Tensile Testing of Polymers
High-Strain Behaviour and Failure

If a material is subjected to high-strain deformation, it deforms permanently (plastic deformation) and ultimately fails. In the figure, we show a graph of stress-strain behaviour over the entire strain range and the ultimate failure (rupture) for a typical polymeric material subjected to a tensile test. For sufficiently low stresses and strains, the polymeric material behaves as a linear elastic solid. The point where the behaviour starts to be non-linear is called the proportional limit. The local maximum in the stress-strain curve is called the yield point and indicates the onset of plastic (i.e. permanent) deformation. The corresponding stress and elongation are called yield strength and elongation at yield. Beyond the yield point the material stretches out considerably and a "neck" is formed; this region is called the plastic region. Further elongation leads to an abrupt increase in stress (strain hardening) and the ultimate rupture of the material. At the rupture point the corresponding stress and strain are called the ultimate strength and the elongation at break, respectively. The stress-strain behaviour of a polymeric material depends on various parameters such as molecular characteristics, microstructure, strain-rate and temperature.
Tensile Testing: Isochronous stress-strain curves

- Deviation from linearity begins at strains 0.001 to 0.01
- At higher strains (0.01 to 0.1) the deviation becomes so large that

$$\frac{d\sigma}{d\varepsilon} = 0 \rightarrow \text{Yield Point}$$

- Some plastics fracture before yielding (e.g. PS) or immediately after while others (ductile plastics such as PE) can reach strains as high as 25 before final failure
- By contrast with metals, it is difficult to make a distinction between recoverable (elastic) and non-recoverable (plastic) strain, because the extent to which a polymer recovers its original dimensions depends upon temperature and upon time allowed for recovery (the driving force for recovery is entropic).
EXAMPLE 1: LDPE vs HDPE

The low density polyethylene (LDPE) has branched polymer chains and therefore the structure of this grade of polyethylene is largely amorphous. It has a density of approximately 0.92 and a melting temperature of 115°C. The merits of the polymer are its low cost, flexibility at temperatures down to −120°C, high toughness and chemical inertness to a wide range of liquids and solids. The major applications of low density polyethylene are therefore in packaging, toys, housewares and insulation for electrical cables.

High density polyethylene (HDPE) has a higher degree of crystallinity than the low density grade, resulting in improved strength and stiffness. The density is approximately 0.96 and melting temperature 135°C. The improved mechanical properties, coupled with chemical inertness and resistance to permeation, make this type of polymer ideal for blow moulded containers, dustbins, milk crates, tissue film, pipe and structural panels.

![Graph showing force vs extension for LDPE and HDPE](http://www.tq.com/product/index.html)

Extension rate: 26 mm/min
EXAMPLE 2: PS vs toughened PS

Polystyrene and Toughened Polystyrene

Polystyrene is a glassy, brittle polymer with low toughness and a softening temperature of only 100°C. Its advantage over other polymers is the ease with which it can be processed by extrusion, injection and vacuum forming. Polystyrene is therefore used for a wide range of cheap products like trays, boxes and toys. The brittle characteristics of polystyrene can be relieved by the incorporation of around 5% butadiene rubber into the microstructure. The rubber exists as second-phase particles of approximately 1 mm diameter and these increase the toughness of polystyrene by an order of magnitude.

![Graph showing the force-extension relationship for PS and toughened PS. The graph indicates that toughened PS has a higher force at a given extension compared to PS. The extension rate is 26 mm/min.]
 EXAMPLE 3: PA 6,6 vs glass filled PA 6,6  
Nylon and Glass Filled Nylon  

Nylon 66 is a tough, semi-crystalline polymer that is widely used in all branches of industry for load-bearing applications. In particular, its abrasion resistance and low surface friction make it suitable for gears, cams and bearings. In the automotive industry it is employed in door locks, filters, ball joints, bearings in suspension and steering systems. Domestic applications include curtain rail fittings, door furniture, food mixers and vacuum cleaners. Glass fibres can be added to Nylon 66 to increase the strength and stiffness, but at the expense of elongation and toughness. The glass addition also improves dimensional stability. The users of glass-filled nylon are similar to those of the unfilled grade but with the added capability of being operated at higher stress levels, or under conditions where creep resistance is required.

![Graph](http://www.tq.com/product/index.html)
EXAMPLE 4: PC

Polycarbonate is a very tough, glassy polymer. It has good mechanical properties down to –90°C and up to 130°C, excellent dimensional stability, good weather and chemical resistance, transparency to light and resistance to burning. This combination of properties enables the polymer to be used for crash-helmet visors and transparent roof panels. Domestic applications include sterilizable babies’ feeding bottles, hair curlers and hair dryers.

![Graph showing force vs. extension with an extension rate of 26 mm/min](image-url)
EXAMPLE 5: PP
Polypropylene has higher strength and stiffness than polyethylene and better heat resistance (melting temperature approx. 160°C) so it can be used in applications where contact with hot water and steam may be involved, e.g. hospital and laboratory equipment, car radiator reservoirs and washing machine/dishwasher components. Polypropylene sheet is fabricated into chemically-resistant tanks, and filaments are used for rope and netting. The disadvantages of polypropylene are its loss of flexibility at temperatures below 0°C and it is more permeable to gases than is high-density polyethylene due to its lower degree of crystallinity.

Extension rate: 26 mm/min
EXAMPLE 6: PMMA

An example of an acrylic polymer is polymethyl methacrylate (PMMA), which is a glass material a little tougher than polystyrene. In its pure form it is completely transparent and resistant to outdoor weathering. The polymer is therefore widely used as a replacement for glass in applications like lights, signs, lenses, aircraft windows and traffic control lights. The breaking resistance of acrylic sheet is approximately ten times that of window glass.

![Graph showing force vs. extension with an extension rate of 26 mm/min]
<table>
<thead>
<tr>
<th></th>
<th>HDPE</th>
<th>Toughened PS</th>
<th>LDPE</th>
<th>PS</th>
<th>PA 6,6</th>
<th>Glass Filled PA 6,6</th>
<th>PC</th>
<th>PP</th>
<th>PMMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limit of proportionality (MPa)</td>
<td>15</td>
<td>20</td>
<td>5</td>
<td>40</td>
<td>60</td>
<td>125</td>
<td>35</td>
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<td>70</td>
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<tr>
<td>Maximum strength (MPa)</td>
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<td>10</td>
<td>40</td>
<td>70</td>
<td>125</td>
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<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Elongation (%)</td>
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<td>40</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>&gt;50</td>
<td>&gt;100</td>
<td>0</td>
</tr>
</tbody>
</table>

$1 \frac{N}{mm^2} = 1 \frac{N}{(10^{-3}m)^2} = 10^6 Pa = 1 MPa$
COMPARISON TO EXPERIMENT - POLYMERS

Once strains $\sim 1\% - 2\%$ are reached, various types of deviations from ideal behavior are observed:

![Stress vs Strain Graph]

- Glassy polymer or semi-crystalline polymer below Tg
- Semi-crystalline polymer above Tg
- Rubber
THE EFFECT OF HEAT ON THE MECHANICAL PROPERTIES OF GLASSY POLYMERS

Stress-strain curves for polystyrene (PS) and polyethylene (PE)

the strain \( \varepsilon = \frac{L - L_i}{L_i} = \lambda - 1 \), where \( L_i \) is the initial length, \( L \) is the length at which point the force is \( F \) and \( \lambda \) is the extension ratio.

the nominal stress \( \sigma = \frac{F}{A_i} \), where \( A_i \) is the initial area of the cross-section;

For PE:

◆ From 0 to point A, the PE behaves as a linear elastic solid, which the point A is the proportional point. At this region

the Young's modulus \( E = \frac{\sigma}{\varepsilon} \)

◆ Point B is called the yield point and indicates the onset of plastic deformation. The corresponding stress and strain are called yield strength and elongation at yield.
For PE:

- From B to C it is the plastic region. Beyond B the material stretches out considerably and a “neck” is formed. The neck stabilizes and begins to extend by drawing fresh materials from the tapering regions on either side until the whole of the parallel section of the specimen has yield. Then during the alignment and orientation of the polymer chains, which is called strain hardening, the neck will continue to thin down until it breaks. The point C is the break point, at which point the corresponding stress and strain are called the ultimate strength and the elongation at break.

- The necking of polymers is affected by two opposing factors: 1) Dissipation of mechanical energy as heat can raise the temperature in the neck, causing significant softening; 2) the deformation resistance of the neck, which has a higher strain rate than the surrounding polymer, can rise as a result of the strain-rate-rate dependence of the yield stress.

- Slip occurs: both in the crystalline lamellae and the individual lamellae.
For PS:
• Behaves very differently, forming crazes (πορώδεις ρωγμές) at very low strain and fracturing without showing any significant deviation from a linear stress-strain curve.
• The graph shows the intricate network of fibrils (ινώδεις γέφυρες) connecting the two bulk surfaces of the polymer. The fibrils are drawn out of the solid polymer to an extent that is controlled by the concentration of molecular entanglements.
• There are interesting parallels between macroscopic drawing in PE and the microscopic internal drawing of craze fibrils in PS.

A craze in polystyrene; the arrow indicates direction of tensile stress (after R.P. Kambour)