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소성재료역학
(Metal Plasticity)

Chapter 1: Introduction

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Introduction

Motivation

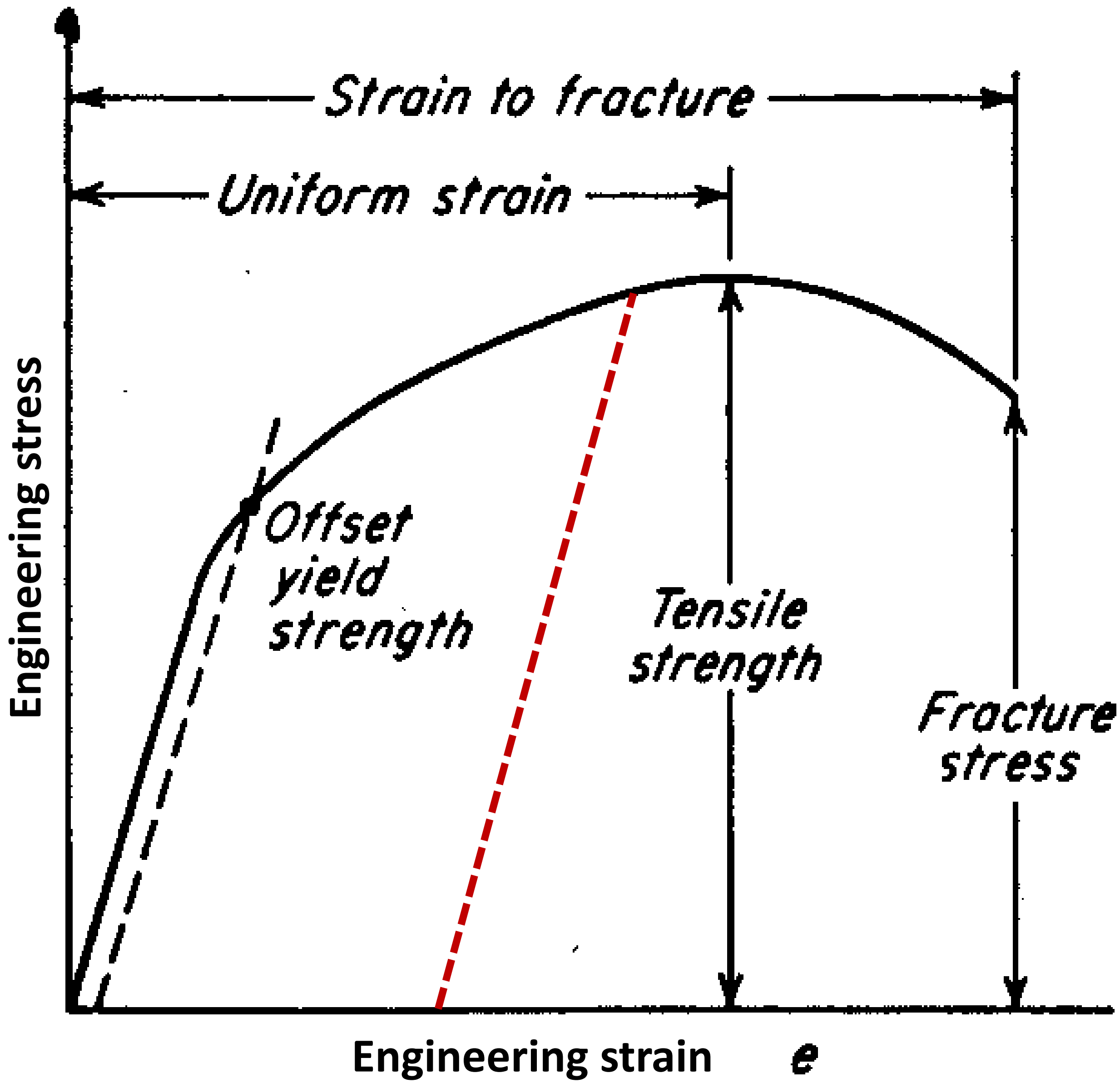
- Numerical simulations based on finite element (FE) method are very useful for process and product optimizations in manufacturing
- One of key factors deciding the accuracy of numerical simulations is “Constitutive modeling” or “constitutive laws” which consist of descriptions of mechanical properties such as elasticity, plasticity, visco-elastic/plastic etc.
- In metal plasticity, the multiscale modeling has been instrumental to relate the microstructure features and resultant macroscopic properties
- However, the macroscopic or continuum based plasticity models are still cost and time efficient for finite element simulations

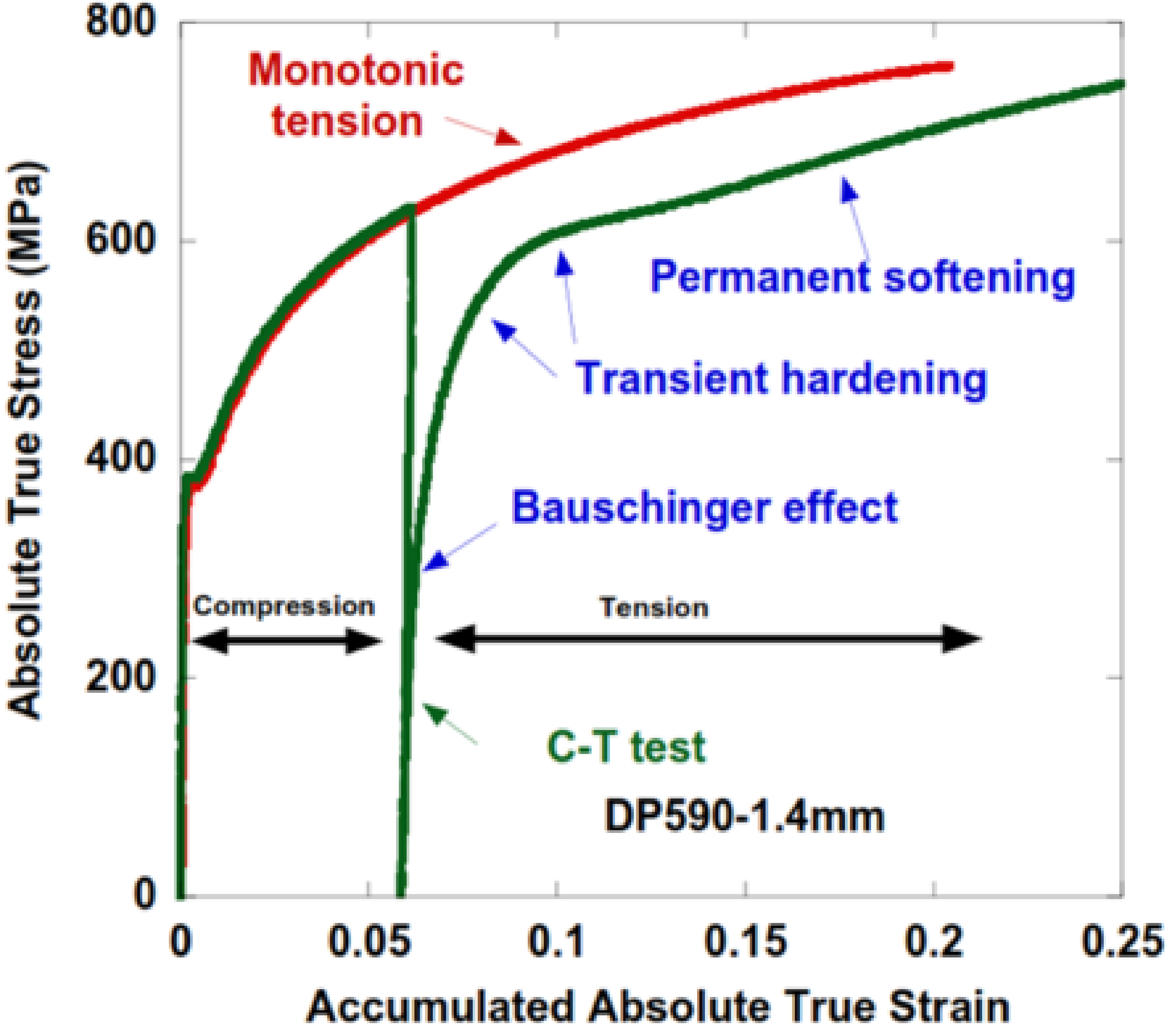
Objectives

- How to model the plasticity for metallic materials at the continuum level
- Understand the relationship between microstructure characteristics and macroscopic plastic properties
- Formulate the two major constitutive models of plasticity; i.e., yield function/flow rule and plastic hardening
- Applications of plasticity theory to metal forming – prediction of failure and shape stability

Observation of plasticity: Overview

- Plasticity has been often featured as nonlinear, irreversible mechanical responses in stress-strain curves of metallic materials
- The limit of elastic deformation is called as “yield stress”
- Flow stress increases as the increase of amount of plastic dissipation or plastic strain – plastic hardening
- The flow stress becomes a new yield stress after unloading and reloading
- In general, (for fully dense metals) the plasticity does not involve volume change and not depend on hydrostatic stress state
- Bauschinger effect is common feature – the new yield stress after load reversal is lower than the yield stress before unloading

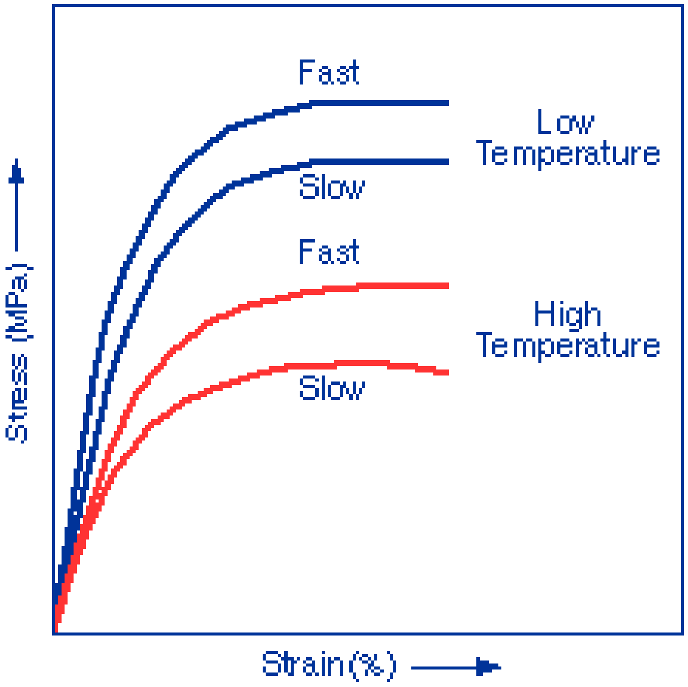

Strain to fracture
Uniform strain
Engineering stress
Offset yield strength
Tensile strength
Fracture stress
Engineering strain e

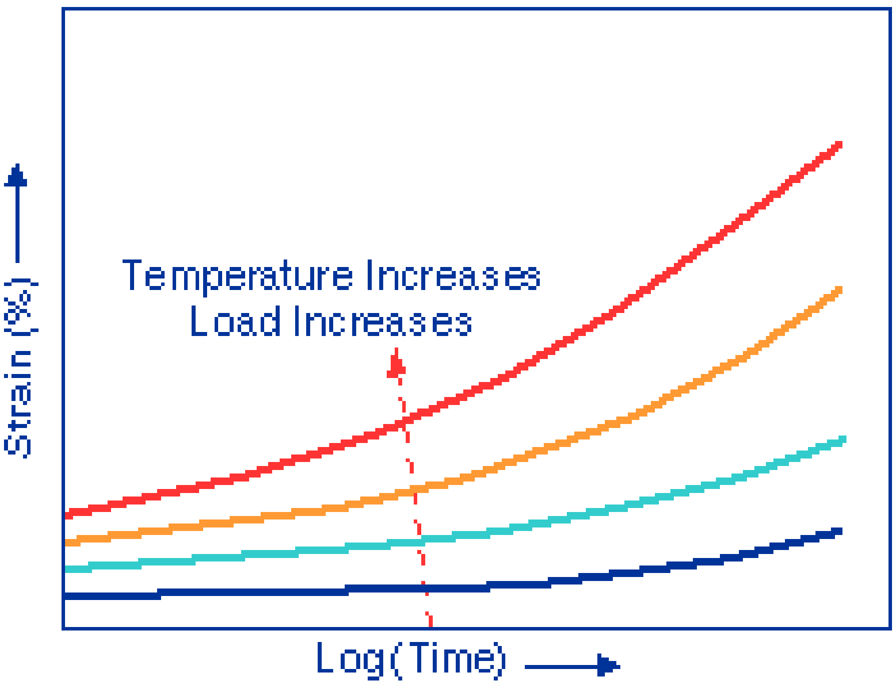


Monotonic
tension
Permanent softening
Transient hardening
Bauschinger effect
Compression
Tension
C-T test
DP590-1.4mm
Absolute True Stress (MPa)
Accumulated Absolute True Strain
800
600
400
200
0
0
0.05
0.1
0.15
0.2
0.25

Observation of plasticity: Overview

- Flow stress decreases as temperature increases
- Time has very limited influence on the flow stress and plasticity in general
- But, at higher temperature the effect of strain rate becomes more important
- Strain rate and temperature have similar effect on the plasticity of metallic materials
- At high temperature, creep (and relaxation) is another plastic properties of metallic materials
- Solid state transformation can occur in materials due to the applied stress – the transformation changes phases under lower stress than yield stress and induces the plasticity

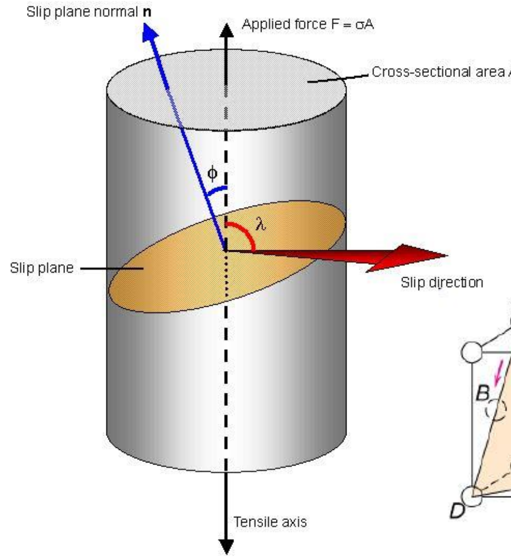


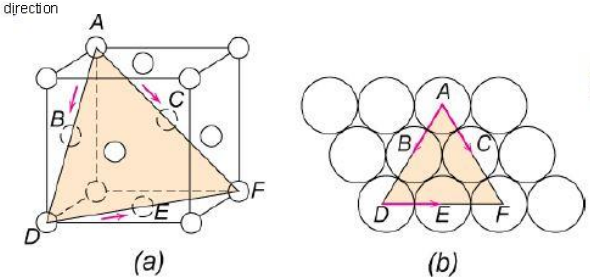


http://www.dc.engr.scu.edu/cmdoc/dg_doc/develop/material/property/a2200002.htm

Plasticity in microscale: Overview

- Metals consist of aggregates of grains (or single crystals)
- At low homologous temperature, plastic deformation of metals and alloys occur by dislocation gliding and twinning on preferred crystallographic planes and directions, which result in microscopic shear strains
- Strain incompatibilities between grains, short-range residual stresses
- Gradual lattice rotation (for slip) and abrupt lattice orientation change (for twinning)
- Crystal structure determines the number of available slip systems – for example, HCP has limited slip systems
- Dislocations accumulate at microscopic obstacles such as grain boundaries, dislocations, precipitates etc., which increase slip resistances – plastic hardening





Adapted from Fig. 7.6, *Callister 7e.*

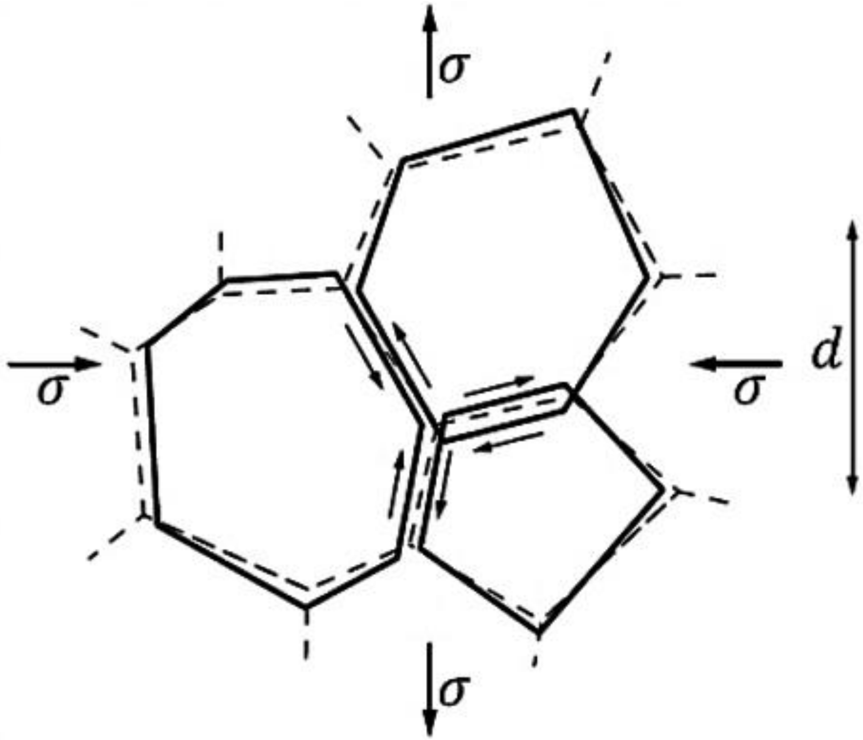
Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle 1\bar{1}0\rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	$\{110\}$	$\langle \bar{1}11\rangle$	12
α-Fe, W	$\{211\}$	$\langle \bar{1}11\rangle$	12
α-Fe, K	$\{321\}$	$\langle \bar{1}11\rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	$\{0001\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

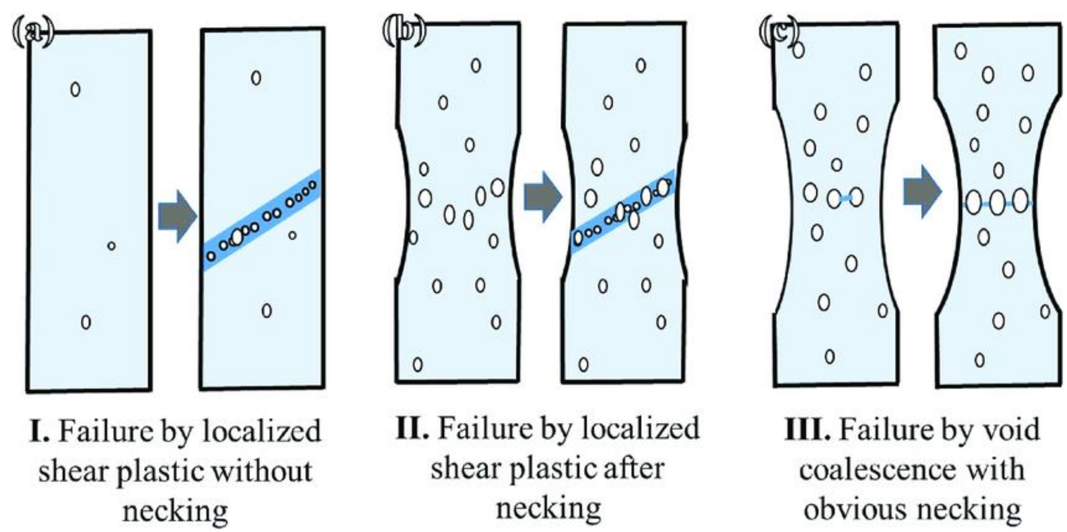
Plasticity in microscale: Overview

- At higher temperature, more slip systems are available
- At high temperature, atomic diffusion plays another role for plastic deformation – creep, and grain boundary sliding can be another reason for creep or super-plasticity (grain size or shape become more important)
- The presence of non-homogeneities changes the mechanical properties by interactions with dislocations – plastic hardening, back stress (or Bauschinger effect) etc..

Plasticity in microscale: Overview

- Mechanism of failure for metallic materials and alloys can be explained by localization and fracture
- Localization occurs in the form of shear band (micro- or macro-bands). Micro-band is crystallographic while the macro-band is not.
- Ductile fracture is featured by void nucleation, growth, and coalescence.
- The micro-porosity changes the volume while the deformation of matrix is incompressible – hydrostatic pressure influences the mechanical properties
- At low temperature, second-phases can be the site for damage
- The stress concentration around the second phase phases lead to void nucleation, and growth by plasticity, coalescence is the result of micro-localization of ligaments between voids
- At high temperature, cavities at grain boundaries are nucleated





Luo Zhichao et al., Revealing the Fracture Mechanism of Twinning-Induced Plasticity Steels, Steel Research International

Constitutive modeling: Overview

- As a general frame work, the following simplifications are applied in this course
  - Continuum scale
  - Rate in-dependent plasticity
  - Isotropic material
- Yield condition in uniaxial tension

Yield stress in tension (or compression)

$$\Phi = \sigma - \sigma_{\mathrm{y}} = 0$$

- Yield condition in general

Temperature

$$\Phi\left(\sigma, \Theta, X_i\right) = 0$$

State variables

- Strain rate when yield condition is satisfied

$$\dot{\varepsilon} = \dot{\varepsilon}\left(\sigma, \Theta, X_i\right)$$

- Evolution of state variables due to the microstructure changes

$$\dot{X}_i = \dot{X}_i\left(\sigma, \Theta, X_i\right)$$