

Chapter 1: Crystalline solids

Unit cell: Single basic structural repeat unit that, when duplicated and translated, reproduces the entire crystal structure.

Coordination number: (of an atom) is the number of nearest neighbouring atoms touching it.

AAAG(6) ABA(12) ABC(12)/FCC

close packed: BCC: 8(non-close packed)

Number of atoms per unit Cell: how many unit-cell has this atom?

Simple: 1

BCC: 1 + 8(1/8) = 2

FCC: 8(1/8) + 6(1/2) = 4

Atom per u/c = Σ n<sub>i</sub> \* part of atom in u/c

Atomic radius & u/c dimensions relation:

BCC: a = 4r

FCC: a = 2√2 r

Atomic Packing Factor: how efficient the atoms are packed in a crystal strc.

APF = Total volume of atoms in a unit cell V<sub>a</sub> / Total volume of unit cell V<sub>c</sub>

FCC: face centre = 1/2, corner = 1/8 atm

BCC: centre = 1, corner = 1/8 atom

Density of unit cell:

Density of unit cell, ρ<sub>c</sub> = (n × A<sub>m</sub>) / (N<sub>A</sub> × V<sub>c</sub>)

n = no. atoms per unit cell  
A<sub>m</sub> = Atomic mass of atom  
N<sub>A</sub> = Avogadro's Number  
V<sub>c</sub> = Volume of Unit Cell

Single Crystal vs Polycrystalline Solids

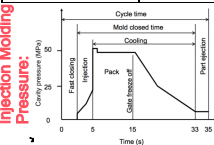
Perfect 3-D periodic arrangement of atoms throughout the entire structure. All unit cells interlock in the same way and have the same crystallographic orientation. Varying degree of anisotropy depending on symmetry of crystal structure (the anisotropy refers to direction dependent material properties).

Chapter 2: Crystallography

Point Coordinates: Location of atom in a u/c given by its coordinates

Crystallographic Directions: vector connecting coordinate origin and a specific point in a u/c [u v w]. Selection of origin: if number is negative [ī], shift origin to "1".

Indices given	Direction Drawn
1. Select Origin	1. Select Origin (start of vector)
2. Reduce maximum number to 1	2. Determine coord of endpoint of vector from origin
3. Locate vector direction from new origin	3. Reduce values to whole numbers
4. Draw	4. Place "[]"



Injection Molding Pressure: Curing pressure (MPa) vs Time (s).

Weld Defects

Families of directions in u/c: Set of directions that are crystallographically identical <u v w>

Important because members of the same crystallographic direction will have the same properties i.e packing density & physical properties

Directions must be unique i.e not parallel to each other

family eg: <110>

[110][ī10][110][īī0]

[101][ī01][101][ī0ī]

[011][0ī1][011][0īī]

Crystallographic Planes: set of parallel and equally spaced planes that pass-through atom centres (no centre must be situated between planes) {h k l}

distance between successive planes depends on their direction in relation to the arrangement of atomic centres

planes are important for mechanical deformation of metals (anisotropy & isotropy) & transportation or electrons/ conductivity

Miller indices given	Drawn plane
1. Select origin	1. Choose closest corner (plane cannot touch origin)
2. Reciprocate indices	2. Select corner as origin
1/0 = ∞ = parallel	3. Find intercepts with x-y-z axis
3. Reciprocated indices is the intercept	4. take reciprocals of intercepts
4. Mark intercept along x-y-z axes	5. reduce multiples, eliminate fractions & add bar for negative (parallelism)
5. Connect intercepts to get plane	6. Round brackets

Family of planes: members of planes in the same unit crystal that are crystallographically equivalent {h k l}

Same packing density, same atomic environment, same mechanical & physical properties i.e {100} (100)(ī00)(010)(010)(001)(001) basically having one "1" makes it the same family

Linear Density: determines directional equivalence of a single crystal. Vector MUST cut through the middle of the atom

LD = No. of atoms centered on directional vector / Length of directional vector

FCC: FCC: Al, Ni, Cu, Au  
BCC: Cr, W, Fe (α), Mo, V, Nb

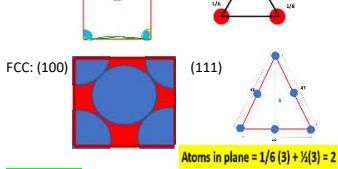
Planar Density

PD = No. of atoms centered on a plane / Area of plane unit: nm<sup>-2</sup>

Plane must cut through CENTRE of atom

ONLY AREA of the atom IN THE PLANE is considered its coordinates

BCC: (110) (111) does not cut centre atm



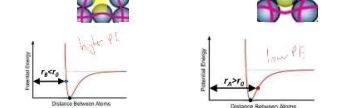
Atoms in plane = 1/6 (3) + 1/2 (3) = 2

Chapter 3: Defects

Point, Line, Interfacial, bulk/volume defects

Point defect: Vacancies & self-interstitials

Vacancy: Self-interstitials:



Impurity: Substitutional Interstitial

Energy-cost of crystalline defects: Most crystalline defects create strain, distorts lattice -> Increase energy of system (G). System will tend to reach an equilibrium structural state, minimising G

G = H (enthalpy) - TS (entropy)

Entropy - energy associated with creation of states

Enthalpy - energy-cost to break atomic bonds

T = Constant ΔG = ΔH - TΔS

Arrhenius Law: Vacancy concentration, N<sub>v</sub> = n<sub>0</sub> exp(-Q<sub>v</sub>/kT)

n = exp(-Q<sub>v</sub>/kT)

Formation of point defects: Annealing & Quenching - Kinetically trapping defects

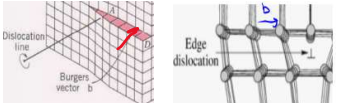
Irradiation by high energy particles Ion implantation - high energy ions implanted in material

Cold working - irreversible mechanical deformation at low temperatures

Dislocations Burger's vector, b: Magnitude and direction of the lattice distortion of a dislocation

Edge dislocation: b perpendicular to the dislocation

Screw dislocation: b parallel to dislocation



Polycrystalline Materials

Grain Boundaries: Regions between crystals

Transition line from lattice to lattice

slightly disordered

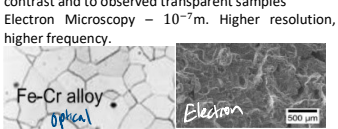
low density of atomic packing in grain boundaries

High mobility, diffusivity & chemical reactivity

Can be equiaxed(same size) or columnar (elongated)

Microscopy Optical microscopy - 2000X magnification. Boundaries revealed as darklines, change in crystal orientations can be observed. Can use polarized light to increase contrast and to observed transparent samples

Electron Microscopy - 10<sup>-7</sup>m. Higher resolution, higher frequency.



Chapter 4: Phase Diagrams

Solubility limit - max conc. for a single phase solution to exist

Equilibrium phase diagrams - all phase diagrams are computed when system is at thermodynamic equilibrium (G min) i.e do not change with time, T constant

Solute - Minority component in an alloy

Solvent - Majority component in an alloy

Hume-Rothery rules for complete solid solutions

- 1) Atomic Size factor - Difference in atomic radii between atoms less than ±15%
- 2) Crystal Structure - crystal structures formed by both atoms must be of the same type, FCC etc.
- 3) Electronegativity - Both components' atoms must be similar, if not ions will be formed
- 4) Valency - combining capacity of both elements must be similar

More than 2 elements can form a solid solution, including ions (of similar charge)

Isomorphous binary phase diagram

Simplest possible diagram

2 independent variables T & conc.) P = 1atm

Composition of that phase i.e., B: both α & L present

C<sub>L</sub> = 32% (trace left)

C<sub>α</sub> = 43% (trace right)

A: only L C: only α

Phase weight fraction

B: Opposite! i.e for weight fraction of liquid, take

S = C<sub>α</sub> - C<sub>L</sub> (line to solidus)

W<sub>L</sub> = S / (R + S) W<sub>α</sub> = R / (R + S)

Solidification during cooling: Trace conc line down as temperature decreases.

Faster rate of cooling - coored structure

Slower rate of cooling - Equilibrium struc

Binary Eutectic System

Above the solubility limit, a new phase is formed (β)

B has different compositions with α (both solutions)

May have different crystal structure

multiple phases coexist when:

i) immiscible or ii) solubility limit reached

Contains 3 single phase regions

T<sub>E</sub>: No liquid below T<sub>E</sub> (eutectic temperature)

C<sub>E</sub>: Composition at temperature T<sub>E</sub>

Weight compositions: Similar to isomorphous

Find the point with T & C. Extend to the right & left to find the phases present. Calculate using the "opposite" analogy.

Development of eutectic alloy

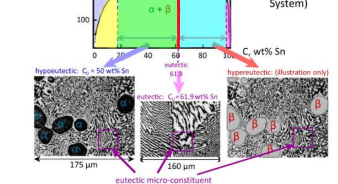
For 2 < C<sub>0</sub> < 18.3: Formation of polycrystalline with α grains β-phase particles/precipitates

For 18.3 < C<sub>0</sub> < 66: Formation of near-eutectic alloys

For 66 < C<sub>0</sub> < 97.8: Direct formation of α & β

Results in eutectic alloy, with eutectic microstructure (lamellar)

For 97.8 < C<sub>0</sub> < 99: Formation of polycrystalline with β grains α-phase particles/precipitates



Treat intermetallic compounds as two different phase diagrams that are conjoined

Eutectic: Liquid cool solid1 + solid2

Eutectoid: Solid1 cool solid2 + solid3

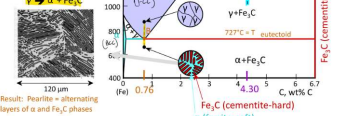
Peritectic: Liquid + solid1 cool solid2

Phase diagram uses: explains what processing to use to control composition, size and arrangement of phases in a certain system

We control the microstructure of the alloy through such processes to achieve the alloy properties that we want

Fe-C Phase Diagram

2 important points



Pearlite The combination of cementite and ferrite makes pearlite a tough phase

ferrite is soft and ductile, while cementite is hard and brittle

For this reason, pearlite is ideal of blade BODY

Martensite - Martensite originates from rapid cooling/quenching of austenite

As such, it is a non-equilibrium phase and thus does not show up in the C-Fe phase diagram.

Martensite is the strongest and hardest phase that is available in the C-Fe system

Because of its strength, Martensite is ideal for the blade cutting edge

Cementite decomposes to ferrite & graphite

Differential quenching is the quenching process of cooling down a single piece of metal at different rates, using different thickness of clay layers to control the rate the metal cools.

Metal alloys: Ferrous - iron based, non-ferrous - others

Ferrous: High densities, low electrical conductivities, poor corrosion resistance

Types of iron alloys: Cast iron - more than 2.1 wt% (usually 3-4.5). Low melting point, generally brittle.

Non-metals - Ionic (need to avoid similar signed)

Covalent (little slip systems - angular bonds & complex)

Ceramics - few slip systems, break before plastic def.

Strengthening Grain boundary strengthening: T < 0.5T<sub>m</sub>, boundaries act as barriers to dislocation motion. Higher energy required for change in direction.

Smaller grain size, more barriers to slip, higher stress required, higher str. σ<sub>y</sub> = σ<sub>0</sub> + kD<sup>-0.5</sup>

Solid Solution: addition of solute to generate a strain field to resist dislocation - act as barriers to dislocation. Smaller atoms tend to conc at regions of compressive strains, causing cancellation of dislocation compressive strains, reducing disl. mobility.

Cold work: σ<sub>y</sub> ↑ Tensile Str ↑ Ductility ↓ (trade off)

Dislocations multiply and entangle, causing dislocation motion to be more difficult. CW occurs at Room Temp.

%CW = (A<sub>0</sub> - A<sub>f</sub>) / A<sub>0</sub> × 100

Annealing: CW uses intermittent annealing, restore ductility. Nullifies effect of CW (heating)

1. Recovery: diffusion: atoms move to regions of tension and annihilate dislocations to form perf plane.

Climbing: dislocations climb into vacant slots after diffusion to reduce dislocation density

2. Recrystallisation: new grains form to have low dislocation densities, smaller in size and replace parent grains

3. Grain Growth: big grains grow, small grains disappear.

Empirical Relation: coefficient dependent on material and T.

0.37T<sub>m</sub> < T<sub>R</sub> < 0.67T<sub>m</sub> T<sub>R</sub>: temp where recrystallisation finishes in 1 hr. Depends on

%CW - T<sub>R</sub> T as CW ↑ & Purity: T<sub>R</sub> ↓ as purity ↑

Hot Working: deformations at ABOVE T<sub>R</sub>

Toughness: Energy required to break a unit volume of material = area under curve till failure

True Stress & Strain: Area change when stretched

σ<sub>T</sub> = F/A<sub>i</sub> ε<sub>T</sub> = ln(l<sub>i</sub>/l<sub>0</sub>)

e = engineering strain

Work/strain Hardening: Increase in σ<sub>y</sub> due to plastic deformation

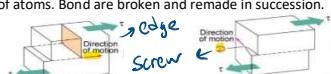
Hardness: Resistance of a material to permanent indentation. Hardness = Pmax/Area

Chapter 6: Dislocations & Strengthening mechanisms

Plastic deformation occurs by slip - edge dislocation slides over adjacent planes

Dislocation motion: Moves along slip plane in a slip direction (same as b) perpendicular to dislocation line.

Dislocation requires successive bumping of half plane of atoms. Bond are broken and remade in succession.



Dislocations are defects that increase the energy of the system proportional to b<sup>2</sup> (burgers vector)

Dislocation interaction: Same sign repel, similar sign attract and cancel each other out (energy ↓)

LD & Burgers vector: min b will be in direction of max linear density. Atoms are closer, require less energy to move along atoms -> energy required lower.

FCC: min b along u/c face BCC: min b across diagonal

Slip: Slip plane - highest PD, slip direction - highest LD

Stress & dislocation motion: T<sub>R</sub> - from tensile stresses

1. Resolve tensile stress & shear area

T<sub>R</sub> = σ cos λ cos φ direction

λ angle between slip plane and force

φ angle between slip plane normal and F

T<sub>R</sub> max = σ/2, both angle 45° σ = yield stress

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Chapter 6: Overview of Manufacturing

Metal Casting – casting Metal Forming – joining – Metal Machining – drilling, milling Metal extrusion – welding

**Additive Manufacturing** – increase weight(3d printing)

**Subtractive Manufacturing** – decrease weight(Milling)

**Formative Manufacturing** – no weight change(Casting)

**NET shape process:** Little of no waste and no machining is required

**Good environmentally conscious manufacturing:**

Proper choice of materials, design products that minimize environmental impact. Manufacturing processes that are environmentally friendly

**Dimensions:** Part sizes desired by the designer if the part could be made with no errors or variations.

**Tolerance:** Total amount by which a specific dimension is permitted to vary

**Tolerance = positive tolerance – (negative tolerance)**

**ACCURACY:** True value of the quantity **PRECISION :** degree of repeatability

**Apparatus:** micrometer – diameter, vernier caliper, bevel protractor, sine bar (sin Angle = Height/Length)  
**Surface Roughness:** Average vertical deviations from nominal surface over a specified surface length

$$R_a = \sum_{i=1}^n \frac{|y_i|}{n} = \frac{y_1 + y_2 + y_3}{n} \text{ (ABS VALUE, no sign)}$$

Chapter 7: Metal Casting

**PROS:** Create complex geometries for both external and internal shapes. Large parts, suited for mass productions. (Near) Net Shape.

**CONS:** Environmental problems. Safety hazards to workers, poor dimensional accuracy and surface finish, limitations on tech. properties.

**Terminology -** Cope (Upper half of mold), Drag (Bottom half), Flask (Box contains the mold halves), Parting Line, Core (Used for interior geometry), Downsprue (a runner towards the main cavity), Pouring cup, Riser (Compensate for shrinkage & freeze later), Gate

**Flow velocity**  $V_d = \sqrt{2gh}$ , (cm/s)

Fluidity – how fast to fill the cavity  
High Viscosity = Low Fluidity (Spiral test)

**Continuity law**

$$Q = A_1(Vel)_1 = A_2(Vel)_2 \text{ (cm}^3/\text{s)}$$

**Mold Filling:**  $T_{UF} = Vol / Q \text{ (cm}^3\text{)}$

Min. time, ignore fraction

**Chvorinov's rule (Solidification)**

$$T_{TS} = C_m (V/A)^n \text{ [Entire SURFACE]}$$

**Areal** Type of metal density, temp/heat capacity  
Net Shape: Complex features w/ additional operations.

**Pouring of Metal**

**Pouring Time:** Raise temp to M.P, latent heat of fusion, raise temp. to desired pouring temp.

**Rate:** Slow, metal freeze before filling cavity. Fast, turbulence(cavity + degrade casting quality), irregular flow. Tapered Sprue - Prevents aspiration of air

**Riser Design:** Time for riser to solidify > Time for rest of casting to solidify -> Maximize V/A

**Casting quality:** Fluidity (too hard), Pouring temp (too low), Velocity (too slow), Improper design, turbulence, shrinkage

**Casting General Defects:**

**Misrun:** Casting solidified before completely filling mold cavity.

**Cold Shut:** Two position of metal flow together but there is a lack of fusion due to premature freezing.

**Cold Shot:** Metal splatters during pouring lading to formation of globules, which become entrapped in the casting.

**Shrinkage Cavity:** Depression in the surface caused by solidification shrinkage that restricts molten metal to freeze.

**Microporosity:** Small voids distributed throughout the casting caused by localized solidification shrinkage of final molten metal within dendritic structure.

**Hot Tears/Cracks:** Casting restrained from contraction because of mold from final stages of solidification or early stage of cooling.

**Bernoulli's:**  $h_1 + \frac{P_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + f$

**Sheet metal forming:** Done by: Ho Min Han

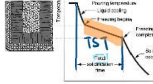
**PROS** sheet metal: Strong, dimensionally accurate, good surface finish, low cost, mass production

**Blanking & punching:** shearing operation

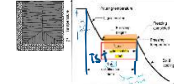
**Mitigating Hot Tears:** Place internal chills inside thick liquid regions to control solidification rate; may be left inside the casting after solidified /

Control cooling in critical sections using exothermic compounds.

ALLOY:



Pure Metal:



**Achieving Directional Solidification:** CHILLS (internal or external heat sinks that cause rapid freezing in certain regions of the casting)

**Product Design Considerations:** Geometric Simplicity / Corners on the casting / Section thickness / Draft angle (taper) /eliminate the need of core / Dimensional tolerance & surface finish / Machining allowances.

**Expendable mold casting:** Investment Casting, Sand casting.

**Sand Casting:** Most widely used, nearly all alloys can be used, varying sizes can be done, high quantities produced

**Investment Casting:** 1. Wax pattern is produced. 2. Patterns attached to sprue to form pattern tree. 3. Tree is coated with layer of refractory material. 4. Full mold is formed by covering coated tree with sufficient refractory material to make it rigid. 5. Mold held inverted position and heated to melt wax and permit it to leak out of the cavity. 6. Mold preheated to high temp, molten poured & solidify. 7. Mold is broken away from the finished casting and parts are separated from the sprue.

**PROS:** Net shape process, wax can be reused. Close dimensional control, good surface finish.

**CONS:** Expensive and many steps required.

**Permanent Mold Casting** (aluminum magnesium iron)

Mold is preheated & coated for lubrication & heat dissipation. Cores (if used) are inserted, and mold is closed. Molten metal poured into mold & solidifies.

**PROS:** Dimensional control and surface finish. Rapid solidification results in finer grain structure so casting is stronger. Mold can be reused. Economical for large production. Thin sections possible.

**CONS:** Generally limited to metals of lower melting point, simpler part geometries compared to sand casting because need to open mold. Mold expensive.

**Die Casting:** high pressure to force metal into die cavity

**Hot chamber die casting:** Casting metals: zinc, tin, lead, and magnesium [ Low MP ] Heated Chamber

Steps: With the die closed and plunger withdrawn, molten metal flows into chamber. Plunger force metal flow to die under constant pressure. Withdraw ram; open die, eject parts

**Cold Chamber die casting:** Casting metals: aluminum, brass, and magnesium alloys [ Unheated Chamber

Steps: With the die closed and ram withdrawn, molten metal is ladled (thus extra time) into chamber. Ram forces metal to flow into die, maintaining pressure during cooling and solidification. Withdraw ram; open die, eject part

**PROS:** Economic for large production, good accuracy, thin section possible, rapid cooling - small gain size & good strength of the cast product.

**CONS:** Limited to metal with low melting point, part geometry limited for removal from the die.

Chapter 8: Metal Forming

**Sheet metal working:** Thickness of sheet metal = 0.4mm to 6mm, larger-plate

**Rolling:** Hot rolling – above  $T_{recrys}$  Cold rolling- below (better surface finish as no scale formation, better tolerance and better mech properties.

2/3-high rolls: used for hot rolling(3 reverse direction) 4-high: smaller diameter rolls, lower rolling force, reduce spreading. Usually cold rolling. (planetary)

**Rotary tube piercing** – hot-working process for long thick-walled seamless pipes. Round bar subjected to radial compressive forces and develops tensile stresses at its centre-> cavity. Internal mandrel expands hole and defines bore of tube

**Sheet metal forming:** Done by: Ho Min Han

**PROS** sheet metal: Strong, dimensionally accurate, good surface finish, low cost, mass production

**Blanking & punching:** shearing operation

**Roller:** Depression made by punch. **Burnish:** Smooth region due to penetration. **Fracture zone:** Quite rough surface due to fracture. **Burr:** Sharp corner edge due to elongation of metal. **Shearing:** Separate large sheets

**Blanking:** Cut part perimeters from sheet metal. **Punching:** Make holes. **Clearance:** usually 2-10% T

**Clearance:** As  $c^\circ$ , sheet pulled into clearance zone rather than sheared, gives rougher edges, burr height↑, punch force↓, die wear↓  $c = at$ , a = allowance, t = thickness

**Round blank  $D_d$ :** Punch diameter =  $D_b - 2c$ , die diameter =  $D_b$

**Round hole  $D_d$ :** Punch diameter =  $D_h$ , die diameter =  $D_h + 2c$

Angular clearance – allow blank to drop (0.25 – 1.5)°

**Max Punching Force:**  $F = 0.7(UTS)TL = STL$ , S = Shear Strength, T = sheet thickness, L = length of shear(perimeter), UTS = ultimate tensile strength

**Changing die** reduces cutting force: Bevel shear i.e where the centre cuts first followed by outside

**Other Shearing operations:** Shaving – extra material removed to get straight edge (small clearance between punch & die)

**Fine Blanking** – Blanking with a cushion below + pressure pads  $c < 1\%$

**Bending** **Bend Allowance,  $L_b$**   $L_b = \alpha(R + kT)$ ,  $\alpha$  = bend angle (rad) R = bend Radius k = constant(0.33~0.5) T = sheet metal thickness

**R<2T, k = 0.33 R>2T, k = 0.5**

**Minimum bend radius:** eng strain  $\epsilon$  is As R/T ↑, tensile strain at outer fibre ↑, causing cracks. Cracks first occur -> min bend radius. Usually expressed in terms of T.

**Anisotropy:** different behaviour in diff directions, acquired during sheet metal processing (rolling)

1. preferred grain direction – caused by compression of equiaxed grains, boundaries align horizontally (preference in grain orientation)

2. Mechanical fibering – alignment of impurities, inclusions, and voids during deformation

=>bending should be done perpendicular to rolling direction

**Springback:** elastic recovery after load removed, bend angle ↓, bend radius ↑

$R_f = d \left( \frac{R_p Y^3}{E} - \left( \frac{R_T Y}{E} \right) + I \right)$  Y = yield stress, R = radius of curvature, E = Elastic modulus

Compensation: **Overbending, bottoming** (high compressive pressure causes plastic deformation to reduce thickness at bend area) & **stretch bending** (sheet stretched past yield stress then bent). Including Ribs or darts can increase stiffness and ↓ springback

**Bending operations:** V-die bending Wiping die V-die simple, cheap, acute obtuse

Wiping die- complicated, high quantity, precise

**Bending force:**  $P = \frac{k(UTS)LT^2}{L}$   $k = 1.33$   $k = 0.33$

**Deep Drawing:** Clearance = 1.1 t

1. Blankholder holds sheet metal

In place. 2. Punch moves down, bends sheet metal 3. Straighten to form cup wall, high tension along walls and high compression in flange, causes tearing and wrinkling respectively

B holder force: too high -> tearing, too low -> wrinkles

**Drawability:** DR, reduction, thickness-diameter ratio

**Drawing Ratio (DR)** = blank diameter/punch diameter If  $DR > 2.0$ , not feasible

**Reduction:**  $(D_b - D_p) / D_b$  [%reduction in diameter]  $< 0.5$  = feasible

**Thickness to diameter ratio:**  $t / D_b > 0.01$  = feasible

t/D<sub>b</sub> ↓, tendency to wrinkle

If conditions are not met, redrawing is required, with annealing between each drawing.

**Redrawing:** Drawn cup faced UPWARDS on die

**Reverse Drawing:** Drawn cup faced DOWNWARDS on die – requires lesser force than redrawing

**Blank size:** Volume doesn't change!

**Drawing Force:**  $F = \pi D_p(TS) \left\{ \frac{D_b}{D_p} - 0.7 \right\}$  0.7 accnts for friction

**Blankholder Force:**  $F_{h1} = 0.015Y\pi \left\{ D_b^2 - (D_p + 2.2t + 2R_d)^2 \right\}$

**Drawing defects:** wrinkling, tearing, earring(anisotropy), surface scratches

**Chapter 9: Metal Machining** **PROS:** Good dimensional accuracy and surface finish

**CONS:** Waste materials, takes a long time to shape

**Cutting Models:** Oblique(<90deg) & Orthogonal(90°) V = Cutting velocity

$\alpha$  = rake angle  $\phi$  = shear angle

t0 = undeformed thickness tc = chip thickness

**Merchant's equation:** assumed that  $\phi$  adjusts itself to give minimum cutting force (use when given)  $\beta$  = friction angle

**Cutting Forces:**  $R = \sqrt{F_t^2 + F_r^2}$  Friction coeff:  $\mu = F/N = \tan \beta$

Shear stress =  $\frac{F_s}{A_s}$  (w = width of chip)

$A_s = wt_0 / \sin \phi$  NOT thickness

**Power & Material Removal Rate**  $F_c V = F_t V_t + F_r V_r$   $MRR = wt_0 V / mm^3 / s$

$\phi = 45^\circ + \frac{\alpha}{2}$

**Specific energy = Power/MRR**  $1 / mm^3$  Energy conservation applies here!

**Temperature:** energy lost converted to heat => shear zone & tool chip interface

T ↑ -> 1. Strength, hardness, wear resistance ↓ (cutting tool) 2. Dimensional inaccuracies in w/p, thermal damage, fail easier(Workpiece) 3. Uneven temps distort machine, difficult to control dimensions (machine tools) **Cutting fluid:** Lubricant & coolant(oils)

**Tool wear:** flank (rubbing of tool & high temps) & crater (high Temp & chemical affinity with w/p -> use coated with TiN)

**Signs for replacement:** 1. Obvious tool wear 2. w/p surface finish gets worse 3.  $F_r$  ↑ signif 4. T ↑ signif.

**Taylor's tool life eqn:**  $VT^n = C$  V = cutting speed, T = tool life(min), n = exponent(<1), C = constant

**Cutting tool material:** 1) Hot hardness 2) Toughness 3) Thermal shock+Wear resistant 4) Chemically stable

4 **Types of chips:** continuous – ductile material, good surface finish, entangles tools [Change machining parameters or use chip breaker] **Discontinuous** – brittle materials, hard impurities, cutting force varies during cutting **Built-up edge** – layers of w/p deposited on tool. BUE ↑, tool breaks. Some BUE will be deposited on w/p surface, poor surface finish. BUE also makes tool dull

**Serrated** – low thermal conductivity & strength decreases with temperature

**Surface finish:** factors: Chip types, feed mark left by cutting, vibration\* (surface roughness)

$R_a = \frac{f}{12} \cdot \frac{1}{\cos \alpha} \cdot \frac{1}{\cos \phi}$  (peak to valley) | either ↑, finish ↓

\* forced – force from machine tool, chattering – self-excited vibration from interaction of cutting process and machine tool. Starts from disturbance in cutting

**Others:** 1. **Turning:**  $MRR = \text{depth of cut} * \text{feed} * \text{rota. V}$   $V = \pi D \text{ rev}/\text{min}$ , N = rotation speed,  $D_{avg} = (D_i + D_f) / 2$   $d_{avg}$

Cuts at high f, then lower f for good surface finish

**Drilling:**  $MRR = \frac{\pi D^2}{4} f N$ , f = feed. Time taken =  $\frac{\text{length cut}}{f N}$

Power = torque \* rotational speed (rad/s)

**Milling:** Conventional (upwards) & climb milling(downwards)

**Chip velocity**  $V_c = V \sin \phi$   $V_s$  = shear velocity  $V_f$  = feed velocity

**Power** = torque \* rotational speed (rad/s)

**Milling:** Conventional (upwards) & climb milling(downwards)

**Chip velocity**  $V_c = V \sin \phi$   $V_s$  = shear velocity  $V_f$  = feed velocity

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**Power** = torque \* rotational speed (rad/s)

**Milling:** Conventional (upwards) & climb milling(downwards)

**Conventional** -max thickness at end of cut, does not affect tool life, will chatter so need clamp w/p **climb** -max thickness at start of cut(bad), downward cutting force holds w/p in place(good), scales will cause dmg on cutter, high impact forces require rigid set up.

**Grinding** – dimensional accuracy and surface finish

**Chapter 10: Metal Joining** **Welding:** Fusion Welding: melts base metal, sometimes have filler metal(w/o – autogenous) **GTAW** i.e. **TIG**

Solid State Welding: no melting of base metal, no filler metal is added

**Power:** Power density = P/A [intensity of power within A Unit energy for melting =  $kT_m$ ,  $k = 3.33 \times 10^{-6}$ , T in kelvin

**Heat transfer:**  $f_1$  - (heat received by w/p) / total heat  $f_2$  - proportion of heat received by w/p used to melting =>  $H_w = f_1 f_2 H$ ,  $H_w$  = heat for welding, H = total heat  $f_1$  – affected by welding process

$f_2$  – affected by thermal conductivity & welding process

**Energy Balance:** Welding speed  $v = \frac{H_w A_{weld}}{U_{melt} A_{weld}}$   $H_w = \eta I V$   $\eta = \text{efficiency}$

$A_w$  = weld area,  $H_{rate}$  = rate heat is generated from source. Welding volume rate =  $HR_w / U_m$ ,  $HR_w$  = rate of energy delivered.  $WVR = VA$ ;  $HR_w$  is one term

**Arc Welding:** using electric arc to heat metal **Shielding:** inert gas or flux(flux prevents formation of oxides & provides protective atm. Stabilises arc, reduce spatter) Application of flux: coat electrode with flux which melts during welding. Or flux contained in core of consumable electrode, flux release as it is consumed.

**Electrodes:** Consumable – filler metal, non-consumable – tungsten(gradiently depletes) **unquen need inert gas**

**Resistance Spot welding:** current flow thru cross section of spot weld, generate heat with resistance

**SSW: Roll Bonding** – roll metal together with pressure **Friction welding:** twist parts in contact to generate heat - narrow HAZ, join dissimilar metals | Explosive Welding – clad metals over large areas

**Weld quality:** HAZ – microstructural changes to metals tap experience temp below melting – usually negatively

**Weld Defects:** Incomplete fusion – low quality weld beads, formation of oxide, incomplete fusion at grooves

**Underfill** **Undercut & Excessive overlap** **Good**

**Cracks** – cause: 1. thermal stressed(temp gradient) 2. Variation in composition 3. embrittlement of grain boundaries(segregation) 4. hydrogen embrittlement

5. inability to contract **Distortion:** differential thermal expansion and contraction of different parts of welded assembly

**Others: Brazing:** filler metal of low MP(>450C), no melting of base metal only filler. For metals of poor weldability + ceramics. Increased contact areas is good

**Soldering:** brazing but MP<450. Filler metal called solder, usually for electrical. **Adhesive bonding:** basically glue, need large contact areas for good bond

**Chapter 11: Engineering polymers & Polymer forming** **Polymer Molecule:** Monomer unit (H-C-H) joined by covalent bonds.

**Polymer Structure:** Linear Polymers: chains of polymer lying on each other, inter-chain bonds weak. **Branched Polymer:** like a tree (chain packing efficiency ↓) **Cross-linked polymer:** adjacent linear chain joined by strong covalent bonds, achieved by growth at high temps and is irreversible i.e Rubber **Network polymer:** tri-functional monomer units that form more than 3 covalent bonds -> 3-D network. i.e Epoxies

**Types of polymers:** **Thermoplastics** – soften upon heating, made to flow with stress. Solidify when cooled. Recyclable. **Thermoset** – becomes irreversibly hard/rigid when heated. Chain motion restricted by high degrees i.e. need to be cured

**Thermosetting:** compression molding as fluid. Thermoset loaded into chamber, heated, then pressure applied on soft polymer to flow into heated mold, cured Pot: charge injection from a pot | plunger: injects charge from a heated well. (vs compression) 1. Both have unreusable scrap(cul) 2. Transfer molding more intricate coz fluid, good for molding with inserts

**Blow molding:** thermoplastic only, using air pressure to inflate soft plastic into mold cavity. 1. Form starting tube (parison) **extrusion/injection** 2. Inflation of tube Types: extrusion BM – parison extruded | injection BM – parison injected into mold before blowing | Stretch BM – injection, stretch (by blowing rod) THEN blow. **Thermoforming:** sheet heated, placed over mold cavity, vacuum draws sheet to form shape, cured. ONLY THERMOPLASTICS

**Pressure TF** – done in pressure box to use pressure from ABOVE to push plastic down. Mechanical TF – Positive mold pushes from above. **Good dimensional control,** surface details on both sides but costly.

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of cross-linking. Stronger but better dimensional stability compared with thermoplastic. Non-Recyclable