Module 1

Principles of Physical Metallurgy: an introduction to the course content

Lecture 1

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Keywords: Cost of metals & materials, energy needed to produce metals & materials, CO_2 emission, correlation between cost and embodied energy or CO_2 emission

Introduction

Metals and alloys have been in use since ages as jewelries, coins, tools, arms, and armors. Periods of human civilization have been named after metals & alloys viz. Copper Age / Bronze Age / Iron Age. However bulk use of metallic materials started with the commercial production of pig iron in blast furnace during the eighteenth century. Steel the most widely used metallic material became available in bulk only with the introduction of Bessemer Converters in mid nineteenth century (1856). Today it is one of the most extensively used engineering material. It is next to cement in terms of annual world production figures. Around 1.35 billion tons of crude steel is being produced in the world every year. India is the 5^{th} largest producer of steel today. Our current production is around 75Million ton. Selection of metals & alloys for a given application depends primarily on its properties, cost and availability. Materials are often not available in the form that could be directly put to use. It has to be extracted or synthesized from naturally occurring ingredients and subsequently processed to give it the desired shape and properties so that it is useful. Its cost has a direct correlation with the effort that is required to produce it. Energy spent in this process is a good indicator of such an effort. This is often referred to as embodied energy (stored energy). Table 1 gives a list of common metals & materials along with their cost and energy required for their production from natural resources. It also includes the amount of CO_2 generated for every kg of the material being produced. Apart from energy this too gives a measure of the adverse impact a manmade material is likely to have on the environment. The amount of energy needed to produce aluminum alloys and the amount of CO_2 it produces are much higher than those for steel or concrete (a composite of cement sand and stone chips). The data in this table also suggests that there is a direct correlation between the cost of a material with either the magnitude of energy spent to produce it or the amount of CO_2 it emits during its production. No wonder that concrete and steel happen to be the cheapest materials of construction. Cu base alloys appear to an exception. High cost of raw materials could possibly a reason for this anomaly.

Table 1

A comparison of energy needed to produce come of the common materials, their cost and their impact on environment measured in terms of CO2 generated per unit of mass.

Material	Energy (MJ/kg)	Cost in $ /kg	CO_2 kg/kg
Al alloys	200-220	1.5-1.7	11.2-12.8
Polyethylene	75-78	1.3-1.5	2.0-2.2
Cu alloys	68-74	3.2-3.5	4.9-5.6
Steel	29-35	0.63 – 0.89	2.2-2.8
Glass	14-17	1.4-1.7	0.7-1.0
Concrete	1-1.3	0.041-0.062	0.13-0.15

Source: M F Ashby, Material Selection in Mechanical Design IV edition (2011) Elsevier

Metallic materials are known for their ductility, electrical & thermal conductivity, strength, toughness and characteristic luster. A few of them have attractive magnetic properties as well. If you hit a piece of metal it gives a characteristic metallic sound. No wonder bells are made of metals (a special copper alloy). Apart from its ability to be cast in any desired shape and size; it is possible to form it by deformation and a variety of fabrication techniques.

Table 2: Gives annual production of a few common metals & a few manmade materials. It also gives a rough range of their tensile strengths (*compressive in the case concrete).

Metal	World MT	India MT	Min MPa	Max MPa
Concrete	16000	2800	14*	130*
Steel	1545	75	240	3000
Paper	400	6.4	0.2	0.5
Al	49.3	1.6	50	550
Cu	18.5	0.65	200	1200
Zn	11.5	0.7	100	375

In this course we shall try to learn about evolution of structures in metals as it transforms into solid from liquid, the effect of subsequent processing techniques on its structure, influence of alloy addition (or mixing) on transformation processes, and explore the relationships between properties of metals and alloys with their internal structures. The main objective is to provide a basic understanding of the underlying principles that determine the evolution of structures in metals and alloys during their processing and its relation with their properties & performance in service.

The broad outline of the course content is given in the following table 2. The entire course has been divided into 42 modules. A few of these are clubbed together. These may be considered as distinct chapters. There is a parallel video course on the same subject. It is available at www.nptel.ac.in. The module of lectures in this web course nearly follows the same sequence as the video lectures on Principles of Physical Metallurgy. In order to understand the transformation processes undergoing within metals or alloys various experimental tools and techniques are used. An attempt has been made to give brief outlines of these too within this course.

Table 2: A broad outline of the course

S. No.	Topic	Modules
1	An introduction to the course content (modules), Atomic bonding & crystal structure: metallic bond, unit cell, atomic	1 - 4

	packing, interstitial sites, Miller indices, crystal orientation, stereographic projection	
2	Experimental tools & techniques: metallography (Optical TEM, SEM), X ray diffraction, mechanical properties, thermal analysis	5 - 6
3	Solidification of pure metal: phase rule, concept of free energy, entropy, surface energy (grain boundary) & under cooling, nucleation & growth, homogeneous & heterogeneous nucleation, directional solidification	7
4	Plastic deformation of pure metal: mechanisms(slip & twin), critical resolved shear stress, single crystal: tensile stress strain curve (fcc), theoretical strength of ideal crystal	8 - 9
5	Crystal defects in metals: vacancy, interstitial & substitutional atoms, free energy of mixing, dislocation (elementary concepts only), edge / screw dislocation, partial dislocation, stacking fault, dislocation lock, dislocation pile up, Hall Petch relation, grain boundary structure	10 - 14
6	Diffusion: elementary concepts of phenomenological & atomistic approaches	15 - 17
7	Solidification of binary alloys: limits of solubility, isomorphous system, lever rule, constitutional super cooling, effect of non equilibrium cooling, eutectic, peritectic, eutectoid & peritectoid system, complex phase diagram, structure of cast metal, segregation & porosity,	18 - 22
8	Iron-carbon diagram, structure of steel & cast iron, introduction to TTT diagram	23 – 24
9	Ternary phase diagram, composition triangle, ternary isomorphous system, ternary eutectic, vertical & horizontal sections,	25
10	Binary phase diagrams of common commercial alloys: Cu-Ni, Au-Cu, Ni-Cr, Al-Si, Al-Zn, Al-Ag, Pb-Sn, Cu-Zn, Cu-Sn, Cu-Al, Ti-Al, Ti-V: interpretation of microstructure & properties	26
11	Deformation processing: cold work & annealing: recovery, re-crystallization & grain growth, phenomenological & mechanistic approaches	27 - 28
12	Precipitation from super-saturated terminal solid solution: thermodynamics & kinetics of precipitation, precipitation hardening	29 - 30
13	Heat treatment of steel: T-T-T diagram, Pearlitic, Martensitic & Bainitic transformation, effect of alloy elements on phase diagram & TTT diagram, CCT diagram, Annealing, normalizing, hardening & tempering, hardenability,	31 - 36
14	Surface hardening	37
15	Structural steel, strengthening mechanism, thermo-mechanical	38 - 39

	processing, micro alloyed steel	
16	Ultra high strength steel, alloy steel, creep resistant steel	40
17	Preferred orientation, pole figure, cold work & annealing texture, control of texture, deep draw-ability, electrical grade steel (CRGO, CRNO), DS & SC super-alloy	41
18	Physical metallurgy of metal joining: mechanism of bond formation, effect of local heating on the evolution of structures in metals, heat flow characteristics	42

There are excellent text books on physical metallurgy. A few of these are given below. Students may refer to these in order to get a much deeper insight on this topic. Often to solve some of the problems it may be necessary to look for relevant material data. For this one could refer to handbooks included in this list.

- Physical Metallurgy Principles: Robert E Reed-Hill and Reza Abbaschian
- Phase Transformation in Metals & Alloys: D A Porter & K Easterling
- Fundamentals of Physical Metallurgy: John D Verhoeven
- Physical Metallurgy: Peter Haasen
- Structure and Properties of Alloys: R M Brick, R B Gordon, A. Phillips
- Physical Foundations of Materials Science: G. Gottstein
- Paul G Shewmon : Transformation in Metals, Mc Graw-Hill (1969)
- Paul Gordon : Principles of Phase Diagrams in Materials Systems, Mc Graw-Hill series in Materials Science & Engineering (1968)
- Frederick N Rhines : Phase Diagrams in Metallurgy – Development & Application, Mc-Graw-Hill (1956)
- Max Hansen : Constitution of Binary Alloys, Mc-Graw-Hill (1958)
- M C Flemings : Solidification Processing, Mc Graw-Hill series in Materials Science & Engineering (1974)
- William C Leslie : The Physical Metallurgy of Steels Mc Graw-Hill series in Materials Science & Engineering (1981)
- W F Hosford, Mechanical Behaviour of Materials, Cambridge University Press, (2010)
- M F Ashby & D R H Jones, Engineering Materials 1: An introduction to properties applications and design, Elsevier (2012)
- Y Lakhtin, Engineering Physical Metallurgy, Mir Publishers Moscow
- ASM Metals Handbook – ASM International Metals Park, Columbus, Ohio, USA
- Smithells Metals Reference Book – Butterworth, Heinemann, London

Apart from the list of books given above there are several websites that are worth visiting. A few of these are as follows:

www.msm.cam.ac.uk/Teaching
www.doitpoms.ac.uk
www.ndt-ed.org/EducationResources/CommunityCollege/Materials

Table 3: Gives annual production of a few common metals & a few manmade materials. It also gives a rough range of their tensile strengths (*compressive in the case concrete).

Metal	World MT	India MT	Min MPa	Max MPa
Steel	1545	75	240	3000
Al	49.3	1.6	50	550
Cu	18.5	0.65	100	550
Zn	11.5	0.7	135	520
Concrete	16000	2800	14*	130*
Paper	400	6.4	0.00018	0.00085

What is the internal structure of metal? What happens when we try to deform it to give a specific shape? If we try to mix two or more metals how does its internal configuration change? Physical Metallurgy provides answers to these questions. The subject as we know today started evolving since the beginning of the 20th century. It was also the time when internal structures of atoms were unraveled. Examination of polished and etched surfaces of metals under microscope revealed that these are made of different grains with distinct boundaries. Metals are malleable. They can be formed into any shape by deformation. There is no restriction on the shapes the grains could have. Examination of metals using X-Ray revealed its crystalline nature. Grains in metals often do not have well developed crystalline faces found in inorganic solids. As we go through the course you would come to know about it.

Table 3 gives an idea of the current production figures of steel and a few common metals. It also includes one of the mechanical properties (tensile strength). Truly speaking steel is an alloy of iron and carbon. It has certain characteristic features which makes it amenable to various processing techniques. This is why its strength could be increased by several folds by controlling its composition and processing route. As we go through the course you would know how the properties can be altered by mixing two or more elements and also by controlling subsequent processing techniques. Although in this course the main focus will be on metals and alloys many of the physical concepts introduced would be applicable to other categories of materials like ceramic, plastic, glass and composites. For example window panes are made of soda lime glass. This is made by mixing soda, lime silica and alumina. With the advent of polymers (plastic) and composite material today's engineer has a much wider variety of materials to choose from. Interested students may refer to an article by Professor M F Ashby giving a historical sketch of evolution of engineering materials during the entire span of human civilization. The basic difference between the natures of metal with others lies in the nature of their bonding. This is why it is appropriate to begin this course with a couple of lectures on the nature of atomic bonds and crystal structure of materials. A video version of this course is available on internet. This is the web version of the same course. This version of the course is divided into several modules arranged in the same sequence as that followed in its video version.

Further reading:

1. N A Fleck, V S Deshpande & M F Ashby, Micro-Architectured Material: Past Present & Future, Proc Royal Soc A(2010) 466, p 2495-2516

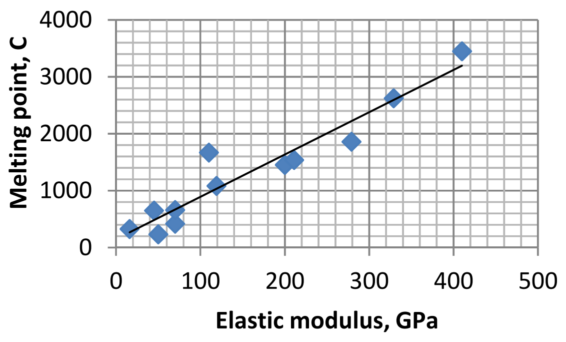
Exercise:

1. From handbook find out melting points and Young's Modulus of a few common metals (Fe, Al, Cu, Pb, Ni, Zn, Sn, W, Ti, Mg, Cr). Is there a correlation between the two?
2. Find out from handbook atomic weights and density of Au, Ag, Al, Cu, Ni, Pb. Is there a correlation between the two?

Answer:

1. The following table gives the melting point and elastic modulus of a few elements. The graph shows that by & large there metals having high modulus has high melting point. Note there is an exception in case of Ti.

	C	Gpa
Sn	232	50
Pb	327	16
Zn	419	70
Mg	650	45
Al	660	70
Cu	1083	119
Ni	1453	200
Fe	1539	211
Ti	1670	110
Cr	1860	279
Mo	2623	329
W	3450	410



2. The following table and the graph display the correlation that higher the atomic number higher is the density (exception Pb. You will know reason in when the concept of lattice defect is introduced)

	At. Wt.	Density
Al	26.98	2.7
Ni	58.69	8.9
Cu	63.55	8.96
Ag	107.87	10.5
Au	196.96	19.3
Pb	207.2	11.34