# BASICS OF MATERIALS ENGINEERING

**PROF. RATNA KUMAR ANNABATTULA**
Department of Mechanical Engineering
IIT Madras

**TYPE OF COURSE** : New | Core | UG
**COURSE DURATION** : 12 weeks (20 Jul' 20 - 9 Oct' 20)
**EXAM DATE** : 18 Oct 2020

**PRE-REQUISITES :** Basic strength of materials, Basic Engineering Mathematics (Matrices, Calculus)

**INTENDED AUDIENCE :**
- B.Tech students and faculty from AICTE approved engineering colleges
- Aspirants of competitive exams such as GATE in mechanical engineering
- Working professionals interested in revisiting their fundamental concepts in materials science and engineering

**INDUSTRIES APPLICABLE TO :** Caterpillar India Private Limited, Sundaram Clayton, Mahindra & Mahindra, TVS Motors, Lam Research, Siemens Gamesa

**COURSE OUTLINE :**

The objective of this course is to introduce the basic concepts of materials science and failure theories for design to undergraduate mechanical engineering students. The course is a first level course and hence various concepts such as structure of crystalline materials, defects and their implications to mechanical behavior, the processing of materials through phase diagrams, a detailed discussion on iron-iron carbide equilibrium diagram and heat treatment of steels will be introduced at the introductory level.

**ABOUT INSTRUCTOR :**

Prof. (Dr.) Ratna Kumar Annabattula is currently an Associate Professor in the department of Mechanical Engineering at Indian Institute of Technology Madras, Chennai. He received his PhD (micromechanics of materials) in 2011 from the University of Groningen, The Netherlands. He obtained his ME in 2004 from Indian Institute of Science, Bengaluru and BE in 2002 from College of Engineering, Andhra University both in Mechanical Engineering. Prior to starting his PhD, he worked for about a year with General Electric India Technology Center, Bangalore. Before joining as a faculty at IIT Madras, he was a postdoc researcher at Karlsruhe Institute of Technology, Germany. His research interests are in the area of mechanics of stimuli-responsive materials, granular materials and multi physics modeling of materials with applications to lithium ion batteries and nuclear fusion.

**COURSE PLAN :**

**Week 1:** Introduction, Crystal Structure

**Week 2:** Imperfections in solids

**Week 3:** Imperfections in solids (Contd)

**Week 4:** Mechanical properties of materials

**Week 5:** Failure of Materials

**Week 6:** Failure of Materials (Contd)

**Week 7:** Basics of Fracture Mechanics

**Week 8:** Fatigue failure theories

**Week 9:** Fatigue failure theories (Contd)

**Week 10**: Phase diagrams

**Week 11:** Phase diagrams (Contd)

**Week 12**: Heat treatment of steels, Introduction to composite materials

# Detailed Syllabus for Basics of Materials Engineering

1. The main the book for this course is "William D Callister Jr. and David G. Rethwisch, Materials Science and Engineering: An Introduction, John Wiley, 8th Edition (2009)", unless indicated otherwise.

2. The numbers within "( )" besides each chapter heading correspond to the Chapter numbers and the section numbers in the text book.

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1. **Introduction and classification of materials** (1.1 – 1.7)

2. **Crystal structure** (3.1 – 3.15)
   2.1. Unit cells and Crystal Systems (3.1 – 3.3)
   2.2. Metallic crystal structures (3.4 – 3.12)
      a) Types of unit cells (BCC, FCC and HCP)
      b) Co-ordination number, atomic packing factor and density computations
      c) Representation of crystallographic points, directions and planes (Miller Indices), Linear and planar atomic densities
      d) Single crystals (3.13)
      e) Polycrystalline materials (3.14)
      f) Anisotropy (3.15)
   2.3. X-Ray diffraction – determination of crystal structure (3.16)

3. **Imperfections in solids** (4.1 – 4.7, 7.1 – 7.10)
   3.1. Point defects (4.1 - 4.2)
   3.2. Impurities (4.3 – 4.4)
   3.3. Dislocations (4.5)
   3.4. Interfacial defects (4.6)
   3.5. Bulk or volume defects (4.7)
   3.6. Dislocations and strengthening mechanisms (7.1-7.10)
      a) Basic concepts (7.1 – 7.3)
      b) Slip systems (7.4)
      c) Slip in single crystals, critically resolved shear stress (7.5)
      d) Plastic deformation in polycrystalline materials (7.6)
      e) Deformation by twinning (7.7)
      f) Strengthening mechanisms (7.8 – 7.10)

4. **Mechanical properties of metals** (6.1 – 6.10)
   4.1. Tensile test, compression test, shear and torsion test (6.1 – 6.2)
   4.2. Elastic deformation: Stress-strain plot, engineering and true stress-strain plots, relations between true and engineering values, Young's modulus, relation between elastic constants, Hooke's law (6.3 – 6.5)
   4.3. Plastic deformation: yielding and yield strength, tensile strength, Considere's criterion, ductility, resilience and toughness, elastic recovery (6.6 – 6.8)
   4.4. Hardness: Brinell, Rockwell and Vicker's hardness and their conversion, correlation between hardness and tensile strength (6.10)

5. **Failure of materials**[1] (Chapters 5 and 6)
   5.1. Introduction
      a) Stress concentration factors
      b) Stress tensor and its invariants
   5.2. Static failure theories
      a) Ductile materials: Tresca, Von-mises
      b) Brittle materials: Maximum normal stress theory, Mohr-Coulomb, Modified Mohr-Coulomb

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[1] Machine Design: An Integrated approach by Robert L. Norton

c) Factor of Safety
d) Application of failure theories

5.3. Fracture mechanics
a) Griffith criterion
b) Stress-intensity factor
c) Modes of crack extension
d) Fracture toughness
e) Applications

5.4. Fatigue failure theories
a) Low cycle and high cycle fatigue
b) Stages of fatigue crack propagation
c) Stress-life approach and LEFM approach
d) Types of fatigue loading
e) Rotating beam test and Marin factors
f) Endurance limit, Fatigue strength
g) Effect of mean stress on fatigue life: Gerber parabola, Gough ellipse, Soderberg line, Modified Goodman diagram
h) Paris' law
i) Multiaxial fatigue

6. **Phase diagrams** (9.1 – 9.20)
6.1. Introduction- What is phase?, solidus line, liquidus line, components of a typical phase diagram
6.2. Interpretation of binary phase diagrams of simple alloy systems
6.3. Determination of phases, amounts and composition of each phase
6.4. Development of microstructure under equilibrium cooling and effects of non-equilibrium cooling
6.5. Important reactions (Eutectic, peritectic, eutectoid, peritectoid and monotectic)
6.6. Iron-Iron Carbide (Fe-$Fe_3C$) Phase diagram
6.7. Microstructural aspects of Austenite, ferrite, ledeburite, cementite, pearlite and cast iron)
6.8. Influence of alloying elements like (Chromium, Nickel and Titanium) on the Iron-Iron carbide phase diagram

7. **Heat treatment of Steel** [10, 11.7]
7.1. The kinetics of phase transformations (10.1 – 10.4)
7.2. Isothermal transformation diagram (10.5)
a) Microstructural changes during phase transformation
b) Different types of microstructures formed during heat treatment and their relative hardness and mechanical properties: Fine Pearlite, Coarse Pearlite, Bainite, Martensite, Tempered Martensite
c) Continuous cooling transformation diagram (10.6-10.8)

7.3. Types of heat treatment and associates microstructure (11.7)
a) Annealing, Tempering, Normalizing, Quenching, Spheroidizing

# Learning Outcomes

1. **Introduction and classification of materials**

    1.1. List types of materials based on their structure
    1.2. List at least 10 crystalline and amorphous materials

2. **Crystal structure**

    2.1. Define a unit cell
    2.2. Extract the unit cell from a given pattern
    2.3. List the seven crystal systems with the relationships between their lattice parameters
    2.4. Draw crystal structures of BCC, FCC and HCP
    2.5. List at least 10 examples of metals under each crystal structure
    2.6. Calculate the co-ordination number of each crystal structure
    2.7. Calculate the atomic packing factor for a given crystal structure
    2.8. Calculate theoretical density for a given metal
    2.9. Distinguish the representation of a point, direction and a plane using Miller Indices
    2.10. Identify the close-packed directions and planes for BCC, FCC and HCP unit cells

3. **Imperfections in solids**

    3.1. List different types of defects in a solid
    3.2. Calculate the equilibrium number of vacancies in a material at a specific temperature given the relevant formation energy
    3.3. List different types of solid solutions and give at least 5 examples for each
    3.4. Write the conditions for formation of each of the above solid solutions
    3.5. Given masses and atomic weights of two or more elements in a metal alloy calculate the weight and atomic percent for each element
    3.6. Make a drawing of edge, screw and mixed dislocation. Identify the dislocation line and Burger's vector
    3.7. List and draw different types of grain boundaries
    3.8. List different types of microscopic equipment used to study atomic defects and also have a knowledge on their limitations
    3.9. Explain the role of grain boundaries in impeding dislocation motion
    3.10. Explain why nano-crystalline materials could be stronger that their coarse grained counterparts
    3.11. List different strengthening mechanisms and describe their principles
    3.12. Plot a schematic of the variation of the tensile strength, yield strength and percentage elongation as a function of weight percentage of alloying element (Ni) for Cu-Ni system
    3.13. Derive expression for critically resolved shear stress

4. **Mechanical properties of materials**

    4.1. Define engineering stress and strain
    4.2. State Hooke's law and its limitations
    4.3. Define Poisson's ratio
    4.4. Given an engineering stress-strain curve determine (A) modulus of elasticity (B) yield strength (C) tensile strength (D) percentage elongation
    4.5. Discuss the microscopic details of the deformation and failure of a mild steel specimen under uniaxial tensile test
    4.6. Given dimensions of the specimen before and after test plot the true stress-strain curve from the engineering stress-strain curve
    4.7. Name three different hardness test and note the differences
    4.8. Convert hardness to approximate strength values

5. **Failure of materials**

5.1. Write the invariants of a stress tensor
5.2. Deduce the relation between eigen values of a stress tensor and principal stresses
5.3. Write the stress concentration factors for specific types of loading and geometry
5.4. Write the names failure theories for ductile and brittle material
5.5. Derive the expressions for von-Mises and Tresca yield criterion and write the underlying assumptions
5.6. Plot the 2D yield surface for each failure theory mentioned above
5.7. Design simple members (like bar, shaft, beam) under different loading conditions using failure theories
5.8. Discuss relative merits of each theory in design
5.9. Discuss the difference between stress-intensity and stress-concentration factor
5.10. Draw schematic S-N curves for ferrous and non-ferrous materials
5.11. Determine life of a given member from the S-N curve
5.12. Draw schematics for fully reversed, repeated and fluctuating loads and label the stress range, alternating stress, mean stress on the schematic.
5.13. Describe rotating beam test
5.14. Draw the failure locus of different fatigue failure theories with the effect of mean stress
5.15. Discuss Paris law and underlying assumptions
5.16. Apply Stress-Life and LEFM approaches to design simple machine member under uniaxial and multi-axial fatigue loading
5.17. Calculate the factor of safety using Goodman diagram

6. **Phase diagrams**

6.1. Sketch simple isomorphous and eutectic phase diagrams; label various regions and liquidus, solidus and solvus lines.
6.2. Determine (a) the phases present (b) composition of phases (c) mass fraction of phases, given a binary phase diagram, composition of the alloy, its temperature by assuming the alloy is at equilibrium.
6.3. Label all phases, reactions in a given binary phase diagram
6.4. Draw the microstructures of an alloy when it is cooled slowly from molten state to room temperature at a given alloy composition
6.5. Draw the schematic of the Fe-$Fe_3C$ equilibrium phase diagram and label all the phases and temperatures which represent all phase transformations
6.6. Determine whether the alloy is hypoeutectoid or hypereutectoid given the weight percent of carbon in Fe-$Fe_3C$ equilibrium diagram

7. **Thermal Processing and Heat treatment of steel**

7.1. Derive the expression for critical radius and activation free energy for homogeneous solidification.
7.2. Plot a schematic showing the fraction of transformation versus logarithm of time for a typical solid-solid transformation and cite the governing equation of the plot.
7.3. Given a isothermal transformation or continuous cooling transformation diagram for some iron-carbon alloy, design a heat treatment that will produce a specific microstructure.
7.4. Draw in Fe-$Fe_3C$ equilibrium diagram in the vicinity of the eutectoid composition and indicate the various heat treating temperature ranges for plain carbon steels
7.5. Describe briefly the microstructure and mechanical properties of the micro constituents in steel:

Fine pearlite, coarse pearlite, spheroidite, bainite martensite and tempered martenstite.