Ductility in steel reinforcement

Dr.Fahmida Gulshan
Assistant Professor
Department of Materials and Metallurgical Engineering
Bangladesh University of Engineering and Technology

Dhaka, Bangladesh. July 01, 2013

Ductile and Brittle material

- Ductility is a measure of the ability of a material to sustain plastic deformations before collapse.
- A material that experiences very little or no plastic deformation upon fracture is termed brittle.
- Concrete is a brittle material. The ductility within a reinforced c provided by

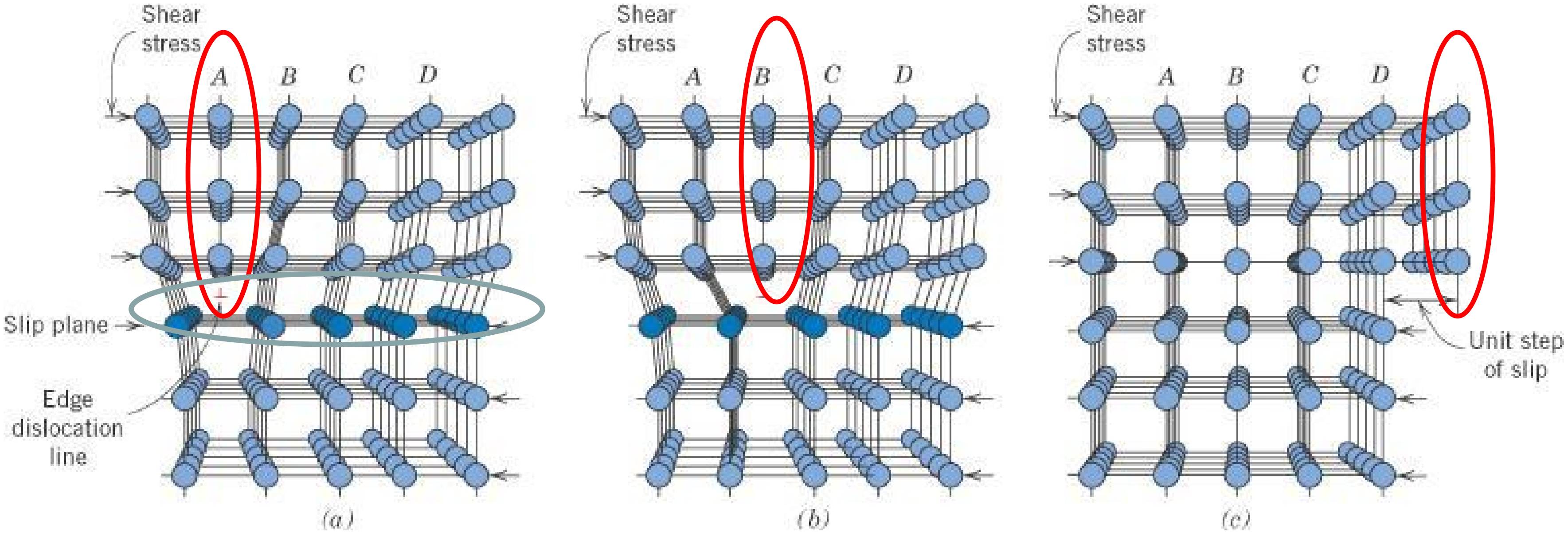
(a)

Cup and cone fracture

(b)

Brittle fracture

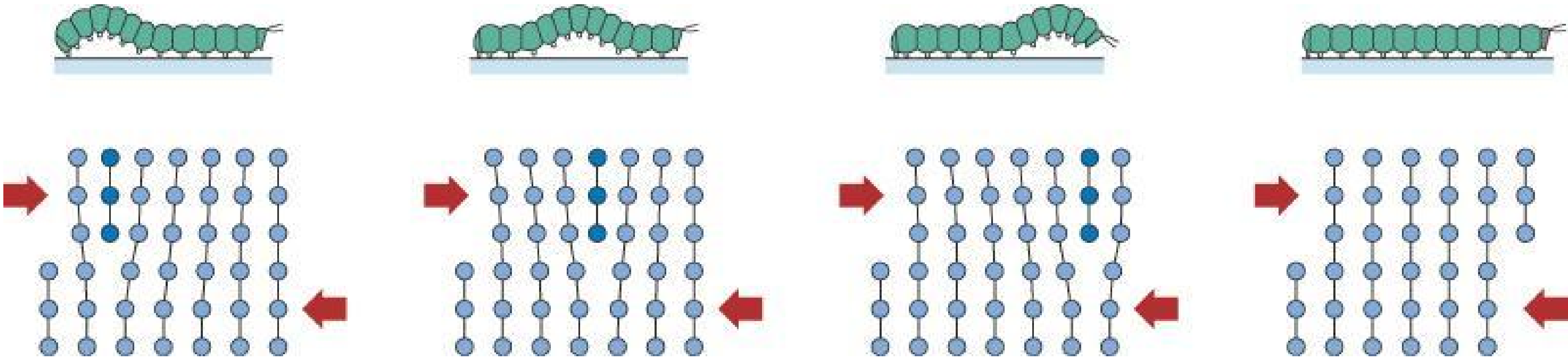
How a material deforms

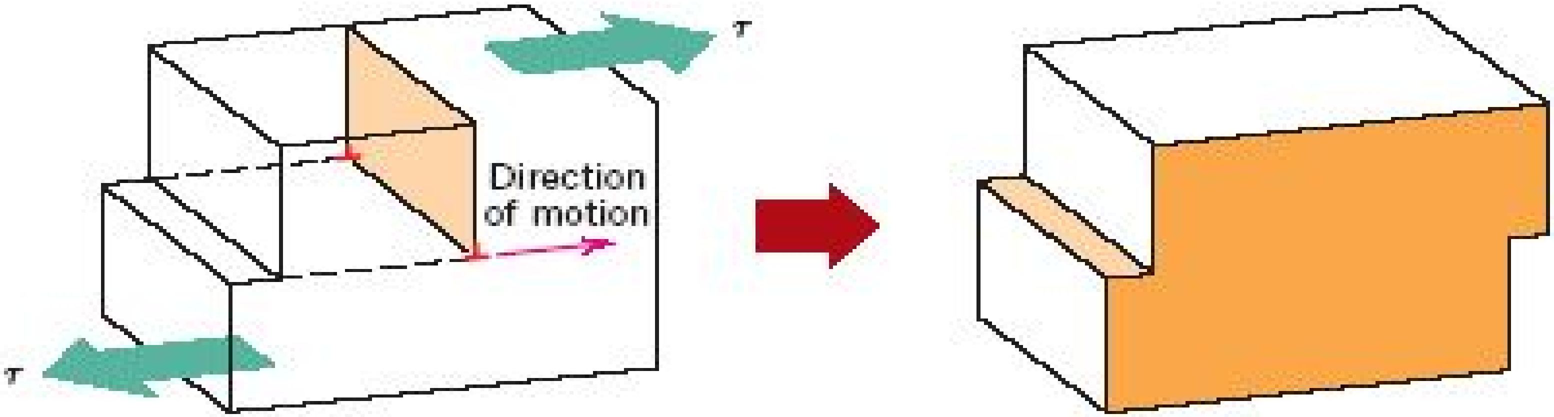


- Atomic rearrangements that accompany the motion of dislocation as it moves in response to an applied shear stress.
  - The process by which plastic deformation is produced by dislocation motion is called slip (movement of dislocations).
  - The extra ½-plane moves along the slip plane.

c08f03

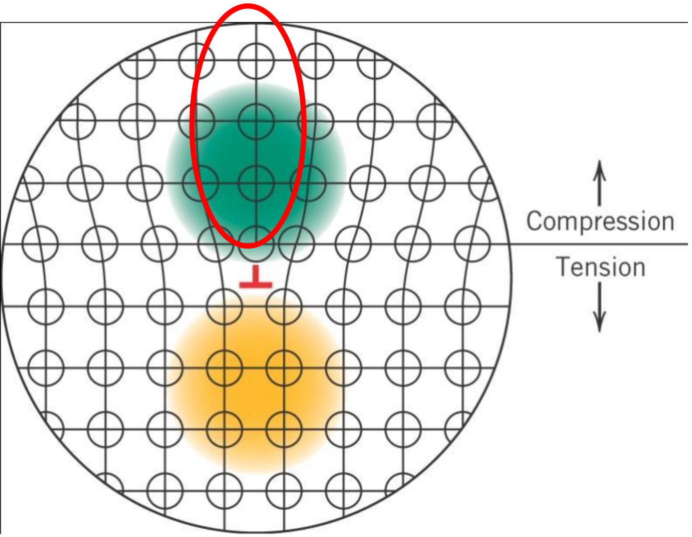
How a material deforms



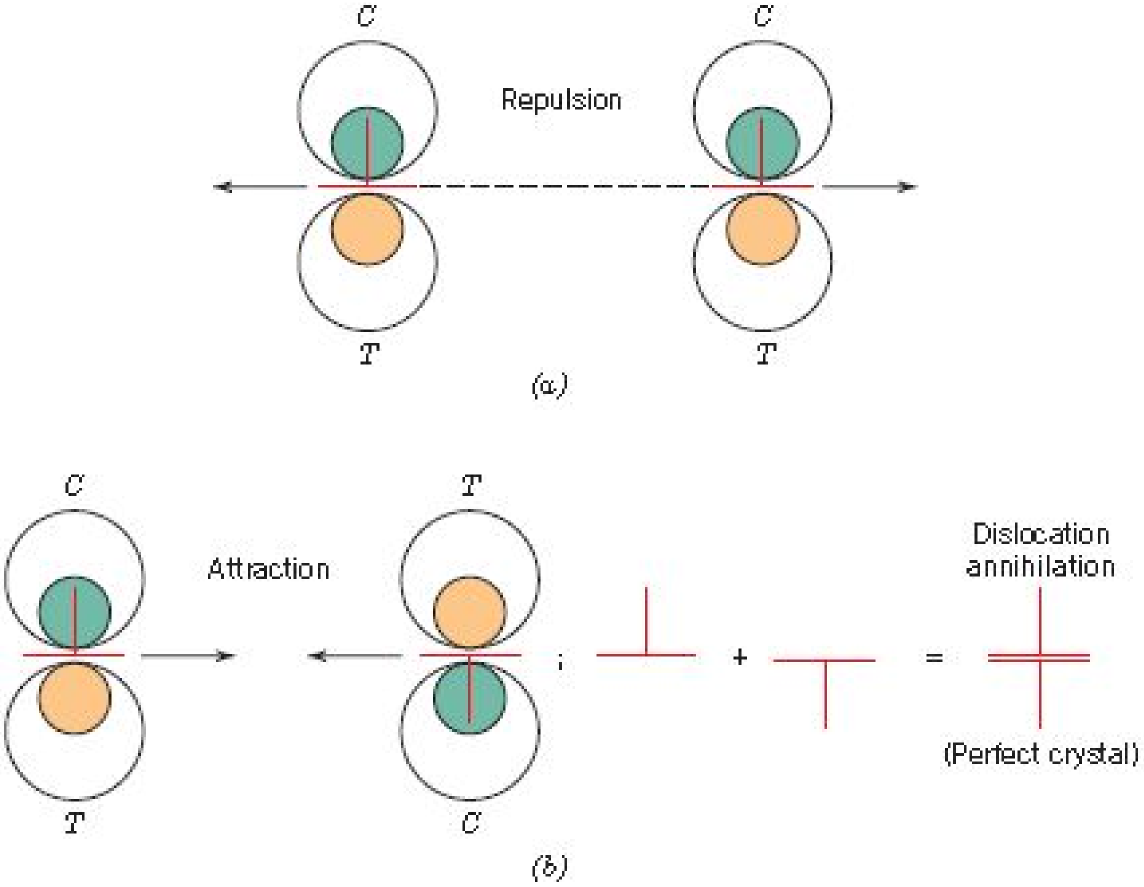


c08f04

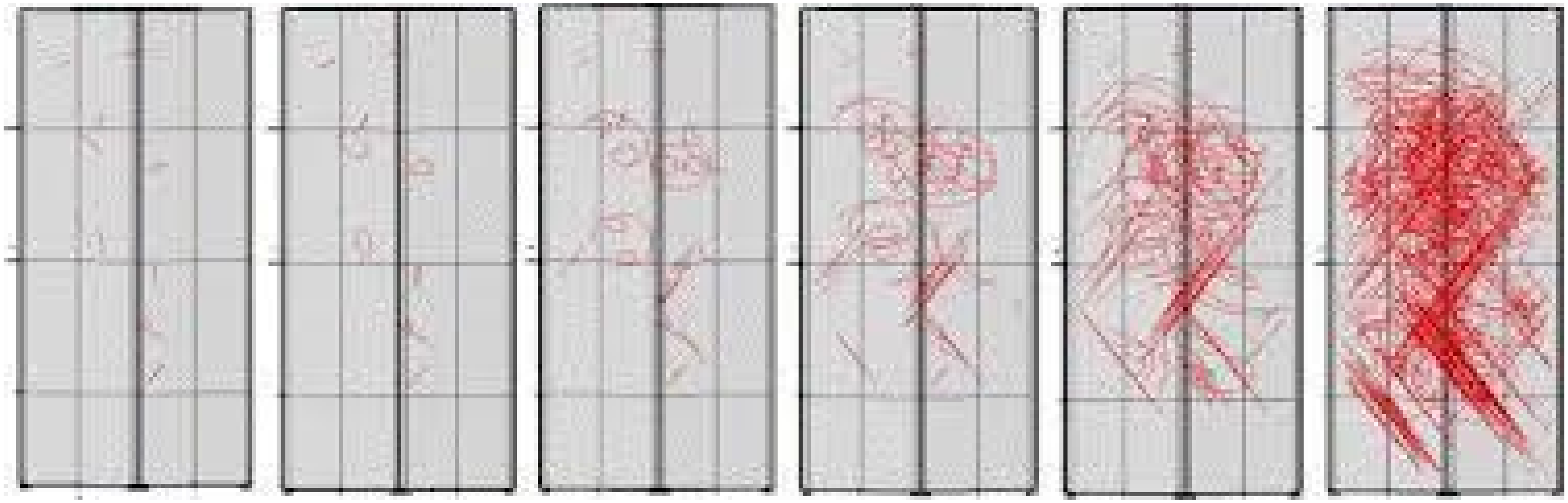
How a material deforms



Lattice distortions exist around the dislocation line.

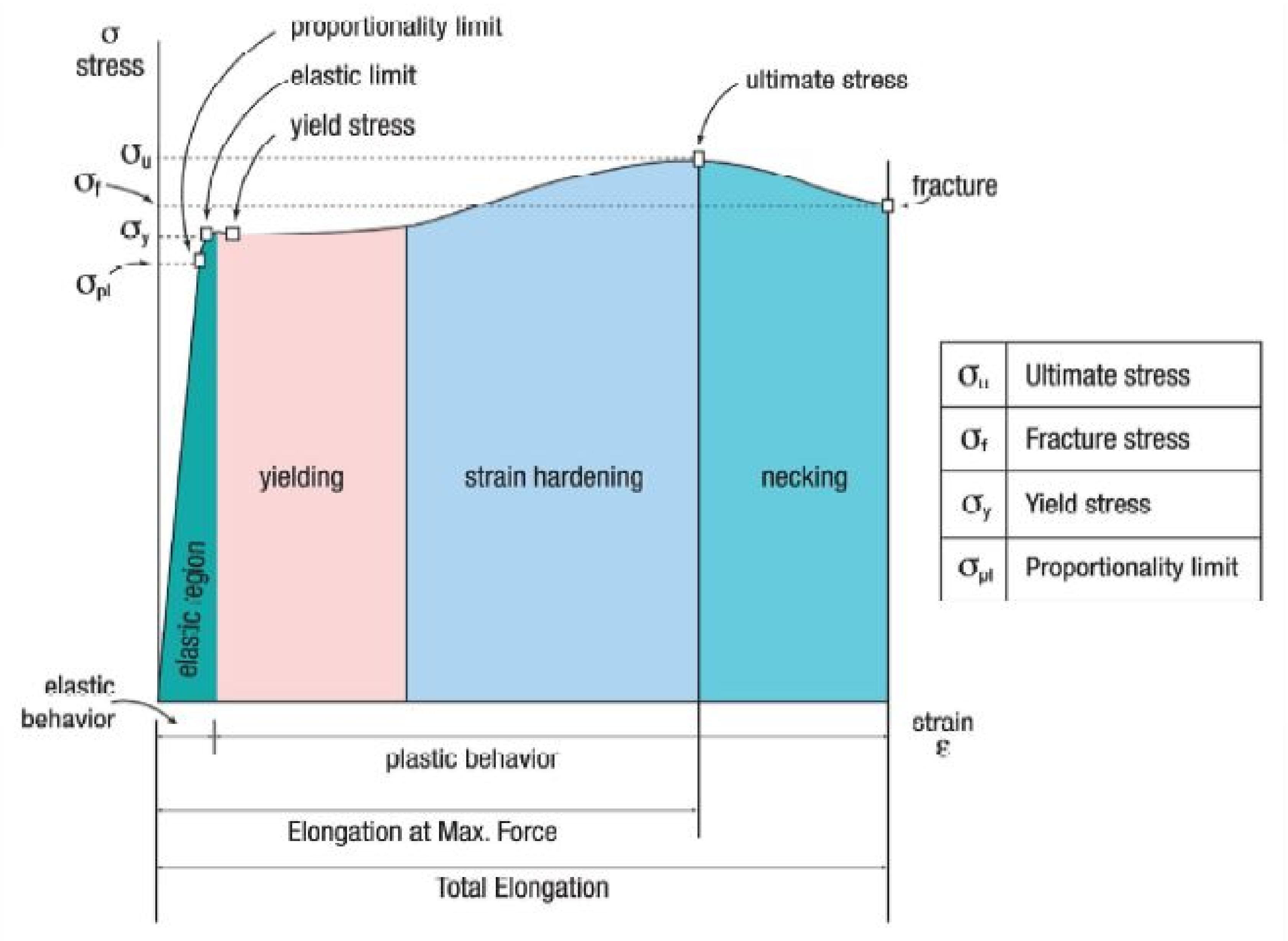


How a material deforms



Dislocation density (ρ_d) increases in a material due to dislocation multiplication.
The motion of a dislocation is hindered by the presence of other dislocations.

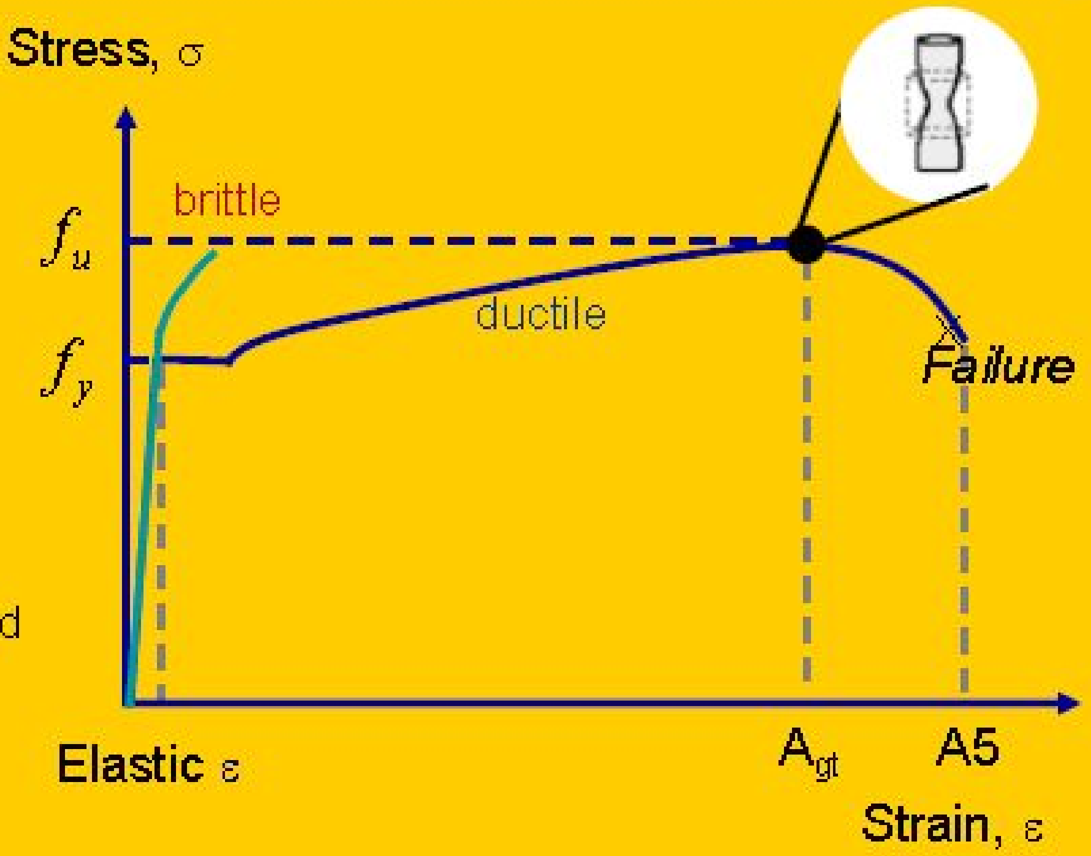
Carefully prepared sample: $\rho_d \sim 10^3$ mm/mm^3
Heavily deformed sample: $\rho_d \sim 10^{10}$ mm/mm^3



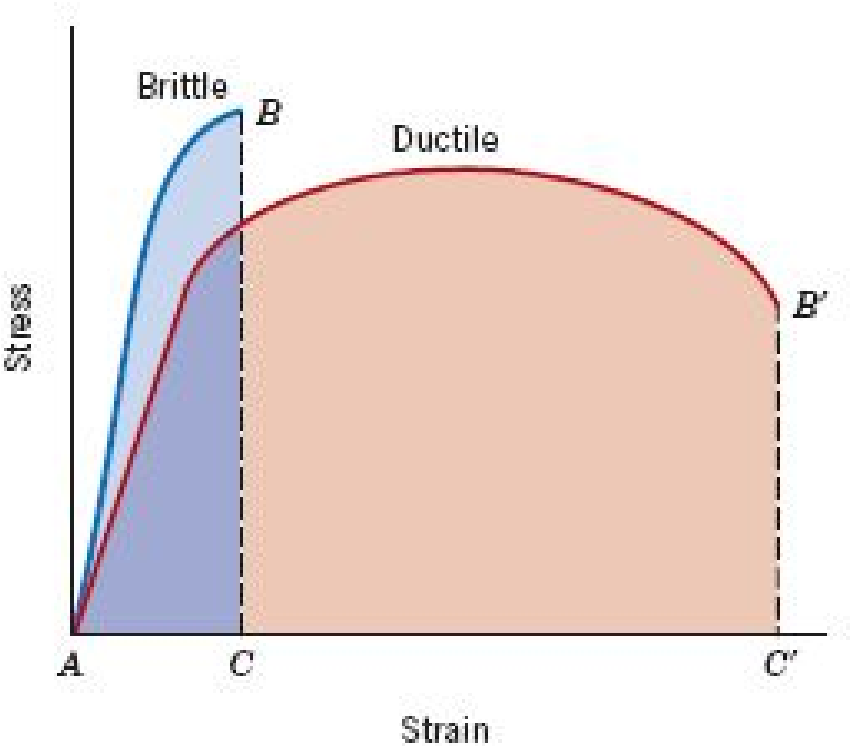
σ_u	Ultimate stress
σ_f	Fracture stress
σ_y	Yield stress
σ_{pl}	Proportionality limit

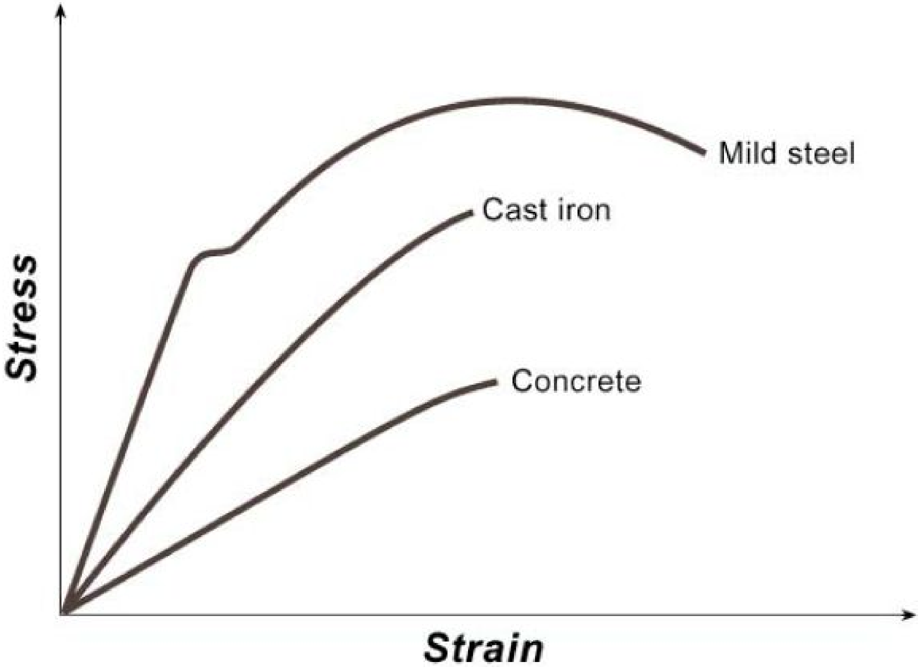
Measure of Ductility

1. Elongation at break $(A5)$
2. Ductility ratio, $(\frac{f_u}{f_y})$
3. Elongation at max. load (A_{gt})



Importance of ductility





- Ductile materials

  - Show large displacements before collapse (as opposed to a *brittle* material, which fails suddenly)

  - Dissipate energy as the steel yields (important for resisting earthquakes and other overloading)

Steel reinforcement: The quest for strength and ductility

Global civil engineering demand

A low cost reinforcing bar that has higher strength combined with good ductility and weldability.

Trends in rebars:

Cold twisting
Microalloying
Heat treatment

Steel reinforcement: The quest for strength and ductility

Plain mild steel rebars:

Until 1960

Yield strength 250 N/mm^2

Ribbed mild steel bars:

Around 1960

Better bond with concrete

Both the plain and ribbed bars had very high ductility

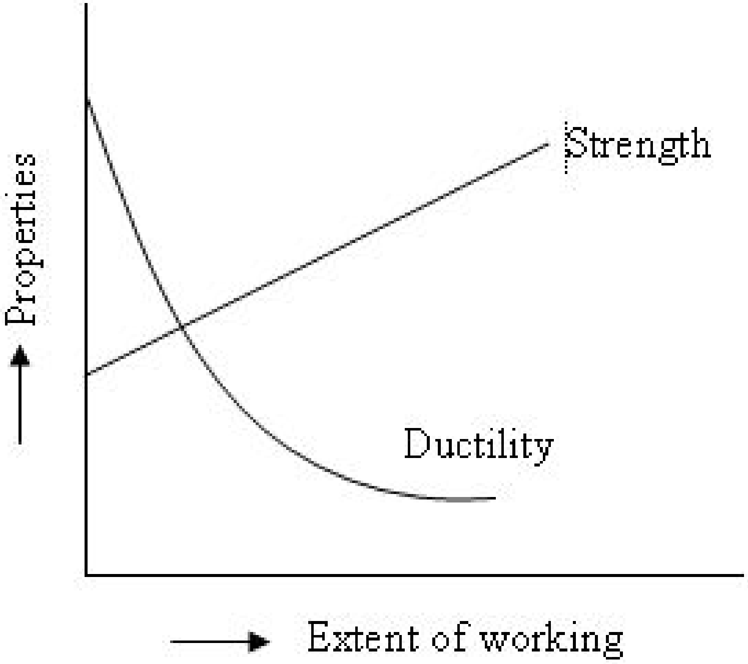
Steel reinforcement: The quest for strength and ductility

Cold twisted deformed bars (CTD bars):

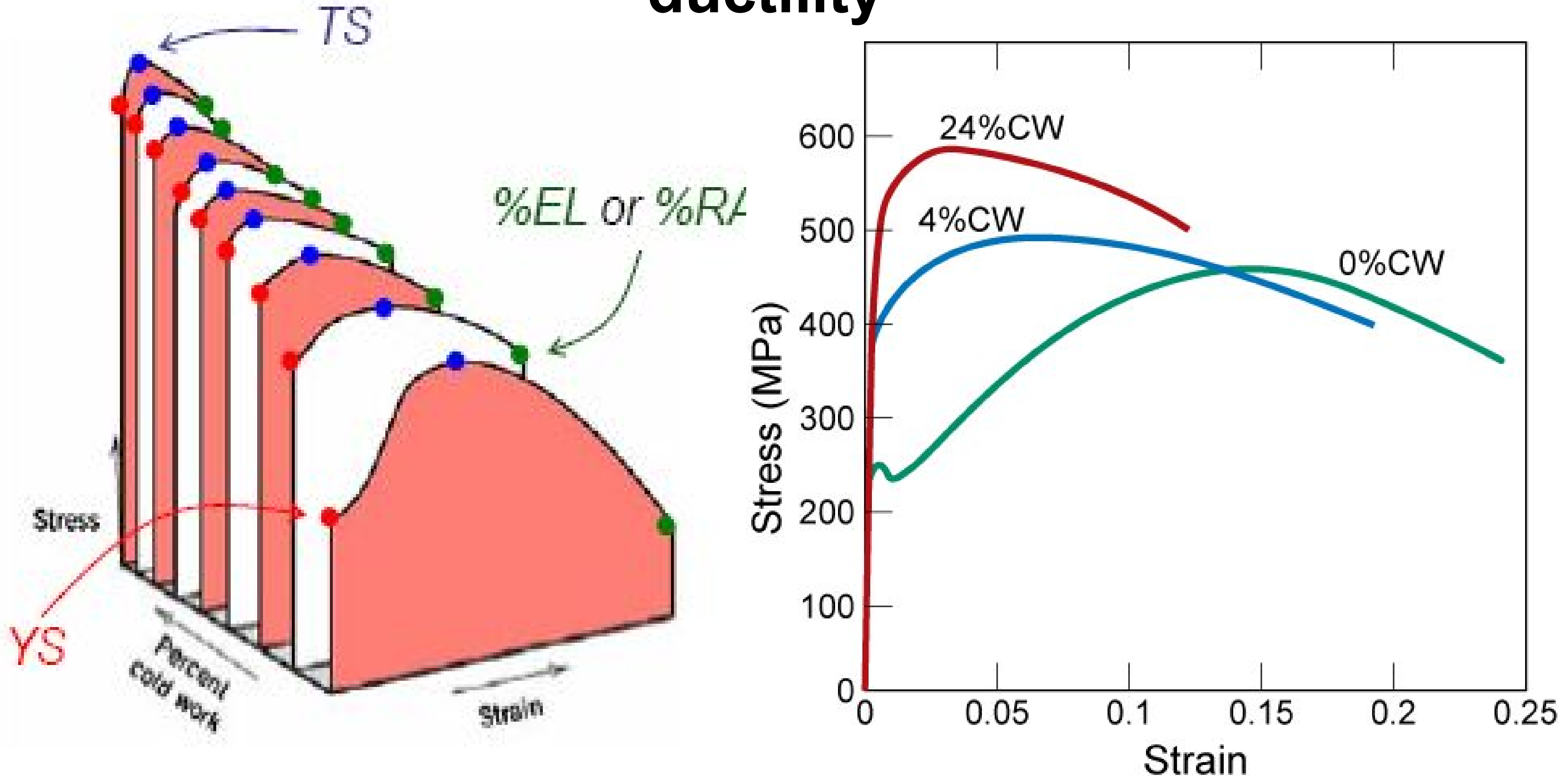
In late 1960

Yield strength of around 400 N/mm^2

High strength was achieved at the cost of ductility



Steel reinforcement: The quest for strength and ductility



Strain Hardening

Steel reinforcement: The quest for strength and ductility

CTD bars….

- Europe, where the CTD process was developed gave up its use in the 1970s
- The demand of civil engineers for rebars of yield strength 500 N/mm2 with sufficient ductility remained unfilled.

Microalloying:

In recent years
Addition of alloying elements as: C, Mn, V, Nb etc. Yield strength of 500 - 550 N/mm2
Production cost is high and ductility is low

Steel reinforcement: The quest for strength and ductility

The Quench and Temper (Q and T) Technology :

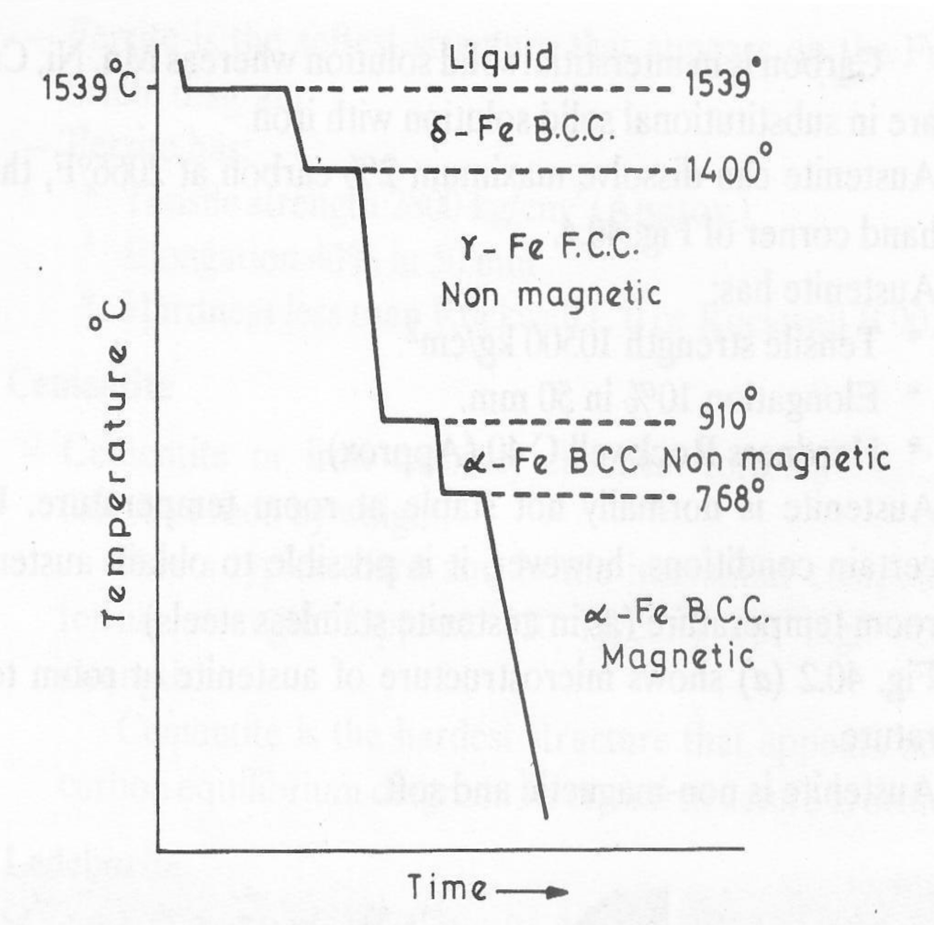
Developed in the 1980s can produce higher strength bars with adequate ductility.

Received global acceptance among the civil engineers because it met all their requirements.

Steel reinforcement: The quest for strength and ductility

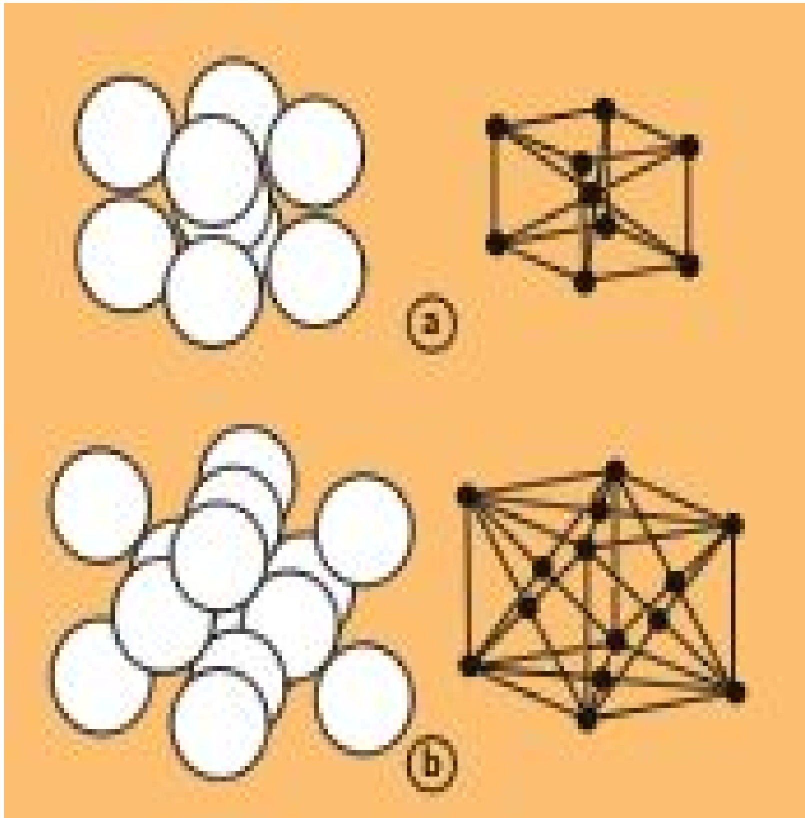
Steel is an alloy of iron and carbon.

In iron the arrangement of atoms is dependent on temperature



Cooling curve for pure iron

Steel reinforcement: The quest for strength and ductility



B.C.C.. Structures

At room temperature α-iron can contain in solution upto 0.025% C

F.C.C.. Structures

At high temperature γ-iron can contain in solution a maximum of 1.7% C

C- atoms have to move out to allow transformations at low temperatures.

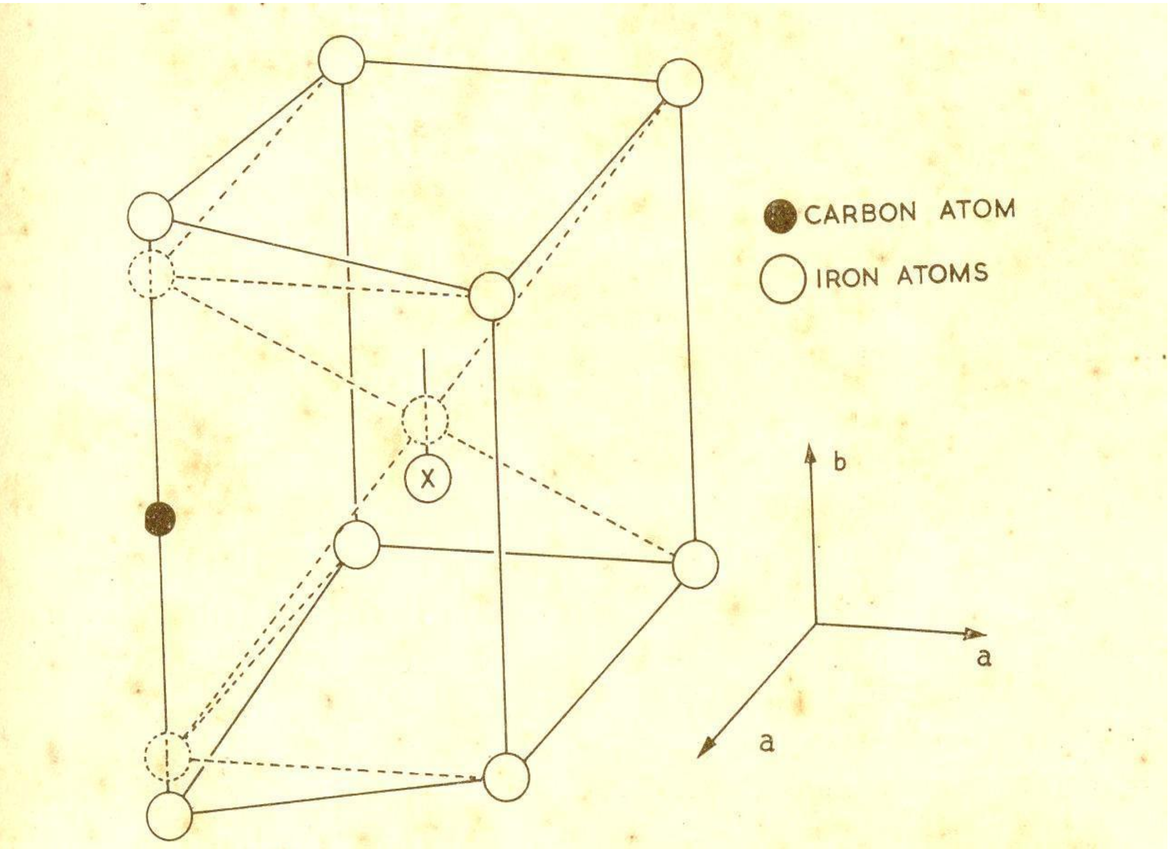
This allotropic change in iron and the resultant change of solubility of C in iron make it possible to change the properties of iron by controlling the rate of cooling.

Steel reinforcement: The quest for strength and ductility

If a γ-iron is quenched in water then C-atoms do not have enough time to move out.

C- atoms get trapped in the structure, set up local strains that block movement of dislocation.

The structure becomes extremely hard and strong but very brittle.



Steel reinforcement: The quest for strength and ductility

Microstructure of Rapid
Cooled/quenched Steel at RT

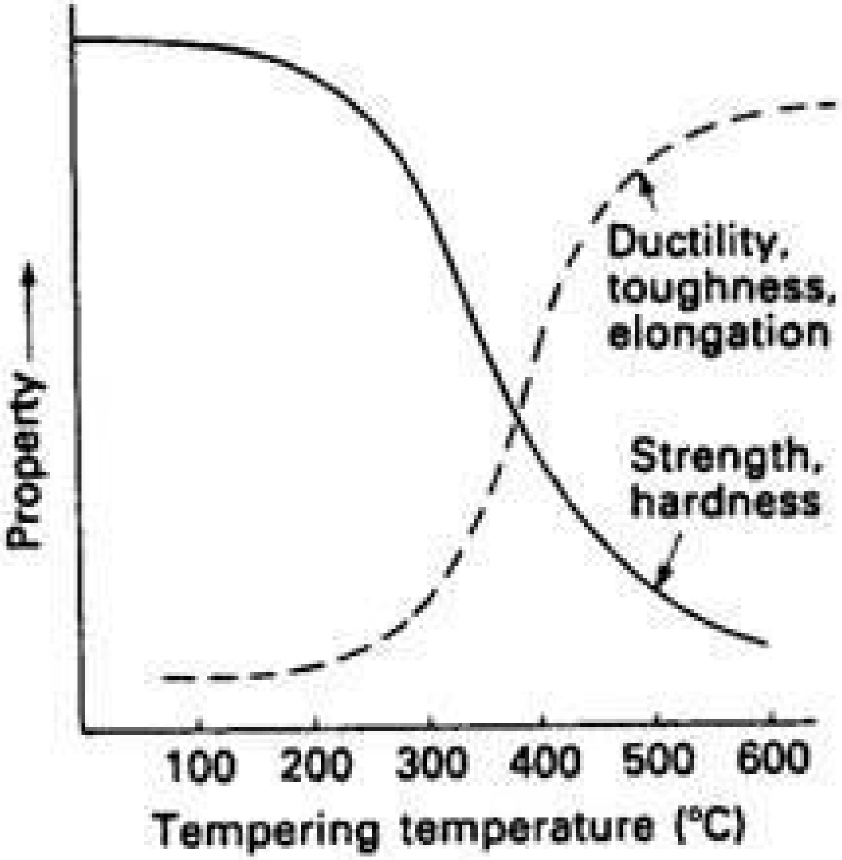
Microstructure of Slow
Cooled Steel at RT

Among all structures of steel **Martensite** is the hardest, strongest and most brittle one –Difficult to exploit in practice.

Tempering reduces residual stress, breaks Martensite needles to fine ferrite and cementite, increases ductility and toughness.

Steel reinforcement: The quest for strength and ductility

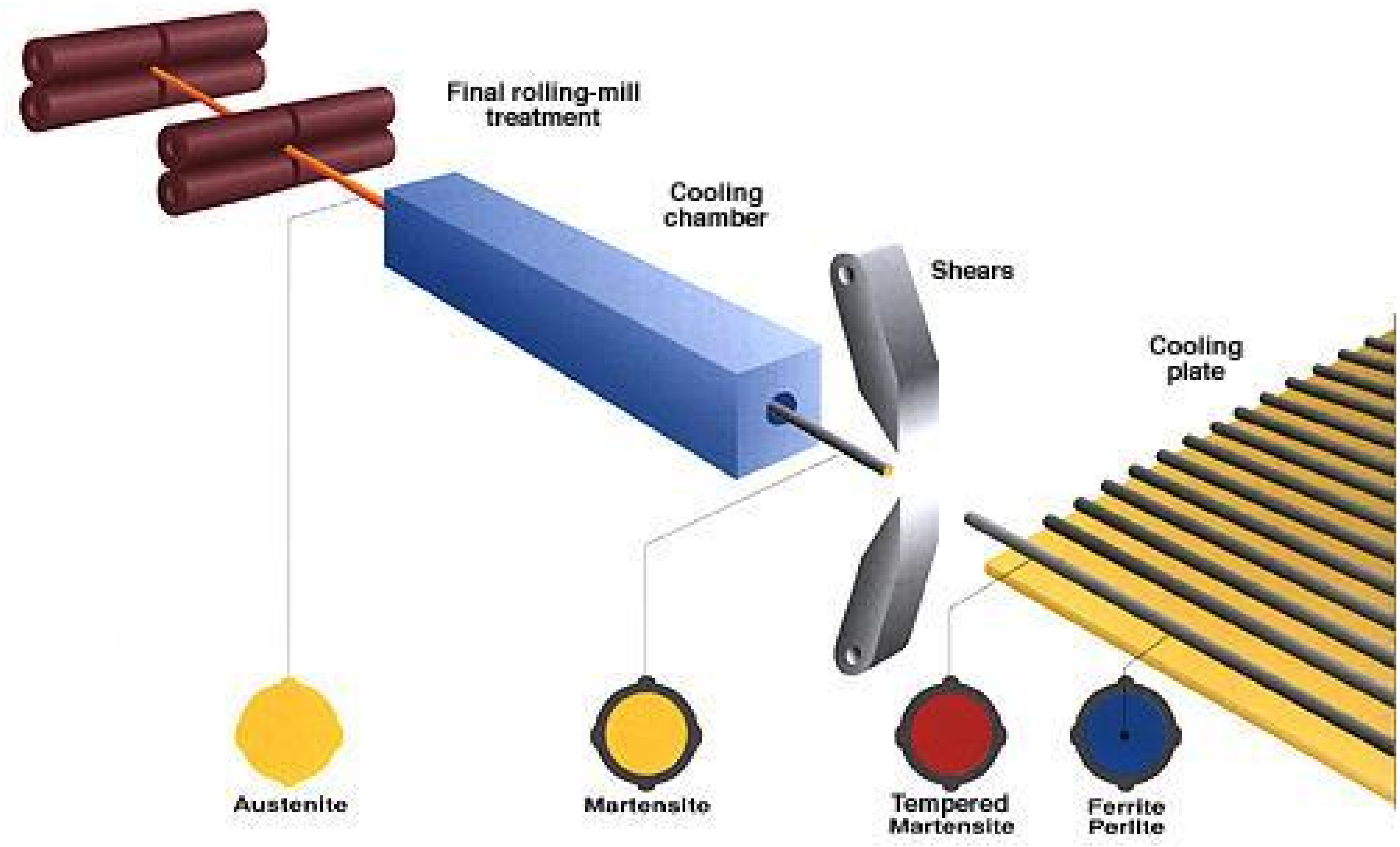
Martensitic Microstructure



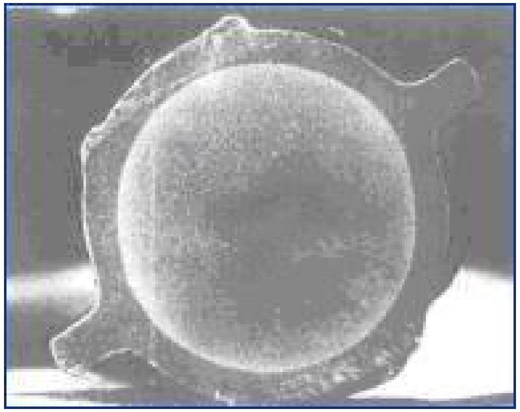
(Tempered Martensite)

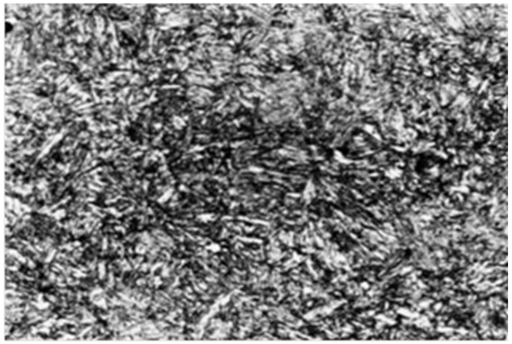
martensite (BCT, single phase) → tempered martensite ($\alpha + Fe_3C$ phases)

Steel reinforcement: The quest for strength and ductility

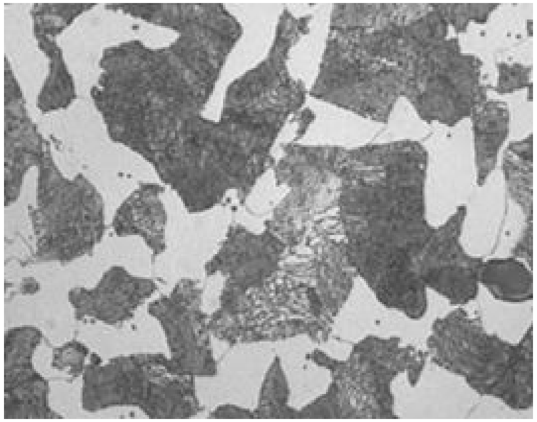


Steel reinforcement: The quest for strength and ductility





Outer case:
Tempered
Martensite



Core:
Ferrite/Pearlite

Microstructure of quenched and tempered bar

Steel reinforcement: The quest for strength and ductility

Production process	Treatment	Cost	Mechanical Properties	
			Ductility	Weld-ability
Cold Twisting	Cold work hardening	High	Poor	Good
Micro Alloying	Addition of alloying elements as: C, Mn, V, Nb etc.	High	Good	Poor (Due to high carbon equivalent)
Q and T Process	Rapid cooling and controlled cooling from rolling heat	Low	Excellent	Excellent (Due to low carbon equivalent)

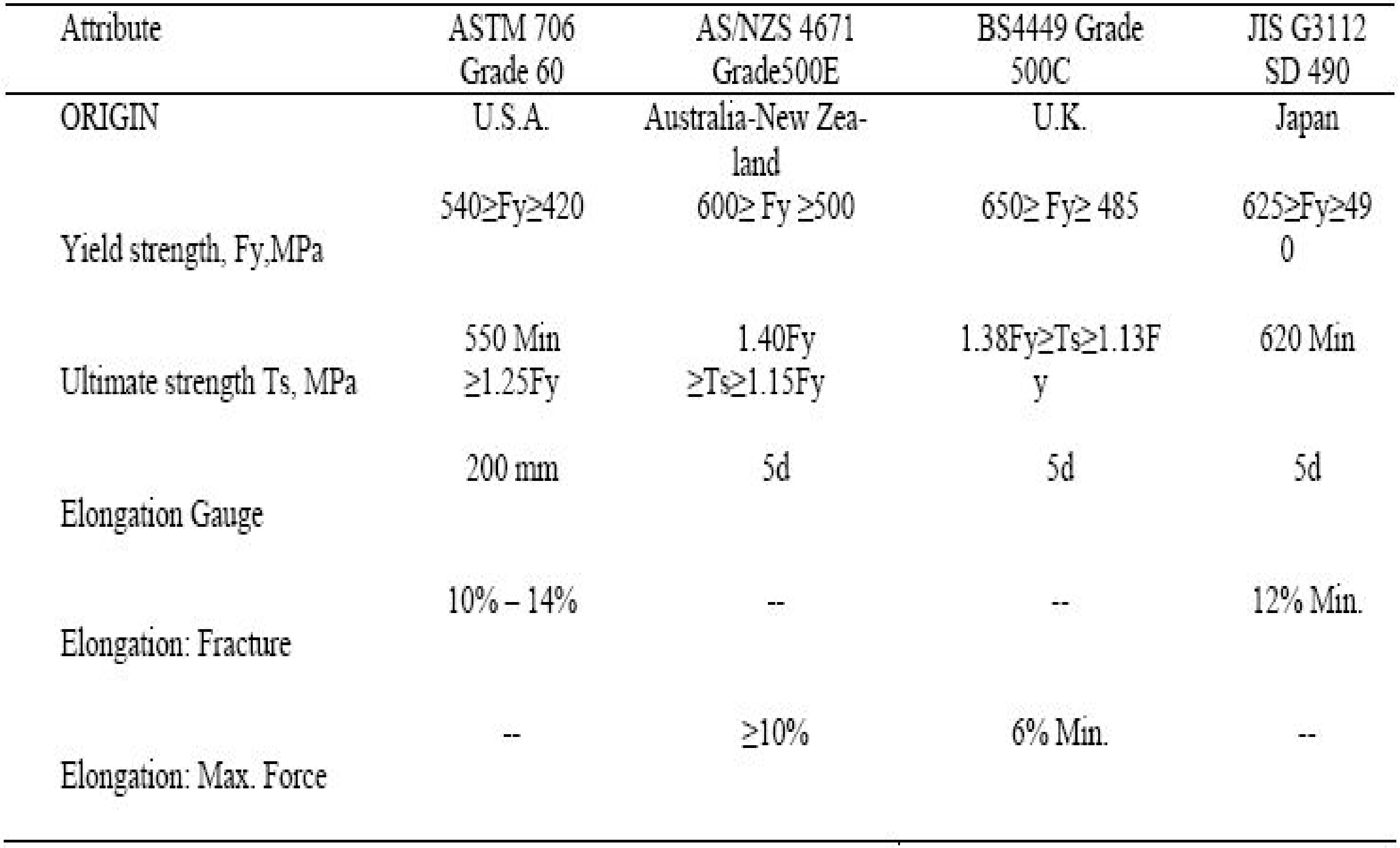
Concluding remarks

- Demand for still higher strength rebars with adequate ductility and weldability has led to interesting developments in the technology of rebar production.

- In Bangladesh it is time for us to rise and face this reality and prepare ourselves to make our contributions to future developments in the field of production of rebars with still higher strength and ductility.

Thank You

Some of the more internationally recognized ‘Ductile’ also literally known as earthquake grades of steel are shown below



Attribute	ASTM 706 Grade 60	AS/NZS 4671 Grade500E	BS4449 Grade 500C	JIS G3112 SD 490
ORIGIN	U.S.A.	Australia-New Zealand	U.K.	Japan
Yield strength, Fy,MPa	540≥Fy≥420	600≥ Fy ≥500	650≥ Fy≥ 485	625≥Fy≥490
Ultimate strength Ts, MPa	550 Min ≥1.25Fy	1.40Fy ≥Ts≥1.15Fy	1.38Fy≥Ts≥1.13Fy	620 Min
Elongation Gauge	200 mm	5d	5d	5d
Elongation: Fracture	10% – 14%	--	--	12% Min.
Elongation: Max. Force	--	≥10%	6% Min.	--

SEISMIC STANDARDS

Country	Standard	Quality	Yield	Tensile	Elongation	% Agt	Re/Rm	Carbon %	Carbon Eq. %
USA	ASTM A 706	Gr 60	420-540	550	14		>1.25	0,30	0,55
Australia	AS 4671	GR 500 E	500-600			10	>1.15 - 1.40	0,22	0,50
U.K.	BS 4449	B 500 C	500-650			7,5	>1.15 - <1.35	0,22	0,50
Norway	NS 3576-3	B 500 C	500-650			7,5	>1.15 - <1.35	0,22	0,50
Greece	Elot 1421-3	B 500 C	500-625			7,5	>1.15 - <1.35	0,22	0,50
Italy	UNI 6407	FeB 44 K	450-580			7	>1.13 - <1.35	0,22	0,50
Spain	UNE 36065	B 400 SD	400-480	480	20	9	>1.15 - <1.35	0,22	0,50
		B 500 SD	500-625	575	16	8	>1.15 - <1.35	0,22	0,50
Portugal	E 455	A 400 NR SD	400-480			8	>1.15 - <1.35	0,22	0,50
	E 460	A 500 NR SD	500-600			8	>1.15 - <1.35	0,22	0,50
New Zealand	NSZ 4671	GR 500 E	500-600			10	>1.15 - 1.40	0,22	0,50
Canada	CSA.G.30.18-M92	Gr 400	400-525	550	13		>1.15	0,30	0,55
		Gr 500	500-625	625	12		>1.15	0,30	0,55
Colombia	NTC 2289	Diaco 60	420-540	550	14		>1.25	0,30	0,55
Israel	SI 4466-3	400 W	400-520	500	12		>1.25	0,24	0,55
Venezuela	Covenin 316	W60	415-540	620	14		>1.25	0,30	0,55
		W70	490-637	620	14		>1.25	0,30	0,55
EKSISMIK			500-650	600		8	>1.15 - <1.35	0,22	0,50

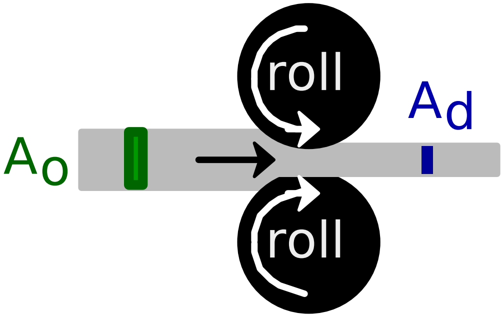
Agt = Percentage total elongation at maximum force

Table.2 Chemistry of ASTM and ISO Standards

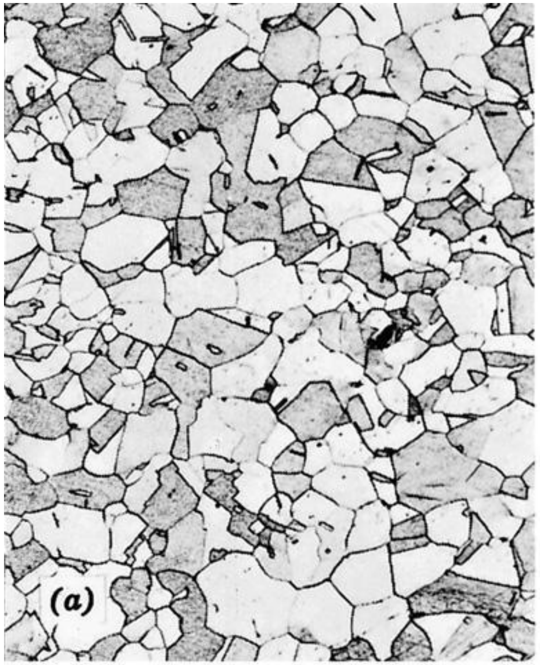
Chemical Composition	ASTM A 615 Grade 60	ISO 6935 Grade 500W
Carbon %	No limit	0.24% Max
Manganese %	No limit	1.65% Max
Silicon %	No limit	0.60% Max
Phosphorous%	0.06% Max.	0.06% Max
Sulphur %	No limit	0.06% Max
Carbon Eqv.	No limit	0.51% Max

Strain Hardening/Cold working

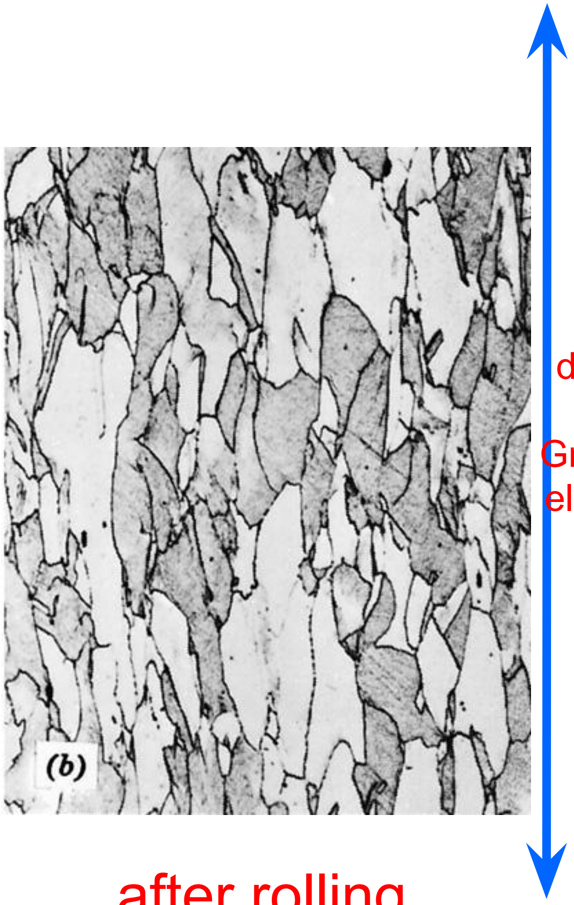
Rolling



$$\%CW = \frac{A_o - A_d}{A_o} x100$$



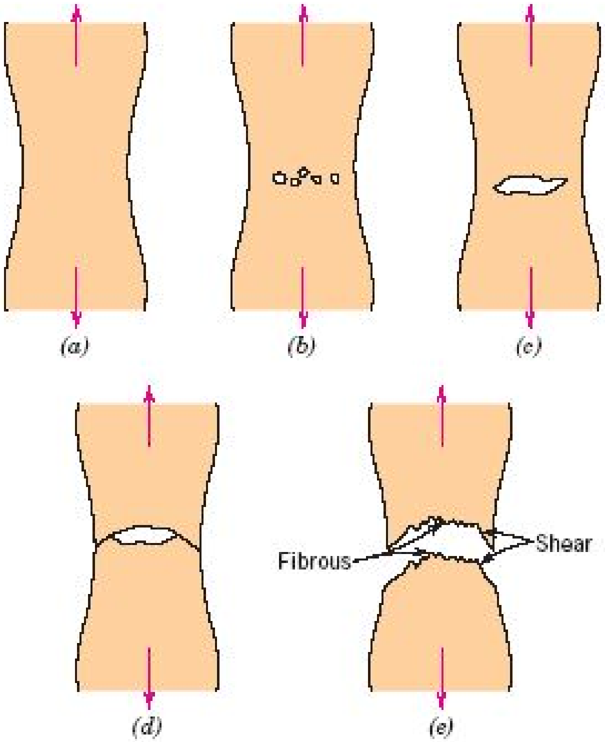
before rolling

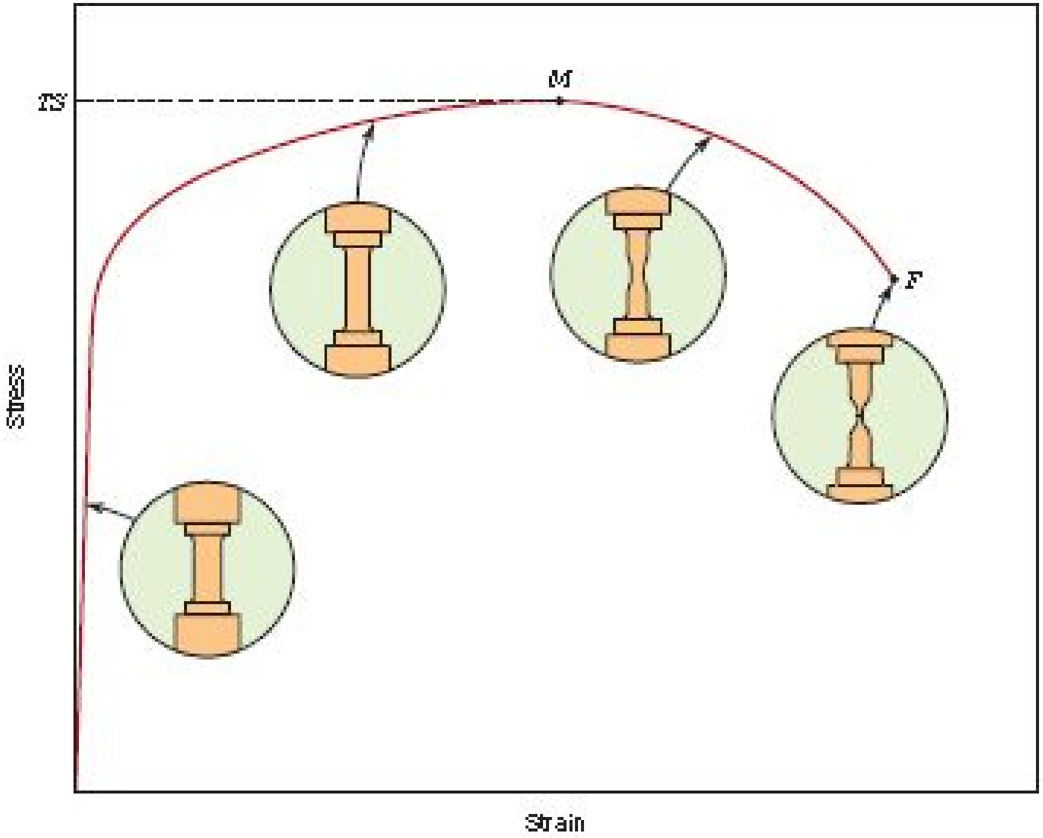


after rolling

rolling direction
-
Grains are elongated

Ductile fracture





a.**Initial necking**
(b) Small cavity formation
(c) Coalescence of cavities to form a crack
(d) Crack propagation
(e) Final shear fracture