Manufacturing Science

Unit-I

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Lecture-01

Contents

- Introduction to Manufacturing Processes
- Importance of Manufacturing
- Course contents and objective
- History of Manufacturing

Introduction to Manufacturing Processes

- **Manufacturing is concerned with making products.**
- **Manufacturing (Latin word) : Manu + factus: Made by hands.**
- **Present perspective: Involves making products from raw material by various processes, machinery, & operations following a well organized plan for each activity required.**

❖ What is Value Addition?

- ✓ **Price of clay: Rs. 1/kg**
- ✓ **Price of a dinner (ceramic) plate –Rs. 50/ piece (200 g)**
- ✓ **Clay has gone a number of changes to be as a dinner plate**
- ✓ **See the objects around you :fan , chair, pen, etc.**

⟹ **had different shapes at one time.**

⟹ **not found in nature as they appear.**

⟹ **most of these products/objects(made of a combination of several parts made of a variety of materials)**

Manufacturing System

- Manufacturing as a term for making goods or articles reveals nothing about the complexity of the product. In fact, manufacturing involves a series of operations and activities such as product design and development, material selection, process planning, inventory control, quality assurance and marketing.

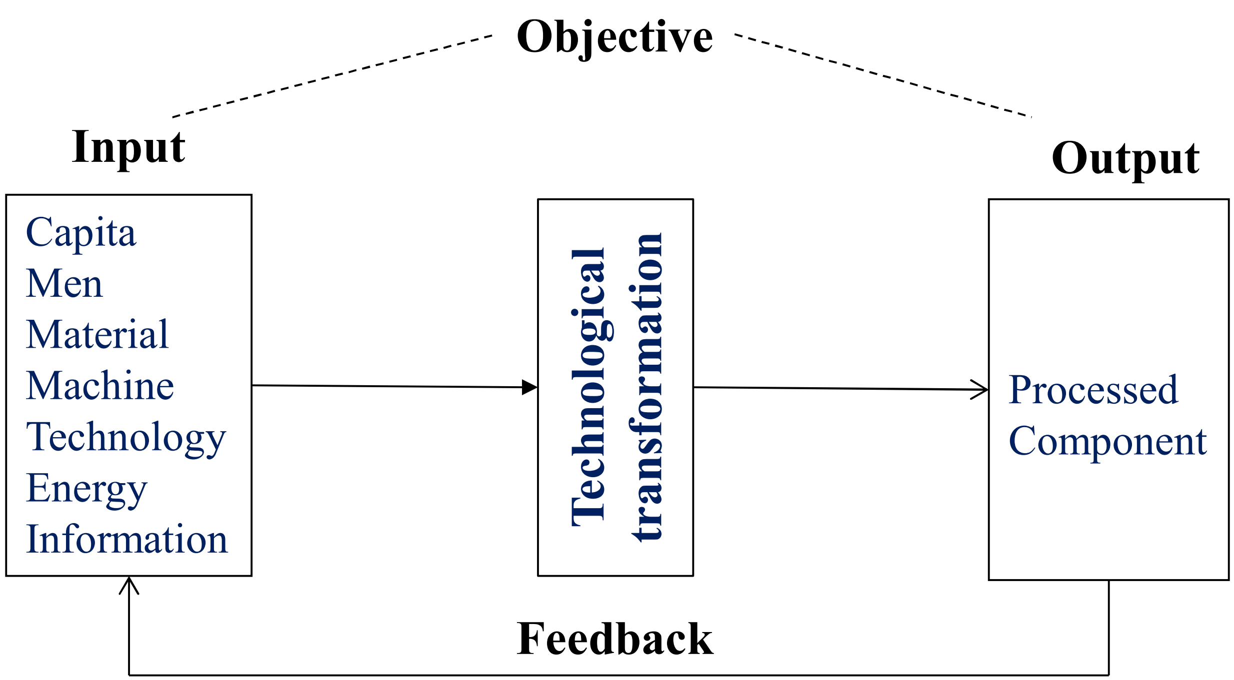


Fig. Manufacturing as an input-output system

MANUFACTURING: IMPORTANCE

- Manufacturing is critical to a country's economic welfare and standard of living because standard of living in any society is determined, primarily by goods and services that are available to its people.
- Converting materials from one form to another adds value to them.

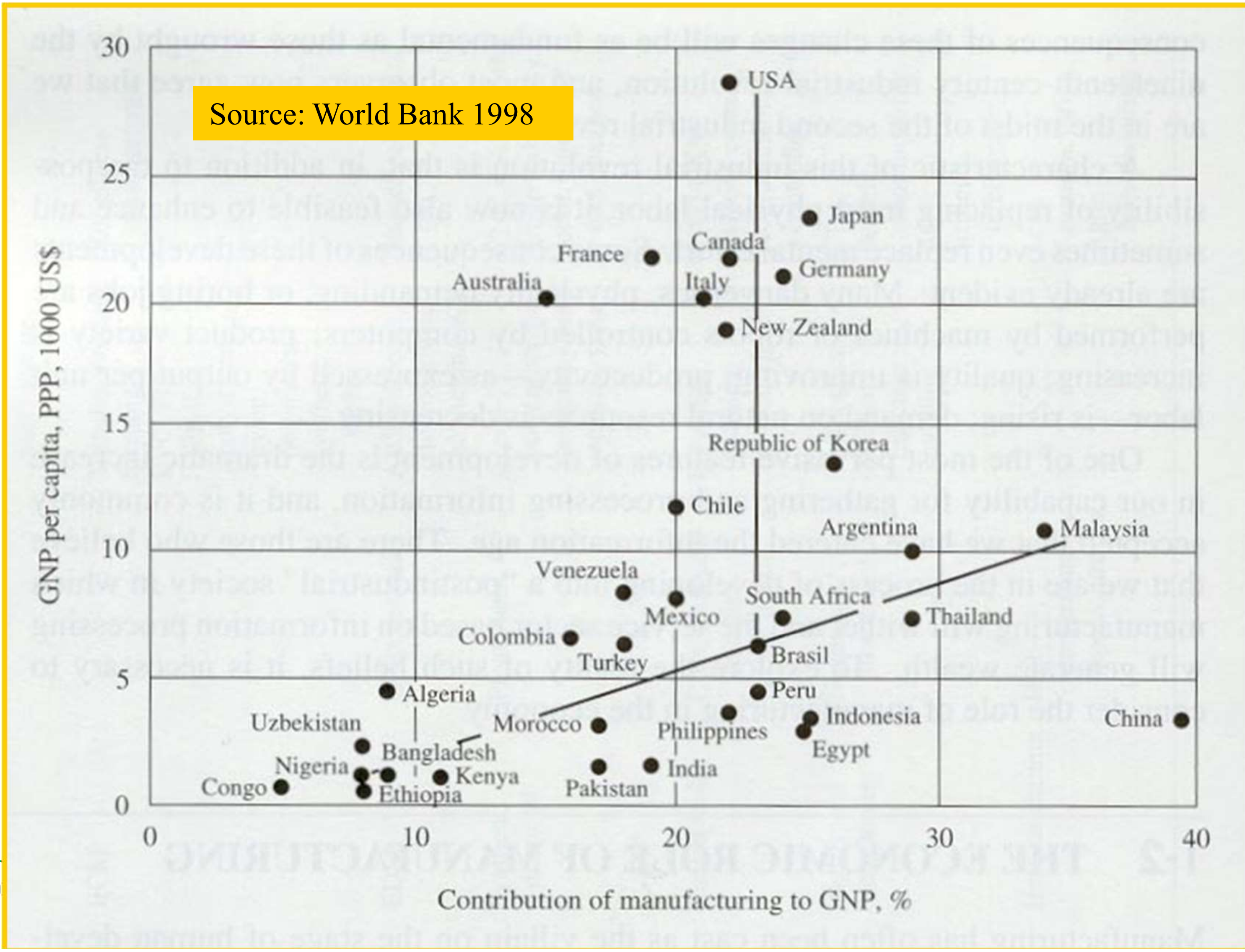
  ⟹ Discrete product and continuous product

metal ore ⟹ metal ⟹ wire ⟹ a paper clip
similarly other products ⟹ hangers, forks ..

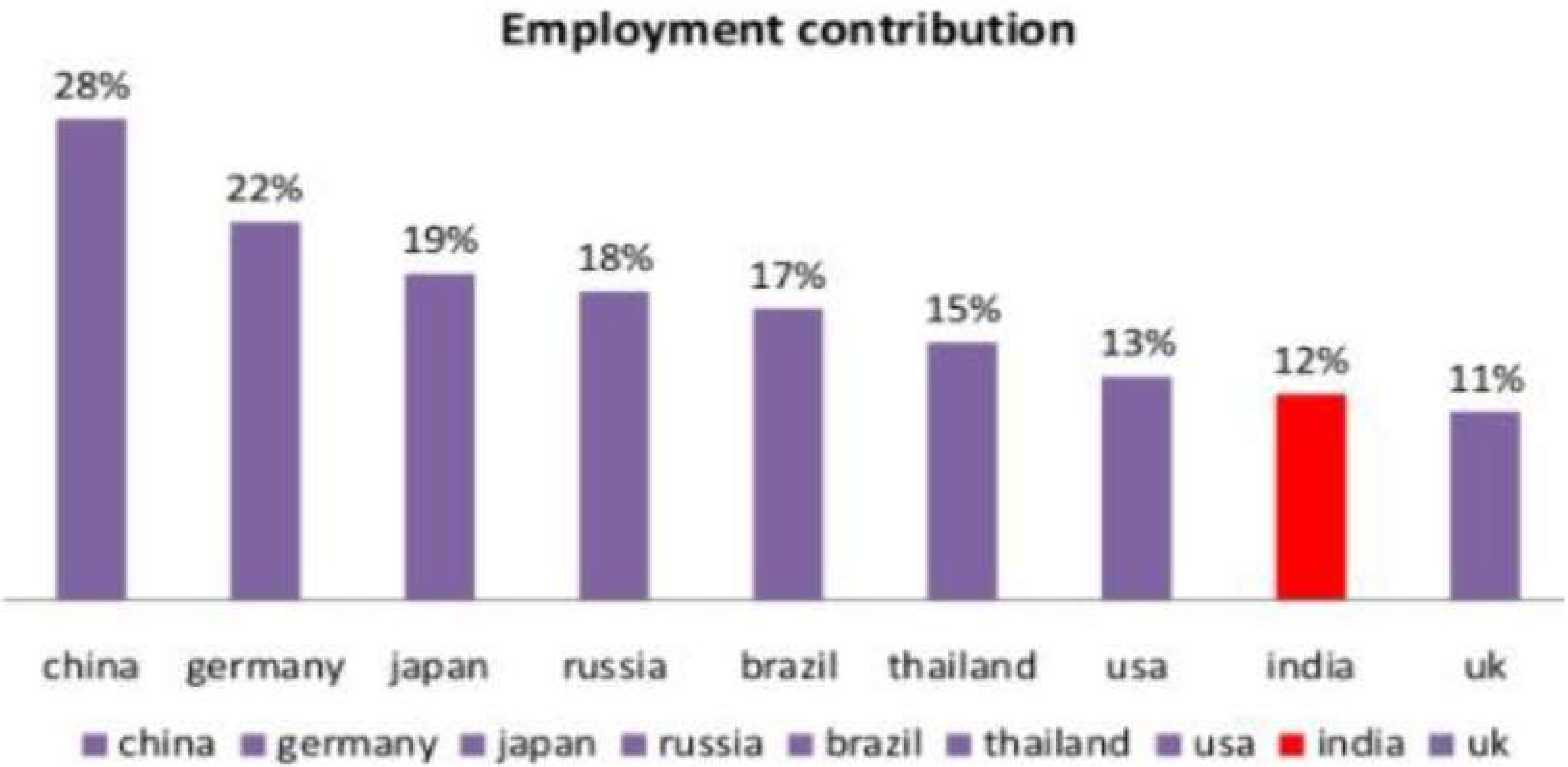
- Some objects made of a combination of several parts, made from a variety of materials (ex-bicycle, computer, car:15000 parts etc)
- Manufacturing is a complex activity that involves : people, machinery, tooling with various levels of automation (computers, robots, AGV etc) etc.

Contribution of Manufacturing to GDP

- Manufacturing Companies contribute significantly GDP and Employment.
- Manufacturing is an important factors in all developed countries.



Manufacturing and Employment Relationship



Course Contents

Unit-I

Introduction

Importance of manufacturing, economic & technological considerations in manufacturing, classification of manufacturing processes, materials & manufacturing processes for common items

Metal forming processes-1

Elastic & plastic deformation. Tresca's & Von Mises' Yield's criteria. Hot & cold working processes. Analysis of forging process for load estimation with sliding friction, sticking friction and mixed condition for slab and disc. Work required for forging. Hand, power & drop Forging. Analysis of Rolling Process. Condition for rolling force and power in rolling. Rolling mills & rolled-sections

Unit-II

Metal forming processes-11

Analysis of Wire/strip drawing and maximum-reduction, Tube drawing, Extrusion and its application. Design, lubrication and defects in metal forming processes.

Sheet metal working:

Presses and their classification Die & punch assembly and press work methods and processes. Cutting/Punching mechanism, Blanking & piercing. Compound & progressive dies. Flat-face & Inclined-face punches and load calculation. Analysis of forming process like cup/deep drawing. Bending & spring-back.

Unconventional metal forming processes

Unconventional metal forming or High Energy Rate Forming (HERF) processes — explosive forming, electromagnetic, electro-hydraulic forming.

Unit-III

Welding: Survey of welding and allied processes. Gas welding and cutting, process and equipment. Arc welding: Power sources and consumables. TIG & MIG processes and their parameters. Resistance welding - spot, seam projection etc. Other welding processes — atomic hydrogen, submerged arc, electroslag, friction. Soldering & Brazing. Thermodynamic and Metallurgical aspects in welding. Shrinkage/residual stress in welds. Defects in welds and their remedies. Weld decay in Heat affected zone (HAZ).

Unit-IV

Casting (Foundry)

Basic principle & survey of casting processes. Types of patterns and allowances. Types and properties of moulding sand, sand testing. Design considerations for elements of mould—Gate, Riser, Runner & Core. Solidification of casting. Sand casting— defects, remedies. Cupola furnace. Other casting processes— Die Casting, Centrifugal casting, Investment casting, Continuous casting and CO_2 casting etc.

Recommended Books

- Manufacturing Science -Ghosh and Mallik (EWP)
- Manufacturing Engineering & Technology- Kalpakjian (Pearson)
- Materials and Manufacturing by Paul Degarmo. (TMH)
- Manufacturing technology – Foundry, Forming and Welding- P. N. Rao(TMH).
- Physical Metallurgy- George E. Dieter (TMH)
- Manufacturing Processes Vol I – H. S. Shan (Pearson)
- Fundamental of Modern Manufacturing – M. P. Groover (PHI)
- Production Engineering Science - P.C. Pandey (Standard publisher)
- Production Technology - R.K. Jain (Khanna publication)
- Production Engineering – P. C. Sharma (S. Chand)
- Workshop Technology Vol1-B. S. Raghubanshi (Dhanpat Rai and Sons)

Course objectives

- Able to understand the fundamentals and analysis of Forging and Rolling processes.
- Knowledge of wire drawing, extrusion, sheet metal working, and unconventional metal forming process such as explosive forming and electromagnetic forming.
- Know about principles, working and applications of various types of welding processes and their thermodynamic and metallurgical aspects.
- Able to understand pattern allowances, moulding sand properties, elements of mould and casting processes.

Historical Development of Manufacturing Processes

Year	Material	Casting	Forming	Machining	Welding
4000 BC	Gold Silver Copper	Clay mould	Cold forging	Stone tools	
2500 BC	Bronze	Lost wax process	Sheet metal forming	Drilling	Brazing
1000 BC	Iron		Hot forging	Iron saw	Forge welding
0 AD	Brass			Wood Turning Stone grinding	

Contd.

Year	Material	Casting	Forming	Machining	Welding
1000 AD			Wire drawing		
1400 AD		Sand casting	Water hammer	Pole lathe	
1600 AD		Permanent mould	Lead rolling	Wheel lathe	
1800 AD	Carbon steel		Steel rolling Deep drawing Lead extrusion	Turning Boring Screw cutting	

Year	Material	Casting	Forming	Machining	Welding
1900 AD	HSS Al oxide		Tube extrusion	Electric drive, Gear cutting, Hobbing,	Gas welding, Arc welding
1920 AD	WC	Die casting		Special purpose machines	Coated electrodes
1940 AD	Plastics		Hot extrusion		
1950 AD			Cold extrusion	EDM, ECM, USM	TIG, MIG
1980 AD				Robots, CAM, FMS	

Manufacturing Today

- Automatic Storage and Retrieval System (ASRS)

  Moves material vertically or horizontally between storage compartment and transfer station or within a process

- Automated Guided Vehicles (AGV)

  Computer-controlled system using pallets to transport work pieces to NC machine tools and other equipment in a flexible manufacturing system

- Artificial Intelligence (AI)

  Machines learn from experience

  Knowledge used to problem solve

- Computer Integrated Manufacturing (CIM)

  Company-wide management philosophy for planning, integration, and implementation of automation

- Flexible Manufacturing Systems (FMS)
- Rapid Prototyping
- 3D Printing

References

- Manufacturing Engineering & Technology- Kalpakjian (Pearson)
- Manufacturing Processes Vol I – H. S. Shan (Pearson)
- Fundamental of Manufacturing Processes- G. K. Lal (Narosa)


THANK YOU

Classification of Manufacturing Processes
Lecture-02

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Contents

Broad classification of Manufacturing Processes

- **Additive Processes**
- **Subtractive Processes**
- **Formative Processes**
- **Joining and Assembly Processes**
- **Heat treatment or Bulk property enhancing processes**
- **Finishing and Surface Treatment Processes**

Manufacturing Processes

- The main activity in the manufacturing system is to convert the raw material/ unfinished product into finished products. This can be achieved using three principal types of manufacturing.

- Process type manufacturing : involves continuous flow of materials through a series of process steps to obtain a finished products like chemical.

- Fabrication type manufacturing: involves manufacturing of individual parts or components by series of operations such as rolling, machining and welding

- Assembly type manufacturing: parts of components are put together to get a complete product such as a machine

Classification of Manufacturing Processes

❖ Primary Forming Processes (Additive Or Accretion)

- Casting and Moulding Processes
- Powder Metallurgy, Rapid Prototyping

❖ Deforming Processes (Formatives)

- Hot Working
- Cold Working (Forging, Rolling, Wire Drawing, etc.)

❖ Material Removal Processes (Subtractive)

- Conventional (Turning, Milling, Etc.)
- Advanced Machining Processes (ECM, EDM, LBM, etc.)

❖ Joining and Assembly Processes

❖ Welding, Revetting, Brazing, Soldering, etc.

Classification of Manufacturing Processes

❖ Finishing and Surface Treatment Processes

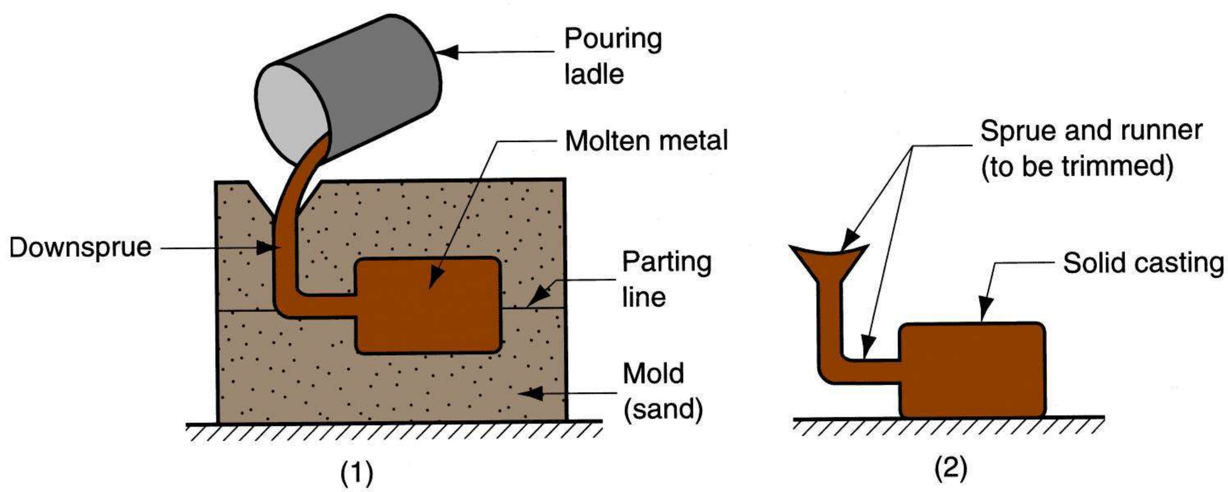
- Burr Removal (Deburring)
- Mechanical Cleaning and Finishing
- Chemical Cleaning
- Coating
- Vaporized Metal Coating

❖ Heat Treatment or Bulk Property Enhancing Processes

- Hardening
- Ductility, Toughness And Machinability
- Strengthening

Casting and Moulding Processes ⟹ Solidification

❖ Solidification process: starting material is heated sufficiently to transform it to the liquid state. With the material (metals, plastics and ceramic glasses) in the liquid state, it can be poured into a mold cavity and allowed to solidify , thus taking a solid shape that is the same as the cavity.



Various types of Casting Processes

- Sand Mould Casting
- Shell Casting
- Investment Casting
- Die Casting
- Centrifugal Casting
- Continuous Casting

………

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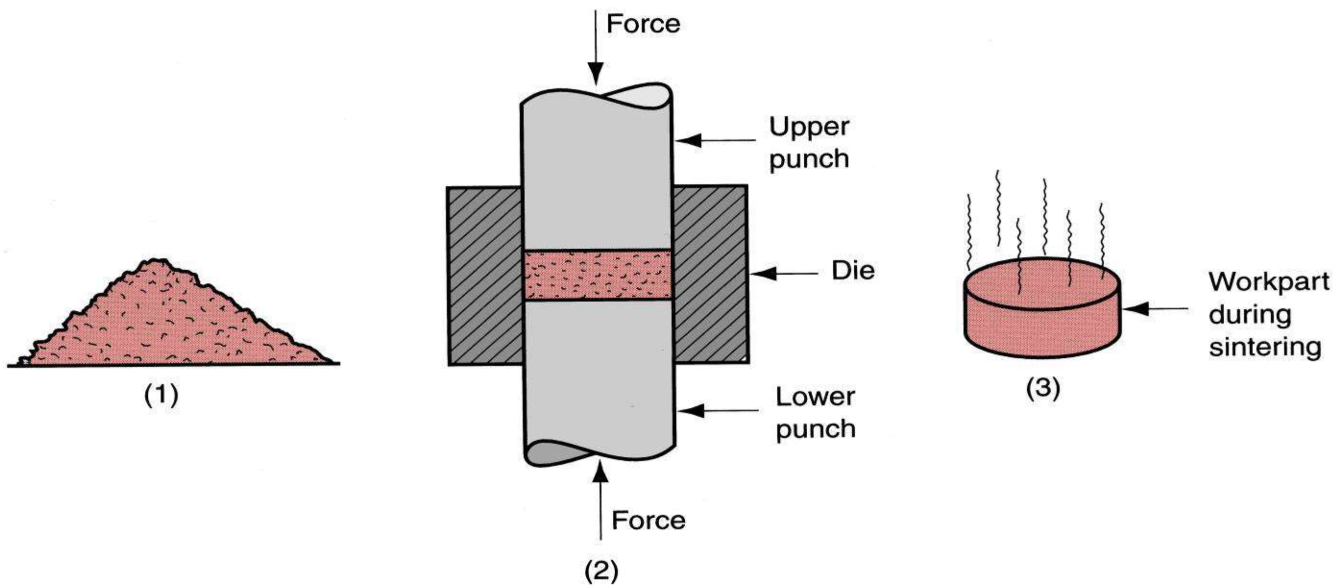
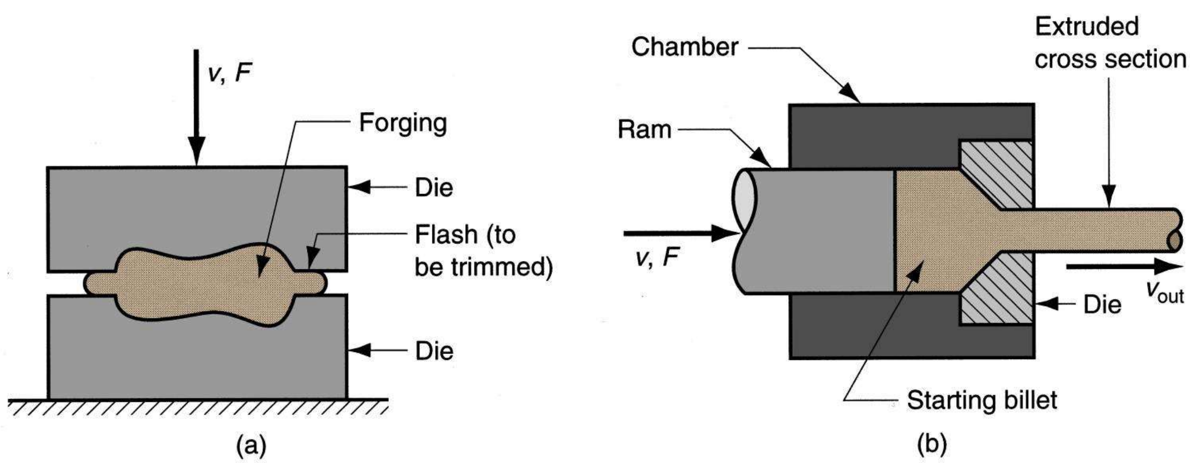
Powder Metallurgy-Particulate Processes

- Particulate processing: Starting materials are powders of metals or ceramics. The powders are then pressed and sintered. The powders are first squeezed into a die cavity under a high pressure and then heated to bond the individual particles together.



Deforming Processes :Formatives

- Metal forming process does not incorporate metal removing.
- The starting workpart is shaped by application of pressure/ stress, forces like compression or tension or shear or the combination of both that exceed the yield strength of the material.(Metal
- forming always include plastic deformation.)
- By applying these forces permanent deformation of the metal is achieved. These processes are also known as mechanical working processes.
- These mechanical working processes are classified into two categories, one – hot working processes and two-cold working processes.



Various types of Forming Operations

- Conventional Forming Processes
- Forging
- Rolling
- Extrusion
- Drawing
- Sheet metal working
- Unconventional Forming Processes
- Explosive Forming
- Electro-magnetic Forming
- Electro-hydraulic Forming

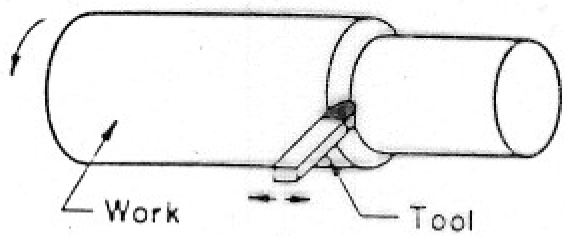
Material Removal Processes: Subtractive

- Machining involves removing of excess materials from selected areas of the starting material to get the desired shape of the component.

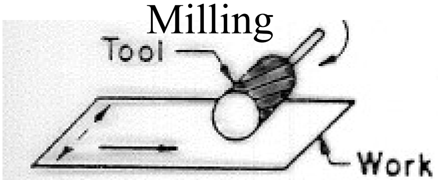
- Traditional Machining Processes
  - •Turning
  - •Milling
  - •Drilling
  - •Grinding

  …………

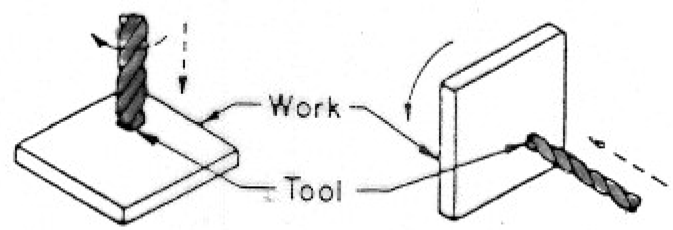
Turning



Milling



Drilling



Material Removal Processes

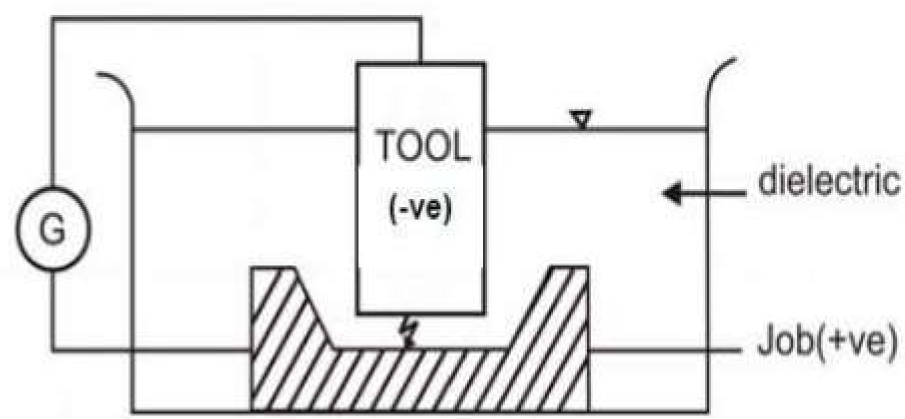
Contd.

❖ Advanced Machining Processes

- Mechanical : AJM, USM, WJM, AWJM, AFM, MAF, MRAF, MFP…….
- Thermo electric: EDM, LBM, EBM, PAM, IBM……
- Electrochemical & chemical: ECM, CM……

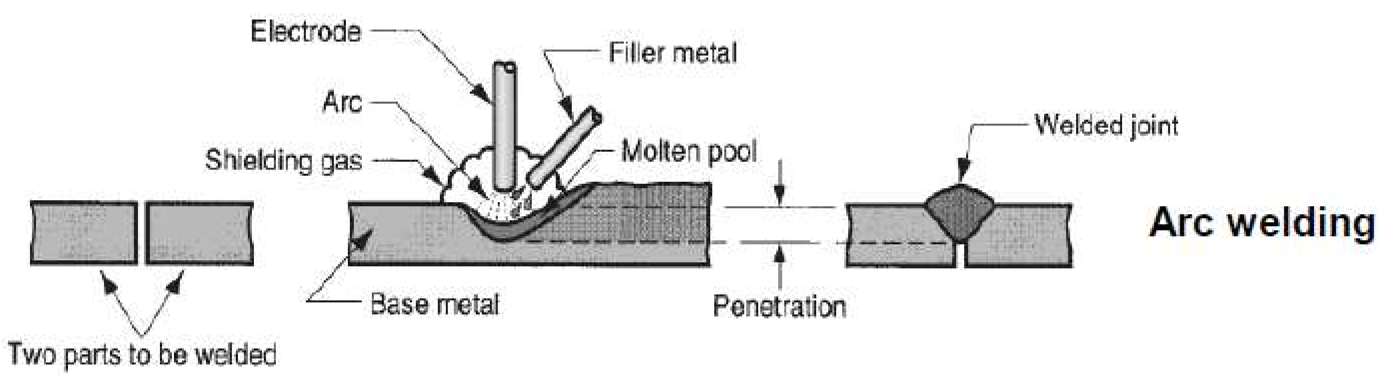
  Hybrid processes : ECSM, ECM, EDG……
- Computer controlled machine tools: CNC, DNC, Machining centre

Electro- discharge Machining.



Joining and Assembly Processes

- Joining operation in which two parts or more are joined permanently or semi permanently to form a new entity.
- Permanent joining includes welding, soldering, adhesive bonding, etc.
- Mechanical assembly fastens parts in a joint that can be conveniently disassembled (using threaded fasteners such as bolts, rivets, nuts, etc).



Finishing and Surface Treatment Processes

- Surface finishing process are used ensure a smooth surface, to improve appearance or to provided a protective coating.
- Some of process are like honing and lapping are remove the unwanted material, there primary aim is to produces a good surface finish.
- **Surface finishing operations are as followed…**

  1) Polishing 2) Honing 3) buffing 4) Barrel Tumbling

  5) Lapping 6) electroplating 7) Abrasive belt grinding

  8) Inorganic coating 9) Anodizing

Heat Treatment or Bulk Property Enhancing Processes

- **Physical properties of material can be change by heat treatment like**

1) Carbonizing

2) tempering

3) Hardening

By hammering, bending and cold rolling of iron materials and nonferrous metals a strengthening of the metal structure is changed systematically. This kind of heat treatment is used for making the steels hard and wear-resistant for certain purposes.

4) Annealing

The hardness for an annealing process is usually listed on the HRB scale as a maximum value. It is a process to refine grain size, improve strength, remove residual stress and affect the electromagnetic properties.

5) Stress relieving

is a technique to remove or reduce the internal stresses created in a metal. Stress relieving is usually accomplished by heating a metal

Reference Books

- **Manufacturing Engineering & Technology- S.Kalpakjian and S. R. Schmid (Pearson).**
- **Manufacturing Processes Vol I – H. S. Shan (Pearson)**
- **Manufacturing Science: A. Ghosh and A.K. Mallik (East-West Press).**
- **Fundamental of Manufacturing Processes: G. K. Lal and S. K. Choudhuary (Narosa).**
- **Advanced Machining Processes: V. K. Jain (Allied Publishers).**


THANK YOU

Manufacturing Materials
Lecture-03

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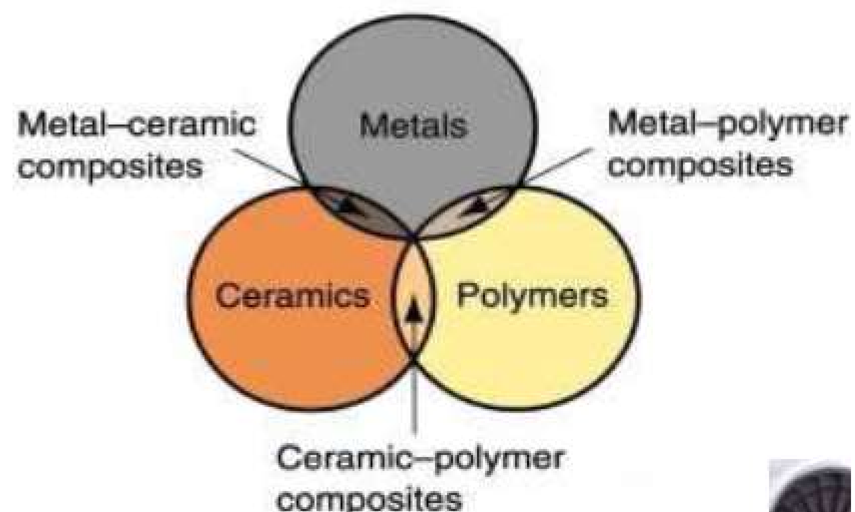
Contents

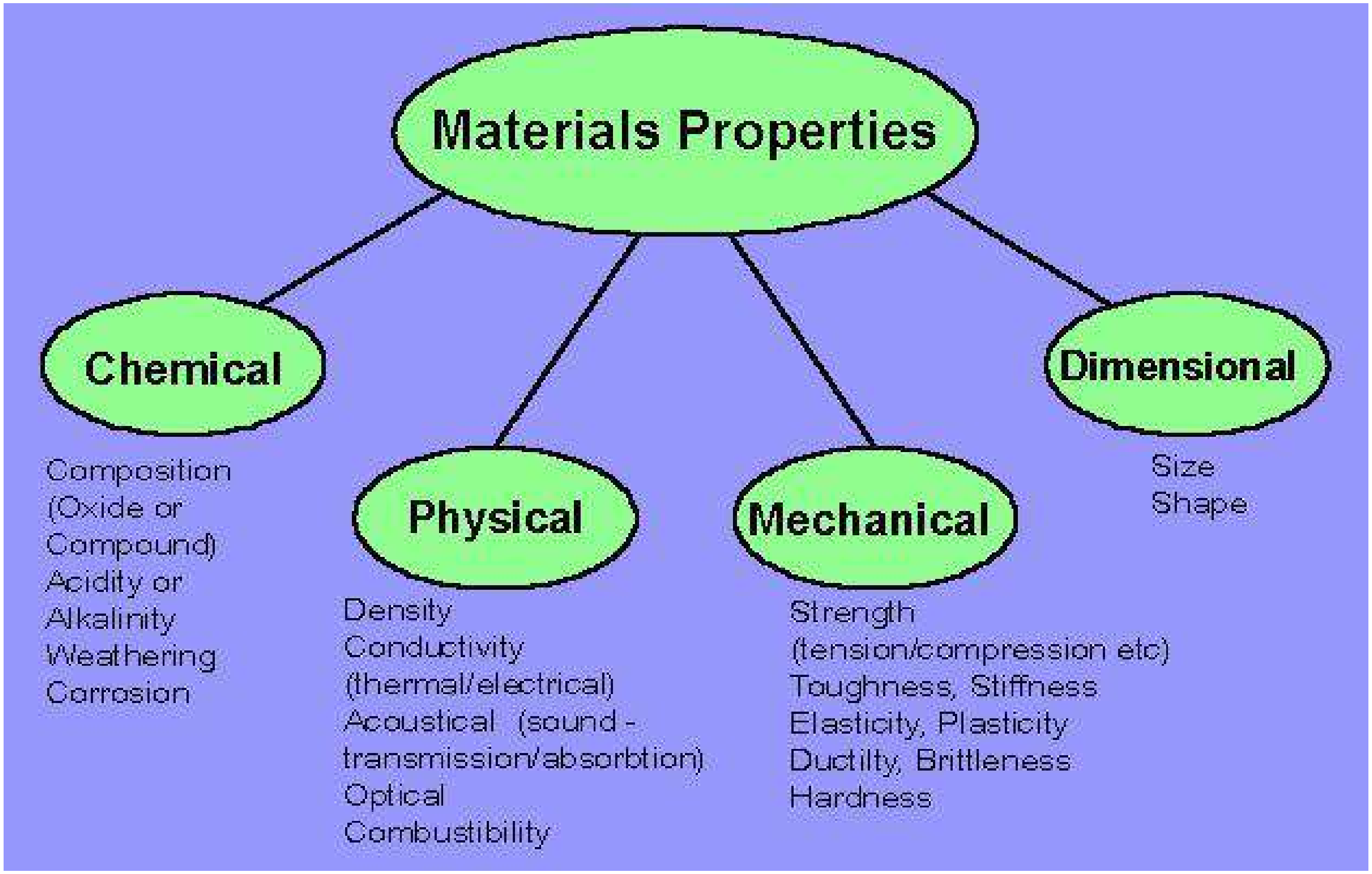
- **Manufacturing Materials and their Properties**
- **Selection of Materials**
- **Selection of Manufacturing Processes**

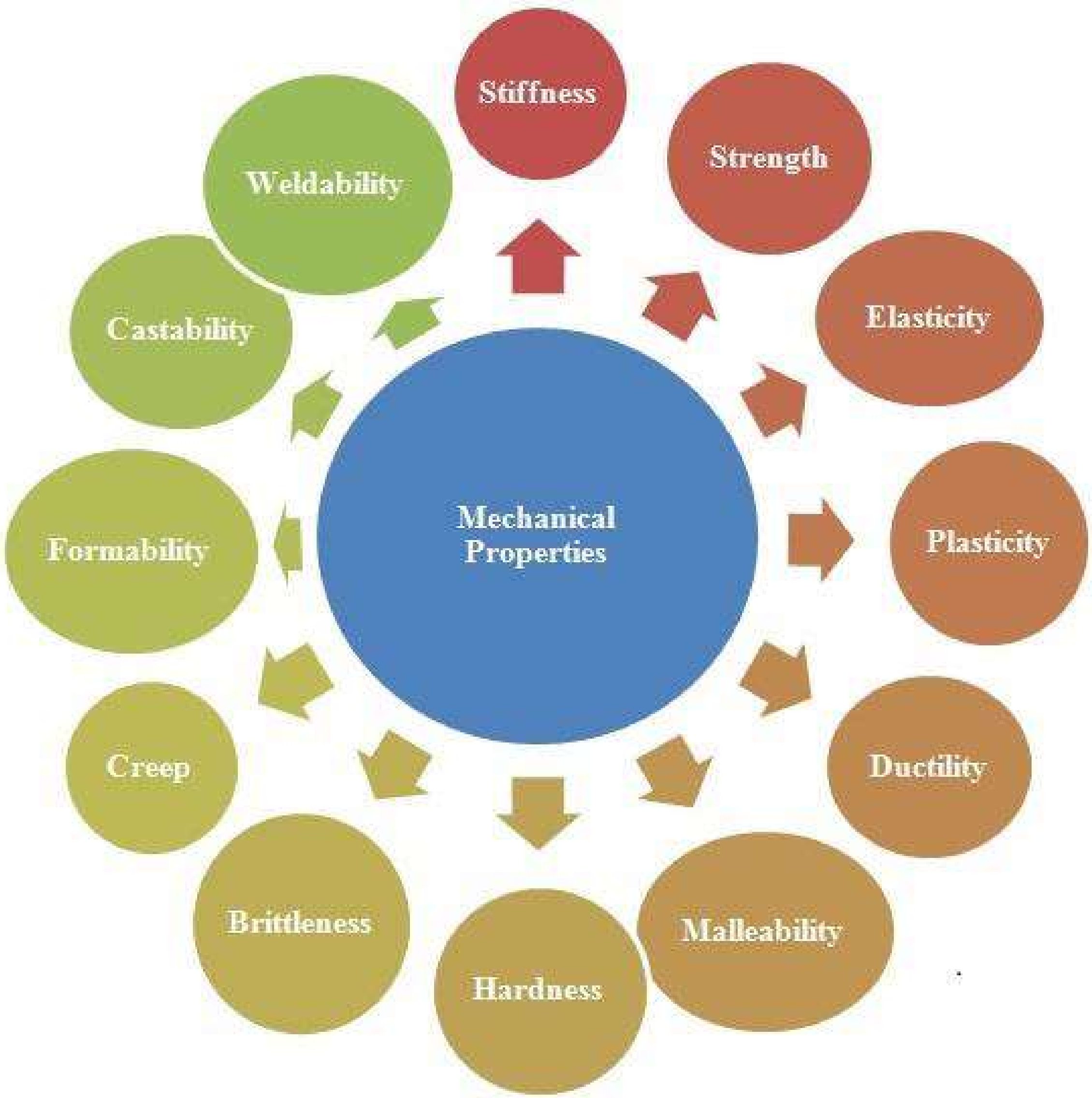
Manufacturing Materials

- Most engineering materials can be classified into one of the three basic categories: (1) Metals, (2) Ceramics and (3) Polymers.
- They have different chemistries and their mechanical and physical properties are dissimilar.
- These differences affect the manufacturing processes that can be used to produce products from them.
- In addition, there are (4) Composites: nonhomogeneous mixtures of the other three basic types rather than a unique category

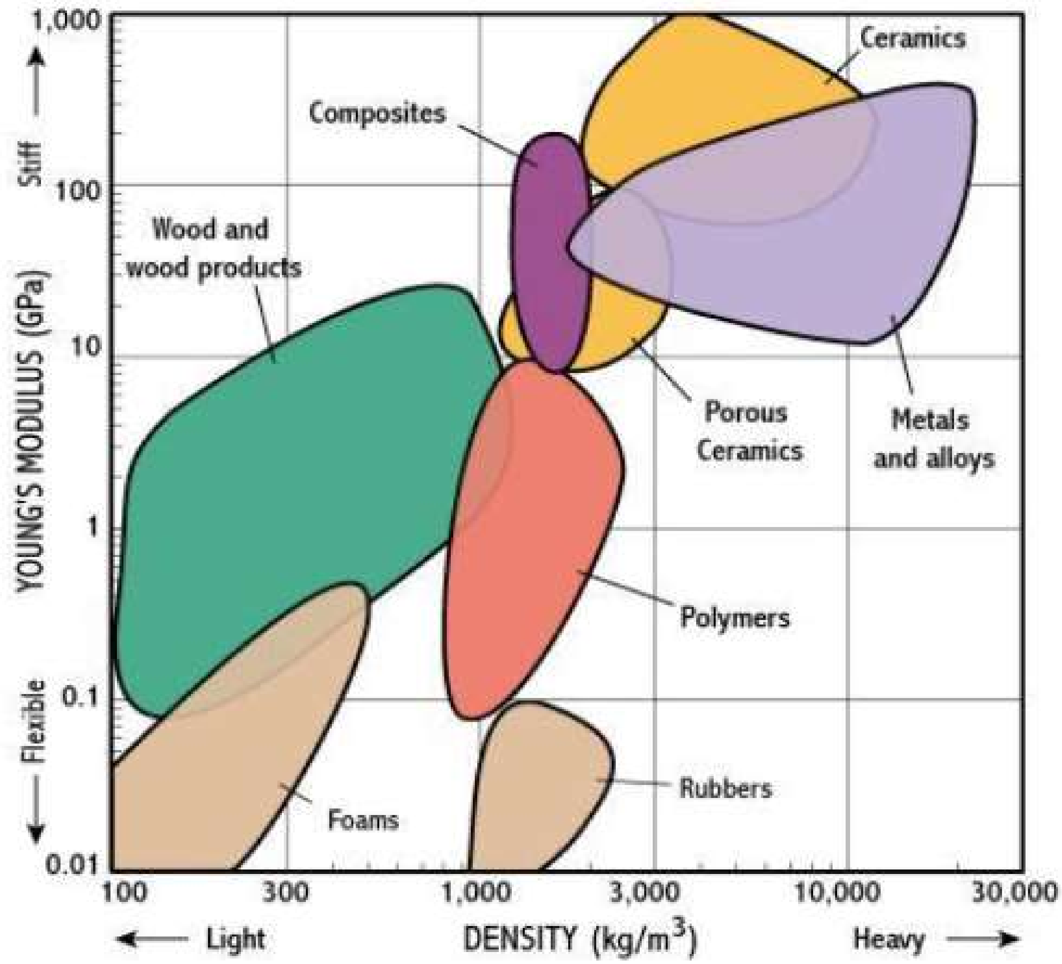
- The relationship of the four groups is pictured




Materials Properties
Chemical
Composition (Oxide or Compound)
Acidity or Alkalinity
Weathering
Corrosion
Physical
Density
Conductivity (thermal/electrical)
Acoustical (sound - transmission/absorbtion)
Optical
Combustibility
Mechanical
Strength (tension/compression etc)
Toughness, Stiffness
Elasticity, Plasticity
Ductilty, Brittleness
Hardness
Dimensional
Size
Shape


Mechanical Properties
Stiffness
Strength
Elasticity
Plasticity
Ductility
Malleability
Hardness
Brittleness
Creep
Formability
Castability
Weldability

Ashby Curve



1,000
100
10
1
0.1
0.01
Stiff
Flexible
YOUNG'S MODULUS (GPa)
Ceramics
Composites
Wood and wood products
Porous Ceramics
Metals and alloys
Polymers
Rubbers
Foams
100
300
1,000
3,000
10,000
30,000
Light
DENSITY (kg/m³)
Heavy

Mechanical Properties

Tensile strength – Measures the force required to pull something such as rope,wire or a structural beam to the point where it breaks

Ductility – A measure of how much strain a material can take before rupturing.

Malleability – The pproperty of a material that can be worked or hammered or shaped without breaking

Brittleness –Breaking or shattering of a material when subjected to stress (when force is applied to it).

Elasticity – The property of a material that returns to its original shape after stress (e.g. external forces) that made it deform or distort is removed

Plasticity - The deformation of a material undergoing non-reversible changes of shape in response to applied forces

Toughness – The ability of a material to absorb energy and plastically deform without fracturing

Hardness – The property of being rigid and resistant to pressure; not easily scratched

Machinability – The property of a material that can be shaped by hammering, pressing, rolling

Physical Properties

- **specific heat** – The heat required to raise the temperature of one gram of a substance by one degree centigrade (J/kg K)
- **Density** – Mass per unit volume expressed in such units as kg/cm^3
- **Thermal conductivity** –Rate at which heat flows through a given material (W/m K).
- **Melting point** – A temperature at which a solid begins to liquify
- **Electrical conductivity** – A measure of how strongly a material opposes the flow of electric current (Ω·m)
- **Coefficient of thermal expansion** – Degree of expansion divided by the change in temperature (m/°C)

Physical Properties of Material

(in descending order)

Density	Melting point	Specific heat	Thermal conductivity	Thermal expansion	Electrical conductivity
Platinum	Tungsten	Wood	Silver	Plastics	Silver
Gold	Tantalum	Beryllium	Copper	Lead	Copper
Tungsten	Molybdenum	Porcelain	Gold	Tin	Gold
Tantalum	Columbium	Aluminum	Aluminum	Magnesium	Aluminum
Lead	Titanium	Graphite	Magnesium	Aluminum	Magnesium
Silver	Iron	Glass	Graphite	Copper	Tungsten
Molybdenum	Beryllium	Titanium	Tungsten	Steel	Beryllium
Copper	Copper	Iron	Beryllium	Gold	Steel
Steel	Gold	Copper	Zinc	Ceramics	Tin
Titanium	Silver	Molybdenum	Steel	Glass	Graphite
Aluminum	Aluminum	Tungsten	Tantalum	Tungsten	Ceramics
Beryllium	Magnesium	Lead	Ceramics		Glass
Glass	Lead		Titanium		Plastics
Magnesium	Tin		Glass		Quartz
Plastics	Plastics		Plastics		

Metals

- Metals used in manufacturing are usually in the form of alloys (two ore more elements, at least one of which is metallic). Metals are divided into two basic groups; ferrous and nonferrous.
- Ferrous metals: based on Iron (Fe) as the major alloying element. This group includes steel and cast iron
- Fe has limited commercial use, but when alloyed with carbon (C), Fe has more use and greater commercial value than any other metal.
- Fe when alloyed with C forms Steel or Cast Iron.
- **Steel**: Is an Iron-Carbon alloy containing 0.02 to 2.11 wt.% C.
- Most important category within the ferrous metals group, due to low cost and good mechanical and physical properties.
- Its composition contains other metals such as Mg, Cr, Ni, Mo, etc, to enhance the properties of the alloy.
- Used widely in construction, transportation and consumer products

Contd.

Metals

- **Cast iron**: Iron-Carbon alloy containing ~2 to ~4 wt.% C.
- Used primarily in sand casting.
- Other elements such as Si (0.5 to 3 wt.%) is present in the alloy. Other elements are often added as well.
- Gray cast iron is the most common type of cast iron; its applications include blocks and heads for internal combustion engines, manholes covers, etc.
- Nonferrous metals: These include other metallic elements and their alloys.
- In almost all cases, the alloys are more important commercially than the pure metals.
- Some examples are Gold alloys, Titanium alloys, Copper alloys, etc

General Characteristics of Nonferrous Metal and alloys

Material	Characteristics
Nonferrous alloys	More expensive than steels and plastics; wide range of mechanical, physical, and electrical properties; good corrosion resistance; high-temperature applications.
Aluminum	High strength-to-weight ratio; high thermal and electrical conductivity; good corrosion resistance; good manufacturing properties.
Magnesium	Lightest metal; good strength-to-weight ratio.
Copper	High electrical and thermal conductivity; good corrosion resistance; good manufacturing properties.
Superalloys	Good strength and resistance to corrosion at elevated temperatures; can be iron-, cobalt-, and nickel-base.
Titanium	Highest strength-to-weight ratio of all metals; good strength and corrosion resistance at high temperatures.
Refractory metals	Molybdenum, niobium (columbium), tungsten, and tantalum; high strength at elevated temperatures.
Precious metals	Gold, silver, and platinum; generally good corrosion resistance.

Ceramics

Compounds containing metallic (or semi-metallic) and nonmetallic elements.

Typical nonmetallic elements are oxygen, nitrogen, and carbon

For processing, ceramics divide into:

1. Crystalline ceramics – includes:

Traditional ceramics, such as clay, and modern ceramics, such as alumina (Al_2O_3)

2. Amorphous :Glasses – mostly based on silica (SiO_2)

Properties:

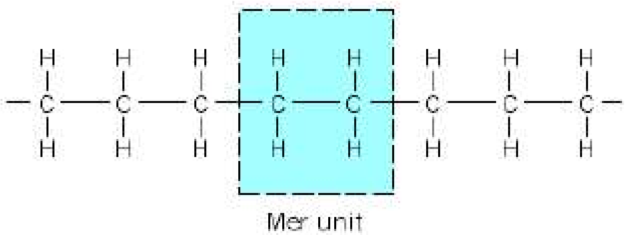
❖Thermally and electrically insulating

❖Resistant to high temperatures and harsh environments

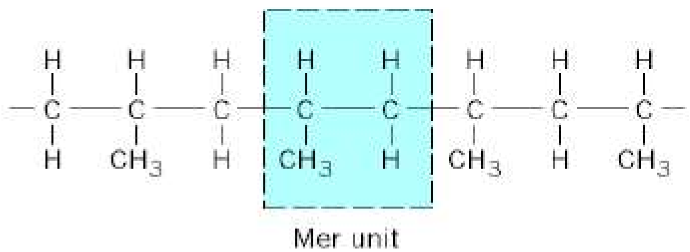
❖Hard, but brittle

Polymers

- Compound formed of repeating structural units called mers, whose atoms share electrons to form very large molecules
- Polymer usually consists of carbon plus one or more elements such as hydrogen and nitrogen



Polyethylene: (the mer unit is C_2H_4)



Polypropylene: (the mer unit is C_3H_6)

- Composed primarily of C and H (hydrocarbons).
- Low melting temperature.
- Most are poor conductors of electricity and heat.
- Many have high plasticity.
- A few have good elasticity.
- Some are transparent, some are opaque.

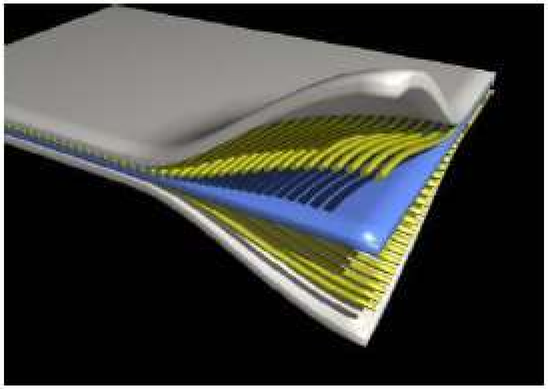
Composites

Material consisting of two or more phases that are processed separately and then bonded together to achieve properties superior to its constituents

- ❖ Phase - homogeneous mass of material, such as grains of identical unit cell structure in a solid metal
- ❖ Usual structure consists of particles or fibers of one phase mixed in a second phase
- ❖ Properties depend on components, physical shapes of components, and the way they are combined to form the final material.

In two material system, there are two phases : Primary phase & Secondary phase.

- ➢ The primary phase forms the matrix within which the secondary phase imbedded
- ➢ The imbedded phase is also known as dispersed phase or reinforcing phase



Types and general charecteristics of Composite materials

Material	Characteristics
Fibers	
Glass	High strength, low stiffness, high density; lowest cost; E (calcium aluminoborosilicate) and S (magnesia-aluminosilicate) types commonly used.
Graphite	Available as high-modulus or high-strength; low cost; less dense than glass.
Boron	High strength and stiffness; highest density; highest cost; has tungsten filament at its center.
Aramids (Kevlar)	Highest strength-to-weight ratio of all fibers; high cost.
Other fibers	Nylon, silicon carbide, silicon nitride, aluminum oxide, boron carbide, boron nitride, tantalum carbide, steel, tungsten, molybdenum.
Matrix materials	
Thermosets	Epoxy and polyester, with the former most commonly used; others are phenolics, fluorocarbons, polyethersulfone, silicon, and polyimides.
Thermoplastics	Polyetheretherketone; tougher than thermosets but lower resistance to temperature.
Metals	Aluminum, aluminum-lithium, magnesium, and titanium; fibers are graphite, aluminum oxide, silicon carbide, and boron.
Ceramics	Silicon carbide, silicon nitride, aluminum oxide, and mullite; fibers are various ceramics.

Metal- matrix composite material and application

Fiber	Matrix	Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fission power reactors
	Lead	Storage-battery plates
	Magnesium	Helicopter transmission structures
Silicon carbide	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt-base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

Selection of materials

- **A particular material is selected on the basis of following Characteristics:**

✓ **Properties of Material**

✓ **Cost of Material**

✓ **Availability of material and reliability of supply**

✓ **Service life of material**

✓ **Appearance (colour and surface texture) of material**

Selection of a Manufacturing Process

- Types and nature of starting material
- Size and geometrical shape of the part
- Volume of production
- Desired quality and properties of the part
- Technical viability of the process
- Economy

Reference Books

- **Manufacturing Engineering & Technology- S. Kalpakjian and S. R. Schmid (Pearson).**
- **Manufacturing Processes Vol I – H. S. Shan (Pearson)**
- **Fundamental of Manufacturing Processes: G. K. Lal and S. K. Choudhuary (Narosa).**


THANK YOU

Manufacturing – Economical and other aspects
Lecture-04

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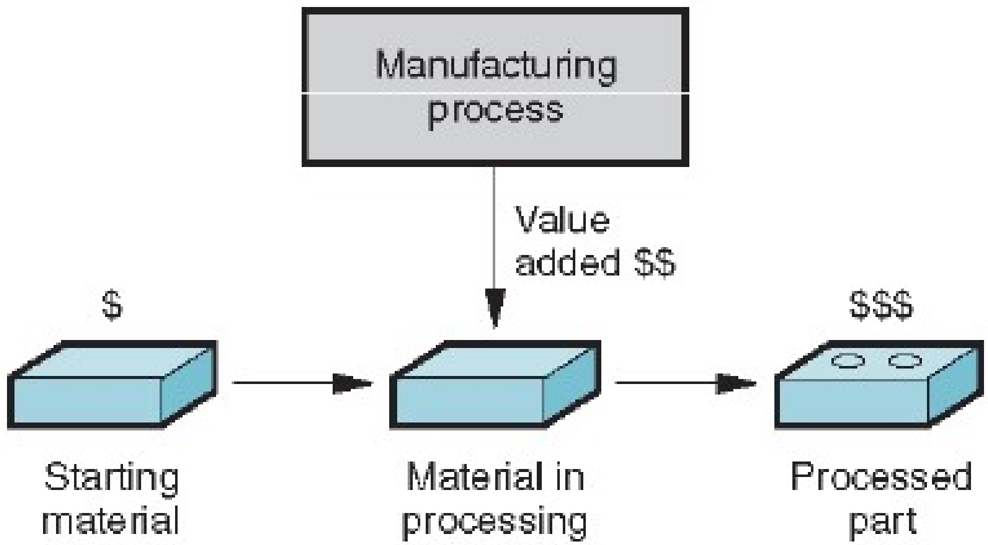
Contents

- **Economical aspect of Manufacturing**
- **Role of Engineers in Manufacturing Activities**
- **Break-even Analysis**
- **General Trends in Manufacturing**

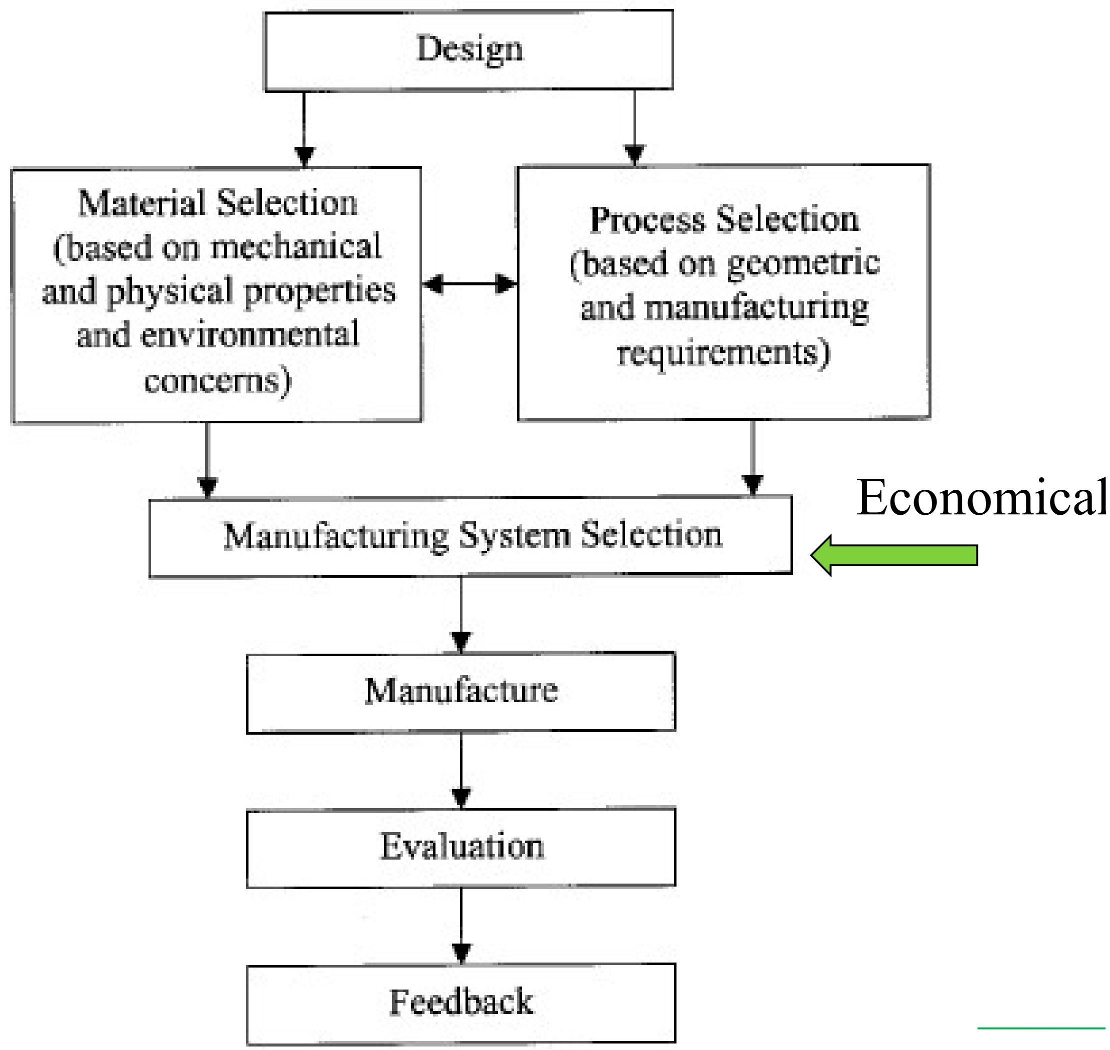
Manufacturing – Economic

- Transformation of materials into items of greater value by one or more processing and/or assembly operations.



Role of Engineers in Manufacturing Activities

- Design Engineer
- Material Engineer
- Manufacturing Engineer
- Industrial Engineer



Selection of Manufacturing Process

- An important responsibility of the engineer is to choose a manufacturing process which makes the required quality of a product to the specification and the lowest cost possible.
- Analytical method (Break- even) is used to select the appropriate manufacturing process out of the various suitable process.
- In Break-even analysis, two types of costs are considered.
  - **Fixed cost** which relates to the initial investment on the equipment and the tools required for the process. This cost would be constant and does not vary with the quantity produced.
  - **Variable cost** varies with the actual number of the objects made. This takes account the raw material required, energy consumed, labour cost, cost of special tooling, cost of tools used and other administrative overheads. Requirements of these are directly proportional to the quantity produced.

Break-even Analysis

- **Total Cost** is sum of fixed cost and variable cost.

  TC= FC+VCxQ

TC= Total cost, FC= Fixed Cost

VC= Variable cost per piece, Q=production quantity

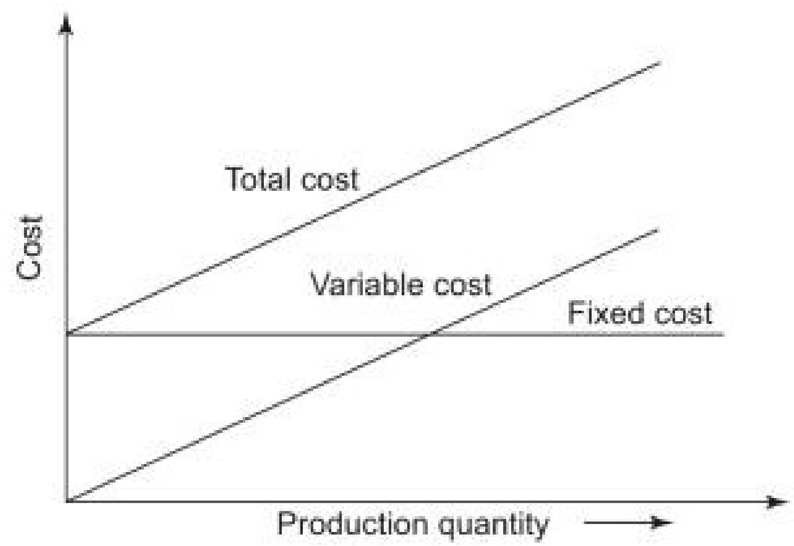


Fig. Typical cost curves

Break-even Analysis

Contd.

- A component which can be produced by two manufacturing processes without compromising the quality of component.
- Estimate fixed cost and variable costs for the both processes and plot the total cost curves for the both (fig.)
- The point where these curves intersect is called the break-even point.
- Fig. indicate that the first process will be economical if the quantity of production is less than that of the break-even point, while beyond it the second process is economical.

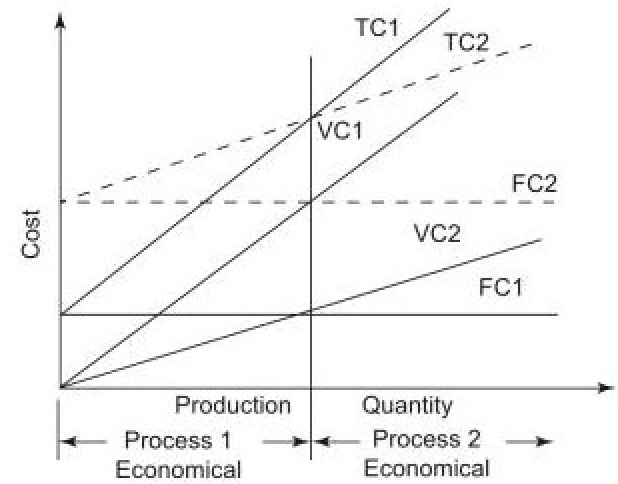


Fig. Break-even curve

❖ The-even quantity , *n,* can also be obtained by equating the total costs in both the processes. $\mathbf{FC_1 + n \times VC_1 = FC_2 + n \times VC_2}$

$$n = \frac{FC_2 - FC_1}{V_C \quad V_C}$$

General Trends in Manufacturing

❖ Global manufacturing trends

- Product variety and complexity continue to increase.
- Product life cycles are becoming shorter.
- Markets have become multinational and global competition has been increasing rapidly.
- Market conditions fluctuate widely.
- Customers are consistently demanding high-quality, low-cost products and on time delivery.

❖ Materials

- Material composition, purity, and defects (impurities, inclusions, and flaws) are coming under more control in order to further enhance overall properties, manufacturing characteristics, reliability, and service life.
- Developments have occurred in the selection of materials for improved recyclability.
- Developments continue in nanomaterials, nanopowders, composites, superconductors, semiconductors, amorphous alloys, shape-memory alloys (smart materials), tool and die materials, and coatings.
- Testing methods and equipment, including the use of advanced computers and software, particularly for ceramics, carbides, and composite materials, are continually being improved.
- Increasing control over the thermal treatment of materials is resulting in more predictable and reliable properties.
- Weight savings are being achieved with the use of materials with higher strength-to-weight and stiffness-to-weight ratios, particularly in the automotive and aerospace industries.

❖ Manufacturing operations

- Improvements are being made in predictive models of the effects of material processing parameters on product integrity, applied during a product's design stage.
- Developments continue in ultraprecision manufacturing, micromanufacturing, and nanomanufacturing, approaching the level of atomic dimensions.
- Computer simulation, modeling, and control strategies are being applied to all areas of manufacturing.
- Rapid-prototyping technologies are increasingly being applied to the production of tooling and direct digital manufacturing.
- Optimization of manufacturing processes and production systems are making them more agile.

❖ Manufacturing systems

- Advances in computer software and hardware are being applied to all aspects of production.
- Developments have occurred in control systems, industrial robots, automated inspection, handling and assembly, and sensor technology.
- Lean production and information technology are being implemented as tools to help meet major global challenges.

❖ Goals in manufacturing

- View manufacturing activities not as individual, separate tasks, but as making up a large system, with all its parts interrelated.
- Meet all design requirements, product specifications, and relevant national and international standards for products.
- Build quality into the product at each stage of its production.

Contd.

❖ Goals in manufacturing

- Implement the most economical and environmentally friendly (green) manufacturing methods.
- Continually evaluate advances in materials, production methods, and computer integration, with a view toward realizing their appropriate, timely, and economical implementation.
- Adopt production methods that are sufficiently flexible in order to rapidly respond to changing global market demands and provide on-time delivery to the customer.
- Continue efforts aimed at achieving higher levels of productivity and eliminating or minimizing waste with optimum use of an organization’s resources.
- Cooperate with customers for timely feedback for continuous improvement of a company’s products.

Reference Books

- **Manufacturing Technology Vol I – P. N. Rao (TMH)**
- **Manufacturing Engineering & Technology- S. Kalpakjian and S. R. Schmid (Pearson).**
- **Manufacturing Processes Vol I – H. S. Shan (Pearson)**
- **Fundamental of Manufacturing Processes: G. K. Lal and S. K. Choudhuary (Narosa).**


THANK YOU

Elastic and Plastic deformation
Lecture-05

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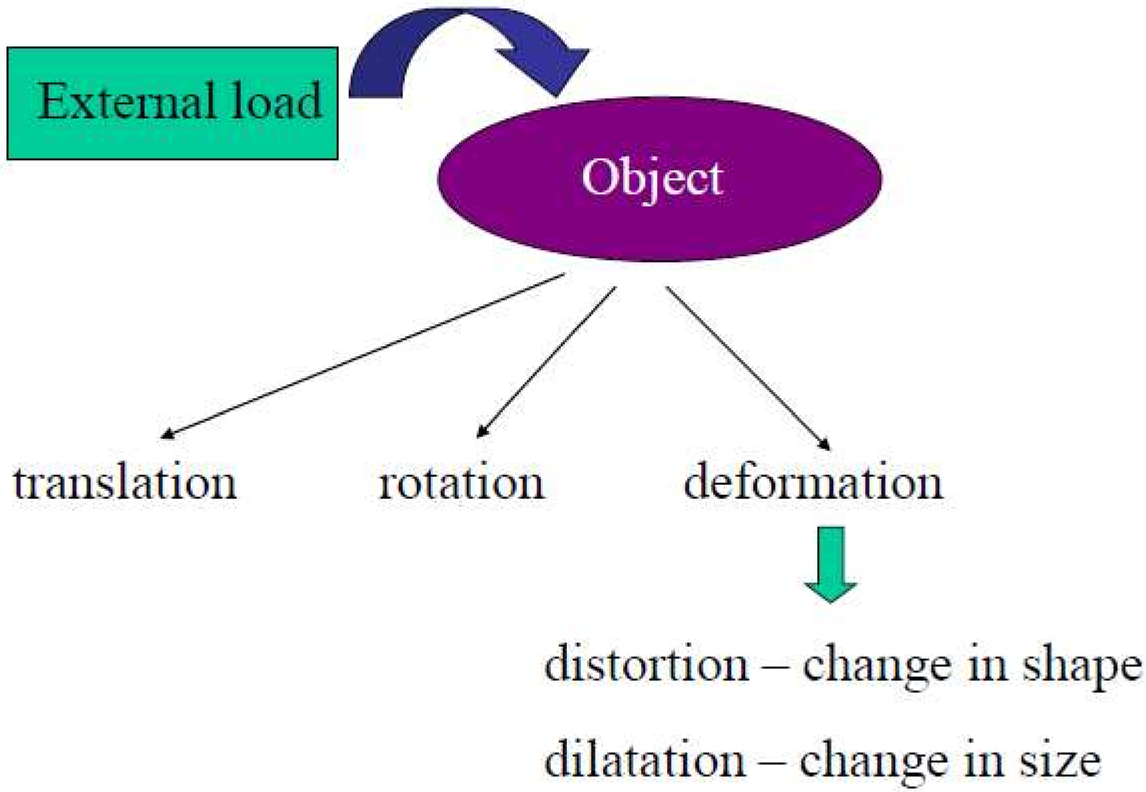
Contents

- **Deformation**
- **Elastic and Plastic deformation**
- **Mechanism of Plastic deformation**
- **Hot and Cold working**
- **Plastic deformation and Yield Criteria**

Mechanical Loads - Deformation



Deformation

Temporary / recoverable

time independent –

elastic

time dependent –

anelastic (under load),

elastic aftereffect (after removal of load)

Permanent

time independent –

plastic

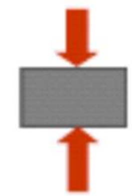
time dependent –

creep (under load),

combination of recoverable and permanent, but time dependent – visco-elastic

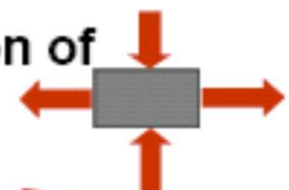
Methods of Deformation can be classified into five different groups based mainly upon differences in stress applications:

1. ***Compressive forming***. Deformation of a solid body is achieved through uni- or multi-axial compressive loading



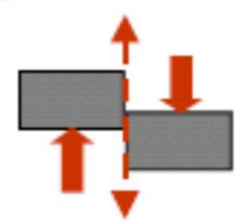
2. ***Tensile forming***. A plastic deformed shape is achieved through either uni-axial or multi-axial deformation

3. ***Combined tensile and compressive loading***. A combination of tension and compression to achieve plastic deformation

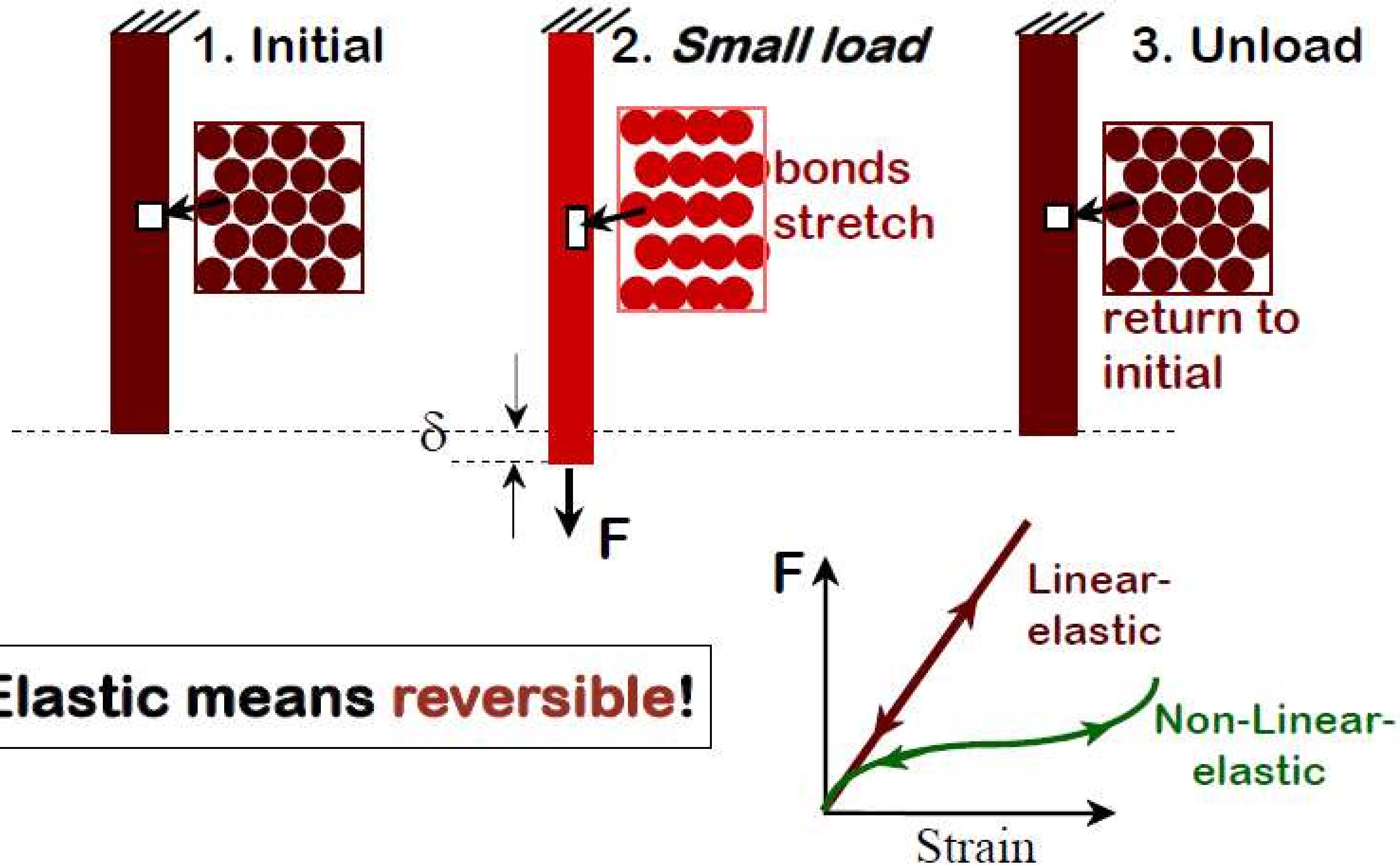


4. ***Forming by bending***. Permanent deformation is achieved by a bending load

5. ***Forming by shearing***. A solid body in which the plastic deformed state has been achieved by a shearing load



Elastic deformation



Elastic means reversible!

Elastic deformation

- A material under goes elastic deformation first followed by plastic deformation. The transition is not sharp in many instances.

- For most of the engineering materials, complete elastic deformation is characterized by strain proportional to stress. Proportionality constant is called *elastic modulus* or *Young's modulus*, *E*.

$$\sigma \propto \varepsilon \qquad\qquad \sigma = E\varepsilon$$

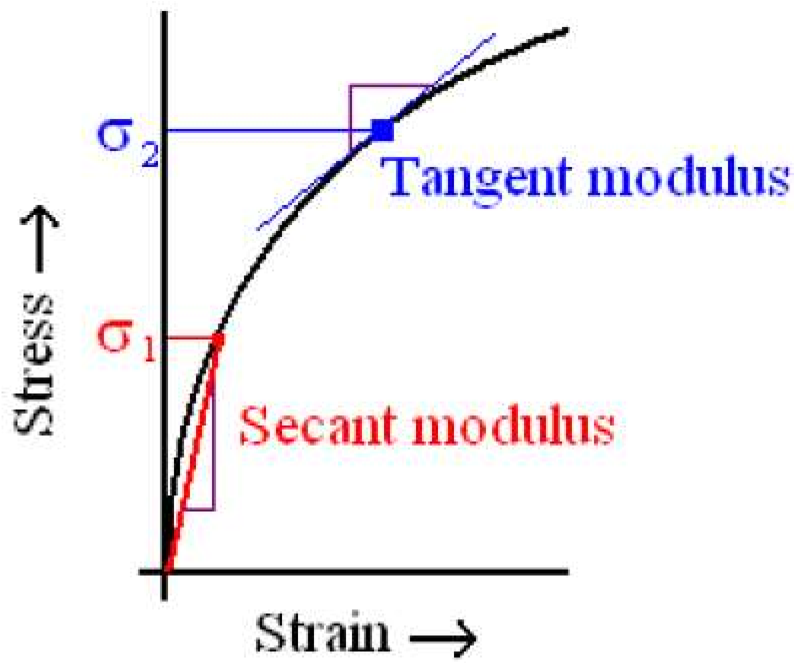
- Non-linear stress-strain relation is applicable for materials. E.g.: rubber.

Elastic deformation (contd.)

- For materials without linear stress-strain portion, either tangent or secant modulus is used in design calculations.

The tangent modulus is taken as the slope of stress-strain curve at some specified level.

Secant module represents the slope of secant drawn from the origin to some given point of the σ-ε curve.



Elastic deformation (contd.)

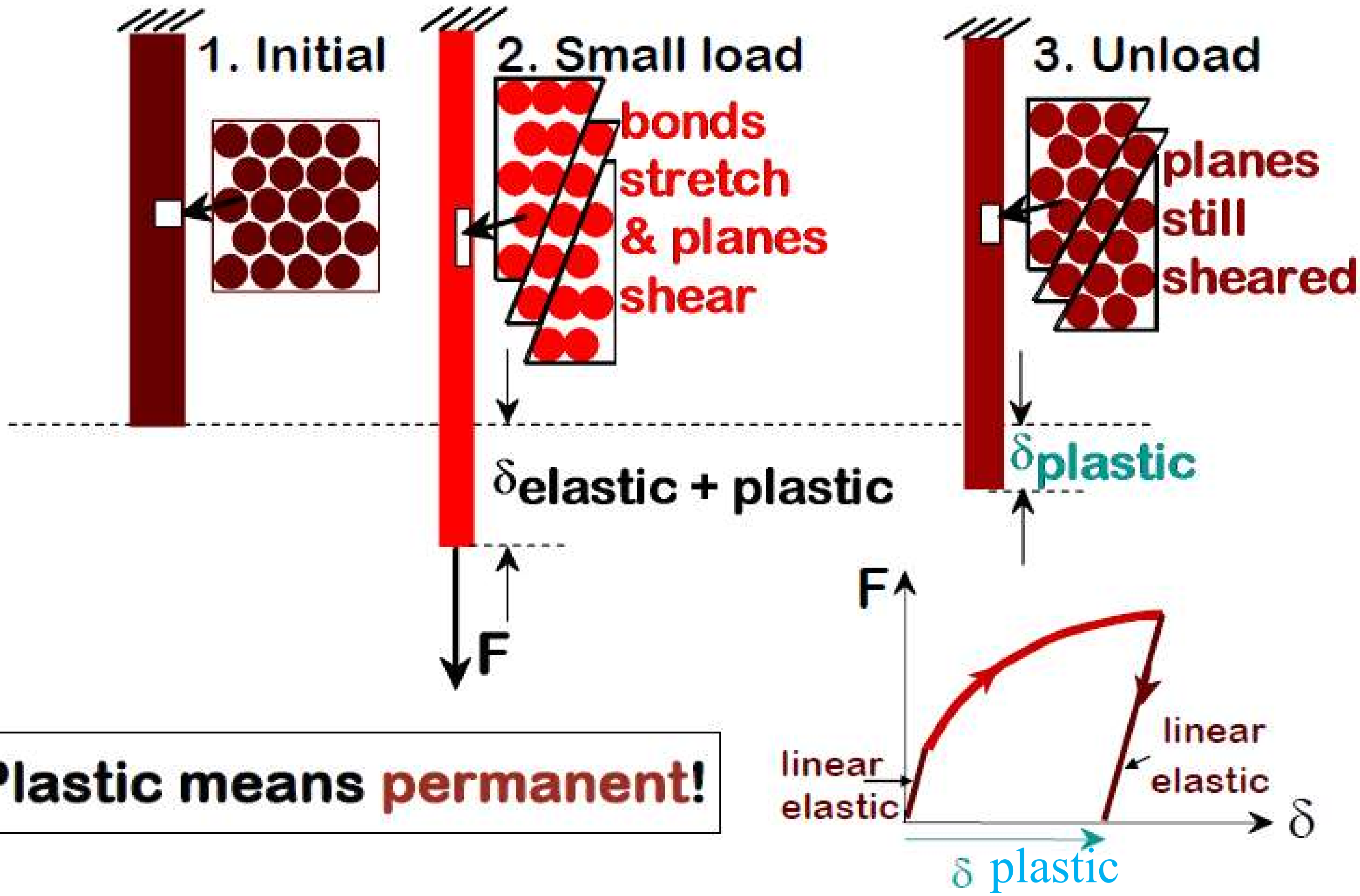
- Theoretical basis for elastic deformation – reversible displacements of atoms from their equilibrium positions – stretching of atomic bonds.
- Elastic moduli measures *stiffness* of material. It can also be a measure of resistance to separation of adjacent atoms.
- Elastic modulus = *fn* (inter-atomic forces)
  = *fn* (inter-atomic distance)
  = *fn* (crystal structure, orientation)
  => For single crystal elastic moduli are not isotropic.
- For a polycrystalline material, it is considered as isotropic.
- Elastic moduli slightly changes with temperature (decreases with increase in temperature).

Elastic deformation (contd.)

- Linear strain is always accompanied by lateral strain, to maintain volume constant.
- The ratio of lateral to linear strain is called Poisson's ratio (ν).
- Shear stresses and strains are related as $\tau = G\gamma$, where G is shear modulus or elastic modulus in shear.
- Bulk modulus or volumetric modulus of elasticity is defined as ratio between mean stress to volumetric strain. $K = \sigma_m/\Delta$
- All moduli are related through Poisson's ratio.

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{\sigma_m}{\Delta} = \frac{E}{3(1-2\nu)}$$

Plastic deformation



Plastic means permanent!

Plastic deformation (contd.)

- Following the elastic deformation, material undergoes plastic deformation.
- Also characterized by relation between stress and strain at constant strain rate and temperature.
- Microscopically…it involves breaking atomic bonds, moving atoms, then restoration of bonds.
- Stress-Strain relation here is complex because of atomic plane movement, dislocation movement, and the obstacles they encounter.
- Crystalline solids deform by processes – slip and twinning in particular directions.
- Amorphous solids deform by viscous flow mechanism without any directionality.

Plastic deformation (contd.)

- Because of the complexity involved, theory of plasticity neglects the following effects:

  - Anelastic strain, which is time dependent recoverable strain.

  - Hysteresis behavior resulting from loading and un-loading of material.

  - Bauschinger effect – dependence of yield stress on loading path and direction.

- Equations relating stress and strain are called *constitutive equations*.
- A true stress-strain curve is called *flow curve* as it gives the stress required to cause the material to flow plastically to certain strain.

Plastic deformation (contd.)

- Because of the complexity involved, there have been many stress-strain relations proposed.

$$\sigma = fn(\varepsilon, \dot{\varepsilon}, T, microstructure)$$

$$\sigma = K\varepsilon^n$$ Strain hardening exponent, n = 0.1-0.5

$$\sigma = K\dot{\varepsilon}^m$$ Strain-rate sensitivity, m = 0.4-0.9

$$\sigma = K(\varepsilon_0 + \varepsilon)^n$$ Strain from previous work – ε_0

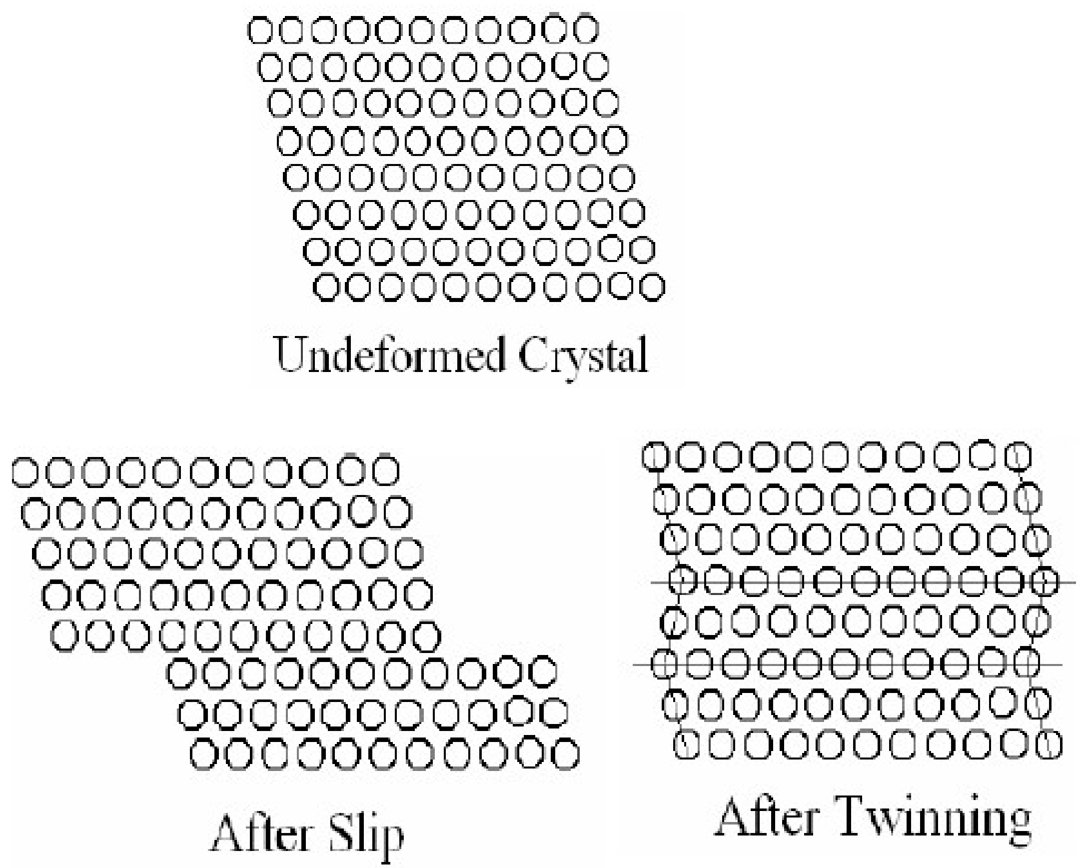
$$\sigma = \sigma_o + K\varepsilon^n$$ Yield strength – σ_0

Mechanism of Plastic deformation

- Permanent change in shape and size.
- The macroscopic change of the shape and dimensions can be brought about without any change in the unit cell dimension by two process (i) Slip (ii) Twinning
- **Slip:** Atom moves a number of inter- atomic distances. Displaced region is same as original undeformed region.
- **Twinning:** Atom moves by only a fraction of inter- atomic distances. The orientation of the twinned region is different from the untwinned region.

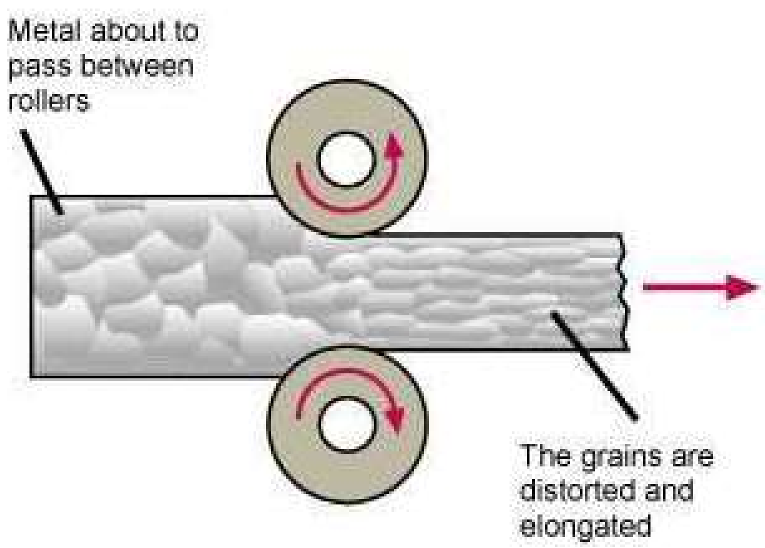
Contd.

Mechanism of Plastic deformation



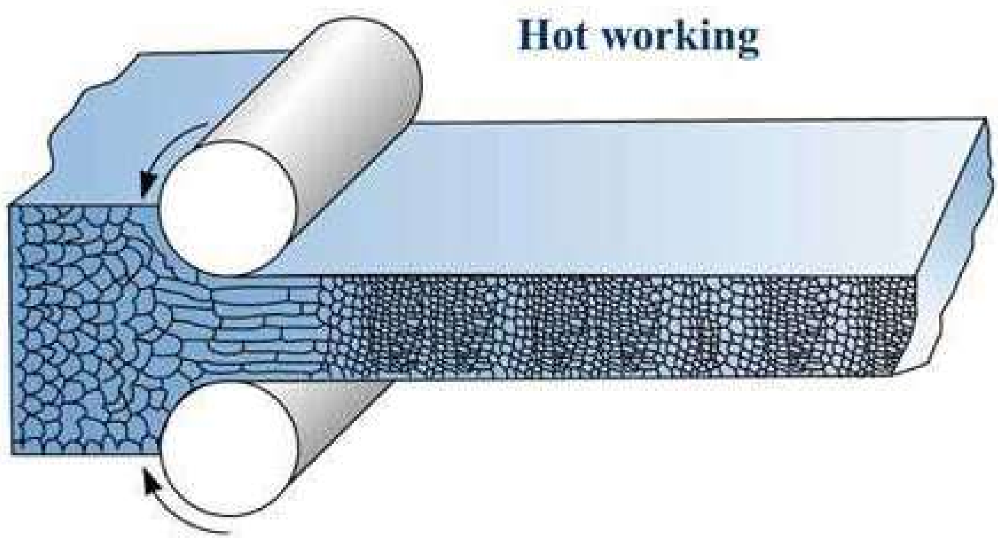
Cold Working of Metal

- Plastic deformation at a temperature below the recrystallization temperature.
- Distort or elongate the grain in the direction of flow of metal.
- Greater pressures
- Tensile strength, yield strength and hardness of steel increased.
- Ductility is reduced, internal and residual stresses are produced.



Hot Working

- Plastic deformation at a temperature above the recrystallization temperature.
- Under the action of heat and force, when the atoms of metal reach a certain higher energy levels, the new crystals start forming.



Hot Working

Contd.

❖ Advantages

- Refinement of grain occur
- Porosity of ingot is eliminated
- Uniformity and directional property is improved
- Toughness and ductility are improved.
- Power required is less, Rapid and economical process

❖ Limitations

- Rapid oxidation or scaling of surface results in poor surface finish
- Close tolerances cannot be maintained
- Tooling and handling costs are high.

Plastic deformation and Yield Criteria

❖ Tresca's Maximum Shear Stress Criterion

- Tresca suggested in 1965 that the plastic flow initiates when the maximum shear stress reaches a limiting value.
- This limiting value is defined as shear yield stress K.
- If the principal stresses at a point of material in the material are σ_1, σ_2 and σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$), then the maximum shear stress $\tau_{\max}$ is given by

$$\tau_{\max} = \frac{1}{2}(\sigma_1 - \sigma_3)$$

- Plastic deformation occurs when $\tau_{\max}$ is equal to K. Tresca's criterion becomes

$$\frac{1}{2}(\sigma_1 - \sigma_3) = K \quad \text{......(1)}$$

- It indicates that the yielding is independent of the intermediate principal stress σ_2.

Von Mises' Maximum Distortion Energy Criterion

- In 1913, Von Mises proposed that the plastic flow occurs when the shear strain energy reaches a critical value.
- The shear strain energy per unit volume ($\in$) can be expressed in terms of the three principal stresses as

$$\in = \frac{1}{6G}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right] \quad ....(2)$$

Where G is the shear modulus of material. Hence according to this criterion, the plastic flow initiates when the right hand side reaches a particular value (say A). Finally, the Von Mises criterion takes the form

$$(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2 = 6GA = C(\text{Constant}) \quad ....(3)$$

According to this criterion, the initiation of plastic flow depends on all the principle stress.

Relationship between Tensile and Shear yield stresses

- In case of uniaxial tensile load test, the value of tensile shear yield stress (σ_{ys}) can be used to determine the shear yield stress K.
- When yielding occurs under uniaxial tensile loading,

$$\sigma_1 = \sigma_y, \quad \sigma_2 = \sigma_3 = 0$$

Using these Constant C in Eqn(3) $\Rightarrow$ $C = 2\sigma_y^{\ 2}$ .....(4)

- Considering yielding under pure torsion, the state of stresses

$$\sigma_1 = K, \quad \sigma_3 = -K, \quad \sigma_2 = 0$$

Putting these in eqn(3) $C = 6K^2$ ....(5)

- Since the magnitude of C in Von Mises Criterion is independent of loading $\Rightarrow$ $K = \sigma_y / \sqrt{3}$ ....(6)
- Applying Tresca's yield criterion in pure loading condition $K = \sigma_y / 2$ ..(7)

Reference Books

- Manufacturing Science – Ghosh and Mallik (East- West Press)
- Manufacturing Technology Vol I – P. N. Rao (TMH)
- Manufacturing Engineering & Technology- S. Kalpakjian and S. R. Schmid (Pearson).
- Manufacturing Processes Vol I – H. S. Shan (Pearson)
- Fundamental of Manufacturing Processes: G. K. Lal and S. K. Choudhuary (Narosa).


THANK YOU

Metal Forging Processes
Lecture-06

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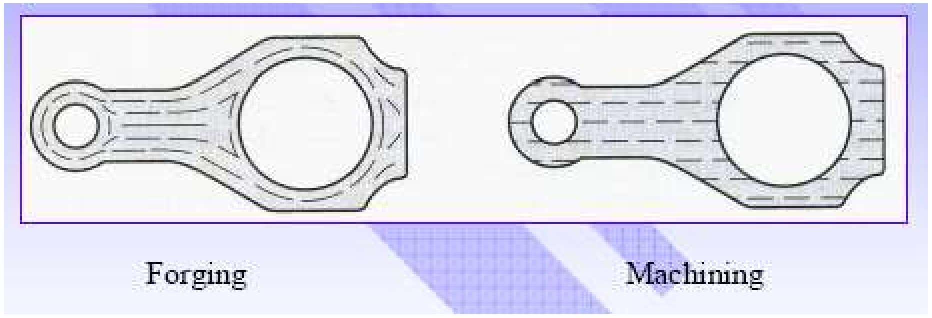
Contents

- **Introduction**
- **Forging operations**
- **Classification of Forging Processes**
- **Typical forging defects**
- **Advantages and disadvantages of forging**

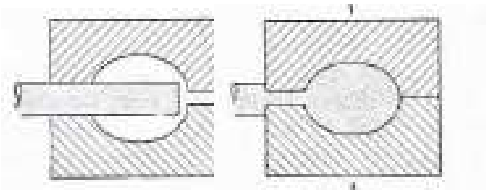
Forging Process : Introduction

- **Forging is perhaps oldest metal working process and was known even during prehistoric days when metallic tools were made by heating and hammering.**
- **Forging is basically involves plastic deformation of material between two dies to achieve desired configuration.**
- **In forging favorable grain orientation of metal is obtained.**

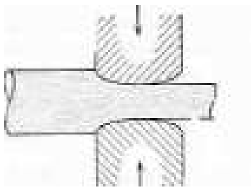


- **Forging is an effective method of producing many useful shaped parts such as rivets, crane hooks, connecting rod, turbine shafts etc.**

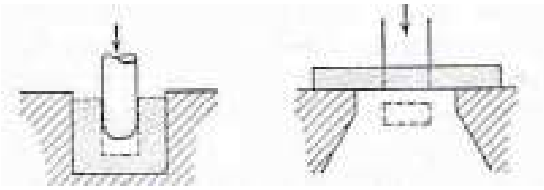
Forging Operations



Edging is used to shape the ends of the bars and gather Metal. The metal flow is confined in the horizontal direction but it is free to flow laterally to fill the die.



Drawing is used to reduce the cross-sectional area of the workpiece with concurrent increase in length.

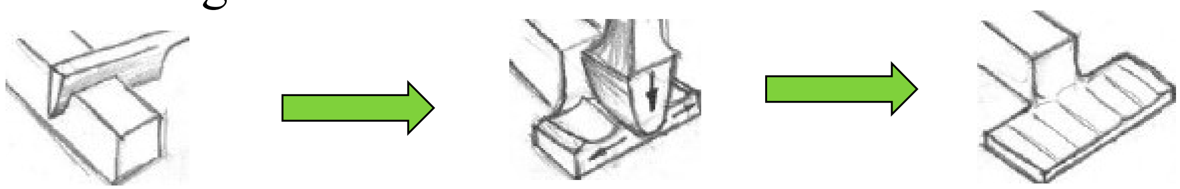


Piercing and punching are used to produce holes in metals.

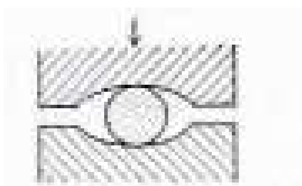
Contd.

Forging operations

Fullering is used to reduce the cross-sectional area of a portion of the stock. The metal flow is outward and away from the centre of the fuller. i.e. forging of connecting rod for an internal-combustion engine.



- **Swaging** is used to produce a bar with a smaller diameter using dies.
- Swaging is a special type of forging in which metal is formed by a succession of rapid hammer blow.
- Swaging provides a reduced round cross section suitable for tapping, threading, upsetting or other subsequent forming and machining operations.



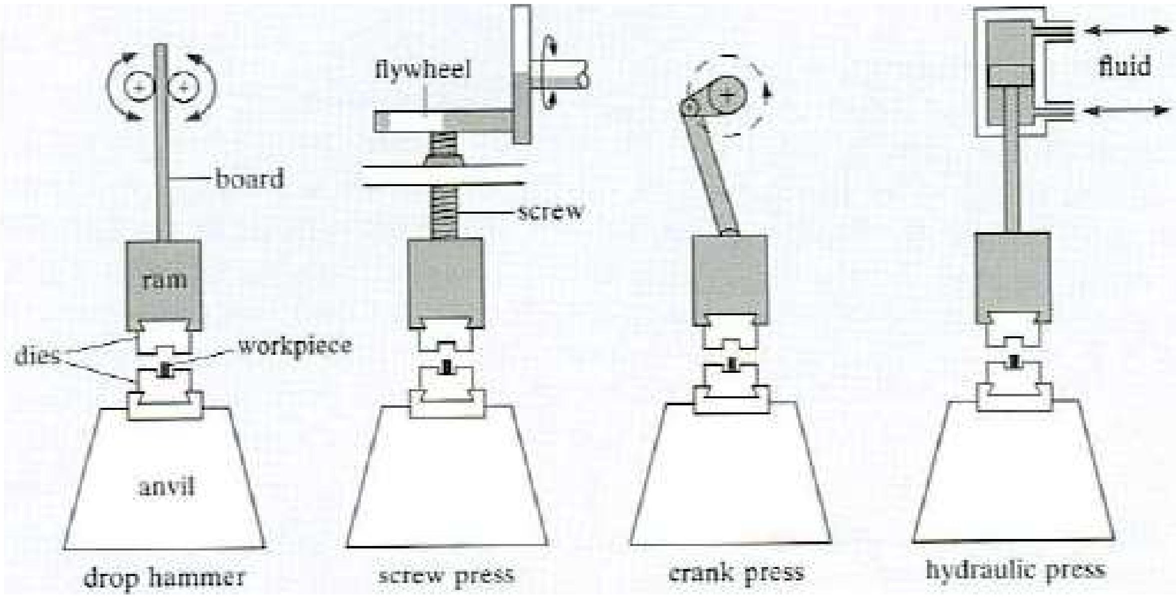
Classification of Forging Processes

- **By Equipment**
  - i) Forging hammer or drop hammer
  - ii) Press forging

- **By process**
  - i) open die forging
  - ii) Closed die forging

Forging Machines

There are four basic types of forging machines.



Hammer and press forging processes

Forging hammers

There are two basic types of forging hammers used;

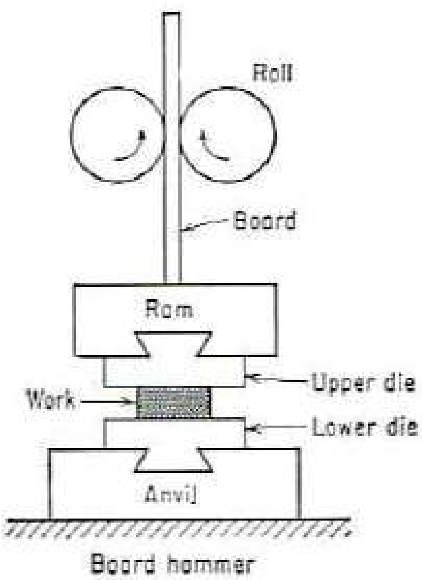
- Board hammer
- Power hammer

Forging presses

There are two basic types of forging presses available;

- Mechanical presses
- Hydraulic presses

Board hammer –forging hammer



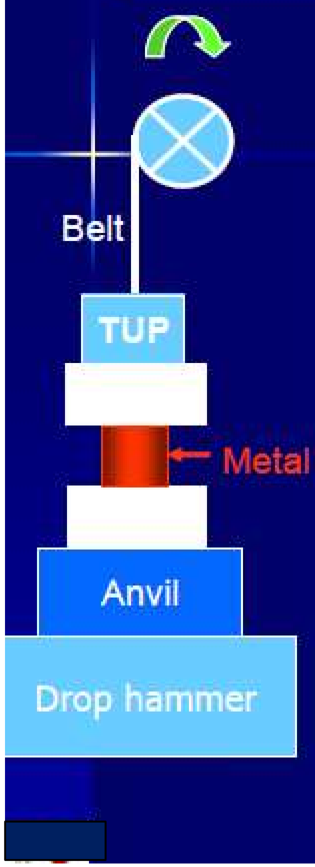
Board hammer

- The upper die and ram are raised by ***friction rolls*** gripping the board.
- After releasing the board, the ram falls under gravity to produce the ***blow energy***.
- The hammer can strike between ***60-150 blows*** per minute depending on size and capacity.
- The board hammer is an energy-restricted machine. The blow energy supplied equal the ***potential energy*** due to the weight and the height of the fall.

$$\boxed{\text{Potential energy} = mgh} \quad \text{...Eq 1}$$

- This energy will be delivered to the metal workpiece to produce ***plastic deformation***.

Forging hammer or drop hammer

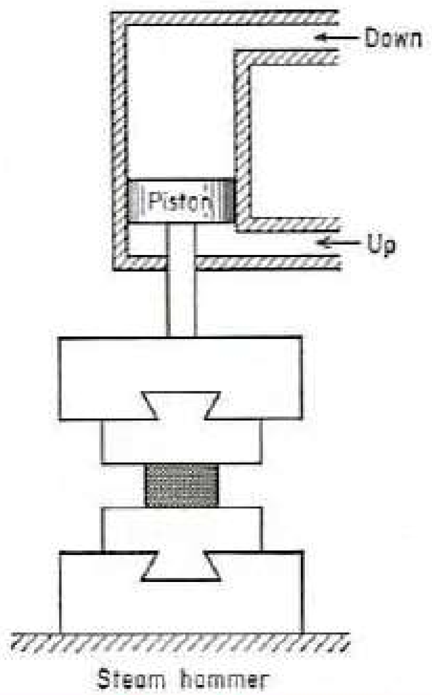


- Provide rapid impact blows to the surface of the metal.
- Dies are in two halves
  - *Lower : fixed to anvil*
  - *Upper : moves up and down with the TUP.*
- Energy (from a gravity drop) is adsorbed onto the metal, in which the maximum impact is on the metal surface.
- Dies are expensive being accurately machined from special alloys (susceptible to thermal shock).
- ***Drop forging*** is good for mass production of complex shapes.

The energy supplied by the blow is equal to the potential energy due to the weight of the ram and the height of the fall.

Potential energy = *mgh*

Power hammer



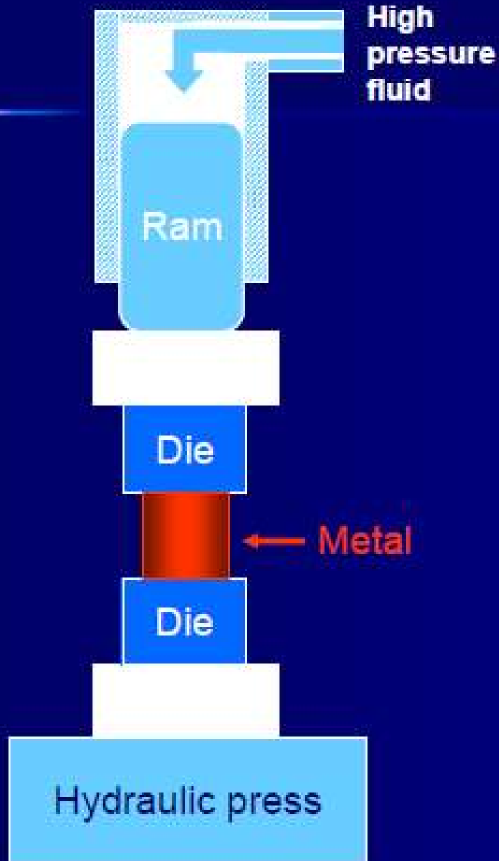
Power hammer

- **Power hammer** provides greater capacity, in which the ***ram is accelerated*** on the downstroke by steam or air pressure in addition to gravity.
- Steam or air pressure is also used to raise the ram on the upstroke.
- *The **total energy** supplied to the blow in a power drop hammer is given by*

$$W = \frac{1}{2}mv^2 + pAH = (mg + pA)H \quad \text{...Eq 2}$$

Where
- m = mass
- v = velocity of ram at start of deformation
- g = acceleration of gravity
- p = air or steam pressure acting on ram cylinder on downstroke
- A = area of ram cylinder
- H = height of the ram drop

Hydraulic press forging



- Using a ***hydraulic press or a mechanical press*** to forge the metal, therefore, gives continuous forming at a slower rate.
- Provide deeper penetration.
- Better properties (more homogeneous).
- Equipment is ***expensive***.

- ***Hydraulic presses*** are load-restricted machines in which hydraulic pressure moves a piston in a cylinder.

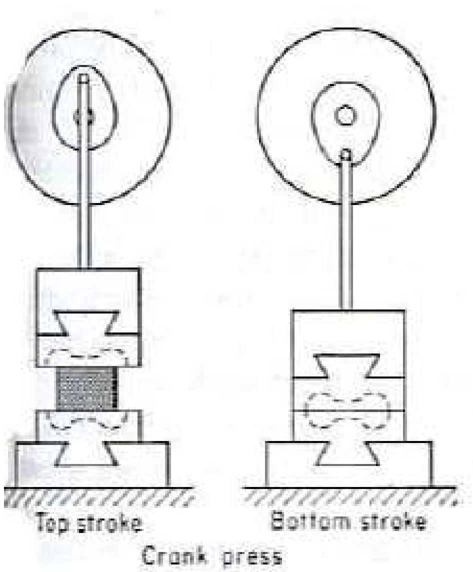
- The full press load is available at any point during the full stroke of the ram. Therefore, hydraulic presses are ideally suited for ***extrusion-type forging operation***.

- Due to slow speed, ***contact time is longer*** at the die-metal interface, which causes problems such as heat lost from workpiece and die deterioration.

- Also provide close-tolerance forging.

- Hydraulic presses are ***more expensive*** than mechanical presses and hammers.

Mechanical press forging



Mechanical press

- Crank press translates rotary motion into reciprocating linear motion of the press slide.
- The ram stroke is shorter than in a hammer or hydraulic press.
- Presses are rated on the basis of the force developed at the end of the stroke.
- The *blow press* is more like *squeeze* than like the impact of the hammer, therefore, dies can be less massive and die life is longer than with a hammer.
- The *total energy* supplied during the stroke of a press is given by

$$W = \frac{1}{2} I\left[\omega_o^2 - \omega_f^2\right] \qquad \text{...Eq 3}$$

Where I is moment of inertia of the flywheel

ω is angular velocity, ω_o-original, ω_f-after deformation, rad.s^{-1}

Typical values of velocity for different forging equipment

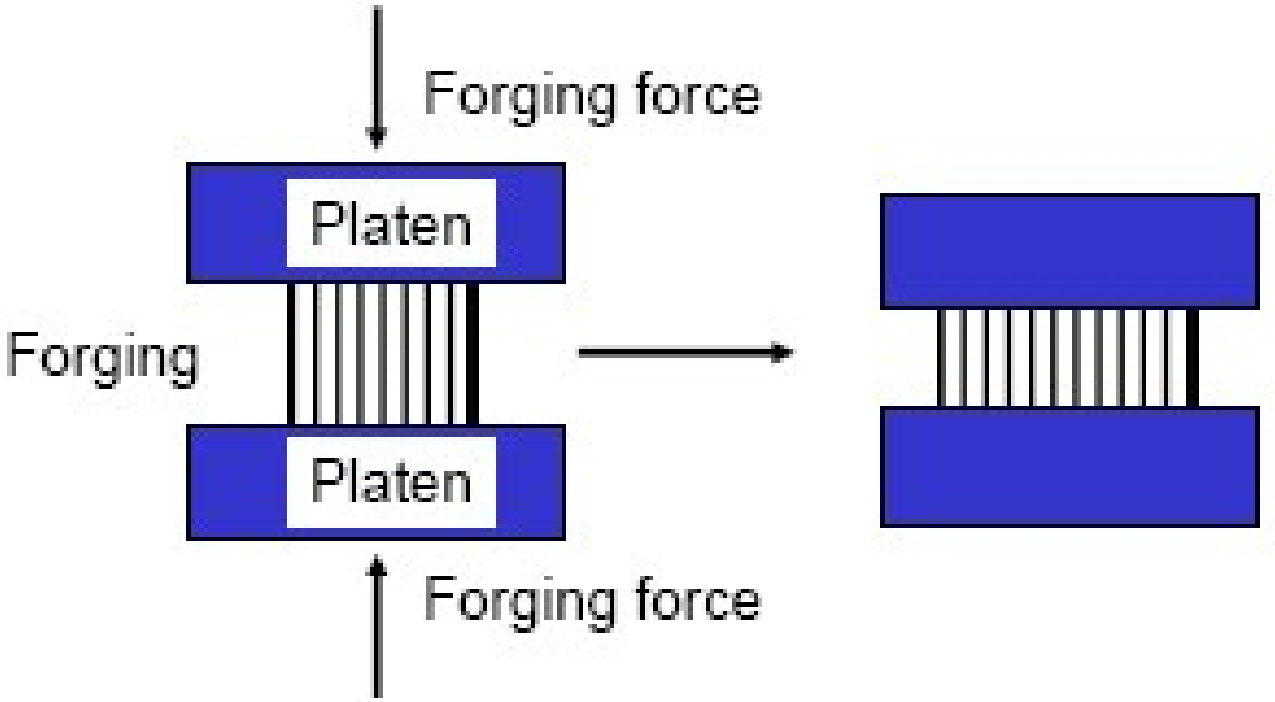
Forging machine	Velocity range, ms^{-1}
Gravity drop hammer	3.6-4.8
Power drop hammer	3.0-9.0
HERF machine	6.0-24.0
Mechanical press	0.06-1.5
Hydraulic press	0.06-0.30

Remark: HERF – High Energy Rate Forging

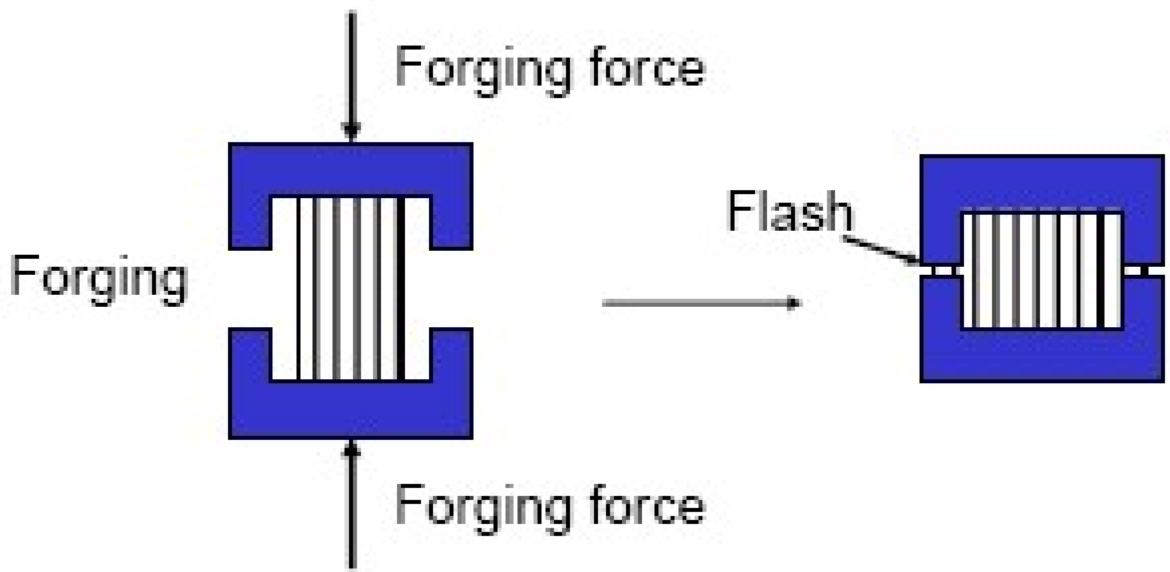
Open die Forging

- Simplest and cheapest
- Also called upsetting or flat-die forging
- Advantages
  - Cheap
  - Can form a wide variety of simple shapes with the same dies
    - Squares, cylindrical
  - Useful for preparing material for other forms of forging or machining
  - Can handle large items (35 tons)
- Disadvantages
  - Barreling of shape due to high friction

Open die forging



Closed die forging



Die Design

- Requires knowledge of
  - Material strength
  - Sensitivity of these to deformation rate and temperature
  - Friction and its control
  - Shape and complexity of workpiece
  - How the metal will flow to fill the die cavity
  - Great skill and expertise
  - Multiple dies to move the material in the right direction

FORGING D E F E C T S

- Though the forging process generally gives superior quality products compared to other manufacturing processes, there are some defects that are likely to come if proper care is not taken in the forging process design.

Unfilled sections

In this, some sections of the die cavity are not completely filled by the flowing metal. The causes of this defect are improper design of forging die or using faulty forging techniques.

Cold shut

This appears as a small crack at the corners of the forging. This is caused mainly by the improper design of the die wherein the corner and fillet radii are small as a result of which the metal does not flow properly into the corner and ends up as a cold shut.

Scale pits

This is seen as irregular depressions on the surface of the forging. This is primarily caused because of the improper cleaning of the stock used for forging. The oxide and scale present on the stock surface gets embedded into the finished forging surface. When the forging is cleaned by pickling, these are seen as depressions on the forging surface

Die Shift

This is caused by the misalignment of the two die halves, making the two halves of the forging to be of improper shape

Improper Grain Flow

This is caused by the improper design of the die which makes the flow of metal not following the final intended directions.

Flakes

These are basically internal ruptures caused by the improper cooling of the large forging. Rapid cooling causes the exteriors to cool quickly causing internal fractures. This can be remedied by following proper cooling practice.

Forging Processes

- Advantages
  - Metal flow and grain structure can be controlled
  - Results in good strength and toughness
  - Near net shape (low buy to fly ratio)
  - Parts of reasonable complexity can be created
    - Landing gear
    - Connecting rods
    - Complex shafts
- Disadvantages
  - Dies are expensive, particularly for hot forging
  - Highly skilled labor required

Reference Books

- **Manufacturing Science – Ghosh and Mallik (East- West Press)**
- **Manufacturing Technology Vol I – P. N. Rao (TMH)**
- **Manufacturing Engineering & Technology- S. Kalpakjian and S. R. Schmid (Pearson).**
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- **Fundamental of Manufacturing Processes: G. K. Lal and S. K. Choudhuary (Narosa).**


THANK YOU

Analysis of Forging of a strip
Lecture-07

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Methods used for analysis of Metal Forming process

- Slab method
- Uniform – deformation energy method
- Slip-line field theory
- Upper and lower bound solutions
- Finite element method

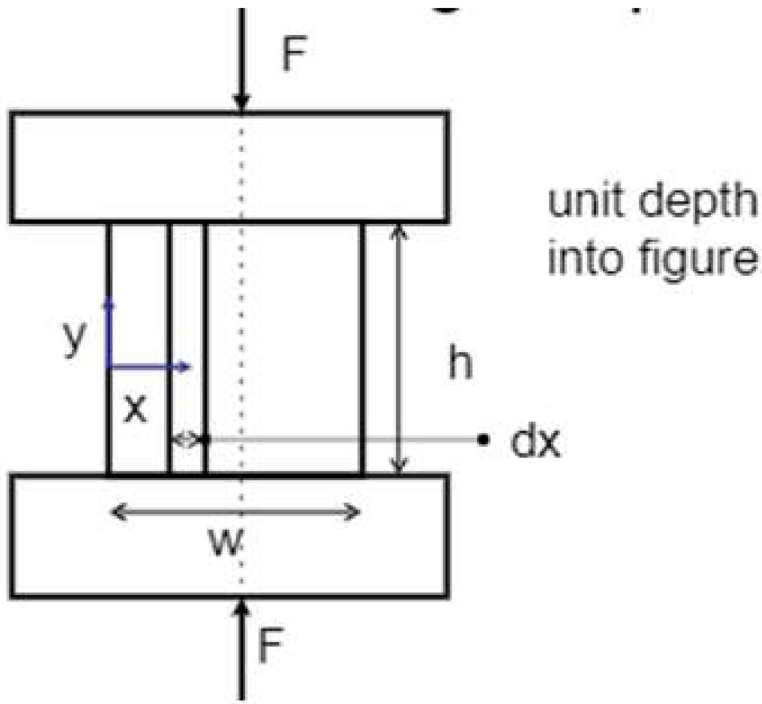
Forging Analysis of a Strip

Assumptions

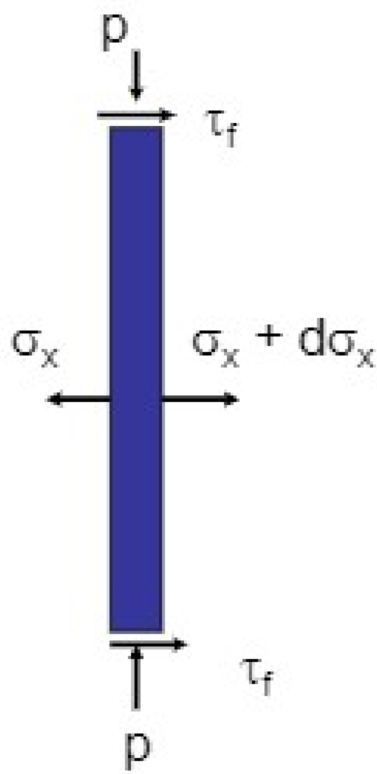
- Entire forging is plastic
  - no elasticity
- Material is perfectly plastic
  - strain hardening and strain rate effects later
- Friction coefficient (μ) is constant
  - all sliding, to start
- Plane strain
  - no z-direction deformation
- In any thin slab, stresses are uniform

Open die Forging Analysis

Rectangular part



Expanding the dx slice on LHS



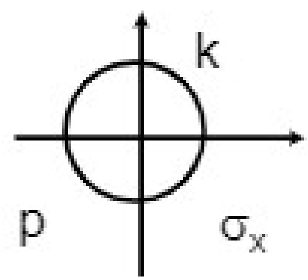
- p = die pressure
- σ_x, $d\sigma_x$ from material on side
- $\tau_{friction}$ = friction force = μp

Force balance in x-direction

$$h d\sigma_x + 2\tau_{friction} dx = 0$$

$$d\sigma_x = -\frac{2\tau_{friction}}{h} dx$$

Mohr's circle



$$\sigma_x + p = 2k = \frac{2}{\sqrt{3}} \sigma_{flow} = 1.15 \cdot \sigma_{flow}$$

(distortion energy (von Mises) criterion, plane strain)

Force balance

Differentiating, and substituting into Mohr's circle equation

$$d(2k) = d(\sigma_x + p) \quad \therefore\ dp = -d\sigma_x$$

$$d\sigma_x = -\frac{2\tau_{friction}}{h}dx \quad \therefore\ dp = \left(\frac{2\tau_{friction}}{h}\right)dx$$

noting: $\tau_{friction} = \mu p$

$$dp = \frac{2\mu}{h}pdx \longrightarrow \frac{dp}{p} = \frac{2\mu}{h}dx$$

Sliding region

$$\int_{2k}^{p_x} \frac{dp}{p} = \int_{0}^{x} \frac{2\mu}{h} dx$$

- Noting: @ x = 0, $\sigma_x = 2k = 1.15\ \sigma_{flow}$

Forging pressure – sliding region

$$\ln p_x - \ln(2k) = 2\mu \frac{x}{h}$$

Sliding region result ($0 < x < x_k$)

$$\frac{p_x}{2k} = \exp\left(\frac{2\mu x}{h}\right)$$

$$p_x = 1.15 \cdot \sigma_{flow} \cdot \exp\left(\frac{2\mu x}{h}\right)$$

Forging pressure – approximation

- Taking the first two terms of a Taylor's series expansion for the exponential about 0, for $|x| \le 1$

$$\exp(x) = 1 + x + \cancelto{0}{\frac{x^2}{2!}} + \cancelto{0}{\frac{x^3}{3!}} + \cdots + \frac{x^n}{n!} = \sum_{k=0}^{n} \frac{x^k}{k!}$$

yields

$$\frac{p_x}{2k} = \left(1 + \frac{2\mu x}{h}\right) \qquad p_x = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{2\mu x}{h}\right)$$

Average forging pressure – all sliding approximation

- using the Taylor's series approximation

$$\frac{p_{ave}}{2k} = \frac{\int_0^{\frac{w}{2}} \frac{p_x}{2k}\,dx}{\frac{w}{2}} = \frac{\int_0^{\frac{w}{2}} \left(1+\frac{2\mu x}{h}\right)dx}{\frac{w}{2}} = \frac{\left.\left(x+\frac{2\mu x^2}{2h}\right)\right|_0^{\frac{w}{2}}}{\frac{w}{2}}$$

$$\frac{p_{ave}}{2k} = \left(1+\frac{\mu w}{2h}\right)$$

$$p_{ave} = 1.15 \cdot \sigma_{flow} \cdot \left(1+\frac{\mu w}{2h}\right)$$

N.B done on a per unit depth basis

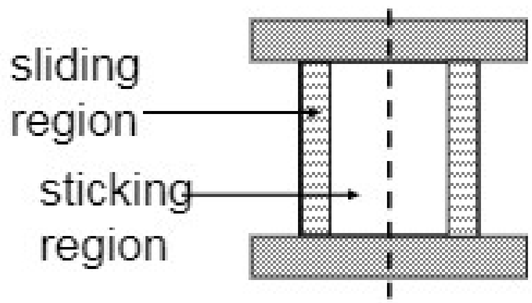
Forging force – all sliding approximation

$$F_{forging} = p_{ave} \cdot width \cdot depth$$

$$F_{forging} = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{\mu w}{2h}\right) \cdot w \cdot depth$$

Slab - die interface

- Sliding if $\tau_f < \tau_{flow}$
- Sticking if $\tau_f \geq \tau_{flow}$
  - can't have a force on a material greater than its flow (yield) stress
  - deformation occurs in a sub-layer just within the material with stress τ_{flow}



Sliding / sticking transition

- Transition will occur at x_k
- using $k = \mu p$, in:

$$\frac{p_x}{2k} = \exp\left(\frac{2\mu x}{h}\right) \qquad \frac{k}{2\mu k} = \exp\left(\frac{2\mu x_k}{h}\right)$$

- hence:

$$\frac{x_k}{h} = \frac{1}{2\mu} \ln \frac{1}{2\mu}$$

Sticking region

$$dp = \frac{2\mu}{h} p dx$$

- Using p = k/ μ

$$dp = \frac{2\mu}{h} \frac{k}{\mu} dx$$

$$\int_{p_{x_k}}^{p_x} dp = \int_{x_k}^{x} \frac{2k}{h} dx$$

$$p_x - p_{x_k} = \frac{2k}{h}(x - x_k)$$

Sticking region

We know that

- at $x = x_k$, $p_{x_k} = k/\mu$

- and $$\frac{x_k}{h} = \frac{1}{2\mu}\ln\frac{1}{2\mu}$$

Forging pressure - sticking region

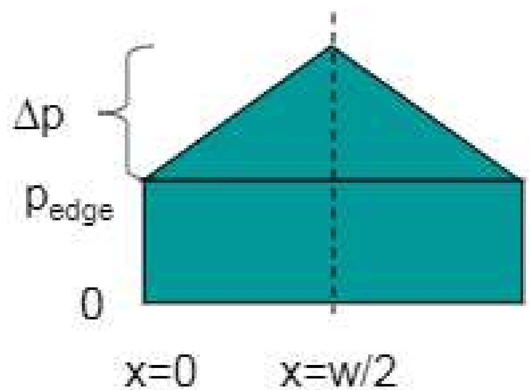
Combining (for $x_k < x < w/2$)

$$\frac{p_x}{2k} = \frac{1}{2\mu}\left(1 - \ln\left(\frac{1}{2\mu}\right)\right) + \frac{x}{h}$$

$$p_x = 1.15 \cdot \sigma_{flow} \cdot \left[\frac{1}{2\mu}\left(1 - \ln\left(\frac{1}{2\mu}\right)\right) + \frac{x}{h}\right]$$

Forging pressure – all sticking approximation

- If x_k << w, we can assume all sticking, and approximate the total forging force per unit depth (into the figure) by:



Forging pressure – all sticking approximation

$$p_{edge} = 2k$$

$$\int_{2k}^{p_x} dp = \int_0^x \frac{2k}{h} dx \qquad p_x - 2k = \frac{2k}{h}(x)$$

$$\therefore \frac{p_x}{2k} = \left(1 + \frac{x}{h}\right)$$

$$p_x = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{x}{h}\right)$$

Average forging pressure – all sticking approximation

$$\frac{p_{ave}}{2k} = \frac{\int_0^{\frac{w}{2}} \frac{p_x}{2k}\,dx}{w/2} = \frac{\int_0^{\frac{w}{2}} \left(1+\frac{x}{h}\right)dx}{w/2} = \frac{\left(x+\frac{x^2}{2h}\right)\Big|_0^{\frac{w}{2}}}{w/2}$$

$$\frac{p_{ave}}{2k} = \left(1+\frac{w}{4h}\right)$$

$$p_{ave} = 1.15\cdot\sigma_{flow}\cdot\left(1+\frac{w}{4h}\right)$$

Forging force – all sticking approximation

$$F_{forging} = p_{ave} \cdot width \cdot depth$$

$$F_{forging} = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{w}{4h}\right) \cdot w \cdot depth$$

Sticking and sliding

- If you have both sticking and sliding, and you can't approximate by one or the other,
- Then you need to include both in your pressure and average pressure calculations.

$$F_{forging} = F_{sliding} + F_{sticking}$$

$$F_{forging} = (p_{ave} \cdot A)_{sliding} + (p_{ave} \cdot A)_{sticking}$$

Reference Books

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THANK YOU

Analysis of Forging of disc
Lecture-08

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Methods used for analysis of Metal Forming process

- Slab method
- Uniform – deformation energy method
- Slip-line field theory
- Upper and lower bound solutions
- Finite element method

Forging Analysis of a Disc

- ❖ Fig. shows a typical open die forging of a circular disc at the end of operation, when the disc has a thickness h and a radius R.
- ❖ The origin of the cylindrical coordinate system r, θ, z is taken at the centre of the disc.

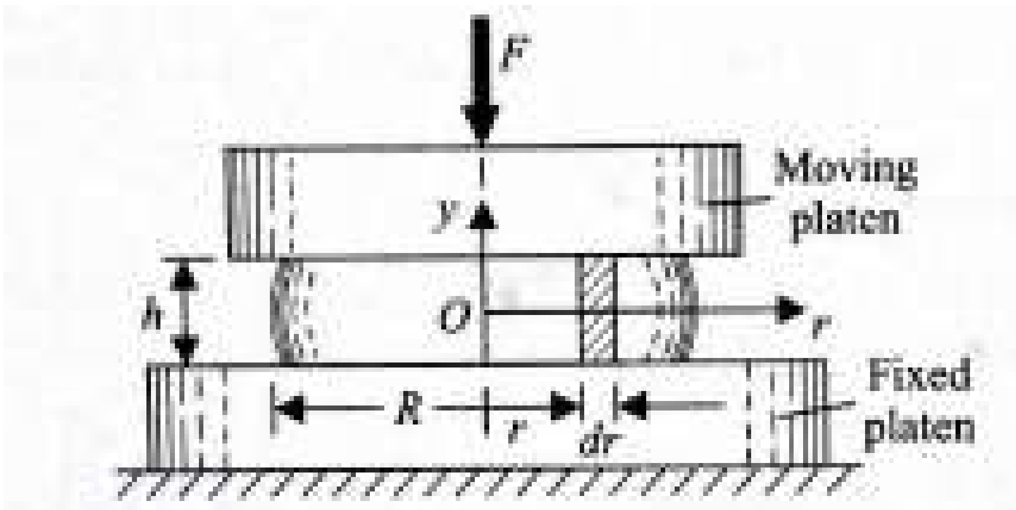
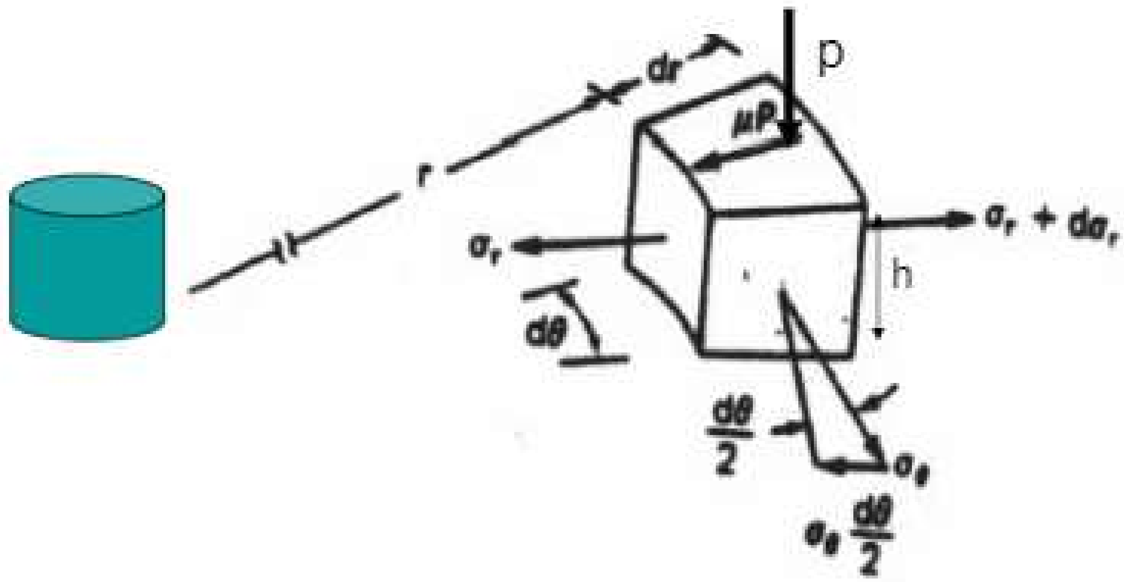


Fig. Forging of disc

Forging – cylindrical part sliding region



Equilibrium in r direction

$$\sum dF_r = 0 = -\sigma_r \cdot h \cdot r \cdot d\theta - 2 \cdot \mu \cdot p \cdot r \cdot d\theta \cdot dr$$

$$-2 \cdot \sigma_\theta \cdot h \cdot dr \cdot \frac{d\theta}{2} + \left(\sigma_r + d\sigma_r\right) \cdot \left(r + dr\right) \cdot h \cdot d\theta$$

N.B. $\sin\left(\frac{d\theta}{2}\right) = \frac{d\theta}{2}$

neglecting HOTs

$$2\mu pr \cdot dr + h\sigma_\theta \cdot dr - h\sigma_r \cdot dr - hr \cdot d\sigma_r = 0$$

Axisymmetric flow and yield

For axisymmetric flow

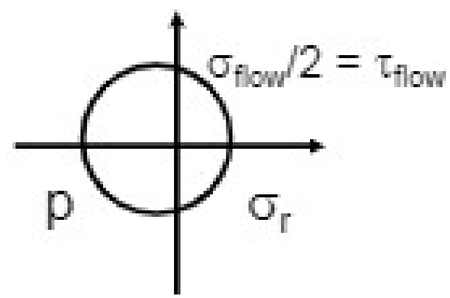
$$\varepsilon_r = \frac{dr}{r}; \quad \varepsilon_\theta = \frac{2\pi(r+dr) - 2\pi r}{2\pi r} = \frac{dr}{r}$$

$$\varepsilon_r = \varepsilon_\theta; \sigma_r = \sigma_\theta$$

By Tresca

$$\sigma_r + p = \sigma_{flow} = 2k = 2\tau_{flow}$$

$$d\sigma_r = -dp$$



Stress in z direction

substituting

$$2\mu pr \cdot dr + h\sigma_r \cdot dr - h\sigma_r \cdot dr + hr \cdot dp = 0$$

or

$$2\mu pr \cdot dr = -hr \cdot dp$$

rearranging

$$\frac{dp}{p} = -\frac{2\mu}{h} dr$$

Forging pressure - sliding

$$\int_{p_r}^{2\tau_{flow}} \frac{dp}{p} = -\int_{r}^{R} \frac{2\mu}{h} \cdot dr$$

for $r_k < r < R$

$$\frac{p_r}{2\tau_{flow}} = \exp\left[\frac{2\mu}{h}(R-r)\right]$$

Average forging pressure – all sliding approximation ($r_k = 0$)

- Taking the first four terms of a Taylor's series expansion for the exponential about 0 for $|x| \le 1$

$$\exp(x) = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots + \frac{x^n}{n!} = \sum_{k=0}^{n} \frac{x^k}{k!}$$

yields

$$\frac{p_{ave}}{2\tau_{flow}} = \left[1 + \left(\frac{2\mu R}{3h}\right)\right]$$

Forging force – all sliding approximation

$$F_{forging} = p_{ave} \cdot A = p_{ave} \cdot \pi \cdot R^2$$

$$F_{forging} = 2\tau_{flow} \cdot \left[1 + \left(\frac{2\mu R}{3h} \right) \right] \cdot \pi R^2$$

Transition sticking / sliding

- Set $\tau_{flow} = \mu p$ and solve for r_k

$$\frac{p}{2\tau_{flow}} = \exp\left[2\mu\left(\frac{R-r_k}{h}\right)\right] \rightarrow \frac{p}{2\mu \cdot p} = \exp\left[2\mu\left(\frac{R-r_k}{h}\right)\right]$$

$$\ln\left(\frac{1}{2\mu}\right) = 2\mu\left(\frac{R-r_k}{h}\right) \longrightarrow r_k = R - \frac{h}{2\mu}\ln\left(\frac{1}{2\mu}\right)$$

Forging pressure - sticking region

- Use the same method as for sliding
- Substitute $\mu p = \tau_{flow}$,
- Assume Tresca yield criterion

$$2\mu pr \cdot dr = -hr \cdot dp$$

$$2\tau_{flow} r \cdot dr = -hr \cdot dp$$

$$dp = -\frac{2\tau_{flow}}{h} dr$$

Forging pressure - sticking region

$$\int_{p_{r_k}}^{p_r} dp = -\int_{r_k}^{r} \frac{2\tau_{flow}}{h} dr$$

$$p_r - p_{r_k} = -\frac{2\tau_{flow}}{h}(r - r_k)$$

$$\frac{p_r - p_{r_k}}{2\tau_{flow}} = \frac{(r_k - r)}{h}$$

Forging pressure - sticking region

p_{r_k} determined from sliding equation

$$\frac{p_{r_k}}{2\tau_{flow}} = \exp\left[\frac{2\mu}{h}(R - r_k)\right]$$

for $0 < r < r_k$

$$\frac{p_r}{2\tau_{flow}} = \exp\left[\frac{2\mu}{h}(R - r_k)\right] + \frac{(r_k - r)}{h}$$

Average forging pressure - sticking

$$\frac{p_{ave}}{2\tau_{flow}} = \frac{1}{\pi r_k^2}\int_0^{r_k} p_r \cdot 2\pi r \cdot dr = \frac{2}{r_k^2}\int_0^{r_k}\left(\exp\left[\frac{2\mu}{h}(R-r_k)\right] + \frac{r_k - r}{h}\right)\cdot r dr$$

$$\frac{p_{ave}}{2\tau_{flow}} = \frac{2}{r_k^2}\int_0^{r_k}\left(r \cdot \exp\left[\frac{2\mu}{h}(R-r_k)\right] + \frac{r_k \cdot r}{h} - \frac{1}{h}r^2\right)\cdot dr$$

$$\frac{p_{ave}}{2\tau_{flow}} = \frac{2}{r_k^2}\left(\frac{r^2}{2}\cdot \exp\left[\frac{2\mu}{h}(R-r_k)\right] + \frac{r_k \cdot r^2}{2h} - \frac{r^3}{3h}\right)\Bigg|_0^{r_k}$$

Average forging pressure - sticking

$$\frac{p_{ave}}{2\tau_{flow}} = \frac{2}{r_k^2}\left(\frac{r^2}{2}\cdot\exp\left[\frac{2\mu}{h}(R-r_k)\right] + \frac{r_k\cdot r^2}{2h} - \frac{r^3}{3h}\right)\Bigg|_0^{r_k}$$

$$\frac{p_{ave}}{2\tau_{flow}} = \frac{2}{r_k^2}\left(\frac{r_k^2}{2}\cdot\exp\left[\frac{2\mu}{h}(R-r_k)\right] + \frac{r_k^3}{2h} - \frac{r_k^3}{3h}\right)$$

$$\frac{p_{ave}}{2\tau_{flow}} = \left(\exp\left[\frac{2\mu}{h}(R-r_k)\right] + \frac{r_k}{3h}\right)$$

Forging force – sticking region

$$F_{forging} = p_{ave} \cdot A = p_{ave} \cdot \pi \cdot r_k^2$$

$$F_{forging} = 2\tau_{flow} \cdot \left(\exp\left[\frac{2\mu}{h}(R - r_k) \right] + \frac{r_k}{3h} \right) \cdot \pi \cdot r_k^2$$

Sticking and sliding

- If you have both sticking and sliding, and you can't approximate by one or the other,
- Then you need to include both in your pressure and average pressure calculations.

$$F_{forging} = F_{sliding} + F_{sticking}$$

$$F_{forging} = (p_{ave} \cdot A)_{sliding} + (p_{ave} \cdot A)_{sticking}$$

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THANK YOU

Rolling Process
Lecture-09

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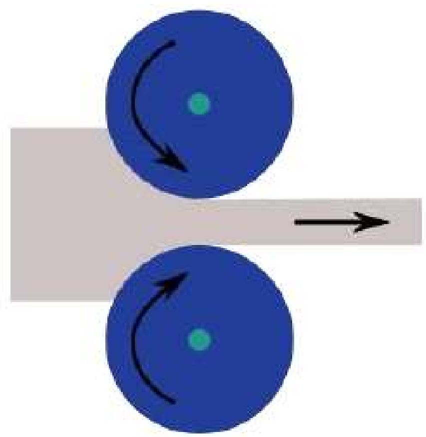
Contents

- Process
- Equipment
- Products
- Defects

ROLLING

- The process of plastically deforming metals by passing it between rolls is known as rolling.
- The material is subjected to high compressive stresses from the squeezing action of the rolls and to surface shear stresses as a result of the friction between the rolls and the metal.



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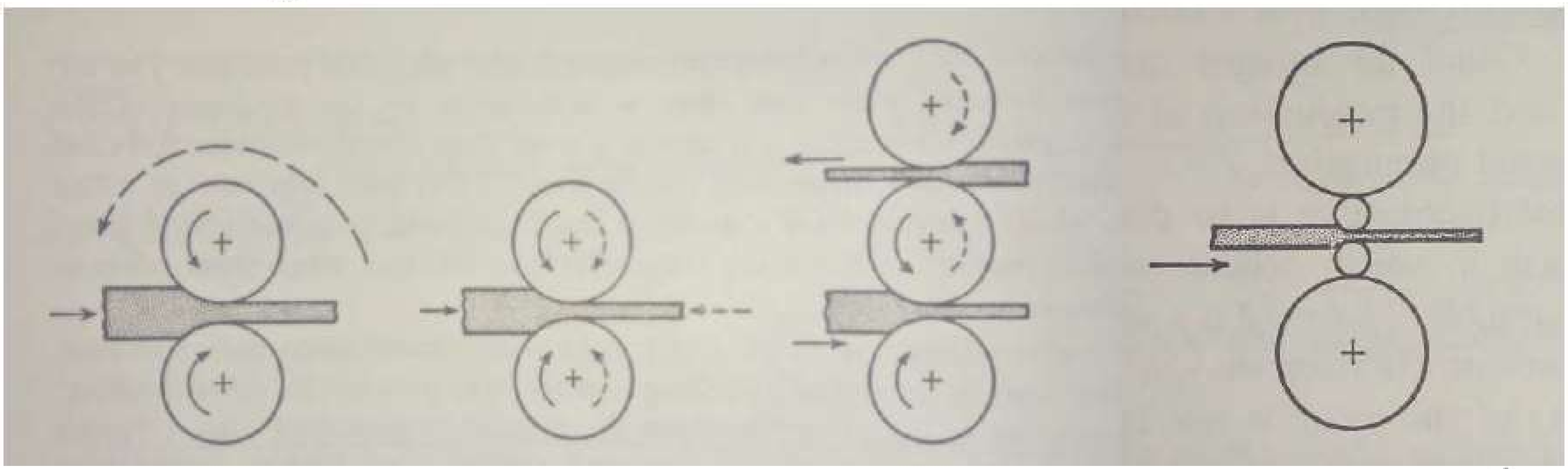
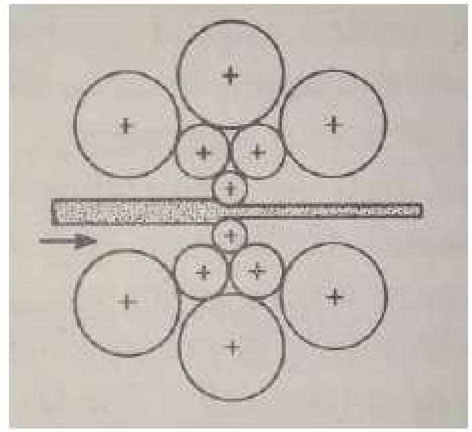
ROLLING MILLS (classified as number of arrangements of rolls)

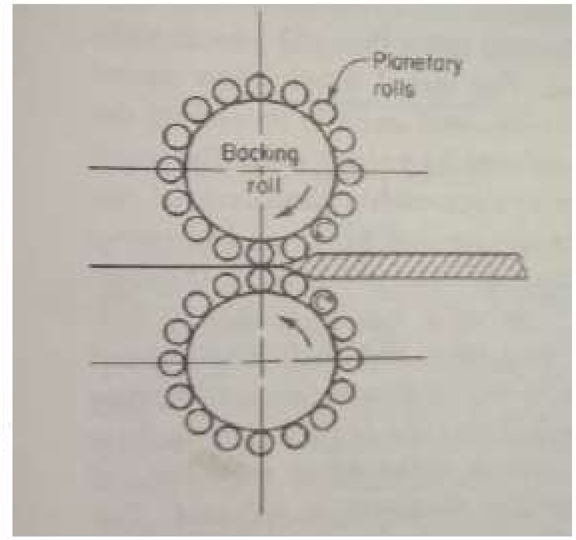
1. Two-high mill
2. Two-high reversing mill
3. Three-high mill
4. Four-high mill

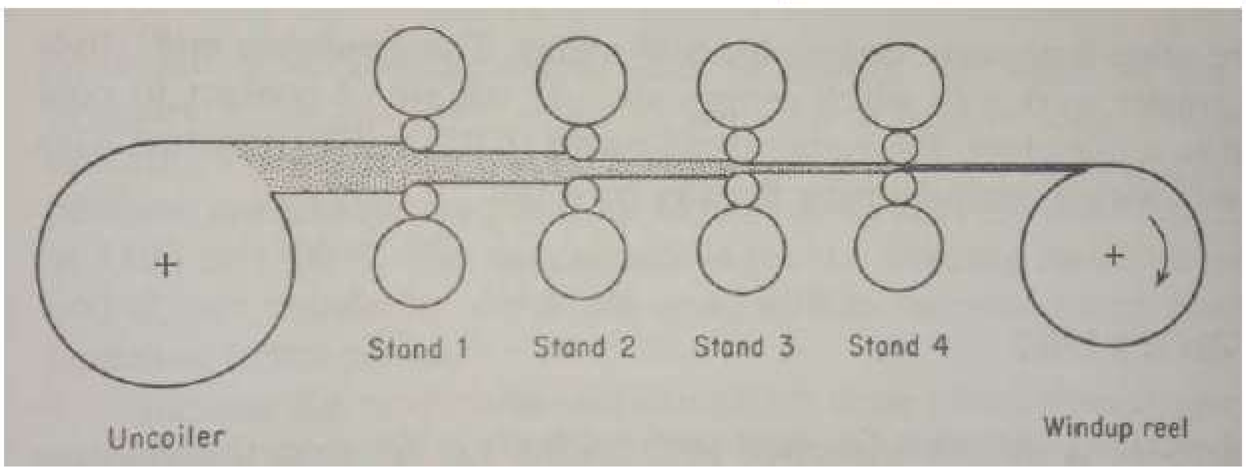


A large decrease in the power required for rolling can be achieved by the use of small-diameter rolls.

5. Cluster mill
6. Planetary mill
7. Four stand continuous mill





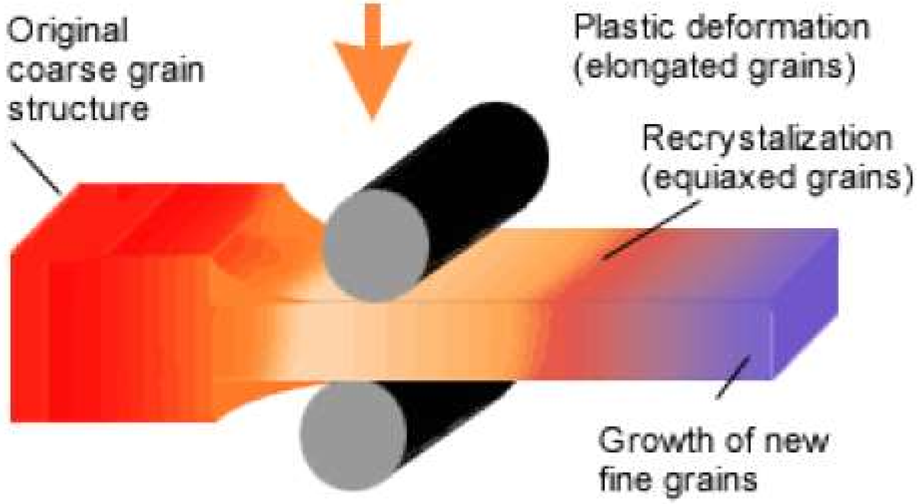


Rolls

- Rolls are made from cast iron, cast steel or forged steel depending on the required strength and allowed resistance to wear
- Small diameter rolls such as the work rolls used in cluster mill – tungsten carbide.
- Forged steel rolls have greater strength, stiffness and toughness than cast iron rolls but are more expensive
- Rolls designed for cold rolling operation should not used for hot rolling, because cracks can develop from thermal cycling.

The initial breakdown of ingots into blooms & billets is generally done by hot-rolling. And then cold-rolling is to be done to get good surface finish and close control over dimension.

HOT ROLLING - occurs above the recrystallization temperature of the material.



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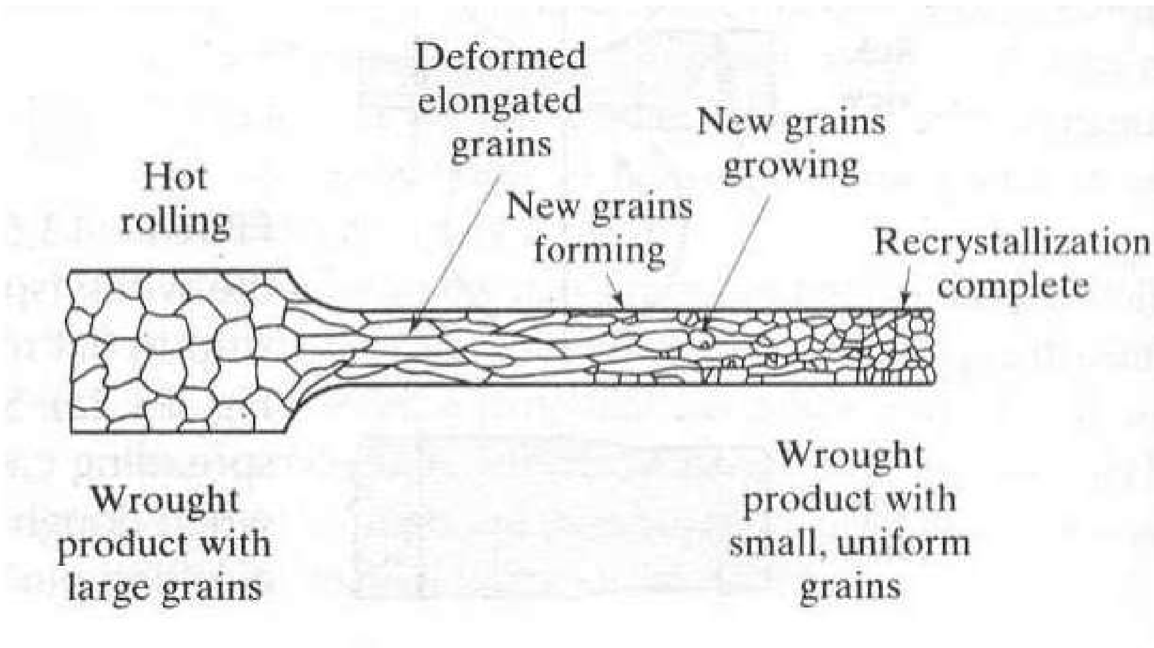
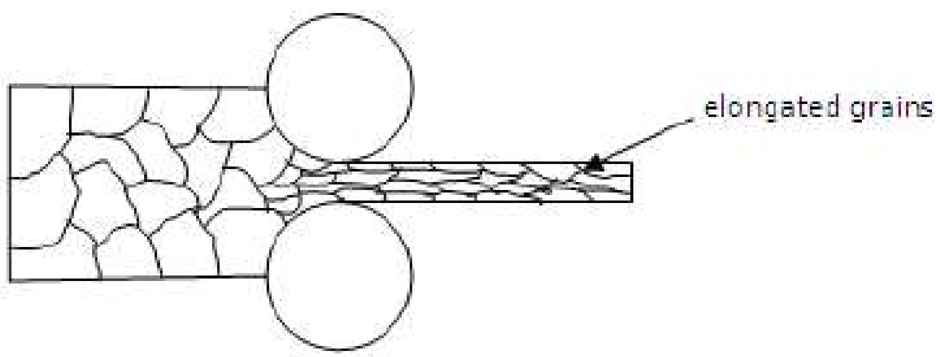


- Hot rolling is used mainly to produce sheet metal or simple cross sections, such as rail tracks.
- It will reduce the average grain size of metal, this improves the strength of material.

COLD ROLLING – Used to produce sheet & strip with superior surface finish and dimensional tolerance.

Also, the strain hardening results from the cold reduction may be used to give increased strength.

- Total reduction achieved will vary from 50 to 90 percent.
- The lowest %age reduction is taken in the last pass to permit better control of flatness, gage and surface finish.
- Done usually at room temperature.



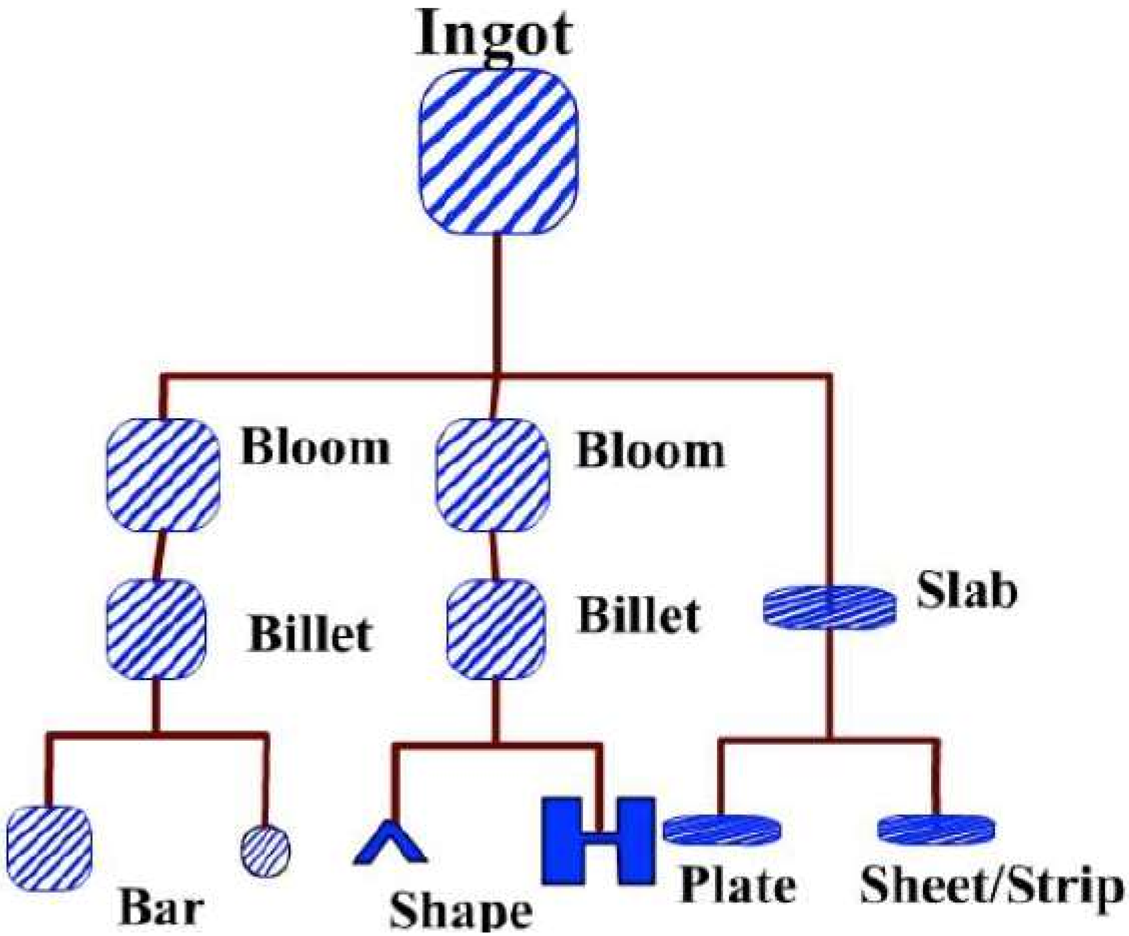
HOT ROLLING	COLD ROLLING
1. Blowholes and porosity eliminates by welding together.	1. Results in increased strength or hard -ness.
2. This will results into better ductility and toughness.	2. Better dimensional control.
	3. Good surface finish.
3. Surface decarburization of steels.	4. Ductility decreases.
4. Not good surface finish.	5. Yield point phenomenon (results in inhomogeneous deformation), occur in annealed steel sheet.
5. Dimensional tolerance due to expan -sion/contraction of metal.	

PRECAUTIONS

- The roll gap must be perfectly parallel, otherwise one edge of the sheet will be decreased more.
- It is necessary to know the elastic constant of mill. (elastic flattening of the rolls with increasing roll pressure results in a condition where the rolls eventually deform more easily than the workpiece)
- Roll speed must be constant during the operation.

Rolling Products

- From start Ingot-blooms-billet-slab which are further rolled into plate, sheet, rod, bar pipe, rails



Rolling Products

- **A greater volume of metal is rolled than the process by any other means.**

- Shapes
  - I-beams, railroad tracks
- Sections
  - door frames, gutters
- Flat plates
- Rings
- Screws

Products


SECTIONS ROLLED-FORMED–
TO EXACT SPECIFICATIONS
Rolled Pipe And Tubing
Easy-Way Rectangular Tubing
Rolled Square Tubing
Hard-Way Rectangular Tubing
Zees E-Z Way
Beams Hard Way
Beams E-Z Way
Channels Flanges In
Channels–Hard Way
Channels Flanges Out
Angles–Leg Out
Angles–Both Legs In
Angles Leg In
Bars–Hard Way
Bars–E-Z Way
Bars Spiral
Tees–Stem Up
Tees–Stem Out
Tees–Stem In
Rails–Ball Out
Rails–Ball Up
Rails–Ball In

- A greater volume of metal is rolled than processed by any other means.

Products

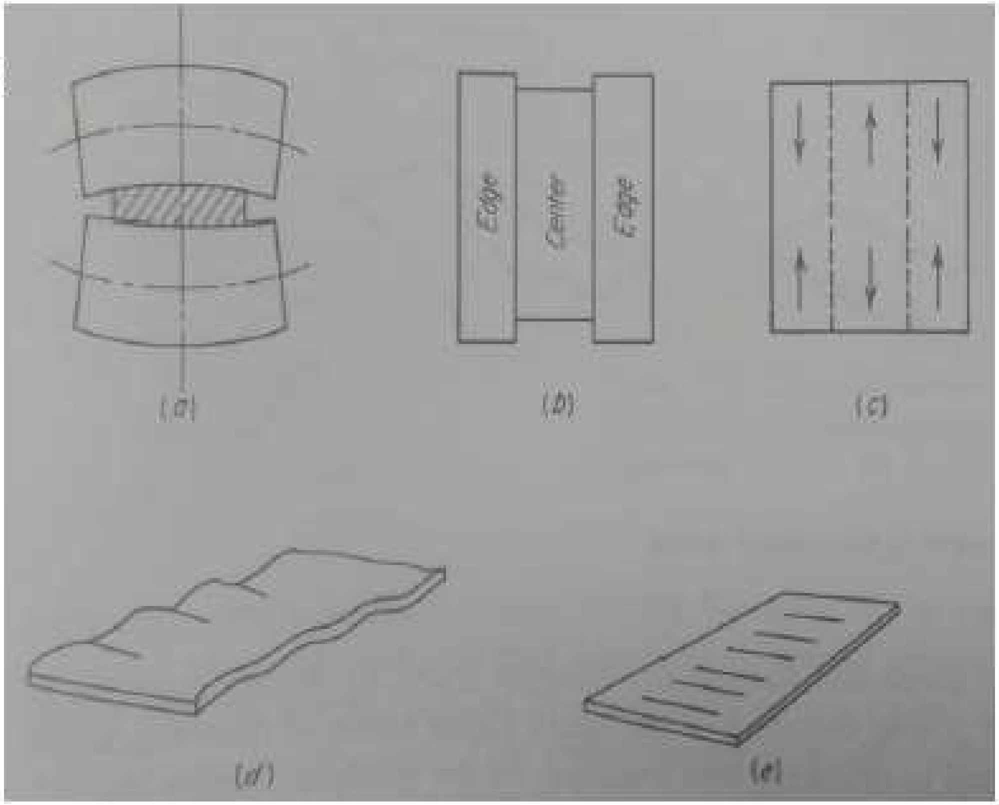
- Shapes
  - I-beams, railroad tracks
- Sections
  - door frames, gutters
- Flat plates
- Rings
- Screws

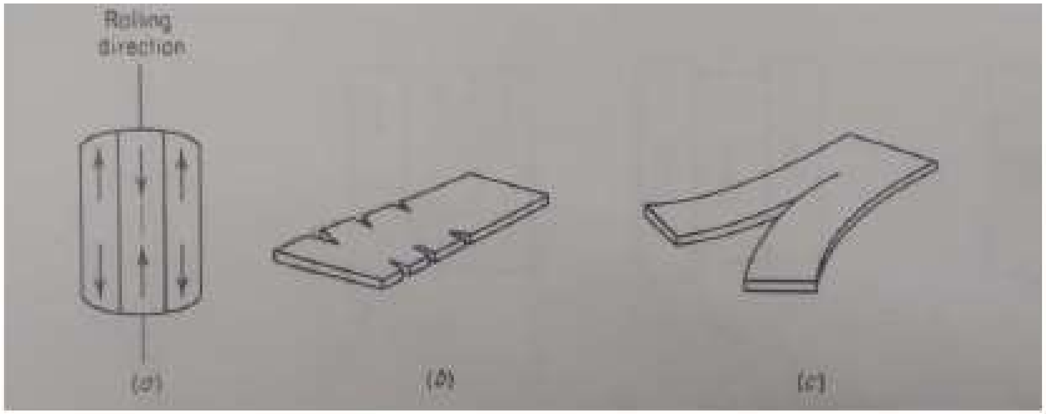
Products

Rolling defects

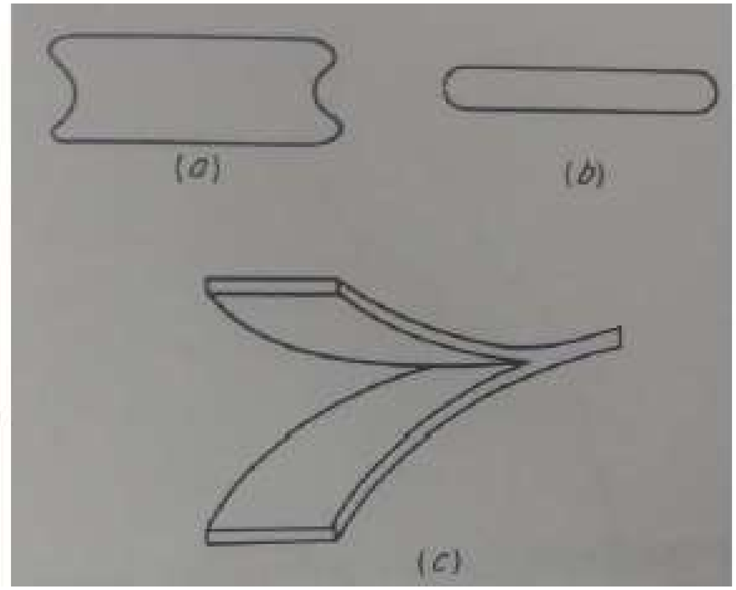
- Surface irregularities – Raw material or ingot having irregularities due to scaling.
- Non-Metallic inclusions – Oxides, nitrides or silicates especially in steels, they may produce severe cracks separating the product into two halves.
- Internal Pores – Due to presence of gases like hydrogen, oxygen, nitrogen. This leads to elongation of pores and product may become weaker.
- Waviness – Occurs because the roll gap is not perfectly parallel and due to the uneven speed of rolls.
- Edge Cracking – Length of the center portion increases but the edges are prevented due to the frictional force.

(a) – edges of the sheet elongated to a greater extent in the longitudinal direction than the center.
(b) – If the edges are free to move relative to center.
(c) – Center portion of sheet is stretched in tension and the edges are compressed in rolling direction.
(d) – wavy edge or edge buckle.
(e) – Cracks in the center of the sheet.





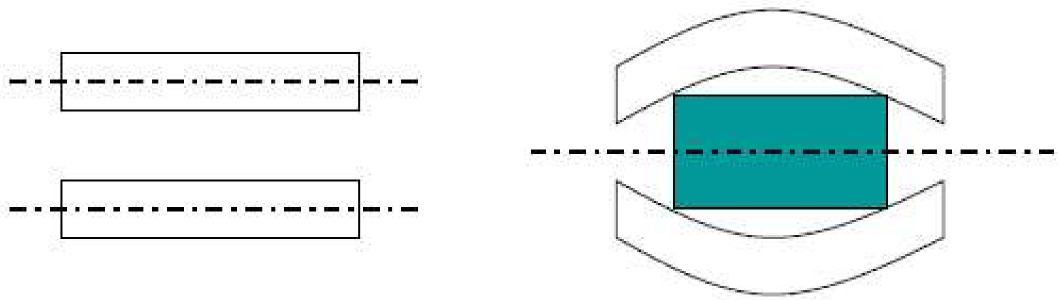
Defects resulting from lateral spread.
Edge cracking and center split.



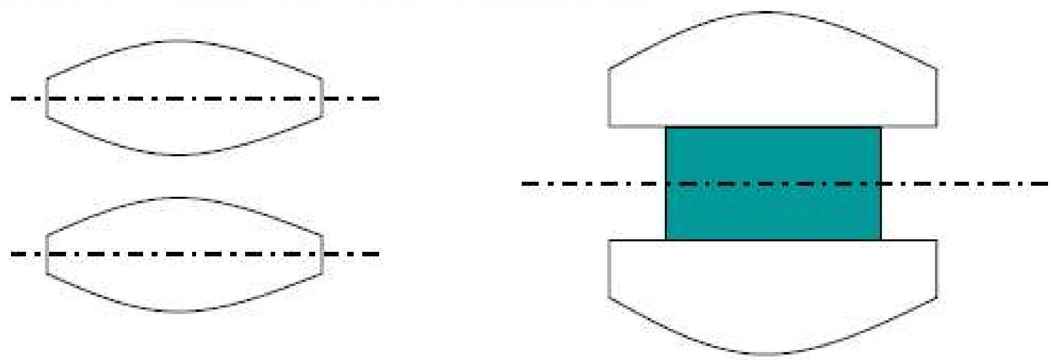
(a) Light reduction
(b) Heavy reduction
(c) Alligatoring

Roll deflection

Rolls can deflect under load



Rolls can be crowned



Reference Books

- **Manufacturing Science – Ghosh and Mallik (East- West Press)**
- **Manufacturing Technology Vol I – P. N. Rao (TMH)**
- **Physical Metallurgy – Dieter (TMH)**
- **Manufacturing Engineering & Technology- S. Kalpakjian and S. R. Schmid (Pearson).**
- **Manufacturing Processes Vol I – H. S. Shan (Pearson)**
- **Fundamental of Manufacturing Processes: G. K. Lal and S. K. Choudhuary (Narosa).**


THANK YOU

Analysis of Rolling
Lecture-08

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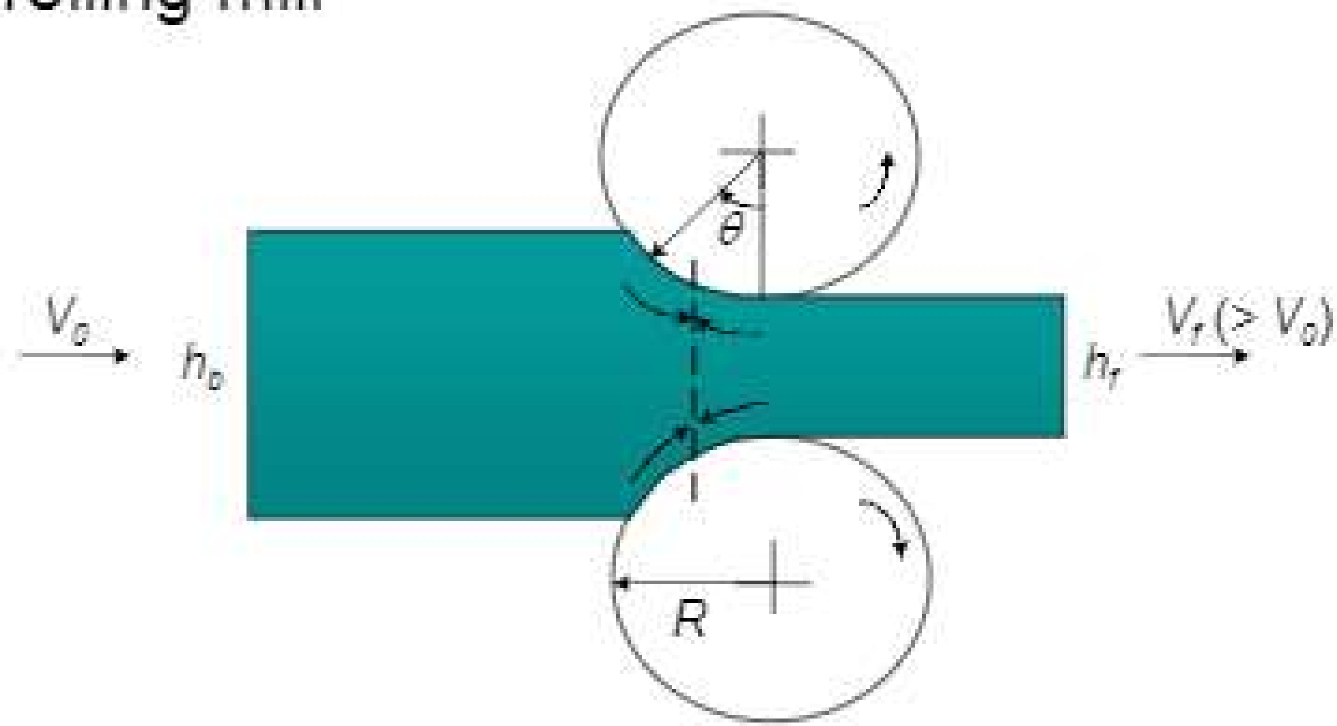
Rolling Analysis

- Objectives
  - Find distribution of roll pressure
  - Calculate roll separation force ("rolling force") and torque
  - Processing Limits
  - Calculate rolling power

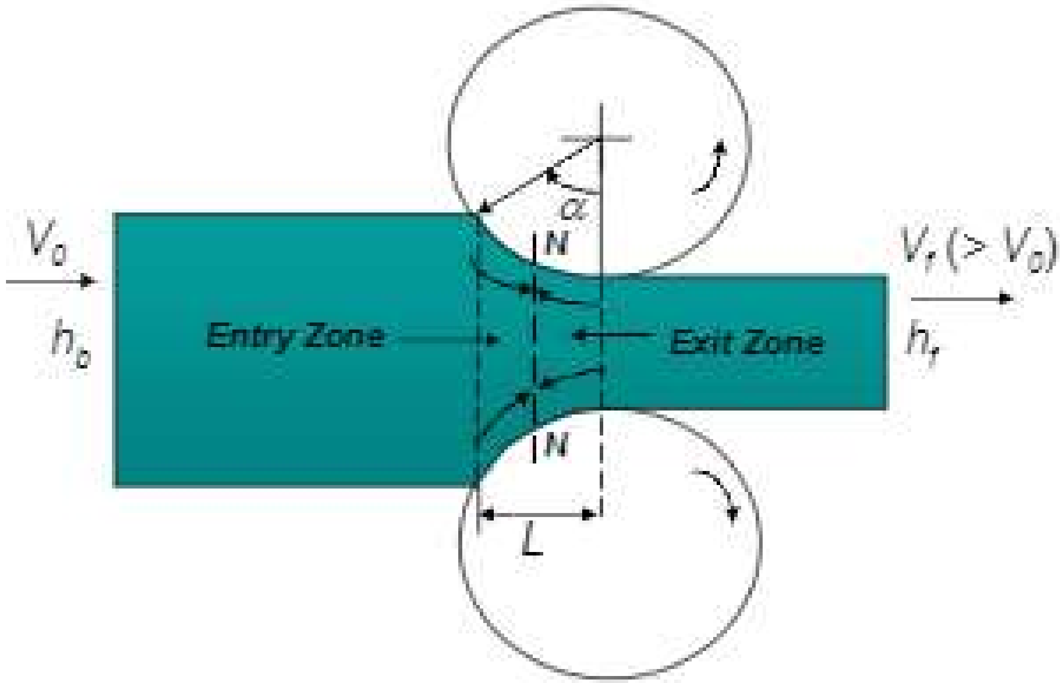
Flat Rolling Analysis

- Consider rolling of a flat plate in a 2-high rolling mill



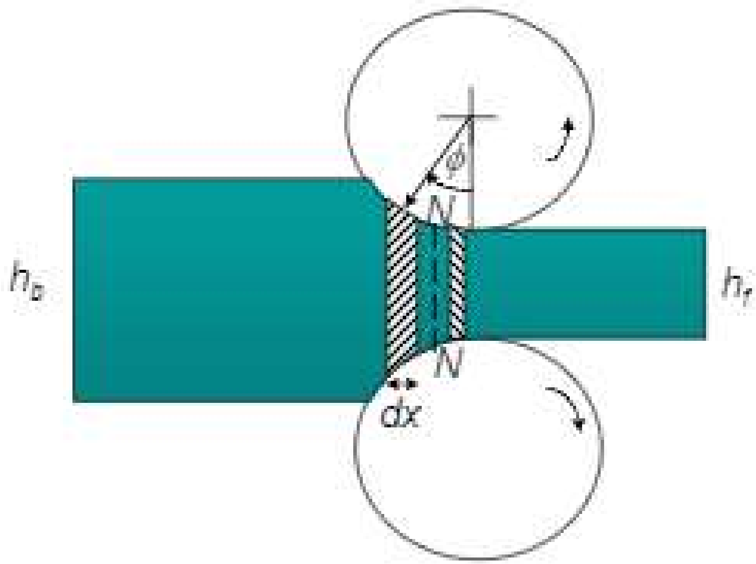
Width of plate w is large → plane strain

Flat Rolling Analysis

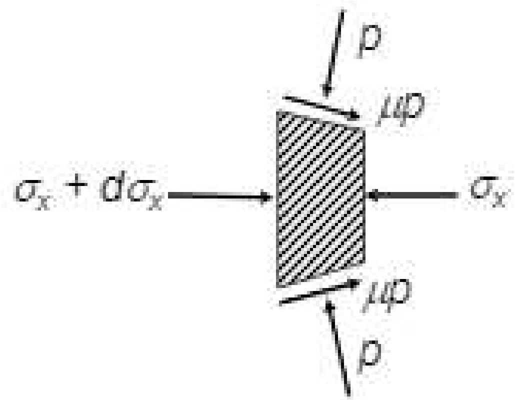


- Friction plays a critical role in enabling rolling → $\mu \geq \tan\alpha$ cannot roll without friction; for rolling to occur
- Reversal of frictional forces at neutral plane (*NN*)

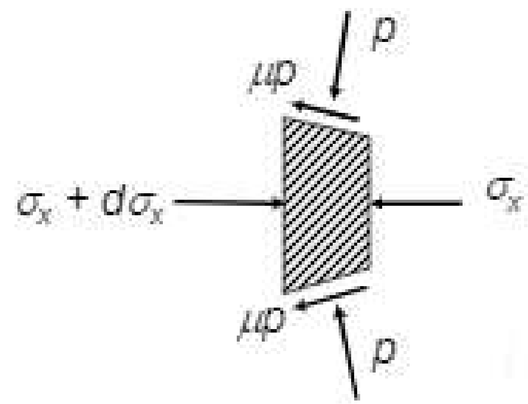
Flat Rolling Analysis



Stresses on Slab in Entry Zone



Stresses on Slab in Exit Zone



Equilibrium

- Appling equilibrium in x (top entry, bottom exit)

$$(\sigma_x + d\sigma_x)\cdot(h+dh) - 2pR\cdot d\phi\cdot\sin\phi \pm 2\mu pR\cdot d\phi\cdot\cos\phi - \sigma_x h = 0$$

Simplifying and ignoring HOTs

$$\frac{d(\sigma_x h)}{d\phi} = 2pR\cdot(\sin\phi \mp \mu\cos\phi)$$

Simplifying

- Since $\alpha << 1$, then $\sin\phi = \phi$, $\cos\phi = 1$

$$\frac{d(\sigma_x h)}{d\phi} = 2pR \cdot (\phi \mp \mu)$$

- Plane strain, von Mises

$$p - \sigma_x = 1.15 \cdot Y_{flow} \equiv Y'_{flow}$$

Differentiating

- Substituting

$$\frac{d\left[\left(p - Y'_{flow}\right)\cdot h\right]}{d\phi} = 2pR\cdot(\phi \mp \mu)$$

- or

$$\frac{d}{d\phi}\left[Y'_{flow}\cdot\left(\frac{p}{Y'_{flow}} - 1\right)\cdot h\right] = 2pR\cdot(\phi \mp \mu)$$

Differentiating

$$Y'_{flow}\cdot h\cdot\frac{d}{d\phi}\left(\frac{p}{Y'_{flow}}\right)+\left(\frac{p}{Y'_{flow}}-1\right)\cdot\frac{d}{d\phi}\left(Y'_{flow}\cdot h\right)=2pR\cdot(\phi\mp\mu)$$

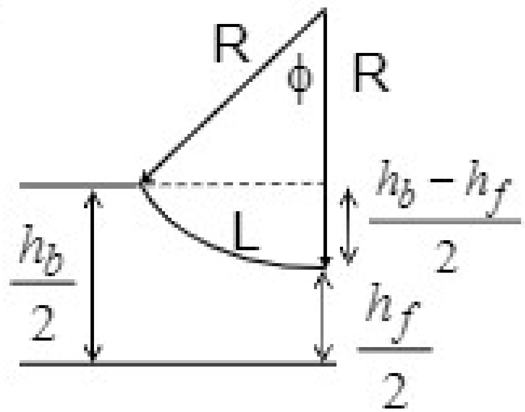
Rearranging, the variation $Y'_{flow}.h$ with respect to ϕ is small compared to the variation p/Y'_{flow} with respect to ϕ so the second term is ignored

$$\frac{\dfrac{d}{d\phi}\left(\dfrac{p}{Y'_{flow}}\right)}{\dfrac{p}{Y'_{flow}}}=\frac{2R}{h}(\phi\mp\mu)$$

Thickness

$$h = h_f + 2R \cdot (1 - \cos\phi)$$

from the definition
of a circular segment



or, after using a Taylor's series expansion, for small ϕ

$$\cos\phi = 1 - \frac{\phi^2}{2!} + \cancelto{0}{\frac{\phi^4}{4!}} \cdots$$

$$h = h_f + R \cdot \phi^2$$

Substituting and integrating

$$\int \frac{d\left(\frac{p}{Y'_{flow}}\right)}{\frac{p}{Y'_{flow}}} = \int \frac{2R}{h_f + R\cdot\phi^2}(\phi \mp \mu)\,d\phi$$

In[1]:= $\int \frac{2\,R\,(\phi-\mu)}{hf + R\,\phi^2}\,d\phi$

Out[1]= $2\,R\left(-\frac{\mu\,\mathrm{ArcTan}\left[\frac{\sqrt{R}\,\phi}{\sqrt{hf}}\right]}{\sqrt{hf}\,\sqrt{R}} + \frac{\mathrm{Log}\left[hf + R\,\phi^2\right]}{2\,R}\right)$

$$\ln\frac{p}{Y'_f} = \ln\frac{h}{R} \mp 2\mu\sqrt{\frac{R}{h_f}}\tan^{-1}\left(\phi\sqrt{\frac{R}{h_f}}\right) + \ln C$$

Eliminating *ln()*

$$p = C \cdot Y'_{flow} \cdot \frac{h}{R} \exp(\mp \mu H)$$

$$H = 2\sqrt{\frac{R}{h_f}} \tan^{-1}\left(\phi \sqrt{\frac{R}{h_f}} \right)$$

Entry region

- at $\phi = \alpha$, $H = H_b$,

$$p = C \cdot Y'_{flow} \cdot \frac{h}{R} \exp(-\mu H)$$

$$C = \frac{R}{h_b} \exp(\mu H_b)$$

$$p = Y'_{flow} \frac{h}{h_b} \exp(\mu [H_b - H])$$

$$p = (Y'_{flow} - \sigma_{xb}) \frac{h}{h_b} \exp(\mu [H_b - H])$$

With back tension=(Y'flow – σ_{xb})

$$H_b = 2\sqrt{\frac{R}{h_f}} \tan^{-1}\left(\alpha \sqrt{\frac{R}{h_f}}\right)$$

$$H = 2\sqrt{\frac{R}{h_f}} \tan^{-1}\left(\phi \sqrt{\frac{R}{h_f}}\right)$$

Exit region

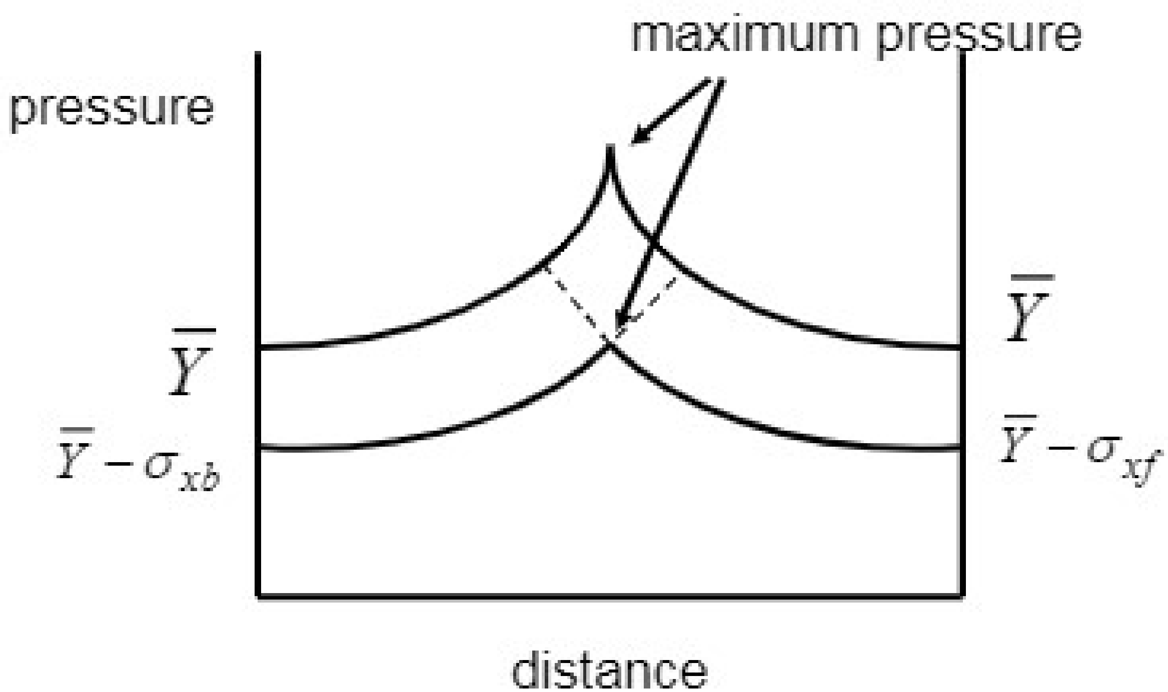
at $\phi = 0$, $H = H_f = 0$,

$$C = \frac{R}{h_f} \qquad p = \left(Y'_{flow}\right)\frac{h}{h_f}\exp(\mu H)$$

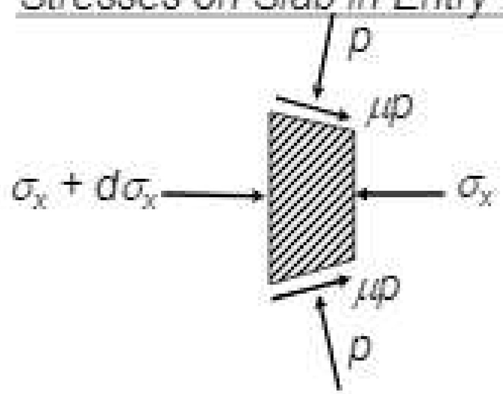
$$p = \left(Y'_{flow} - \sigma_{xf}\right)\frac{h}{h_f}\exp(\mu H)$$ With forward tension

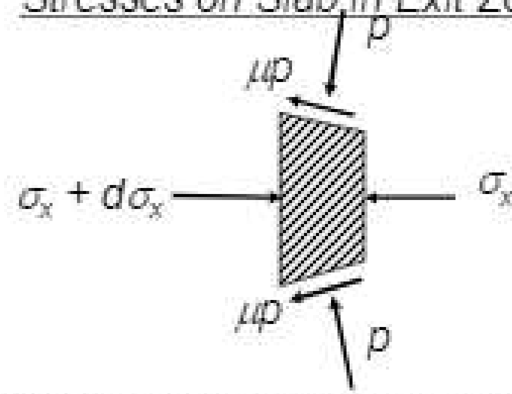
$$H = 2\sqrt{\frac{R}{h_f}}\tan^{-1}\left(\phi\sqrt{\frac{R}{h_f}}\right)$$

Effect of back and front tension



Flat Rolling Analysis Results – without front and back tension





Using slab analysis we can derive roll pressure distributions for the entry and exit zones as: h_0 and h_b are the same thing

$$\boxed{p = \frac{2}{\sqrt{3}} Y_f \frac{h}{h_0} e^{\mu(H_0 - H)}}$$

Entry Zone

$$H = 2\sqrt{\frac{R}{h_f}} \tan^{-1}\left(\sqrt{\frac{R}{h_f}}\phi\right)$$

$$H_0 = H @ \phi = \alpha$$

$$\boxed{p = \frac{2}{\sqrt{3}} Y_f \frac{h}{h_f} e^{\mu H}}$$

Exit Zone

Average rolling pressure – per unit width

$$p_{ave,entry} = -\frac{1}{R(\alpha - \phi_n)} \int_{\alpha}^{\phi_n} p_{entry} R d\phi; \quad p_{ave,exit} = \frac{1}{R\phi_n} \int_{0}^{\phi_n} p_{exit} R d\phi$$

Rolling force

- $F = p_{ave,entry} \times Area_{entry} + p_{ave,exit} \times Area_{exit}$

Force

- An alternative method

$$F = \int_{\phi_n}^{\alpha} w \cdot p_{entry} \cdot R \cdot d\phi + \int_{0}^{\phi_n} w \cdot p_{exit} \cdot R \cdot d\phi$$

- again, very difficult to do.

Force - approximation

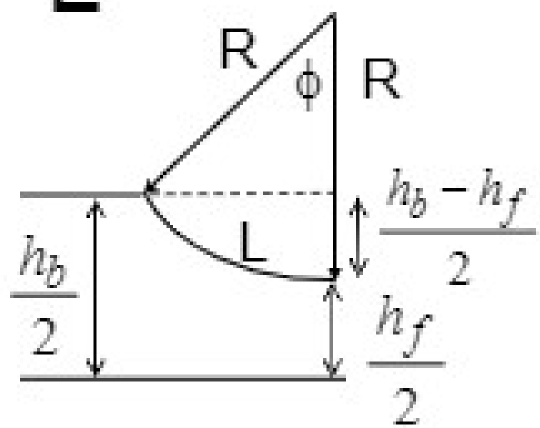
F / roller = $L\ w\ p_{ave}$

$$L \approx \sqrt{R\Delta h}$$

$\Delta h = h_b - h_f$

$$p_{ave} = f\left(\frac{h_{ave}}{L}\right)$$

Derivation of “L”



circular segment

$$h = h_f + 2R \cdot (1 - \cos\phi)$$

Taylor's expansion

$$\cos\phi = 1 - \frac{\phi^2}{2!} + \cancelto{0}{\frac{\phi^4}{4!}} \cdots$$

$$h = h_f + R \cdot \phi^2$$

$$R \cdot \phi = L$$

Derivation of "L"

setting h = h_b at $\phi = \alpha$, substituting, and rearranging

$$h_b - h_f = \Delta h = R \cdot \left(\frac{L}{R} \right)^2$$

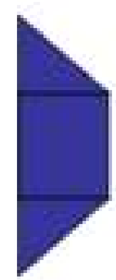
or

$$L = \sqrt{R \cdot \Delta h}$$

Approximation based on forging plane strain – von Mises

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow}\left(1 + \frac{\mu L}{2h_{ave}}\right)$$

average flow stress:
due to shape of element



Small rolls or small reductions

$$\Delta = \frac{h_{ave}}{L} >> 1$$

- friction is not significant (μ -> 0)

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow}\left(1 + \underbrace{\cancel{\frac{\mu L}{2h_{ave}}}}_{0}\right)$$

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow}$$

Large rolls or large reductions

$$\Delta \equiv \frac{h_{ave}}{L} << 1$$

- Friction is significant (forging approximation)

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow} \left(1 + \frac{\mu L}{2 h_{ave}} \right)$$

Force approximation: low friction

$$\Delta \equiv \frac{h_{ave}}{L} >> 1$$

$$F\Big/_{roller} = 1.15 \cdot Lw\overline{Y}_{flow}$$

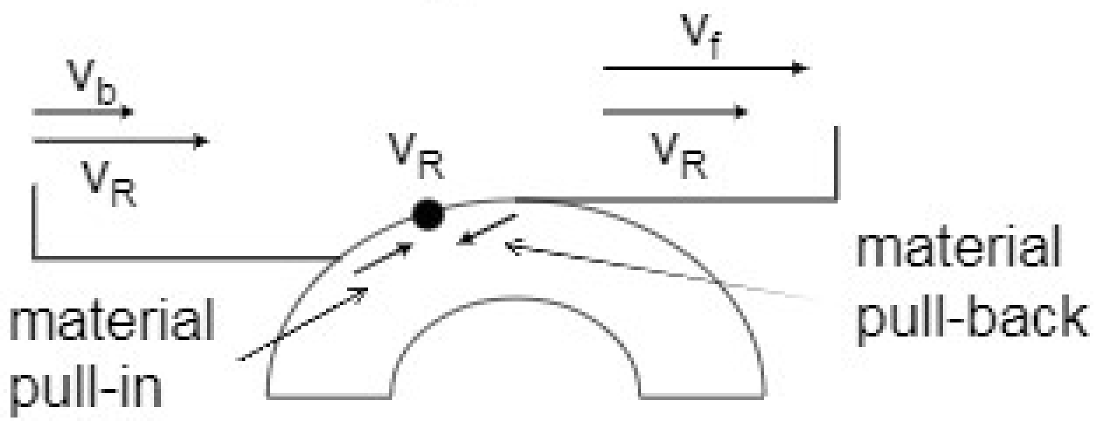
Force approximation: high friction

$$\Delta \equiv \frac{h_{ave}}{L} << 1$$

$$F/_{roller} = 1.15 \cdot Lw\bar{Y}_{flow}\left(1 + \frac{\mu L}{2h_{ave}}\right)$$

Zero slip (neutral) point

- Entrance: material is pulled into the nip
  - roller is moving faster than material
- Exit: material is pulled back into nip
  - roller is moving slower than material



System equilibrium

- Frictional forces between roller and material must be in balance.
  - or material will be torn apart
- Hence, the zero point must be where the two pressure equations are equal.

$$\frac{h_b}{h_f} = \frac{\exp(\mu H_b)}{\exp(2\mu H_n)} = \exp(\mu(H_b - 2H_n))$$

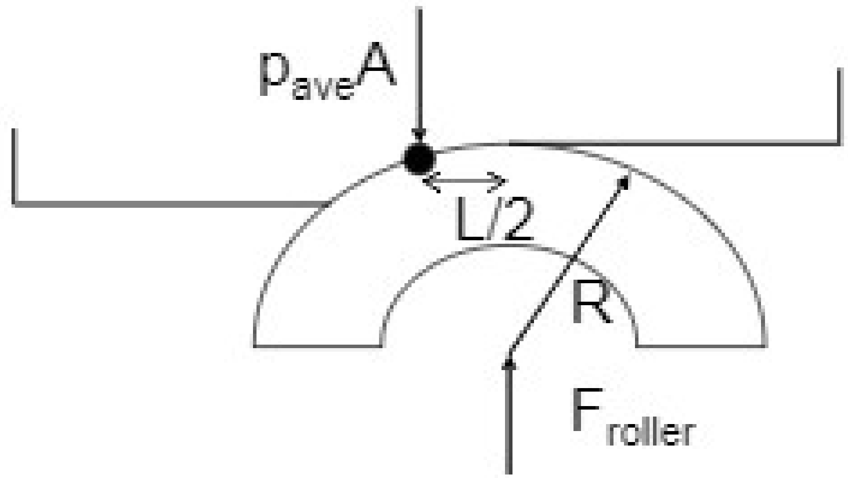
Neutral point

$$H_n = \frac{1}{2}\left(H_b - \frac{1}{\mu} \ln \frac{h_b}{h_f} \right)$$

$$\phi_n = \sqrt{\frac{h_f}{R}} \tan\left(\frac{H_n}{2} \sqrt{\frac{h_f}{R}} \right)$$

Torque

$$L \approx \sqrt{R\Delta h}$$



$$\Delta h = h_b - h_f$$

$$\sum F_y = 0$$
$$\therefore F_{roller} = p_{ave}A$$

$$T = \underset{\text{entry}}{\int_{\phi_n}^{\alpha} w\mu p R^2 d\phi} - \underset{\text{exit}}{\int_{0}^{\phi_n} w\mu p R^2 d\phi}$$

$$Torque / roller = r \cdot F_{roller} = \frac{L}{2} \cdot F_{roller} = \frac{F_{roller} L}{2}$$

Power

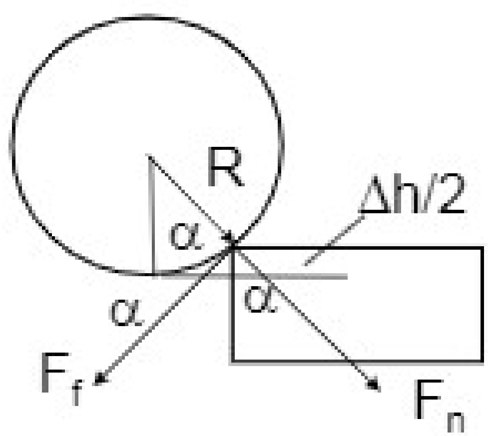
Power / roller = $T\omega$ = $F_{roller}L\omega / 2$

$\omega = 2\pi N$

N = [rev/min]

Processing limits

- The material will be drawn into the nip if the horizontal component of the friction force (F_f) is larger, or at least equal to the opposing horizontal component of the normal force (F_n).



$$F_f \cos\alpha \geq F_n \sin\alpha$$

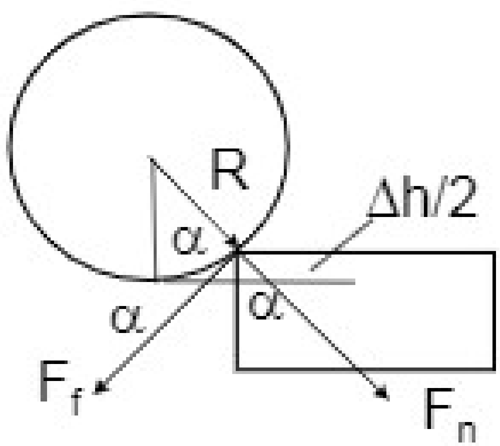
$$F_f = \mu \cdot F_n$$

$$\tan\alpha = \mu$$

μ = friction coefficient

Processing limits

- The material will be drawn into the nip if the horizontal component of the friction force (F_f) is larger, or at least equal to the opposing horizontal component of the normal force (F_n).



$$F_f \cos\alpha \geq F_n \sin\alpha$$

$$F_f = \mu \cdot F_n$$

$$\tan\alpha = \mu$$

μ = friction coefficient

Processing limits

Also

$$\cos\alpha = \frac{R - \frac{\Delta h}{2}}{R} = 1 - \frac{\Delta h}{2R}$$

and $\Delta h << R$

$$\sin\alpha = \sqrt{1 - \cos^2\alpha}$$

$$\sin\alpha = \sqrt{1 - 1 + \frac{\Delta h}{2R} - \cancelto{0}{\left(\frac{\Delta h}{2R}\right)^2}} \qquad \sin\alpha \approx \sqrt{\frac{\Delta h}{R}}$$

$$\tan\alpha = \sqrt{\frac{\frac{\Delta h}{R}}{1 - \frac{\Delta h}{R} + \left(\frac{\Delta h}{2R}\right)^2}} \cong \sqrt{\frac{\Delta h}{R - \Delta h}} \approx \sqrt{\frac{\Delta h}{R}}$$

Processing limits

So, approximately

$$(\tan\alpha)^2 = \mu^2 = \frac{\Delta h}{R}$$

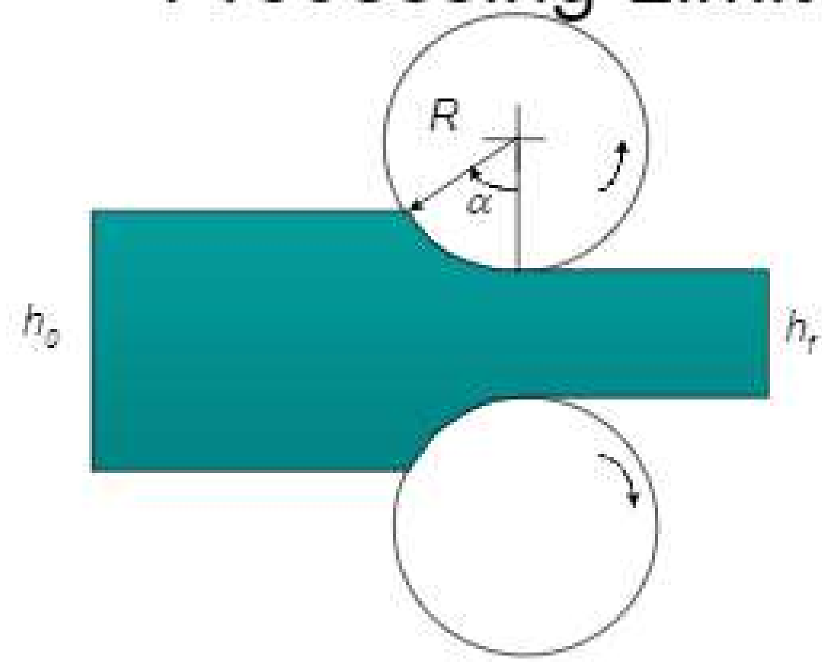
Hence, maximum draft

$$\Delta h_{\max} = \mu^2 R$$

Maximum angle of acceptance

$$\phi_{\max} = \alpha = \tan^{-1}\mu$$

Processing Limits



Max reduction in thickness

$$(\Delta h)_{max} = \mu^2 R$$

Max angle of acceptance

$$\phi_{max} = \alpha = \tan^{-1}\mu$$

Reference Books

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THANK YOU