LECTURE NOTE ON MATERIALS FOR ADVANCED APPLICATIONS 7th SEMESTER



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SYLLABUS

Module – I

Introduction: The urge for advancement in materials development and processing, Special and high temperature alloys: Ti alloys: physical and mechanical properties, thermomechanical treatment of Ti-alloys, Ti shape memory alloys, Fe based super alloys, Ni based alloys, Со based alloys, engineering applications at elevated temperatures, High Entropy Alloys. Metallic Foams: Material Definition and Processing, Characterization of cellular metals, Material properties and applications.

MODULE-I

Materials Evolution



Ashby, M.F. Materials Selection in Mechanical Design; Elsevier: Oxford, UK, 2011



Properties

Metals

Pros:

- High Strength & Ductility
- High Toughness
- Deformable
- Good Conductor

Cons:

- High Density
- Low Corrosion & Creep resistance

Ceramics

Pros:

- Insulator
- Low Coefficient of Thermal Expansion
- High strength & Modulus
- Creep resistant

Cons:

- Brittle
- Not easily deformable

Polymers

Pros:

- High Specific Strength
- Corrosion resistant
- Easy to form & cheap Cons:
- Low strength
- Not suitable for high temperature

Material Selection Criteria



- Material Tetrahedron depicts the inter-relationship between the structure, properties, performance and processes of a material.
- Selection of materials is done on the basis of the properties that is required for the application.
- Properties depend upon the structure and processing of the material.

Material Selection Criteria

- Performance requirement.
- Size, Shape & Mass requirements.
- Corrosion or Oxidation resistance.
- Minimizing cost while meeting required performance.
- Procedure for selection of the best material for a particular product or application begins with considering the properties and cost of the available candidate materials.
- Producer or designer should essentially have knowledge of the properties of the materials and their behaviour under the working conditions.
- Some of the properties the designer should know are strength, durability, weight, corrosion resistance, flexibility, castability, hardenability, machinability, electrical and thermal conductivity etc. of the materials.



http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/stiffness-density/NS6Chart.html

Ashby, M. F. (2013). *Material selection strategies*. *Materials and the Environment*, 227–273

What are Advanced Materials?

• Advance material is defined as all materials that represent advances over the conventional materials that have been used for hundreds of years. It also refers to all new materials, processing and modifications to existing materials to obtain superior and increased performance in one or more characteristics that are critical for the application under consideration.

e.g.

Semiconductors, Smart Materials, Bio-Materials, Nano-materials etc.

Ti-alloys can not with stand high temperature applications, thus Nitinol (Ni-Ti alloy) is being developed to meet the needs.





- The air goes inside the compressor, it is then pushed inside the combustion chamber where power is generated. The extra air goes away by the exhaust.
- Zones in a gas turbine engine:
- Fan, Low Pressure Compressor(LPC), High Pressure Compressor(HPC), High Pressure Turbine(HPT),Intermediate Pressure Turbine(IPT) Low Pressure Turbine(LPT)
- Pressure increases up to approx. 40 atm at the zone where fuel is injected and then decreases.
- Temperature goes up to around 1400-1500°C because of the combustion.
- Turbine extracts the power because these activities.
- As the turbine components are exposed to the high temperature and pressure, it is important to study the different materials that can withstand these conditions.



Turbine Entry Temperature variation vs. Time

• Temperature falls when mechanical work is extracted from the gas stream.



Reed, The Superalloys: Fundamentals and Applications



Special & High Temperature Alloys

In general, the strength of most metals decreases with • increasing temperature. At elevated temperatures, the increased rates of diffusion controlled and thermally activated processes result in the increased mobility of atoms and increased vacancy concentrations, and can activate additional slip systems or change slip systems. Furthermore, although grain boundaries can strengthen a metal at low temperatures, deformation at and along grain boundaries can occur more easily at high temperatures. Due to the more rapid diffusion rates at high temperature, particles or precipitates can coarsen, eventually resulting in an over-aged condition with reduced strength. Lastly, at elevated test temperatures, significant interactions between the metal and the environment can occur. Rapid oxidation of the surface or grain boundary penetration can occur at elevated temperatures and will result in reduced strengths and perhaps reduced ductility.

The materials selected for high temperature applications, are typically referred to as high temperature alloys, are known for their ability to resist, and exhibit useful strengths at, elevated temperatures. In general, the physical properties of the elements that could be utilized as the alloy base for high temperature materials include melting temperatures, elastic modulus, and density. Some of these properties are more important than others, depending on the application.

Special & High Temperature Alloys



Properties of Titanium

Titanium



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Ti is 4th most abundant metal in the earth's crust.

Extraction process: Kroll's & Hunter's Process.

Commercially pure (99.2% pure) grades of **Titanium** have ultimate tensile **strength** of about **434 MPa (63,000 psi)** equal to that of common, low-grade steel alloys, but are less dense. **Titanium** is 60% denser than Aluminium, but more than twice as strong as the most commonly used 6061-T6 Aluminium alloy.

Advantages of Titanium Alloys

- High strength to weight ratio,
- Tough
- Low density
- Good corrosion resistance by forming a passivating oxide layer.
- Titanium can be passivated, and thereby exhibit a high degree of immunity to attack by most mineral acids and chlorides.
- Biocompatible



http://www.cscaa.org/news/2015928/advantages-of-titanium-incorrosion-resistance

Ti Alloys

- The metallurgy of titanium is dominated by the crystallographic transformation which takes place in the pure metal at 882°C. Below this temperature, pure titanium has a hexagonal close packed structure known as alpha (α); above it, the structure is body centered cubic and termed beta (β). The fundamental effect of alloying additions to titanium is alteration of the transformation temperature and production of a two-phase field in which both alpha and beta phases are present.
- At 882°C







Heat Treatment

- Strength increases with alloying elements.
- Quenching from β –
 Phase causes
 Martensite
- High alloyed Ti imparts high strength after quenching followed by ageing.



Thermo-Mechanical Treatment β-Alloy



Thermo-Mechanical Treatment α+β-Alloy



• alpha (α) alloys:

- non-heat treatable
- very weldable.
- They have low to medium strength,
- good notch toughness,
- reasonably good ductility
- excellent properties at cryogenic temperatures.
- The more highly alpha or near alpha alloys offer high temperature creep strength and oxidation resistance.

• beta (β) alloys:

- Beta or near beta alloys are readily heat treatable,
- generally weldable
- high strength up to intermediate temperature levels.
- In the solution treated condition, cold formability is excellent.

- (α +β) alloys:
- heat treatable to varying extents
- weldable with the risk of some loss of ductility in the weld area.
- strength levels are medium to high.
- Hot forming qualities are good but cold forming often presents difficulties.
- Creep strength is not usually as good as in most alpha alloys.

Ti-6Al-4V or Ti-64 is the most commonly used alloy. It has a chemical composition of 6% aluminum, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen, and the remainder titanium.[[] It is significantly stronger than commercially pure titanium. Among its many advantages, it is heat treatable. This grade is an excellent combination of strength, corrosion resistance, weld and fabricability.

Alloy	Tensile strength (UTS) (MPa)	Yield strength	Elongation (%)	Elastic modulus (GPa)
αtype				
Pure Ti grade 1	240	170	24	102.7
Pure Ti grade2	345	275	20	102.7
Pure Ti grade3	450	380	18	103.4
Pure Ti grade4	550	485	15	104.1
α + <i>β type</i>				
Ti–6Al–4V ELI (mill annealed)	860–965	795–875	10–15	101–110
Ti–6Al–4V (annealed)	895–930	825–869	6–10	110–114
Ti–6Al–7Nb	900–1050	880–950	8.1–15	114
Ti–5Al–2.5Fe	1020	895	15	112
Ti-5Al-1.5B	925–1080	820–930	15–17.0	110
Ti–15Zr–4Nb–4Ta–0.2Pd				
Annealed	715	693	21	89
Aged	919	806	10	103
Ti–15Zr–4Nb–4Ta–0.2Pd				
Annealed	715	693	28	94
Aged	919	806	18	99
в type				
Ti–13Nb–13Zr (aged)	973–1037	836–908	10–16	79–84
Ti–12Mo–6Zr–2Fe	1060–1100	100–1060	18–22	74–85
Ti–15Mo (annealed)	874	544	21	78
Ti–15Mo–5Zr–3Al	852-1100	838–1060	18–25	80
Ti-15Mo-2.8Nb-0.2Si	979–999	945–987	16-18	83
Ti-35.3Nb-5.1Ta-7.1Zr	596.7	547.1	19.0	55.0
Ti–29Nb–13Ta–4.6Zr	911	864	13.2	80

Applications

- Blades, discs, rings
- Airframes, Turbine blades & other aerospace applications.
- Defence applications
- Fasteners, components.
- Vessels, cases
- Forgings.
- Biomedical implants.

SHAPE MEMORY ALLOYS

SHAPE MEMORY ALLOYS

- A alloy that can be deformed when cold but returns to its pre-deformed ("remembered") shape when heated is called a shape-memory alloy.
- If such alloys are plastically deformed at a temperature, they will completely recover their original shape upon heated to a higher temperature.
- It may also be called memory metal, memory alloy, smart metal, smart alloy

Types

- Cu Zn Al
- Cu Al Ni
- NiTi-commercially available

These mostly have:

- 2 different phases (high temperature & low temperature)
 - 3 different crystal structures(twinned, detwinned & austenite)

MECHANISM

- High temperature phase-Austenite
- Low temperature phase-Martensite

Stability Conditions:

- Austenite-High Temperature-Low Stress
- Martensite-Low Temperature-High Stress



Hysteresis Curve



Transformation Process



4: Austenite, 1: Twinned Martensite, 2: Detwinned Martensite

WHY IS STEEL NOT A SMA?

• It does not show reversible phase changes.

IN SMA UPON COOLING FROM AUSTENITIC PHASE INTERNALLY ADJUSTMENT TAKES PLACE THUS NO CHANGE IN STRAIN, BUT THIS IS NOT TRUE IN CASE OF STEEL.

TYPES OF SHAPE MEMORY EFFECTS(SME)

- ONE WAY SME
- TWO WAY SME
- **PSEUDOELASTICITY**

One way SME

 When a shape-memory alloy is in its cold state (below As), the metal can be bent or stretched and will hold those shapes until heated above the transition temperature.

Upon heating,

the shape changes to its original shape.

When the metal cools again it will remain in the hot shape, until deformed again.



Two Way SME

This effect is not intrinsic to SMA.

The alloy is trained to remember two shapes:High temperature shape

- Low temperature shape
- At microscopic level, the reason for which a specimen remembers the shape is explained as follows:
- Upon heavy deformation in martensitic phase, dislocations are produced so as to stabilize the martensitic phase. These dislocation exist even in the parent phase after reverse martensite upon heating. In particular, there are three key microstructural forms for SMA. The first is austenite, the second is martensite ,the third is a stress– biased martensite, is created either by stressing martensite below M_f, or by stressing austenite near but above A_f.
- This key microstructure is preferred in which becomes learned by the alloy during training process. Therefore, this structure promotes the Two way SME.



Facolta di Ingegneria, 'One Way and Two Way–Shape Memory Effect: Thermo–Mechanical Characterization of Ni–Ti wires'

Pseudoelasticity





1: Austenite
 2:Elastic limit
 3:Martensite


Ni-Ti Alloy (NITINOL)

- Ni-Nickel, Ti-Titanium, NOL-Naval Ordnance Laboratory
- NITINOL exhibits **shape memory effects**.
- Ni-Ti alloy (also known as Nitinol) is an alloy with a nearequiatomic composition (i.e., 49%–51%) of nickel and

titanium.





Crystal Structure



- The B2 structure is an ordered BCC structure consisting of two simple cubic interpenetrating sub lattices, and stoichiometrically it can be represented by 50:50 atomic distributions- AUSTENITE
- **B19** refers to **Orthorhombic** structure- **MARTENSITE**

Properties of NITINOL

Properties	Austenite	Martensite
Melting temperature, C	1300	
Density, g/cm ³	654	
Resistivity, Ω-cm	Approx. 100	Approx. 70
Thermal conductivity, W cm/° C	18	8.5
Corrosion resistance	Similar to 300 series stainless steel or titanium alloys	
Young's Modulus, GPa	Approx. 83	Approx. 28
Yield strength, Mpa	195 to 690	70 to 140
Ultimate tensile strength, MPa	895	
Transformation temperature,°C	-200 to 110	
Latent heat of transformation, C	167	

APPLICATIONS

- Biomedical Applications(Dentistry, joining of bones etc.)
- Used in civil structures such as bridges and buildings.
- Used in Aerospace applications.
- Used in heat engines
- Making of eye glass frames.

Joining Broken bones



BIOMEDICAL APPLICATION

Joining Broken bones



NiTi Wires in Aircraft wings

 Electric pulses sent though the wires to allow precise movement of aircraft.







WHY SUPERALLOYS??

- Previously Stainless steels were used for high temperature applications. But when working at temperature range of 450-900°C they became prone to sensitization due to depletion of chromium which leads to cracking.
- Also alloys failed to resist fatigue & creep.
 Thus Superalloys came in to existence.

SUPERALLOYS

- A Superalloy is a type of alloy that exhibits high temperature properties like creep resistance, oxidation & corrosion resistance, good surface stability and sufficient high mechanical properties.
- It can be used up to ~0.7 Melting Temperature.
- Crystal structure is typically FCC.
- Examples: Ni-Based, Fe-Based, Co-Based

IMPORTANT PROPERTIES

- High Strength even at high temperature(700-900°C)
- Good Corrosion & Oxidation resistance
- Good Thermal Creep resistance
- Surface stability at high temperature
- Good toughness & ductility

Ni-Based Superalloys

- Ni-based superalloys mostly contain 8% Al and/or Ti, 10-20% Cr, small amounts of Zr, B and C.
- These alloys can show strengthening effects by solid solution strengthening and precipitate hardening.
- Carbide formers like Mo,W,Nb play significant role as they form carbides and also act as strengthening solutes.
- Cr, Al help in corrosion & oxidation resistance.

TYPES

Nimonic C-263	Ni 51.0, Cr 20.0, Co 20.0, Mo 5.8, Ti 2.2, Al 0.5	A readily weldable, age-hardenable superalloy with excellent strength, ductility, and corrosion resistance up to around 850°C. Molybdenum for solid-solution strengthening
Nimonic 105	Ni 54.0, Co 20.0, Cr 15.0, Mo 5.0, Al 4.7, Ti 1.3	An age-hardenable superalloy within creased aluminum for improved oxidation-resistance and strength, and high creep-rupture properties up to around 950°C. Strengthened by additions of molybdenum, aluminum, and titanium
Nimonic 75	Ni 80.5, Cr 19.5	Good corrosion and heat resistance, high-temperature strength, and outstanding oxidation-resistance
Nimonic 80 A	Ni 76.0, Cr 19.5, Ti 2.4, Al 1.4	An age-hardenable creep-resistant alloy for service at temperatures up to around 815°C
Hastelloy alloy C-2000	Ni 47, Cr 22, Fe 18, Mo 9, Co 1.5, W 0.6	Localized corrosion resistance, good resistance to hot acids, and excellent resistance to stress-corrosion cracking
Haynes 282	Ni 57, Cr 20, Co 10, Mo 8.5, Ti 2.1, Al 1.5, Fe 1.5, Mn 0.3, Si 0.15, C 0.06, B 0.005	γ' precipitation strengthened nickel- based superalloy along with excellent creep properties, fabricability, and thermal stability

Main Phases & Microstructure

• Gamma (γ) phase:

- It is the continuous matrix phase having disordered FCC structure.
- Ni and other elements in solid solution.
- Provides ductility & structure for precipitates.
- Alloying elements found in most commercial Ni-based alloys are C, Cr, Mo, W, Nb, Fe, Ti, Al, V, and Ta
- No phase transformation up to T_m



γ phase with all unit cell corners occupied by Ni atoms (grey)



• Gamma-prime (γ'):

- It is the γ' which is largely responsible for the elevated-temperature strength of the material and its incredible resistance to creep deformation
- Precipitates of Ni(Al, Ti) having different shapes e.g. spherical, cuboidal and plate-like shapes
- In the γ´-phase the Nickel atoms are at the Face-centers and the Aluminium or Titanium atoms at the Cube corners.
- Brittle phase which restricts the dislocation movements.



Ni 3 Al γ' phase with Al atoms (black) at corners and Ni atoms (grey) at the face centers



- Carbides:
- MC, M₂₃C₆, and M₆C (M=metals(Cr, W etc)) compounds form and they provide dispersion strengthening & grain boundary stabilization.
- These form at grain boundaries which strengthen the grain boundary at high temperatures.
- Carbide forming elements like Mo,W,Nb and Ta are present.
- Topologically close-packed (TCP) phases:
- The term "TCP phase" refers to any member of a family of phases (including the σ phase, the χ phase, the μ phase. TCP phases are characterized by their tendency to be highly brittle and deplete the γ matrix of strengthening. So these phases should be avoided.

Microstructure



Effect of Alloying Elements



https://www.phase-trans.msm.cam.ac.uk/2003/Superalloys/superalloys.html

Strengthening Mechanisms

• Solid Solution Strengthening:

Al, Cr, Mo, Nb etc. enters the solid solution and replaces the solvent atoms thus creating local stress fields around them which in terms resist the dislocations and increase the strength.

• Precipitation Hardening:

Precipitates those form as **Gammaprime (\gamma')- Ni(Al,Ti)** and impede the dislocation movement thus increase γ the strength.

 Strengthening by Carbide Precipitates:

The brittle carbide precipitates like MC, $M_{23}C_6$, and M_6C act as strengthening particles.



Yield Stress vs. Temperature

- The yield stress increases up to certain high temperature but decreases further when temperature is increased.
- Up to 800°C: The dislocations in γ' phase become immobile screw dislocations that are locked due to cross slip. So they act as barriers for further dislocations and flow stress is increased.
- Above 800°C: Cube planes are activated which are not primary slip systems in FCC. All the dislocations on the cube planes move without any cross slip causing flow stress begins to decrease.



Fe-Based Superalloys

The use of steels in superalloy applications is of interest because certain steel alloys have showed creep and oxidation resistance similar to that of Ni-based superalloys, while being far less expensive to produce.

- Gamma (γ): Like the phases found in Ni-based superalloys, Fe-based alloys feature a matrix phase of austenite iron (FCC). Alloying elements that are commonly found in these stainless steel alloys include: Al, B, C, Co, Cr, Mo, Ni, Nb, Si, Ti, W, and Y. While Al is introduced for its oxidation benefits, Al additions must be kept at low weight fractions (wt.%) because Al stabilizes a ferritic (BCC) primary phase matrix, which is an undesirable phase in superalloy microstructures, as it is inferior to the high temperature strength exhibited by an austenitic (FCC) primary phase matrix.
- Gamma-prime (γ'): This phase is introduced as precipitates to strengthen the alloy. Like in Ni-based alloys, γ'-Ni₃Al precipitates can be introduced with the proper balance of Al, Ni, Nb, and Ti additions.
- Types: Incoloy series, Fe-Co-Ni Inconel Series (Very corrosion resistant)

Co-Based Superalloys

- Gamma (γ): Similar to Ni-based superalloys, this is the phase of the superalloy's matrix. While not used commercially to the extent of Ni-based superalloys, alloying elements found in research Co-based alloys are C, Cr, W, Ni, Ti, Al,
- Chromium is also used in Cobalt based superalloys (occasionally up to 20 wt.%) as it provides oxidation and corrosion resistance, critical for material use in gas turbines.
- Gamma Prime (γ'): As in Ni-based super alloys, this phase constitutes the precipitate used to strengthen the alloy. In this case, it is usually close packed with structure of Co₃Ti or FCC Co₃Ta, though both W and Al have been found to integrate into these cuboidal precipitates quite well. The elements Ta, Nb, and Ti integrate into the γ' phase and are quite effective at stabilizing it at high temperatures. Carbide Phases: As is common with carbide formation, its appearance in Co-based superalloys does provide precipitation hardening, but decreases low-temperature ductility
- These superalloys can retain high strength at high temperature also show good weldability and fatigue resistance over Ni based superalloys.
- **Types:** Hynes-25, Hynes Ultimet, Co 6, Stellite(Co-Cr)

APPLICATIONS

- Used in Aero-engine and steam turbines.
- Single crystal turbines have more creep resistance.
- Surgical Implants
- Used in Rocket motors and Jet engines.
- Hot working tooling and dies.
- Nuclear reactors.



HIGH ENTROPY ALLOYS

HIGH ENTROPY ALLOYS

- **HEAs** are the newest materials to the class of advanced materials.
- **HEA**s are defined as alloys with **five or more** principal elements having equal atom percentage.
- Each principal element should have a concentration between 5 and 35 atom%.
- Crystal structures mostly of cubic(BCC,FCC or FCC-BCC)
- The term "high-entropy alloys" was coined because the entropy of mixing is substantially higher when there is a larger number of elements in the mix, and their proportions are more nearly equal.
- Examples: FeCrMnNiCo, CoCrFeMnNi, AlCoCrCuFeNi, Refractory HEAs etc.

CRYSTAL STRUCTURES



1. High Entropy:

- Affects Gibb's Free Energy and favours solid solution over intermetallic compound.
- Gibb's free energy,

$$\Delta G = \Delta H - T \Delta S$$

$$\Delta S \triangleq \Delta G \clubsuit$$

$$\Delta S_{\text{config}} = -R \sum_{i=1}^{n} X_i \ln X_i.$$

 X_i is the mole fraction of i^{th} element.

As no. of elements increases, configurational entropy increases(+ve) due to which Gibb's free energy decreases(-ve) thus it makes the product phase feasible & stable.



 ΔS_{conf} is maximum at equiatomic proportion

2. Lattice Distortion Effect:

- Lattice distortion occurs due to large no of alloying elements having different atom sizes which increases the lattice mismatch.
- This distortion helps in creating stress fields which in terms impede dislocation motion thus strength increases.



Distorted lattice structure

3. Sluggish Diffusion:

- **HEA**s retain their solid solution strength even at higher temperature.
- The lattice strain energy due to the different atom sizes produces significant atomic traps and blocks, thus there is not much diffusion.

This phenomenon increases the **creep resistance**.

4. Cocktail Effect:

- Overall unpredictable result or effect which is more than the combined effects of all the constituent elements.
- This effect depends on composition, structure etc.

Mechanical Properties

- High Strength & Hardness
- Good Creep resistance
- Good Fatigue resistance
- Wear resistance
- High Corrosion resistance
- High temperature structural stability.

Processing

Mechanical Alloying

• A solid-state and powder processing technique involving repeated cold welding, fracturing, and re-welding of blended powder particles in a high-energy ball mill to produce a homogeneous material. Sintering of the powder gives HEA.

Arc Melting

 A standard Tungsten Inert Gas (TIG) welding unit is used as a power source. Heat generated by the electric arc struck between the electrode and the metals serves to melt the metals placed in the crucible to form an alloy. Repeated melting is performed to improve the homogeneity of the alloy. Evacuation of the chamber avoids oxidation of the melt.

Sputtering

 Ionic bombardment on the target to ejects atoms in vapour form which then deposited on the substrate to produse a thin film.



APPLICATIONS

- Aerospace industry
- High entropy alloy coatings
- Bulk Metallic glasses
- Refractories

METALLIC FOAMS

- Metal foam is a cellular structure made up of a solid metal containing a large volume fraction of gas-filled pores.
- These have solid cellular structure and are **75-90%** porous.
- These retain the physical properties of the base metal used.
- Most common metal for producing metallic foam is Aluminium. Titanium, Copper & some alloys are also being used.
- These pores can either be sealed (closed-cell foam), or they can be an interconnected network (open-cell foam). The closed-cell foam is referred to as metal foams, while the open-cell foam is referred to simply as porous metal.



Aluminium Foam
Open Cell Foam

 Pores form an open interconnected network



- Closed Cell Foam
- Pores are sealed.



Properties

- High Porosity (75-90%)
- Ultra-light Material(only 5–25% of the base metal volume)
- High Compressive strength
- High energy absorption ability.
- High Strength to Weight ratio
- High stiffness
- Low thermal conductivity.
- Good permeability.



Compressive Test curve

Processing Techniques

- Foaming Metallic Melt by Gas Injection Process(Direct Foaming Method).
- Foaming of Melt by Blowing Agents(Direct Foaming by in-situ gas formation).
- Foaming of Powdered Compact.

Foaming Melt by Gas Injection:

- Gases like Air, Ar, N or CO₂ can be injected.
- Sufficient bubbles are created so which in terms helps in obtaining a suitable foam.
- This foam will accelerate to the top where it can be pulled out by a conveyor belt and then allowed to solidify.
- Utmost care should be taken so that the pore structure is not damaged while in semi-solid phase.
- After solidification the foam is cut to required shapes.

- Metallic melt can be foamed by forming bubbles using gas.
- Foams may rise upward quickly due to the buoyancy force and drained out.
- So there is need of stabilizing the foams by making the melt viscous.
- Ceramic powders like Al₂O₃ or SiC can be added to make the melt viscous.



Foaming Melt by Gas Injection:



Foaming of Melt by Blowing Agents

- A blowing agent is added to form the foam without any gas injection.
- Mainly Titanium Hydride(TiH₂) is used (after desired viscosity is achieved) to create bubbles by releasing hydrogen gas.
- Under the influence of heat the blowing agent decomposes and helps in foaming process.
- This process takes place at constant pressure. Gradually the foam fills the mould and after solidification the foam is taken out and sent for further processing.

Foaming of Melt by Blowing Agents





Foaming of Powdered Compact

- The production process begins with the mixing of metal powders-elementary metal powders, alloy powders, or metal powder blends with a blowing agent, after which the mix is compacted to yield a dense, semi-finished product
- The compaction can be achieved using any technique in which the blowing agent is embedded into the metal matrix without any notable residual open porosity.
- The next step is heat treatment at temperatures near the melting point of the matrix material. The blowing agent, which is homogeneously distributed within the dense metallic matrix, decomposes and the released gas forces the melting precursor material to expand, forming its highly porous structure.

Foaming of Powdered Compact



Question:

Match the four tensile stress-strain curves (P,Q, R, S) with the materials listed in the box:



Solid-Gas Eutectic Solidification (Gasar)

- **Gasar** Gas Reinforced (Russian Abbreviation)
- The metal to be foamed is melted in ۲ autoclave with a controlled an pressure of hydrogen, so that the melt saturated becomes with hydrogen. The melt is then directionally solidified and as it cools through the solid-gas eutectic point, it becomes supersaturated. A two phase solid/gas mixture is simultaneously formed from the melt, yielding an solid anisotropic porous with cylindrical pores oriented in the solidification direction.



John Banhart, Manufacture, characterisation and application of cellular metals and metal foams

Processing Routes

• **Cellular Materials** (also known as FOAMS) are two phases **materials** in which a continuous gas phase has been dispersed in a solid phase.



John Banhart, Manufacture, characterisation and application of cellular metals and metal foams

Spray Forming

- Metallic melt is continuously atomized and a spray of fast flying small metal droplets is created. The droplets are collected on a substrate where they grow to a dense deposit in a given shape, e.g. a billet, sheet or tube.
- Attractive Feature:

The possibility for modifying the properties of the blowing deposit by injecting powders such as oxides, agent carbides or pure metals into the spray and allowing them to react with or be wetted by the liquid metal droplets and to be incorporated into the metal as it is deposited on the substrate.

 If the injected powders are substances which decompose upon contact with the molten metal and release large amounts of gas, they may generate pores in the deposit.

Example: $SiO_2 + 2C \rightarrow Si + 2CO$



Cellular Metals based on Space Holders (using fine metal powder)

- The metal powder is either filled into a dry bulk of fillers or a suitable solvent or even an organic binder maybe used to mix the space holders and the metal powders
- The filled bulk is then either simply compacted at room temperature or, if the space holders are heat resistant, pressed at elevated temperatures to improve compaction and to start sintering processes between the metal powder particles.



Casting using Space Holders

- Light-weight porous metals can be produced by casting liquid metal around inorganic or even organic granules or hollow spheres of low density, or by introducing such materials into a metallic melt.
- The granules either remain in the metallic product after casting yielding what is called a "syntactic foam" — or are removed by leaching in suitable solvents or acids or by thermal treatment
- Sand pellets, fired clay pellets, foamed glass spheres can be used as space holders.



Electro-deposition Technique

- Deposition techniques start from the ionic state of metals, i.e. a solution of ions in an electrolyte. The metal is electrically deposited onto a polymeric foam with open cells which is later removed
- Electro-deposition on a polymer foam requires some electrical conductivity of the initial polymer foam. This can be achieved by dipping the polymer foam into an electrically conductive slurry
- After electroplating the polymer can be removed from the metal/polymer composite by thermal treatment.
- A three-dimensional arrangement of hollow metallic foam is obtained

John Banhart, Manufacture, characterisation and application of cellular metals and metal foams



Characterization of Cellular Metals

- Non-destructive and Destructive methods.
- These processes can be distinguished by considering if the foam is deformed or remain unchanged during the characterization.
- Non Destructive Methods:
- **Density Measurement**(weighing and measuring volume by Archimedes principle)
- Dye Penetrant Method(for detecting surface cracks by Capillary mechanism)
- X-Ray Radiography (Densification can be monitored)
- Eddy Current Test(Foams can be characterized by their density & pore sizes by electrical impedance measurement)
- Acoustic Measurement(Sound absorption properties of foam)
- Gas absorption technique(determination of total internal surface area.)

• Destructive Methods:

- Optical Image Analysis:
- Cell morphology and microstructure of cellular metals can be analyzed by optical observations using various magnifications.
- As sample preparation needs cutting and polishing it is destructive method.
- Mechanical Testing:
- This is done to characterize cellular metals in terms of mechanical properties they possess.
- Corrosion Testing:
- Can be done by applying load cycle in a corrosive atmosphere.

Advantages

- Excellent energy absorption feature at a higher strength level.
- Easy processing
- Good Weldability.
- Erosion resistance
- Can be recycled.

• Limitations

- Difficulty in using high melting point metals.
- Utmost care is required while processing.
- Not much cost effective.
- Once damaged can not be repaired. It has to be replaced by a new one.
- More understanding required.

APPLICATIONS

- Automobile industries(where high energy absorption is required).
- In Defence equipment including Bullet proof vests.
- Metallic filter.
- Load bearing parts.
- Medical applications(Ti foams).
- Other light weight applications.





