

# General concept of material properties

strain(tensile) :  $e$  or  $\epsilon$  : Amount of deformation per unit

length from applied stress  
(Displacement or Elongation)  
Displacement is relative, so often  
expressed as

$$\frac{(I - I_0)}{I_0} = \frac{\Delta I}{I_0}$$

( $I$  : after deformed  $I_0$  : before deformed)

**Plastic strain** (irreversible when the applied stresses are removed)

**Elastic strain** (reversible when the applied stresses are removed)

stress(tensile):  $s$  : force per unit area

$$s = \frac{F}{A}$$

F : applied force

A : cross-section area

(unit : dynes/cm<sup>2</sup>(CGS), N/cm<sup>2</sup>(SI), lb<sub>f</sub>/in<sup>2</sup>(AM) = psi, Pa, Mpa)

# 1. Deformation

strain ~ stress

(Tensile) Modulus (= young's Modulus = Elastic Modulus = Modulus of elasticity) : **E**

: Ratio between the stress and strain

$$E = \frac{\text{stress}}{\text{strain}} \quad (\text{same unit as stress})$$

~ Resistance to (Tensile) stress

~ A measure of interatomic bonding forces

Most commonly used parameter characterizing material stiffness( )

Simply measured as a linear slope of a stress-strain(S-S) curve

If not linear, often from the slope at 0.2~1% elongation

- \* Low slope                      Ductile, weak
- \* High slope                     Stiff, Brittle

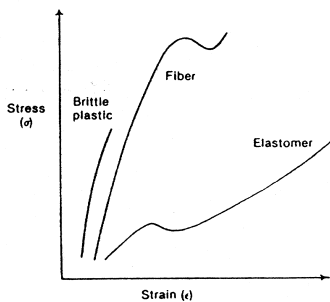


Figure 4.7. Characteristic tensile stress-strain behavior.

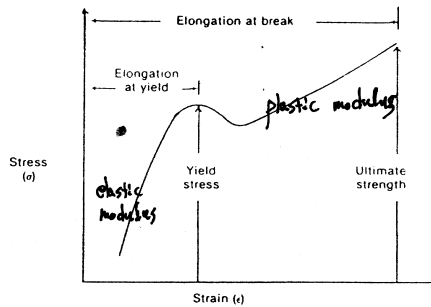
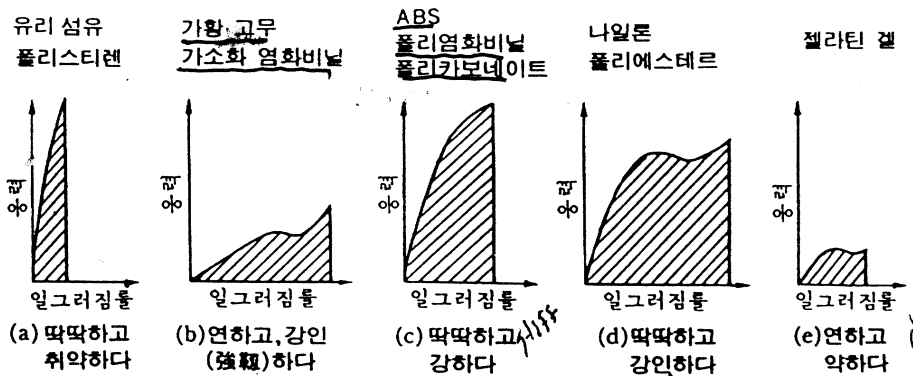


Figure 4.8. General tensile-strain curve for a typical thermoplastic



## Strength

: A measure of the level of the stress required to make a material fail  
 ~ Resistance to mechanical stresses

Calculated by dividing maximum load by original cross-sectional area of specimen (same unit as stress)

\* **Yield strength** : ability of a material to resist plastic deformation

Calculated by dividing the force initiating the yield by cross-sectional area

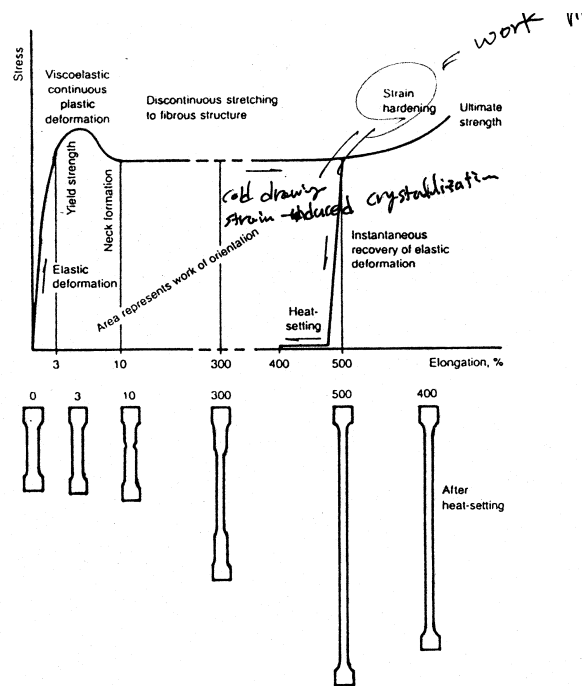


FIGURE 6.24. Schematic diagram of orientation process under cold drawing conditions and with heat stabilization.

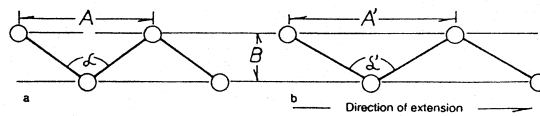


FIGURE 7.2. Positions of atoms (atom groups) (a) at rest and (b) under elastic strain (exaggerated). Initial changes take place in distance A and angle  $\alpha$  but not in distance B.

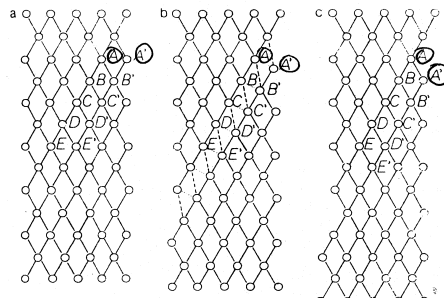


FIGURE 7.3. Positions of metal atoms (a) prior to extension, (b) during extension not surpassing 1%, and (c) after further extension. —, Tensile load-carrying bonds; load-carrying ability decreasing, ---, and increasing, ..., with extension.

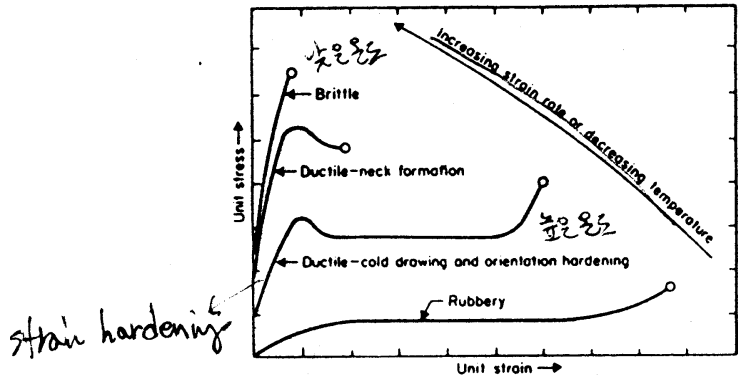


FIGURE 7.1 Typical stress-strain curves for thermoplastic materials. From J.R. Fried, *Plastics Engineering*, 33, July 1982.

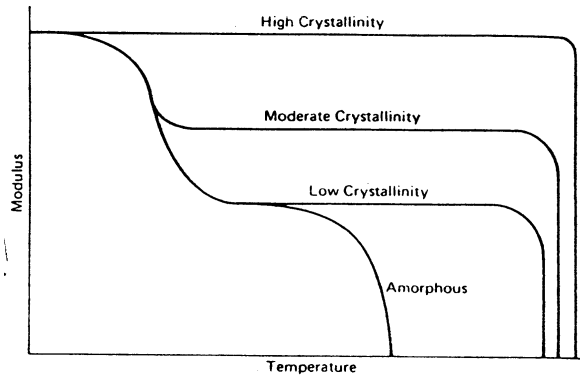
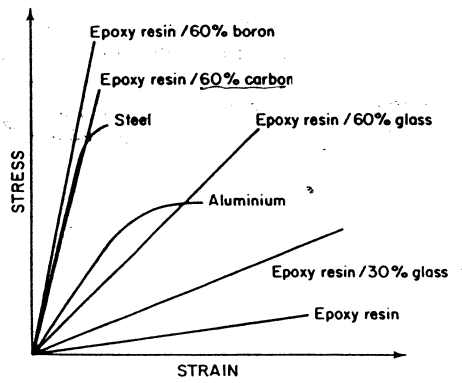


FIG. 3.5. Tensile behaviour of fibre-reinforced plastics and other structural materials. (Reproduced with permission of Marcel Dekker, Inc.<sup>14</sup>)



## Ductility ( )

: Amount of strain at failure ( Permanent deformation < Plastic strain > before failure)

Ductility                      Cross-section reduction before breaking

Measured as elongation or reduction in area at the point of fracture

$$\frac{(L_f - L_0)}{L_0} \qquad \frac{(A_0 - A_f)}{A_0}$$

\* **Elongation** : Increase in length of a tensile test specimen (fraction or %)

~ Axial strain accompanying fracture

~ Depends upon gage length

## Brittleness

: Opposite to toughness

Fractures with little energy absorption

~ Lower impact strength, Higher stiffness

## Toughness

: Energy required to break a material

(= Amount of energy absorbed by a material during failure)

Energy = Force × Distance

= area under the stress-strain curve

Energy                      Toughness

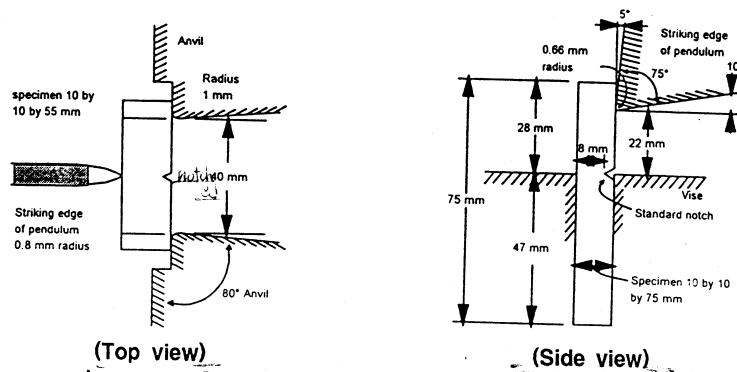
## Impact strength

- : Loss in energy on breaking the specimen obtained by recording the height of pendulum followed thought or dropped steel ball

### Note: Compression-after-impact(CAI)

- Used to measure the toughness of composites
- Used to simulate the in-service requirement to endure low energy impact
- Usually for composite materials being subjected to a low energy impact followed by a compression test to fracture

### § Standard Impact Test Methods



--- Pendulum impact tests---

#### [Charpy Method]

- Horizontally mounted
- Not clamped
- V-shape notched or unnotched

#### [Izod Method]

- Perpendicularly mounted
- Clamped
- V-shape notched or unnotched

#### [Falling-Weight Method]

- Ball, dart, missile types

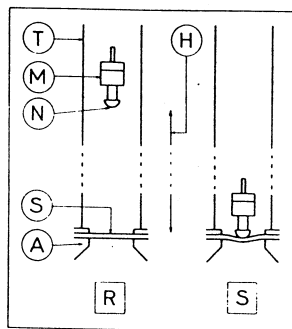


Figure 4.35 · Falling weight impact · [R] Release; [S] Strike; [T] Tower (drop tube); (M) Striker weights; (N) Striker nose; (S) Test specimen; (A) Annular support; (H) Drop height

## Fracture

: The creation of new surface within an object which leads to its disintegration, usually as a result of an applied load.

Fracture results in failure of the object

Fracture may be accompanied by associated crazing around the crack, especially with brittle materials, or by shear yielding, especially with ductile materials

- \* **Brittle Fracture** : Failure by crack propagation and with the absence of significant ductility at the crack tip
- \* **Ductile Fracture (Tough fracture)** : Failure by crack propagation accompanied by plastic deformation  
Significant plastic flow occurs before fracture

## Hardness

: Resistance of a material to penetration of its surface

Hardness ~ Strength

- \* **Brinell hardness number (BHN)**

: hardness index calculated from the area of penetration by a large indenter (Hard steel ball) {during 15 sec of the load}

$$BHN = \frac{2F}{\pi D^2 \left(1 - \sqrt{1 - \left(\frac{d}{D}\right)^2}\right)}$$

F : Load(kg)    D : Ball diameter    d : Impression diameter

- \* **Rockwell hardness (RH)**

: Measured by the depth of penetration by a small standardized indenter

( Pin & Ball type)

Different Rockwell scales (R, LM, E and K) with different loads and indenter diameters

- \* **Shore hardness (SH)**

: Simple indentation test involving the application of a force to vertical indenter using

a

calibrated spring

### **Crack**

: An actual separation of plastic visible on opposite surfaces of the product extending through the thickness

Represents a fracture of material

### **Crazing**

: The formation of small crack-like cavities in a material of a few micrometers in lengths

May form the sites for subsequent fracture by formation of larger crack

Formed by mechanical factor (stress) or by environmental factors (chemical)

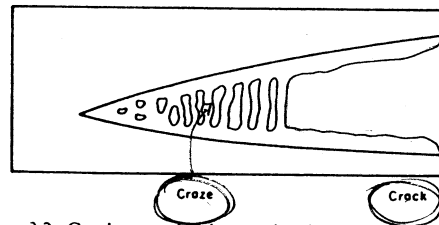


FIG. 3.2. Crack preceded by crazing in polymer failure.

### **Creep**

: A slow deformation by stresses below normal yield strength  
(~ Dimensional change in a viscoelastic material under continuously applied load(stress) over time beyond instantaneous elastic deformation)

\* Cold flow : Creep occurring at ambient temperature

\* Primary creep : Recoverable in time after load releasing

\* Secondary creep : Non- recoverable in time after load releasing

### **Fatigue**

: Progressive weakening of a material component with increasing time under cyclic loads at levels of stress below the static yielding strength

\* Fatigue life : Number of loading cycles to product failure usually by fracture



# Shear Yielding

**Yielding** : Plastic Flow

**Shear Yielding** : Partially crystalline polymer

**High Yield Point** : High elastic modulus, High ductility

## 1. Mechanics of Neck Formation

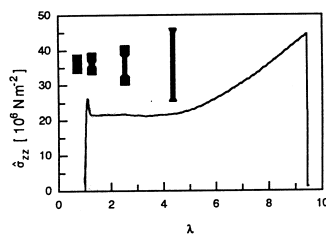


Fig. 8.1. Load ( $\sigma_{zz}$ : nominal tensile stress)-extension ( $\lambda$ : extension ratio) curve of a sample of PE ( $M = 3.6 \cdot 10^5$ , drawing velocity  $d\lambda/dt = 2.4 \cdot 10^{-2} \text{s}^{-1}$ ). The changes in the shape of the sample are schematically indicated



Fig. 8.2. Formation of shear bands at the begin of necking, observed for a sample of PC. The arrows indicate the direction of the applied tensile stress. Micrograph obtained by Morbitzer [82]

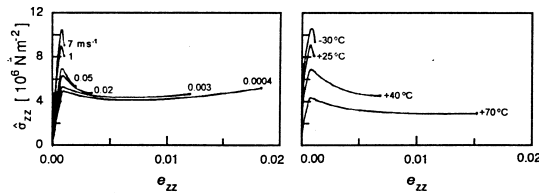
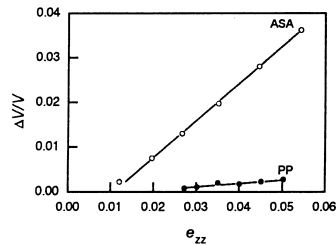


Fig. 8.4. Load-extension curves of PVC measured at room temperature for the indicated strain rates (*left*) and at different temperatures for a constant strain rate ( $\dot{\epsilon}_{zz} = 1 \text{ms}^{-1}$ ) (*right*). From Retting [83]



Tensile creep experiment : ASA indicated a deformation entirely by crazing, whereas the slope close to zero shown by polypropylene indicates nearly pure shear yielding

# 1. Mechanics of Neck Formation

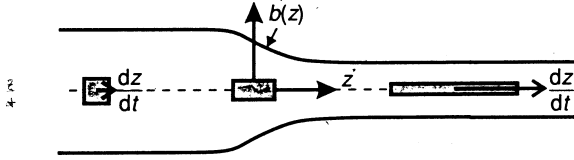


Fig. 8.6. States of deformation of a volume element passed over by a shoulder with the profile  $b(z)$ , and the velocity  $dz/dt$  relative to the shoulder

$$l_z(z) \rho l_p^2(z) = \text{const}$$

radius  $l_p$ , length  $l_z$

Its extension,  $l_z$ , depend on  $z$  only, being given by

$$I(z) = \frac{l_z(z)}{l_z(-\infty)} = \frac{l_p^2(-\infty)}{l_p^2(z)} = \frac{b^2(-\infty)}{b^2(z)}$$

The profile also determines the strain rate, by

$$\frac{dI}{dt} = \frac{dI}{dz} \cdot \frac{dz}{dt} = -\frac{2b^2(-\infty)}{b^3(z)} \cdot \frac{db}{dz} \cdot \frac{dz}{dt}$$

$dz/dt$  denotes the velocity of the volume element relative to the shoulder as measured in the moving coordinate system. Since the material flow through the shoulder is a constant, we may

write

$$b^2(z) \frac{dz}{dt} = \text{const}$$

and therefore obtain

$$\frac{dI}{dt} \approx -\frac{1}{b^5(z)} \cdot \frac{db}{dz}$$

or, in terms of the Henky strain rate employed in rheological treatments

$$e_H := \frac{1}{I} \frac{dI}{dt} \approx -\frac{1}{b^3} \cdot \frac{db}{dz}$$

The extension rate of the volume element is not constant, but strongly time-dependent.

The external force during cold-drawing is constant, the tensile stress acting on the volume element follows form

$$\mathbf{s}_{zz}(z) \cdot b^2(z) = \text{constant}$$

Stress and extension become linearly related

$$\mathbf{s}_{zz}(z) \approx \sigma(z)$$

If flow sets in locally and there the radius  $b$  of the sample begins to decrease, the extension of the volume element at the centerline is given by

$$\mathbf{I}(t) = \frac{b^2(0)}{b^2(t)}$$

The extension rate follows as

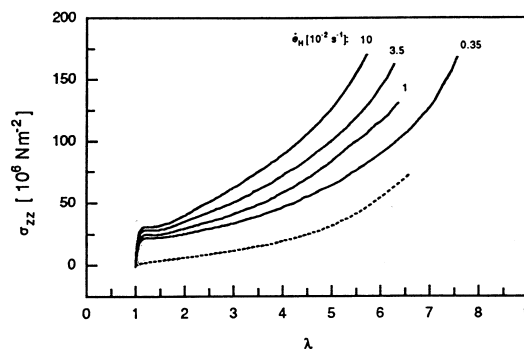
$$\frac{d\mathbf{I}}{dt} = -\frac{2b^2(0)}{b^3(t)} \cdot \frac{db}{dt}$$

and Hencky strain rate as

$$\dot{e}_H := \frac{1}{\mathbf{I}} \frac{d\mathbf{I}}{dt} \approx -\frac{2}{b(t)} \cdot \frac{db}{dz}$$

Thus correspond to an exponential time-dependence of the minimum radius in the flow zone

$$b(t) = b(0) \exp\left(-\frac{\dot{e}_H}{2} t\right)$$



**Fig. 8.7.** Stress-extension curves measured for a sample of PE ( $M = 3.6 \cdot 10^5$ ) at the indicated Hencky strain rates. Constant strain rates were realized by a registration of the strain at the location of a developing neck and a continuous readjustment of the applied tensile force, using an electronically controlled feedback circle. The *broken line* gives the  $\sigma_{zz}(\lambda)$ -curve measured for a poly(ethylene-co-vinylacetate) (27% vac-units,  $\phi_c = 0.30$ ). No strain rate dependence is observed for this rubbery material [85]

Stress increasing, extension decreasing      Hencky strain rate

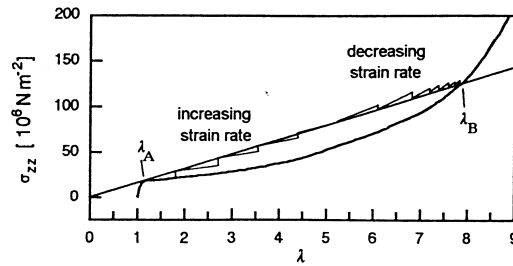


Fig. 8.9. Mechanical response of a volume element in a fiber with the shown  $\sigma(\lambda)$  dependence, if subjected to a linearly increasing stress as represented by the *straight line*. For a hypothetical sample without internal friction there is no equilibrium between  $\lambda_A$  and  $\lambda_B$ . In the real sample, a balance is achieved by the strain rate dependent viscous forces (*thin line with steps*)

If the load is high enough to include shear flow at a critical extension,  $\lambda_A$ , the stress will follow the straight line included in the figure. This implies a continuous transition from  $\lambda_A$  to  $\lambda_B$ . The establishment of force-balanced states also in the transition region is evidently accomplished by the strain rate effects. Quite generally, stresses grow and decay with increasing and decreasing strain rate respectively.

$$\dot{e}_H := \frac{1}{l} \frac{dl}{dt} \approx -\frac{1}{b^3} \cdot \frac{db}{dz}$$

$$s_y = s_0 \log(\text{const} \cdot \dot{e}_H)$$

## 2. Structure changes on cold-drawing

Evidently the extension introduces anisotropy in an originally isotropic sample due to the chain becoming preferentially aligned in drawing direction and this occurs for both partially crystalline and amorphous polymer

The crystallites in the partially crystalline sample or the Solid amorphous region in a glass.

**Stress overcome the yield point** these solid element are no longer stable

lamellar crystallites rotate

the solid glassy structure also is continuously reorganized

The reorganisation of the solid structure continues throughout the plateau region, being accompanied by an increasing chain alignment

Partially crystalline sample like PE The formation of a crystallite texture able to sustain high stresses

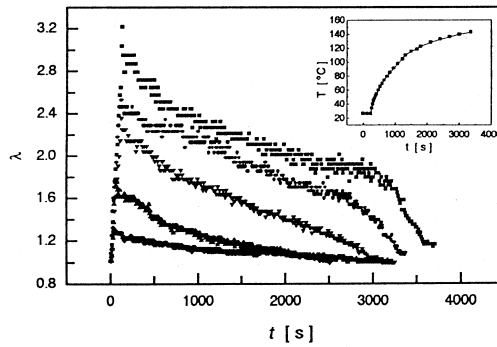


Fig. 8.11. Shrinkage of cold-drawn PE-samples (same as Fig. 8.7) upon heating. The heating-curve is given in the insert [85]

Heat up to  $T_m$ ,  $T_g$  cold-drawing Shrinkage is observed which finally results in a recovery of the shape before cold-drawing heating shrinkage continue finally bring the sample back to its original length the memory is preserved by the entanglement network

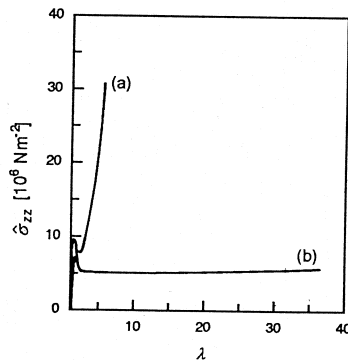


Fig. 8.12. Load-extension curves observed on drawing at room temperature a melt-crystallized sample of PE (a) and a gel-spun PE-fiber (b). From Lemstra et al. [86]

Entanglement density sample drawability

High molecular weight polyethylene is dissolved in a solvent, and the solution is spun through a die into a cooling bath, thus producing a gel-spinning.

Fig. 8.12 shows a typical load-extension curve.

Dissolution process the number of entanglements the drawability has increased tremendously

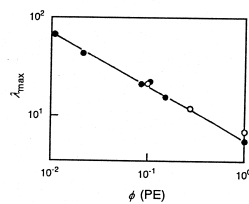


Fig. 8.13. Relation between the maximum draw ratio of a gel-spun PE fiber ( $M > 10^6$ ) and the concentration in the solution. Data from Iguchi and Kyotani [87]

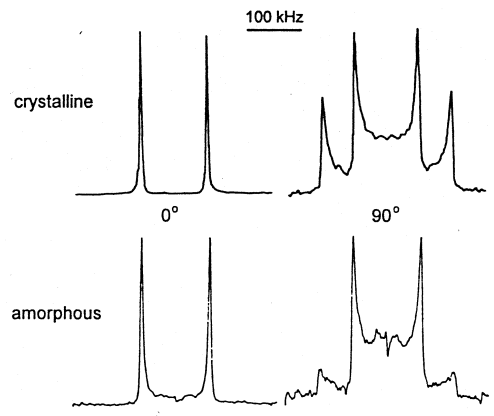


Fig. 8.14.  $^2\text{H}$  NMR spectra registered for the crystalline and the amorphous phase of cold-drawn PE. Spectra were obtained for orientations of the unique axis of the samples parallel ( $0^\circ$ ) and perpendicular ( $90^\circ$ ) to the magnetic field. From Spiess et al. [88]

Evaluation of the data indicates a substantially lower degree of orientation order in the amorphous regions than for the crystallites



Fig. 8.17. X-ray scattering patterns of PE, as registered for the isotropic part (*left*), the center of the shoulder (*center*) and the neck (*right*) of a cold-drawn sample. The two reflections in the isotropic pattern are to be assigned to the 110- and the 200-lattice planes of orthorhombic polyethylene. The third reflection with a larger lattice plane spacing emerging in the textured patterns is due to another metastable crystalline phase which forms during drawing [85]

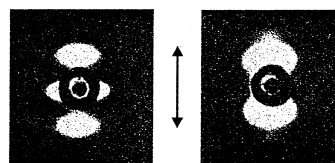


Fig. 8.18. SAXS diagrams registered for PE drawn in the solid state at  $70^\circ\text{C}$  directly after the drawing (*left*) and after a subsequent heat treatment at  $120^\circ\text{C}$  (*right*). The arrow displays the drawing direction. Experiment by Fischer et al. [90]