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Stress Strain Behavior of Polymers

Introduction:

The Stress/Strain behavior of solid polymers can be categorized into several classes of behavior:

> **1) Brittle Fracture- characterized by no yield point, a region of Hookean behavior at low strains and failure characterized by chonchoidal lines such as seen in inorganic glasses.**
>
> **2) Yield Behavior- characterized by a maximum in the stress/strain curve followed by yielding deformation which is usually associated with crazing or shear banding and usually ductile failure. Ductile failure exhibits a high extent of deformation on the failure surface. Yield behavior can result in necking which exhibits a close to constant load regime and a terminal increase in the stress.**
>
> **3) Rubber-Like Behavior- characterized by the absence of a yield point maximum but exhibiting a plateau in an engineering stress/strain curve. Often rubber-like behavior exhibits a terminal increase in the stress followed by failure which results in a tear with little permanent deformation exhibited in the failure surface, e.g. Jell-O.**

The following figure from Ward shows that all three of these failure types can be seen in a single polymer by variation of either time (rate of deformation) or temperature. A good example of this is *silly putty* . Generally, a single polymer sample displays one of the characteristic failure mechanisms under normal conditions, i.e. polystyrene exhibits brittle failure, polyethylene displays necking, crosslinked polydimethylsiloxane displays rubbery behavior, high impact polystyrene displays yielding behavior. The type of behavior can also change with the type of deformation, i.e. polystyrene displays crazing or brittle failure in tension but displays shear banding and yield behavior in compression.

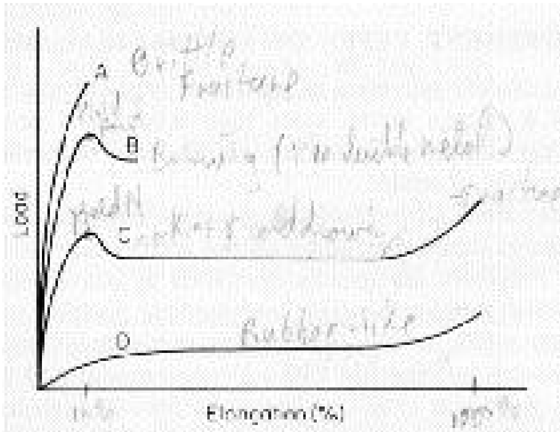


Figure 2.1. Load-elongation curves for a polymer at different temperatures. Curve A, brittle fracture; curve B, ductile failure; curve C, cold-drawing; curve D, rubber-like behaviour.

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

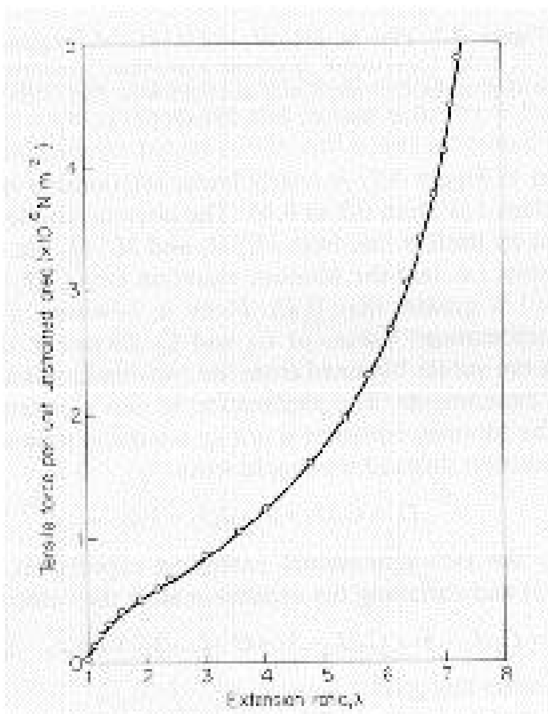


Figure 3.6. Typical force extension curve for natural rubber. [Redrawn with permission from Treloar, *Introduction to Polymer Science.* Wykeham Publications (London) Ltd, London and Winchester 1970.

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

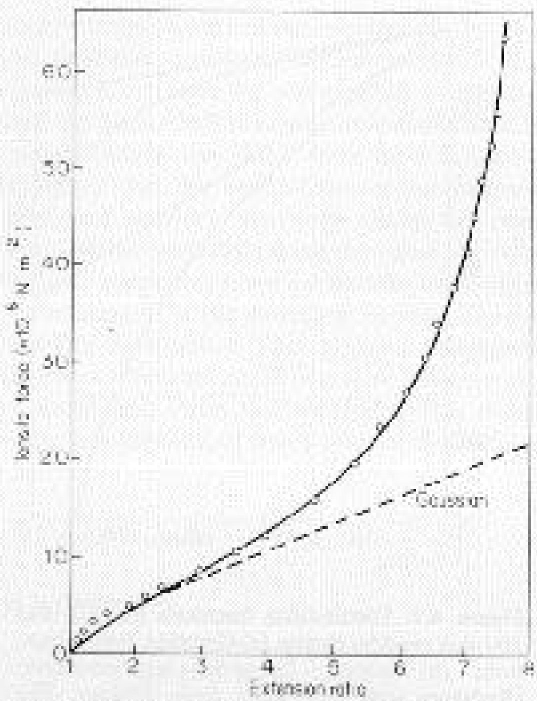


Figure 4.8. Theoretical non-Gaussian free-extension curve—obtained by fitting experimental data 0 to the James and Guth theory, with NkT = 0.273 MNm^{-2}, n = 75. [Redrawn with permission from Treloar, *The Physics of Rubber Elasticity*, 3rd edn, Oxford University Press, Oxford, 1975.]

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

Deformation of Semi-Crystalline Polymers:

Semi-crystalline polymers such as polyethylene typically display necking behavior and a yield point in tensile stress/strain curves. Yield points are always associated with a deformation mechanism which absorbs energy. For semi-crystalline polymers this mechanism involves orientation and destruction of micron to colloidal scale semi-crystalline morphologies.

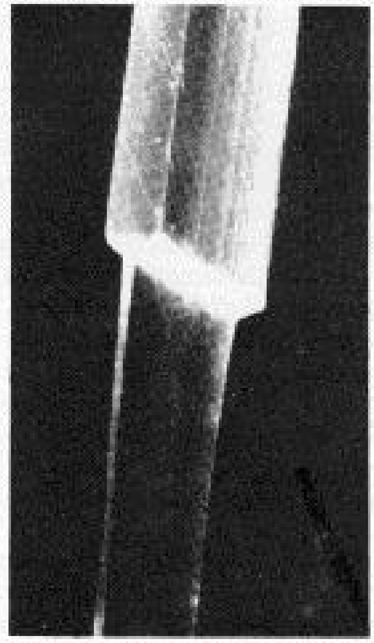


Figure 11.1. Photograph of a neck formed in the redrawing of oriented polyethylene.

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

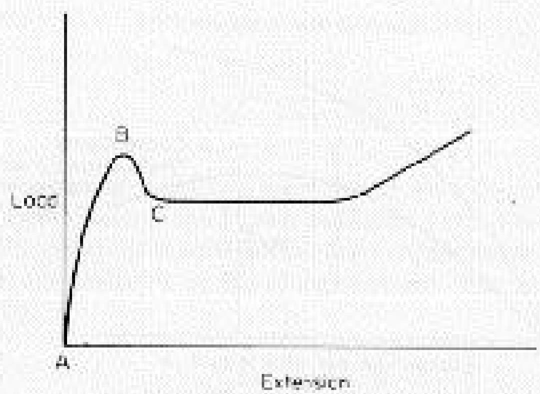


Figure 11.2. Typical load–extension curve for a cold-drawing polymer.

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

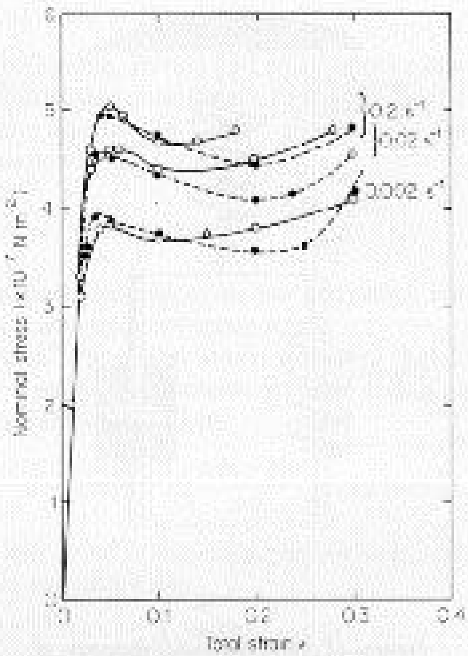


Figure 11.42. Stress–strain curves for cellulose nitrate at 23°C. Experimental curves (○) and calculated curves, Langevin model (●), $n^{-1/2} = 0.30$, $N = 1.57 \times 10^{26}$ chain m^{-3}. [Redrawn with permission from Haward and Thackray, *Proc. Roy. Soc. A*, **302**, 453 (1968).]

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

Shear Banding Deformation:

Many polymers display shear banding which is characterized by planes of slip at 45° to the direction of stress. Shear bands do not involve changes in the volume of the sample (dilatation) seen in crazing. Under an optical microscope using crossed polars samples which have under gone shear banding will display X's reflecting the two planes of maximum shear stress in a tensile sample. Shear banding involves localized orientation of the polymer. Because of this it is highly temperature and rate dependent.

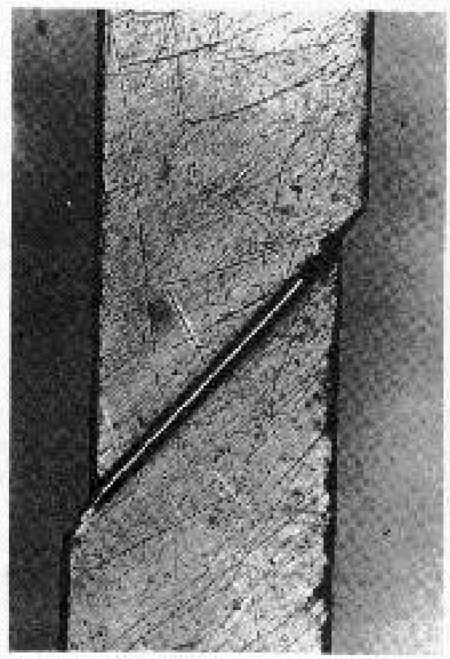


Figure 11.26. Photograph of a deformation band in an oriented sheet of polyethylene terephthalate.

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

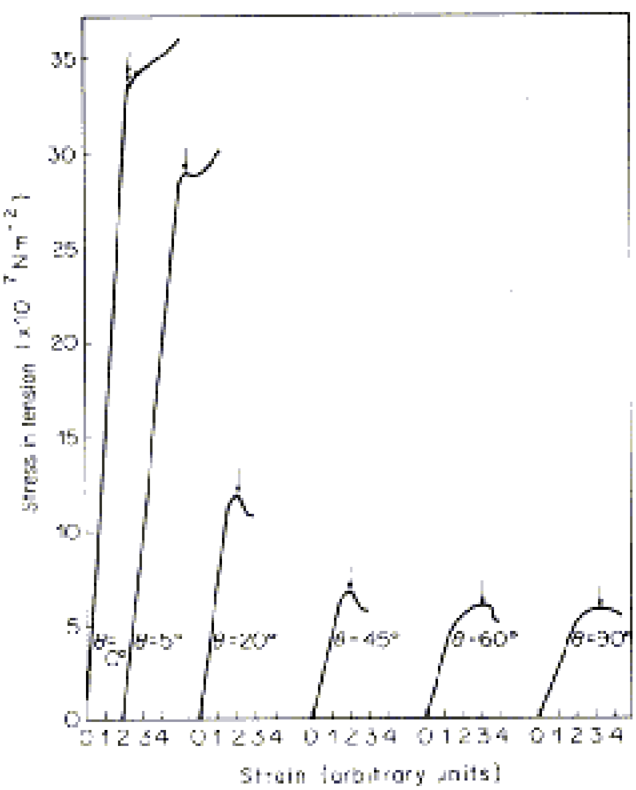


Figure 11.28. Stress-strain curves for various angles θ between the tensile axis and the initial draw direction for tensile tests on drawn polyethylene terephthalate sheets. The yield points are marked by arrows. [Redrawn with permission

from Brown, Duckett and Ward, *Phil. Mag.*, **18**, 483 (1968).]

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

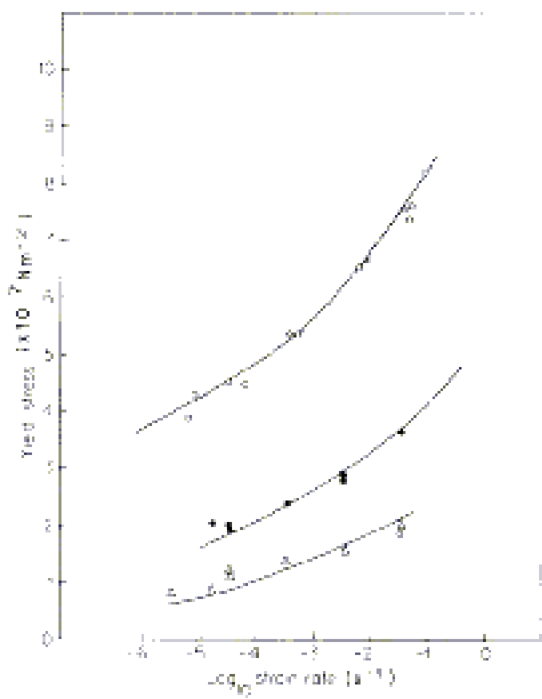


Figure 11.43. Yield stress of polymethyl methacrylate as a function of strain rate. ○, Compression at 23 °C; △, tension at 90 °C; ●, tension at 60 °C. Curves represent the best theoretical fit (see text).

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

Crazing Deformation:

Many polymers display another type of localized yielding behavior which results in whitening of the polymer in the region of maximum deformation. Under a microscope, these localized regions of yielding display an increase in volume (dilatation) through formation of micro-cracks which are bridged by polymer fibrils. Crazing and stress whitening are the typical deformation mechanism for polystyrene. High impact polystyrene contains small elastomer domains which serve to increase the number of crazes thereby preventing catastrophic failure by absorbing the energy of deformation. Because crazing is a dilatational mechanism it is expected to occur in regions of high dilatational stress such as in the interior of thick samples or at the lateral edges of a hole cut in a sample (see figure below).

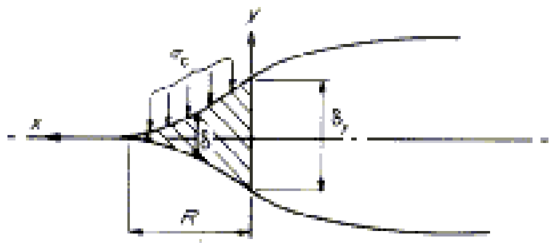


Figure 12.8. The Dugdale plastic zone model for a craze.

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

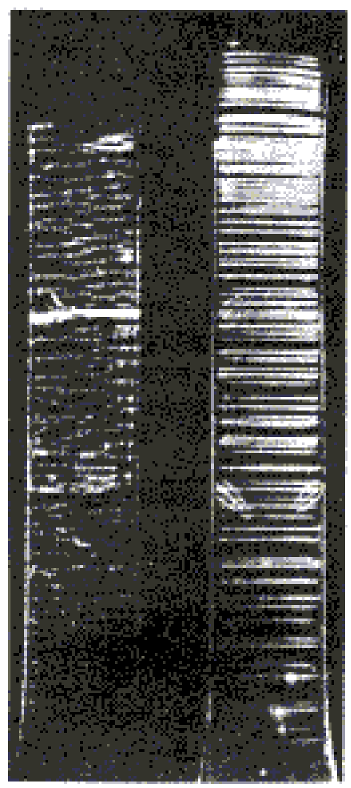
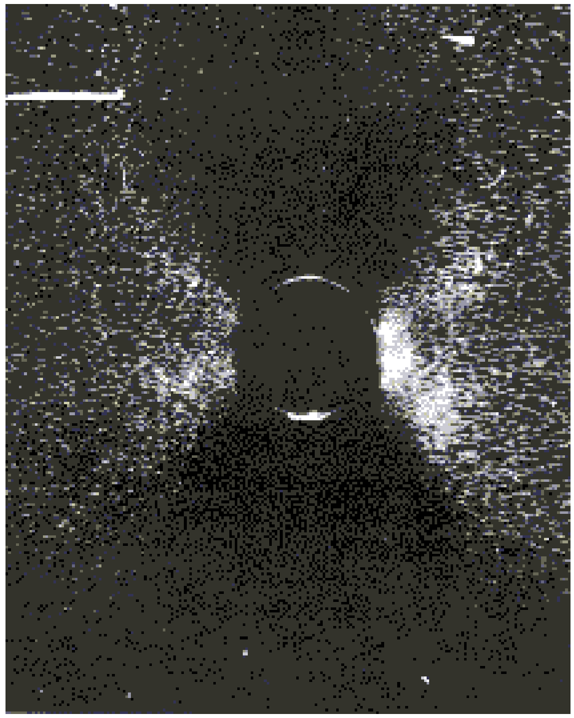


Figure 12.11. Craze formation in polystyrene.

From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***



From: ***I. M. Ward, "Mechanical Properties of Solid Polymers, 2'nd Ed." Wiley, NY, 1983***

Terminal Zone of Stress/Strain:

The terminal failure of a polymer stress strain curve is typically difficult to reproduce since it depends strongly on the presence of flaws. Terminal failure is usually characterized as either brittle or ductile referring to the appearance of the failure surface which is either smooth and sharp or rough and highly deformed. Elastomers typically fail which a high extent of deformation but yield smooth failure surfaces since most of the terminal deformation is reversible. The type of terminal failure is highly dependent on the temperature and rate of deformation and many polymers can display a brittle to ductile transition in temperature or rate of deformation as shown below.

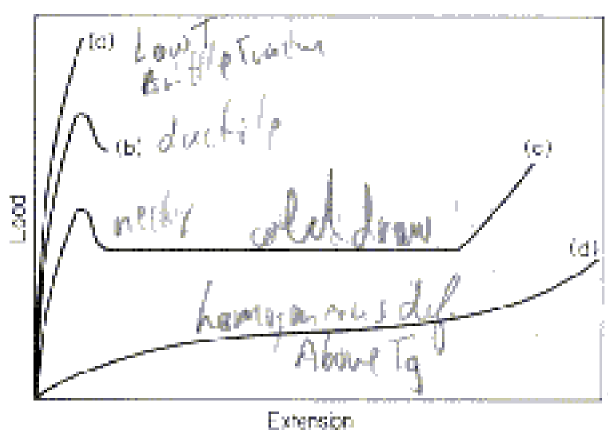


Figure 12.1. Load-extension curves for a typical polymer tested at four temperatures showing different regions of mechanical behaviour. (a) Brittle fracture, (b) ductile failure, (c) necking and cold-drawing and (d) homogeneous deformation (quasi-rubber-like behaviour).