Course Description

- This course provides basic understanding of fundamental and classification of metal forming processes utilized in metallic product manufacturing.
- The main focus is on Bulk Metal Forming Process, Sheet Metal Forming Process and Powder Metal Forming Process.
- The course will also include Material behaviors in Metal forming, Temperature in Metal Forming, Strain Rate Sensitivity, Friction and Lubrication in Metal Forming and etc.
- Analysis of different metal forming processes with main focus on extrusion, forging, wiredrawing and rolling.
The learning objectives

Upon completion of this course, the student will have reliably demonstrated the ability to:

- Understand the basic sheet metal operations of blanking, bending, stretching and drawing.
- The students have theoretical and practical skills related to metal forming.
- To understand effect of forming method on the mechanical properties of automotive parts.
- Explain the processes involved in metal forming mechanics, materials, and tribology.
- Analyze the interrelationships between various factors that influence the quality of manufactured products.
Course Content

- Definitions and classification of metal forming processes
  - Bulk metal forming, Sheet metal forming, Powder metal forming, Hot working, Warm Working and Cold working,
  - Temperature in Metal Forming (recrystallization and growth)

- Material science in Metal Forming
  - Material behavior in Metal forming (Plastic deformation, Flow stress and Strain rate)

- Tribology in Metal forming (Friction, Lubrication and Wear)

- Bulk Metal Forming Processes
  - Forging: Close and Open die forging
  - Rolling: Flat and Shape Rolling Processes
  - Extrusion and Drawing: Direct, indirect and hydrostatic extrusion, Die design and Limitation.
Outline Cont’d

- Sheet Metal Forming Processes
  - Shearing, Stamping, Bending, Blanking, Stretching, Drawings, Sheet metal formability, Other operations. Sheet Metal Properties

- Powder Metal Forming Processes
  - Production of Metal Powders
  - Compaction of Metal Powders
  - Sintering
  - Secondary and Finishing Operations
  - Design Considerations
  - Process Capabilities

- End Use: Mechanical Properties
Text Book

- Fundamentals of powder metallurgy by W. D. Jones
- Powder Metallurgy: Principles and Applications by F. V. Lenel
- Fundamentals of Powder Metallurgy by I. H. Khan
Syllabus:

- Attendance is your job - come to class!
  - Or our regularly scheduled time (Thursday, 12:00-1:00 pm & Friday, 8:00 - 10:00 am)
- Assignments
  - Don't copy from others; don't plagiarize - its just the right thing to do!!
- Tutorials - by Fuseini Abdulai (TA) -
- Grading
  - Class Attendance, Pop Quizzes and Assignments - (10% of your grade!)
  - Class Test- (20%)
  - End of Semester Exams (70%)
Part One

Metal Forming
Forming processes

- Forming processes are used to convert cast ingots into basic product forms such as sheets, rods and plates.
- However, here we will concentrate on forming processes that produce end products or components.
- There are some basic shapes that lend themselves to manufacture by forming.
- Forming processes are particularly good at manufacturing 'linear' objects, that is, long thin ones, where the product has a constant cross section.
- Forming processes involve moving the material through an opening with the desired shape.
- These processes are used for making components such as fibres, wires, tubes and products such as curtain rails.
Metal forming

- Metal forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal work pieces.
- Deformation results from the use of a tool, usually called a die in metal forming, which applies stresses that exceed the yield strength of the metal.
- The metal therefore deforms to take a shape determined by the geometry of the die.
- Stresses applied to plastically deform the metal are usually compressive.

Stresses in Metal Forming

- Stresses to plastically deform the metal are usually compressive
  - Examples: rolling, forging, extrusion

- However, some forming processes
  - Stretch the metal (tensile stresses)
  - Others bend the metal (tensile and compressive)
  - Still others apply shear stresses
Material Properties in Metal Forming

- Desirable material properties:
  - Low yield strength
  - High ductility

- These properties are affected by temperature:
  - Ductility is increased when work temperature is raised.
  - Yield strength is reduced when work temperature is raised.
  - Temperature distinguishes between cold, warm and hot working.

- Other factors:
  - Strain rate and friction
Basic Types of Metal Forming Processes

Metal forming processes can be classified into two basic categories:

- **Bulk deformation**
  - Rolling processes
  - Forging processes
  - Extrusion processes
  - Wire and bar drawing
  - Bending operations

- **Sheet metalworking**
  - Deep or cup drawing
  - Shearing processes
  - Miscellaneous processes
Bulk deformation

- Bulk deformation processes are generally characterized by significant deformations and massive shape changes.
- "Bulk" refers to workparts with relatively low surface area-to-volume ratios.
- Starting work shapes are usually simple geometries.
- Examples:
  - Cylindrical billets
  - Rectangular bars
- Bulk deformation includes:
  - Rolling
  - Forging
  - Extrusion
  - Drawing
Bulk Deformation Processes

(a) Rolling and (b) forging

Rolling is a deformation process in which the thickness of a metal is reduced by compressive forces exerted by opposing forces (rolling mills)

Most rolling is carried out by hot working i.e hot rolling, owing to the large amount of deformation required.

Hot rolled materials are free from residual stresses and properties are isotropic.

They cannot be held to close tolerance.

The surface finish is poor due to oxide scales.
Rolling

- The ingot is rolled into the following:
  - Bloom: square with dimensions (150mm x 150mm)
  - Slab: rectangular with dimensions (250mm x 40mm)
  - Billet: square with dimensions (40mm x 40mm)

- Flat Rolling: is a type of rolling in which work parts with rectangular cross sections e.g. slabs and sheets are squeezed through two rolls to reduce their thickness by an amount called draft.

\[ d = t_o - t_f \]

Where \( d \) is draft, \( t_o \) is starting thickness and \( t_f \) is final thickness.
Flat Rolling

- Draft can also be expressed as a fraction of the starting stock thickness known as **reduction**.

  \[ r = \frac{d}{to} \]

- As rolling is done to decrease thickness it also increases the width of the work piece this is known as **spreading**.

- Spreading occurs in low width to thickness ratio and low coefficients of friction.
  
  - This conserves matter making the volume of metal entering equal to volume exiting.
Flat Rolling

\[ t_0 w_0 l_0 = t_f w_f l_f \]

\( w_0 l_0 \) is starting work width and length
\( w_f l_f \) is exiting work width and length

Before and after volumes can be related to velocity entering and exiting

\[ t_0 w_0 v_0 = t_f w_f v_f \]

The contact point between the roll and the work is \( \sigma \)

Each roll's radius is \( R \)

Surface velocity of roll is \( V_r \)
Flat Rolling

$V_r > V_o$ is entering velocity of work piece
$V_r > V_f$ is final velocity of work piece

No slip point or neutral point is the point along the arc where the work velocity equals the roll velocity.

The amount of slip between the rolls and the work can be measured by means of forward slip ($s$).

\[ s = \frac{V_f - V_r}{V_r} \]

True strain based on before and after stock thickness

\[ \epsilon = \ln \frac{t_o}{t_f} \]
Flat Rolling

- **Average flow stress**: applied to work material in flat rolling.
  \[ \hat{Y} = \frac{K \varepsilon^n}{1 + n} \]

- **Maximum draft** is given as:
  \[ d_{max} = \mu^2 R \]

  where \( \mu \) is coefficient of friction
  \( d_{max} \) is maximum draft
  \( R \) is radius
Flat rolling

\[ F = \dot{Y}_f w L \]

- The above equation is the force required to maintain the separation between the two rolls.

- Where \( L \) is the length of contact between the rolls and the work \( W \) is the width of the work being rolled.

- \( \dot{Y}_f \) is average flow stress
Flat Rolling

- Contact length = \( L = \sqrt{R(t_o - t_f)} \)
- Torque = 0.5FL
- Power required to drive the rolls = \( P = 2\pi NFL \)
- Where F = Rolling force

\[ FL = \text{torque} \]
\[ 2\pi N = \text{angular velocity} \]
\[ 2\pi NT = \text{power for each roll} \]
\[ N = \text{rotational speed (rev/min)} \]
Question

- A 300-mm-wide strip 25-mm thick is fed through a rolling mill with two powered rolls each of radius = 250 mm. The work thickness is to be reduced to 22 mm in one pass at a roll speed of 50 rev/min. The work material has a flow curve defined by $K = 275$ MPa and $n = 0.15$, and the coefficient of friction between the rolls and the work is assumed to be 0.12.

- Determine if the friction is sufficient to permit the rolling operation to be accomplished. If so calculate the:
  1. roll force
  2. torque
  3. horsepower
Shape rolling

- *Shape rolling* is a type of rolling where the work is deformed into a contoured cross section. This is achieved by passing the work through rolls with the reverse of the desired shape.

- Examples of products are Constructional shapes such as:
  - I-beam
  - L-beam
  - U-channel
  - Bars and rod
Roll pass design is designing the sequence of intermediate shapes and their corresponding rolls. Its goal is to achieve uniform deformation throughout the cross section in each reduction.

Rolling mills: Various rolling mill configurations are available to deal with the variety of applications and technical problems in the rolling process.

Two high-rolling mills: it consists of two opposing mills.

The two-high configuration can be either reversing or non-reversing. In the non-reversing mill; the rolls always rotate in the same direction, and the work always passes through from the same side.

The reversing mill; allows the direction of roll rotation to be reversed, so that the work can be passed through in either direction.
Rolling Mills

Three high-rolling mills

- There are three rolls in a vertical column, and the direction of rotation of each roll remains unchanged.
- To achieve a series of reductions, the work can be passed through from either side by raising or lowering the strip after each pass.

Four high-rolling mills

- The four-high rolling mill uses two smaller-diameter rolls to contact the work and two backing rolls behind them. Owing to the high roll forces, these smaller rolls would deflect elastically between their end bearings as the work passes through unless the larger backing rolls were used to support them.
Cluster rolling mill allows smaller working rolls against the work.

Tandem rolling mill is often used to achieve higher throughput rates in standard products.
Several other bulk deformation processes use rolls to form the work part. The operations include thread rolling, ring rolling, gear rolling, and roll piercing.

Thread rolling is used to form threads on cylindrical parts by rolling them between two dies.

It is the most important commercial process for mass producing external threaded components (e.g., bolts and screws).

Most thread rolling operations are performed by cold working in thread Rolling machines.

Advantages of thread rolling over machining

- better material utilization.
- stronger threads due to work hardening.
- smoother surface.
- better fatigue resistance due to compressive stresses introduced by rolling.
Thread rolling

Before thread rolling

After thread rolling
Ring rolling

- **Ring rolling** is a deformation process in which a thick-walled ring of smaller diameter is rolled into a thin-walled ring of larger diameter.
  - Ring rolling is used to reduce the wall thickness and increase the diameter of a ring.

- As the thick-walled ring is compressed, the deformed material elongates, causing the diameter of the ring to be enlarged.

- Ring rolling is usually performed as a hot-working process for large rings and as a cold-working process for smaller rings.

Advantages of ring rolling over alternative methods of making the same parts:

- raw material savings.
- ideal grain orientation for the application.
- strengthening through cold working.
Ring rolling

Before rolling begins

After rolling
Gear rolling

- Gear rolling is a cold working process to produce certain gears. The automotive industry is an important user of these products.
- The setup in gear rolling is similar to thread rolling, except that the deformed features of the cylindrical blank or disk are oriented parallel to its axis (or at an angle in the case of helical gears) rather than spiraled as in thread rolling.

Advantages of gear rolling
- higher production rates.
- better strength and fatigue resistance.
- less material waste.
Roll piercing

- *Ring piercing* is a specialized hot working process for making seamless thick-walled tubes.

- The process is based on the principle that when a solid cylindrical part is compressed on its circumference high tensile stresses are developed at its center.

- Compressive stresses on a solid cylindrical billet are applied by two rolls, whose axes are oriented at slight angles from the axis of the billet, so that their rotation tends to pull the billet through the rolls.

- A mandrel is used to control the size and finish of the hole created by the action.
Roll piercing:
(a) formation of internal stresses and cavity by compression of cylindrical part;
(b) setup of Mannesmann roll mill for producing seamless tubing.
Forging

- **Forging** is a deformation process in which the work is compressed between two dies, using either impact or gradual pressure to form the part.

- These components include engine crankshafts and connecting rods, gears, aircraft structural components, and jet engine turbine parts.

- One way to classify the operations is by

  - **Working temperature;** most forging operations are performed hot or warm, owing to the significant deformation demanded by the process and the need to reduce strength and increase ductility of the work metal.

- **Equipment used;** A forging machine that applies an impact load is called a *forging hammer*, while one that applies gradual pressure is called a *forging press*.
Forging

- Degree to which the flow of the work metal is constrained by the dies.
- By this classification, there are three types of forging operations:
  - open-die forging
  - impression-die forging
  - flashless forging.
- **Open-die forging**: the work is compressed between two flat dies, thus allowing the metal to flow without constraint in a lateral direction relative to the die surfaces.
Forging

- **Impression-die forging**, the die surfaces contain a shape or impression that is imparted to the work during compression, thus constraining metal flow to a significant degree.

- **Flash** is a portion of the work metal that flows beyond the die impression. Excess metal that must be trimmed off later.

- **Flashless forging**, the work is completely constrained within the die and no excess flash is produced. The volume of the starting work piece must be controlled very closely so that it matches the volume of the die cavity.
Upsetting Or Upset Forging

- Upsetting or upset forging is a type of forging in which a cylindrical metal is compressed in two flat dies, reducing its height and increasing its width.

- Analysis of open die forging

- If its carried under conditions of no friction between work and die surface there is homogenous deformation and radial flow is uniform throughout the height.

- Under these ideal conditions, the true strain experienced by the work during the process can be determined by: \( \varepsilon = \ln \frac{h_o}{h} \)

  - where \( h_o \) is starting height of the work, mm (in)
  - and \( h \) is the height at some intermediate point in the process, mm (in).

  At the end of the compression stroke, \( h \) is its final value \( h_f \), and the true strain \( \varepsilon \) reaches its maximum value.
Upset forging
Upset Forging

- The force required to continue the compression at any given height h during the process can be obtained by multiplying the corresponding cross-sectional area by the flow stress: $F = Y_f A$

  - $F$ = force, lb (N);
  - $A$ = cross-sectional area of the part, mm$^2$ (in$^2$);
  - $Y_f$ = flow stress

- Area $A$ continuously increases during the operation as height is reduced. Flow stress $Y_f$ also increases as a result of work hardening, except when the metal is perfectly plastic (e.g., in hot working). In this case, the strain-hardening exponent $n = 0$, and flow stress $Y_f$ equals the metal’s yield strength $Y$. 


Upset Forging

- An actual upsetting operation does not occur quite shown in the above slide because friction opposes the flow of work metal at the die surfaces. This creates the barreling effect.

- When performed on a hot work part with cold dies, the barreling effect is even more pronounced.

- This results from a higher coefficient of friction typical in hot working and heat transfer at and near the die surfaces, which cools the metal and increases its resistance to deformation. The hotter metal in the middle of the part flows more readily than the cooler metal at the ends.

- These effects are more significant as the diameter to-height ratio of the work part increases, due to the greater contact area at the work-die interface.
Upset forging

Actual deformation of a cylindrical workpart in open-die forging, showing pronounced barreling: (1) start of process, (2) partial deformation, and (3) final shape.
Upset forging

- All of these factors cause the actual upsetting force to be greater than what is predicted by the previous equation.

- As an approximation, we can apply a shape factor to the previous eqn to account for effects of the D/h ratio and friction:

  \[ F = K_f Y_f A \]

- \( K_f \) is the forging shape factor

  \[ K_f = 1 + \frac{0.4 \mu D}{h} \]

- where \( \mu \) is coefficient of friction;

- D is work part diameter or other dimension representing contact length with die surface, mm (in);

- h is work part height, mm (in).
A cylindrical work piece is subjected to a cold upset forging operation. The starting piece is 75 mm in height and 50 mm in diameter. It is reduced in the operation to a height of 36 mm. The work material has a flow curve defined by $K=350$ MPa and $n=0.17$. Assume a coefficient of friction of 0.1.

1. Determine the force as the process begins,

2. at intermediate heights of 62 mm, 49 mm, and at the final height of 36 mm.
Related Operation To Upset Forging

- **Fullering** is a forging operation performed to reduce the cross section and redistribute the metal in a work part in preparation for subsequent shape forging. It is accomplished by dies with convex surfaces.

- **Edging** is similar to fullering, except that the dies have concave surfaces.

- **Cogging** operation consists of a sequence of forging compressions along the length of a work piece to reduce cross section and increase length.
Extrusion

*Extrusion* is a compression process in which the work piece is forced to flow through a die opening to produce a desired cross sectional shape.
Extrusion

ADVANTAGES

(1) a variety of shapes are possible, especially with hot extrusion;

(2) grain structure and strength properties are enhanced in cold and warm extrusion

(3) fairly close tolerances are possible, especially in cold extrusion;

(4) in some extrusion operations, little or no wasted material is created.

•NB: A limitation is that the cross section of the extruded part must be uniform throughout its length.
Extrusion

- Extrusion is carried out in various ways i.e either
  - direct extrusion and indirect extrusion.
  - working temperature: cold, warm, or hot extrusion.

- DIRECT EXTRUSION (*forward extrusion*)
  - A metal billet is loaded into a container, and a ram compresses the material, forcing it to flow through the die opening at the opposite end of the container.
  - **BUTT**: it’s a small portion of the metal that remains in the container after the compression. It cuts off just beyond the exit of the die.
Extrusion

Direct extrusion

- One of the problems in direct extrusion is the significant friction that exists between the work surface and the walls of the container as the billet is forced to slide toward the die opening.

- This friction causes a substantial increase in the ram force required in direct extrusion.
Extrusion

- **Hollow sections** (e.g., tubes) are possible in direct extrusion. The starting billet is prepared with a hole parallel to its axis. This allows passage of a mandrel that is attached to the dummy block.

- As the billet is compressed, the material is forced to flow through the clearance between the mandrel and the die opening. The resulting cross section is tubular.
Extrusion

- INDIRECT EXTRUSION (*BACKWARD EXTRUSION AND REVERSE EXTRUSION*)
  - In indirect extrusion, the die is mounted to the ram rather than at the opposite end of the container. As the ram penetrates into the work, the metal is forced to flow through the clearance in direction opposite to the motion of the ram.

Since the billet is not forced to move relative to the ram, there is no friction thereby requires less force in indirect extrusion.
Hot versus Cold extrusion

- Extrusion can be performed either **hot** or **cold**, depending on work metal and amount of strain to which it is subjected during deformation.

- **Hot extrusion** involves prior heating of the billet to a temperature above its recrystallization temperature. This reduces strength and increases ductility of the metal, permitting more extreme size reductions and more complex shapes to be achieved in the process.

- **Additional advantages**
  - reduction of ram force,
  - increased ram speed,
  - reduction of grain flow characteristics in the final product.
Hot versus Cold Extrusion

- **Lubrication** is critical in hot extrusion for certain metals (e.g., steels),

- **Glass** is sometimes used as a lubricant in hot extrusion; in addition to reducing friction, it also provides effective thermal insulation between the billet and the extrusion container.

- **Cold extrusion** and warm extrusion are generally used to produce discrete parts, often in finished (or near finished) form. The term impact extrusion is used to indicate high-speed cold extrusion.

- **ADVANTAGES**
  - increased strength due to strain hardening,
  - Close tolerances
  - improved surface finish,
  - absence of oxide layers, and high production rates.
  - Cold extrusion at room temperature also eliminates the need for heating the starting billet.
Analysis of extrusion

- The diagram assumes that both billet and extrudate are round in cross section. One important parameter is the extrusion ratio, also called the reduction ratio. The ratio is defined:

\[ r_x = \frac{A_o}{A_f} \]  
(19.19)

- Where \( r_x \) = extrusion ratio; \( A_o \) = cross-sectional area of the starting billet, \( mm^2 (in^2) \); and \( A_f \) = final cross-sectional area of the extruded section, \( mm^2 \).

- The ratio applies both for direct and indirect extrusion. The value \( r_x \) can be used to determine true strain in extrusion, given that ideal deformation occurs with no friction and no redundant work:

\[ \varepsilon = \ln r_x = \ln \frac{A_o}{A_f} \]  
(19.20)
Analysis of extrusion

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in our figure can be computed as follows:

$$p = \bar{Y}_f \ln r_x$$

(19.21)

Where $\bar{Y}_f$ = average flow stress during deformation, MPa (lb/in$^2$). For convenience, we restate Eq. (18.2) from the previous chapter:

$$\bar{Y}_f = \frac{Ke^n}{1+n}$$

(19.22)
In fact, extrusion is not a frictionless process, and the previous equations grossly underestimate the strain and pressure in an extrusion operation. Friction exists between the die and the work as the billet squeezes down and passes through the die opening. In direct extrusion, friction also exists between the container wall and the billet surface. The effect of friction is to increase the strain experienced by the metal. Thus, the actual pressure is greater than that given by Eq. (19.21), which assumes no friction.
Analysis of extrusion

Various methods have been suggested to calculate the actual true strain and associated ram pressure in extrusion. The following empirical equation proposed by Johnson for estimating extrusion strain has gained considerable recognition:

$$\varepsilon_x = a + b \ln r_x$$

- where $\varepsilon_x$ = extrusion strain; and $a$ and $b$ are empirical constants for a given die angle.
- Typical values of these constants are: $a=0.8$ and $b=1.2$ to $1.5$. Values of $a$ and $b$ tend to increase with increasing die angle.
- The ram pressure to perform *indirect extrusion* can be estimated based on Johnson’s extrusion strain formula as follows: $p = Y_f \varepsilon_x$
- where is calculated based on ideal strain from Eq. (19.20), rather than extrusion strain in Eq. (19.22).
Analysis of extrusion

- In direct extrusion, the effect of friction between the container walls and the billet causes the ram pressure to be greater than for indirect extrusion. We can write the following expression which isolates the friction force in the direct extrusion container:

\[
\frac{\pi D_0^2 p_f}{4} = \mu p_c \pi D_0 L
\]

- Where \( p_f \) = additional pressure required to overcome friction, MPa (lb/in\(^2\)); \( \frac{\pi D_0^2}{4} \) = billet cross-sectional area, mm\(^2\) (in\(^2\)); \( \mu \) = coefficient of friction at the container wall; \( p_c \) = pressure of the billet against the container wall, MPa (lb/in\(^2\)); \( \pi D_0 L \) = area of the interface between the billet and container wall, mm\(^2\) (in\(^2\)).
Analysis of extrusion

- The right-hand side of this equation indicates the billet-container friction force, and the left-hand side gives the additional ram force to overcome that friction. In worst case, sticking occurs at the container wall so that friction stress equals shear yield strength of the work metal:

  \[ \mu r_c \pi D_o L = Y_s \pi D_o L \]

- Where \( Y_s \) = shear yield strength, MPa (lb/in\(^2\)). If we assume that

  \[ Y_s = \frac{Y_f}{2} \]

  then \( p_f \) reduces to the following:

  \[ p_f = \frac{Y_f 2L}{D_o} \]

- Based on this reasoning, the following formula can be used to compute ram pressure in direct extrusion

  \[ p = \frac{Y_f}{\varepsilon_x} \left( \varepsilon_x + \frac{2L}{D_o} \right) \quad (19.23b) \]
Analysis of Extrusion

- where the term $2L/Do$ accounts for the additional pressure due to friction at the container–billet interface.
- $L$ is the portion of the billet length remaining to be extruded,
- and $Do$ is the original diameter of the billet.
- Note that $p$ is reduced as the remaining billet length decreases during the process.

- Ram force in indirect or direct extrusion is simply pressure $p$ from Eqs. (19.23a) or respectively, multiplied by billet area $Ao$:
- $F = pAo$
QUESTION

A billet 75mm long and 25mm in diameter is to be extruded in a direct extrusion operation with extrusion ratio \( r_x = 4.0 \). The extrudate has a round cross section. The die angle (halfangle) =90. The work metal has a strength coefficient = 415 MPa, and strain-hardening exponent = 0.18. Use the Johnson formula with \( a = 0.8 \) and \( b = 1.5 \) to estimate extrusion strain. Determine the pressure applied to the end of the billet as the ram moves forward.

TIP

Let us examine the ram pressure at billet lengths of \( L=75\text{mm} \) (starting value), \( L=50\text{ mm} \), \( L=25\text{ mm} \), and \( L=0 \).

We compute the ideal true strain, extrusion strain using Johnson’s formula, and average flow stress.
Wire and Bar Drawing

- **Drawing** is an operation in which the cross section of a bar, rod, or wire is reduced by pulling it through a die opening.

- The basic **difference** between bar drawing and wire drawing is the **stock size** that is processed.

- Bar drawing is the term used for large diameter bar and rod stock, while wire drawing applies to small diameter stock.

- Since compression is used to squeeze the metal to be pulled from the die it is termed **indirect compression**.

- **Bar drawing** is generally accomplished as a single-draft operation—the stock is pulled through one die opening to give the smaller final diameter since the beginning stock has a large diameter.
Wire and Bar Drawing

Wire drawing is accomplished using a series of draw dies since its drawn from coils of wires the number of dies varies typically between 4 and 12.

Drawing of bar, rod or wire.
Analysis of drawing

- In a drawing operation, the change in size of the work is usually given by the area Reduction, defined as follows
  \[ r = \frac{A_o - A_f}{A_o} \]

- where \( r \) = area reduction in drawing; \( A_o \) = original area of work, \( \text{mm}^2 \); and \( A_f \) = final area, \( \text{mm}^2 \). Area reduction is often expressed as a percentage.

- If no friction or redundant work occurred in drawing, true strain could be determined as follows:
  \[ \epsilon = \ln \left( \frac{A_o}{A_f} \right) = \ln \left( \frac{1}{1-r} \right) \]

- The stress that results from this ideal deformation is given by
  \[ \sigma = \bar{Y}_f \epsilon = \bar{Y}_f \ln \left( \frac{A_o}{A_f} \right) \]
Analysis of drawing

- When friction is considered

\[ \sigma_d = \bar{Y}_f \left(1 + \frac{\mu}{\tan \alpha}\right) f \ln \frac{A_o}{A_f} \]

- where \( \sigma_d \) = draw stress, MPa; \( \mu \) = die-work coefficient of friction; \( \alpha \) = die angle (half-angle) and \( \phi \) is a factor that accounts for inhomogeneous deformation which is determined as follows for a round cross section:

\[ \phi = 0.88 \pm 0.12 \frac{D}{L_c} \]

- where \( D \) =average diameter of work during drawing, and \( L_c \) =contact length of the work with the draw die.

\[ D = \frac{D_o + D_f}{2} \]
\[ L_c = \frac{D_o - D_f}{2 \sin \alpha} \]
Analysis

- The corresponding draw force is then the area of the drawn cross section multiplied by the draw stress:

\[ F = A_f \sigma_d = A_f Y_f \left( 1 + \frac{\mu}{\tan \alpha} \right) \phi \ln \frac{A_0}{A_f} \]

- Where \( F \) is draw force.

Question

Wire is drawn through a draw die with entrance angle=15. Starting diameter is 2.5mm and final diameter is 2.0 mm. The coefficient of friction at the work-die interface is 0.07. The metal has a strength coefficient \( K \) is 205 MPa and a strain-hardening exponent \( n \) is 0.20. Determine the draw stress and draw force in this operation.
Wire and Bar Drawing

ADVANTAGES
(1) close dimensional control,
(2) good surface finish,
(3) improved mechanical properties such as strength and hardness,
(4) adaptability to economical batch or mass production.
Difference Between Extrusion and Drawing

- Extrusion and wire and bar drawing

- Extrusion is a forming process in which the metal is forced to flow through a die opening to take the shape of the opening as its cross sectional shape.

- Drawing is a forming process in which the diameter of a round wire or bar is reduced by pulling it through a die opening.
Part Two

Sheet Metal Forming
Sheet Metalworking

- Forming and related operations performed on metal sheets, strips, and coils
- High surface area-to-volume ratio of starting metal, which distinguishes these from bulk deformation
- Often called pressworking because these operations are performed on presses
  - Parts are called stampings
  - Usual tooling: punch and die
- Thickness of sheet metal = 0.4 mm (1/64 in) to 6 mm (1/4 in)
- Thickness of plate stock > 6 mm
- Operations usually performed as cold working
Sheet and Plate Metal Products

- Sheet and plate metal parts for consumer and industrial products such as
  - Automobiles and trucks
  - Airplanes
  - Railway cars and locomotives
  - Farm and construction equipment
  - Small and large appliances
  - Office furniture
  - Computers and office equipment
Advantages of Sheet Metal Parts

- High strength
- Good dimensional accuracy
- Good surface finish
- Relatively low cost
- For large quantities, economical mass production operations are available
Sheet Metalworking Terminology

1. “Punch-and-die”
   - Tooling to perform cutting, bending, and drawing

2. “Stamping press”
   - Machine tool that performs most sheet metal operations

3. “Stampings”
   - Sheet metal products
Three Major Categories of Sheet Metal Processes

1. **Cutting**
   - Shearing to separate large sheets; or cut part perimeters or make holes in sheets

2. **Bending**
   - Straining sheet around a straight axis

3. **Drawing**
   - Forming of sheet into convex or concave shapes
I. Cutting

- Cutting and forming operations performed on relatively thin sheets of metal

Shearing between two sharp cutting edges
Shearing, Blanking, and Punching

- Three principal operations in pressworking that cut sheet metal:
  - Shearing
  - Blanking
  - Punching

**Shearing**: Sheet metal cutting operation along a straight line between two cutting edges

- Typically used to cut large sheets into smaller sections for subsequent operations
Blanking and Punching

**Blanking** - sheet metal cutting to separate piece from surrounding stock
- Cut piece is the desired part, called a *blank*

**Punching** - sheet metal cutting similar to blanking except cut piece is scrap, called a *slug*
- Remaining stock is the desired part

(a) Blanking and (b) punching
Clearance in Sheet Metal Cutting

Distance between the punch and die

- Typical values range between 4% and 8% of stock thickness
  - If too small, fracture lines pass each other, causing double burnishing and larger force
  - If too large, metal is pinched between cutting edges and excessive burr results

\[ c = \frac{D_m - d_p}{2} \]
Punch and Die Clearance
The clearance between punch and dies is represented by the total difference, which is one of the critical factors in the punching process.

For example, when using diameter 12 upper die and diameter 12.25 lower die, the optimal clearance is 0.25mm.

Improper clearance will reduce the die service life, or burrs and lead to secondary cutting the irregular opening will increase the demounting force, etc.

Besides, the die clearance is subject to the material and thickness, generally, for carbon steel plate, 12% - 18% of the thickness is best.
How to Determine Punch and Die Clearance

- If no special requirements in CNC punch, you can refer to the following table for selecting the die clearance:

**Punch Machine’s Die Clearance Table**

<table>
<thead>
<tr>
<th>Plate Thickness</th>
<th>Mild Steel</th>
<th>Aluminum</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-1.6</td>
<td>0.15-0.2</td>
<td>0.15-0.2</td>
<td>0.15-0.3</td>
</tr>
<tr>
<td>1.6-2.3</td>
<td>0.2-0.3</td>
<td>0.2-0.3</td>
<td>0.3-0.4</td>
</tr>
<tr>
<td>2.3-3.2</td>
<td>0.3-0.4</td>
<td>0.3-0.4</td>
<td>0.4-0.6</td>
</tr>
<tr>
<td>3.2-4.5</td>
<td>0.4-0.6</td>
<td>0.4-0.5</td>
<td>0.6-1.0</td>
</tr>
<tr>
<td>4.5-6.0</td>
<td>0.6-0.9</td>
<td>0.5-0.7</td>
<td></td>
</tr>
</tbody>
</table>
Punching

- If you punch round holes or square holes, or some other forms of holes through a given thickness of metal, you just want to know the force required to punch a hole in steel.
- You can calculate the punching tonnage been required with the help of the following punching force calculation formula (blanking force formula):

\[
Punching\ Force\ (KN) = Perimeter\ (mm) \times Plate\ Thickness\ (mm) \times Shear\ Strength\ (kN/mm^2)
\]

e.g: If punching one square hole in the 3 mm thickness low carbon steel plate, side length 20 mm, you will get:
- Perimeter=20×4=80 mm
- Thickness=3 mm
- Shear\ Strength=0.3447 kN/mm^2
Punch Force (kN)=80×3×0.3447=82.728kN
convert into tonnage: 82.728kN /9.81= 8.43 ton
II. Bending

- Straining sheetmetal around a straight axis to take a permanent bend

(a) Bending of sheet metal

(b) both compression and tensile elongation of the metal occur in bending
Types of Sheetmetal Bending

- **V-bending** - performed with a V-shaped die
  - For low production
  - Performed on a press brake
  - V-dies are simple and inexpensive

- **Edge bending** - performed with a wiping die
  - For high production
  - Pressure pad required
  - Dies are more complicated and costly
Springback in Bending

- \textit{Springback} = increase in included angle of bent part relative to included angle of forming tool after tool is removed

- Reason for springback:
  - When bending pressure is removed, elastic energy remains in bent part, causing it to recover partially toward its original shape
III. Drawing

Sheet metal forming to make cup-shaped, box-shaped, or other complex-curved, hollow-shaped parts

Products: beverage cans, ammunition shells, automobile body panels
IV. Shapes other than Cylindrical Cups

- Square or rectangular boxes (as in sinks),
- Stepped cups,
- Cones,
- Cups with spherical rather than flat bases,
- Irregular curved forms (as in automobile body panels)

- Each of these shapes presents its own unique technical problems in drawing
Ironing

- Makes wall thickness of cylindrical cup more uniform
- Examples: beverage cans and artillery shells

Ironing to achieve a more uniform wall thickness in a drawn cup:
(1) start of process; (2) during process
Note thinning and elongation of walls
Embossing

- Used to create indentations in sheet, such as raised (or indented) lettering or strengthening ribs

Embossing: (a) cross-section of punch and die configuration during pressing; (b) finished part with embossed ribs
Guerin Process

- Guerin process is a sheet metal forming process that uses a rubber die that flexes to force the sheet metal to take the shape of a form block (punch)

Advantages of Guerin Process

- Low tooling cost
- Form block can be made of wood, plastic, or other materials that are easy to shape
- Rubber pad can be used with different form blocks
- Process attractive in small quantity production
Dies for Sheet Metal Processes

Most pressworking operations performed with conventional *punch-and-die* tooling

- The term *stamping die* sometimes used for high production dies
Dies for Sheet Metal Processes

(a) Progressive die;
(b) associated strip development
Several sheet metal parts produced on a turret press, showing variety of hole shapes possible
(photo courtesy of Strippet, Inc.)
Sheet Metal Operations
Not Performed on Presses

1. Stretch forming
2. Roll bending and forming
3. Spinning
4. High-energy-rate forming processes.
1. Stretch Forming

- Sheet metal is stretched and simultaneously bent to achieve shape change

Stretch forming: (1) start of process; (2) form die is pressed into the work with force $F_{die}$, causing it to be stretched and bent over the form. $F = $ stretching force
2. Roll Bending

- Large metal sheets and plates are formed into curved sections using rolls

Roll bending
2. Roll Forming

- Continuous bending process in which opposing rolls produce long sections of formed shapes from coil or strip stock

Roll forming of a continuous channel section:
(1) straight rolls  (2) partial form  (3) final form
3. Spinning

- Metal forming process in which an axially symmetric part is gradually shaped over a rotating mandrel using a rounded tool or roller.

Conventional spinning: (1) setup at start of process; (2) during spinning; and (3) completion of process.
4. High-Energy-Rate Forming (HERF)

Processes to form metals using large amounts of energy over a very short time

- HERF processes include:
  - Explosive forming
  - Electrohydraulic forming
  - Electromagnetic forming
Explosive Forming

Use of explosive charge to form sheet (or plate) metal into a die cavity

- Explosive charge causes a shock wave whose energy is transmitted to force part into cavity
- Applications: large parts, typical of aerospace industry

Explosive forming:
(1) setup, (2) explosive is detonated, and (3) shock wave forms part and plume escapes water surface
Electromagnetic Forming

Sheet metal is deformed by mechanical force of an electromagnetic field induced in workpart by an energized coil

- Presently, it is the most widely used HERF process
- Applications: tubular parts

Electromagnetic forming: (1) setup in which coil is inserted into tubular workpart surrounded by die; (2) formed part
Temperature in Metal Forming

- For any metal, $K$ and $n$ in the flow curve depend on temperature
  - Both strength ($K$) and strain hardening ($n$) are reduced at higher temperatures
  - In addition, ductility is increased at higher temperatures
- Any deformation operation can be accomplished with lower forces and power at elevated temperature
- Three temperature ranges in metal forming:
  - Cold working
  - Warm working
  - Hot working
Cold Working

- Performed at room temperature or slightly above
- Many cold forming processes are important mass production operations
- Minimum or no machining usually required
  - These operations are near net shape or net shape processes

Advantages of Cold Forming

- Better accuracy, closer tolerances
- Better surface finish
- Strain hardening increases strength and hardness
- Grain flow during deformation can cause desirable directional properties in product
- No heating of work required
Disadvantages of Cold Forming

- Higher forces and power required for deformation
- Surfaces of starting work must be free of scale and dirt
- Ductility and strain hardening limit the amount of forming that can be done
  - In some cases, metal must be annealed before further deformation can be accomplished
  - In other cases, metal is simply not ductile enough to be cold worked
Warm Working

- Performed at temperatures above room temperature but below recrystallization temperature
- Dividing line between cold working and warm working often expressed in terms of melting point:
  - $0.3T_m$, where $T_m = \text{melting point (absolute temperature) for metal}$

- Advantages
  - Lower forces and power than in cold working
  - More intricate work geometries possible
  - Need for annealing may be reduced or eliminated

- Disadvantage
  - Workpiece must be heated
Hot Working

- Deformation at temperatures above the recrystallization temperature
  - Recrystallization temperature = about one-half of melting point on absolute scale
    - In practice, hot working usually performed somewhat above 0.5T_m
    - Metal continues to soften as temperature increases above 0.5T_m, enhancing advantage of hot working above this level
Why Hot Working?

- Capability for substantial plastic deformation - far more than is possible with cold working or warm working

Why?

- Strength coefficient \((K)\) is substantially less than at room temperature
- Strain hardening exponent \((n)\) is zero (theoretically)
- Ductility is significantly increased
Advantages of Hot Working

- Workpart shape can be significantly altered
- Lower forces and power required
- Metals that usually fracture in cold working can be hot formed
- Strength properties of product are generally isotropic
- No strengthening of part occurs from work hardening
  - Advantageous in cases when part is to be subsequently processed by cold forming
Disadvantages of Hot Working

- Lower dimensional accuracy
- Higher total energy required, which is the sum of
  - The thermal energy needed to heat the workpiece
  - Energy to deform the metal
- Work surface oxidation (scale)
  - Thus, poorer surface finish
- Shorter tool life
  - Dies and rolls in bulk deformation
Isothermal forming

- Isothermal forming refers to forming operations that are carried out in such a way as to eliminate surface cooling and the resulting thermal gradients in the work part.
- It is accomplished by preheating the tools that come in contact with the part to the same temperature as the work metal.
- This weakens the tools and reduces tool life.

- NB: read more on isothermal forming!!!
- Read on strain rate sensitivity!!!
Strain Rate Sensitivity

- Theoretically, a metal in hot working behaves like a perfectly plastic material, with strain hardening exponent \( n = 0 \)
  - The metal should continue to flow at the same flow stress, once that stress is reached
  - However, an additional phenomenon occurs during deformation, especially at elevated temperatures:
    - Strain rate sensitivity
What is Strain Rate?

- Strain rate in forming is directly related to speed of deformation \( v \).
- Deformation speed \( v \) = velocity of the ram or other movement of the equipment.
- Strain rate is defined:

\[
\dot{\varepsilon} = \frac{v}{h}
\]

where \( \dot{\varepsilon} \) = true strain rate; and \( h \) = instantaneous height of workpiece being deformed.
Evaluation of Strain Rate

- In most practical operations, valuation of strain rate is complicated by
  - Workpart geometry
  - Variations in strain rate in different regions of the part
- Strain rate can reach $1000 \text{ s}^{-1}$ or more for some metal forming operations
Effect of Strain Rate on Flow Stress

- Flow stress is a function of temperature
- At hot working temperatures, flow stress also depends on strain rate
  - As strain rate increases, resistance to deformation increases
  - This is the effect known as strain-rate sensitivity
Strain Rate Sensitivity

- (a) Effect of strain rate on flow stress at an elevated work temperature
- (b) Same relationship plotted on log-log coordinates
Strain Rate Sensitivity Equation

\[ Y_f = C \varepsilon^m \]

where \( C \) = strength constant (analogous but not equal to strength coefficient in flow curve equation), and \( m \) = strain-rate sensitivity exponent
Effect of Temperature on Flow Stress

- The constant $C$, indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases.
- And $m$ (slope of each plot) increases with increasing temperature.
Observations about Strain Rate Sensitivity

- Increasing temperature decreases $C$ and increases $m$
  - At room temperature, effect of strain rate is almost negligible
    - Flow curve alone is a good representation of material behavior
- As temperature increases
  - Strain rate becomes increasingly important in determining flow stress
Friction in Metal Forming

- Friction in metal forming arises because of the close contact between the tool and work surfaces and the high pressures that drive the surfaces together in these operations.

- In most metal forming processes, friction is undesirable:
  - Disadvantages
    1. Metal flow in the work is retarded, causing residual stresses and sometimes defects in the product.
    2. Forces and power to perform the operation are increased.
    3. Tool wear can lead to loss of dimensional accuracy, resulting in defective parts and requiring replacement of the tooling.
  - Tools in metal forming are generally expensive making tool wear is a major concern.
    - Friction and tool wear is more severe in hot working.
Friction and lubrication in forming

- Friction encountered in metal forming is different from that in most mechanical systems. E.g. Shafts and bearings.
- These involve relative motion between surfaces characterized by low contact, pressure and low to moderate temperatures.
- By contrast, the metal forming environment features high pressures between a hardened tool and a soft work part, plastic deformation of the softer material, and high moderate temperatures. (at least in hot working).
- These conditions can result in relatively high coefficients of friction in metalworking, even in the presence of lubricants.
- If the coefficient of friction becomes large enough, a condition known as sticking occurs.
Friction and lubrication in metal forming

- **Sticking** in metalworking (also called sticking friction) is the tendency for the two surfaces in relative motion to adhere to each other rather than slide.
- It means that the friction stress between the surfaces exceeds the shear flow stress of the work metal, thus causing the metal to deform by a shear process beneath the surface rather than slip at the surface.
  - **Sticking** is prominent in rolling.
- Metalworking lubricants are applied to the tool-work interface in many forming operations to reduce the harmful effects of friction.
- **Advantages:**
  - Reduced sticking, forces, power, tool wear
  - Better surface finish on the product
  - Lubricants also help in removing heat from the tooling
Considerations in Choosing a Lubricant

- Type of forming process (rolling, forging, sheet metal drawing, etc.)
- Hot working or cold working
- Work material
- Chemical reactivity with tool and work metals
- Ease of application
- Cost
Part Three

Powder Metallurgy
Powder Metallurgy: Introduction

- Earliest use of iron powder dates back to 3000 BC. Egyptians used it for making tools.
- Modern era of P/M began when tungsten (W) lamp filaments were developed by Edison.
- Components can be made from pure metals, alloys, or mixture of metallic and non-metallic powders.
- Commonly used materials are iron, copper, aluminium, nickel, titanium, brass, bronze, steels and refractory metals.
- Used widely for manufacturing gears, cams, bushings, cutting tools, piston rings, connecting rods, impellers etc.
Powder Metallurgy

- ...is a forming technique

Essentially, Powder Metallurgy (PM) is an art & science of producing metal or metallic powders, and using them to make finished or semi-finished products.

- Particulate technology is probably the oldest forming technique known to man

- There are archeological evidences to prove that the ancient man knew something about it
History of Powder Metallurgy

- **IRON Metallurgy**
- How did Man make iron in 3000 BC?
- Did he have furnaces to melt iron air blasts, and
- The reduced material, which would then be spongy, used to be hammered to a solid or to a near solid mass.
- Example: The IRON PILLER at Delhi
- An important point that comes out:
  - The entire material need not be melted to fuse it.
  - The working temperature is well below the Tm of the major constituent, making it a very suitable method to work with refractory materials, such as: W, Mo, Ta, Nb, oxides, carbides, etc.
  - It began with Platinum technology about 4 centuries ago ... in those days, Platinum, \([\text{mp} = 1774^\circ \text{C}]\), was "refractory", and could not be melted.
Powder Metal Materials

- Elemental
  - A pure metal, most commonly iron, aluminum or copper

- Prealloyed
  - An alloy of the required composition, most commonly copper alloys, stainless steel or high-speed steel
Powder Metallurgy Process

- Powder metallurgy involves Powder production, Blending or mixing, Powder compaction, Sintering and Finishing Operations
1. Powder Production

- Many methods:
  - Atomization
  - Reduction
  - Electrolytic deposition
  - Carbonyls
  - Comminution
  - Mechanical alloying
  - Miscellaneous methods

- Atomization is the dominant process
Atomization

- Produces a liquid-metal stream by injecting molten metal through a small orifice
- The stream is broken up by jets of inert gas or air
- The size of the particle formed depends on the temperature of the metal, metal flowrate through the orifice, nozzle size and jet characteristics

Water or gas atomization; Fe powders made by atomization
Atomization

- The size and shape of the particles from atomization depend on the temperature, flow rate, size of nozzle, and the jet characteristics.
- When water is used it creates a slurry metal powder and leaves a liquid at the bottom of the atomization chamber.
- The water cools the metal faster for a higher production rates.

Spherical (atomization, carbonyl (Fe), precipitation from a liquid)

Irregular rodlike (chemical decomposition, mechanical comminution)

Rounded (atomization, chemical decomposition)
Centrifugal Atomization

- The process in which the molten-metal drops onto a rapidly rotating disk or cup
- The centrifugal forces break up the molten-metal stream to generate particles
- Another method is that a consumable electrode is rotating rapidly in a helium filled chamber

(a) Centrifugal atomization; (b) Rotating electrode
Electrode Centrifugation

Variation:

A consumable electrode is rotated rapidly in a helium-filled chamber. The centrifugal force breaks up the molten tip of the electrode into metal particles.

Ni-based superalloy made by the rotating electrode process
Reduction of Metal Oxides

- A process that uses gases as a reducing agent
  - Hydrogen and carbon monoxide
- Also known as the removal of oxygen
- Very fine metallic oxides are reduced to the metallic state
- Spongy and porous powders are produced

Porous (reduction of oxides)
Electrolytic Deposition and Carbonyls

- Electrolytic Deposition utilizes either aqueous solutions or fused salts
- Makes the purest powders that are available

- Metal carbonyls are formed by letting iron or nickel react with carbon monoxide
- Reaction product is decomposed to iron and nickel
- Forms small, dense, uniform spherical particles

Spherical (atomization, carbonyl (Fe), precipitation from a liquid)

Angular (mechanical disintegration, carbonyl (Ni))
Mechanical Comminution

- Also known as pulverization
- Involves roll crushing, milling in a ball mill, or grinding of brittle or less ductile metals into small particles
- Brittle materials have angular shapes
- Ductile metals are flaky and not particularly suitable for P/M

Irregular rodlike (chemical decomposition, mechanical comminution)

Flake (mechanical comminution)
Mechanical Alloying

- Powders of two or more pure metals are mixed in a ball mill
- Under the impact of the hard balls the powders fracture and bond together by diffusion, forming alloy powders
- The dispersed phase can result in strengthening of the particles or can impart special electrical or magnetic properties

Angular
(mechanical disintegration, carbonyl (Ni))
Miscellaneous Methods

- Precipitation from a chemical solution
- Production of fine metal chips by machining
- Vapor condensation
Types of Powders

- **Nanopowders**
  - Consist of mostly copper, aluminum, iron, titanium
  - Are pyrophoric (ignite spontaneously)
  - Contaminated when exposed to air
  - The particle size is reduced and becomes porous free when subjected to large plastic deformation by compression and shear stress
  - Posses enhanced properties

- **Microencapsulated powders**
  - Coated completely with a binder
  - The binder acts as an insulator for electrical applications preventing electricity from flowing between particles
  - Compacted by warm pressing
  - The binder is still in place when used
**Particle Shape**

**FIGURE 18.3** Several of the possible (ideal) particle shapes in powder metallurgy.

- Spherical
- Rounded
- Cylindrical
- Spongey
- Acicular
- Flakey
- Cubic
- Aggregated

**Figure 3.9.** SEMs showing the shape diversity in powders. These six pictures only begin to illustrate the diversity, but show how simple terms can be used to describe particle shape: (a) spherical; (b) rounded; (c) angular; (d) irregular; (e) polygonal or cubic; (f) sponge.
Particle Size, Shape, and Distribution

- Particle size is measured by a process called screening.
- Screening is the passing of metal powder through screens of various mesh sizes.
- The main process of screening is Screen Analysis.
- Screen analysis uses a vertical stack of screens with mesh size becoming finer as the powder flows down through screens.

The process of separating particles by size is called classification.

FIGURE 18.2 Screen mesh for sorting particle sizes.
Other Screening Methods

- **Sedimentation**
  - Involves measuring the rate at which particles settle in a fluid

- **Microscopic Analysis**
  - Includes the use of transmission and scanning electron microscopy

- **Optical**
  - Particles block a beam of light and then sensed by a photocell

- **Light Scattering**
  - A laser that illuminates a sample consisting of particles suspended in a liquid medium
  - The particles cause the light to be scattered, and a detector then digitizes and computes the particle-size distribution

- **Suspending Particles**
  - Particles suspended in a liquid and then detected by electrical sensors
Particle Shape and Shape Factor

- Major influence on processing characteristics
- Usually described by aspect ratio and shape factor
- Aspect ratio is the ratio of the largest dimension to the smallest dimension
- Ratio ranges from unity (spherical) to 10 (flake-like, needle-like)

- Shape factor (SF) is also called the shape index
- Is a measure of the ratio of the surface area to its volume
- The volume is normalized by a spherical particle of equivalent volume
- The shape factor for a flake is higher than it is for a sphere
Mixing particles of different sizes allows decreased porosity and a higher packing ratio.

- Larger voids
- Smaller, more numerous voids
- Voids filled by smaller particles, small voids remain
Size Distribution and Other Properties

- Size distribution is important because it affects the processing characteristics of the powder.
- Flow properties, compressibility, and density are other properties that have an affect on metal powders behavior in processing them.

- Flow
  - When metal powders are being filled into dies.

- Compressibility
  - When metal powders are being compressed.

- Density
  - Theoretical density, apparent density, and the density when the powder is shaken or tapped in the die cavity.
Powder Preparation

One-dimensional
- Acicular (chemical decomposition)
- Irregular rodlike (chemical decomposition, mechanical commination)

Two-dimensional
- Flake (mechanical commination)
- Dendritic (electrolytic)

Three-dimensional
- Spherical (atomization, carbonyl (Fe), precipitation from a liquid)
- Rounded (atomization, chemical decomposition)
- Irregular (atomization, chemical decomposition)
- Angular (mechanical disintegration, carbonyl (Ni))
- Porous (reduction of oxides)
2. Blending or Mixing

- Blending a coarser fraction with a finer fraction ensures that the interstices between large particles will be filled out.

- Powders of different metals and other materials may be mixed in order to impart special physical and mechanical properties through metallic alloying.

- Lubricants may be mixed to improve the powders' flow characteristics.

- Binders such as wax or thermoplastic polymers are added to improve green strength.

- Sintering aids are added to accelerate densification on heating.
**Blending**

- To make a homogeneous mass with uniform distribution of particle size and composition
  - Powders made by different processes have different sizes and shapes
  - Mixing powders of different metals/materials
  - Add lubricants (<5%), such as graphite and stearic acid, to improve the flow characteristics and compressibility of mixtures

- **Combining** is generally carried out in
  - Air or inert gases to avoid oxidation
  - Liquids for better mixing, elimination of dusts and reduced explosion hazards

- **Hazards**
  - Metal powders, because of high surface area to volume ratio are explosive, particularly Al, Mg, Ti, Zr, Th
Some common equipment geometries used for blending powders
(a) Cylindrical, (b) rotating cube, (c) double cone, (d) twin shell
Reasons for Blending

- To impart special physical and mechanical properties and characteristics
- Proper mixing is essential to ensure the uniformity of mechanical properties throughout the part
- Even one metal can have powder vary in size and shape
- The ideal mix is one in which all of the particles of each material are distributed uniformly
- Lubricants can be mixed with the powders to improve flow of metal powder into dies, reduce friction between metal particles, and improve the die life
- Binders are used to develop sufficient green strength
- Other additives can be used to facilitate sintering
# Hazards

- Metal powders are explosive because of the high surface area-to-volume ratio (mostly aluminum, magnesium, titanium, zirconium, and thorium).
- Most be blended, stored, handled with great care.
- **Precautions**
  - Grounding equipment
  - Preventing sparks
  - Avoiding friction as a source of heat
  - Avoiding dust clouds
  - Avoiding open flames
  - Avoiding chemical reactions
3. Powder Consolidation

- Cold compaction with 100 – 900 MPa to produce a “Green body”.
  - Die pressing
  - Cold isostatic pressing
  - Rolling
  - Gravity

- Injection Molding small, complex parts.

Die pressing
Compaction

- Press powder into the desired shape and size in dies using a hydraulic or mechanical press
- Pressed powder is known as “green compact”
- Stages of metal powder compaction:

![Diagram of compaction process]
Compaction

- Increased compaction pressure
  - Provides better packing of particles and leads to ↓ porosity
  - ↑ localized deformation allowing new contacts to be formed between particles
At higher pressures, the green density approaches density of the bulk metal.

Pressed density greater than 90% of the bulk density is difficult to obtain.

Compaction pressure used depends on desired density.
Friction problem in cold compaction

- The effectiveness of pressing with a single-acting punch is limited. Wall friction opposes compaction.
- The pressure tapers off rapidly and density diminishes away from the punch.
- Floating container and two counteracting punches help alleviate the problem.
Smaller particles provide greater strength mainly due to reduction in porosity.

Size distribution of particles is very important. For same size particles minimum porosity of 24% will always be there.

- Box filled with tennis balls will always have open space between balls
- Introduction of finer particles will fill voids and result in ↑ density
Because of friction between (i) the metal particles and (ii) between the punches and the die, the density within the compact may vary considerably.

Density variation can be minimized by proper punch and die design.

(a) and (c) Single action press; (b) and (d) Double action press; (e) Pressure contours in compacted copper powder in single action press.
Presses

- Press capacities are on the order of 200 to 300 tons
- Most projects require less than 100 tons
- Small tonnage, crank- or eccentric-type mechanical presses are used
- For higher capacities, toggle or knuckle-joint presses are employed

- Hydraulic presses can have capacities up to 5,000 tons and are used for large parts
- The type of press selected depends on part size and its configuration, density requirements, and production rate
Isostatic Pressing
Cold Isostatic Pressing

- Metal powder placed in a flexible rubber mold
- Mold made of elastomer (neoprene rubber, urethane, polyvinyl chloride)
- Assembly pressurized hydrostatically by water (400 - 1000 MPa)
- Typical: Automotive cylinder liners
Hot Isostatic Pressing (HIP)

- High-melting-point sheet metal
- High temp inert gas or vitreous fluid
- Pressures as high as 100 MPa
- Temperatures of 1200°C (2200°F)
- Used for making high-quality parts
- Ex. valve lifter

Advantages:
- 100% density
- Good metallurgical bonding of the particles
- Good mechanical properties
- Compacts of uniform grain structure and density

Disadvantages:
- Wider dimensional tolerances
- Higher equipment cost and production time
- Small production quantities
4. Sintering

- Parts are heated to 0.7~0.9 $T_m$.
- Transforms compacted mechanical bonds to much stronger metallic bonds.

- Shrinkage always occurs:

$$Vol \_ shrinkage = \frac{V_{sintered}}{V_{green}} = \frac{\rho_{green}}{\rho_{sintered}}$$

$$Linear \_ shrinkage = \left( \frac{\rho_{green}}{\rho_{sintered}} \right)^{1/3}$$
Sintering – Compact Stage

- Green compact obtained after compaction is brittle and low in strength
- Green compacts are heated in a controlled-atmosphere furnace to allow packed metal powders to bond together

Sintering – Three Stages

- Carried out in three stages:
- First stage: Temperature is slowly increased so that all volatile materials in the green compact that would interfere with good bonding is removed
  - Rapid heating in this stage may entrap gases and produce high internal pressure which may fracture the compact
Sintering: High temperature stage

- Promotes vapor-phase transport
- Because material heated very close to MP, metal atoms will be released in the vapor phase from the particles
- Vapor phase resolidifies at the interface

FIGURE 5 Electron micrograph showing a thermal bond produced through sintering to ensure predictable strength and dimensions. Source: Extrude Hone/ProMetal, 2003.
Sintering: High temperature stage

- Third stage: Sintered product is cooled in a controlled atmosphere
  - Prevents oxidation and thermal shock

- Gases commonly used for sintering:
  - $\text{H}_2$, $\text{N}_2$, inert gases or vacuum
Liquid Phase Sintering

- During sintering a liquid phase, from the lower MP component, may exist
- Alloying may take place at the particle-particle interface
- Molten component may surround the particle that has not melted
- High compact density can be quickly attained
- Important variables:
  - Nature of alloy, molten component/particle wetting, capillary action of the liquid
Combined Stages

- Simultaneous compaction + sintering
- Container: High MP sheet metal
- Container subjected to elevated temperature and a very high vacuum to remove air and moisture from the powder
- Pressurizing medium: Inert gas
- Operating conditions
  - 100 MPa at 1100 C
- Produces compacts with almost 100% density
- Good metallurgical bonding between particles and good mechanical strength

Uses
- Superalloy components for aerospace industries
- Final densification step for WC cutting tools and P/M tool steels
(i) Slip is first poured into an absorbent mould
(ii) a layer of clay forms as the mould surface absorbs water
(iii) when the shell is of suitable thickness excess slip is poured away
(iv) the resultant casting
Slip-Casting

- Slip: Suspension of colloidal (small particles that do not settle) in an immiscible liquid (generally water)
- Slip is poured in a porous mold made of plaster of paris. Air entrapment can be a major problem
- After mold has absorbed some water, it is inverted and the remaining suspension poured out.
- The top of the part is then trimmed, the mold opened, and the part removed
- Application: Large and complex parts such as plumbing ware, art objects and dinnerware
5. Finishing

- The porosity of a fully sintered part is still significant (4-15%).
- Density is often kept intentionally low to preserve interconnected porosity for bearings, filters, acoustic barriers, and battery electrodes.
- However, to improve properties, finishing processes are needed:
  - Cold restriking, resintering, and heat treatment.
  - Impregnation of heated oil.
  - Infiltration with metal (e.g., Cu for ferrous parts).
  - Machining to tighter tolerance.
Special Process: Hot compaction

- Advantages can be gained by combining consolidation and sintering,
- High pressure is applied at the sintering temperature to bring the particles together and thus accelerate sintering.
- Methods include:
  - Hot pressing
  - Spark sintering
  - Hot isostatic pressing (HIP)
  - Hot rolling and extrusion
  - Hot forging of powder preform
  - Spray deposition
Design Considerations for P/M Components:

(i) Avoid sharp corners and thus the corners have to be either radiused or chamfered.

(ii) As under-cuts and re-entrant angles cannot be molded into the component (conventional pressing & sintering), these have to be machined subsequently.

(iii) The inability of the powder metallurgy process to introduce cross holes. Such features would have to be machined using a post processing step.

(iv) To prevent excessive wear of the tools chamfers greater than $45^\circ$ are preferred, but in case of less than $45^\circ$ degrees lands are required.

(v) Punches less than 1 mm be avoided.

(vi) Large sectional changes should be avoided as far as possible as they may lead to the cracking of the green component at the change in section through transfer of metal powder into the wide section during the compaction processes.
Design Aspects

(a) Length to thickness ratio limited to 2-4; (b) Steps limited to avoid density variation; (c) Radii provided to extend die life, sleeves greater than 1 mm, through hole greater than 5 mm; (d) Feather-edged punches with flat face; (e) Internal cavity requires a draft; (f) Sharp corner should be avoided; (g) Large wall thickness difference should be avoided; (h) Wall thickness should be larger than 1 mm.
Examples of Poor and Good Design Details for use in PM

Poor

(a) Sharp radius

(b) Sharp radius

(c) Hole must be drilled

(d) Can be molded

Good

(a) Fillet radius

(b) Fillet radius

(c) Thread must be machined

FIGURE 18.17 Part features to be avoided in PM: (a) side holes and (b) side undercuts. Part ejection is impossible.

FIGURE 18.18 Permissible part features in PM: (a) vertical hole, blind and through, (b) vertical stepped hole, and (c) undercut in vertical direction. These features allow part ejection.
Design Considerations for P/M Components:

(vii) The practical minimum diameter which can be easily molded is about 2 mm and holes running parallel to the direction of pressing should normally have a length to diameter ratio of 4:1.

(viii) Groves are generally molded into the top face of the component and these should not extend to more than 30% of the total length.

(ix) Tolerances on sintered components can be improved by sizing at extra cost as per design requirements.

➢ Tolerances after sintering are generally equivalent to those obtained by turning, milling, etc.
➢ But after sizing these may be considered equivalent to medium grinding or broaching.
P/M Applications

- Electrical Contact materials
- Heavy-duty Friction materials
- Self-Lubricating Porous bearings
- P/M filters
- Carbide, Alumina, Diamond cutting tools
- Structural parts
- P/M magnets
- Cermets

and more, such as high tech applications
P/M Applications

Motor Cycle Parts

Vehicles Engine Parts

Industrial Machines Parts

Industrial Machines Parts
P/M Applications

Industrial Machines Parts

For Electric Motors
P/M Applications

Powdered Metal Transmission Gear

Powdered Metal Turbine blade-disk

Oil-impregnated Porous Bronze Bearings

Metal filters
Advantages of P/M for Structural Components:

These may be classified into two main headings;
(a) Cost advantages, and
(b) Advantages due to particular properties of sintered components.

Cost Advantages:
(i) Zero or minimal scrap;
(ii) Avoiding high machining cost in mass production as irregularly shaped holes, flats, counter bores, involute gear teeth, key-ways can be molded into the components;
(iii) Extremely good surface finish at very low additional cost after sizing and coining;
(iv) very close tolerance without a machining operation;
(v) Assembly of two or more parts (by I/M) can be made in one piece;
(vi) Separate parts can be combined before sintering.
(vii) High production rates
Advantages due to the particular properties of sintered components.

(i) By achieving up to 95% density, the mechanical and physical properties are comparable with cast materials and in certain cases with wrought materials. In certain cases 99.9 % dense structure can be obtained (liquid phase sintering);

(ii) Plating is also possible directly at 90% density and above and after impregnation of the pores at lower densities.

(iii) Damping out vibrations and noise property with controlled residual porosity;

(iv) Ability to retain lubricants such as lead, graphite and oil giving less wear and longer life to bearings;

(v) Achieving a close control of porosity to give a specified balance between strength and lubrication properties (a superiority over wrought materials);
Advantages

(i) Improved surface finish with close control of mass, volume and density;

(ii) Components are malleable and can be bent without cracking.

- P/M makes possible the production of hard tools like diamond impregnated tools for cutting porcelain, glass and tungsten carbides.
- Reactive and non-reactive metals (both having high m.p & low m.p) can be processed.
Limitations of P/M Process

There are numbers of limitations of Powder Metallurgy process as given below:

(i) In general, the principal limitations of the process are those imposed by the size and shape of the part, the compacting pressure required and the material used.

(ii) The process is capital intensive and initial high costs mean that the production ranges in excess of 10,000 are necessary for economic viability (cost of dies is very high).

(iii) The configuration of the component should be such that it can be easily formed and ejected from a die, undercuts and re-entrant angles can not be molded (when using conventional pressing and sintering) and have to be machined subsequently.
Limitations of P/M Process

(iv) The capacity and stroke of the compacting press and the compacting pressure required limit the cross-sectional area and length of the component.

(v) Spheres cannot be molded and hence a central cylindrical portion is required.

(vi) Sintering of low melting point powders like lead, zinc, tin etc., offer serious difficulties.
Economics of Powder Metallurgy

- P/M can produce parts neat net-shape, eliminating secondary manufacturing and assembly operations.
- Because of initial costs of punches, dies, and equipment; production of quantities of over 10,000 pieces are economical.
- Tooling costs for HIP and powder injection molding are higher than powder processing (because its near-net-shape manufacturing method, the cost of finishing operations in P/M are low compared to casting and forging.)
Summary

- Powder metallurgy can create parts that would otherwise be difficult to form, including those with complex shapes or porosity.

- Sintering bonds particles together by allowing atoms to move, forming necks and grain boundaries between the particles.
Thank you