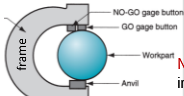
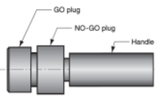
Techincal & Economic process - provides shape, dimensions, properties & value.
Metals – alloys (>=2, >=1 metallic); ferrous: cast iron,steel(75% of world metal tonnage); nonferrous: all other metallic elements and their alloys: aluminium, copper, nickel, silver, tin
Polymers – repeating structural units of mers; atoms share electrons; form large molecules; carbon + >=1 other element (e.g. hydrogen, nitrogen, oxygen, chlorine)
Thermoplastic: multiple heating/cooling w/o altering molecular structure; usually soften; no cross-linking.
Thermosetting: molecules chemically transform to rigid stuct during curing; usually hardens
Elastomers: elastic; e.g. rubber, silicon
Ceramics: contains (semi)metallic and nonmetallic(oxygen, nitrogen, carbon)
Crystalline ceramics: traditional (clay) & modern (alumina);
Glasses: like silica
Composites: mixture of all 3
Materials Differences are: chemical, mechanical & physical properties -> affects manu. processes that can be used
Shaping - change geometry of material;
Solidification: use heated liquid/semifluid; moulding & casting. Particulate: use metal/ ceramic powders; pressed or sintered; Deformation: use ductile solid (e.g. metal); apply force > yield strength (forging & extrusion)
Material Removal: start material ductile/brittle solid; turning, drilling, milling
Minimize waste in shaping; e.g. molding waste less than material removal
Net shape process – little/no waste & no machining. Near net shape process – min. machining
Assembly – joining: permanent joint; welding, brazing, soldering, adhesive bonding. Mechanical: fastening; threaded fasteners (screws, bolts); press fitting; expansion fits.
Trends – environment; microfabrication; nanotechnology; additive: freeform & toolless

Snap gage – for checking outside dimension



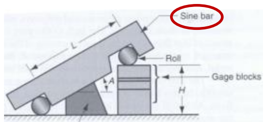
GO gage – part **can** be inserted; **max** material; **smallest** hole diameter; **HAS** wear allowance
NO-GO gage – part **cannot** be inserted; **min** material; **biggest** hole diameter; **NO** wear allowance

- If **does not** go in **GO** gage : **>** max dimensions
- If **does** go in **NO-GO** gage : **<** min dimensions



Plug gage – internal dimensions

- If **does not** go in **GO** gage : hole too small
- If **does** go in **NO-GO** gage : hole too big



Workpart to be measured

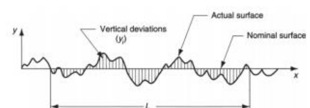
$\sin A = \frac{H}{L}$
H: dependent on no. of gage blocks
L: standard dimension of sine bar

Example: Length of sine bar = 15cm; Rolls diameter = 2.5cm; gage blocks = 4cm, 0.5cm,0.065cm; find angle.
Answer: Angle (A) = $\sin^{-1}$(total height of gage blocks / Length of sine bar) = $\sin^{-1}$((4+0.5+0.065)/15) = 17.72°
Other angular measurements: Bevel protractor with vernier scale
Electronic gages: based on transducers capable of converting a linear displacement into electrical signal
Other considerations: Flat stable surface; Non-contact metrology (optical systems like lasers)

Lay(predominant direction or pattern of surface texture)
Methods of measurement for surface roughness:
Fingernail test, Stylus, Optical
Stylus head traverses horizontally across surface; stylus moves vertically to follow surface profile; vertical movement converted to electronic signal – profile of actual surface or average roughness value; stylus path smoother than actual as cannot go into small peaks
Surface Roughness Equations
R_a = average roughness

$$R_a = \int_0^{L_m} \frac{|y|}{L_m} dx$$

y = vertical deviation from nominal surface (absolute value)
L_m= specified distance over which the surface deviations are measured



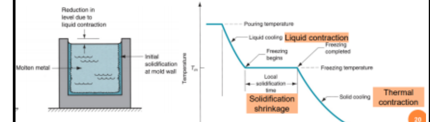
Approximation of the previous equation:

$$R_a = \sum_{i=1}^{n} \frac{|y_i|}{n} = \frac{y_a + y_b + \cdots + y_k + y_i + \cdots}{n}$$

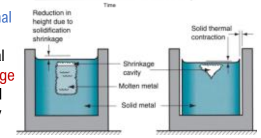
y_i= vertical deviations (absolute value) identified by subscript i
n = number of deviations included in L_m

Problems with R_a – waviness included; Lay not accounted for
Cutoff length – filter to separate waviness from roughness deviations; sampling distance along the surface; sampling distance shorter than waviness eliminates waviness deviations and only has roughness deviations; typically 0.8mm and L_m is normally x5 of cutoff length
Lay direction – stylus should traverse perpendicular to lay direction
* Do not confuse hardness with roughness

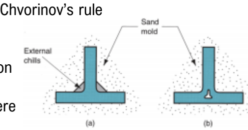
Expendable mold advantages: more intricate geometries; don't need to worry about getting material out of mold
Expendable mold disadvantages: one-time use
Permanent mold advantages: more economic in mass production
Permanent mold disadvantages: limited by the need to open the mold
(refer to mold diagram on the bottom right)
Cope – upper half; Drag – lower half; separated by parting line; Flask – box containing cope and drag; Mold Cavity – external surfaces of cast; Core – internal surfaces of cast; Downsprue – entrance to runner leading to cavity; Pouring Cup – minimizes splash/turbulence as metal flows down; Riser – reservoir in mold, source of liquid metal to compensate shrinkage during solidification (designed to freeze after main casting); Gate – entrance of mold cavity
Factors for successful mold – pouring temp; pouring rate; turbulence
Bernoulli's Theorem: $h_1 + \frac{p_1}{\rho g} + \frac{{v_1}^2}{2g} + F_1 = h_2 + \frac{p_2}{\rho g} + \frac{{v_2}^2}{2g} + F_2$
h = head(cm),p=liquid pressure(n/cm²), ρ=density(g/cm³), v=flow velocity(cm/s), g = gravitational acceleration constant = 981cm/s², F=head losses due to friction(cm)
Can ignore friction losses and assume system remains at atmospheric pressure; velocity at base of sprue assuming that point 1:top of sprue→ v1=0;
point 2:base of sprue→ h2=0   Flow velocity: $\boxed{v_2 = \sqrt{2gh_1}}$
Continuity law:
$\boxed{Q = A_1 v_1 = A_2 v_2}$
Q = volumetric flow rate(cm³/s)
A = area (cm²)
V = flow velocity(com/s)
Flow velocity increases towards the base of the sprue. To maintain the continuity law, the cross sectional area decreases → tapered sprue (prevent aspiration).
Mold cavity filling time – assume runner to cavity horizontal (h = sprue base)
Time to fill the mold cavity: $\boxed{T_{MF} = \frac{V}{Q}}$ V=volume of cavity (cm³) Q=see above equation
Fluidity is the capability of molten metal to fill the mold cavity; high viscosity = low fluidity
Spiral mold test - Greater the length of the solidified metal, greater its fluidity.



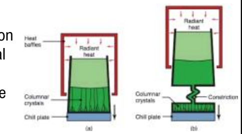
Further reduction in volume due to thermal contraction during cooling of solid metal
Solidification shrinkage happens in almost all metals cause density in solid > liquid
Hence, causes reduction in volume.



Exception: cast iron with high C content (expands instead)
Pattern shrinkage allowance – amount by which mold larger than final casting size
Directional Solidification – minimize effect of shrinkage; want regions of casting furthest away from liquid metal to freeze first & solidify towards riser → molten metal continually available from risers to prevent shrinkage voids; makes use of Chvorinov's rule
(a)External chills to encourage rapid freezing in thin section Of casting
(b) Result if chills were NOT used

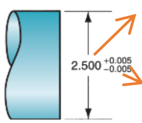


Turbine Blade Casting
(a)Directional solidification
(b)Produce single-crystal blade

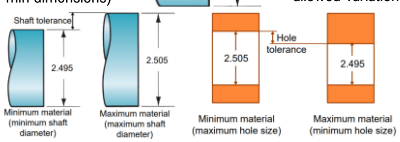


Riser Design – is a waste Metal separated from Casting and remelted to make more castings; minimize waste by using min. vol of metal in riser; shape of riser designed to maximize V/A ratio → allows riser volume to be reduced

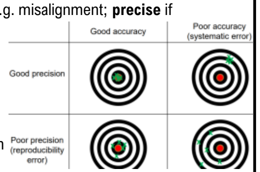
Types of tolerances:
Bilateral(+&-; can be unbalanced);
Unilateral(+/-);
Limit(shows max and min dimensions)



Dimension – indicates basic/ nominal size
Tolerance – define limits of allowed variation

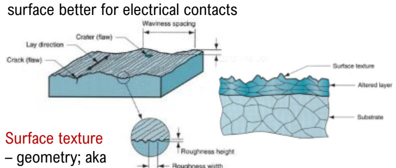


Measurement errors: systematic(+/- deviations; **accurate** if don't have); random(e.g. misalignment; **precise** if minimise)
Precision: Repeatability
Accuracy: Close to True value
Resolution: Smallest discrimination
Precision gage blocks:

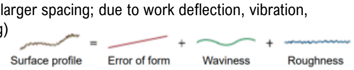


calibration of instruments; not really measurements
Linear dimensions: graduated(has scale; ruler, vernier calliper, micrometer(measure part length)); nongraduated (no scale; compare/ transfer dimension for measurement by graduated device; outside callipers, etc)
Comparative instruments: mech gages(mechanically magnify deviation of permit observation)
Dial indicator(linear movement of contact pointer into rotation; measure straightness, flatness, runout by comparison with ref surface or circle, etc.)

Tolerances (variation from dimension) vary depending on process parameters; increases with part size
Processes that give good surface finishing: honing, lapping, polishing, superfinishing
Nominal surface: designer's intended surface contour
Importance of surfaces: Aesthetic, Safety, Friction/Wear, Mechanical/Physical Properties, Assembly of parts, smooth surface better for electrical contacts

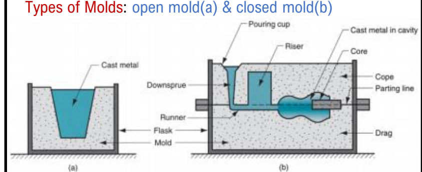


Surface texture – geometry; aka roughness; repetitive/random deviations from nominal surface
Surface integrity – material characteristics immediately beneath the surface; changes to this subsurface that resulted from the processes that created it
Elements of surface texture – roughness(small deviations from nominal surface; determined by material characteristics and processes), waviness(deviations of much larger spacing; due to work deflection, vibration, tooling)



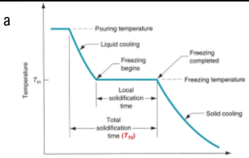
Elements of surface texture – roughness(small deviations from nominal surface; determined by material characteristics and processes), waviness(deviations of much larger spacing; due to work deflection, vibration, tooling); Flaws(irregularities that occur occasionally on surface; cracks, scratches,etc; affect surface integrity); Lay

Casting of Metal: molten metal flows by gravity/other force into mold where it solidifies in shape of mold cavity; Steps: melt the metal, pour into mold, let it freeze
Pros of Casting: create complex part geometries; create external & internal shapes; some processes are net/near net shape; produce large parts(sand casting) & small parts; mass production (permanent mold casting)
Cons of Casting: limitations on mechanical processes; poor dimensional accuracy/surface finish (e.g. sand casting); safety hazard to workers; environment
Mold in Casting – cavity: determines shape (actual size & shape of cavity must be enlarged to allow shrinkage); made from diff materials, e.g. metal(used for low melting point metals(aluminium))
Types of Molds: open mold(a) & closed mold(b)

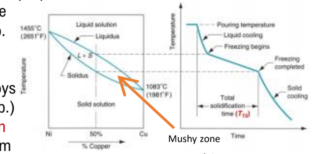


Expendable mold processes – destroyed to remove casting (materials: sand (moist),plaster, binders(maintains shape))
Permanent mold processes – mass production (use metal)

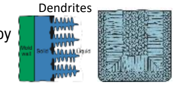
Pure metal solidifies at a constant temp. = to its Freezing/melting point



Solidification (pure metal) - thin skin of solid metal formed immediately; thickness increases to form shell ard molten metal; rate of freezing depends on heat transfer into mood/thermal properties of metal
Alloys freeze over a temp. range
Exceptions: Eutectic alloys (single temp.)
Solidification (alloy) – form dendrites in mushy zone;



Dendrites



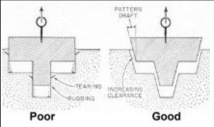
Grain structure segregation of alloy components in center of casting

Chvorinov's rule $\boxed{T_{TS} = C_m \left(\frac{V}{A}\right)^n}$

T_{TS} = total solidification time
V = volume of the casting
A = surface area of casting
n = exponent with typical value = 2
C_m = mold constant

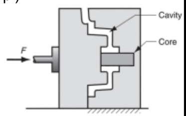
Mold Constant C_m depends on: Mold material; thermal properties of casting material; pouring temperature relative to melting point
T_{TS} depends on size and shape of cast
Required: T_{TS} (riser) > T_{TS} (cast)
But since C_m is equal, riser need to have larger V-to-A ratio → main casting solidify first

General Defects –Misrun: casting solidified before completely filling the mold cavity; Cold Shut: two portions of metal flow tgt but lack of fusion due to premature freezing; Cold Shot: Metal splatters during pouring leading to formation of solid globules; Shrinkage cavity:depression on surface/internal void (solidification shrinkage) that restricts amount of molten metal available in last region to freeze; Microporosity: Small voids (holes) distributed throughout the casting (localized solidification shrinkage) of the final molten metal within the dendritic structure; Hot Tears: casting restrained from contraction due to the mold during final stages of solidification/early stages of cooling after solidification; Sand Blow: Balloon-shaped gas cavity caused by release of mold gases during pouring; Pin Holes: Formation of many small gas cavities at or slightly below the surface of the casting; Penetration: fluidity of the liquid metal is high, it may penetrate into the sand mold or core, causing the casting surface to consist of a mixture of sand grains and metal; Mold Crack: crack develops in the mold, into which liquid metal can seep to form a "fin" on the final casting; Mold Shift: step in the cast product at the parting line caused by sidewise relative displacement of cope and drag;
Product Design Considerations – Geometric Simplicity & avoid unnecessary complexities(Simplifies mold-making; Reduces the need for cores; Improves the strength of the casting); Suggestions - Corners on casting: sources of stress concentrations → cause hot tearing & cracks; Section Thickness: Should be uniform to avoid shrinkage cavities; Design change to eliminate the need for a core; Draft angle (taper): expendable/permanent mold casting → facilitates removal of pattern/part from mold
(refer to image behind)



Dimensional accuracy & finish → vary depends on process
Sand Casting: <u>POOR</u> dimensional accuracy/finish
Die/Investment Casting: <u>GOOD</u> dimensional accuracy/finish
Machining Allowances – sand casting likely to be machined to achieve required dimensions/features; Machining Allowance: add. Material left on casting in those surfaces when machining is necessary; Typical machining allowances for sand castings → ard 1.5 and 3 mm (part after shrinkage will be 1.5/3 mm bigger than required, machining to achieve final dimensions)

Investment Casting (aka lost wax process) - pattern made of wax coated with refractory material to make mold → wax is melted away prior to pouring molten metal; precision casting process → high accuracy/intricate details
Steps – (1)Wax patterns produced; (2) Several patterns are attached to a sprue → pattern tree; (3) coat tree with thin layer of refractory material (slurry; e.g. silicon compotes); (4) full mold formed by covering the coated tree with sufficient refractory material (make it rigid); (5) mold is held in an inverted position, heated to melt the wax & permit it to drip out of the cavity; (6) mold is preheated to a high temp., molten metal poured → solidifies; (7) The mold is broken away from finished casting and parts are separated from the sprue
Advantages – casting parts of great complexity; Close dimensional control & good surface finish; Wax can usually be recovered for reuse; net shape process (no machining)
Disadvantages – many steps; expensive
Basic Permanent Mold Process - Molds used for casting lower melting point alloys are commonly made of steel or cast iron; for casting steel must be made of refractory material (due to high pouring temp.)
Steps – (1) mold is preheated & coated for lubrication & heat dissipation; (2) Cores (if any) are inserted and mold is closed; (3) Molten metal is poured into the mold, where it solidifies



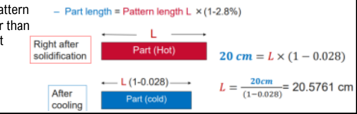
Advantages – Good dimensional control & surface finish; Rapid solidification caused by the metal mold results in a finer grain structure, so castings are stronger
Disadvantages – limited to metals of lower melting point; Simpler part geometries compared to sand casting because of the need to open the mold; High mold cost
Applications – high mold cost → best suited to high volume production; automated; Metals commonly cast: aluminum, magnesium, copper-base alloys, and cast iron (NO steel → pouring temp too high)
Die Casting - permanent mold casting process in which molten metal is injected into mold cavity under high pressure; Pressure is maintained during solidification, then the mold is opened and the part is removed
Hot-Chamber Die Casting – Metal is melted in a container, piston injects liquid metal under high pressure into the die; high production rates; low melting-point metals that do not chemically attack the plunger and other mechanical components; Casting metals: zinc, tin, lead, & magnesium
Cold-Chamber Die Casting – Molten metal poured into unheated chamber from external melting container, and a piston injects metal under high pressure into die cavity; High production rate(not as fast as hot-chamber due to pouring step; Casting metals: aluminum, brass, and magnesium alloys; Can be used on low melting-point alloys (zinc, tin, lead) → hot-chamber process would be more advantageous for those alloys.
Molds for Die casting – made of tool/mold/maraging steel; tungsten/molybdenum used to die cast iron/steel; ejector pins required to remove part from die when opened; use lubricants to prevent sticking & better heat transfer

Advantages - Economical for large production; Good accuracy & surface finish; Thin sections possible; Rapid cooling → small grain size & good strength of cast product
Disadvantages - limited to metals with low melting points; part geometry must allow removal from the die

Sand Casting – most widely used; volumetric size of pattern is bigger than cast part

Mold makers have to design a pattern for die casting of zinc. Given that for zinc, the <u>linear shrinkage value due to solid thermal contraction is 2.8%</u>, what should be the length of the pattern in cm (with three decimal places) if the <u>nominal length of the part is 20 cm</u>.

– Part length = Pattern length L × (1-2.8%)



$20\,cm = L \times (1-0.028)$

$L = \frac{20cm}{(1-0.028)} = 20.5761$ cm

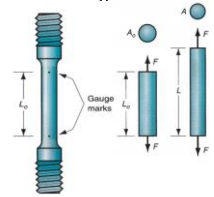
Stress-strain relationships – types of static stress: tensile(stretching);compressive(squeezing);shear(adjacent portions slide against each other)
Stress-strain curve - basic relationship that describes mechanical properties for all three types
Tensile Test – most common test

Engineering stress:

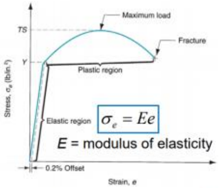
$$\sigma_e = \frac{F}{A_o}$$

Engineering strain:

$$e = \frac{L - L_o}{L_o}$$



Tensile test sequence: (1) No load; (2) uniform elongation; (3) maximum load; (4) necking(dent inwards); (5) fracture (breakage); (6) putting pieces back together to measure final length
Stress-strain plot –
Elastic region: Material returns to its original length when the stress is removed.
Plastic region: Permanent deformation, material does not return to its original length when the stress is removed.

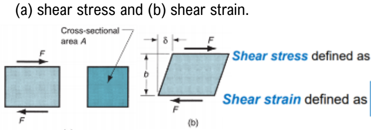


$\sigma_e = Ee$

E = modulus of elasticity

Y = yield stress
TS = tensile strength

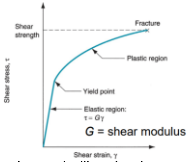
Strain/work hardening: metal is becoming stronger as strain increases.
Shear Properties – application of stresses in opposite directions on either side of a thin element: (a) shear stress and (b) shear strain.



Shear stress defined as $\tau = \frac{F}{A}$

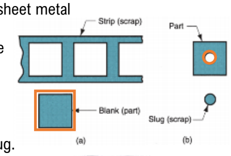
Shear strain defined as $\gamma = \frac{\delta}{b}$

F = applied force; A = area over which force is applied; δ = deflection of the element; and b = distance over which deflection occurs
Typical shear stress-strain curve from a torsion test:
* Shear stress at fracture = shear strength S
* Shear strength can be estimated from tensile strength: $S \cong 0.7(TS)$

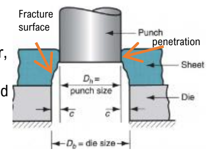


Bulk deformation – compression forces (rolling, forging, extrusion) & tension force (wire/bar drawing)
Sheet Metalworking - Cutting & forming operations performed on relatively thin sheets of metal; Thickness of sheet metal = 0.4 mm to 6 mm (if thickness > 6 mm → plate); Operations usually performed as cold working, i.e. operating temperature below 30% of the melting point of the metal (Kelvin); Most commonly used metals: low carbon steel (0.06 to 0.15% carbon).

Advantages of sheet metal parts - High strength; Good dimensional accuracy; Good surface finish; Relatively low cost; Economical mass production for large quantities.
Sheet metalworking Terminology - Punch-and-die = tooling to perform cutting, bending, and drawing;
Stamping press = machine tool that performs most sheet metal operations; Stampings = sheet metal products.
Shearing - cutting material without producing chips.
Steps - (1) Just before the punch contacts the workpiece; (2) the punch pushes into the workpiece, causing plastic deformation; (3) the punch penetrates the workpiece causing a smooth cut surface; and (4) fracture is initiated at opposing cutting edges to separate the sheet.
Characteristics of Shear Edges – Rollover: Depression made by punch prior to cutting. Burnish: Smooth region resulting from penetration of the punch prior to fracture. Fracture zone: Relatively rough surface caused by fracture of the metal as punch goes down. Burr: Sharp corner edge due to elongation of metal during final stage of separation.
Shearing Processes - Shearing: separate large sheets; Blanking: cut part perimeters out of sheet metal; Punching: make holes in sheet metal
Blanking (a) - sheet metal cutting to separate a piece of metal (blank) from the surrounding sheet.
Punching (b) - similar to blanking except that cut piece is scrap, called a slug.



Punch & Die Sizes –
c is clearance: too small → fracture lines pass each other, double burnishing & larger force; too big →metal pinched between cutting edges & excessive burr results.

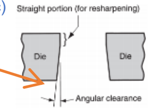


$\boxed{c = at}$

a = allowance (depends on type of metal)
t = sheet thickness

Punching (hole size = Punch size D_h);
Blanking (blank size = Die size D_b)
* $D_b = D_h + 2(c)$

Angular clearance –
Purpose: allows slug/blank to drop through die; commonly 0.25° to 1.5° on each side



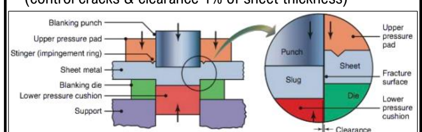
Questions - ultimate tensile strength = max load divide original area of specimen; stress-strain curve: elastic region = proportional relationship between stress & strain, plastic region = power function → flow curve; "shear strength of metal < tensile strength"→ shear = (0.7)tensile

Cutting Force Calculations – determine press size(tonnage)

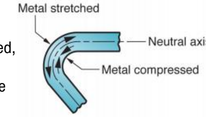
$\boxed{F = S\,t\,L = 0.7(TS)\,t\,L}$

* Refer to blank/punch image above

t = sheet thickness, L = length of cut (perimeter of shape that is cut), S = shear strength of metal (MPa = N/mm²);
Shear Angles Advantages – reduce cutting force/shock from press & cutting gradually over a longer stroke
Other Cutting Operations - Cutoff & Parting
Fine blanking - shearing process which produces very highly precise workpieces with completely smooth, tear-free sheared surfaces; more costly; triple action press (control cracks & clearance 1% of sheet thickness)

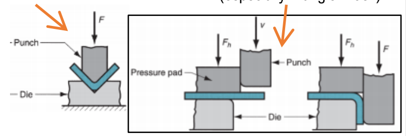


Bending - forming of solid parts, where angled/ring-shaped workpieces are produced from sheet or strip metal
Sheet Metal Bending – Metal on the inside of the neutral plane is compressed, while the metal on the outside of the neutral plane is stretched



V-bending – performed with a V-shaped die.
* Low production quantity
* V-dies are simple & inexpensive

Edge bending - performed with a wiping die
* High production quantity
* more complicated & costly (especially if angle > 90°).

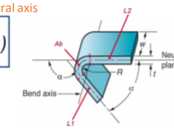


Bend Allowance Formula

Position of neutral axis

$$A_b = 2\pi \frac{\alpha}{360}(R + K_{ba}t)$$

Convert to radian
A_b = bend allowance
α = bend angle (in degree)
R = bend radius
t = sheet thickness
K_{ba} = stretching factor:
– If R < 2t, K_{ba} = 0.33
– If R ≥ 2t, K_{ba} = 0.50
little stretch
Large stretch

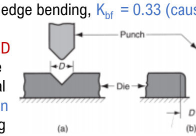


Starting blank size:
$L = L_1 + A_b + L_2$
w = blank width

A_b: length of neutral axis within bended portion
Neutral axis length the <u>same</u> before & after bending
Springback(bending) - decrease in bend angle and an increase in bend radius; elastic recovery of metal
Reason - bending pressure removed → elastic energy remains in bent part → recovers partially toward its original shape.
Springback Compensation – Overbending: bend more to allow springback; Bottoming: high compressive pressure causes plastic deformation at bend area
Maximum bending force – TS = sheet strength of sheet metal; w = part width in direction of bend axis; D = die opening; t = sheet thickness

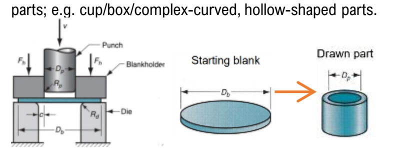
$$F = \frac{K_{bf}(TS)wt^2}{D}$$

* v-bending, K_{bf} = 1.33; edge bending, K_{bf} = 0.33 (cause pushing 1 side only)
Die opening dimension D - (a)V-die, (b)wiping die



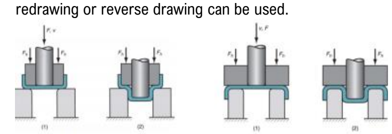
Questions – Sheet metal Bending involves tension & compression; bending force depends on Ultimate Tensile strength

Drawing – forming of smooth (sheet) blanks into hollow parts; e.g. cup/box/complex-curved, hollow-shaped parts.



Db = blank diameter, Rd = die radius
Dp = punch diameter, Rp = punch radius
F = drawing force(applied at v), Fh = blankholder force
Sides of punch&die separated by a clearance c = 1.1t
t = sheet thickness (c >10% of sheet thickness)

Drawing Sequence
* As metal bends along die, tensile stress on cup wall as it is straightened; Friction & compression; compressive stress on the flange; Final cup shape showing effects of thinning in the cup walls
Major Stresses in Flange and Wall
Flange: Compressive hoop stress (may cause wrinkling)
Wall: Longitudinal tensile stress (blank being pulled into the cavity, may cause tearing)
Compression: Perimeter reduces but volume is constant → thickness must increase
* Wrinkling: As initial sheet thickness t decreases, wrinkles increases
Blankholder – prevent/reduce wrinkles on flange (flange thickens); F_h = blankholder force
F_h too low: cause wrinkles; F_h too high: prevents metal from flowing into die cavity; tearing due to stretching
Tests for drawing feasibility (3 criteria) –
[D_b = blank diameter, D_p = punch diameter]
1. Drawing ratio DR (DR = D_b/D_p)
* Indicates severity if given drawing operation → Upper limit: DR ≤ 2.0; i.e. if DR > 2.0, the operation is not feasible
2. Reduction r (r = $(D_b - D_p)/D_b$) → * should be ≤ 0.50
3. Thickness-to-diameter ratio (T/D_b)
T = thickness of starting blank
* Desirable for t/D_b ratio to be greater than 1%; As t/D_b <u>decreases</u>, tendency for wrinkling <u>increases</u>.
Overall: if 1,2,3 not respected → operation not feasible → redrawing required; blank can be drawn in >=2 steps with annealing between the steps
Redrawing & Reverse Drawing – If shape change is too severe to be produced in one single drawing step, redrawing or reverse drawing can be used.



After fulfilling the 3 conditions for drawing, do blank size determination → Starting sheet metal blank volume >= final product volume
Drawing Force (needed to determine tonnage of press)
F = maximum drawing force (N)
D_p = punch diameter (mm)
D_b = starting blank diameter (mm)
t = original sheet thickness (mm)
TS = tensile strength (MPa)
0.7 = correction factor to account for friction

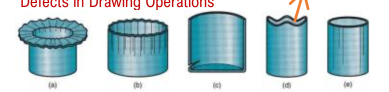
$$F = \pi D_p t(TS)\left(\frac{D_b}{D_p} - 0.7\right)$$

Blankholder Force or Holding Force
Holding pressure ≈ 0.015 x yield strength
Holding force ≈ holding pressure x starting area of blank held by blankholder (refer to image beside)
F_h = blankholder force (N) ;Y = yield strength of sheet metal (MPa); Rd = die corner radius (mm)

$$F_h = \frac{0.015Y\pi}{4}\left(D_b^2 - (D_p + 2.2t + 2R_d)^2\right)$$

sheet metal produced by rolling

Defects in Drawing Operations



Common defects in drawn parts: (a) *wrinkling* can occur either in the flange or (b) in the wall (due to compression), (c) *tearing* (due to high tensile stresses that cause thinning and failure), (d) *earing* (due to anistropy), and (e) *surface scratches* (due to poor lubrication, punch/die not smooth).