CHY1005 INDUSTRIAL CHEMISTRY FOR ENGINEERS
Module 4 - Alloys and Steels

Theory and purpose of making alloys

Ferrous and Non-Ferrous alloys

Modes of formation and preparation of alloys

Specific properties of elements in alloys, light alloys, cast alloys.

Heat and vacuum treatments of steel: annealing types, normalizing, tempering, hardening.

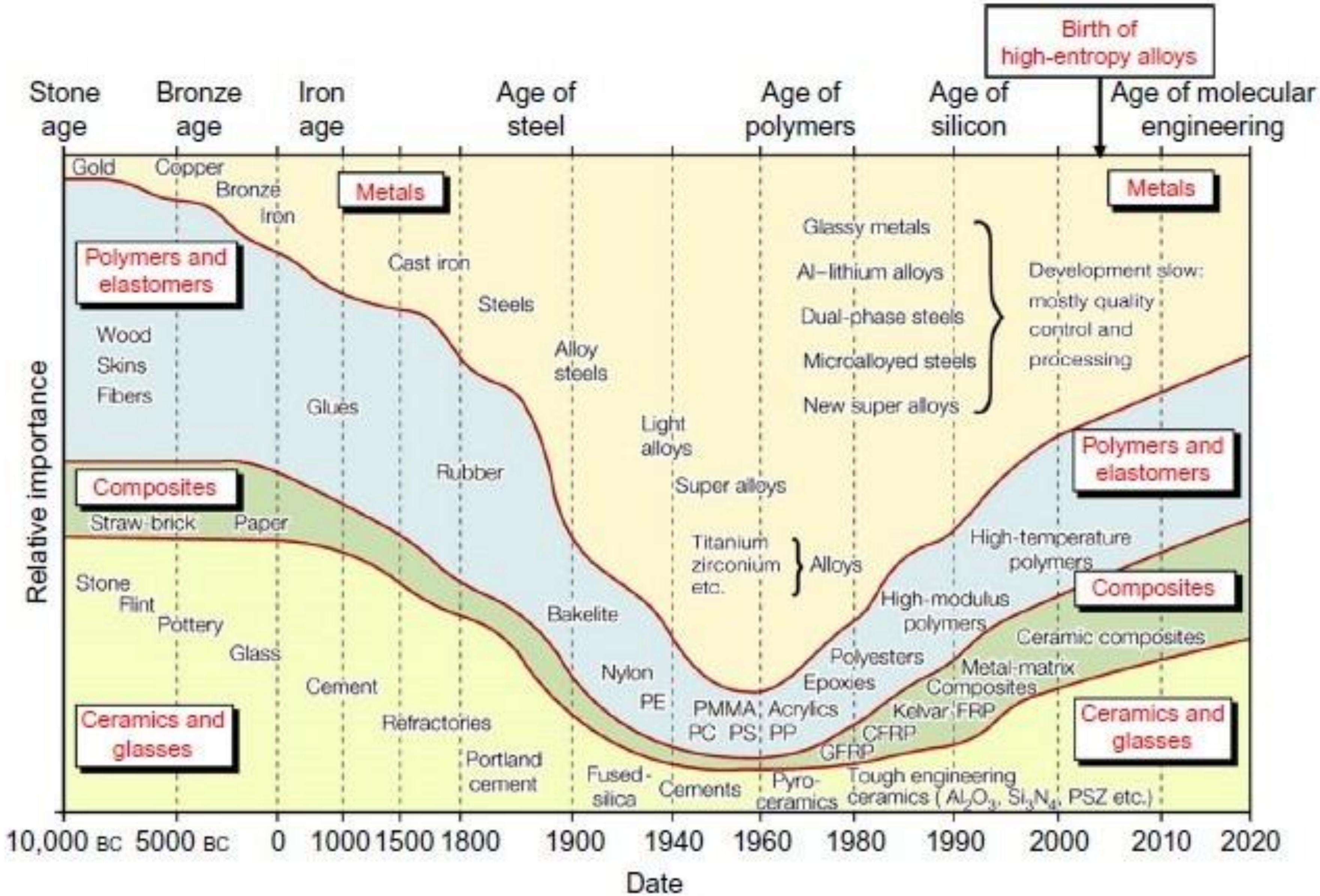
Tool steels, stainless steels

Cast iron - malleable and ductile types and properties.

Alloys of Cu, Al, Ti and their applications. Cermets.

3D printable materials: metal, ceramic and composite powders to make precision end-use parts (for automotive, aerospace, defense, medical devices, healthcare, art & fashion, energy and consumer applications).

Engineering Materials – Evolution History



Alloys

- Pure metals are soft ductile and have tensile strength.
- High malleability, ductility, luster and good electrical conductivity are metallic nature.
- for most of the applications, their tensile strength, corrosion resistance and hardness are not sufficient.
- These properties can be improved by alloying.

"Alloy is homogeneous solid solution of two or more different elements, atleast one of which is a metal".

"A metal dissolving in another metal in molten state forming homogeneous liquid mixture which on cooling solidifies to a solid mixture is called alloy".

Difference Between Metals and Alloys

S. No.	Metals	Alloys
1.	It is made of one type of atom and orderly arranged and closely packed.	Alloy is basically a solid solution. Alloy is a homologous mixture of two or more metals or non metal.
2.	They are soft and brittle.	Alloys are stronger and harder.
3.	They are prone to corrosion.	Alloys are more resistant to corrosion.
4.	Pure metals have very high melting point.	Alloys have less melting point.
5.	Electrical conductivity and thermal conductivity is high.	Electrical conductivity and thermal conductivity of alloys are less than the pure metals.

Types of Alloys

1. **Based on the constituents, alloys are of three types.**

   (a) Alloys formed by two or more metals. Brass (Cu–Zn)

   (b) Alloys formed between a metal and a nonmetal. WC alloy

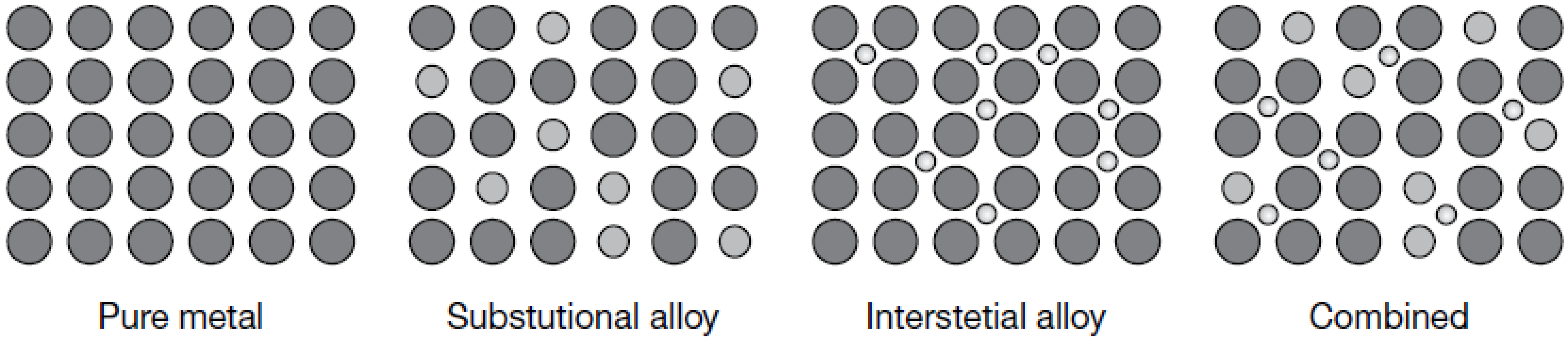
   (c) Alloy amalgam formed between mercury and another metal. Zinc amalgam

2. **Based on position in lattice of atom**

   (a) Substitutional alloys

   (b) Interstitial alloys

   (c) Combined alloys



Types of Alloys

3. Based on metallurgical structure

(i) Single phase alloys.

(ii) Multiphase phase alloys.

4. Based on presence and absence of iron

(i) Ferrous alloys are those in which iron is the principal constituent, include steels and cast irons.

(ii) Nonferrous alloys are all alloys that are not iron based.

5. Based on main metal in alloys

(i) Alloys of Magnesium

(ii) Alloys of copper

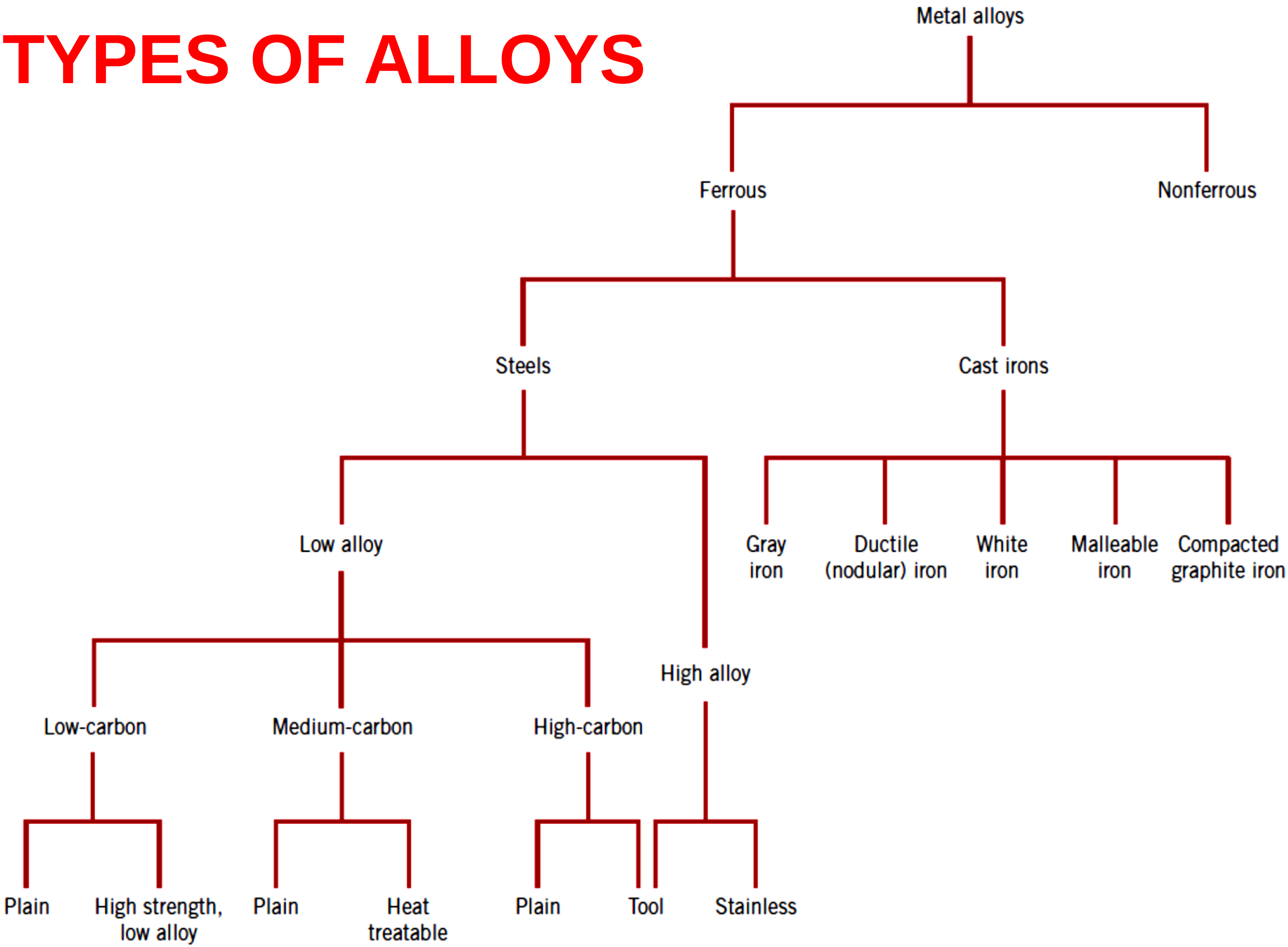
(iii) Alloys of nickel *etc*.

6. Based on methods of fabrications

(i) Wrought alloys

(ii) Casting alloys

TYPES OF ALLOYS



Properties of Alloys

Alloys are manufactured to enhance the properties of metal for specific application.

It is Engineers material.

Based on the applications the properties enhanced are:

high tensile strength, high ductility, high toughness, high elasticity,

high heat-resistance, high corrosion resistance, high hardness,

high resistance to abrasion, high resistance to oxidation,

high magnetic permeability and so on.

Effect of Alloying Elements

S. No.	Element	Effect on properties	Use of alloys
1.	Nickel	Improves ductility, tensile strength, toughness, elasticity, heat and corrosion resistances.	For making balance wheels.
2.	Chromium	Enhances tensile strength, corrosion resistance, hardness and toughness.	For making surgical instruments, cutlery and connecting rods.
3.	Manganese	Increases strength, toughness and brittleness.	For making grinding wheels, rails and stearing spindles.
4.	Molybdenum	Improves abrasion and corrosion resistance. It becomes strong at high temperature.	For making high speed tools.
5.	Tungsten	Increases magnetic retentivity and cutting hardness. Also it improves toughness, abrasion and shock resistance.	For making cutting tools, permanent magnets.
6.	Vanadium	Increases tensile strength, ductility and shock resistance.	For making axles, crank pins and piston rods.
7.	Nickel and Chromium	Increases corrosion resistance and tensile strength.	For making stainless steel.

Alloys are made to:

Enhance the hardness of a metal: An alloy is harder than its components. The hardness of a metal can be enhanced by alloying it with another metal or nonmetal.

Lower the melting point: Pure metals have a high melting point. The melting point lowers when pure metals are alloyed with other metals or nonmetals. This makes the metals easily fusible. This property is utilized to make alloys called solders.

Enhance tensile strength: Alloy formation increases the tensile strength of the parent metal.

Enhance corrosion resistance: Alloys are more resistant to corrosion than pure metals. Metals in pure form are chemically reactive and can be easily corroded by the surrounding atmospheric gases and moisture. Alloying a metal increases the inertness of the metal, which, in turn, increases corrosion resistance.

Modify color: The color of pure metal can be modified by alloying it with other metals or nonmetals containing suitable color pigments.

Provide better castability: One of the most essential requirements of getting good castings is the expansion of the metal on solidification. Pure molten metals undergo contraction on solidification. Metals need to be alloyed to obtain good castings because alloys expand

Properties of Alloys

Each alloy has certain useful properties.

An alloy's properties are distinct from those of the individual metals from which it is produced.

Some properties of alloys are given below.

1. Alloys are harder than their constituent metals.
2. Alloys are more resistant to corrosion than pure metals.
3. Alloys are more durable than the metals they are made from.
4. The electrical conductivity of alloys is lower than that of pure metals.
5. Alloys have a lower melting point than the metals from which they are made.
6. Alloys have greater ductility than their constituent metals.

Uses of Alloys

Alloys are used in a number of ways in our daily lives.

Brass: cooking utensils, screws, locks, doorknobs, electrical appliances, zippers, musical instruments, decoration and gift items

Bronze: statues, coins, medals, cooking utensils, and musical instruments, among other things.

Alnico is a ferromagnetic substance and is used in permanent magnets.

Solder is used to repair or join two pieces of metals. It is used to permanently join electrical components.

sterling silver: Surgical devices, musical instruments, cutlery, and jewellery.

Stainless steel: construction of railways, bridges, roads, airports etc. It is also used for making cooking utensils and other products.

Aluminium alloys: lightweight, so they are used for making bodies of aircraft and their parts.

Titanium alloys: Because of high-temperature strength and superplastic behaviour, used in the aerospace industry.

Amalgam (a mercury alloy): medicinal procedures. Dentists also use it to fix cavities in teeth.

Rose gold: Jewellery making purposes.

Treatment of Alloys

Alloys have to pass through one or more of the following processes before they are converted into finished products:

i. Melting:

ii. Casting:

iii. Sintering:

iv. Hot Working:

v. Cold Working:

vi. Surface Treatments:

vii. Joining:

viii. Heat Treatment:

Heat treatments of following types are commonly used:

(a) Annealing:

(b) Precipitation Hardening:

(c) Martensite Hardening:

Effects of Alloying Elements in Steel

Al ALUMINUM

The most common deoxidizers in making steel.
Used to produce a fine grain structure and to control grain growth.

C CARBON

Increase in carbon content correspondingly increases tensile strength and hardness.
Increasing carbon makes the steel increasingly responsive to heat treatment.

Cr CHROMIUM

When used in large quantities, possesses a remarkable resistance to oxidation and erosion used in conjunction with other alloys.

Cu COPPER

Added in amounts of 0.20 – 0.30% makes steel resisting corrosion and also increase tensile and yield strengths a little with only a slight loss in ductility.

Pb LEAD

Used in small amounts of 0.15 – 0.30% in steel to improve machinability.

Effects of Alloying Elements in Steel

Co COBALT

It adds much life to a tool by its ability to maintain hardness and cutting ability when it’s heated to a dull red during a machining operation.

Mn MANGANESE

Used to resist hot shortness or the tendency to tear while being forged or rolled. Manganese is used in just about every steel made and increases responsiveness to heat treatment and acts as a deoxidizer.

Mo MOLYBDENUM

Raises hot strength, has good creep resistance and helps steel resist softening at elevated temperatures. It is used to a large extent in tools and dies intended for the hot working of metal.

Ni NICKEL

Increases strength and toughness and has good fatigue resistance. Steels with nickel usually have more impact resistance than steels where nickel is absent. This is true especially at lower temperatures.

P PHOSPHORUS

Phosphorus is present in all steels and tends to increase resistance to corrosion while increasing yield strength.

Effects of Alloying Elements in Steel

Si SILICON

Is the most common deoxidizing agent. In amounts up to 1% it has a marked strengthening and toughening effect. In higher amounts it produces electrical resistance and give high magnetic permeability.

S SULFUR

Is usually found in all steels and like phosphorus is considered machinability. The amount for this purpose is usually from .06 -.30

W TUNGSTEN

Promotes red hardness and hot strength in addition to producing dense grain and a keen cutting edge. Very useful for hot working applications such as cutting tools when the steel is hot enough to be low red in color.

V VANADIUM

Is a strong deoxidizer and promotes fine grain structure. It helps steel resist softening at elevated temperatures and seems to resist shock better than steels without it.

Engineering Alloys

- **Light alloys: Based on Al, Mg and Ti**
- **Copper alloys**
- **Lead alloys**
- **Zinc alloys**
- **Nickel alloys, Ni-Cu alloys and Ni-Cr alloys**
- **Steels**
    - **(i) Low carbon steels**
    - **(ii) Engineering steels**
    - **(iii) Stainless steels**
- **Cast iron**
- **Nodular or Ductile or Spheroidal Graphite cast iron**

Alloy Die Casting: Types of Alloys and Their Uses

- ❑ Zinc Alloys.
- ❑ Tin Alloys.
- ❑ Bronze and Brass Alloys.
- ❑ Aluminum Alloys.
- ❑ Lead Alloys.

Common heat treatment methods

- Annealing.
- Normalising.
- Hardening.
- Ageing.
- Stress relieving.
- Tempering.
- Carburisation.

Annealing of Steel

- To produce the highest level of ductility.
- Heat the metal slowly to the appropriate temperature, soak it.
- Then allow it to cool slowly by either burying it in some sort of insulating material or by simply turning off the furnace and letting both the furnace and the part cool slowly together.
- The amount of time for metal soak depends on both its type and its mass.
- If it's low-carbon steel, it'll require the highest possible annealing temperature.
- The carbon content increases, its annealing temperature will decrease.

Normalizing

- The purpose of normalizing is to remove any internal stresses from heat treatment, machining, forging, forming, welding, or casting.
- Metal failure can result from uncontrolled stress, so normalizing steel before any hardening is needed.
- Normalized steel is stronger than annealed steel.
- With both high strength and high ductility, it is tougher than annealed steel.

1) Carbon Steels:

Carbon steels contain trace amounts of alloying elements and account for 90% of total steel production. Carbon steels can be further categorized into three groups depending on their carbon content:

- Low Carbon Steels/Mild Steels contain up to 0.3% carbon
- Medium Carbon Steels contain 0.3 – 0.6% carbon.

2) Alloy Steels:

Alloy steels contain alloying elements (e.g. manganese, silicon, nickel, titanium, copper, chromium and aluminum) in varying proportions in order to manipulate the steel's properties, such as its hardenability, corrosion resistance, strength, formability, weldability or ductility.

Applications for alloys steel include pipelines, auto parts, transformers, power generators and electric motors.

3) Stainless Steels:

Stainless steels generally contain between 10-20% chromium as the main alloying element and are valued for high corrosion resistance. With over 11% chromium, steel is about 200 times more resistant to corrosion than mild steel.

4) Tool Steels:

Tool steels contain tungsten, molybdenum, cobalt and vanadium in varying quantities to increase heat resistance and durability, making them ideal for cutting and drilling equipment.

Cast iron

Cast iron is iron or a ferrous alloy which has been heated until it liquefies, and is then poured into a mould to solidify. It is usually made from pig iron. Types: Grey cast iron, White cast iron, Malleable cast iron and Ductile cast iron.

The alloy constituents affect its colour when fractured:

white cast iron has carbide impurities which allow cracks to pass straight through.

Grey cast iron has graphite flakes which deflect a passing crack and initiate countless new cracks as the material breaks.

NON FERROUS METAL & ALLOYS

Copper

- Copper is one of the earliest metals discovered by man.
- The boilers on early steamboats were made from copper.
- The copper tubing used in water plumbing in Pyramids was found in serviceable condition after more than 5,000 years.
- Cu is a ductile metal. Pure Cu is soft and malleable, difficult to machine.
- Very high electrical conductivity – second only to silver.
- Copper is refined to high purity for many electrical applications.
- Excellent thermal conductivity – Copper cookware most highly regarded – fast and uniform heating.
- Electrical and construction industries are the largest users of Cu.

Copper Alloys

- Brasses and Bronzes are most commonly used alloys of Cu. Brass is an alloy with Zn.
- Bronzes contain tin, aluminum, silicon or beryllium.
- Other copper alloy families include copper-nickels and nickel silvers.
- More than 400 copper-base alloys are recognized.
- Used for making coins and ornaments along with gold and other metals.

Applications

Electrical wires, roofing, nails, rivets, Automotive radiator core, lamp fixture, clutch disk, diaphragm, fuse clips, springs, Furniture, radiator fittings, battery clamps, light fixtures, Bearings, bushings, valve seats and guards, Electrical, valves, pumps, Condenser, heat exchanger piping, Bearings, bushing, piston rings, gears.

Aluminum

- Al is a light metal & easily machinable; has wide variety of surface finishes; good electrical and thermal conductivities; highly reflective to heat and light.
- Versatile metal - can be cast, rolled, stamped, drawn, spun, roll-formed, hammered, extruded and forged into many shapes.
- Al can be riveted, welded, brazed, or resin bonded.
- Al is used in cooking vessels, packing wraps (aluminium foils) for food items heat exchangers/sinks, chemical reactors, medical equipment, refrigeration units and gas pipelines.
- Al is a good electrical conductor and cheap, hence used in electrical overhead electric cables with steel core for strength.
- Corrosion resistant - no protective coating needed, however it is often anodized to improve surface finish, appearance.
- Al and its alloys - high strength-to-weight ratio (high specific strength) owing to low density.
- Widely used in aerospace and automotive applications where weight savings are needed for better fuel efficiency and performance.
- Al-Li alloys are lightest among all Al alloys and find wide applications in the aerospace industry.

Application of some Al Alloys

- Food/chemical handling equipment, heat exchangers, light reflectors
- Utensils, pressure vessels and piping,
- Bellows, clutch disk, diaphragm, fuse clips, springs
- Heat treated aircraft structure, rivets, truck wheel
- Trucks, canoes, railroad cars
- furniture, pipelines
- Aircraft structures and other highly loaded applications
- Aircraft pump parts,
- Automotive transmission cases, cylinder blocks

TITANIUM ALLOYS

Alpha phase Ti metal, below 882ºC, HCP structure

Beta phase Ti metal, above 882ºC, BCC structure

Classification of Titanium Alloys:

- Alpha alloys
- Near alpha alloys
- Alpha+beta alloys
- Near beta alloys
- Beta alloys

Applications of Titanium and its Alloys

- Titanium is safe from environmental effects.
- The life of titanium is better than metals.
- Titanium and its alloys have excellent mechanical properties such as corrosion resistance strength, fatigue, creep resistance.
- Titanium and its alloys have broad applications in aerospace engines, industries, construction, architecture, automobile.
- In addition, it is an environment-friendly alloy, so have significant application in medicine.
- Aircraft, ordnance, marine, food, petroleum, electrical and chemical industrial applications due to the exceptional properties of titanium alloys.

Applications of Titanium and its Alloys

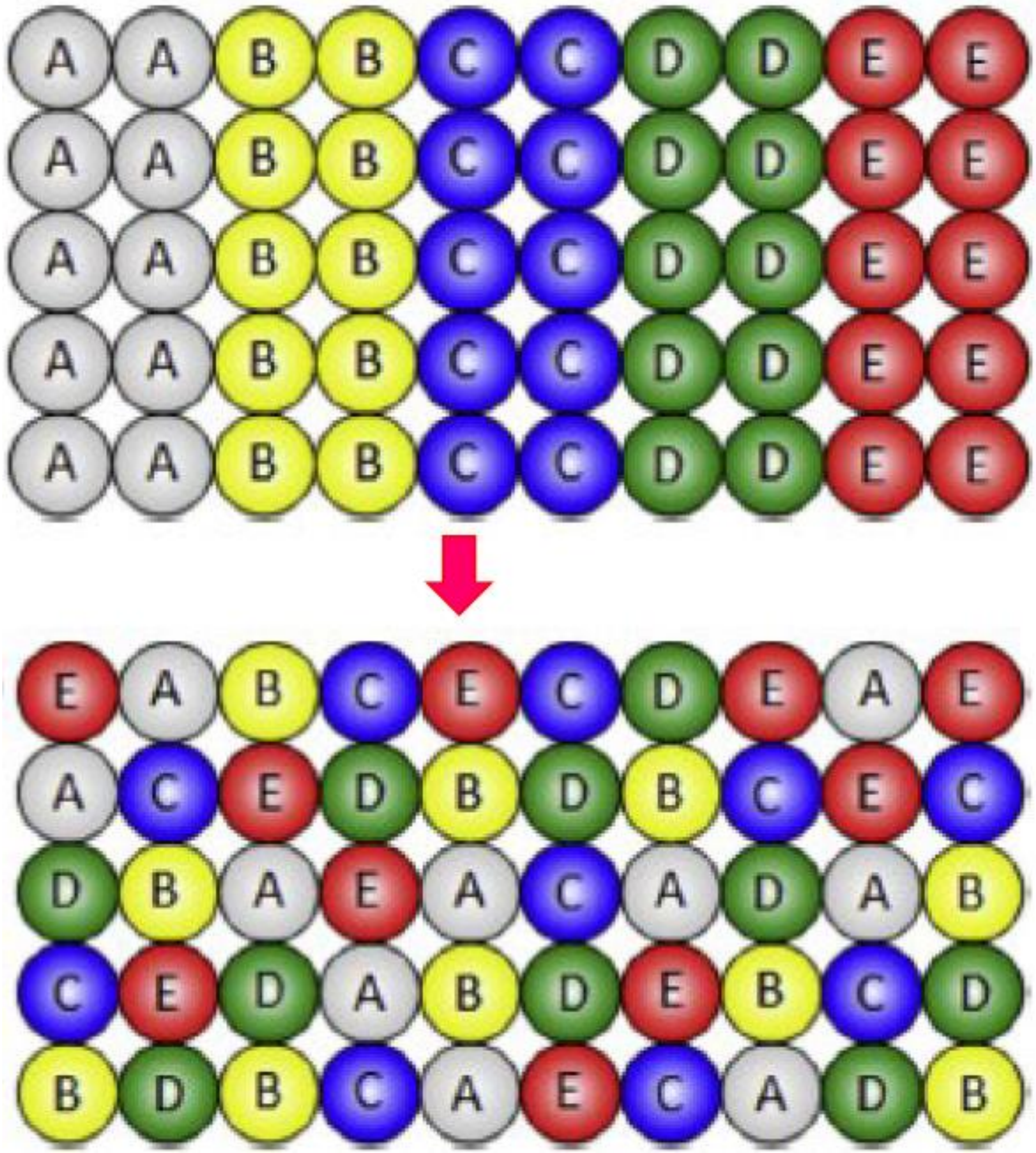
- Because of some extraordinary mechanical abilities, physical properties, and highly corrosion resistive, Titanium and its alloys are some of the promising engineering materials that possess a versatile application range in various industries.
- Ti and its alloys have a unique combination of better strength-to-weigh, high corrosion resistance, fracture toughness, high temperature strength, and outstanding elevated temperature.
- In aerospace engines, Ti alloys are used in jet engines parts, airplane bodies, fan blades, engine compartment, fuel tank due to their superior fatigue and performance capabilities and improving the functionality. It a major application area.
- Titanium alloys provide the right combination of antibacterial and corrosion protection properties.
- Due to these properties give a broad implementation in artificial joints, dental implants, orthodontics, surgical instruments.

HIGH ENTROPY ALLOYS

- Each high-entropy alloy contains multiple elements, often five or more in equiatomic or near-equiatomic ratios, and minor elements

- HEAs is that significantly high mixing entropies of solid solution phases enhance their stability as compared with intermetallic compounds, especially at high temperatures

- HEAs are preferentially defined as those alloys containing at least five principal elements, each having the atomic percentage between 5% and 35%.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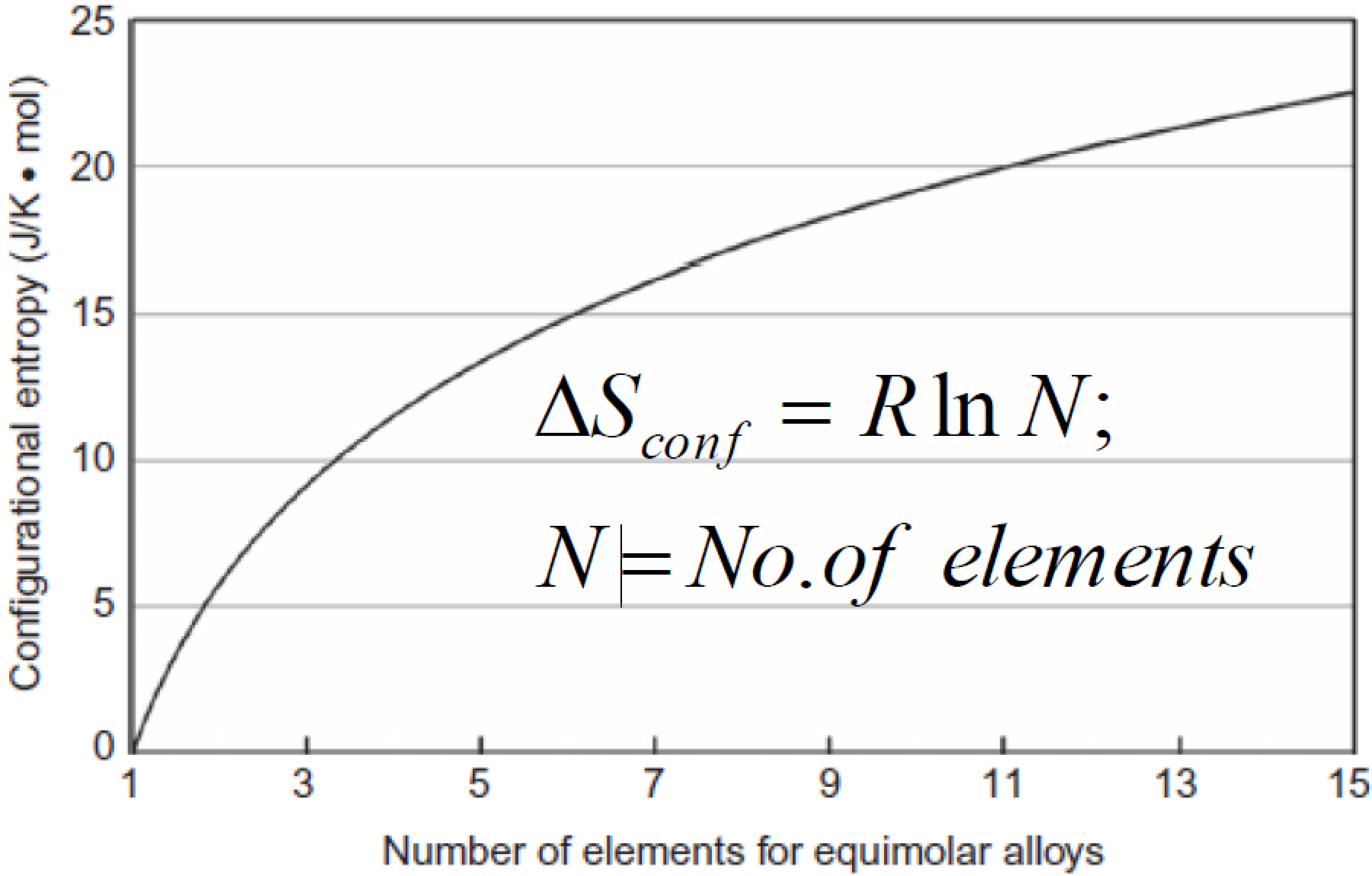
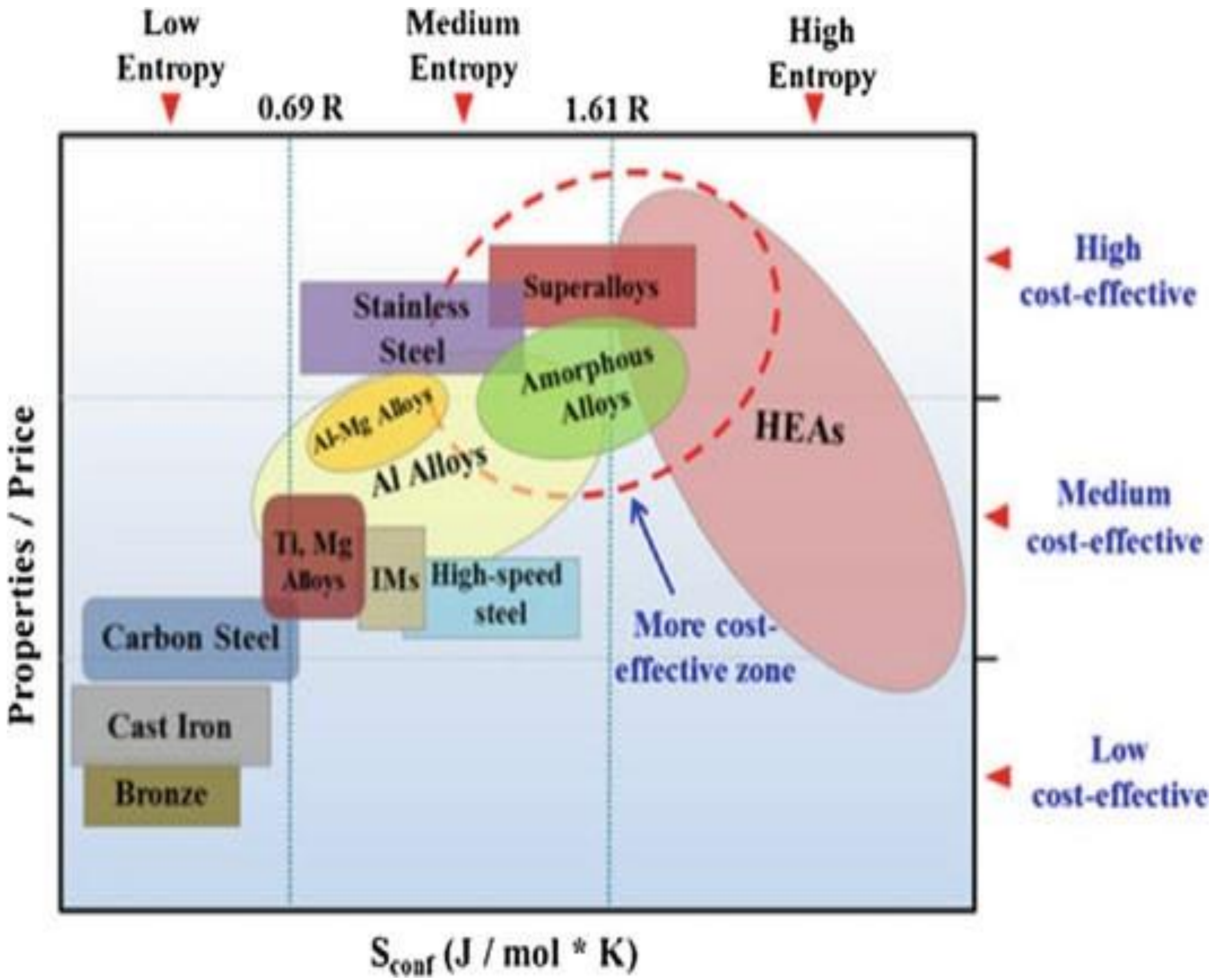
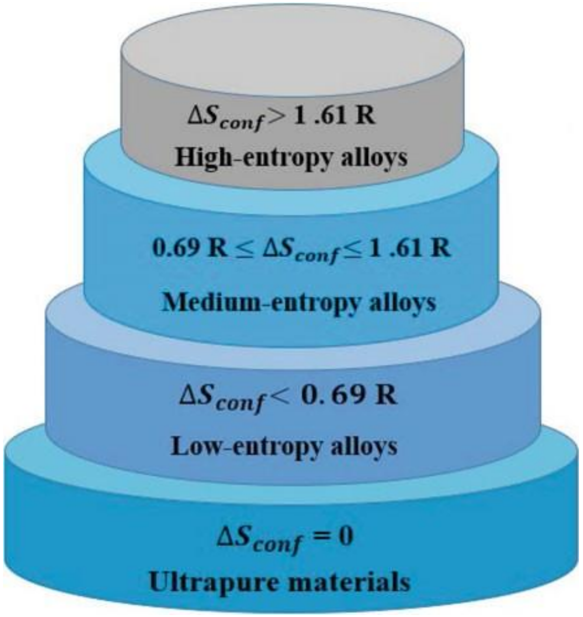
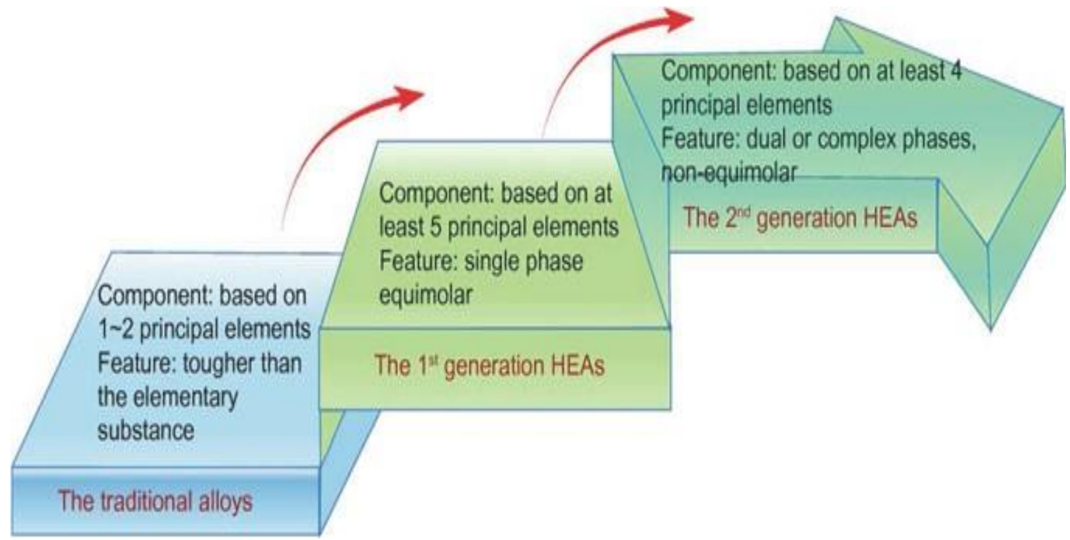
ENTROPY EFFECT IN HEAs ALLOYS





Low
Entropy
0.69 R
Medium
Entropy
1.61 R
High
Entropy
High
cost-effective
Medium
cost-effective
Low
cost-effective
Superalloys
Stainless
Steel
Amorphous
Alloys
Al-Mg Alloys
Al Alloys
HEAs
Ti, Mg
Alloys
IMs
High-speed
steel
More cost-
effective zone
Carbon Steel
Cast Iron
Bronze
Properties / Price
S_conf (J / mol * K)





CORE EFFECTS OF HEAs

- ❖ **High Entropy Effect (Stable solid solution)**
- ❖ **Sluggish Diffusion (Low kinetic transformation)**
- ❖ **Sever Lattice Distortion (Crystal structure deformed)**
- ❖ **Strength of HEA > Avg. strength of composing elements)**
- ❖ **Well performance at high Temp. (due to low kinetics)**
- ❖ **Excellent creep behaviour as more stability**
- ❖ **High corrosion resistance at elevated temp.**

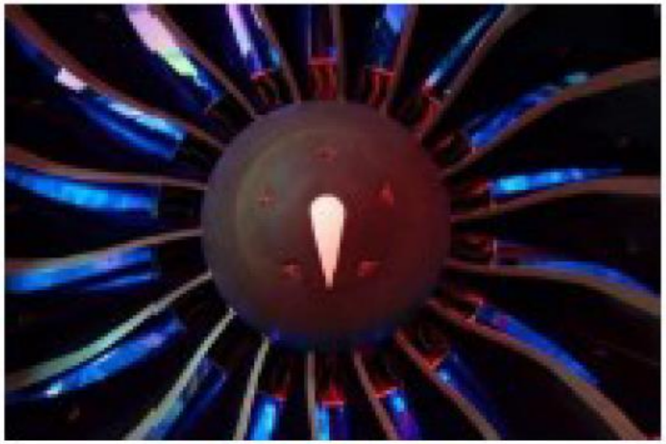
SYNTHESIS AND PROCESSING OF HEAs

- Arc Melting – Liquid state
- Mechanical Alloying – Solid state
- Sputtering – Gas state
- Rapid solidification – Liquid state
- Laser cladding & Electro deposition – Electrochemical process
- 3D Printing – Laser Engineered Net shape (LENS) – Solid state

APPLICATIONS OF HEAs

Engine materials

- better elevated-temperature strength,
- oxidation resistance
- hot corrosion resistance

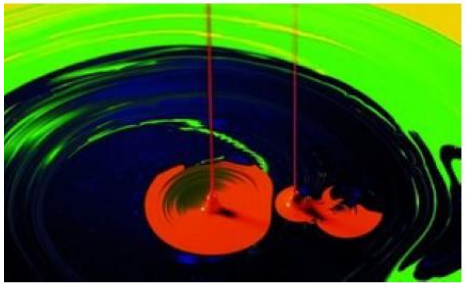


Light transportation materials

- Strength
- Toughness
- Creep resistance
- Workability

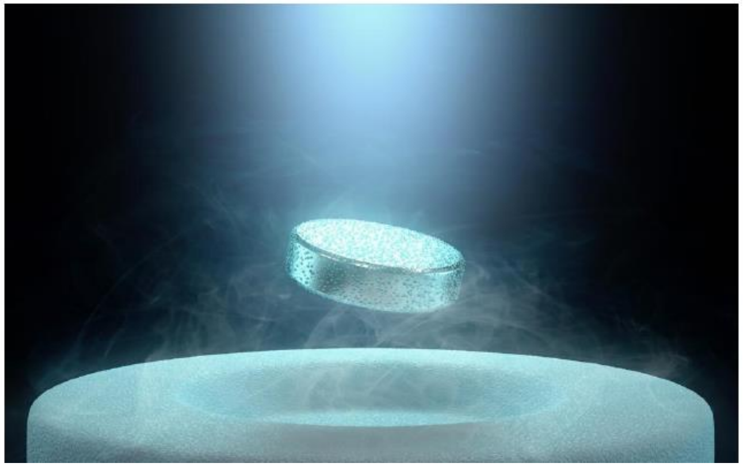
Functional coatings materials

- Better wear resistance
- Anti-sticky
- Anti-finger print
- Anti-bacterial
- Aesthetics



Superconductor materials (no electrical resist

- **Higher critical temperature and**
- **Critical current**



Golf club head

- **Higher strength and**
- **Resilience**

CERMETS

- **Cermets** are composites in which ceramic materials and metals join together.
- Cermets have high temperature resistance of a ceramic but the greater flexibility and electrical conductivity of a metal.
- Cermet is composed of metals and ceramics.
- Cermets are used instead of metals and ceramics to avoid corrosion.
- Cermet is used for better conductivity.
- Cermet has a high thermal conductivity and a good electrical conductivity compared to ceramic.
- Cermet has a very high melting point because of its elements which is metals and ceramics.
- Its boiling point is also very high.

What are cermets?

- **Cer**amic plus **met**al = cermet.
- It's really that simple!
- Why would you want to combine a metal and a ceramic?
- Metals, though versatile, aren't capable of withstanding the incredibly high temperatures you typically encounter in airplane jet engines or space rockets.
- Ceramics are brilliant at high temperatures and able to resist attack by chemicals and things like oxygen in the air, but their sheer inertness means they're just pretty boring most of the time.
- Brilliant for teapots and false teeth, but fairly hopeless when it comes to doing interesting things like conducting electricity or heat or bending and flexing.
- If you want something that can survive in really tough environments and still behave in interesting ways, you need to switch your attention to things like alloys, composites—and cermets.

What are cermets?

- "Cermet" is a generic name for a whole range of different composites.
- Ceramic is the biggest ingredient and acts as the matrix (effectively the base or binder) to which particles of the metal are attached.
- The metal component (typically an element such as cobalt, molybdenum, or nickel) can also be the matrix—giving a metal matrix composite (MMC).
- Cermets "work" by producing a material with a crystalline structure that has certain things in common with each of its different constituents.
- The metal ingredient effectively allows electrons to flow through the material enabling to conduct electricity.
- Cermets are relatively stable structures in which the metal and the ceramic are fixed in place.
- Under some conditions, cermets behave as though they have a dynamic surface layer, with metal particles constantly detaching and reattaching themselves.
- This effectively forms a smoother, harder, and more wear-resistant upper layer that makes a metal behave more like a ceramic.

What are cermets used for?

- Electrical components are one obvious application.
- Cermets offer a perfect solution in components such as resistors and vacuum tubes (valves).
- Machine tools are another increasingly common use for cermets.
- Tungsten carbide cermet is used for many cutting and drilling tools.
- Titanium based cermet tools are used in milling, turning and boring, and for making threads and grooves.
- Generally, cermets provide higher cutting-tool speeds, better surface finish, and last much longer than traditional tool parts.
- Unlike tools coated in carbide, cermet-coated tools do not wear in the same way but effectively regenerate themselves.

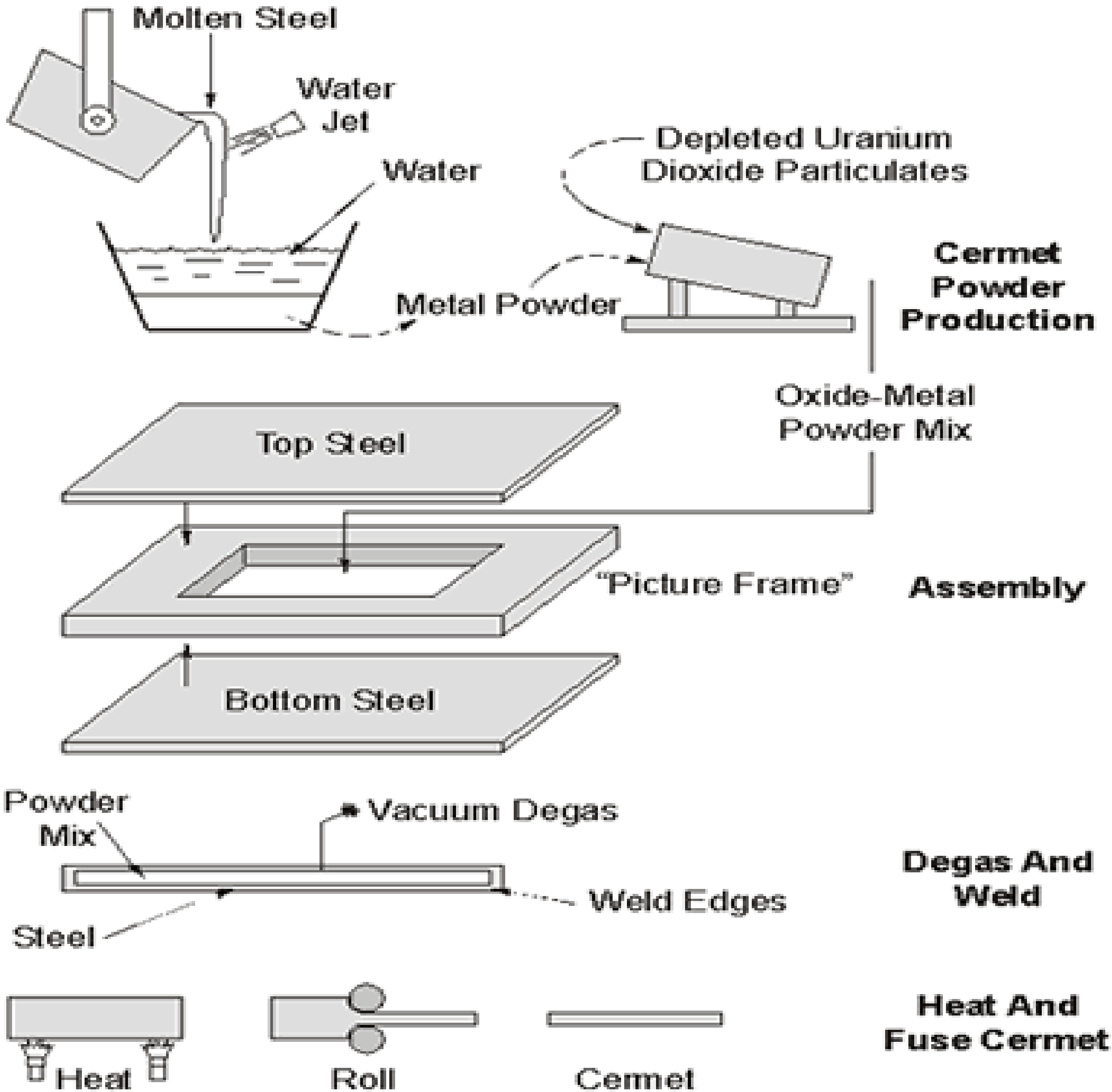
What are cermets used for?

- The interesting surface properties of cermets also make them useful for reducing friction in machine parts.
- **“Ceramic metal conditioners"** for engines that simultaneously make metal surfaces both smoother and tougher, reducing friction and wear at the same time, giving the dual benefits of greater fuel economy and longer engine life.
- Products such as this provide similar benefits to lubricants but work in an entirely different way by effectively modifying the surface structure of metal machine parts to make them behave more like ceramics.
- Military applications of cermets include their use as lightweight protective coatings on clothing and friction-reducing surface layers on nuclear submarines.

Manufacture of Cermets

- There are many methods to manufacture cermets.
- Uranium dioxide and steel powder are mixed, placed between clean sheets of steel, the "sandwich" is heated, and the sandwich is rolled.
- The result is a solid cermet, which has clean steel exterior surfaces.
- Uranium dioxide cermets have been manufactured as nuclear fuels.
- Non-uranium cermets are produced in large quantities for the manufacture of cutting tools, brake pads, and similar applications.
- The steel powder to manufacture the cermet waste packages could be obtained by recycling the potentially contaminated steel from the decommissioning of government nuclear facilities.
- Recycling would allow the reuse and disposal of many hundreds of thousands of tons of steel.

Manufacture of Cermets



3D PRINTING APPLICATIONS

1 Manufacturing applications

1.1 Cloud-based additive manufacturing
1.2 Mass customization
1.3 Rapid manufacturing
1.4 Rapid prototyping
1.5 Research
1.6 Food
1.7 Agile tooling

2 Medical applications

2.1 Bio-printing
2.2 Medical devices
2.3 Pharmaceutical Formulations

3D PRINTING APPLICATIONS

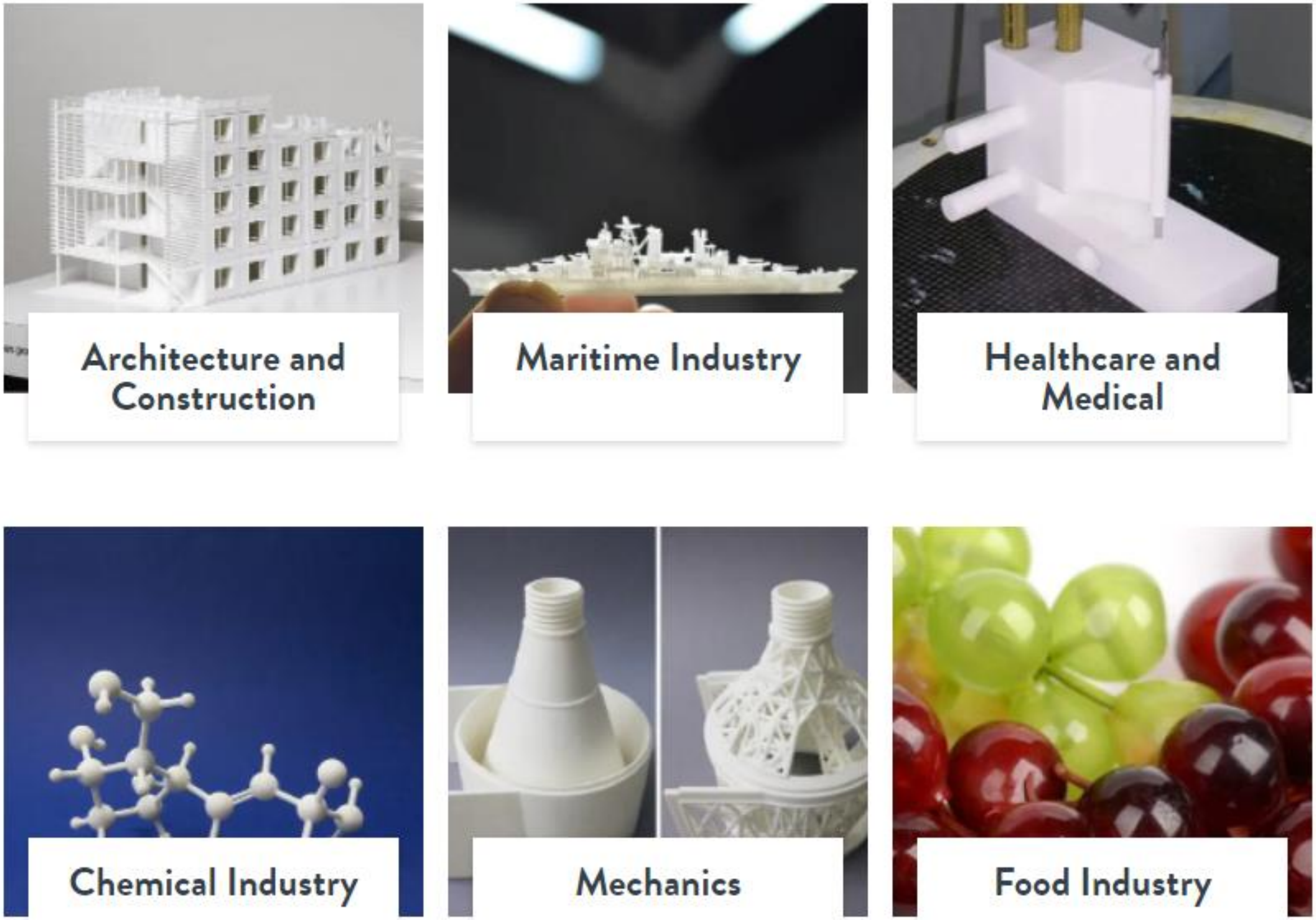
3 Industrial applications

3.1 Apparel
3.2 Industrial art and jewelry
3.3 Automotive industry
3.4 Construction, home development
3.5 Firearms and Space
3.6 Computers and robots
3.7 Soft sensors and actuators

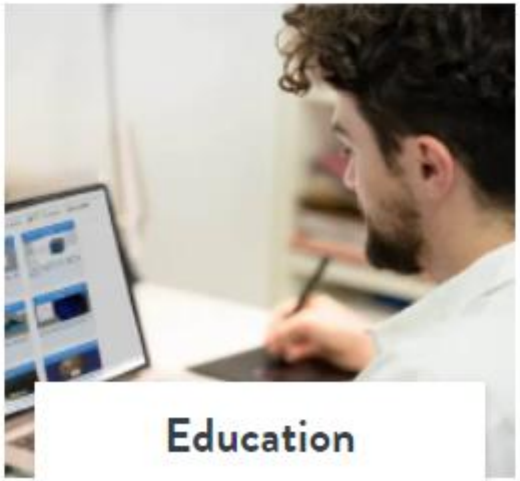
4 Sociocultural applications

4.1 Art and jewellery
4.2 3D selfies
4.3 Communication
4.4 Domestic use
4.5 Education and research
4.6 Environmental use and Cultural heritage
4.7 Specialty materials

3D PRINTING APPLICATIONS



3D PRINTING APPLICATIONS



Education

Aeronautics and Space

High Tech

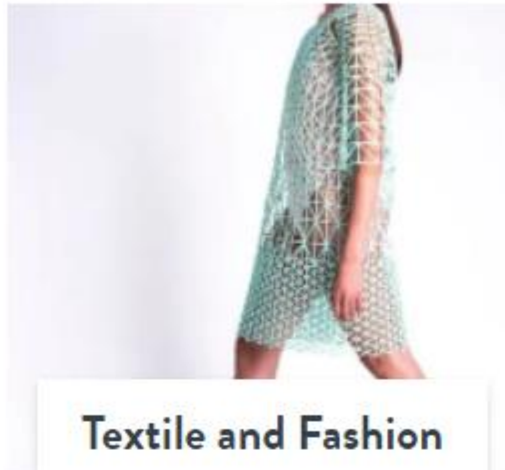
Drones

Retail

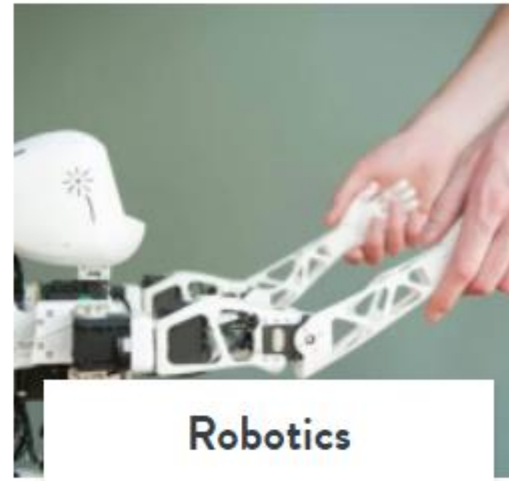
Energy

3D PRINTING APPLICATIONS

Automotive



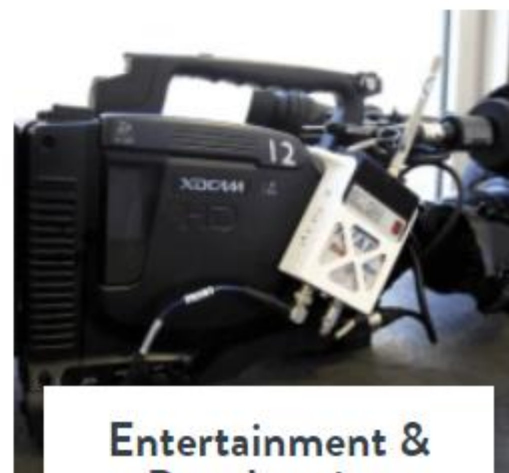
Textile and Fashion



Robotics

Optics

Industrial Goods



Entertainment & Broadcasting

Industrial Applications of 3D Printing

- 3D printing, also known as additive manufacturing, has come a long way since it was first developed in the 1980s.
- While 3D printing originated as a tool for rapid prototyping, it has now evolved to cover a number of different technologies.
- The evolution of 3D printing has seen a rapid growth in the number of companies adopting the technology.
- The applications and use cases vary across industries, but broadly include tooling aids, visual and functional prototypes and also end-use parts.
- As the potential applications for 3D printing increase, companies are beginning to find ways to create new business models and opportunities with the technology.

Industrial Applications of 3D Printing

Aerospace and defense (A&D) industry is one of the earliest adopters of 3D printing from 1989.

- ❑ Functional prototypes
- ❑ Lightweight components, Weight reduction
- ❑ highly complex parts in low volumes
- ❑ part consolidation: integrate multiple parts into a single component.
- ❑ Maintenance & repair by Direct Energy Deposition
- ❑ 3D-Printed Rocket Components
- ❑ Aircraft interior components
- ❑ Structural components for defense systems
- ❑ Tooling and Spare parts

Industrial Applications of 3D Printing

Automotive industry is a growing user of Additive Manufacturing.

- Faster product development
- Greater design flexibility
- Customization
- Create complex geometries
- 3D-Printed custom seats
- Tooling
- Spares and Replacement parts
- End-use parts

Industrial Applications of 3D Printing

Medical and Dental industry is a growing user of Additive Manufacturing.

- Enhanced medical devices and Personalised health-care
- Digital dentistry and Dental Implantology
- Clear aligners – Dental devices used to adjust and straighten teeth
- Intraoral scanning and 3D printing – for crowns, bridges and bite splints
- Hip and knee joint replacements
- Cranial reconstruction implants and spinal implants
- Surgical planning and testing
- Bioprinting – 3D bioprinters layer living cells (bio-ink!), mimicking organ tissues used to test new drugs and therapies

Industrial Applications of 3D Printing

Consumer Goods

- Retailers and consumer-oriented industries adapt to evolving consumer demands and industrial trends in an agile way.
- Additive manufacturing meets these needs, providing a cost-effective approach to product development, testing and production.
- From consumer electronics to toys and sportswear, 3D printing is a valuable addition to existing manufacturing solutions.
- Enhanced product development, faster time-to-market, Mass customization,
- Uses: Footwear, Beauty & cosmetics,
  Bikes – Bicycles using integrated 3D-printed components

Industrial Applications of 3D Printing

Industrial Goods

- Design complexity
- Shorter lead times
- On-demand production
- End-use parts, Tooling, Spare parts

Additive Manufacturing

Methods

(1) binder jetting

(2) directed energy deposition

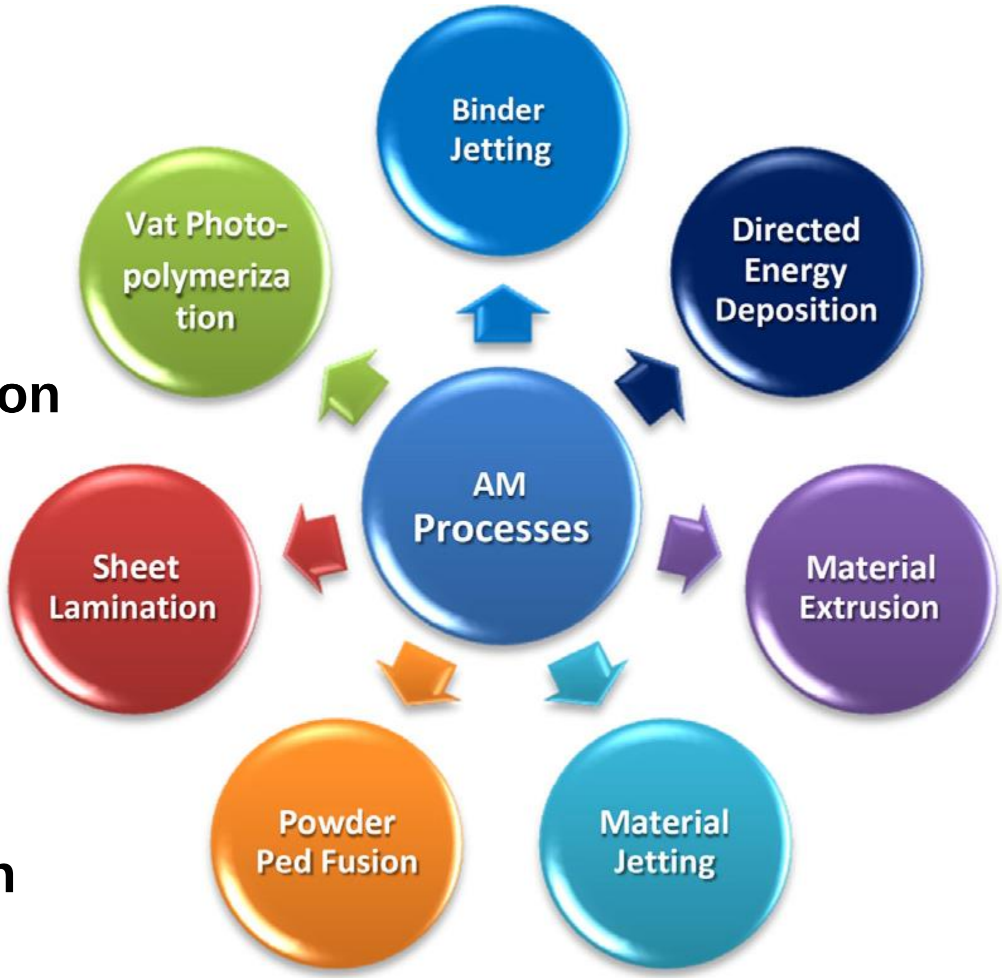
(3) material extrusion

(4) Material jetting

(5) powder bed fusion

(6) sheet lamination

(7) Vat photo-polymerization



Additive Manufacturing

Materials

(1) 3D printing materials

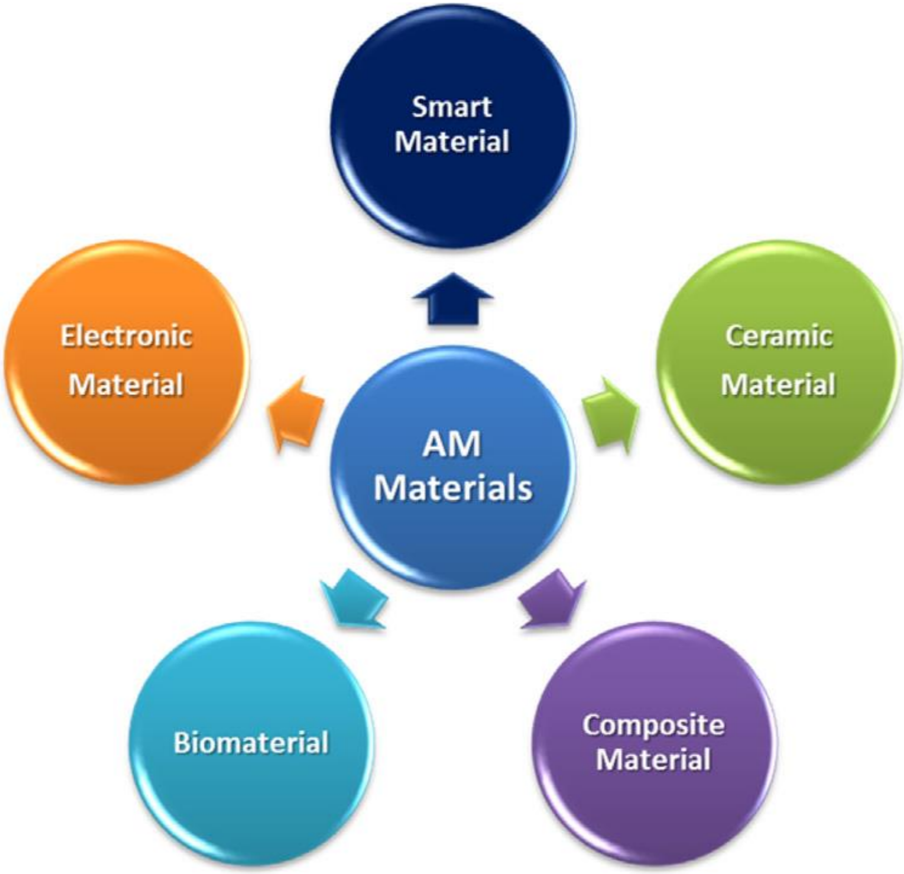
(2) Smart materials

(3) Ceramics materials

(4) Electronics materials

(5) Biomaterials

(6) Composite materials



Additive Manufacturing

Process	Advantages
Binder Jetting	Large number of potential materials Able to create ceramic molds for metal casting Support structures are included automatically in layer fabrication Low-imaging specific energy
Direct Energy Deposition	High material deposition rate and high material utilization High efficiency for repair and add-on features Mainly metal and suitable for large components Deposition of thin layers wear resistant metals on components
Material Extrusion	Low cost of the entry-level machines A variety of raw materials are available Versatile and easy to customize
Material Jetting	No waste of model material High resolution and accuracy Multiple materials and multiple colors
Powder Bed Fusion	Support is not required for polymer powder Both polymer and metal powder can be recycled High part complexity and wide range of materials Good accuracy and resolution for metals
Sheet Lamination	High fabrication speed No support structures are needed Low warping and internal stress Multi-materials and multi-colors are possible
Vat Photopolymerization	High-resolution and accuracy, good surface finish High fabrication speed Low-imaging specific energy Wide range of materials

Novel Materials in 3D Printing

Category	Specific material	Application
Digital and smart materials	Shape memory polymers	Actuator, sensor, jewelry, gripper
Ceramic materials	UV curable monomers	Thermal protection
Electronic materials	Silver nanoparticle ink	Thin-film transistor, antenna emitter
	Conductive polymer	Resistors
	Quantum dot	Light emitting diodes
Biomaterials	Hydrogels	Tissue engineering
	Functional inks	Cardiac micro-physiological devices
Composite materials	CB/PCL	Sensors
	VeroWhite Plus & TangoBlack Plus	Fracture resistant composites
	Barium titanate nanoparticle/polyethylene glycol diacrylate	3D piezoelectric polymers

Challenges for Next-generation AM Processes

1. Improvement in the speed and resolution of AM processes with lower energy consumption
2. Development of new 3D printing materials with tunable mechanical, chemical, physical properties

Development Directions for AM Processes

1. Hybrid AM process (i.e. additive + subtractive technologies) such as DMG MORI machine for higher dimensional accuracy and elimination of separate post-processing.
   In addition to better surface finish, hybrid AM process can also achieve bigger build volume, and multi-material within the same layer.
2. Significant breakthrough of 3D printing materials and processes with higher dimensional accuracy, smaller scale (e.g. nanoscale) and faster speed.
3. Direct Digital Manufacturing (DDM): the use of AM to produce parts that will be used as an end-product and to manufacture products in low volumes or unique products using AM.