer chains stop being able to slither over one another, the plastic begins to stiffen up and effectively becomes a glassy solid. As with the ductile-brittle transition, the glass transition takes place over a range of temperature (between 10-50°C) and once a plastic has been cooled below Tg then, in general, it is stable and no other transitions occur. At temperatures greatly below Tg, plastics act as stiff and glassy solids, impact resistance is hugely decreased and low energy brittle failure becomes the main cause of failure. At temperatures greatly above Tg, plastics act as rubbery solids and impact failure does not generally occur.

3. The fractography of brittle and ductile failure

Fractography (the study of fracture surfaces) reveals a distinct difference between brittle and ductile fracture surfaces. Brittle fracture is characterized by a shiny, smooth surface and there are often 'parabolic markings' which tend to point back to the crack initiation point or region whereas ductile fracture is characterized by a dull, rough surface and significant amounts of surface deformation (tearing). This is shown below:



Fracture surfaces for brittle and ductile failure

This difference in the fracture surface reflects the difference in the energy needed for failure. The smooth surface of brittle fracture is the result of rapid crack propagation where very little energy is used to separate the crack surfaces. The rough dull surface of ductile fracture is the result of slower crack propagation where a lot of energy is used to separate the crack surfaces.

4. Impact failure of plastics

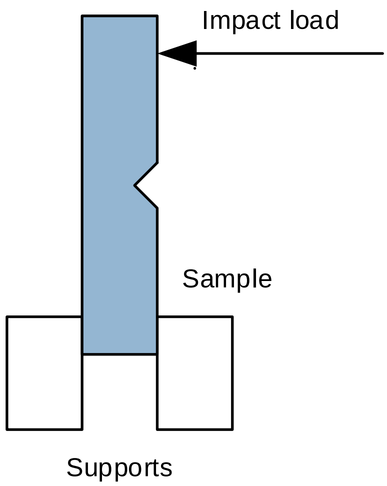
Impact failure of plastics is always brittle failure, uses low amounts of energy to propagate the crack and has relatively smooth crack surfaces (compared to ductile failure). Failure under impact loading is very important to product designers because it is always rapid and catastrophic. There is no 'safety net' of ductile failure and yield and the result is a complete failure of the product.

Despite the importance of impact failure to product designers, assessing the resistance of finished product to impact failure is very hard. The impact strength of a sample of a given material is relatively easy to assess from the standard tests (see below). It is the translation of this impact resistance number into useful design data that presents the real problem.

5. Testing for impact performance

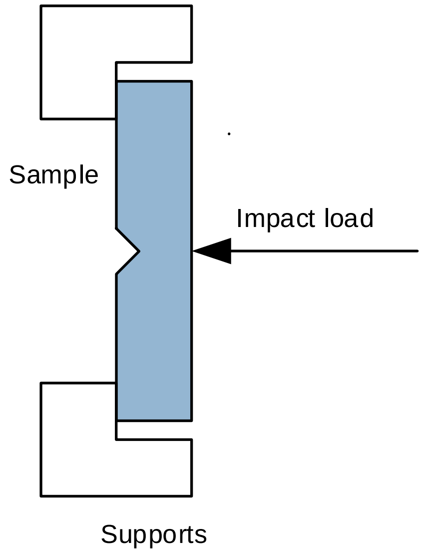
Impact testing measures the amount of energy used to fracture the material and is relatively easy to carry out and some of the most common methods used are:

- Izod impact testing – This is used for rigid plastics and a falling weight on a pendulum strikes a notched cantilevered sample as shown below. The loss of energy from the pendulum on breakage of the sample is a measure of the fracture energy and the impact resistance of the material.



Schematic of the Izod impact test

- Charpy impact testing – This is also used for rigid plastics and is similar to the Izod test except the sample is supported in both sides to give three point bending and may be notched or un-notched. The falling weight strikes the sample as shown below:



Schematic of the Charpy impact test

- Falling dart impact testing – This is used for testing thin films or sheets and a steel dart is released from a specified height to fall onto a supported sheet of the material.
- Tensile impact testing – This uses a sample which is fractured not in the bending mode (as for the Izod and Charpy tests) but in the tensile mode.

Most of these tests provide similar results for similar materials and there is a very good correlation between Izod and Charpy test results for plastics. Whichever method is used, the fundamental problem is in relating the test results for a given material to the behaviour of the material in service particularly when a complete product is considered. Impact testing can provide a relative ranking of materials for a given test but does not allow scale-up of the results to larger samples and certainly does not allow assessment of the performance of a given part in a specific application and under specific environmental conditions.

Toughness (which an impact test attempts to measure) is very sensitive to sample geometry and loading conditions. Impact test results should therefore be used with great care and testing on production articles at the specific service conditions is necessary for confidence that the product is suitable for use.

6. Improving the impact performance of materials and products

Whilst it is difficult to predict the response of specific material or product design to impact loading, there are a range of methods available to improve the impact performance of a material or product and designers need to be aware of these for both materials selection and product design.

Materials

The impact resistance of a specific plastic is a function of many materials factors but as a general rule, any factor which improves the ductility of a plastic will increase the impact strength of the material. The main methods used to improve impact performance of a material are:

- Copolymers – Adding or grafting an impact resistant polymer to the main polymer chain can be used to form a copolymer with better impact properties. Perhaps the best know application of this method is the addition of butadiene rubber to styrene acrylonitrile (SAN) to produce acrylonitrile butadiene styrene (ABS). The rubbery butadiene molecules change the very brittle SAN into the more ductile and impact resistant ABS.
- Blending polymers – Adding a second polymer (with better impact properties) to form a blend can improve impact performance, i.e., adding PE-HD to PP can improve the impact performance of the PP. Addition of a rubbery material is particularly effective as the rubber phase deforms easily and slows down the crack. The addition of small amounts of rubber is used to improve the impact performance of PVC, i.e., impact modified PVC.

Note: Producing a blend is not the same as forming a copolymer where the changes are in the actual polymer chains themselves.

- Plasticizers – The inclusion of plasticizers in plastics will make the plastic more flexible and increase the impact strength. One of the largest uses of this method is in PVC where plasticizers are used to convert the normally brittle unplasticized PVC into plasticized PVC with much better impact resistance.
- Crystallinity – High levels of crystallinity in a crystalline polymer tend to make the material stiffer and less impact resistant than similar materials with lower levels of crystallinity. This is because the large volumes of crystalline material tend to be difficult to move and reduce the ductility of the plastic.
- Reinforcement – Plastics containing reinforcements, e.g., fibres, are a special case for impact measurement. For most materials, high impact strength implies a 'tough' ductile failure but materials such as fibre reinforced polyesters can have very high impact strength as a complete material despite the fact that the matrix fails in a brittle manner. This is because a large amount of energy is absorbed in the crack running along the fibre/matrix interface (debonding).

7. Product design

The main methods used to improve impact performance of a product are:

- Notch sensitivity – A notch or defect acts as a stress concentrator and impact failure will almost always occur at these stress concentrators. For any material the presence of a notch or defect will reduce the impact strength because of high stress levels at the notch or defect. Reducing the radius of the notch or the effective defect radius will increase the impact strength and other stress related service properties. Product designers should recognize this and product designs should always include generous corner radii to remove stress concentrations. Increasing the number or size of notches present in the material or part will lead to a decrease in the impact resistance.

Note: Some materials are more sensitive to the presence of stress concentrators than others, they are termed 'notch sensitive', and for these materials the presence of a notch will reduce the impact strength even more than for materials that are relatively 'notch insensitive'.

- Orientation – The impact strength of a material depends on the orientation of the polymer chains and will be less when the load is applied parallel to the polymer chains than when the load is applied across the polymer chains. Tooling designs or practices that lead to high degrees of post-moulding orientation will result in products that are more susceptible to impact failure in certain directions.

8. Summary

Impact loading and the resultant brittle failure is a major cause of catastrophic failure in plastics products. Designing products to be impact resistant is a combination of intelligent materials selection and good design practices. The selection of the best material for impact resistance can be assisted by testing but test results provide a ranking of materials rather than a design parameter. Design for impact resistance is critical also important and product designers need to not only follow good design principles but also be aware of the potential for tooling to adversely affect the impact resistance of the final product.