Module #0

Introduction

READING LIST

DIETER: Ch. 1, pp. 1-6

Introduction

- Components used in engineering structures usually need to bear mechanical loads.
- Engineers are mainly interested in design rules that allow them to dimension components.
- Materials scientists/engineers usually focus on the physical processes that occur in the material (i.e., physical metallurgy/materials) during mechanical loading.
- A good materials engineer should be able to understand and apply both.

Mechanical Behavior of Materials

- This is a subject that addresses *<u>how materials respond to forces and loads</u>*.

- *We shall address this subject mechanistically <u>and</u> mathematically.*

General Characteristics of Materials

- Metals
  - *Strong*, *stiff*, conductive, *tough*
- Ceramics
  - *Strong*, *stiff*, *hard*, temperature and corrosion resistant, *brittle*
- Polymers
  - Cheap, light weight, corrosion resistant, *low strength*, *low stiffness*, *creep prone*
- Composites
  - *Strong*, *stiff*, light weight, expensive

The different properties exhibited by each class of materials can be tied directly to their macro/micro/nano-structures

Typical process engineering problem

You are the chief metallurgist at a stamping plant. At your plant, 304L stainless steel sheets are stamped into oil cans. You produce 20 cans/minute. The first 1000 cans form perfectly with no defects or failures. However, ten of the next 200 cans fail during stamping. Then, 25 of the next 200 fail. 100 of the next 200 fail. This is summarized below.

# cans	total # cans	#failures
1000	1000	0
200	1200	10
200	1400	25
200	1600	100

Your job is to determine what is causing the failures during processing.

Solution to process engineering problem

MATERIAL PROCESS

In this particular problem, deformation characteristics change with time.

- ✓ Dislocation generation & motion
- ✓ Work hardening
- ✓ Transformation induced plasticity
- ✓ M_s, M_d (martensite temperature)

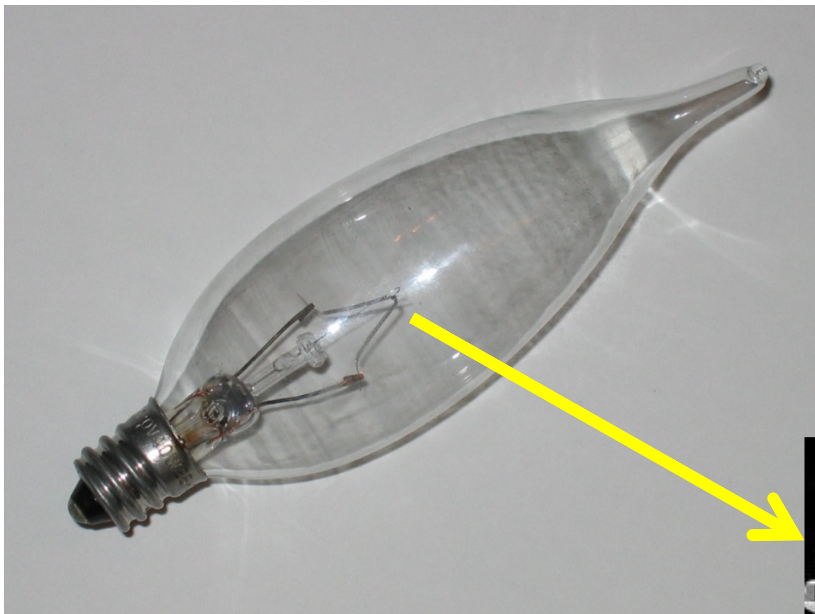
Solution to process problem – cont’d

Temperature of die rises above the martensite start temperature during processing.

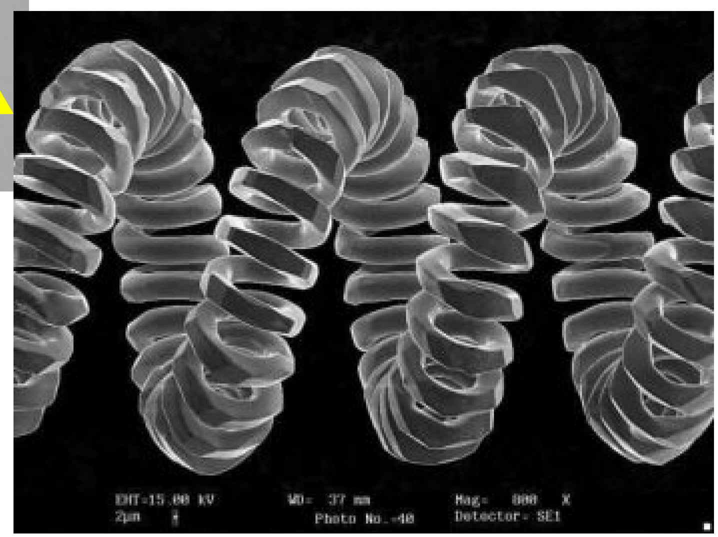
This increases work hardening during processing, which is good for increasing the amount of uniform plastic elongation, but which also makes it more difficult to deform the material uniformly.

The solution is not just an application or mechanics problem. Rather it is related to intrinsic materials properties.

A Typical Materials Engineering Problem



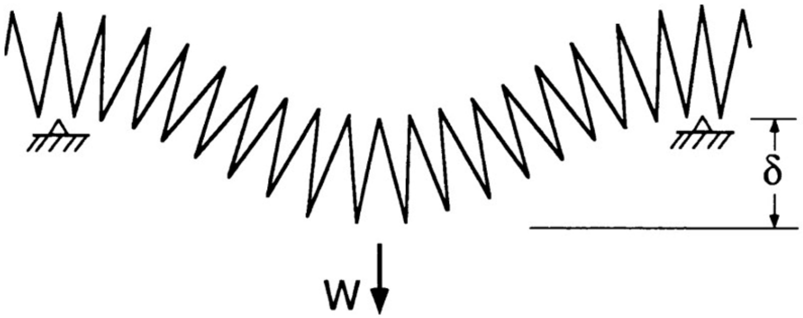
- Tungsten light bulb filaments fail after a few thousand hours.

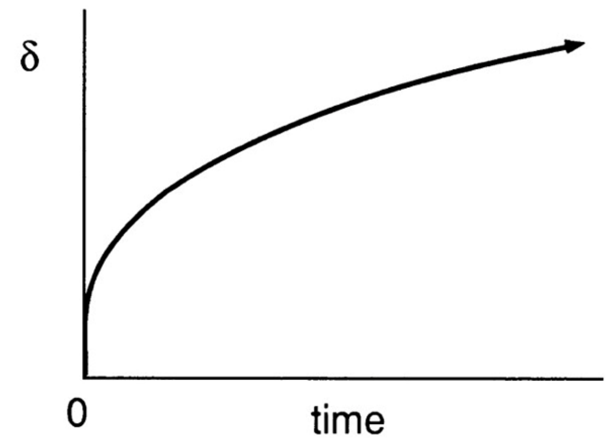


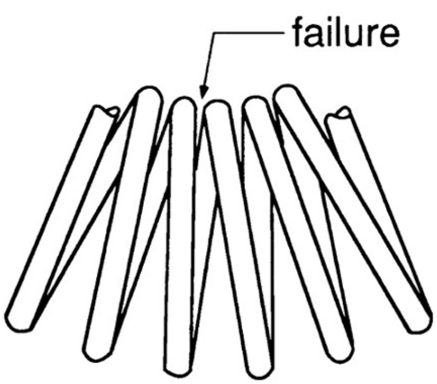
Centre de Recherche Public, Gabriel Lippmann
http://www.crpgl.lu/en/sam/sem_metals.php3

- Why?
- How?
- What can be done to increase their service lifetimes?

Solution to Filament Problem



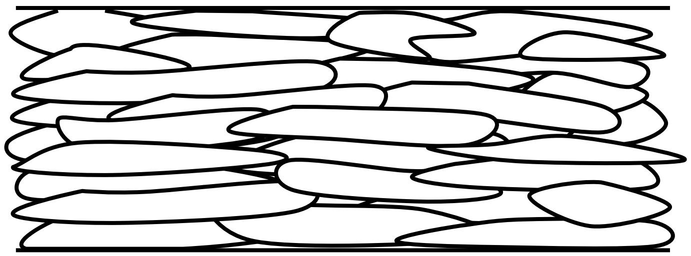




Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue, Third Edition, by Norman E. Dowling. ISBN 0-13-186312-6.

- A tungsten light bulb filament can creep under its own weight, which can lead to shorting due to the touching of adjacent coils.
- It is well known that the W wire will recrystallize during operation resulting in a "bamboo" structure (see the next page).
- When a light bulb is turned on, the filament undergoes thermal expansion along its length. This expansion is transient and non-uniform. The resulting expansion gradient imparts a tensile force along the length of the wire resulting in a force perpendicular to the grain boundaries in a recrystallized filament. After a long enough period of operation, the force will become large enough to cause the filament to fracture intergranularly.

Solution to Filament Problem – cont'd

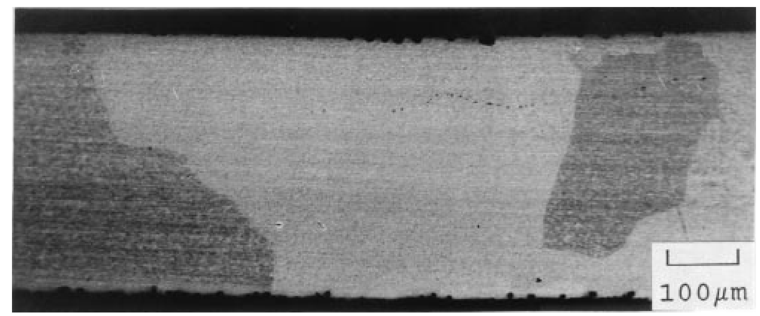


(a)

Drawing direction

(b)

(c)



(d)

Schematic microstructures of (a) drawn W wire and (b) such a wire following high-temperature exposure. Figures (c) and (d) are light optical micrographs of W before and after high-temperature exposure.

The schematic illustrates a fine-grained microstructure where the grains are elongated along the drawing direction. Upon exposure to high temperatures, the cold worked structure in the drawn wire recrystallizes producing a "bamboo" structure. The bamboo structure consists of grains having diameters equal to the wire diameter and grain lengths several times this diameter. The boundaries between grains will display cusp-like features as illustrated above.

Figures (a) and (b) were adapted from T.H. Courtney, Mechanical Behavior of Materials, 2nd Ed., Waveland Press (2005), p. 322. Figures (c) and (d) were adapted from P. Szozdowski and G. Welsch, *Scripta Materialia*, **41** (1999) pp. 1241-1245

A Typical Materials Selection Problem

- Engineers designing computer systems for long-term use in Earth orbit or in space deliberately use 1980's era microprocessors as opposed to modern ones. Explain why and hypothesize a solution that would allow the use of modern microprocessors.

- To solve this problem you will need a good understanding of physical metallurgy, in particular point defect generation in space (due to irradiation), and deformation mechanisms.

A Typical Materials Engineering Problem

- Pure copper (Cu), which has a face centered cubic crystal structure, is highly deformable and work hardens slowly. With the addition of a small quantity of Au in solid solution, the deformability of Cu decreases significantly and its work hardening rate increases. Explain what is happening.

- An understanding of physical metallurgy and deformation mechanisms is needed here.

Engineering structures are subject to many different types of forces/loads

- *Surface forces/loads*:
  - forces from contact
    - *Ex.*, friction, point load, etc…

- *Volume forces/loads*:
  - forces that act over the entire body
    - *Ex.*, gravity, magnetic forces, etc…

In most engineering applications, surface forces are more significant than volume forces; but there are exceptions…

- “can you think of any?”

Engineering structures are subject to many different forces

- *Static forces/loads*:
  - Forces that do not vary with time. They are constant in magnitude, direction and location.
- *Quasi-static forces/loads*:
  - Forces that vary “slowly” with time.
- *Dynamic forces/loads*:
  - Forces that vary with time
  - *Steady-state forces* –maintain the same character (frequency, amplitude, etc) over a long time.
  - *Transient forces* – change their character with time (e.g., decay).

WHEN EXPOSED TO EXTERNAL FORCES, MATERIALS WILL EITHER

DEFORM

OR

FRACTURE

Basic Types of Deformation

Deformation

[i.e., change shape]

<u>Time Independent</u>

- Elasticity*
- Plasticity*

<u>Time Dependent</u>

- <u>Visco</u>elasticity
- <u>Visco</u>plasticity / Creep*

After N.E. Dowling, <u>Mechanical Behavior of Materials, Engineering Methods for Deformation, Fracture, and Fatigue, 3rd Ed.</u>, (Prentice Hall, Upper Saddle River, 2007) p. 2.

TIME INDEPENDENT DEFORMATION

1. **Elastic deformation:** reversible deformation that is recovered immediately upon unloading. It is analogous to the stretching of atomic bonds. In the elastic regime, stress σ is usually linearly proportional to strain ε. Hooke's law applies: $\sigma = E\varepsilon$ where E is the modulus of elasticity.

2. **Plastic deformation:** permanent deformation that is not recovered upon unloading. Plastic deformation commences at the *proportional limit*. At this point the material is said to *yield*. Yielding is characterized by the *yield strength* σ_o. After yielding, σ is not linearly proportional to ε. Empirical relationships other than Hooke's law have been developed to describe the relationship between σ and ε.

TIME-DEPENDENT DEFORMATION

3. **Creep/viscoplastic**: permanent deformation that occurs with time. Usually occurs at high homologous temperatures (i.e., $T/T_{mp} \geq 0.4$). Creep deformation is permanent and is not recovered upon unloading.
   – Think of it as deformation that occurs in a material that is subjected to a constant load or stress that is often below the yield point of the material.

4. **Viscoelastic**: reversible deformation that occurs with time. "Rubbery" behavior.

Types of or Causes for Fracture

Fracture*

[i.e., “break” into pieces]

Static Loading
- Brittle
- Ductile
- Environmental
- Creep* Rupture

Cyclic Loading (Fatigue*)
- High cycle
- Low cycle
- Fatigue crack growth
- Corrosion fatigue

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FRACTURE

Separation of body or object into pieces.

1. **Ductile materials** can sustain lots of plastic deformation prior to fracture.

2. **Brittle materials** fracture with little or no plastic deformation are called “brittle.”

Failure

- *Anything that might cause a component to lose its structural tolerances*, thus prevent it from serving its intended purpose.

- This generally this means:
  - (i) fracture,
  - (ii) plastic deformation, or
  - (iii) excessive elastic deformation.

- *We design and select materials to avoid failure.*

★ The Engineer's Approach to Mechanical Behavior

- Strength of materials approach (1)

  – Principles of *elasticity* and *plasticity* are used to *predict material response*. You learned about these things in *statics*, *dynamics* and *strength of materials* courses.

  – This approach is applied with great frequency in design. Still very useful!

  – The advantages of this approach are that relatively few constants are needed to predict mechanical behavior.

★ The Engineer's Approach to Mechanical Behavior

- Strength of materials approach (2)
  - Problem: *general theories break down when the atomic nature of materials is introduced* as a variable.
  - Examples:
    - Creep (a form of high temperature deformation). Microstructure changes with time.
    - Stress concentrations at crack tips. Local stress may be higher than global stress.
    - Ductile-to-brittle transition temperature (DBTT) in steels. Fundamental changes in the material behavior cause a brittle solid to function like a "plastic" material.

★ The Engineer's Approach to Mechanical Behavior

- <u>Strength of materials approach (3)</u>
  - In engineering design, *strength of materials is still used*.
  - To effectively design or properly select a material for a given application, *structure* ***must*** *be taken in to account* at some level.

    Macrostructure (x1)

    Microstructure ($x10^6$)

    Nanostructure ($x10^9$)

General Assumptions

- The member is in *static equilibrium*
  - $\Delta F_i=0$; $\Delta M_i=0$ (external forces = internal resisting forces)

- The *body is continuous*
  - It contains no voids, holes, or spaces.
  -

- The *body is homogeneous*
  - It has properties that are identical at any point
  -

- The *body is isotropic*
  - Properties don't vary with direction or orientation.
  - If properties do vary, then the body is *anisotropic*.
  -

Problems with Assumptions

– The member is in *static equilibrium*

- $\Delta F_i=0$; $\Delta M_i=0$ (external forces = internal resisting forces)

– The *body is continuous*

- It contains no voids, holes, or spaces.

►**ALL materials contain flaws (on some level).**

– The *body is homogeneous*

- It has properties that are identical at any point

►**ALL materials and structures contain local inhomogeneities.**

– The *body is isotropic*

- Properties don’t vary with direction or orientation.
- If properties do vary, then the body is *anisotropic*.

►**Crystalline materials are inherently anisotropic.**

B*

★Fundamental Types of Mechanical Behavior

- Elasticity -
- Plasticity -
- Fracture -
- Creep -
- Fatigue -