MAHAVEER INSTITUTE OF SCIENCE AND TECHNOLOGY

(AN UGC AUTONOMOUS INSTITUTION)

Approved by AICTE, Affiliated to JNTUH, Accredited by NAAC with 'A' Grade
Recognized Under Section 2(f) of UGC Act 1956, ISO 9001:2015 Certified
Vyasapuri, Bandlaguda, Post: Keshavgiri, Hyderabad- 500 005, Telangana, India.
https://www.mist.ac.in E-mail:principal.mahaveer@gmail.com, Mobile: 8978380692

ESTD : 2001

Department of Aeronautical Engineering

(R22)

Introduction to Manufacturing Processes

B.Tech II YEAR – II SEM

Prepared by

LAKSHMI PRIYA MUTHE

(ASSISTANT PROFESSOR)

DEPT. AERO

INTRODUCTION TO MANUFACTURING PROCESSES

B.Tech. II Year II Sem. **L T/P/D C**
3 0/0/0 3

Course objectives:

1. To introduce the students to the working principles of different metal casting processes and gating systems.
2. To impart knowledge on plastic deformation, cold and hot working process, working of a rolling mill and types, extrusion processes.
3. To teach principles of forging, tools and dies, working of forging processes.
4. To develop fundamental understanding on classification of the welding processes, working of different types of welding processes and welding defects.
5. To impart knowledge on manufacturing methods of plastics, ceramics and powder metallurgy.
6. To introduce the basic concepts of Unconventional Machining Processes.

Course Outcomes:

1. Demonstrate different metal casting processes and gating systems.
2. Classify working of various welding processes.
3. Evaluate the forces and power requirements in rolling process.
4. Principles of various forging operations.
5. Outline the manufacturing methods of plastics, ceramics and powder metallurgy.
6. Identify different unconventional processes and their applications.

UNIT - I

Casting processes: Importance and selection of manufacturing processes. Introduction to casting process, process steps; pattern and design of gating system; Solidification of casting: Concept, solidification of pure metal and alloy; Special casting processes: Shell casting, investment casting, die casting, centrifugal casting, casting defects and remedies.

UNIT - II

Metal Forming & Forging: Introduction, nature of plastic deformation, hot and cold working of metals, mechanics of metal forming; Rolling: Principle, types of rolling mill and products, roll passes, forces in rolling and power requirements; Extrusion: Basic extrusion process and its characteristics, hot extrusion and cold extrusion, wire drawing, tube drawing.

Principles of forging, tools and dies. Types: Smith forging, drop forging, forging hammers, rotary forging and forging defects. Sheet metal forming: Mechanics of sheet metal working, blanking, piercing, bending, stamping.

UNIT - III

Metal Joining Processes: Classification of welding processes, types of welds and welded joints and V-I characteristics, arc welding, weld bead geometry, submerged arc welding, gas tungsten arc welding, gas metal arc welding. applications, advantages and disadvantages of the above processes, Plasma Arc welding, Laser Beam Welding, Electron Beam Welding and Friction Stir Welding. Heat affected zones in welding; soldering and brazing: Types and their applications, Welding defects: causes and remedies

UNIT - IV

Plastic Processing, Ceramics and Powder Metallurgy: Plastics: Types, properties and their applications, processing of plastics, extrusion of plastics, transfer molding and compression molding, injection molding, thermoforming, rotational molding, and blow molding

Ceramics: Classification of ceramic materials, properties and their application, ceramic powder preparation; Processing of ceramic parts: Pressing, casting, sintering; Secondary processing of ceramics: Coatings, finishing.

Powder Metallurgy: Principle, manufacture of powders, steps involved.

UNIT - V

Additive manufacturing: Introduction to layered manufacturing, Importance of Additive Manufacturing Additive Manufacturing in Product Development Classification of additive manufacturing processes, Common additive manufacturing technologies; Fused Deposition Modeling(FDM), Selective Laser Sintering(SLS), Stereo Lithography(SLA), Selection Laser Melting (SLM),Jetting,3D Printing, materials, costs, advantages and limitations of different systems.

TEXT BOOKS:

1. Rao P.N., Manufacturing Technology – Volume I, 5/e, McGraw-Hill Education, 2018.
2. Kalpakjain S and Schmid S.R., Manufacturing Engineering and Technology, 7/e, Pearson,2018.
3. Gibson, I., Rosen, D.W. and Stucker, B., “Additive Manufacturing Methodologies: Rapid Prototyping to Direct Digital Manufacturing”, Springer, 2015.
4. Chua, C.K., Leong K.F. and Lim C.S., “Rapid prototyping: Principles and applications”, Third edition, World Scientific Publishers, 2010.

REFERENCE BOOKS:

1. Introduction to Physical Metallurgy by Sidney H.Avner
2. Millek P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes and Systems,4/e, John Wiley and Sons Inc, 2010.
3. Sharma P.C., A Text book of Production Technology, 8/e, S Chand Publishing, 2014.
4. Liou, L.W. and Liou, F.W., “Rapid Prototyping and Engineering applications: A tool box for prototype development”, CRC Press, 2011.
5. Kamrani, A.K. and Nasr, E.A., “Rapid Prototyping: Theory and practice”, Springer, 200

INTRODUCTION TO MANUFACTURING

DEFINITIONS

Manufacturing:

Manufacturing is making things. Transforming raw materials into usable goods is defined as manufacturing.

Imagine you want to make a wooden chair. Manufacturing, in this context, refers to the entire process of creating the chair, from obtaining the raw materials (wood, screws, paint) to shaping, assembling, and finishing the chair. It involves the use of machinery, tools, and labour to transform raw materials into the final product.

Production:

Production is an economic term used to describe the process of manufacturing goods/services for a profit.

In the case of the wooden chair, production would refer to the number of chairs produced within a specific time frame. It is the result of the manufacturing process and indicates the quantity of goods produced.

History of Manufacturing

Pre-Industrial Revolution: Before the Industrial Revolution, manufacturing was primarily done through craft production, where skilled artisans or craftsmen created goods by hand. This method was often slow and limited in scale, with each item being unique.

Industrial Revolution (18th and 19th centuries): The Industrial Revolution marked a significant shift in manufacturing. This period saw the introduction of mechanized manufacturing processes powered by water wheels and steam engines. The simple principle of the steam engine is to convert the heat energy from steam into mechanical work, revolutionized manufacturing. Factories emerged, leading to mass production of goods and a significant increase in productivity. The late 19th and early 20th centuries, which saw the rise of the aviation industry, were a period of rapid industrialization and technological advancement

Mass Production (20th century): The 20th century brought further advancements in manufacturing, particularly with the introduction of assembly lines and the concept of

mass production pioneered by Henry Ford. This method allowed for the efficient production of large quantities of standardized goods, leading to lower costs and increased affordability for consumers.

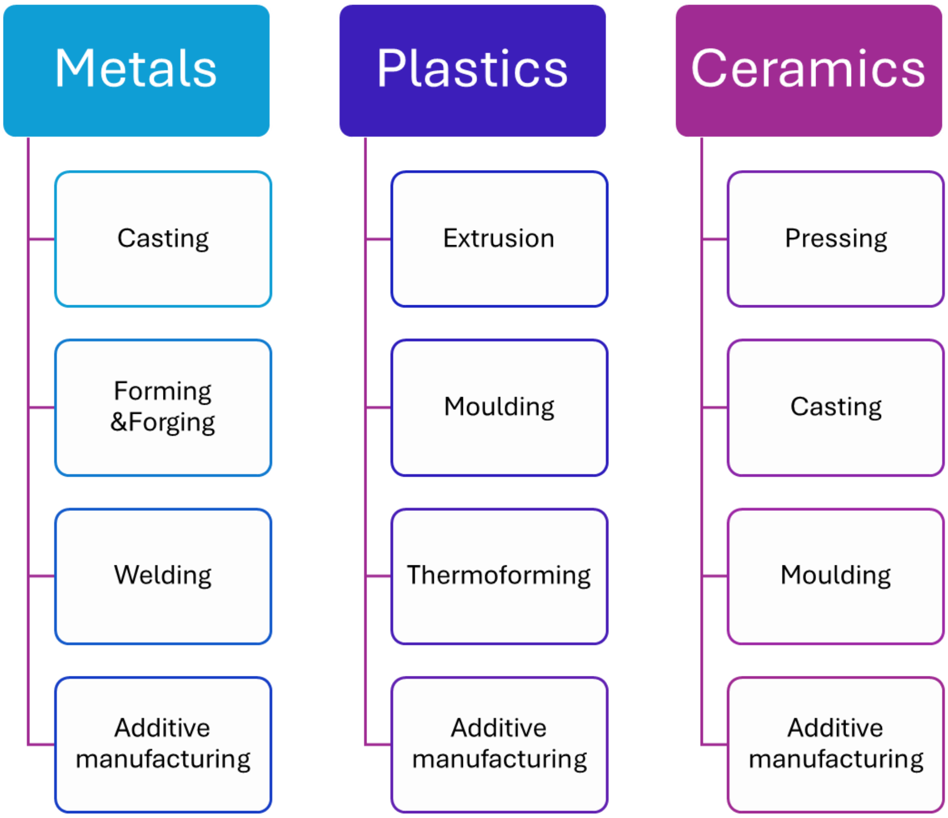
Automation and Robotics (Late 20th century to present): With the advancement of technology, automation and robotics have become increasingly prevalent in manufacturing. These technologies have allowed for greater precision, efficiency, and speed in production processes, leading to further improvements in productivity and product quality.

Industry 4.0 (Present and Future): Industry 4.0, also known as the fourth industrial revolution, is characterized by the integration of digital technologies into manufacturing processes. This includes the use of artificial intelligence, the Internet of Things (IoT), big data, and cloud computing to create smart factories and enable more flexible, efficient, and connected manufacturing systems.

Why is manufacturing engineering important for Mechanical/Aeronautical engineers?

Manufacturing engineering is crucial for mechanical and aeronautical engineers because it bridges the gap between design and production. By learning manufacturing concepts, engineers can design products that are not only innovative and functional but also feasible to produce efficiently and cost-effectively. This knowledge is essential for ensuring that designs can be turned into real-world products that meet quality standards.

What are the key manufacturing technologies essential in today's world?



Casting: Casting is a manufacturing process in which a liquid material (often metal or plastic) is poured into a mould, where it solidifies into the desired shape. Examples include casting metal parts for machinery or casting plastic toys.

Extrusion: Extrusion is a manufacturing process in which a material, often a metal or plastic, is forced through a die to create a long, uniform shape with a constant cross-section. Examples include extruding aluminium profiles for window frames or plastic pipes.

Forging: Forging is a manufacturing process in which metal is heated and then shaped using compressive forces, typically with a hammer or a die. Examples include forging automotive parts like crankshafts or forging tools like wrenches.

Welding: Welding is a manufacturing process that joins materials, usually metals, by melting the surfaces to be joined and adding a filler material, if needed, to create a strong bond when the material cools. Examples include welding steel beams in construction or welding metal parts in automotive manufacturing.

Thermoforming: Thermoforming is a manufacturing process in which a plastic sheet is heated until it is pliable and then formed into a specific shape using a mould. Examples include thermoforming plastic packaging trays or disposable cups.

Pressing: Pressing, also known as compression moulding, is a manufacturing process in which a material, often a powder or a sheet, is placed in a mould and compressed under high pressure and heat to form a solid object. Examples include pressing ceramic tiles or pressing metal coins.

Questionnaire

1. What is the process of converting raw materials into finished goods?

- A) Design
- B) Manufacturing
- C) Testing
- D) Packaging

2. What is a common method for shaping plastics?

- A) Extrusion
- B) Welding

- C) Forging

- D) Thermoforming

3. Casting is a process used to create objects from which materials?

- Fill in the blank: _______ (Metal/Plastic) objects

4. Which of the following is NOT a common manufacturing process?

- A) Injection Molding

- B) Thermoforming

- C) Extrusion

- D) Impressionism

5. What is a key characteristic of ceramics?

- A) Softness

- B) Low melting point

- C) High hardness

- D) Low cost

6. What is the term for joining materials by melting and then cooling them?

- Fill in the blank: _______.

7. Which manufacturing process involves heating a plastic sheet until it is pliable and then forming it into a shape?

- A) Extrusion

- B) Thermoforming

- C) Casting

- D) Forging

8. What is a common method for shaping metals?

- A) Extrusion

- B) Thermoforming

- C) Casting

Vyasapuri, Bandlaguda, Post:Keshavgiri
Hyderabad-500005,Telangana, India
Tel:040-29880079, 86,8978380692, 9642703342
9652216001, 9550544411, Website:www.mist.ac.in
Email:principal@mist.ac.in
principal.mahaveer@gmail.com
Counseling code:MHVR, University Code:E3

MAHAVEER
INSTITUTE OF SCIENCE & TECHNOLOGY
(AN UGC AUTONOMOUS INSTITUTION)
Approved by AICTE, Affiliated to JNTU,Hyderabad
Accredited by NAAC with 'A' Grade
Recognized Under 2(f) of UGC Act 1956,ISO 9001:2015 Certified
ESTD : 2001

D) Welding

9. Which of the following is an inorganic material?

- A) Plastic
- B) Metal
- C) Ceramic
- D) Organic

10. What is a manufacturing process that involves compressing a powder material under high pressure and heat to form a solid object?

- Fill in the blank: _______.

Questionnaire answers:

1. B) Manufacturing
2. Extrusion
3. Metal
4. D) Impressionism

C) High hardness

5. Welding
6. B) Thermoforming
7. D) Welding
8. C) Ceramic
9. Pressing

Casting

Casting is one of the oldest manufacturing processes. It is the first step in making most of the products.
Steps:
- Making mould cavity
- Material is first liquefied by properly heating it in a suitable furnace.
- Liquid is poured into a prepared mould cavity
- allowed to solidify
- product is taken out of the mould cavity, trimmed, and made to shape

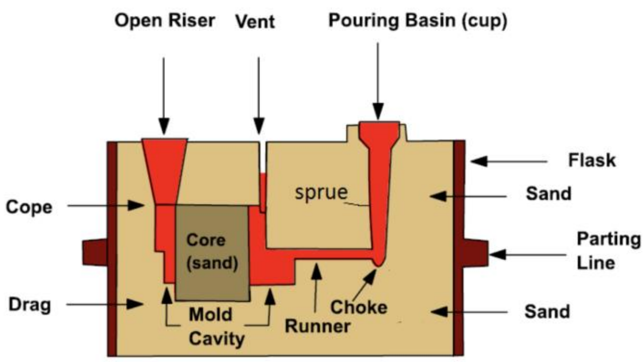
We should concentrate on the following for a successful casting operation:
(i)Preparation of moulds of patterns
(ii)Melting and pouring of the liquefied metal
(iii)Solidification and further cooling to room temperature
(iv)Defects and inspection

Advantages

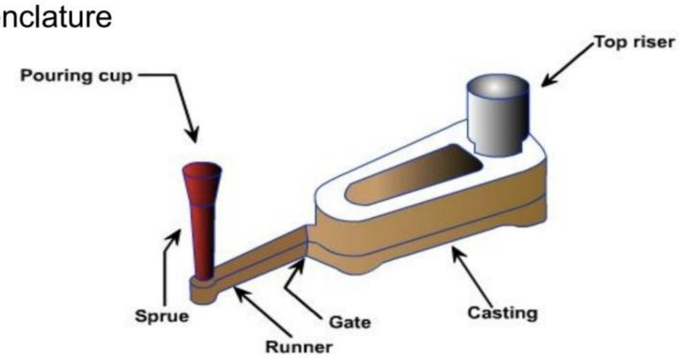
- Molten material can flow into very small sections so that intricate shapes can
- be made by this process. As a result, many other operations, such as machining, forging, and welding, can be minimized.
- Possible to cast practically any material: ferrous or non-ferrous.
- The necessary tools for casting moulds are very simple and inexpensive. As a result, it is the ideal process for the production of a small lot.
- Certain parts (like turbine blades) made from metals and alloys can only be processed this way. Turbine blades: Fully casting + last machining.
- Size and weight of the product are not a limitation for the casting process.

Disadvantages

- Dimensional accuracy and surface finish of the castings made by sand casting processes are a limitation of this technique.
- Many new casting processes have been developed which can take into consideration the aspects of dimensional accuracy and surface finish. Some of these processes are die casting process, investment casting process, vacuum-sealed moulding process, and shell moulding process.
- Metal casting is a labour-intensive process
- Automation: a question



Mould Section and casting nomenclature



1. **Mold**: The cavity or negative impression used to shape the molten material into the desired form.
2. **Pattern**: A replica of the final object used to create the mold cavity.
3. **Core**: A separate piece used to create internal features of the casting.
4. **Pouring Basin**: The area where molten metal is poured into the mold.
5. **Sprue**: The passage through which molten metal flows from the pouring basin to the mold cavity.
6. **Runner**: A channel that directs molten metal from the sprue to the gate.

7. Gate: The entrance through which molten metal enters the mold cavity.

7. **Riser**: A reservoir of molten metal that feeds the casting as it solidifies, preventing shrinkage defects.
8. **Shrinkage**: The reduction in volume of the metal as it solidifies, which can cause defects if not properly managed.
9. **Cope and Drag**: The two halves of a split mold, with the cope being the top and the drag being the bottom.
10. **Parting Line**: The line where the cope and drag meet and where the two halves of the mold separate.
11. **Core Print**: A projection on a pattern that creates an impression in the mold for placing a core.
12. **Draft**: The taper applied to the vertical surfaces of a pattern to facilitate easy removal from the mold.

The six basic steps in making sand castings are (i) Pattern making, (ii) Core making, (iii) Moulding, (iv) Melting and pouring, and (v) Cleaning.

Pattern Making

Pattern: Replica of the part to be cast and is used to prepare the mould cavity. It is the physical model of the casting used to make the mould. Made of either wood or metal. - The mould is made by packing some readily formed aggregate material, such as moulding sand, surrounding the pattern. When the pattern is withdrawn, its imprint provides the mould cavity. This cavity is filled with metal to become the casting. - If the casting is to be hollow, additional patterns called ‘cores’ are used to form these cavities.

Core Making

Cores are placed into a mould cavity to form the interior surfaces of castings. Thus, the void space is filled with molten metal and eventually becomes the casting.

Moulding

Moulding is nothing but the mould preparation activities for receiving molten metal. Moulding usually involves (i) preparing the consolidated sand mould around a pattern held within a supporting metal frame and (ii) removing the pattern to leave the mould cavity with cores. The mould cavity is the primary cavity. The mould cavity contains the liquid metal, and it acts as a negative of the desired product. The mould also contains secondary cavities for pouring and channelling the liquid material into the primary cavity and will act as a reservoir if required.

Melting and Pouring

Melting is the preparation of molten metal for casting. The molten metal is transferred to the pouring area, where the moulds are filled.

Cleaning

Cleaning involves the removal of sand, scale, and excess metal from the casting. Burned-on sand and scale are removed to improve the surface appearance of the casting. Excess metal, in the form of fins, wires, parting line fins, and gates, is removed. Inspection of the casting for defects and general quality is performed.

Pattern

The pattern and the part to be made are not the same. They differ in the following aspects.

1. A pattern is always made larger than the final part to be made. The excess dimension is known as Pattern allowance. Pattern allowance => shrinkage allowance, machining allowance
2. A **shrinkage allowance** will take care of a casting's contractions as the metal cools to room temperature.
3. Liquid Shrinkage: Reduction in volume when the metal changes from liquid state to solid state. A riser which feeds the liquid metal to the casting is provided in the mould to compensate for this.
4. Solid Shrinkage: A reduction in volume caused when a metal loses temperature in the solid state. The patterns provide a shrinkage allowance to account for this.
5. The shrink rule is used to compensate for solid shrinkage depending on the material contraction rate.

Cast iron: One foot (=12 inches) on the 1/8-in-per-foot shrink rule actually measures 12-1/8 inches. So, 4 inches will be 4-1/24 inches for considering shrinkage allowance.

6. The shrinkage allowance depends on the coefficient of thermal expansion of the material (α). A simple relation indicates that the higher the value of α, more is the shrinkage allowance.
7. For a dimension 'l', shrinkage allowance is αl ($\theta^f - \theta^0$). Here θ^f is the freezing temperature, and θ^0 is the room temperature.

Shrink rule for other materials

Material	Dimension	Shrinkage allowance (inch/ft)
Grey Cast Iron	Up to 2 feet	0.125
	2 feet to 4 feet	0.105
	over 4 feet	0.083
Cast Steel	Up to 2 feet	0.251
	2 feet to 6 feet	0.191
	over 6 feet	0.155
Aluminum	Up to 4 feet	0.155
	4 feet to 6 feet	0.143
	over 6 feet	0.125
Magnesium	Up to 4 feet	0.173
	Over 4 feet	0.155

Machining allowance

Machining allowance will take care of the extra material that will be removed to obtain a finished product. In this the rough surface in the cast product will be removed. The machining allowance depends on the size of the casting, material properties, material distortion, finishing accuracy and machining method.

Machining allowances of various metals

Metal	Dimension (inch)	Allowance (inch)
Cast iron	Up to 12	0.12
	12 to 20	0.20
	20 to 40	0.25
Cast steel	Up to 6	0.12
	6 to 20	0.25
	20 to 40	0.30
Non ferrous	Up to 8	0.09
	8 to 12	0.12
	12 to 40	0.16

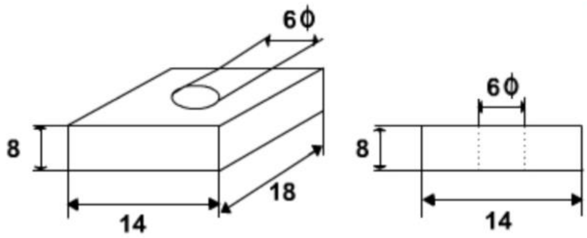
Draft allowance

All the surfaces parallel to the direction in which the pattern will be removed are tapered slightly inward to facilitate the safe removal of the pattern. This is called 'draft allowance'.

Typical Draft Allowances

Pattern material	Height of the given surface (inch)	**Draft angle (External surface)**	**Draft angle (Internal surface)**
Wood	1	3.00	3.00
	1 to 2	1.50	2.50
	2 to 4	1.00	1.50
	4 to 8	0.75	1.00
	8 to 32	0.50	1.00
Metal and plastic	1	1.50	3.00
	1 to 2	1.00	2.00
	2 to 4	0.75	1.00
	4 to 8	0.50	1.00
	8 to 32	0.50	0.75

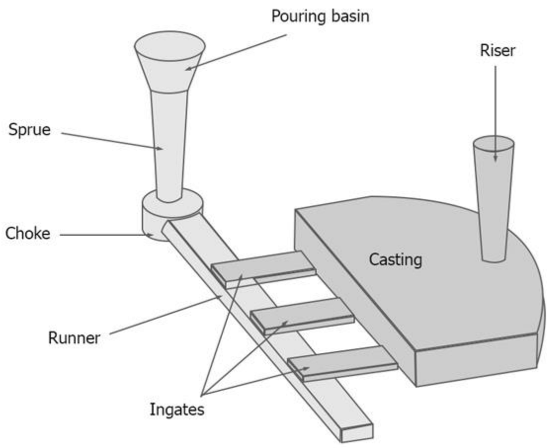
The casting shown is to be made in CI using a wooden pattern. Assuming only shrinkage allowance, calculate the dimensions of the pattern. All dimensions are in inches



Material	Dimension	Shrinkage allowance (inch/ft)
Grey Cast Iron	Up to 2 feet	0.125
	2 feet to 4 feet	0.105
	over 4 feet	0.083

Gating System

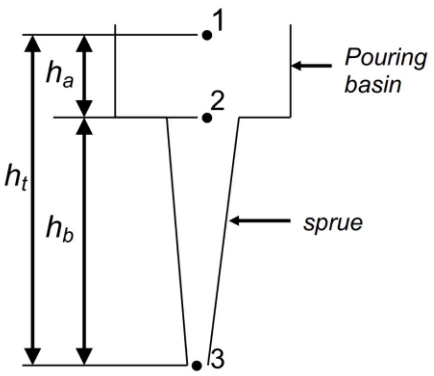
A good gating design should ensure proper distribution of molten metal without excessive temperature loss, turbulence, gas entrapping and slags. If the molten metal is poured very slowly, since time taken to fill the mould cavity will become longer, solidification will start even before the mould is completely filled. This can be restricted by using super-heated metal, but in this case, solubility will be a problem. If the molten metal is poured very faster, it can erode the mould cavity. So gating design is important, and it depends on the metal and molten metal composition. For example, aluminium can get oxidized easily.

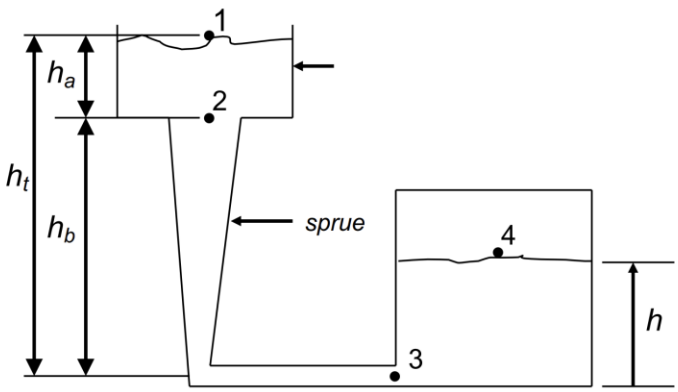


Two types of gates

a) Vertical gating

b) Bottom gating





Gating System Design – Vertical Gating System

For analysis we use energy balance equation like Bernoulli's equation between points 1 and 3.

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} + F_1 = h_3 + \frac{p_3}{\rho g} + \frac{v_3^2}{2g} + F_3$$

Assuming p1 = p3 and level at 1 is maintained constant, so v1 = 0; frictional losses are neglected. The energy balance between point 1 and 3 gives,

$$gh_t = v_3^2 / 2 \qquad v_3 = \sqrt{2gh_t}$$

Continuity equation: Volumetric flow rate

$Q = A_1 v_1 = A_3 v_3$

As the metal flows into the sprue opening, it increases in velocity, and hence, the cross-sectional area of the channel must be reduced. Otherwise, as the velocity of the flowing molten metal increases toward the base of the sprue, air can be aspirated into the liquid and taken into the mould cavity. To prevent this condition, the sprue is designed with a taper so that the volume flow rate, Q = Av, remains the same at the top and bottom of the sprue.

The mould filling time is given by

$$t_f = \frac{V}{Q} = \frac{V}{A_g v_3}$$

A_g = cross-sectional area of gate; V = volume of mould

Gating System Design – Bottom Gating System

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} + F_1 = h_3 + \frac{p_3}{\rho g} + \frac{v_3^2}{2g} + F_3$$

Apply Bernoulli's eqn. between points 1 and 3 and between 3 and 4 is equivalent to modifying V3 equation in the previous gating.

$$v_g = v_3 = \sqrt{2g(\underline{h_t - h})}$$

Effective head

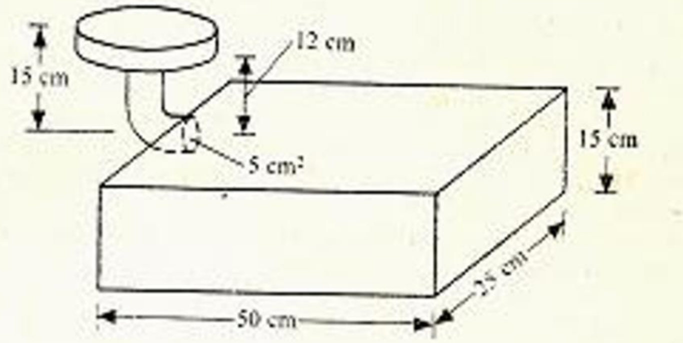
Assuming in the mould the height moves up by 'dh' in a time 'dt'; A_m and A_g are mould area and gate area, then

$$A_m dh = A_g v_g dt$$

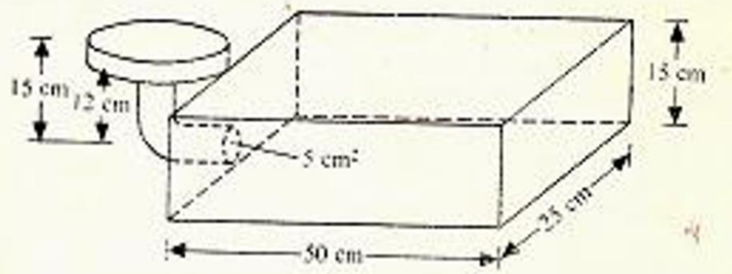
Combining above two eqns., we get $\frac{1}{\sqrt{2g}} \frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m} dt$

$$\frac{1}{\sqrt{2g}} \int_0^{h_m} \frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m} \int_0^{t_f} dt \Rightarrow \boxed{t_f = \frac{A_m}{A_g} \frac{1}{\sqrt{2g}} 2\left(\sqrt{h_t} - \sqrt{h_t - h_m}\right)}$$

Find the filling time for both the mould types. Area of C.S. of gate = 5 cm^2



(a) Top gating



(b) Bottom gating

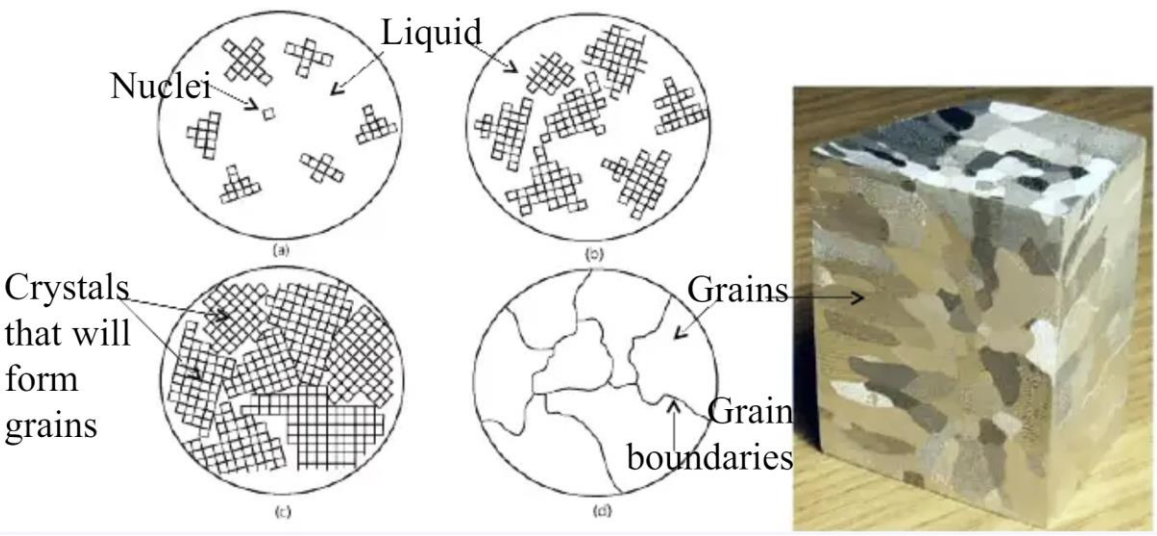
Solidification of Alloys

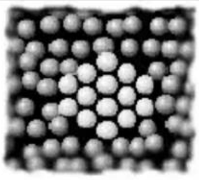
Solidification occurs in the solidification range of metals in two main steps:

1. **Nucleation:**
   - Nucleation is the initial formation of solid crystals in the liquid metal.
   - Homogeneous nucleation occurs randomly in the liquid, while heterogeneous nucleation occurs at impurities or surfaces.
2. **Growth of Crystals:**
   - Once nuclei form, they grow as more atoms join the crystal lattice.
   - The growth rate depends on factors like temperature, alloy composition, and the presence of impurities.

Growth of Crystals and Formation of Grain Structure

- **Nucleus grow into crystals in different orientations.**
- **Crystal boundaries are formed when crystals join together at complete solidification.**
- **Crystals in solidified metals are called grains.**
- **Grains are separated by grain boundaries.**

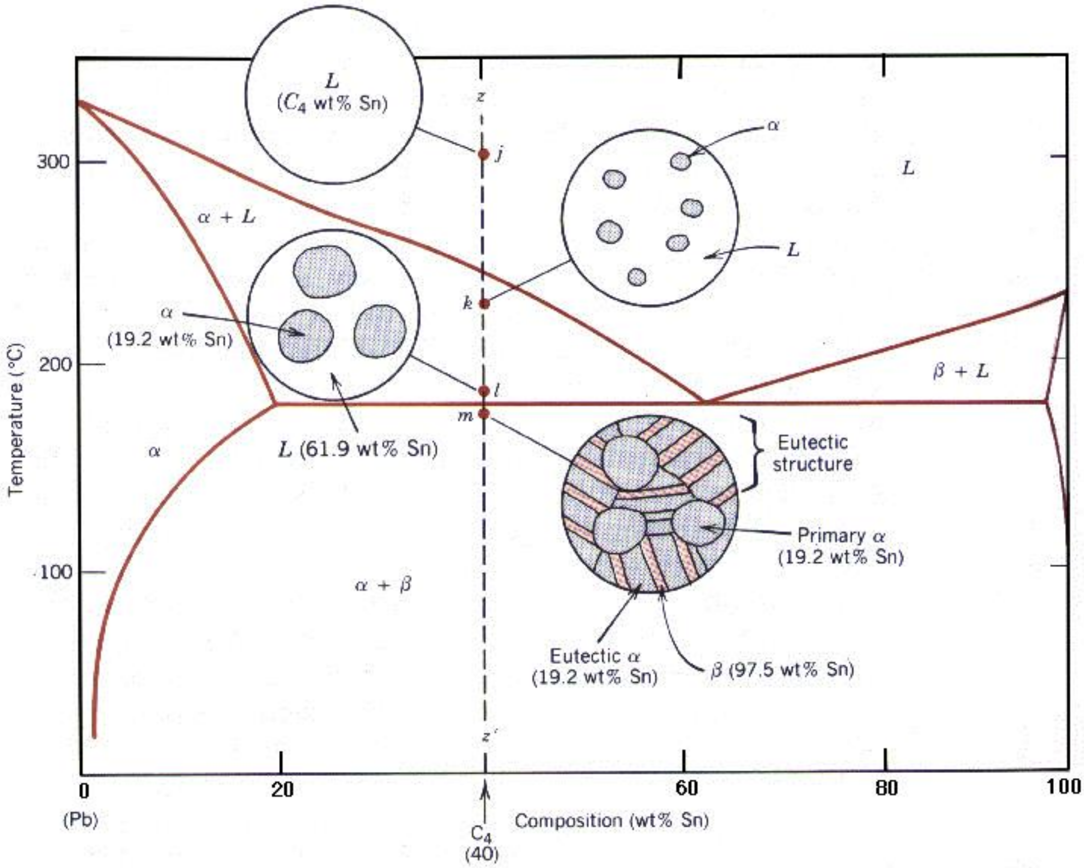




The small clusters of crystallized solid forming from a liquid metal. These arise due to the random motion of atoms within the liquid

- ***Homogeneous Nucleation*** – precipitation occurs within a completely homogeneous medium

- **Heterogeneous Nucleation** – precipitation may occur also on the surfaces, which separate different media, e.g. walls of the reactor



The phase diagram shows the phases present at different compositions (in wt% tin) and temperatures. It consists of a liquid phase field, a solid phase field (α-phase, which is a solid solution of tin in lead), and a eutectic phase field.

Solidification Process:

- When a lead-tin alloy with a composition within the α-phase field is cooled, it solidifies directly into the α-phase.
- As the temperature decreases further, the composition reaches the eutectic composition, and the eutectic reaction occurs, forming a mixture of α-phase and β-phase (tin) at the eutectic temperature.

Microstructure Evolution:

- During solidification, the microstructure evolves from a single-phase solid solution to a two-phase eutectic structure.
- The eutectic structure provides improved properties like strength and hardness compared to a single-phase solid solution.

Heterogeneous Nucleation

- **Nucleation occurs in a liquid on the surfaces of structural materials Eg:- Insoluble impurities.**
- **These structures, called *nucleating agents*, lower the free energy required to form stable nucleus.**

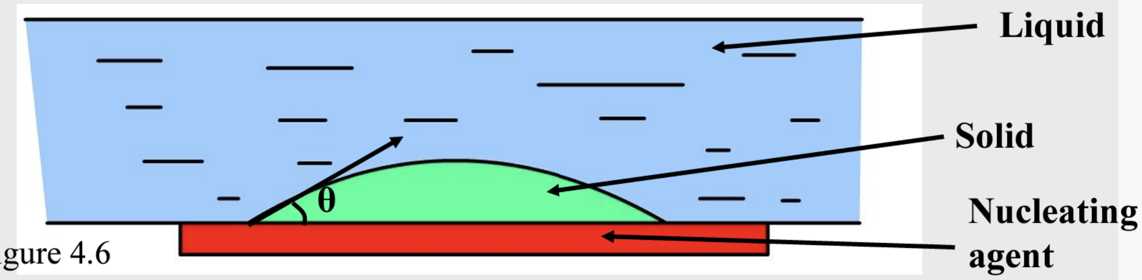


Figure 4.6

- **Nucleating agents also lower the critical size.**
- **Smaller amount of undercooling is required to solidify.**
- **Used excessively in industries.**

Types of Grains

- **Equiaxed Grains**:
  - **Crystals, smaller in size, grow equally in all directions.**
  - **Formed at the sites of high concentration of the nuclie.**
  - **Example:- Cold mold wall**
- **Columnar Grains**:
  - **Long thin and coarse.**
  - **Grow predominantly in one direction.**
  - **Formed at the sites of slow cooling and steep temperature gradient.**
  - **Example:- Grains that are away from the mold wall.**

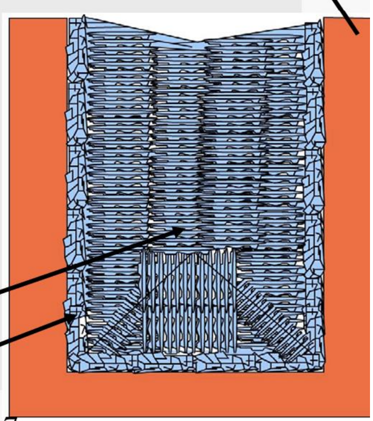


Figure 4.7a

Defects

During solidification, several defects can occur, affecting the quality of the final casting.

1. Gas defects
2. Shrinkage defects
3. Moulding material defects
4. Pouring metal defects
5. Metallurgical defects
6. Pattern defects

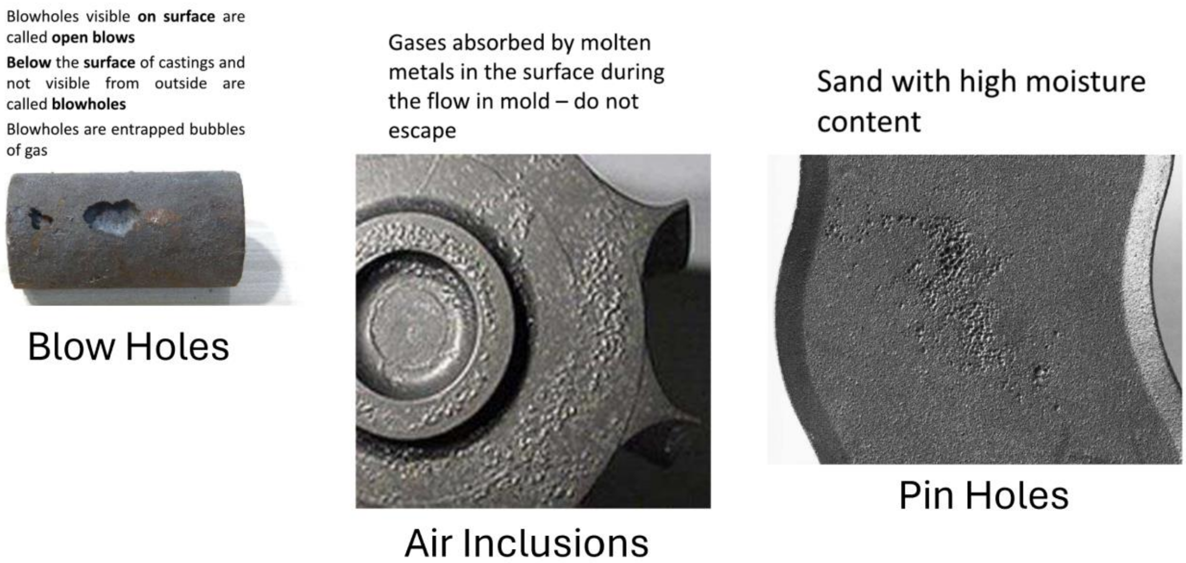


Figure 1 Gas Defects

Figure 2 Shrinkage defects

- Sand may fuse and stick to the casting surface with resultant and glossy surface

- Molten metal leaks from the mold due to faulty molding or faulty molding box equipment

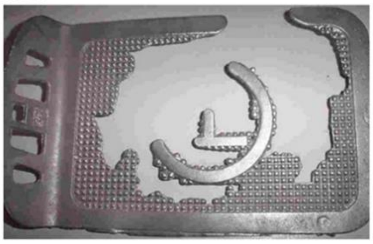


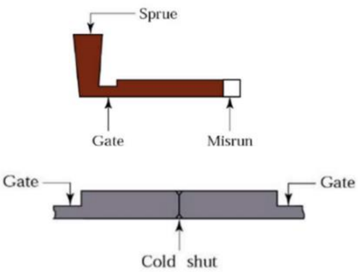
Figure 3 Moulding material defects

Misruns and coldshuts

Causes

- Too cold molten metal
- To thin casting section
- Too small gates
- Too many restrictions in gating system
- Lack in fluidity of metals

Description



- Slag is to be properly removed from ladle
- If not removed, casting would be weak and have a rough appearance

Figure 4 Pouring defects

A hot tear can occur because as a material solidifies, it will generally want to contract. If some force or restraint impedes this contraction, then a hot tear will occur

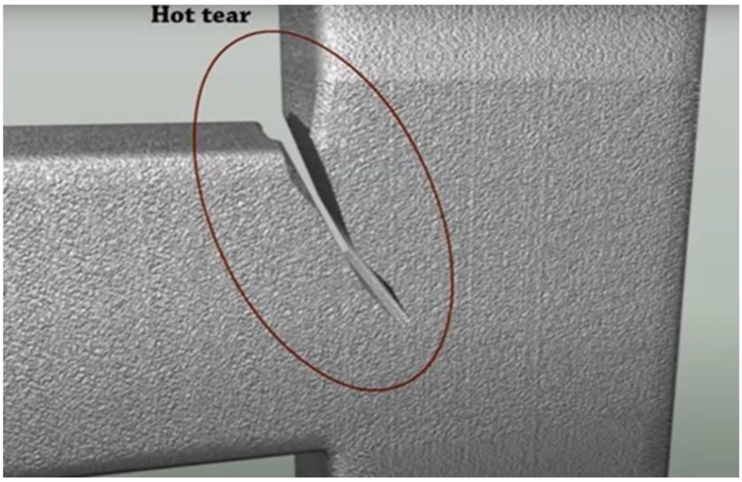
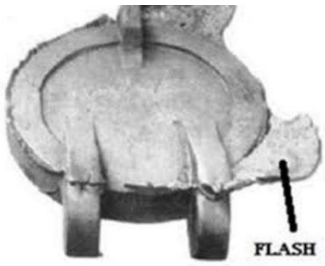


Figure 5 Metallurgical defects

- Mismatch
- Flash



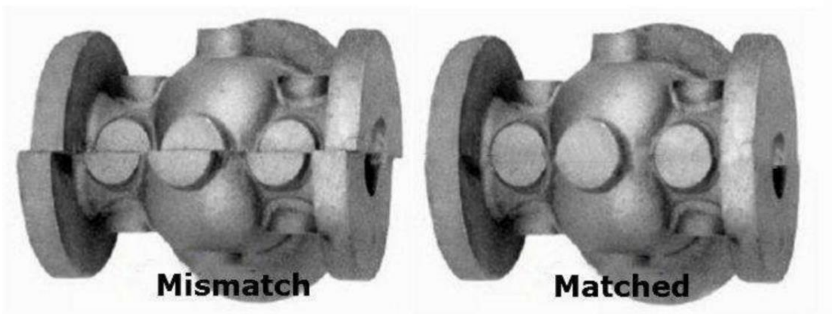


Figure 6 Pattern defects

MAHAVEER INSTITUTE OF SCIENCE AND TECHNOLOGY

(AN UGC AUTONOMOUS INSTITUTION)

Approved by AICTE, Affiliated to JNTUH, Accredited by NAAC with 'A' Grade
Recognized Under Section 2(f) of UGC Act 1956, ISO 9001:2015 Certified
Vyasapuri, Bandlaguda, Post: Keshavgiri, Hyderabad- 500 005, Telangana, India.
https://www.mist.ac.in E-mail:principal.mahaveer@gmail.com, Mobile: 8978380692

ESTD : 2001

Department of Aeronautical Engineering

(R22)

Introduction to Manufacturing Processes

B.Tech II YEAR – II SEM

Prepared by

LAKSHMI PRIYA MUTHE

(ASSISTANT PROFESSOR)

DEPT. AERO

INTRODUCTION TO MANUFACTURING PROCESSES

B.Tech. II Year II Sem. **L T/P/D C**
3 0/0/0 3

Course objectives:

1. To introduce the students to working principle of different metal casting processes and gating system.
2. To impart knowledge on plastic deformation, cold and hot working process, working of a rolling mill and types, extrusion processes.
3. To teach principles of forging, tools and dies, working of forging processes.
4. To develop fundamental understanding on classification of the welding processes, working of different types of welding processes and welding defects.
5. To impart knowledge on manufacturing methods of plastics, ceramics and powder metallurgy.
6. To introduce the basic concepts of Unconventional Machining Processes.

Course Outcomes:

1. Demonstrate different metal casting processes and gating systems.
2. Classify working of various welding processes.
3. Evaluate the forces and power requirements in rolling process.
4. Principles of various forging operations.
5. Outline the manufacturing methods of plastics, ceramics and powder metallurgy.
6. Identify different unconventional processes and their applications.

UNIT - I

Casting processes: Importance and selection of manufacturing processes. Introduction to casting process, process steps; pattern and design of gating system; Solidification of casting: Concept, solidification of pure metal and alloy; Special casting processes: Shell casting, investment casting, die casting, centrifugal casting, casting defects and remedies.

UNIT - II

Metal Forming & Forging: Introduction, nature of plastic deformation, hot and cold working of metals, mechanics of metal forming; Rolling: Principle, types of rolling mill and products, roll passes, forces in rolling and power requirements; Extrusion: Basic extrusion process and its characteristics, hot extrusion and cold extrusion, wire drawing, tube drawing.

Principles of forging, tools and dies. Types: Smith forging, drop forging, forging hammers, rotary forging and forging defects. Sheet metal forming: Mechanics of sheet metal working, blanking, piercing, bending, stamping.

UNIT - III

Metal Joining Processes: Classification of welding processes, types of welds and welded joints and V-I characteristics, arc welding, weld bead geometry, submerged arc welding, gas tungsten arc welding, gas metal arc welding. applications, advantages and disadvantages of the above processes, Plasma Arc welding, Laser Beam Welding, Electron Beam Welding and Friction Stir Welding. Heat affected zones in welding; soldering and brazing: Types and their applications, Welding defects: causes and remedies

UNIT - IV

Plastic Processing, Ceramics and Powder Metallurgy: Plastics: Types, properties and their applications, processing of plastics, extrusion of plastics, transfer molding and compression molding, injection molding, thermoforming, rotational molding, and blow molding

Ceramics: Classification of ceramic materials, properties and their application, ceramic powder preparation; Processing of ceramic parts: Pressing, casting, sintering; Secondary processing of ceramics: Coatings, finishing.

Powder Metallurgy: Principle, manufacture of powders, steps involved.

UNIT - V

Additive manufacturing: Introduction to layered manufacturing, Importance of Additive Manufacturing Additive Manufacturing in Product Development Classification of additive manufacturing processes, Common additive manufacturing technologies; Fused Deposition Modeling(FDM), Selective Laser Sintering(SLS), Stereo Lithography(SLA), Selection Laser Melting (SLM),Jetting,3D Printing, materials, costs, advantages and limitations of different systems.

TEXT BOOKS:

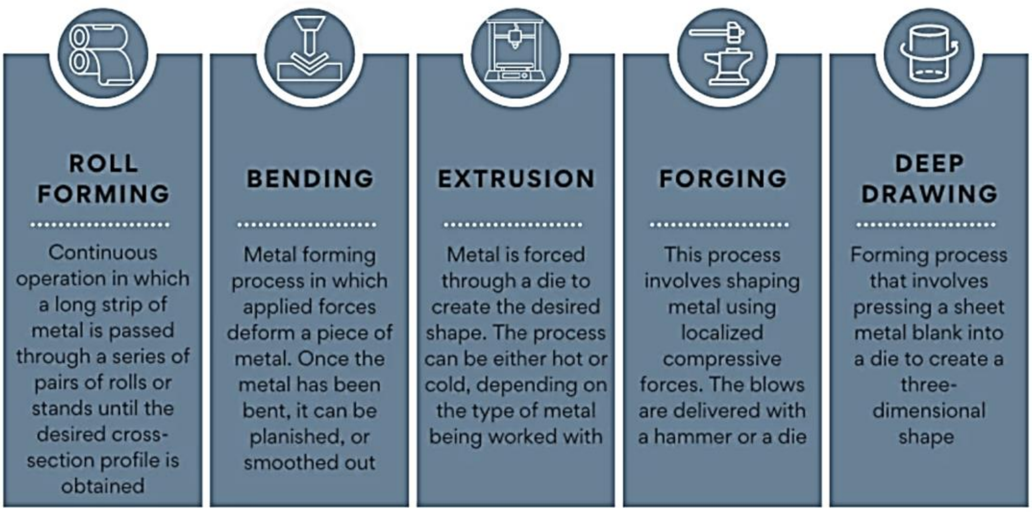
1. Rao P.N., Manufacturing Technology – Volume I, 5/e, McGraw-Hill Education, 2018.
2. Kalpakjain S and Schmid S.R., Manufacturing Engineering and Technology, 7/e, Pearson,2018.
3. Gibson, I., Rosen, D.W. and Stucker, B., “Additive Manufacturing Methodologies: Rapid Prototyping to Direct Digital Manufacturing”, Springer, 2015.
4. Chua, C.K., Leong K.F. and Lim C.S., “Rapid prototyping: Principles and applications”, Third edition, World Scientific Publishers, 2010.

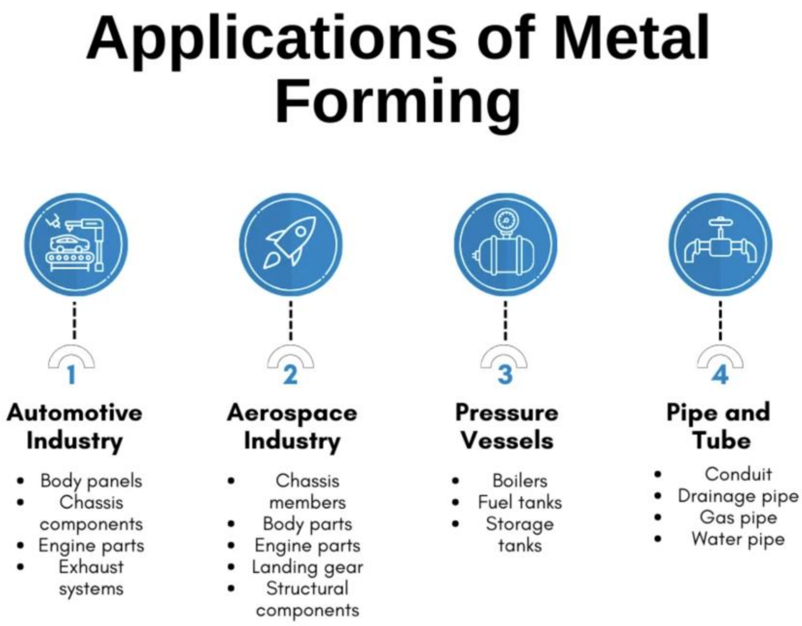
REFERENCE BOOKS:

1. Introduction to Physical Metallurgy by Sidney H.Avner
2. Millek P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes and Systems,4/e, John Wiley and Sons Inc, 2010.
3. Sharma P.C., A Text book of Production Technology, 8/e, S Chand Publishing, 2014.
4. Liou, L.W. and Liou, F.W., “Rapid Prototyping and Engineering applications: A tool box for prototype development”, CRC Press, 2011.
5. Kamrani, A.K. and Nasr, E.A., “Rapid Prototyping: Theory and practice”, Springer, 2006

Forming

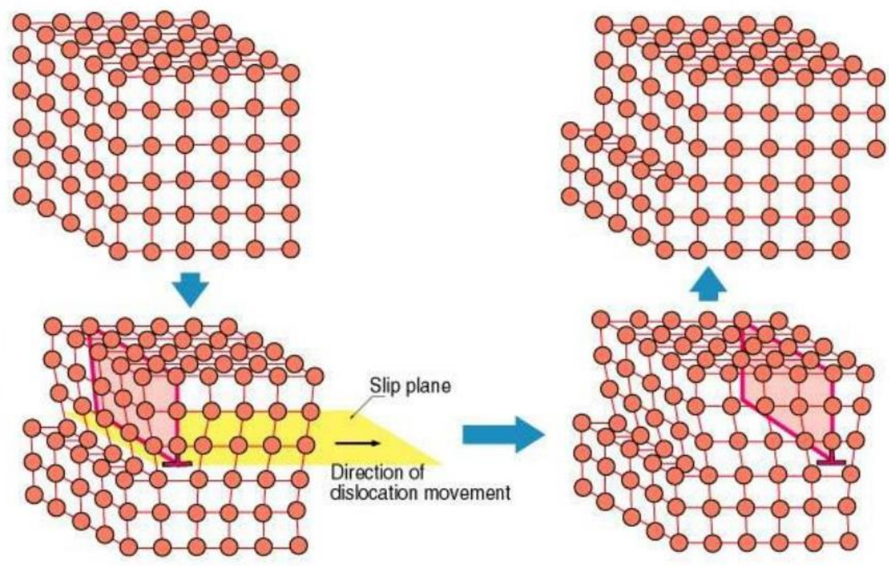
Metal forming refers to the process of shaping metal into a desired form without removing any material. It involves applying mechanical force, such as bending, stretching, or compressing, to the metal workpiece to change its shape. Depending on the material and desired outcome, metal forming can be performed at room temperature (cold forming) or elevated temperatures (hot forming).





Plastic Deformation in Metals

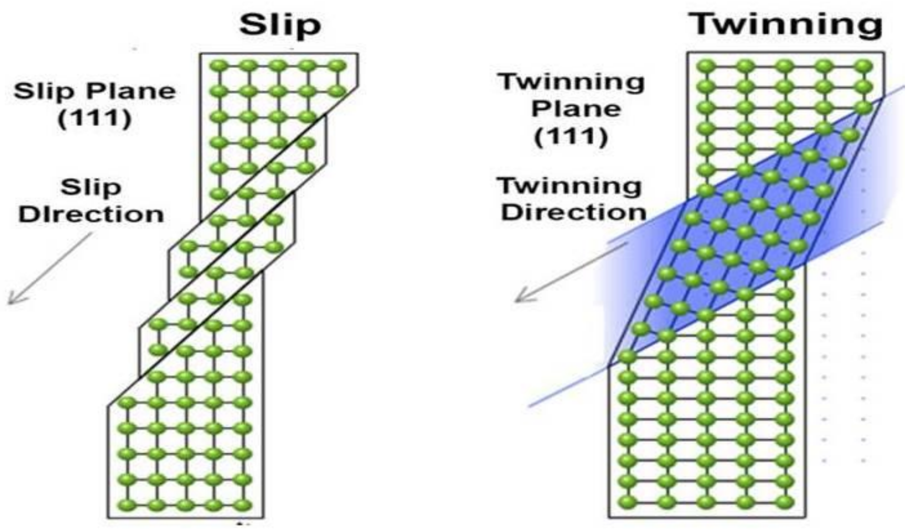
Plastic deformation in metals is a crucial process that allows them to change shape permanently under applied stress. Unlike elastic deformation, which is temporary and reversible, plastic deformation involves the movement of dislocations within the crystal lattice structure of the metal. Dislocations are defects in the crystal lattice where atoms are out of their ideal positions. When a metal is subjected to an external force, dislocations move, allowing layers of atoms to slide over each other. This movement of dislocations results in the metal deforming plastically, meaning it retains its new shape even after the stress is removed.



Plastic deformation is essential in various industries, including manufacturing, construction, and aerospace. It allows metals to be shaped into complex forms through processes like rolling, forging, and extrusion. The ability of metals to undergo plastic deformation is influenced by factors such as temperature, strain rate, and alloy composition. Higher temperatures increase the mobility of dislocations, making plastic deformation easier. Similarly, certain alloying elements can strengthen or weaken the material, affecting its ability to deform plastically. Understanding plastic deformation is crucial for engineers and material scientists to design and manufacture products with the desired mechanical properties and shapes.

Slip and twinning are two mechanisms by which the atoms in the crystal lattice can rearrange themselves to accommodate external stress and allow the material to change shape.

Slip: Slip is the most common mechanism of plastic deformation in crystalline materials. It involves the movement of dislocations—line defects in the crystal structure—through the lattice. When an external force is applied to a metal, dislocations move along specific planes in the crystal lattice, causing layers of atoms to slide past each other. This movement of dislocations allows the metal to deform plastically without fracturing. Slip occurs in the direction of the highest shear stress and is responsible for the characteristic plastic flow observed in metals.



Slip and Twinning

1. **Twinning:** Twinning is another mechanism of plastic deformation, though less common than slip. It involves the formation of a mirror-image twin plane within the crystal lattice. When twinning occurs, part of the crystal structure reflects the arrangement of atoms in another part, creating a twin boundary between them. Twinning can occur in response to shear stress and can contribute to the overall deformation of the material. Twin boundaries can act as barriers to dislocation movement, influencing the material's mechanical properties.

Hot working and Cold working

Metalworking processes can broadly be categorized into two types: hot working and cold working. These processes shape metals into various forms, but they differ in terms of temperature and the effects on the material. Let's explore the differences between hot working and cold working.

Hot Working: Hot working involves shaping metals at elevated temperatures, typically above their recrystallization temperature. This process is used to achieve large deformations and complex shapes. The high temperature reduces the strength and hardness of the metal, making it more malleable and easier to deform. Common hot working processes include forging, extrusion, and rolling. Hot working is preferred for materials that are difficult to deform at room temperature or for producing parts that require significant shaping.

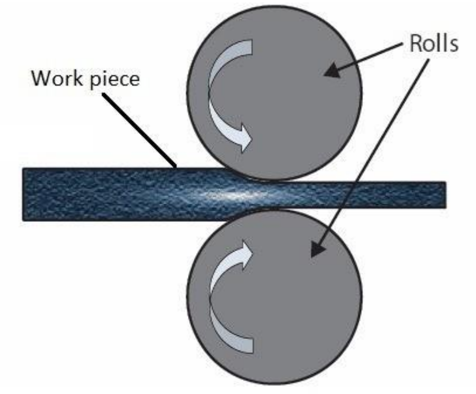
Cold Working: Cold working, also known as cold forming or cold processing, involves shaping metals at or near room temperature. Unlike hot working, cold working increases the strength and hardness of the metal due to strain hardening. This process is suitable for producing precision parts with tight tolerances and excellent surface finish. Common cold working processes include cold rolling, cold forging, and drawing. Cold working is preferred for materials that are ductile enough to undergo deformation at room temperature without cracking or fracturing.

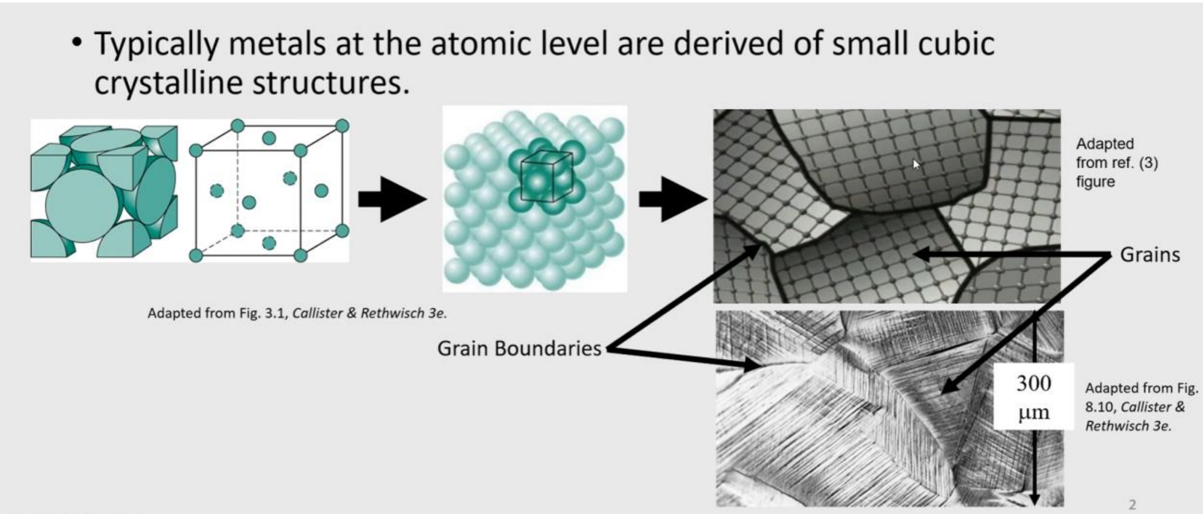
Advantages and Disadvantages:

Aspect	**Hot Working**	**Cold Working**
Advantages	- Lower forces required for deformation	- Increased strength and hardness of the material
	- Enhanced material ductility and formability	- Improved dimensional accuracy and surface finish
	- Reduction in material defects such as porosity	- No heating equipment required, lower energy costs
	- Recrystallization eliminates strain hardening effects	- Less material waste compared to machining processes
Disadvantages	- Elevated temperature requirements, energy-intensive	- Limited deformation capability compared to hot working
	- Greater risk of oxidation and scaling	- Potential for cracking or fracturing in brittle materials

Rolling

Rolling is a process that involves passing metal through a gap between rollers rotating in opposite directions. This gap is smaller than the thickness of the part being worked. Therefore, the rollers compress the metal while simultaneously shifting it forward because of friction at the roller-metal interfaces.

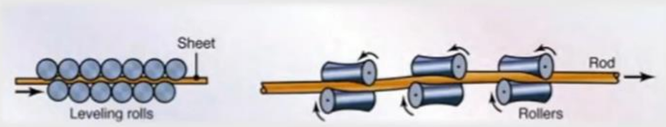




Vyasapuri, Bandlaguda, Post:Keshavgiri
Hyderabad-500005,Telangana, India
Tel:040-29880079, 86,8978380692, 9642703342
9652216001, 9550544411, Website:www.mist.ac.in
Email:principal@mist.ac.in
principal.mahaveer@gmail.com
Counseling code:MHVR, University Code:E3

MAHAVEER
INSTITUTE OF SCIENCE & TECHNOLOGY
(AN UGC AUTONOMOUS INSTITUTION)
Approved by AICTE, Affiliated to JNTU,Hyderabad
Accredited by NAAC with 'A' Grade
Recognized Under 2(f) of UGC Act 1956,ISO 9001:2015 Certified
ESTD : 2001

- The process of plastically deforming metal by passing it between shaped rolls.



Adapted from Fig. 13.7, *Kalpakjian & Schmid*

- Rolling accounts for 90% of all metals produced by metal working processes.
- Rolling allows for high production rates and high dimensional accuracies.

Terminology

Semi-finished products

Bloom is the product of first breakdown of ingot (cross sectional area > 230 cm^2).

Billet is the product obtained from a further reduction by hot rolling (cross sectional area > 40x40 mm^2).

Slab is the hot rolled ingot (cross sectional area > 100 cm^2 and with a width $\geq$ 2 x thickness).

Further rolling steps

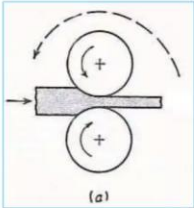
Mill products

Plate is the product with a thickness > 6 mm.

Sheet is the product with a thickness < 6 mm and width > 600 mm.

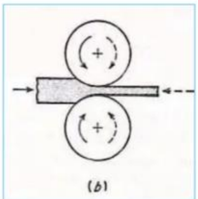
Strip is the product with a thickness < 6 mm and width < 600 mm.

Typical arrangement of rollers for rolling mills



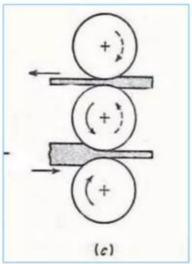
Two-high mill, pullover

The stock is returned to the entrance for further reduction.



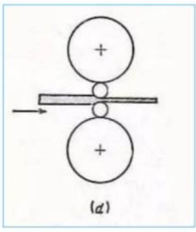
Two-high mill, reversing

The work can be passed back and forth through the rolls by reversing their direction of rotation.



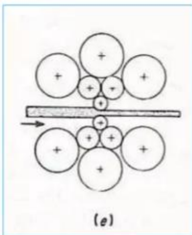
Three-high mill

Consist of upper and lower driven rolls and a middle roll, which rotates by friction.



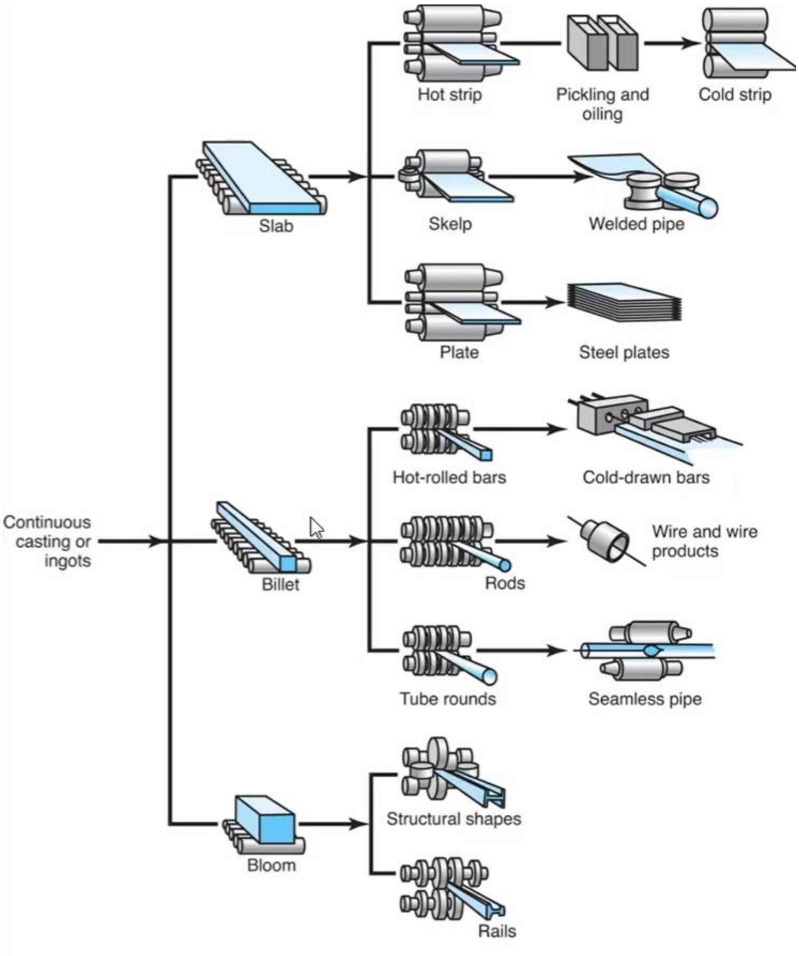
Four-high mill

Small-diameter rolls (less strength & rigidity) are supported by larger-diameter backup rolls



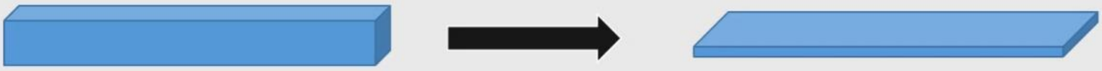
Cluster mill or Sendzimir mill

Each of the work rolls is supported by two backing rolls.


Continuous casting or ingots
Slab
Billet
Bloom
Hot strip
Pickling and oiling
Cold strip
Skelp
Welded pipe
Plate
Steel plates
Hot-rolled bars
Cold-drawn bars
Rods
Wire and wire products
Tube rounds
Seamless pipe
Structural shapes
Rails

The Flat-rolling Process

It is important to note that during the flat-rolling process we get varying velocities as we reduce the thickness of our metal strip.



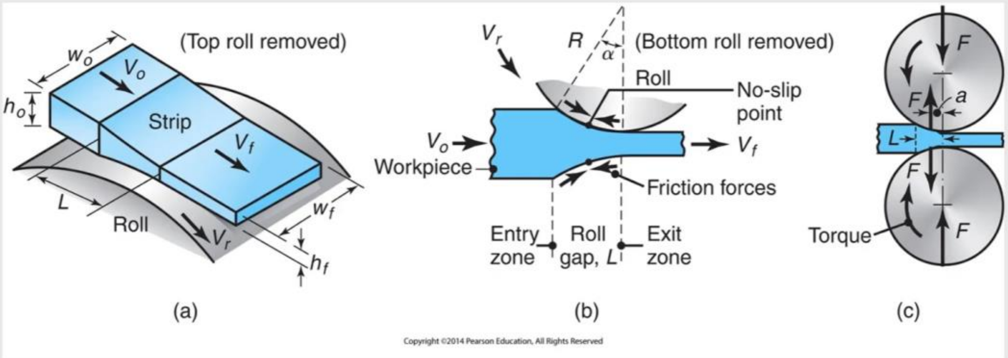


FIGURE 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) Roll force, *F*, and torque, *T*, acting on the rolls. The width of the strip, *w*, usually increases during rolling, as shown in Fig. 13.5.

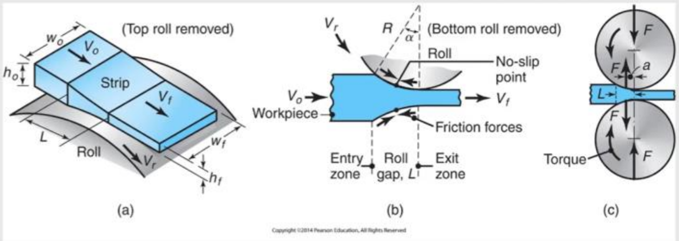
Flat rolling is a metal forming process that involves passing a metal strip or sheet between two rotating rolls to reduce its thickness and increase its length. This process is widely used in the production of sheet metal for various applications, including automotive, aerospace, and construction industries.

The forces involved in flat rolling can be categorized into two main types: **normal forces and friction forces**. Normal forces are exerted perpendicular to the direction of rolling and are responsible for reducing the thickness of the metal. Friction forces, on the other hand, act parallel to the direction of rolling and are responsible for transferring torque from the rolls to the metal.

Forward Slip

- Forward slip is a ratio of the difference in wheel speed to final strip speed

$$Forward\ Slip = \frac{V_f - V_r}{V_r}$$



- This is important since Forward Slip is directly correlated to the surface finish of the rolled strip.
  - A lower forward slip values are preferred over the higher values.

Forward slip in rolling refers to the difference between the peripheral velocity of the rolls and the velocity of the material being rolled. In ideal rolling, the material moves at the same speed as the rolls, ensuring no relative sliding between the material and the rolls. However, in reality, some slipping or forward slip occurs due to various factors, such as the elastic deformation of the rolls, the presence of lubricants, and the characteristics of the material being rolled.

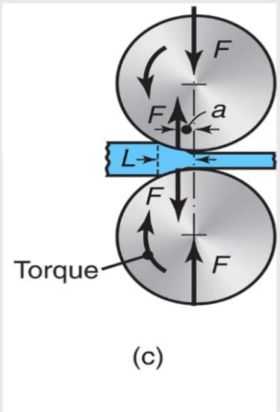
Forward slip is undesirable in rolling processes as it can lead to uneven thickness distribution, surface defects, and reduced productivity. Therefore, efforts are made to minimize forward slip by controlling the rolling parameters, such as roll speed, tension, and lubrication, to ensure efficient and high-quality rolling operations.

Rolling Force

- The force, F, needed in flat rolling can be estimated with the following equation,

$$F = LwY_{avg}$$

L: is the roll-strip contact length
w: is the width of the strip
Y_{avg}: is the average true stress of the strip in the roll gap.



(c) Roll force, *F*, and torque, *T*, acting on the rolls. The width of the strip, *w*, usually increases during rolling, as shown in Fig. 13.5.

8

Rolling force is the force required to deform a metal strip or sheet during the rolling process. It is necessary to overcome the material's resistance to deformation and ensure that the material flows smoothly between the rolls. Rolling force is influenced by various factors, including the material properties, thickness reduction, roll diameter, and friction between the rolls and the material.

Rolling Torque and Power Requirements

The Force previously calculated is used find the Torque, T, needed.

$$T = F * a$$

Rolling Power (P):

$$P = \frac{2\pi \times N \times T}{60{,}000}$$

Where:

- P is the rolling power (in kilowatts),
- N is the rotational speed of the rolls (in revolutions per minute), and
- T is the rolling torque (in newton-meters).

To calculate rolling torque and power, you first need to determine the rolling force (F) using the formula mentioned earlier. Then, you can calculate the rolling torque (T) using the first formula. Finally, you can calculate the rolling power (P) using the second formula, where you need to know the rotational speed of the rolls (N).

Problem:

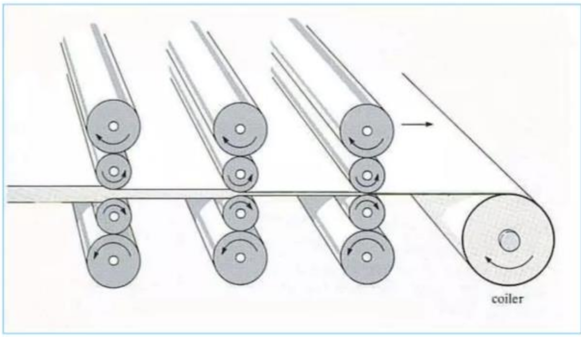
A steel strip is being rolled in a mill with a roll diameter of 0.5 meters. The strip is 1 meter wide and 0.02 meters thick. The material's flow stress is 200 MPa. If the strip is moving at a speed of 2 m/s and the roll is moving at a speed of 5.2 m/s, and the rotational speed of the rolls is 100 rpm, calculate:

1. The forward slip percentage.
2. The rolling force required.
3. The power required for rolling (assuming 90% efficiency).

Types of Rolling Processes

Conventional hot or cold-rolling

The objective is to *decrease the thickness* of the metal with an *increase in length* and with little increase in width.

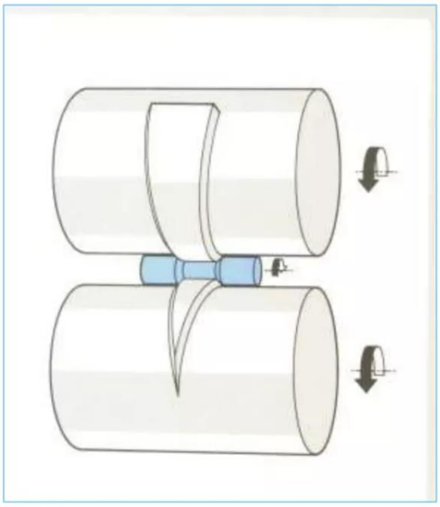


•The material in the centre of the sheet is constrained in the *z* direction (across the width of the sheet) and the *constraints of undeformed shoulders of material* on each side of the rolls prevent extension of the sheet in the width direction.

•This condition is known as *plane strain*. The material therefore gets longer and not wider.

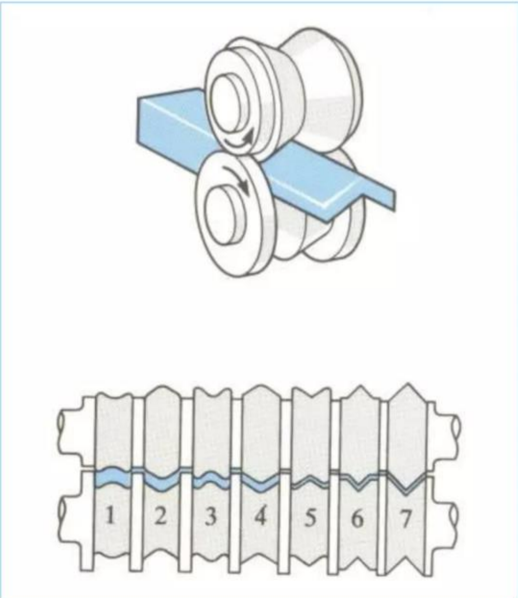
•Otherwise we would need the width of a *football pitch* to roll down a steel ingot to make tin plate!

Transverse rolling

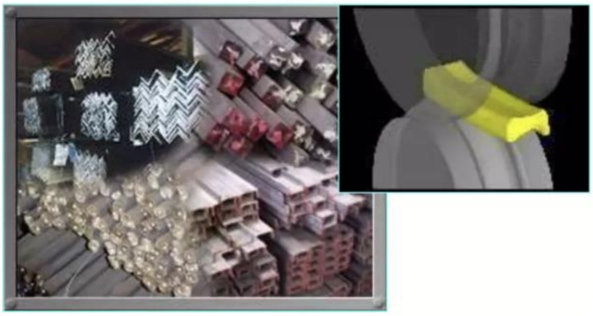


- Using circular wedge rolls.
- Heated bar is cropped to length and fed in transversely between rolls.
- Rolls are revolved in one direction.

Shaped rolling or section rolling

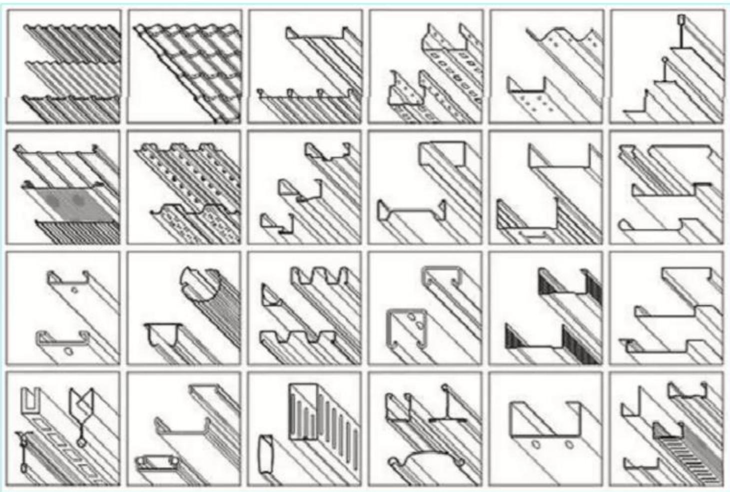


- A special type of cold rolling in which flat slap is progressively bent into *complex shapes* by passing it through a series of *driven rolls*.
- No appreciable change in the thickness of the metal during this process.
- Suitable for producing moulded sections such as irregular shaped channels and trim.



Shaped rolling or section rolling

A variety of sections can be produced by roll forming process using a series of forming rollers in a continuous method to roll the metal sheet to a specific shape

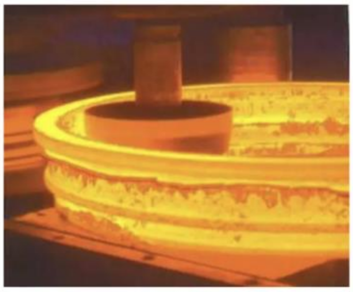


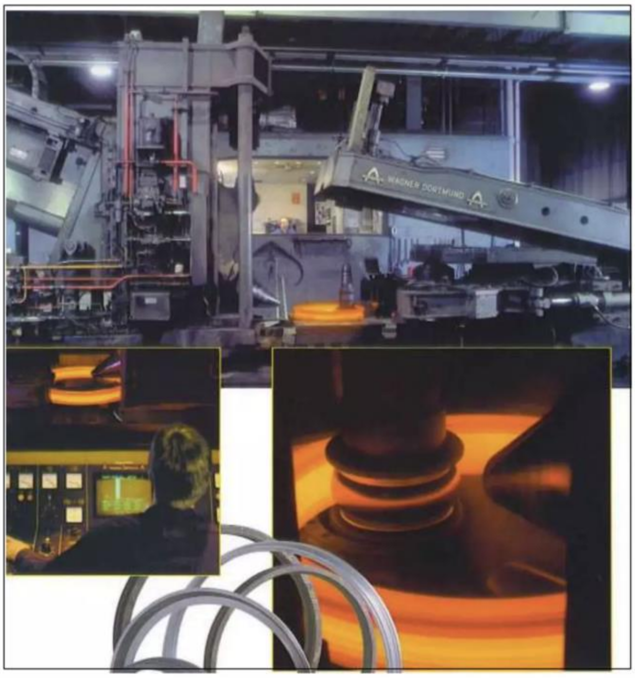
Applications:

- construction materials,
- partition beam
- ceiling panel
- roofing panels.
- steel pipe
- automotive parts
- household appliances
- metal furniture,
- door and window frames
- other metal products.

Ring rolling

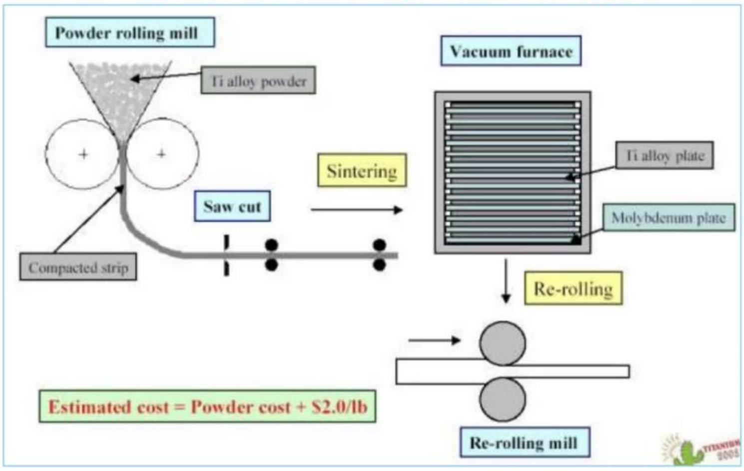
- Seamless (*i.e.*, without a joint) rings find wide application in industry.
- The inner and outer races of ball and roller bearings, steel tyres for railway wheel are some such applications.
- These rings are made by a special rolling process called ring rolling.





Powder rolling

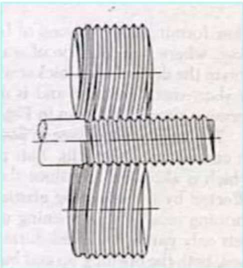
Metal powder is introduced between the rolls and compacted into a '*green strip*', which is subsequently sintered and subjected to further hot-working and/or cold working and annealing cycles.



Advantage :

- Cut down the initial hot-ingot breakdown step (reduced capital investment). *Economical* - metal powder is cheaply produced during the extraction process.
- Minimise contamination in hot-rolling.
- Provide *fine grain size* with a minimum of preferred orientation.

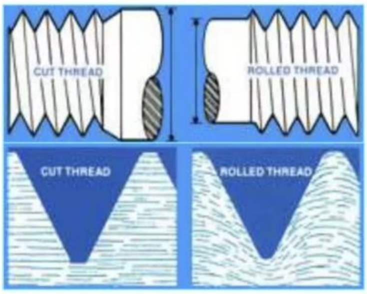
Thread rolling



•*Dies* are pressed against the surface of cylindrical blank. As the blank rolls against the in-feeding die faces, the material is displaced to form the *roots* of the thread, and the displaced material flows *radially outward* to form the *thread's crest*.

•A blank is fed between *two grooved die plates* to form the threads.

•The thread is formed by the *axial flow* of material in the work piece. The grain structure of the material is not cut, but is *distorted* to follow the thread form.

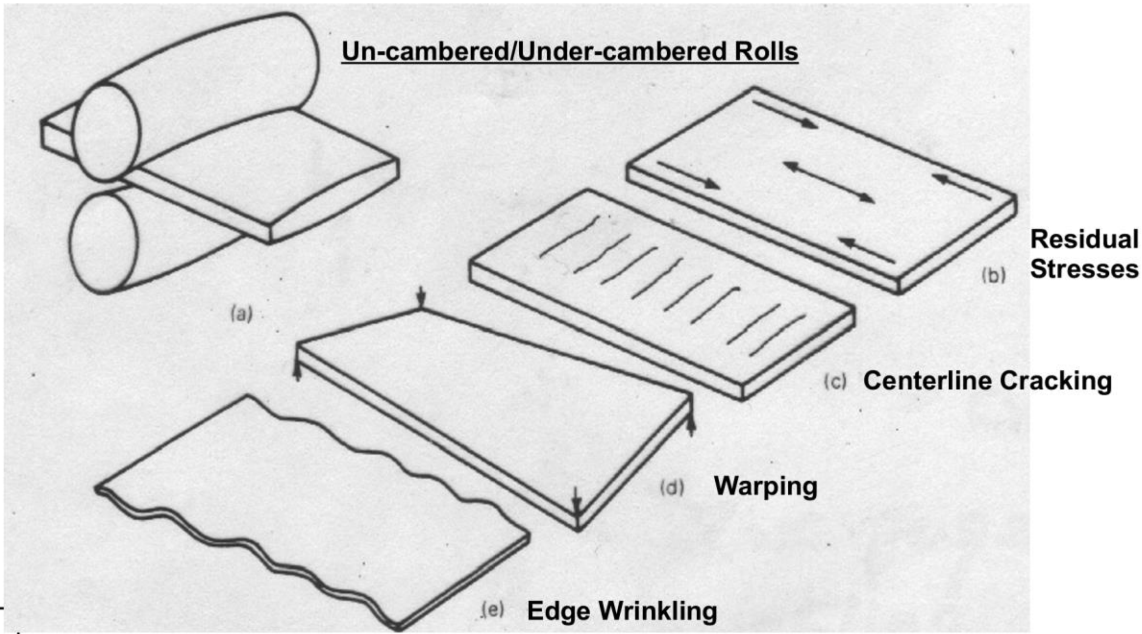


Cut thread and rolled thread

•Rolled threads are produced in a *single pass* at speeds far in excess of those used to cut threads.

• The resultant thread is very much *stronger* than a cut thread. It has a greater resistance to mechanical stress and an increase in fatigue strength. Also the surface is burnished and *work hardened*.

Un-cambered or under-cambered rolls



Roll flattening: similar to tyre flattening

- Due to elasticity of rolls
- Increases roll radius and hence rolling force

Remedy

- Choose rolls with high elastic modulus
- Reduce rolling force

MAHAVEER INSTITUTE OF SCIENCE AND TECHNOLOGY

(AN UGC AUTONOMOUS INSTITUTION)

Approved by AICTE, Affiliated to JNTUH, Accredited by NAAC with 'A' Grade
Recognized Under Section 2(f) of UGC Act 1956, ISO 9001:2015 Certified
Vyasapuri, Bandlaguda, Post: Keshavgiri, Hyderabad- 500 005, Telangana, India.
https://www.mist.ac.in E-mail:principal.mahaveer@gmail.com, Mobile: 8978380692

ESTD : 2001

Department of Aeronautical Engineering

(R22)

Introduction to Manufacturing Processes

B.Tech II YEAR – II SEM

Prepared by

LAKSHMI PRIYA MUTHE

(ASSISTANT PROFESSOR)

DEPT. AERO

INTRODUCTION TO MANUFACTURING PROCESSES

B.Tech. II Year II Sem. **L**
T/P/D C

3 0/0/0 3

Course objectives:

1. To introduce the students to the working principles of different metal casting processes and gating systems.
2. To impart knowledge on plastic deformation, cold and hot working process, working of a rolling mill and types, extrusion processes.
3. To teach principles of forging, tools and dies, working of forging processes.
4. To develop fundamental understanding on classification of the welding processes, working of different types of welding processes and welding defects.
5. To impart knowledge on manufacturing methods of plastics, ceramics and powder metallurgy.
6. To introduce the basic concepts of Unconventional Machining Processes.

Course Outcomes:

1. Demonstrate different metal casting processes and gating systems.
2. Classify working of various welding processes.
3. Evaluate the forces and power requirements in rolling process.
4. Principles of various forging operations.
5. Outline the manufacturing methods of plastics, ceramics and powder metallurgy.
6. Identify different unconventional processes and their applications.

UNIT - I

Casting processes: Importance and selection of manufacturing processes. Introduction to casting process, process steps; pattern and design of gating system; Solidification of casting: Concept, solidification of pure metal and alloy; Special casting processes: Shell casting, investment casting, die casting, centrifugal casting, casting defects and remedies.

UNIT - II

Metal Forming & Forging: Introduction, nature of plastic deformation, hot and cold working of metals, mechanics of metal forming; Rolling: Principle, types of rolling mill and products, roll passes, forces in rolling and power requirements; Extrusion: Basic extrusion process and its characteristics, hot extrusion and cold extrusion, wire drawing, tube drawing.

Principles of forging, tools and dies. Types: Smith forging, drop forging, forging hammers, rotary forging and forging defects. Sheet metal forming: Mechanics of sheet metal working, blanking, piercing, bending, stamping.

UNIT - III

Metal Joining Processes: Classification of welding processes, types of welds and welded joints and V-I characteristics, arc welding, weld bead geometry, submerged arc welding, gas tungsten arc welding, gas metal arc welding. applications, advantages and disadvantages of the above processes, Plasma Arc welding, Laser Beam Welding, Electron Beam Welding and Friction Stir Welding. Heat affected zones in welding; soldering and brazing: Types and their applications, Welding defects: causes and remedies

UNIT - IV

Plastic Processing, Ceramics and Powder Metallurgy: Plastics: Types, properties and their applications, processing of plastics, extrusion of plastics, transfer molding and compression molding, injection molding, thermoforming, rotational molding, and blow molding

Ceramics: Classification of ceramic materials, properties and their application, ceramic powder preparation; Processing of ceramic parts: Pressing, casting, sintering; Secondary processing of ceramics: Coatings, finishing.

Powder Metallurgy: Principle, manufacture of powders, steps involved.

UNIT - V

Additive manufacturing: Introduction to layered manufacturing, Importance of Additive Manufacturing Additive Manufacturing in Product Development Classification of additive manufacturing processes, Common additive manufacturing technologies; Fused Deposition Modeling(FDM), Selective Laser Sintering(SLS), Stereo Lithography(SLA), Selection Laser Melting (SLM),Jetting,3D Printing, materials, costs, advantages and limitations of different systems.

TEXT BOOKS:

1. Rao P.N., Manufacturing Technology – Volume I, 5/e, McGraw-Hill Education, 2018.
2. Kalpakjain S and Schmid S.R., Manufacturing Engineering and Technology, 7/e, Pearson,2018.
3. Gibson, I., Rosen, D.W. and Stucker, B., "Additive Manufacturing Methodologies: Rapid Prototyping to Direct Digital Manufacturing", Springer, 2015.
4. Chua, C.K., Leong K.F. and Lim C.S., "Rapid prototyping: Principles and applications", Third edition, World Scientific Publishers, 2010.

REFERENCE BOOKS:

1. Introduction to Physical Metallurgy by Sidney H.Avner
2. Millek P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes and Systems,4/e, John Wiley and Sons Inc, 2010.
3. Sharma P.C., A Text book of Production Technology, 8/e, S Chand Publishing, 2014.
4. Liou, L.W. and Liou, F.W., "Rapid Prototyping and Engineering applications: A tool box for prototype development", CRC Press, 2011.
5. Kamrani, A.K. and Nasr, E.A., "Rapid Prototyping: Theory and practice", Springer, 20

1.1 DEFINITION OF WELDING

"Welding is the process of joining together two pieces of metal so that bonding takes place at their original boundary surfaces". When two parts to be joined are melted together, heat or pressure or both is applied and with or without added metal for formation of metallic bond.

1.2 NEED FOR WELDING

With ever increasing demand for both high production rates and high precision, fully mechanized or automated welding processes have taken a prominent place in the welding field. The rate at which automation is being introduced into welding process is astonishing and it may be expected that by the end of this century more automated machines than men in welding fabrication units will be found. In addition, computers play critical role in running the automated welding processes and the commands given by the computer will be taken from the programs, which in turn, need algorithms of the welding variables in the form of mathematical equations. To make effective use of the automated systems it is essential that a high degree of confidence be achieved in predicting the weld parameters to attain the desired mechanical strength in welded joints.

To develop mathematical models to accurately predict the weld strength to be fed to the automated welding systems has become more essential.

1.3 CLASSIFICATION OF WELDING PROCESSES

There are many types of welding techniques used to join metals. The welding processes differ in the manner in which temperature and pressure are combined and achieved. The welding process is divided into two major categories: Plastic Welding or Pressure Welding and Fusion Welding or Non-Pressure Welding.

Plastic Welding or Pressure Welding: When the metal piece acquires plastic state on heating, external pressure is applied. In this process, externally applied forces play an important role in the bonding operation. "A group of welding processes which produces coalescence at temperatures essentially below the melting point of the base materials being joined without the addition of a filler metal" is Pressure Welding Process. Without melting the base metal, due to temperature, time and pressure coalescence is produced. Some of the very oldest processes are included in solid state welding process. The advantage of this process is the base metal does not melt and hence the original properties are retained with the metals being joined.

Fusion Welding or Non-Pressure Welding: The material at the joint is heated to a molten state and allowed to solidify. In this process the joining operation involves melting and solidification and any external forces applied to the system do not play an active role in producing coalescence. Usually fusion welding uses a filler material to ensure that the joint is filled. All fusion welding processes have three requirements: Heat, Shielding and Filler material.

1.4 TYPES OF WELDING

Welding process can also be classified as follows:

1. Gas Welding
    - Oxy Acetylene Welding
    - Oxy Hydrogen Welding
    - Pressure Gas Welding
2. Arc Welding
    - Carbon Arc Welding
    - Shield Metal Arc Welding
    - Submerged Arc Welding
    - Metal Inert Gas Welding
    - Tungsten Inert Gas Welding
    - Electro Slag Welding
    - Plasma Arc Welding

3. Resistance Welding
    - Spot Welding
    - Flash Welding
    - Resistance Butt Welding
    - Seam Welding

4. Solid State Welding
    - Forge Welding
    - Cold Welding
    - Friction Welding
    - Explosive Welding
    - Diffusion Welding
    - Ultrasonic Welding

5. Thermo-Chemical Welding
    - Thermit Welding
    - Atomic H_2 Welding

6. Radiant Energy Welding
    - Electron Beam Welding
    - Laser Welding

1.5 WELDING OF DIFFERENT MATERIALS

The most available metal in the earth's crust is aluminum whereas, steel is the most used metal. In majority of cases aluminum alloys are replacing steels in industrial applications. Aluminum alloys have low density i.e. nearly one third when compared to steels. Some of these materials are allowing for a significant reduction of weight when compared with structural steels. Aluminum alloys are important for the fabrication of components and structures which require high strength, low weight or electric current carrying capabilities to meet their service requirements. The aluminum alloys can resist the oxidation process, corrosion by water and salt, which steel cannot. The most desirable properties of aluminum and its alloys are the light weight, appearance, ability for fabrication, strength and corrosion resistance and hence it is used for wide variety of applications. When used in aerospace, rail and road vehicles these attributes enable energy efficient operation. In the aerospace applications, materials with high strength-to-weight ratio are required such as aluminum alloys. The production of components of aluminum alloys is not very complex; but joining of these materials can sometimes cause serious problems. Among all aluminum alloys, 6XXX plays a major role in the aerospace industry. They are widely used in the aerospace applications because it has good formability, weldability, machinability, corrosion resistance and good strength when compared to other series of aluminum alloys. Hence these alloys are chosen in this work for FSW process.

1.5.1 Defects in welding

The lack of training to the operator or careless application of welding technologies may cause discontinuities in welding. In aluminum joints obtained by fusion welding, the defects such as porosity, slag inclusion, solidification cracks etc., are observed and these defects deteriorates the weld quality and joint properties.

Common weld defects found in welded joints: These defects may result in sudden failures which are unexpected as they give rise to stress intensities. The common weld defects include

i. Porosity
ii. Lack of fusion
iii. Inclusions
iv. Cracking
v. Undercut
vi. Lamellar tearing

i. Porosity

Porosity occurs, when the solidifying weld metal has gases trapped in it. The presence of porosity in most of the welded joints is due to dirt on the surface of the metal to be welded or damp consumables.

It is found in the shape of sphere or as elongated pockets. The region of distribution of the porosity is random and sometimes it is more concentrated in a certain region. By storing all the consumables in dry conditions and degreasing and cleaning the surface before welding, porosity can be avoided.

ii. Lack of Fusion

Due to too little input or too slow traverse of the welding torch, lack of fusion arises. By increasing the temperature, by properly cleaning the weld surface before welding and by selecting the appropriate joint design and electrodes, a better weld can be obtained. On extending the fusion zone to the thickness of the joints fully, a good quality joint can be obtained.

iii. Inclusions

Due to the trapping of the oxides, fluxes and electrode coating materials in the weld zone the inclusions are occurred. Inclusions occur while joining thick plates in several runs using flux cored or flux coated rods and the slag covering a run is not totally removed after every run and before the next run starts. By maintaining a clean surface before the run is started, providing sufficient space for the molten weld metal between the pieces to be joined, the inclusions can be prevented.

iv. Cracking

Due to thermal shrinkage, strain at the time of phase change, cracks may occur in various directions and in various locations in the weld area. Due to poor design and inappropriate procedure of joining high residual stresses, cracking is observed. A stage-wise pre-heating process and stage-wise slow cooling will prevent such type of cracks. This can greatly increase the cost of welded joints. Cracks are classified as hot cracking and hydrogen induced cracking. A schematic diagram of centerline crack is shown below fig. 1.1.

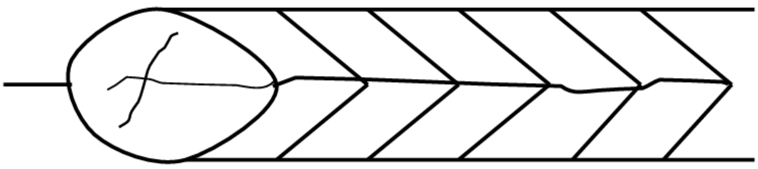


Fig. 1.1 Schematic diagram of centerline crack

The cracking can be minimized by preferring fillers with low carbon and low impurity levels. The solidification cracking can be avoided by reducing the gaps and cleaning the surface before welding.

v. Undercutting

The undercut is caused due to incorrect settings or using improper procedure. Undercutting can be detected by a naked eye and the excess penetration can be visually detected.

vi. Lamellar Tearing

Due to non metallic inclusions, the lamellar tearing occurs through the thickness direction. This is more evidently found in rolled plates. As the fusion boundary is parallel to the rolling plane in T and corner joints, the lamellar tearing occur. By redesigning the joint and by buttering the weld area with ductile material, the lamellar tearing can be minimized.

1.6 ALUMINUM ALLOYS DESIGNATION CRITERIA

Based on the ability to respond to thermal and mechanical treatment, the aluminum alloys are characterized into number of groups. Aluminum alloys may be divided into two broad classes: Cast and Wrought products. These two classes can be further subdivided into families of alloys based on chemical composition and finally on temper designation. To identify the condition of the alloy, the heat treatment condition, the amount of cold work it has undergone i.e. the temper designation is used. Among the many methods available to identify the alloy and its conditions, the numeric method CEN (European Committee for Standardization) is used as standard in which four digits are used to identify the wrought alloys and five digits for the cast alloys.

1.6.1 Alloying Elements

Copper, silicon, lithium, zinc, magnesium and manganese are the principal alloying elements in addition to titanium, chromium, scandium and zirconium which are available in small quantities to achieve some specific properties. Other unwanted elements are also present as impurities and are known as residual or tramp elements. An attempt is made by the producers to eliminate these residual properties from the products.

The prefix AB denotes ingots for remelting, AC denotes a cast product, AM a cast master alloy and AW a wrought product. While numbering or considering the identification system for aluminum alloys, the characteristics like ability to respond to thermal and mechanical treatment are identified. The wrought aluminum has a four digit system and the other have three digit and one decimal place system. In the wrought aluminum designation system the first digit indicates the principal alloying element, second individual number indicates modification of the specific alloys and the third and fourth digits are arbitrary numbers to identify specific alloys in the series.

- AW 1XXX – Commercially Pure Aluminum.
- AW 2XXX – Aluminum – Copper Alloys.
- AW 3XXX – Aluminum – Manganese Alloys.
- AW 4XXX – Aluminum – Silicon Alloys.
- AW 5XXX – Aluminum – Magnesium Alloys.
- AW 6XXX – Aluminum – Magnesium – Silicon Alloys.
- AW 7XXX – Aluminum – Zinc – Magnesium Alloys.
- AW 8XXX – Other Elements e.g. Lithium, Iron.
- AW 9XXX – No alloy groups assigned.

Temper Designation system

Letter	Meaning
F	As fabricated
O	Annealed
H	Strain Hardened
W	Solution Heat Treated
T	Thermally treated to produce stable tempers other than F, O or H
T1	Naturally aged after cooling from an elevated temperature shaping process such as extruding.
T2	Cold Worked after cooling from as elevated temperature shaping process and then naturally aged.
T3	Solution heat treated, cold worked and naturally aged.

T4	Solution heat treated and naturally aged.
T5	Artificially aged after cooling from an elevated temperature shaping process.
T6	Solution heat treated and artificially aged
T7	Solution heat treated and stabilized (over aged)
T8	Solution heat treated, cold worked and artificially aged
T9	Solution heat treated artificially aged and cold worked
T10	Cold worked after cooling from an elevated temperature shaping process then artificially aged.

1.6.2 Characteristics of Aluminum Alloys

The physical and chemical characteristics of aluminum, contrasted with those of steel are

- The aluminum alloys are excellently corrosive resistance as the oxide film on aluminum is durable, highly tenacious and self healing.
- The coefficient of thermal expansion of aluminum is approximately twice and thermal conductivity is approximately six times that of steel.
- The specific heat of aluminum is twice that of steel.
- Aluminum has high electrical conductivity, only three quarters that of copper, but six times that of steel.
- Aluminum doesn’t change color as its temperature rises.
- Aluminum has a modulus of elasticity three times that of steel.

Out of all the aluminum alloys of 2XXX, 5XXX, 6XXX and 7XXX series find their application in aerospace, shipbuilding and automobile industries.

The AA6XXX are suitable for decorative architectural sections and used for structural applications as they have good corrosive resistance, surface finish, formability and medium strength. The AA6XXX series aluminum alloys are heat treatable and capable of achieving medium strength due to the formation of stochiometric compound and magnesium silicide. The major alloys of this series include AA6351, AA6061, AA6005 and AA6082. By taking these various applications into consideration 6XXX series aluminum alloy is chosen as the base material. The base material AA6061, AA6351 and AA6082 are in use from 5mm to 50mm thickness ranges.

Heat treatable AA6XXX are of medium strength and possess excellent welding characteristics over the high strength aluminum alloys. Hence, alloys of this class are extensively employed in marine frames, pipelines, storage tanks and aircraft applications. Although Al-Mg-Si alloys are readily weldable, they suffer from severe softening in the heat affected zone (HAZ) because of reversion (dissolution) of Mg_2Si precipitates during weld thermal cycle.

1.7 COMPARISON OF OTHER PROCESSES FOR WELDING ALUMINUM ALLOYS

Tungsten inert gas welding (TIG) and Laser beam welding are used for welding aluminum alloys in aerospace welding. TIG has replaced other arc welding processes for joining aluminum alloys. As the fusion welding of aluminum alloys poses problems like porosity, distortion due to high thermal conductivity and solidification shrinkage, it is not preferred. Welding long butt or lap joints of aluminum alloys using conventional welding techniques is difficult as it cannot be made without distortion. Higher welder skills and special procedures are required as all fusion techniques cause loss of alloying elements through evaporation. To avoid the loss through evaporation, special filler material having 5% of silicon is to be used. If AA 6XXX welds are subjected to post weld solutionizing and aging, the mechanical properties can be further improved. As there is increase in welding of aluminum metals in aerospace and other light weight alloys, it leads to development of Friction Stir Welding. As there is no melting during welding, and also the joints are made in the solid state itself, defects are found to be minimum.

1.8 SCOPE AND OBJECTIVE OF STUDY

Friction Stir Welding has many benefits when applied to welding of aluminum alloys and dissimilar materials which were difficult to weld. In order to prevent defective welded joints, utmost care should be taken into account of all the pertinent variables. Tool pin diameter and taper of the pin, flute design which includes number, depth and taper angle and pitch of any thread form on the pin are the important parameters in addition to the tool rotational speed(TRS), weld speed(traverse speed/WS) and the axial force (F) [1]. However, to achieve these objectives, individually or together, considerable difficulties arose. The main parameter considered in the present work is, variation of properties with the variation of tool geometry, tool rotational speed, axial force and weld speed. Experimental results obtained are analyzed.

The Literature available on formation of friction stir zone varying by the effect of tool profiles is comparatively less. Different pin profiles are designed and manufactured. The joints obtained by using various tool profiles with varied process parameters are investigated. An ANN model is developed using MATLAB, and optimization of the process parameters is carried out by comparing the results obtained by the Design of Experiments (DOE). Using each tool, Friction Stir Welding is carried out at various parameters on different materials AA6061, AA6351 and AA6082.

MAHAVEER INSTITUTE OF SCIENCE AND TECHNOLOGY
(AN UGC AUTONOMOUS INSTITUTION)
Approved by AICTE, Affiliated to JNTUH, Accredited by NAAC with 'A' Grade
Recognized Under Section 2(f) of UGC Act 1956, ISO 9001:2015 Certified
Vyasapuri, Bandlaguda, Post: Keshavgiri, Hyderabad- 500 005, Telangana, India.
https://www.mist.ac.in E-mail:principal.mahaveer@gmail.com, Mobile: 8978380692

ESTD : 2001

Department of Aeronautical Engineering

(R22)

Introduction to Manufacturing Processes

B.Tech II YEAR – II SEM

Prepared by

LAKSHMI PRIYA MUTHE

(ASSISTANT PROFESSOR)

DEPT. AERO

INTRODUCTION TO MANUFACTURING PROCESSES

B.Tech. II Year II Sem. **L T/P/D C**

3 0/0/0 3

Course objectives:

1. To introduce the students to the working principles of different metal casting processes and gating systems.
2. To impart knowledge on plastic deformation, cold and hot working process, working of a rolling mill and types, extrusion processes.
3. To teach principles of forging, tools and dies, working of forging processes.
4. To develop fundamental understanding on classification of the welding processes, working of different types of welding processes and welding defects.
5. To impart knowledge on manufacturing methods of plastics, ceramics and powder metallurgy.
6. To introduce the basic concepts of Unconventional Machining Processes.

Course Outcomes:

1. Demonstrate different metal casting processes and gating systems.
2. Classify working of various welding processes.
3. Evaluate the forces and power requirements in rolling process.
4. Principles of various forging operations.
5. Outline the manufacturing methods of plastics, ceramics and powder metallurgy.
6. Identify different unconventional processes and their applications.

UNIT - I

Casting processes: Importance and selection of manufacturing processes. Introduction to casting process, process steps; pattern and design of gating system; Solidification of casting: Concept, solidification of pure metal and alloy; Special casting processes: Shell casting, investment casting, die casting, centrifugal casting, casting defects and remedies.

UNIT - II

Metal Forming & Forging: Introduction, nature of plastic deformation, hot and cold working of metals, mechanics of metal forming; Rolling: Principle, types of rolling mill and products, roll passes, forces in rolling and power requirements; Extrusion: Basic extrusion process and its characteristics, hot extrusion and cold extrusion, wire drawing, tube drawing.

Principles of forging, tools and dies. Types: Smith forging, drop forging, forging hammers, rotary forging and forging defects. Sheet metal forming: Mechanics of sheet metal working, blanking, piercing, bending, stamping.

UNIT - III

Metal Joining Processes: Classification of welding processes, types of welds and welded joints and V-I characteristics, arc welding, weld bead geometry, submerged arc welding, gas tungsten arc welding, gas metal arc welding. applications, advantages and disadvantages of the above processes, Plasma Arc welding, Laser Beam Welding, Electron Beam Welding and Friction Stir Welding. Heat affected zones in welding; soldering and brazing: Types and their applications, Welding defects: causes and remedies

UNIT - IV

Plastic Processing, Ceramics and Powder Metallurgy: Plastics: Types, properties and their applications, processing of plastics, extrusion of plastics, transfer molding and compression molding, injection molding, thermoforming, rotational molding, and blow molding

Ceramics: Classification of ceramic materials, properties and their application, ceramic powder preparation; Processing of ceramic parts: Pressing, casting, sintering; Secondary processing of ceramics: Coatings, finishing.
Powder Metallurgy: Principle, manufacture of powders, steps involved.

UNIT - V

Additive manufacturing: Introduction to layered manufacturing, Importance of Additive Manufacturing Additive Manufacturing in Product Development Classification of additive manufacturing processes, Common additive manufacturing technologies; Fused Deposition Modeling(FDM), Selective Laser Sintering(SLS), Stereo Lithography(SLA), Selection Laser Melting (SLM),Jetting,3D Printing, materials, costs, advantages and limitations of different systems.

TEXT BOOKS:

1. Rao P.N., Manufacturing Technology – Volume I, 5/e, McGraw-Hill Education, 2018.
2. Kalpakjain S and Schmid S.R., Manufacturing Engineering and Technology, 7/e, Pearson,2018.
3. Gibson, I., Rosen, D.W. and Stucker, B., "Additive Manufacturing Methodologies: Rapid Prototyping to Direct Digital Manufacturing", Springer, 2015.
4. Chua, C.K., Leong K.F. and Lim C.S., "Rapid prototyping: Principles and applications", Third edition, World Scientific Publishers, 2010.

REFERENCE BOOKS:

1. Introduction to Physical Metallurgy by Sidney H.Avner
2. Millek P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes and Systems,4/e, John Wiley and Sons Inc, 2010.
3. Sharma P.C., A Text book of Production Technology, 8/e, S Chand Publishing, 2014.
4. Liou, L.W. and Liou, F.W., "Rapid Prototyping and Engineering applications: A tool box for prototype development", CRC Press, 2011.
5. Kamrani, A.K. and Nasr, E.A., "Rapid Prototyping: Theory and practice", Springer, 20

Polymer: A large molecule (macromolecule) built up by repetitive bonding (covalent) of smaller molecules (monomers)

- Generally not a well defined structure, or molecular weight.
- Need to use statistical properties to describe.

Polymers are formed by linking monomers through chemical reaction—called polymerization. You don't end up with a unique molecule.

i monomers → chain of monomers

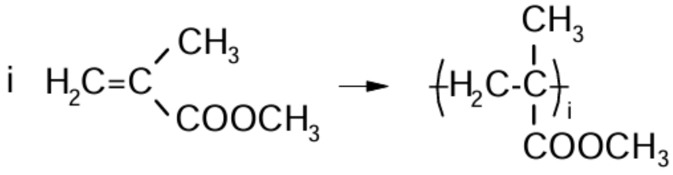
$$i\ A \rightarrow —(A–A–A)_{i/3}—$$

Homopolymer: all *A* identical

- The most produced/used polymers are homopolymers of terminal alkenes.
- Produced by radical polymerization.

$$i\ CH_2{=}CH_2 \rightarrow —(CH_2–CH_2)_i—$$

ethylene → polyethylene



methylmethacrylate → PMMA

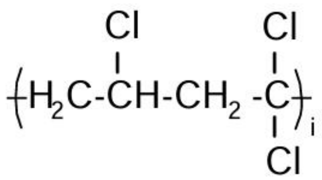
Copolymers:

made up of different monomers

i A + i B → —(A-B)$_i$—

i $H_2C{=}CHCl$ + i $H_2C{=}CCl_2$ →

vinyl chloride　　vinylidene chloride



poly(vinylchloride-co-vinylidene chloride)
→ Saran

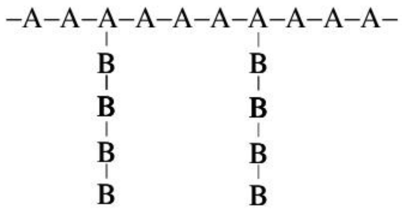
—A-B-A-B-A-B— alternating copolymer

—A-A-A-A-B-A-B— random copolymer

Both of these are rare. Most common is a statistical copolymer, which has a statistical distribution of repeat units.

Block copolymers—Two long sequences of repeat units

—A-A-A-A-A-A-A-B-B-B-B-B-B-B— AB diblock copolymer

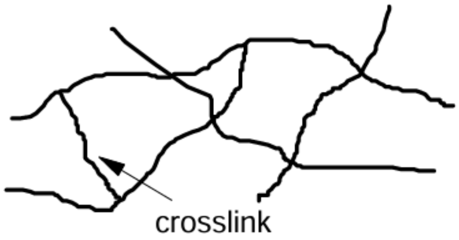


AB graft copolymer

Structural characteristics – Closely related to material properties

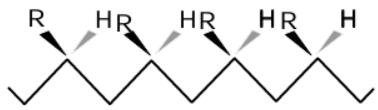
linear (uninterrupted straight chain)

branched (occasional branches off longer chain)

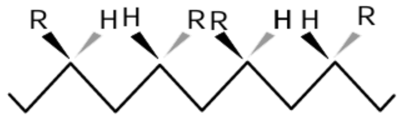


networked (many interconnected linear chains; one giant molecule)

Stereochemistry of Linkages



ISOTACTIC – R groups on same side of backbone



SYNDIOTACTIC – R groups on alternating sides of backbone

ATACTIC — Random (most common)

Ziegler-Natta catalysts used for iso- and syndio-

Classification of polymers:

Polymers (synthetic)

1) ***Thermoplastics*** (plastics) — linear, some cross-linking
can be melted and reformed on heating

   a) **Amorphous**—no ordered structure

   b) **Semi-crystalline**—composed of microscopic crystallites—
   domains of crystalline structure. Can be ordered.

   Fibers (nylon, polyester)

2) ***Elastomers*** (rubbers) — moderately cross-linked
can be stretched and rapidly recover their original dimension

3) ***Thermostats***—(resins)—massively cross-linked
very rigid; degrade on heating

4) ***Dendrimers***—multiply branched—multiple consecutive (regular) branches

Biopolymers

polypeptides—proteins-amino acid heteropolymer

nucleic acids—RNA/DNA

polysaccharides—sugars

Characterization

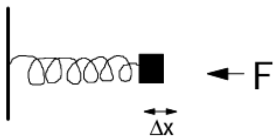
1) How do polymers respond to an applied force?

(study of flow and deformation: rheology)

→ viscoelastic medium

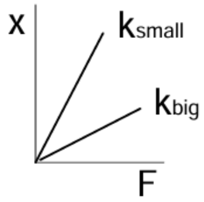
- An elastic medium is described by Newton's Law:

$$F = -k\ x$$



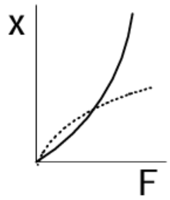
- If you apply a force (a stress), the material displaces by an amount x:

$$x = -\frac{F}{k}$$



  - ➢ small k: weak spring → easily displaced
  - ➢ big K: stiff spring → difficult to displace

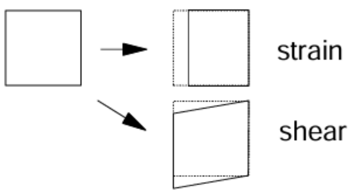
- Polymers are often non-Newtonian



For polymers, we apply a **stress**, and it leads to internal distortion → **strain**.

$$\sigma \quad = \quad m \quad S$$

stress — elastic modulus — strain → displacement



- small *m* → stretches easily/compresses easily (rubber)
- large *m* → small strain produced by stress σ (hard plastics—PMMA)

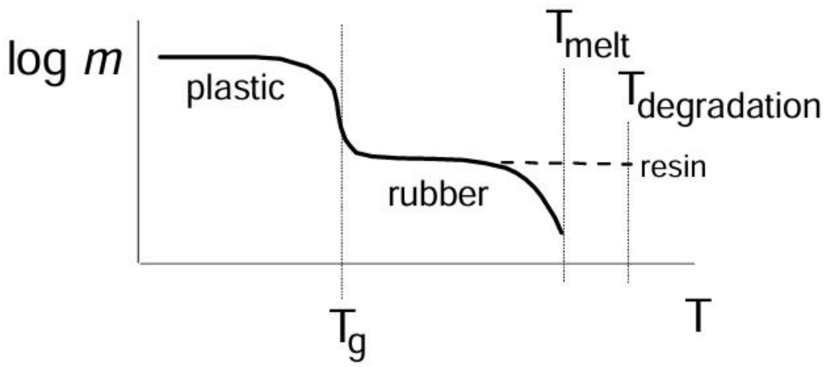
The elastic modulus* m *is highly temperature dependent!

Rubber has small *m* at room temperature → ball bounces

At low T, *m* much larger → rubber ball in liquid N_2 shatters when bounced → hard plastic

Also, plastics heated above room temperature are less stiff.

TYPICAL PLOT OF *m*(T)



Where is room temperature on this plot? (depends on whether you have a rubber or plastic)

The various temperatures characterize polymers.

2) Molecular Weight – Molar Mass (M)

i: degree of polymerization (# of monomer units)

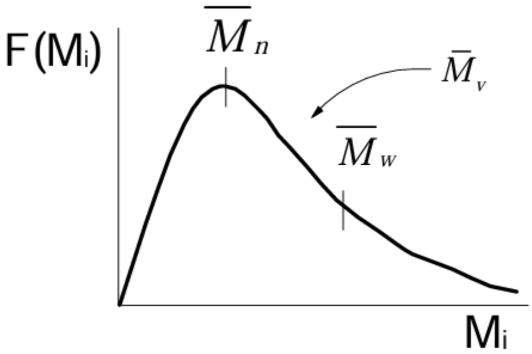
$M_i = i\,M_0$ — M_i : molar mass of polymer molecule *i*; M_0 : molecular weight of monomer

Typically have distribution of masses (all chain lengths aren't equally long)

monodisperse—equal chain lengths → purified proteins, dendriners

polydisperse—unequal lengths

Characterize the polydispersity through $F(M_i)$: distribution of molar masses.



We can find several statistical ways of describing the molar mass.
Comparison of these numbers helps describe F(M).

A) Number-average molar mass, $\overline{M}_n$

$$\overline{M}_n = \frac{\sum_i N_i M_i}{\sum_i N_i} \Rightarrow \frac{\int_0^\infty M\,F(M)\,dM}{\int_0^\infty F(M)\,dM} \qquad \text{(first moment)}$$

N_i: # of molecules with degree of polymerization *i*
M_i: molar mass for degree of polymerization *I*

B) Mass- or Weight-average molar mass, $\overline{M}_w$

$$\bar{M}_w = \sum_i w_i M_i$$

w_i is the weight fraction: the total mass of molecules with mass M_i divided by the total mass of all molecules

$$w_i = \frac{N_i M_i}{\sum_i N_i M_i}$$

$$\bar{M}_w = \frac{\sum_i N_i M_i^2}{\sum_i N_i M_i} \Rightarrow \frac{\int_0^\infty F(M) M^2 dM}{\int_0^\infty F(M) M \, dM} \qquad \text{(second moment of M.M.)}$$

C) **In experiment 4, we are studying viscosity-average molar mass, $\bar{M}_v$**

$$\left(\bar{M}_v\right)^a = \frac{\int_0^\infty M^{1+a} F(M) \, dM}{\int_0^\infty F(M) \, dM}$$

Polydispersity—We can describe the polydispersity through the width of the distribution of molar masses.

$$\bar{M}_n < \bar{M}_v < \bar{M}_w$$

$$\frac{\bar{M}_w}{\bar{M}_n} \geq 1$$ perfectly monodisperse = 1

B) Mass- or Weight-average molar mass, $\overline{M}_w$

$$\bar{M}_w = \sum_i w_i M_i$$

w_i is the <u>weight fraction</u>: the total mass of molecules with mass M_i divided by the total mass of all molecules

$$w_i = \frac{N_i M_i}{\sum_i N_i M_i}$$

$$\bar{M}_w = \frac{\sum_i N_i M_i^2}{\sum_i N_i M_i} \Rightarrow \frac{\int_0^\infty F(M) M^2 dM}{\int_0^\infty F(M) M \, dM}$$ (second moment of M.M.)

C) **In experiment 4, we are studying viscosity-average molar mass, $\bar{M}_v$**

$$\left(\bar{M}_v\right)^a = \frac{\int_0^\infty M^{1+a} F(M) \, dM}{\int_0^\infty F(M) \, dM}$$

<u>Polydispersity</u>—We can describe the polydispersity through the width of the distribution of molar masses.

$$\bar{M}_n < \bar{M}_v < \bar{M}_w$$

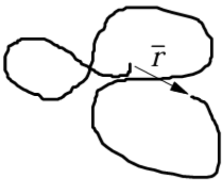
$$\frac{\bar{M}_w}{\bar{M}_n} \geq 1$$ perfectly monodisperse = 1

3) *Chain dimensions*

Contour length: length along backbone

n bonds of length l → n · l

End-to-end distance: More common - measure of the coiled system



The distribution of $\bar{r}$ is characterized by the rms end-to-end distance $\sqrt{\langle r^2 \rangle}$

For a freely jointed chain with n links and no restrictions on bond angle:

$$\sqrt{\langle r^2 \rangle} = \sqrt{n}\,\ell$$

Radius of gyration, R_g

R_g is the rms distance of a chain segment from the center of mass of the polymer.

intrinsic viscosity →

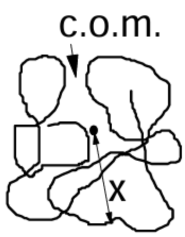
$$R_g = \sqrt{\frac{\langle r^2 \rangle}{6}}$$

$$[\eta] \propto \frac{R_g^{\,3}}{M}$$

Define a center of mass; then each chain segment has a certain distance from the center of mass

average x^2 to get R_g

$$\langle x^2 \rangle^{1/2} = R_g$$



MAHAVEER INSTITUTE OF SCIENCE AND TECHNOLOGY

(AN UGC AUTONOMOUS INSTITUTION)

Approved by AICTE, Affiliated to JNTUH, Accredited by NAAC with 'A' Grade
Recognized Under Section 2(f) of UGC Act 1956, ISO 9001:2015 Certified
Vyasapuri, Bandlaguda, Post: Keshavgiri, Hyderabad- 500 005, Telangana, India.
https://www.mist.ac.in E-mail:principal.mahaveer@gmail.com, Mobile: 8978380692

ESTD : 2001

Department of Aeronautical Engineering

(R22)

Introduction to Manufacturing Processes

B.Tech II YEAR – II SEM

Prepared by

LAKSHMI PRIYA MUTHE

(ASSISTANT PROFESSOR)

DEPT. AERO

INTRODUCTION TO MANUFACTURING PROCESSES

B.Tech. II Year II Sem. **L**
T/P/D C

3 0/0/0 3

Course objectives:

1. To introduce the students to the working principles of different metal casting processes and gating systems.
2. To impart knowledge on plastic deformation, cold and hot working process, working of a rolling mill and types, extrusion processes.
3. To teach principles of forging, tools and dies, working of forging processes.
4. To develop fundamental understanding on classification of the welding processes, working of different types of welding processes and welding defects.
5. To impart knowledge on manufacturing methods of plastics, ceramics and powder metallurgy.
6. To introduce the basic concepts of Unconventional Machining Processes.

Course Outcomes:

1. Demonstrate different metal casting processes and gating systems.
2. Classify working of various welding processes.
3. Evaluate the forces and power requirements in rolling process.
4. Principles of various forging operations.
5. Outline the manufacturing methods of plastics, ceramics and powder metallurgy.
6. Identify different unconventional processes and their applications.

UNIT - I

Casting processes: Importance and selection of manufacturing processes. Introduction to casting process, process steps; pattern and design of gating system; Solidification of casting: Concept, solidification of pure metal and alloy; Special casting processes: Shell casting, investment casting, die casting, centrifugal casting, casting defects and remedies.

UNIT - II

Metal Forming & Forging: Introduction, nature of plastic deformation, hot and cold working of metals, mechanics of metal forming; Rolling: Principle, types of rolling mill and products, roll passes, forces in rolling and power requirements; Extrusion: Basic extrusion process and its characteristics, hot extrusion and cold extrusion, wire drawing, tube drawing.

Principles of forging, tools and dies. Types: Smith forging, drop forging, forging hammers, rotary forging and forging defects. Sheet metal forming: Mechanics of sheet metal working, blanking, piercing, bending, stamping.

UNIT - III

Metal Joining Processes: Classification of welding processes, types of welds and welded joints and V-I characteristics, arc welding, weld bead geometry, submerged arc welding, gas tungsten arc welding, gas metal arc welding. applications, advantages and disadvantages of the above processes, Plasma Arc welding, Laser Beam Welding, Electron Beam Welding and Friction Stir Welding. Heat affected zones in welding; soldering and brazing: Types and their applications, Welding defects: causes and remedies

UNIT - IV

Plastic Processing, Ceramics and Powder Metallurgy: Plastics: Types, properties and their applications, processing of plastics, extrusion of plastics, transfer molding and compression molding, injection molding, thermoforming, rotational molding, and blow molding

Ceramics: Classification of ceramic materials, properties and their application, ceramic powder preparation; Processing of ceramic parts: Pressing, casting, sintering; Secondary processing of ceramics: Coatings, finishing.

Powder Metallurgy: Principle, manufacture of powders, steps involved.

UNIT - V

Additive manufacturing: Introduction to layered manufacturing, Importance of Additive Manufacturing Additive Manufacturing in Product Development Classification of additive manufacturing processes, Common additive manufacturing technologies; Fused Deposition Modeling(FDM), Selective Laser Sintering(SLS), Stereo Lithography(SLA), Selection Laser Melting (SLM),Jetting,3D Printing, materials, costs, advantages and limitations of different systems.

TEXT BOOKS:

1. Rao P.N., Manufacturing Technology – Volume I, 5/e, McGraw-Hill Education, 2018.
2. Kalpakjain S and Schmid S.R., Manufacturing Engineering and Technology, 7/e, Pearson,2018.
3. Gibson, I., Rosen, D.W. and Stucker, B., “Additive Manufacturing Methodologies: Rapid Prototyping to Direct Digital Manufacturing”, Springer, 2015.
4. Chua, C.K., Leong K.F. and Lim C.S., “Rapid prototyping: Principles and applications”, Third edition, World Scientific Publishers, 2010.

REFERENCE BOOKS:

1. Introduction to Physical Metallurgy by Sidney H.Avner
2. Millek P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes and Systems,4/e, John Wiley and Sons Inc, 2010.
3. Sharma P.C., A Text book of Production Technology, 8/e, S Chand Publishing, 2014.
4. Liou, L.W. and Liou, F.W., “Rapid Prototyping and Engineering applications: A tool box for prototype development”, CRC Press, 2011.
5. Kamrani, A.K. and Nasr, E.A., “Rapid Prototyping: Theory and practice”, Springer, 20

Introduction to Additive Manufacturing

Every human-made object around us has a unique history. This history is the evolution of raw materials that are extracted from the earth through human intervention and made into a usable form. The development of humankind has always been linked to modifying the history of raw material evolution into a usable product (manufacturing) in the pursuit of making it more efficient and flexible. Today, in the early decades of the twenty-first century, additive manufacturing (AM) is the most advanced and cutting-edge technique used in manufacturing. It entered the limelight as '*3D printing*' and has flipped the tables in research and development with a paradigm shift, gradually ushering in the fourth Industrial Revolution. However, we can only recognize the full worth of AM by understanding traditional manufacturing techniques and their evolution. This chapter first presents the history of manufacturing and the AM approach. It addresses the advantage of AM over conventional manufacturing while considering the challenges AM currently faces. The remainder of the chapter introduces laser-based AM, which is at the forefront of AM techniques. Overall, understanding the fundamental aspects of these techniques and their effects is the primary goal of this book.

1.1 Evolution of Manufacturing

Manufacturing is the process of forming a usable product out of raw materials using manual labor or mechanical machinery. The archaeological evidence for manufacturing dates back to the Stone Age, when *Homo habilis* produced the earliest tools carved out of stones [De la Torre, 2011]. This record suggests a subtractive manufacturing technique, where material is removed from a single piece to transform it into another usable form. Other techniques emerged progressively, including joining, machining, casting, and transformation (deformation) of materials. However, these processes were carried out by hand at a small scale to produce household commodities.

With the addition of machines, the scale of manufacturing surged dramatically during the first Industrial Revolution, which began in European countries in the eighteenth century and later spread to other parts of the world [Deane, and Deane, 1979]. This phase mainly centered around technologies that extracted metals (cast iron) from their natural forms (ores) and produced final products using industrial equipment. The improvement in the quality and characteristics of materials for the new types of applications and continuous production via conveyor equipment led to the second Industrial Revolution in the late nineteenth and early twentieth century [Popkova et al., 2019]. With the invention of techniques such as the Bessemer process to produce steel and electromagnetic rotary devices to electrify the technology, this phase was a technological revolution [Mokyr, 1998]. The second half of the twentieth century was driven mostly by renewable sources of energy and the emergence of digital technologies, constituting the third Industrial Revolution [Popkova et al., 2019]. The progress and features of the Industrial Revolutions are illustrated in Figure 1.1.

Today, in the early decades of the twenty-first century, AM is an integral part of the ongoing fourth Industrial Revolution. This new technological mode of manufacturing offers broad flexibility for materials science, process development, and structural design. Using AM, intricate and complex parts can be manufactured with the desired quality, which would be extremely challenging using earlier subtractive (machining) and formative (casting) manufacturing modes. Moreover, the inherent nature of AM is leading manufacturing toward fully automated digital manufacturing through robotic equipment. In contrast to earlier manufacturing techniques, which steadily evolved and advanced in response to challenges experienced by earlier versions, AM is an entirely new technique. Therefore, AM may be considered not an evolution but

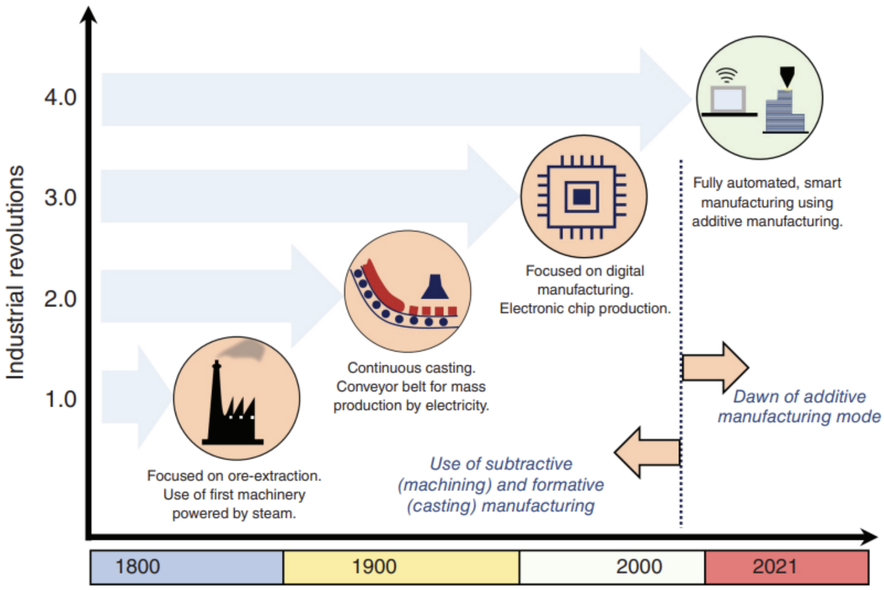


Figure 1.1 Timeline of the Industrial Revolutions.

the dawn of a new manufacturing era. Before diving deep into the technical features and current status of AM, we examine its intriguing fundamental nature in the following section.

1.2 Concept of AM

Although AM seems to be a new manufacturing mode in the twenty-first century, it existed silently as an auxiliary manufacturing technique for several decades in the previous century. The origin of all metallic AM types can be traced back and linked to welding and surface coating techniques. For instance, the friction stir AM technique evolved from friction stir welding and processing. These auxiliary manufacturing techniques were mature and only required a trigger to evolve into AM.

Eventually, AM was conceived as a fabrication method in the polymeric system in 1981 by Hideo Kodama, from Japan [Kodama, 1981]. He developed and demonstrated a prototype of the automatic fabrication of intricately shaped polymers, using layer-by-layer curing of the liquid and photo-hardening the polymer with ultraviolet rays. An intricate relief map of the mountain fabricated by Kodama using transparent polymer is presented in Figure 1.2. Charles Hull later advanced this technique and patented it as stereolithography (SLA) [Hull, 1984]. The concept of layer-upon-layer fabrication was then coupled with existing metallic welding and surface coating techniques, which led to the emergence of various metallic AM techniques.

The American Society for Testing and Materials (ASTM, an international standards organization primarily involved in developing and publishing voluntarily consensus technical standards for a broad range of materials, techniques, services, products, and systems), as per ISO/ASTM 52900:2015 (E), defines AM as "a process

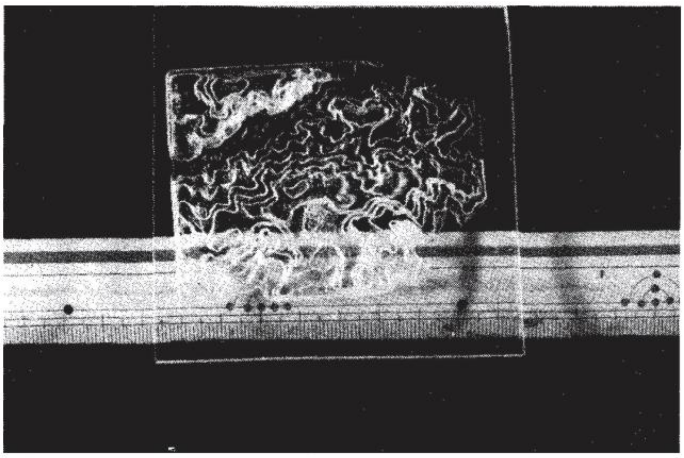


Figure 1.2 An early 3D fabrication via AM: a relief map of mountains using transparent polymer [Kodama, 1981].

Lakshmi Priya Muthe (Asst. Professor)

of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [ASTM Standard, 2015]. Any material in its pure continuum/bulk form is held together by atomic bonds; for example, metal/alloys are bonded by metallic bonds, polymers by covalent and Van der Waal bonds, ceramics by ionic or covalent bonds, and composites by any combinations of these bonds. AM involves joining the material using a distinct physical phenomenon associated with an energy source that leads to the formation of such primary atomic bonds. The energy source can be in any of multiple forms (laser beam, electron beam, ultrasound, or friction); it is transformed into heat or a combination of heat and mechanical energy that joins the material through a primary atomic bond. This joining takes place at a micro- to macro-dimensional scale, depending on the type of energy source and the size and shape of pieces of unjoined material. These pieces of material in a feedstock[1] can be in forms such as powder (spherical particles), wires, rods, bars, and sheets. A moving interaction zone of energy and feedstock forms a single consolidated or joined track/line of material. The successive joining of such tracks in a single plane forms a fabricated layer of a given material. Eventually, this layer-upon-layer consolidation results in a three-dimensional component, and hence the name *additive manufacturing* was coined.

AM allows the flexibility of fabricating any intricate shape that can be created with the aid of CAD (computer-aided design) software. A virtual model of the part to be fabricated is converted into an STL[2] file format, which presents the geometry in a form the AM machines can understand to build the physical part. The STL file allows the AM machine to read the path of the interaction zone of energy and feedstock in a given layer as well as the dimensions and the number of layers to fabricate the geometry encrypted in the STL file. Given this path and the geometric dimensions, the machine allows the user to choose processing parameters such as power and the speed of the moving energy source. The feedstock provides additional flexibility depending on the material type, shape, and size distribution.

The various components of AM provide tremendous flexibility, and their combination can lead to multiple possible fabrication outcomes. These features of AM are as follows:

- Type of energy source
- Physical phenomenon
- Type of material (metal, ceramic, polymer, composite)
- Type of feedstock (shape, size, and distribution)
- Means of distributing the feedstock to interact with the energy source (already laid feedstock and simultaneous deposition of energy and feedstock)
- Combination of processing parameters (power of energy source, speed and path of energy-feedstock interaction zone, and feedstock input)
- Composition of material (alloy development)

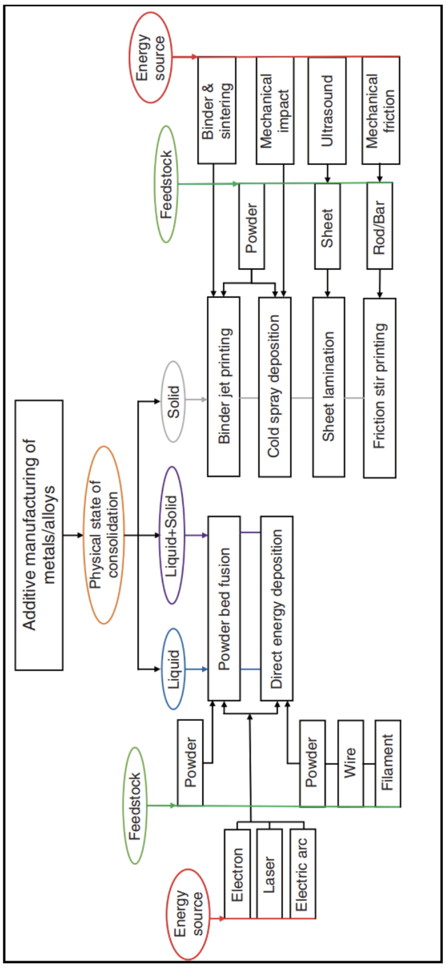


Figure 1.3 Classification of various AM techniques.

Categorization-These features also provide multiple bases for classifying different AM processes. As per ASTM/ISO standards, AM processes have the following seven categories:

- Binder jetting
- Directed energy deposition
- Material extrusion
- Material jetting
- Powder bed fusion
- Sheet lamination
- Vat polymerization

As mentioned earlier, the classification can have multiple forms based on various fundamental features. However, at this point, the reader should bear in mind the scope of the current book, which focuses on the AM of metals/alloys. There are multiple ways to classify the AM of metals and alloys, including classification based on the physical state of consolidation, energy source, feedstock, feedstock input, etc. Classification based on the physical phenomena governing the physical state of consolidation is useful from a materials science perspective. This is because the process-associated physical phenomena substantially control various properties of the AM-fabricated component. This classification based on the physical state of consolidation also considers the type of feedstock and the energy source, as shown in Figure 1.3.

1.3 Advantages over Conventional Manufacturing Techniques

Needless to say, the fundamental difference between AM and conventional manufacturing is due to their distinct processes and fabrication steps leading to the final component. Following are the key features that separate AM from conventional manufacturing.

- *Material efficiency*: The prime functional difference between these approaches arises from the substantially high material efficiency associated with the AM process, whereas conventional manufacturing results in more material loss through the subtractive approach in multiple steps.
- *Complex parts*: The layer-upon-layer approach of AM allows the fabrication of complex geometries, which are nearly impossible or highly challenging to fabricate using a conventional approach in a single processing step.
- *Assembly stage*: Traditionally, a moving system is required to manufacture in stages, first fabricating each component of the system and then assembling them. AM merges manufacturing and assembly into a single step, making a more efficient fabrication chain.
- *Customized printing*: AM provides the freedom to conceive any imaginable shape and make it a reality. In addition, customization through a digital interface allows

personalized products to be made for individuals. Conventional manufacturing does not provide such customization or the freedom to fabricate any shape.

- *Thermokinetic flexibility*: Most AM techniques provide process flexibility and, in turn, thermokinetic flexibility to derive the desired mechanical output from the process, whereas conventional techniques have limited options to vary the thermokinetics in a single step.

Presently, many AM techniques are available, and more are emerging. Among these AM techniques, laser-based AM (LAM) techniques are being widely explored, substantially impacting the research and industry sector. The laser is a rapidly steerable and effective energy source that provides high energy density in a micro-region. This allows microscale feedstock (powder and wire) to rapidly melt and solidify, leading to micro-volume consolidation of feedstock. Therefore, the type of energy source and feedstock used in LAM allow the rapid fabrication of complex geometry with the desired surface finish while providing increased efficiency in both cost and materials. LAM is also a single-step process that provides considerable flexibility through a broad processing window that can monitor the thermodynamic state, morphology, and distribution of the phases as well as the crystallographic and physical texture (surface roughness) of the printed component. The most commonly employed and investigated LAM techniques for fabricating metal/alloys are laser powder bed fusion (LPBF) and laser-based directed energy deposition (LDED). The fundamental principles and operation of these techniques are introduced in the following section.

1.4 Laser-Based AM

Recent advances in design and operation have led to numerous LAM techniques. They vary mostly based on the type, size, and delivery of the feedstock to the laser source. Despite these variations, a few physical phenomena associated with the process can be identified. Thus, LAM techniques can be classified as LPBF and LDED processes.

1.4.1 Laser-Based Directed Energy Deposition

LDED is also referred to as the direct metal deposition (DMD) technique, which evolved from the laser cladding technique in the late twentieth century [Koch, and Mazumder, 1993, Mazumder et al., 1997]. In LDED, the feedstock (usually a powder or wire) is delivered through a nozzle directly to the focal plane of the laser beam, as depicted in Figure 1.4. The powder is carried from the powder feeder via carrier gas, often coaxially focused at the focal region of the laser beam. As the name suggests, the purpose of the carrier gas, such as argon or nitrogen, is to carry the powder to its destination with sufficient momentum to hit the laser beam focal plane. Under the high power density of the laser beam at the focal plane, the powder instantly melts and falls onto the substrate, where it solidifies. This follows the fabrication of a layer through metal deposition via multiple laser tracks, and successive layer-upon-layer

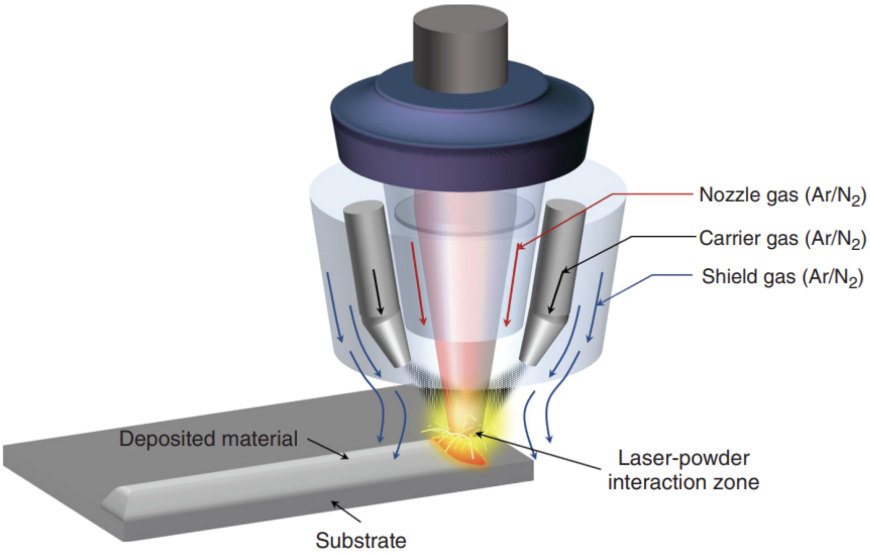


Figure 1.4 Schematic representation of the LDED operation using powder feedstock.

fabrication allows the formation of a 3D component. In most LDED machines, the substrate attached to the stage has three-axis (X, Y, and Z) freedom, while the laser head with the coaxial powder feeder remains stationary. The relative motion between the laser heat source and the stage leads to multiple laser tracks, and the layer thickness in the build direction is monitored by the STL file fed to the LDED machine.

The STL file allows the AM machine to monitor the three-axis stage movement with respect to the laser head. Nozzle gas (Ar/N_2) is often supplied to prevent damage to the laser optics caused by spatter ejected in the feedstock-laser interaction zone at the focal plane region. In addition, shield gas (Ar/N_2) prevents the feedstock-laser interaction zone and melt pool[3] region from oxidation. For most non-reacting (not easily oxidized) metals/alloys, shield gas is sufficient to prevent oxidation. However, such an assembly may not be able to prevent the oxidation of metals that have a high affinity for oxygen, such as Ti and Al. The fabrication of these alloys is often carried out in a closed chamber where oxygen activity can be set to as low as 50 ppm to reduce oxidation. Laser engineered net shaping (LENS) machines by Optomec provide a sealed assembly to fabricate oxidation-prone alloys via LDED.

The type of feedstock (powder or wire) can be varied in size depending on the delivery system to the laser beam source and laser characteristics such as wavelength, intensity distribution, beam diameter, etc. Such variations in the laser beam and feedstock (size and type) can lead to different dynamics, while the physical phenomena remain the same. Before the ASTM/ISO categorization

3 The melt pool is the melted region that results from heating by any heat source, surrounded by the solid material.

of this technique as a directed energy deposition, several names were introduced by researchers and companies trying to develop closed-loop machines. These names included LENS [Atwood et al., 1998], laser metal forming (LMF) [Gäumann et al., 2001], laser consolidation (LC) [Xue et al., 2000], laser direct casting (LDC) [Hand et al., 2000], automated laser powder deposition (ALPD) [Toyserkani, and Khajepour, 2006], shape deposition manufacturing (SDM) [Fessler et al., 1996], and so on. Although these processes had different names, their underlying principle was the same.

1.4.1.1 Machine Design

Modern evolving LDED machines have multiple degrees of freedom with the development of machine design; for instance, a five-axis stage system attached to the substrate. In contrast to the stationary (three-axis) stage, the five-axis system allows rotation of the stage; thus, support structures[4] are not required during fabrication [Liu et al., 2017]. In addition to stage rotation, the moving laser further augments the degree of freedom during fabrication, thereby allowing control over physical texture (surface roughness) and complexity of the component. In the LDED machine, the feedstock can be fed through either a coaxial nozzle or an off-axis lateral nozzle focusing at the laser beam focal plane. A powder-fed LDED machine can have single or multiple nozzles to eject the powder at the focal plane of the laser beam [Mazzucato et al., 2017]. Multiple nozzles with the appropriate use of inert gas lead to improved deposition efficiency by reducing the amount of unmelted powder, as it does not enter the laser-powder interaction zone and falls in the vicinity of the fabricating component. Moreover, multiple nozzles can eject different metal powders at different rates, allowing the fabrication of functionally graded components [Mahamood, and Akinlabi, 2015]. Furthermore, the substrate in LDED can be preheated to change the thermokinetics, especially the thermal gradients associated with the process [Corbin et al., 2018].

1.4.1.2 Process Parameters

Laser. In LDED, the laser is the source of energy used for the consolidation/joining (melting followed by solidification) of the feedstock. Different types of lasers can be employed in LDED fabrication, including Nd:YAG, CO_2, excimer, and fiber lasers. A Yb-doped fiber laser is most commonly employed after solid-state Nd:YAG laser in laser-based AM. Yb-fiber laser, usually pumped by the diodes in a 950-980 nm wavelength, can have an output wavelength in the near-infrared region ranging from 1030 to 1090 nm in a continuous wave or pulse wave mode. Every metal and alloy has a distinct light absorption coefficient at a given wavelength of light, determining the actual laser energy absorbed for melting. In LDED, laser parameters such as the laser power, laser beam diameter, laser intensity distribution (Gaussian or top-hat distribution), speed at which the laser beam moves relative to the substrate, and moving path can be easily varied and optimized to achieve the desired set of characteristics

4 Support structures are often incorporated in the STL file. However, they are not part of the actual 3D component. Support structures are often printed to the main component during fabrication to prevent part deformation and to ensure that it is attached to the substrate.

of a given material to be fabricated. The diameter of laser beam in LDED is often in the range of 0.5 to 5 mm, while the laser/stage moving speed varies from 5 to 20 mm/s. The laser power employed in LDED is usually high, in the range of 300 to 4000 W. Such a combination of process parameters yields a very high deposition rate in LDED.

Feedstock. Powder is most often used as a feedstock in LDED machines as it can fabricate small complex parts with high geometrical accuracy due to its micron-level size (40 to 120 μm). Such micron-sized powder allows the fabrication of thinner parts and simultaneously improves surface roughness. In addition, as discussed earlier, functionally graded material can be explored by feeding powder through multiple nozzles. However, this feedstock has several downsides, such as the high cost of powder preparation, health hazards, and significant loss of material during fabrication.

On the other hand, wire as a feedstock provides highly efficient material fabrication. Moreover, the production of wire feedstock is a simple, cleaner, cheaper process, and handling the wire is not hazardous. The wire is fed through the coaxial nozzle or the off-axis lateral nozzle, focusing at the laser beam focal plane. The diameter of the wire used for LDED feedstock ranges from 1 to 1.5 mm, which restricts the fabrication of thinner components, and the surface roughness is comparatively higher than powder-fed LDED [Rodrigues et al., 2020, Fu et al., 2021, Froend et al., 2018]. In contrast to powder feedstock, wire-fed LDED can be explored for underwater fabrication [Fu et al., 2021]. Nevertheless, wire-fed LDED is widely studied for its unique processing features.

The machine design features and process parameters associated with LDED provide tremendous flexibility to govern the thermokinetics, thermomechanics, and fluid dynamics of the process. These process-inherent physical phenomena affect microstructures; phase transformation; one- and two-dimensional crystallographic defects such as dislocations, twins, and stacking faults; grain/phase interfaces; and three-dimensional defects, including cracks and pores. These aspects, in turn, impact the mechanical and surface properties of the material. Thus, it is essential to know the degree of flexibility provided by the given LAM machine design and process parameters. These machine design and process parameters are detailed in Figure 1.5. The following chapters discuss the effect of machine design and process parameters on the microstructural characteristics listed previously with the aid of computational simulations.

1.4.2 Laser Powder Bed Fusion

LPBF is a widely studied LAM technique. As the name suggests, the feedstock in LPBF is limited to powder, mostly in the range of 10 to 45 μm. Unlike in the LDED technique, the feedstock (powder) is first spread onto the substrate as a thin layer that ranges from 10 to 100 μm. The laser selectively scans this layer. At the location scanned by the laser, the powder instantly melts and solidifies, thereby consolidating the scanned region. The substrate moves down within a hollow cylinder to occupy the powder for subsequent layer deposition. The unmelted powder surrounding the fused region provides support for the subsequent layer. When another layer is spread

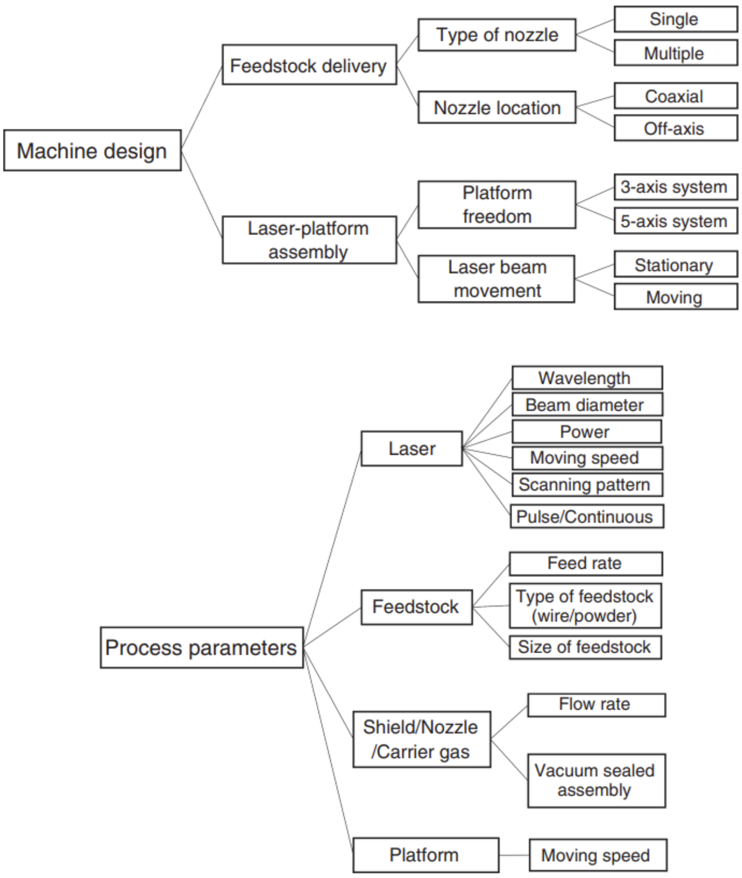


Figure 1.5 Machine design and process parameters associated with LAM.

onto a previously fused layer, the new layer is again scanned by the laser. The process continues until the desired component is built. The LPBF process is illustrated in Figure 1.6.

1.4.2.1 Process Parameters

The laser beam diameter in LPBF can vary from 30 to 600 μm, while the laser scanning speed can be as high as 200 to 4000 mm/s. The laser power varies in a range of 100 to 500 W. The resulting volume of the melt pool generated during LPBF is usually smaller than that of LDED. Therefore, the deposition rate in LPBF is often lower than that of LDED. However, LPBF produces a superior surface finish for the printed component than LDED. The smaller volume of the melt pool produced in LPBF also allows the fabrication of components with greater intricacy at the micron level. All of these process parameter differences in LDED and LPBF are summarized in Table 1.1.

The machine and process design in LPBF do not allow the powder stage to have any axis of freedom, unlike the three-axis and five-axis freedom in the LDED process.

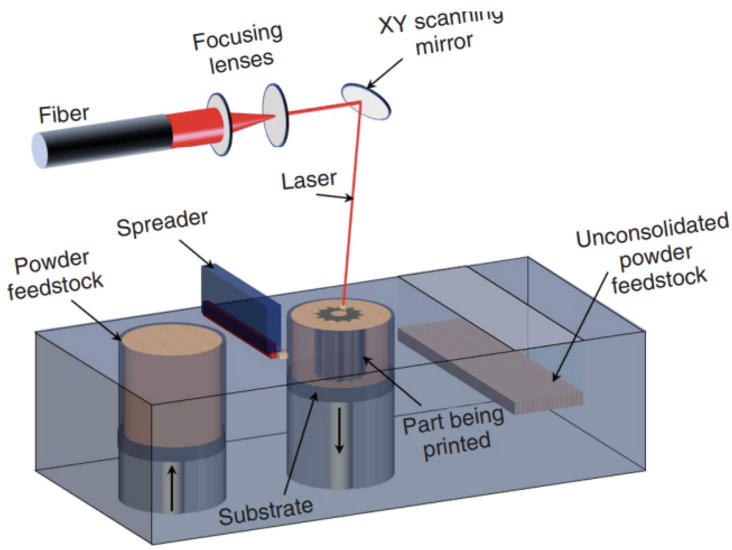


Figure 1.6 Schematic representation of a laser powder bed fusion process.

Table 1.1 Comparison of the processing parameters involved in the LDED and LPBF processes.

Parameters	LDED	LPBF
Laser power (W)	300–4000	100–500
Scanning speed (mm/s)	5–20	200–4000
Laser beam diameter (μm)	500–5000	30–600
Deposition rate	High	low
Surface finish	Moderate	Superior
Feedstock	Wire, powder	powder
Powder size (μm)	45–120	10–45

Source: [Bian et al., 2017]

The stage freedom in LDED allows variable thermokinetics in different directions. Nevertheless, a similar effect can be achieved in LPBF by varying the orientation of the component to be printed with respect to the build direction. For instance, a cylindrical component can be printed in different orientations with respect to the constant build direction, as illustrated in Figure 1.7. The printing component can be oriented to allow heat extraction in the desired direction, which, in turn, governs the crystallographic texture within the component.

Additionally, the powder bed stage in LPBF can be heated to any temperature at the beginning or any time during fabrication, allowing superior control over the thermokinetics of the process. The powder bed is often heated to reduce the thermal gradient, thereby reducing induced thermal stresses to avoid the formation of thermal cracks. Heating during the powder bed stage provides

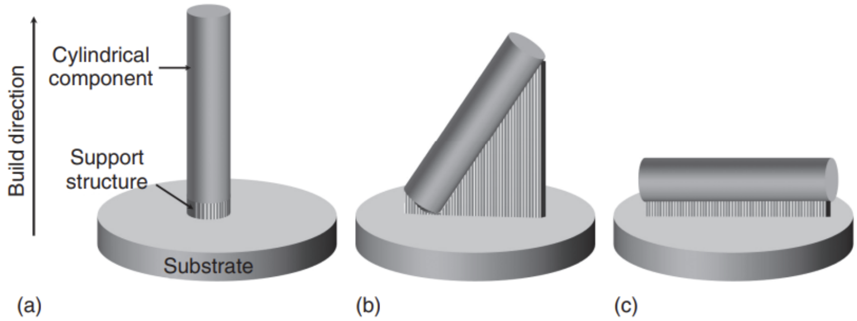


Figure 1.7 Different ways of printing a cylindrical component via laser powder bed fusion.

tremendous thermokinetic control, which, in turn, influences the thermodynamic state (equilibrium/non-equilibrium) of the phases formed during the process.

1.4.3 Estimation of Energy Input in LAM Processes

When optimizing fabricated parts for various properties, recognizing the energy input of the given LAM process is important. Energy input must consider the laser processing parameters to yield the energy density needed to fabricate the material. In the LDED process, the laser energy input is presented in multiple forms. One of them is the power density, also known as irradiance (W/m^2), which can be obtained as

$$\textit{Power Density or Irradiance} = \frac{P}{A} \tag{1.1}$$

where P is the laser power (W) and A is the cross sectional area (m^2) of the laser beam exposed to the material.

Residence time (t_r) is another helpful parameter considered in multiple energy input representations. It is simply the duration for which a laser beam is exposed to a single location while scanning the sample. This can be calculated using the laser beam diameter (D) and laser scanning velocity (V_s):

$$t_r = \frac{D}{V_s} \tag{1.2}$$

Another way to represent energy input is laser fluence (F), which is energy density. Laser energy fluence can also be defined as a time-integrated energy flux. Therefore, the residence time is helpful to obtain the energy density/laser fluence:

$$F = \frac{P \times t_r}{A} \tag{1.3}$$

In addition, linear energy density (LED) (in J/m) is also considered as a parameter during property optimization and can be obtained as

$$LED = \frac{P}{V_s} \tag{1.4}$$

For the LPBF process, while the previous energy input parameters are appropriate, most researchers use volumetric energy density as the energy input parameter, considering the layer thickness (d) and hatch spacing (h). This volumetric energy density (VED) is calculated as follows:

$$VED = \frac{P}{V_s \times h \times d} \tag{1.5}$$

However, the energy parameter *VED* bears some limitations, as identified by several studies [Scipioni Bertoli et al., 2017, Caiazzo et al., 2020, Prashanth et al., 2017, Ferro et al., 2020]. Some of these studies have recognized another way to represent VED by following Eq. 1.6:

$$VED = \frac{P}{V_s \times h \times D} \tag{1.6}$$

While several energy parameter representations exist, none can represent the kinetics and physics associated with the process. Each of these parameters is significant in optimizing and designing various features of the components and their characteristics.

LAM processes assisted by the pulse wave (PW) laser beam entail additional parameters as their energy transfer mechanism differs from that of a continuous-wave laser beam. A pulse laser provides considerable flexibility with its additional parameters. These parameters can be conveniently understood through the energy transfer mechanism of the pulse laser shown in Figure 1.8. In contrast to a continuous-wave laser, which delivers constant power P as indicated by the dotted red line, the pulse laser transfers energy in controllable intervals (Figure 1.8). This involves the pulse on time (t_{on}) when it delivers the power and the pulse off time (t_{off}) when power = 0. Thus, the pulse energy E_{pulse} is given as

$$E_{pulse} = \int_0^{t_{on}} P(t)dt \tag{1.7}$$

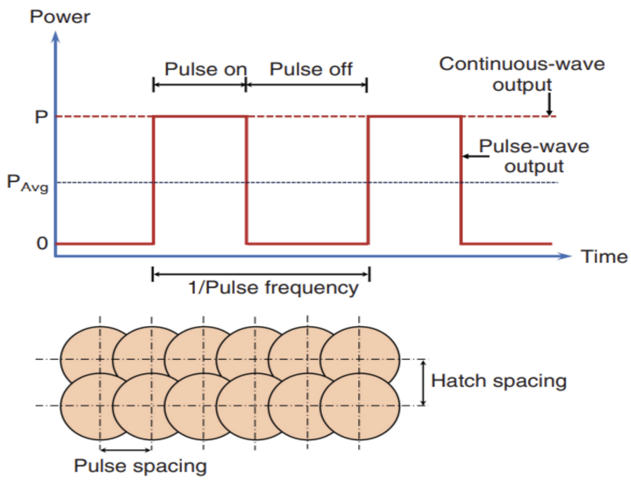


Figure 1.8 schematic of the temporal and spatial characteristics of pulses.

The pulse frequency or pulse repetition rate is the parameter that is often used during pulsing operation and is expressed as

$$Pulse\ Frequency = \frac{1}{t_{on} + t_{off}} \tag{1.8}$$

The duty cycle (δ_d) is another important parameter employed during the PW-LAM process. It is presented as

$$\delta_d = \frac{t_{on}}{t_{on} + t_{off}} \tag{1.9}$$

With pulse frequency, one can obtain the average power delivered by the pulse laser (indicated by a black dotted line in Figure 1.8) as

$$P_{avg} = E_{pulse} \times Pulse\ Frequency \tag{1.10}$$

In pulse laser operation, a single laser track exposure consists of multiple overlapped pulses. Thus, pulse overlapping occurs based on the pulse spacing, i.e. the distance between the centers of two consecutive pulses. The distance between the centers of tracks of pulses is the hatch spacing (h), shown in Figure 1.8. All of these parameters, such as power, pulse frequency, duty cycle, and pulse spacing, are unique to pulse laser operation and can be varied. During pulse laser operation, the scanning speed becomes irrelevant in terms of its direct correlation with any solidification parameter. In contrast, the same parameter is of significant interest when operated in continuous-wave mode as it is directly related to the solidification rate. Nevertheless, the average scanning speed in pulse laser operation can be obtained as

$$V_{avg} = \frac{Pulse\ Spacing}{t_{on} + t_{off}} \tag{1.11}$$

1.4.4 Multi-Step LAM Techniques

The LAM techniques (LDED and LPBF) are often regarded as single-step processes because they involve manufacturing in a single operation considering the intended shape and size of the product [ASTM Standard, 2015]. Some LAM techniques involve multi-step processes, as fabricating the final product may require two or more steps. These multi-step LAM techniques involve forming the green (unconsolidated) shape of the product followed by consolidation through any physical phenomena to form the metallurgical bond.

Selective laser sintering (SLS), a multi-step LAM technique, works on the same principle mentioned earlier [Bian et al., 2017]. The formation of the green component in SLS can involve liquid phase sintering or partial melting. The former uses a mixture of sacrificial polymeric binder (in powder form) and metal powder particles. Upon laser exposure, the binder melts and spreads over the powdered metal particles and holds them with a secondary bond as it solidifies while cooling. As the metal particles do not melt, sintering of the particles occurs while the solidified binder holds them with the secondary bond. On the other hand, during partial melting, the powdered metal particles are partially melted, and their surfaces are fused upon solidification. The green part fabricated via both the processes has 50% or greater porosity. The green part formed by the binder undergoes heating and isothermal heat treatment at a temperature high enough to vaporize the binder, known as the debinding process, to create the brown part. This follows further heat treatment of the part to increase the densification by sintering. Debinding is not required for a green part processed via partial melting of particles by laser. However, the SLS process cannot produce a fully dense part, as the density is limited to 80%. Additional steps in the SLS process, such as hot isostatic pressing (HIP), can further increase the density of the part [Bian et al., 2017].

Based on the description of the SLS and SLS/HIP processes, it is apparent that they do not provide thermokinetic flexibility via processing, which is the prime feature of LDED and LPBF. Moreover, due to its cost, the SLS technique does not fit in among other, cost-efficient rapid prototyping techniques. In addition to being porous and brittle, SLS-fabricated components are often left with thermal distortion, warping, and shrinkage. Consequently, obtaining a near-net-shape is a challenge. The capital cost associated with the machine and its maintenance makes the process expensive and inefficient. Despite the multiple disadvantages, SLS has been gradually improving due to recent innovation and development. However, it is still noteworthy that the SLS process inherently does not allow the thermokinetic flexibility to achieve the desired microstructure. SLS thermokinetics are more relatable to those achieved during traditional isothermal heat treatment.

With the brief introduction to AM and LAM presented in this chapter, one can recognize the true potential of AM over the existing conventional manufacturing techniques. The versatility of the LAM technique through machine design, process parameters, and feedstocks allows the accurate fabrication of any conceivable geometry. Although understanding of LAM techniques viewed through the lens of material science is increasing, these techniques are still in their infancy. Computational material science has played a pivotal role in further expediting this understanding. Hence, Chapter 2 of this book is dedicated to a detailed understanding of computational material science.