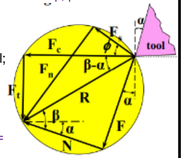
Resistance Spot Welding (RSW): localized heat due to large electrical resistance; used in sheet-metal fabrication/automotive-body assembly; FW processes that use combi of heat & pressure to accomplish coalescence; Heat generated: $H = I^2 R t$; Current I = 5,000 to 20,000 A; Voltage V < 10v; Time t = 0.1 to 0.4 s; Explosive Welding (EXW): bond two diff metals, to clad 1 metal on top of base metal over large areas; Brazing & Soldering: filler metals used to permanently join metal parts; no melting of base metals; brazing/soldering > fusion welding: metal has poor weldability; join dissimilar metals; high heat of welding may damage parts being joined; Geometry of joint cant weld; High strength not required; Adhesive Bonding: Uses forces of attachment between a filler material & two closely-spaced surfaces to bond parts; Filler material not metallic; carried out at room temp/slightly above; Strength of Brazed Joint: solidified joint can be stronger than filler metal; Why? - Small part clearances used; Metallurgical bonding that occurs between base & filler metals; Limitations of Brazing - Joint strength < welded joint; High service temps may weaken a brazed joint; color of brazing metal =/= color of base metal parts, not aesthetic; Pros - Any metals can be joined,e.g.dissimilar metals; allow high production rates; Multiple joints brazed simultaneously; less heat & power required than FW; Problems with HAZ in base metal near joint reduced; inaccessible joint areas can be brazed - capillary action draws molten filler metal into joint; wanted brazing characteristics: low surface tension in liquid phase (good wettability); High fluidity for penetration into interface; avoid chemical & physical interactions with base metal; Brazing Methods: Torch/Furnace/Induction/ Resistance/Dip/Infrared/Diffusion brazing; Torch Brazing: apply filler metal in brazing; torch & filler rod; before & after brazing operation; Brazing Fluxes: prevent formation of oxides & other unwanted byproducts; Good flux: Low melting temp; Low viscosity; aids wetting; Protects joint until solidification of filler metal; Soldering - Joining process where filler metal with T_m <= 450°C is melted & distributed by capillary action between surfaces of metal parts being joined; No melting of base metals, but filler metal wets & combines with base metal; Filler metal called solder; associated with electrical & electronics assembly (wire soldering); Soldering Fluxes Functions: molten at soldering temps; remove oxide films & tarnish from base part surfaces; Prevent oxidation during heating; Promote wetting of faying surfaces; readily displaced by molten solder during process; Leave residue that is non-corrosive & non-conductive; Adhesive Bonding: Joining process where filler material is used to hold >=2 closely-spaced parts together by surface attachment; used in wide range of bonding & sealing applications for joining similar & dissimilar materials like metals, plastics, ceramics, wood, paper, & cardboard; Adhesive: filler material, nonmetallic(e.g.polymer); Adherends: parts being joined; Structural adhesives: capable of forming strong, permanent joints between adherends; Curing: process where physical properties of adhesive change from liquid to solid, usually by chemical reaction, to accomplish surface attachment of parts; Curing often motivated by low heat and/or a catalyst; takes time; Pressure sometimes applied between parts to activate bonding process; Joint Strength: Depends on strength of: Adhesive,attachment between adhesive & adherends; Strength of attachment involves: chemical bonding, physical interactions: bonding forces between atoms of opposing surfaces, Mechanical interlocking:roughness of adherend causes hardened adhesive to become entangled/trapped in its microscopic surface asperities; Joint Design: Adhesive joints not as strong as welded/brazed/soldered joints; Joint contact area should be max; Adhesive joints: strongest in shear, compression & tension; weakest in cleavage or peeling(tension & shear); Poor design: small contact areas between members to be joined; Surface Prep: bond strength depends on degree of adhesion between adhesive and adherend -> cleanliness of surface; For metals, solvent wiping often used for cleaning, & abrading surface by sandblasting improves adhesion; For nonmetallic, some solvent cleaning generally used, & surfaces are sometimes mechanically abraded or chemically etched to increase roughness; Pros: Applicable to wide variety of materials; Bonding occurs over entire surface area of joint; Low temp curing avoids damage to parts being joined; Joint design -often simplified; Limitations - Joints not as strong; Adhesive must be compatible with materials being joined; Service temperatures limited; Cleanliness & surface preparation important; Curing times can impose limit on production rates; Inspection of bonded joint difficult; Fusion Welded Joint Features: Typical fusion weld joint in which filler metal has been added consists of: Fusion zone; Weld interface; Heat affected zone (HAZ); Unaffected base metal zone; Heat Affected Zone - Metal has experienced temps below melting pt, but high enough to cause micro structural changes in solid metal; Chemical composition same as base metal, but region heat treated so its properties & microstructures altered; Effect on mechanical properties in HAZ is usually negative; it is here that welding failures often occur; Defects in Welded Joints – Discontinuities: Porosity, Slag inclusions, Incomplete Fusion & Penetration; Incomplete Fusion; Poor Weld Profile: underfill; undercut; excessive overlap; Cracks – due to thermal stresses developed during solidification & contraction of weld bead and surrounding structure; Causes of Crack in a Weld Bead - Thermal stresses due to temp gradients; Variation in composition; Embrittlement of grain boundaries; Hydrogen embrittlement; Inability to contract; Crack Fix- change joint design to min. stresses from shrinkage during cooling; change parameters, procedures, & sequence; detection of cracks - Ultra-sonic detection; Radiation detection; Distortion after Welding - Butt joints: Distortion caused by differential thermal expansion & contraction of diff parts of welded assembly; Fillet welds: Distortion caused by differential thermal expansion and contraction of different parts of the welded assembly

6 – Machining: Removal of material from a workpiece to give the required shape, dimensions and surface finish; Cutting: turning, milling, drilling, sawing; Abrasive: grinding, polishing, lapping; Advanced machining: electrical-discharge, electron beam, laser beam, water-jet, chemical; Examples of cutting – straight turning; cutting off; slab milling; end milling; face milling; drilling; parts produced by chemical milling - Missile skin-panel section contoured by chem. milling to improve stiffness-to-weight ratio of part; weight reduction of space launch vehicles by chem. milling aluminumalloy plates. Pros: Good dimensional accuracy&surface finish; accurate round holes, very straight edges & surfaces; Cheaper to produce parts by machining, Cons: Waste materials (chips); takes longer time to shape given part; Mechanics of chip formation: Cutting ratio - $r = t_0/t_c$; $t_c > t_0$ ($r < 1$), $t_0 = l_s \sin\varphi$; $t_c = l_s \sin\angle ABC$, $r = t_0/t_c = \sin\varphi/\cos(\varphi - \alpha)$; Shear angle φ – $r = t_0/t_c = \sin\varphi/\cos(\varphi - \alpha)$; $r\cos(\varphi - \alpha) = \sin\varphi$; $r(\cos\varphi\cos\alpha + \sin\varphi\sin\alpha) = \sin\varphi$, Divide by $\cos\varphi$: $r(\cos\alpha + \tan\varphi\sin\alpha) = \tan\varphi$; $\tan\varphi(1 - r\sin\alpha) = r\cos\alpha$, $\tan\varphi = r\cos\alpha/1 - r\sin\alpha$; Shear Strain $\gamma = AB / d$ (AB = the distance deflected); Merchant's equation: $F_c = (\tau\, w t_0 \cos(\beta-\alpha))/(\sin\varphi\cos(\varphi+\beta-\alpha))$, $dF_c/d\varphi = 0$, gives merchant's eqn: $\varphi = 45° + (\alpha/2) - (\beta/2)$, α: rake angle, β: friction angle; As α ↓ or β ↑, φ ↓, As φ ↓, γ ↑, that is, more energy is dissipated → converted to heat. as γ ↑ the temp in cutting zone ↑; Velocity diagram(sine rule): $V/\sin(90-\varphi+\alpha) = V_s/\sin(90-\alpha) = V_c/\sin\varphi$; $V/\cos(\varphi-\alpha) = V_s/\cos\alpha = V_c/\sin\varphi$; Cutting forces (orthogonal cutting model) – focus on tool: Cutting force F_c; Thrust force F_t (⊥ to F_c); Resultant force $R = \sqrt{F_c^2 + F_t^2}$; Forces on tool rake face (tool-chip interface): R can be resolved into 2 components on toolchip interface: Friction force F; Normal force N (⊥ to F); Forces and force circle diagram: Cutting force F_c & thrust force F_t can be measured; Other forces derived: F_s, F_n, F, N, β = friction angle; $F = R\sin\beta$; $N = R\cos\beta$; $\mu = F/N = \tan\beta$; $\mu \approx 0.5$ to 2 Shear stress = shear force/area of shear plane($w t_0/\sin\varphi$); Power = Force x Velocity Power (cutting) = $F_c V$ - dissipated in two main areas: Shear plane - to shear material; Tool-chip interface – to overcome friction; Power (shearing) = $F_s V_s$; Power (friction) = $F V_c$; $F_c V = F_s V_s + F V_c$; Material Removal Rate (MRR) = Area of cross-section of cut x Velocity perpendicular to area; $MRR = w t_0 V$ mm^3/sec; Specific energy = power/MRR($W.s/mm^3$); Shearing: $U_s = F_s V_s/MRR$; Friction: $U_f = F V_c/MRR$; Total specific energy: $U_t = F_c V$(or power)/MRR; $U_t = U_s + U_f$; Temp in cutting - As V ↑, time for heat dissipation ↓ & temp. ↑, % of heat generated in cutting: Chip carries away most of the heat; As V ↑, higher % of heat is carried away by the chip; Tool wear & Tool Life - Cutting tool subject to: a) High localized stresses b) High temp c) Sliding of chip along rake face d) Sliding of tool along freshly cut surface→ tool wear→tool life, quality of machined surface, dim accuracy & cost;Tool wear regions – wear on cutting model/turning tool; Flank wear – occurs in flank face; causes: 1. rubbing of tool along machined surface, 2. high temps affecting properties of tool material; Crater wear - occurs on rake face of tool (tool-chip interface); causes: 1. Temp. at tool – chip interface, 2. Chemical affinity between tool & w/p material – diffusion mechanism (Use coating tools coated with TiC & TiN, slow down diffusion, reducing cater wear); others: nose radius & notch wear; When to re-sharpen/replace cutting tool? – 1. Tool wear, 2. W/p surface finish becomes worse, 3. Cutting forces ↑ significantly, 4. Temperature ↑ significantly; Taylor's tool life equation - $VT^n = C$; V = cutting speed (m/min); T = tool life (min); n = exponent (<1); C = constant; Extended Taylor's tool life equation: $V\, T^n d^x f^y = C$, V = most significant variable; d = depth of cut (mm); f = feed (mm/rev); x & y determined experimentally; Chips - Chips have significant influence on: 1. Surface finish of workpiece 2. Cutting operations (e.g. tool life, vibration, chattering); 4 types of chips: Continuous, Discontinuous, Built-up edge, serrated & segmented; Continuous chips – 1. formed with ductile materials at high cutting speed; 2. good surface finish; 3. Tend to entangle around toolholder, work holding device & w/p – operation has to stop to clear chips; continuous chips fix- 1. Change machining parameters e.g cutting speed, feed 2. Use chip breaker to decrease radius of chip, chip bents & breaks; Discontinuous chips - occur at: 1. brittle materials – cant withstand high shear strains; 2. materials containing hard inclusions/ impurities; Cutting forces vary during cutting; Built-up edge (BUE) – 1. layers of w/p material deposited gradually on tool. BUE ↑, becomes unstable & breaks up eventually; 2. Part of BUE material carried away by chip & rest deposited randomly on w/p surface, giving poorer surface finish; 3. BUE changes geometry of cutting edge&makes it dull; Serrated (segmented chips) - Semi-continuous chips with large zone of low shear strain & small zone of high shear strain (saw tooth like appearance); Found in metals with low thermal conductivity & strength that decreases sharply with temperature e.g. titanium; Factors affecting surface finish – 1. BUE [affects tool-tip profile (great influence on surface finish); Ceramic/ diamond tools form less BUE - gives better surface finish than others]; 2. Feed marks left by cutting operations (Arithmetic mean value: $R_a = f^2/32R$; Peak-to-valley: $R_t = f^2/8R$; f = feed (mm/rev); R = tool nose radius (mm)); As R_a/R_t ↑, surface finish becomes worse; 3.Vibration: forced vibration: periodic applied force present in machine tool, like from gear drives, motor and pumps, chattering: interaction of cutting process & structure of machine tool. begins with disturbance in cutting zone: e.g. types of chips produced, variations in frictional conditions at tool-chip interface; Excessive chattering – cause chipping & premature failure of brittle cutting tools; Cutting Tool – Rake ∠; Throw-away inserts: one insert has several cutting edges; smaller included angle, more likely to chip/break;



Cutting model & tool rake angle - Positive rake angle (+ve α): lower cutting force; lower temp. rise; weaker cutting edge: may cause chipping& failure; Negative rake angle (-ve α): Stronger cutting edge; Both sides of tool inserts can be used; E.g. △ insert - +ve rake: 3 cutting edges; -ve rake: 6 cutting edges; One piece solid cutting tool - e.g. high speed steels tool; slab milling cutter; twist drill; Interrupted cutting Milling - Teeth of milling cutter enter & exit w/p during each revolution; Interrupted cutting action subjects the teeth to a cycle of impact forces & thermal shock on every rotation; good cutting-tool material char: Hot hardness: Hardness of tool at cutting temps. need maintain; Tool dont undergo plastic deformation - shape & sharpness of tool retained; Toughness & impact strength: prevent chipping/fracturing of tool due to impact forces, vibration & chattering; thermal shock resistance: withstand rapid temp. cycle in interrupted cutting; Wear resistance: High wear resistance especially at cutting temps; Acceptable tool life; Chemical stability & inertness - avoid adverse reactions with w/p causing tool wear e.g. carbon diffusion; Cutting Tool: Materials Selection: High speed steel (HSS): High toughness – high resistance to fracture; suitable for: Tool with high +ve rake angle (small included angle); Interrupted cuts; Machine tools with low stiffness (that cause vibration&chattering); Limitation: < cutting speed than WC due to lower hot hardness; Uncoated tungsten carbides: WC without coating; WC – a composite of tungsten carbide particles bonded together in cobalt matrix; High hot hardness, toughness & wear resistance; Uncoated tungsten carbides (WC): for cutting steels, cast irons & abrasive non-ferrous materials; As cobalt ↑, toughness ↑ but other properties (strength/ hardness/wear resistance) ↓; Uncoated titanium carbides (TiC): ↑ wear resistance than WC but not as tough; Suitable for machining hard materials & for cutting speeds ↑ than for WC; Coated tools (e.g. WC carbides coated with TiN , TiC, Al_2O_3): Compared to uncoated carbides->Higher resistance to crack & wear; ↓ friction; ↑ hot hardness; prevents diffusion; longer tool life; multi-phase coatings: substrate -> HSS,carbides; Coating materials -> TiN, TiC, ceramics, diamond; Ceramics: High hot hardness & wear resistance; Less likely to adhere to metals during cutting, less BUE – give good surface finish; good for uninterrupted cutting operations (e.g. turning) – for high speed finishing; Limits: 1. Low toughness & impact strength: may cause premature failure by chipping/ tool fails; -ve rake angle preferred; Low thermal shock: to reduce cracking due to thermal shock, cutting should be performed dry/with limited cutting fluid applied in steady quantity; Cubic boron nitride (CBN): hardest material after diamond; high wear resist & cutting-edge strength; At elevated temp, chemically inert to iron & nickel; Has high oxidation resistance -> suitable for cutting hardened ferrous & high temp alloys (eg nickel-based alloys); Limitations: Brittle & low thermal shock; Diamond: High hardness & wear resistance; Low friction; Can maintain a sharp cutting edge; Used when good surface finish & dim accuracy are required; Limits: Brittle; Low chemical stability at higher temps (become carbon); Most suitable for light, uninterrupted finishing cuts; Not for machining plain-carbon steels, nickel, titanium, due to strong chemical affinity at elevated temperatures; Cutting Fluid - lubricant/coolant/both (e.g. Oils, emulsions, synthetic & semi-synthetic solutions); Lubricant: reduces friction; Coolant: reduces effects of heat; Why use? - Reduce friction & wear – tool life ↑, better surface finish; Cool the cutting zone – temp. & thermal distortion ↓, tool life ↑ . Water removes heat well but causes rusting; reduce forces & power consumption; Wash away chips; protect machined surfaces from corrosion; Problems – may not be able to recycle & Corrosion; Turning – round parts produced by turning the w/p on a lathe. single point cutting tool is used; Various cutting operations on lathe; Comparing turning & cutting model – $f = t_o$, $d = w$, V is the same; Cutting Speed V & rotational speed N - $V = \pi DN$ m/min; N = rotational speed of w/p (rev/min); Use $V = \pi D_{avg} N$; $D_{avg} = (D_o + D_f) / 2$; MRR for turning - $MRR = dfV$ (mm3/s); where: d = depth of cut (mm) = $(D_o + D_f) / 2$; f = feed (mm/rev); $V = \pi D_{avg} N$; $D_{avg} = (D_o + D_f) / 2$; N = rotational speed of w/p (rev/min); Cutting (Machining) time: $t = l / (fN)$; l = length of cut (mm); f = feed (mm/rev); N = rotational speed of w/p (rev/min); Roughing & finishing cuts - Usual procedure: >=1 roughing cuts at high f and d - high MRR (as MRR = dfV); a finishing cut at lower f and d for good surface finish -> $R_a = f^2 / 32R$; $R_t = f^2 / 8R$; Drilling: major & common hole making process; Various drilling & reaming operations: drilling, core/step/center drilling, counterboring; counter-sinking; reaming; machining operations (round shape) - 1.Boring: enlarge hole made by previous process; 2.Tapping: Making internal threads in w/p; Velocity of drill: Dist moves by drill in 1 revolution = f mm; Dist moves by drill in N revolutions = f N mm; Dist moves by drill in N rev/min = f N mm/min; Velocity of drill = f N mm/min; MRR - Velocity of drill ⊥ to drilled hole = fN mm/min; $MRR = (\pi D^2 / 4) \times fN$ mm^3/s; Cutting time – $t = l / fN$; l = length travelled by drill; f = feed mm/rev; N = rotational speed of drill rev/min (rpm); Torque & Power: Power = torque on drill (in Nm) x rotational speed of drill (in rad/s); Cutting Speed: in turning operation: $V = \pi D N$ m/min; Milling: rotating, multi-tooth cutter remove material while moving along horizontal/vertical axis; Slab/peripheral milling: cutter axis is // to w/p surface; Face milling: Cutter mounted on spindle axis ⊥ to w/p surface; End milling: Cutter rotates on axis ⊥ to w/p; can be tilted to machine taper surfaces; Con (up) milling - more common; Max chip thickness (t_c) at end of cut W/p surface characteristics dont affect tool life; Tool may chatter & w/p pulled upward, need proper clamping; Con (down) milling - Cutting starts at surface of w/p – max chip thickness at start of cut; Downward component of cutting forces holds w/p in place; Not suitable for w/p having surface scale (e.g. hot forged parts, castings) as scale is hard & abrasive, causing excessive cutter wear & damage; High impact forces – rigid set-up required, "backlash" must be eliminated;

Grinding - Use for machined parts requiring high dim accuracy & fine surface finish; Uses abrasive grain as cutting tool; Abrasive grain is small non-metallic hard particle having sharp edges & of irregular shape; Conventional abrasives: $Al2O_3$, SiC; Superabrasives: CBN, diamond; avg rake angle is highly –ve, e.g. -60°; Each abrasive grain removes very small amount of material at a time; Thus, abrasives bonded together to form grinding wheel to achieve high material removal rate; Grinding Wheel: Abrasive grains held together by bonding material; Porosity – provide clearance for the chips being produced & to provide cooling; Types of bond (bonding materials): 1. Vitrified bond: Clay ingredients mix with abrasive grains – upon heating becomes glasslike material; Most used; Strong, stiff, porous & resistant to oils, acids & water 2. Resinoid bond: Thermosetting resins (e.g. phenolic resins); More flexible than vitrified bond as elastic modulus of thermosetting resins is lower than glass. 3. Rubber: Most flexible bond used in abrasive wheel; Very thin wheels can be made e.g. like saw use as cut-off blades; **7 –** Integrated Circuit(IC): collection of electronic devices fabricated & electrically intraconnected onto small flat chip of semi-conductor material; Silicon (Si): most widely used semiconductor material for ICs (low cost); Moore' Law: says no. of transistors on ICs double every 2 years; chip: flat plate; Packaging of ICs: protects from damage, chip attached to lead frame & enclosed inside package (made of plastic/ceramic, includes leads by where IC electrically connected to external circuits); silicon processing: sand reduced to very pure silicon & shaped into wafers; Microelectronic chips fabricated on substrate of semi-conductor material; IC fabrication: processing steps add, alter, & remove thin layers in selected regions to form electronic devices; Lithography is used to define regions to be processed on wafer surface; IC packaging - wafer is tested, cut into individual chips, & chips are enclosed in appropriate package; electronic grade silicon: polycrystalline silicon of ultra high purity; Production: purified trichlorsilane is reduced by means of hydrogen gas to produce electronic grade silicon - nearly 100% pure Si, $SiHCl_3(gas) + H_2(gas) \rightarrow Si + 3HCl(gas)$; Crystal Growing: silicon substrate for microelectronic chips must be made of single crystal whose unit cell is oriented in a certain direction; must be of ultra high purity; substrate wafers cut in direction that gets desired planar orientation, method: Czochralski process, a single crystal boule is pulled upward from a pool of molten silicon; Prep of Boule: ends of the boule are cut off; cylindrical grinding used to shape boule into more perfect cylinder; >= 1 flats are ground along the length of the boule, flat functions: cut into the edge of the wafers so users could determine the wafer's identification / dopant-type, orientation & location/reference position; wafer slicing: very thin ring-shaped saw blade with diamond grit bonded to internal diameter is the cutting edge, the ID is used for slicing rather than the OD for better control over flatness, thickness, parallelism, & surface characteristics of the wafer(to min. kerf loss, blades are made very thin); 3 steps in IC making: Layer Processing, Pattern Transfering, Doping; Deposition processes - physical vapor deposition: PVD metallization processes include vacuum evaporation & sputtering, Chemical vapor deposition: CVD deposited materials include tungsten, molybdenum, & silicides used in semiconductor metallization; Electroplating: occasionally used to increase thickness of thin films; Alum: most widely used metallization material, pref for device intraconnections&connections to external circuitry; metallization: Combines various thin film deposition technologies with photolithography to form very fine patterns of conductive material (certain components (e.g. gates) of IC devices, provide intraconnecting conduction paths between devices on chip, connect chip to external circuits); Electroplating: Anode: plating metal, Cathode: workpiece to be plated, Formula: V = ECIt; V = volume of metal deposited (cm3), I = direct current (A), t = time (sec), C = plating constant (depends on ρ), E = cathode efficiency = actual amt of metal deposited on cathode divided by the theoretical amount, coating thickness: V/total area; Connect to cathode (-ve electrode) as Cu in electrolyte carry +ve charges; Generate vapor physically: heating, ion sputtering, laser ablation, in vacuum; chemical vapor deposition: by decomposition of single gas, CVD for W can be achieved from decomposition of tungsten hexafluride (WF_6)[$WF_6 \rightarrow W + 3 F_2$]; thermal oxidation of silicon: Exposure of silicon wafer surface to an oxidizing atmosphere at elevated temp to form layer of silicon dioxide, Oxygen/steam atmospheres are used: $Si + O_2 \rightarrow SiO_2$ OR $Si + 2H_2O \rightarrow SiO_2 + 2H_2$; Function of SiO_2: an insulator, compared to Si which is semiconductor. used as a mask to prevent diffusion/ion implantation of dopants into silicon, isolate devices in circuit; provides electrical insulation between levels in multi-level metallization systems; Alternative Process for adding SiO_2: when silicon dioxide film must be applied to surfaces other than silicon, then direct thermal oxidation does not work; alternative process → chemical vapor deposition; lithography: Each layer is determined by a geometric pattern representing circuit design info. that is transferred to wafer surface; several lithographic technologies used in semiconductor processing: Photo/Electron/X-ray/ Ion-lithography, diff: type of radiation used to transfer the mask pattern to the wafer surface; Photolithography: uses light radiation to expose coating of photoresist on surface of wafer; ultraviolet light, due to its short wave-length, mask containing required geometric pattern for each layer separates light source from wafer, only portions of photoresist not blocked by mask are exposed; Photoresist: organic polymer sensitive to light radiation in wavelength range; sensitivity causes either increase/decrease in solubility of polymer to certain chemicals; use photoresists that are sensitive to ultraviolet light; UV light has short wavelength compared to visible light, permitting sharper imaging of microscopic circuit details on wafer surface; permits fabrication areas in plant to be illuminated at low light levels outside UV band;

Pattern Transferring by Photolithographic Printing: Contact Printing: Mask pressed against resist coating during exposure, pro: high res of pattern on wafer surface, con: contact with wafers wears out mask; Proximity Printing: mask away from resist coating by 10-25 μm. Pro: no mask wear, Con: image res reduced; Projection Printing: High-quality lens system projects image through mask onto wafer; Preferred technique cause non-contact (no mask wear), & optical projection can get high res; processing sequence in photolitho-graphy: surface of the silicon wafer has been oxidized to form thin film of SiO_2; desired to remove SiO_2 film in certain regions as defined by mask pattern; Sequence for a negative resist: wafer properly cleaned to promote wetting & adhesion of resist→liquid resist is fed onto center of wafer & wafer spun to spread liquid & achieve uniform coating thickness →Soft bake - to remove solvents, promote adhesion, & harden resist, temp ~ 90°C (190°F) for 10-20 minutes→ Pattern mask aligned relative to wafer & resist exposed through mask→Exposed wafer immersed in developing solution/solution is sprayed onto surface; for negative resist, unexposed areas are dissolved, leaving SiO_2 surface uncovered in these areas→Hard bake to expel volatiles remaining from developing solution & increases adhesion of resist especially at newly created edges of resist film→Etching removes SiO_2 layer at selected regions where resist has been removed→Resist coating remaining on surface is removed,stripping is done using liquid chemicals/plasma etching; etching: remove portions of layers to achieve desired IC details, masking surface areas that are to be protected & leaving other areas exposed; wet chemical etching: Use of aqueous solution, usually an acid, to etch away target material; dry plasma etching: Uses ionized gas to etch a target material; doping: adding impurities into silicon surface; Diffusion: In semi-conductor processing: diffusion carried out to dope silicon substrate with controlled amts of desired impurity; 2 steps: Predeposition - dopant is deposited onto wafer surface; Drive-in - heat treatment where dopant redistributed to get desired depth & concentration profile; ion implantation: vaporized ions of impurity element are accelerated by an electric field & directed at silicon substrate; atoms penetrate into surface, losing energy & finally stopping at some depth in crystal structure determined by mass of ion & acceleration voltage, pros: can be achieved at room temp, provides exact doping density; Clean room: room where air is purified to reduce airborne particles; classification: US FED STD 209E cleanroom standard: quantity of particles of size >=0.5 μm per cubic foot of air, e.g. a class 100 clean room contains <= 100 such particles per cubic foot; ISO 14644-1 standard: Decimal log of number of particles >= 0.1 μm per m^3 of air, e.g. an ISO class 5 cleanroom has at most 10^5 particles/m^3; Micro&Nano-fabrication using Focused Ion Beam: maskless, resistless, innovative app. of nanostructures – fast prototyping; FIB good for direct nanofabrication; Rent's Rule: Estimates no. of input/ output terminals required in IC package based upon no of logic gates; $n_{io} = C n_{ic}^m$, n_{ic} = no. of logic gates; Design issues in IC packaging: electric connections to external circuits, materials to encase chip & protect it from environment (humidity, corrosion, tem, vibration, mechanical shock), Heat dissipation, reliability, performance & service life, Cost; No of input/output terminals required for IC of given size, Materials used in IC packages, Package styles; IC package material: Ceramic (Al2O3)-pros: hermetic sealing of IC chip and highly complex packages can be produced, cons: poor dimensional control due to shrinkage during firing; Plastic (epoxies, polyimides, and silicones): not hermetically sealed, but lower cost, used for mass produced ICs, where very high reliability not required; Wafer testing: testing done by computer-controlled equipment that uses needle probes matching connecting pads on chip surface, performed while ICs are still on wafer - before separation, when probes contact pads, tests are carried out to indicate short circuits & other faults, followed by functional test, chips that fail test are marked with an ink dot, these defects will not be packaged; Chip Separation: thin diamond-impregnated saw blade used to cut wafer into individual chips, wafer is attached to piece of adhesive tape mounted in frame, adhesive tape holds individual chips in place during & after sawing, frame is convenient in subsequent handling of the chips, Chips with ink dots are now discarded; Die bonding: Automated handling systems pick separated chips from tape frame & place them for die bonding, techniques used to bond chip to packaging substrate: Eutectic die bonding – for ceramic packages, Epoxy die bonding – for plastic packages; after die is bonded to package, electrical connections are made between contact pads on chip surface & package lead frame using small diameter wires; DIP is a common form of IC package, available in both through-hole and surface mount configurations (dual in-line package with 16 terminals, in through-hole configuration); square package: Leads are arranged around periphery so that number of terminals on a side is $n_{io}/4$, square leaded chip carrier(LCC) for surface mounting with gull wing leads; Final testing: Upon completion of packaging sequence, each IC must undergo final test - determine which units, if any, have been damaged during packaging, measure performance characteristics of each device; IC Package Styles for Mounting to a Printed Circuit Board (PCB): Through-hole mounting, aka pin-in-hole (PIH) technology: IC package & other components have leads inserted through holes in PCB & soldered on underside; Surface mount technology (SMT): Components are attached to surface of board (sometimes both top & bottom); PCB Assembly for Surface Mount Technology (SMT): Assembly method in which component leads are soldered to lands on PCB surface rather than into holes running through the board, PCB assemblies with component leads inserted into through holes have certain inherent limitations in terms of packing density - components can be mounted on only one side of board, relatively large center-to-center distances between lead pins in leaded components.

1 – tolerances: allowable variations from specified dim permitted - bilateral/unilateral tolerance, limit dim; precision: repeatability (no random errors: due to imprecise reading, set up variations, temperature change, wear, misalignment); accuracy: close to true value (no systematic errors: consistent +/- deviations from the true value); precision gage blocks: for calibration of instruments; not measurements; GO/NO-GO gages: GO - check dimension at its max material condition (inserted); NO-GO - check min material condition (not inserted); Snap gage – outside dimension; if does not go in GO gauge, above max. dimension; if does go in NO-GO gauge, below min. dimension; Plug gage – internal dimension; GO – check max material condition; if does not go in, too small hole; NO-GO - check min material condition; if go in, too big hole; wear allowance is only applied to GO gage dim; Sine bar: sin A = H/L, H = no. of gauge blocks (height), L = standard dim of sine bar; roughness: small, finely-spaced deviations from nominal surface; determined by material characteristics & processes that formed surface; waviness: deviations of larger spacing; due to work deflection, vibration, tooling, etc

2 – Casting: Pros: create complex part geometries/external & internal shapes, some are net shape/near net shape, produce very large parts, some suited to mass production; cons: Limitations on mechanical properties, poor dim accuracy & surface finish; e.g. sand casting; hazards to workers (hot molten metals), environment; sand casting mold: cope: upper half of mold; drag: bottom half; flask: box container; parting line: separation of halves; mold cavity: external surfaces of cast part; core: internal surfaces, placed inside the mold cavity; gating system: channel where molten metal flows into cavity from outside of mold, has a downsprue, where metal enters runner leading to main cavity; top of downsprue: pouring cup: minimize splash and turbulence as the metal flows into downsprue; riser: reservoir in mold which is a source of liquid metal to compensate for shrinkage of the part during solidification; designed to freeze after the main casting; gate: entrance of the mold cavity; High viscosity = Low fluidity

Chvorinov's Rule: T_{TS}: total solidification time, V: volume of casting, A: Surface area of casting n = exponent (usually '2'); C_m = mold constant ; ↑ volume, ↑ time of solidification;↑ area, ↓ time of solidification (low volume to surface ratio); C_m depends on: mold material; thermal properties of casting metal; Pouring temp. relative to melting point; value of C_m can be based on data from previous operations carried out using the same mold material, metal, and pouring temperature, even if the shape of part may be quite different; casting with a higher volume-to-surface area ratio cools and solidifies more slowly than one with a lower ratio: To feed molten metal to the main cavity, T_{TS} for the riser > T_{TS} for the main casting; mold constants of the riser (vol should be minimal) and casting will be equal, riser to have a larger volume-to-area ratio so that the main casting solidifies first – minimizes effects of shrinkage Steps: (0)Starting level of molten metal immediately after pouring,(1)reduction in level caused by liquid contraction during cooling,(2)reduction in height and formation of shrinkage cavity caused by solidification,(3)further reduction in volume due to thermal contraction during cooling of solid metal; Solidification Shrinkage: occurs in nearly all metals: solid phase ↑ density than liquid phase; solidification causes a reduction in volume per unit weight of metal; exception: cast iron with high C content; Chills: internal/external heat sinks that cause rapid freezing in certain regions of the casting

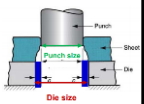
$$T_{TS} = C_m\left(\frac{V}{A}\right)^n$$

defects – misrun: casting solidified before completely filling the mold cavity(problem with pouring temp; velocity of pour; improper design of mold); cold shut:2 portions of metal flow together but lack of fusion due to premature freezing(position of gate not good; temp too low; pouring too slow; cold shot: metal splatters during pouring lading to the formation of solid globules which become entrapped in the casting(turbulence); shrinkage cavity: depression in surface/internal void caused by solidification shrinkage that restricts amt of molten metal available in last region to freeze(design a good riser & die); shrinkage cavity: small voids distributed throughout casting due to localized solidification shrinkage of final molten metal within dendritic structure(use squeeze casting to compress material; die casting which distribute metal inside die); hot tears: casting is restrained from contraction cause of mold during final stages of solidification or early stages of cooling after solidification(high stress concentration; have a collapsible mold; remove part early (just after solidification) – last portion of cooling done outside of mold); sand casting defects: sand blow: balloon-shaped gas cavity caused by release of mold gases during pouring(reduce pouring rate to allow air to escape); pin holes: formation of many small gas cavities at surface of the casting (caused by gases released by surrounding sand); penetration: fluidity of liquid metal is high, it may penetrate into sand mold/core,(change metal/reduce pouring temp); mold shift: step in the cast product at parting line caused by sidewise relative displacement of cope & drag; mold crack: occurs when a crack develops in the mold, into which liquid metal can seep to form a "fin" on the final casting(increase density of sand mold); Product Design Considerations: avoiding unnecessary complexities, blend sharp edges, uniform section thickness(use chills); draft angle (aid in removal of the part from the mold); eliminate use of core; sand casting: poor dimensional accuracies & finish (need machining); die/investment casting: good dimensional accuracies & finish

expandable mold casting: sand casting: (most popz), any size/quantity; investment casting; shell/ vacuum molding; plaster/ceramic mold, expanded polystyrene process; Cons: new mold required for every casting; Investment Casting (Lost Wax Process):pattern made of wax is coated with a refractory material to make the mold, wax is melted away prior to pouring molten metal, a precision casting process; pros: Parts of great complexity & intricacy can be cast; close dimensional control & good surface finish; Wax can be recovered for reuse; a net shape process - more machining is not normally required; cons: Many processing steps; expensive; Permanent Molding Casting Processes: pros: mold is reused many times, good dem control & surface finish; cons: limited to metals of lower melting point; simpler part geometries compared to sand casting cause of the need to open mold; high cost; e.g. basic permanent mold casting, die casting, Squeeze casting, Centrifugal Casting; basic permanent mold process: uses a metal mold constructed of 2 sections designed for easy, precise opening & closing; molds used for casting lower melting point alloys (steel or cast iron);molds used for casting steel must be made of refractory material, due to the very high pouring temps; Die Casting: molten metal is injected into mold cavity under high pressure; pressure maintained during solidification, then mold is opened & part is removed; pros: large production; Good accuracy & surface finish; thin sections possible; rapid cooling(small grain size & good strength); cons: Generally limited to metals with low melting points; part geometry must allow removal from the die; die casting machines: hot chamber die casting: metal is melted in a container, and a piston injects metal under high pressure into the die; cold chamber die casting: molten metal is poured into a unheated chamber from an external melting container, and a piston injects metal under high pressure into the die cavity; hot chamber higher production for low melting pt alloys; diff: how material poured into die; molds for die casting: mostly steel; tungsten & molybdenum (good refractory qualities) used to die cast steel & cast iron; ejector pins required to remove part from die when it opens; lubricants sprayed onto cavity surfaces to prevent sticking (better heat transfer between metal & die)

3 - shear stress = F/A, F: applied force, A:area force applied; shear strain = δ/b; δ: deflection of element, b: dist where deflection occurs; Shear strength can be estimated from tensile strength: S ≅ 0.7(TS); bulk deformation: rolling,forging,extrusion&wire/bar drawing; pros of sheet metal part: high strength,good dim accuracy/surface finish; low cost; mass production; shear edge parts: rollover: depression made by punch prior to cutting, burnish: smooth region - from penetration of punch prior to fracture, fracture zone: rough surface due to fracture of metal as punch goes down, burr: sharp corner edge due to elongation of metal during final stage of separation

For both punching & blanking: Die size = punch size + 2 x clearance; Clearance c = allowance x thickness; Punching: hole size = punch size, - hole punch diameter = Dh; hole die diameter = Dh + 2c; Blanking: blank size = die size - blank punch diameter = Db - 2c, blank die diameter = Db; C too small: causes non-optimal fracture and too large forces; C too big: causes oversized burr; angular clearance: allow blank to drop through die, typically 0.25° to 1.5° on each side; cutting force calculation: F = S t L = 0.7(TS) t L, S: shear strength, t: thickness, L: perimeter of cut edge; Sheet Metal Bending: V-bending & Edge bending;

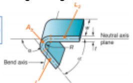


Bend Allowance:

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

bending with little stretch: (bend on big material) If R ≥ 2t, K_{ba} = 0.50
bending with large stretch: (bend on small material) If R < 2t, K_{ba} = 0.33
springback compensation: overbending; pressure

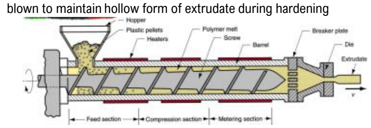
A_b = bend allowance
α = bend angle (in degree)
R = bend radius
t = sheet thickness
K_{ba} = streching factor:
oIf R < 2t, K_{ba} = 0.33
oIf R ≥ 2t, K_{ba} = 0.50



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

Bending force formula(N): TS: tensile strength(MPa); w: part width (direction of bend axis)(mm); D: die opening(mm); t: thickness(mm) Clearance in Drawing: c = 1.1t, ~10% greater than sheet thickness Defects in Drawing: wrinkling on flange or wall (due to compression), tearing (due to high tensile stresses), earing (due to anistropy), and surface scratches (due to poor lubrication, punch/die not smooth) blankholder force F_h: reduce wrinkles on flange; too low: Causes wrinkles; too high: prevents metal from flowing into die cavity; may cause tearing due to stretching of metal (more tension) Conditions for drawing feasibility: DR ≤ 2.0, r ≤ 0.50, t/D_b > 1%; DR = D_b/D_p, D_b,D_p = diameter of blank,punch; r = (D_b-D_p)/Db; t/D_b decreases, tendency for wrinkling increases; if conditions not fulfilled, redraw Drawing Force Formula: F = maximum drawing force (N), Dp = punch diameter (mm), Db = starting blank diameter (mm), t = original sheet thickness (mm), TS = tensile strength (MPa), 0.7 = correction factor to account for friction; Blankholder Force: Holding pressure ≈ 0.015 x yield strength, Holding force ≈ holding pressure x starting area of the blank held by blankholder, Fh = blankholder force (N), Dp = punch diameter (mm), Db = starting blank diameter (mm), t = original sheet thickness (mm), Y = yield strength of sheet metal (MPa), Rd = die corner radius (mm)

4 – Thermoplastics: chemical structure remains unchanged during heating & shaping, recyclable, used more commercially, e.g. acrylics, PVC, polystyrene, polyamides; Thermosets: Undergo curing process during heating & shaping, permanent change in molecular structure, can't be remelted/recycled, e.g. epoxies, polyurethane, unsaturated polyesters, phenolic; diff: cross linking in thermosets; Viscosity ↓ with shear rate / temp, fluid thinner at ↑ shear rates/temps; molecular weight of polymer also affects viscosity; viscoelasticity: change only when strain increases; die swell: for viscoelastic fluids (polymer melts); tendency of the extrudate to expand in the cross-sectional dimensions immediately on exiting the die orifice; plastic casting process: pour liquid resin into mould → gravity to fill cavity → polymer hardens; pros: simpler mold, large quantity, encapsulation for electronics; Extrusion: compression process → material forced to flow through a die orifice, provide long continuous product, cross-sectional shape is determined by the shape of the orifice; Widely used for thermoplastics of elastomers to mass produce items (e.g. pipes, coated electrical wires) ; then cut into desired lengths; Extruder Barrel: feedstock (plastic pellets; melted by electric heater) fed by gravity onto screw whose rotation moves material through barrel; mixing/mechanical working adds heat which maintains melt; Extruder Screw (sections): Feed section → feedstock moved from hopper & preheated; Compression section → polymer becomes fluid, air mixed with pellets extracted from melt, & material is compressed; Metering section → melt is homogenized & sufficient pressure developed to pump it through die opening; Extruder Die: melt passes through a screen pack - series of wire meshes supported by stiff plate containing small axial holes; functions of screen pack: filter out contaminants; Build pressure in metering section; straighten flow of polymer melt and remove its "memory" of circular motion from screw; E.g. Solid profiles, Hollow profiles, such as tubes, Wire and cable coating, Sheet and film, Filaments; Extrusion of solid profiles: regular shapes: rounds, squares, Irregular cross sections: Structural shapes, Door and window moldings, Automobile trim, House siding; Hollow Profiles: e.g. tubes, pipes, hoses, require mandrel (held in place with spider) to form the shape → Polymer melt flows around legs supporting mandrel to reunite into a monolithic tube wall, often includes air channel → air blown to maintain hollow form of extrudate during hardening



Injection Molding: Polymer heated to highly plastic state → forced to flow under high pressure into a mold cavity for solidification → molding removed from cavity, produces discrete components almost always to net shape; Mold may contain multiple cavities, so multiple moldings produced each cycle; Injection Molded Parts: Complex and intricate shapes possible, Shape Limitations: Capability to fabricate a mold whose cavity is the same geometry as part & Shape must allow for part removal from mold; Part size: ∼ 50 g to ∼ 25 kg; for large production quantities (high cost of mold); Polymers for Injection Molding: best for thermoplastics, can thermosets & elastomers, modifications in equipment and operating parameters must be made to avoid premature cross-linking of these materials before injection; Injection Molding Machine: Injection system: Melts and delivers polymer melt, like extruder; Clamping system: Opens & closes mold each injection cycle; Injection Molding Cycle: Mold is closed, Melt is injected into cavity, Screw is retracted, Mold opens and part is ejected; molds for injection molding: 2-plate/3-plate/Hot-runner mold (saves material); 3-plate mold pros over 2-plate: mold opens, runner & parts disconnect & drop into two containers under mold, allows automatic operation of molding machine; Shrinkage – Nylon 6.6: 0.020mm/mm, Polyethylene: 0.025; Polystyrene: 0.004; PVC: 0.005; Compensation for shrinkage: D_c = D_p + D_pS + D_pS^2 , D_c = dimension of cavity; D_p = molded part dimension (nominal size); S = shrinkage value Factors affecting Shrinkage: higher pressures force more material into mold cavity to reduce shrinkage, longer time forces more material into the cavity before solidification to reduce shrinkage, higher temps lower polymer melt viscosity, allowing more material to be packed into mold to reduce shrinkage, thicker parts have higher shrinkage Defects in Injection Molding: Short shot: Molding has solidified before completion, Flash: Polymer melt squeezes into the parting surface or around ejection pins, Sink marks & voids: Usually due to too thick molded sections where there is insufficient material to compensate for shrinkage, Weld line: Polymer flows around a core or other convex section and meets from opposite directions; Compression Molding: thermosetting plastics, amt of charge must be precisely controlled to obtain repeatable consistency in molded product, steps: charge is loaded, charge is compressed and cured, apart is ejected & removed; molding materials: Phenolics, melamine, epoxies, elastomers, etc. e.g. products: Electric plugs, sockets, and housings; pot handles, and dinnerware plates; compression molding = close die forging (metals); Molds for Compression Molding: Simpler than injection molds, no sprue & runner system, limited to simpler part geometries due to lower flow capabilities of thermosetting materials, mold must be heated, usually by electric resistance, steam, or hot oil circulation

Transfer Molding: modified from compression molding, polymer enters the mold cavity as a fluid; thermoset charge is loaded into a chamber immediately ahead of the mold cavity, where it is heated; pressure applied to force soft polymer to flow into heated mold where it cures; Pot transfer molding – charge is injected from a "pot" through a vertical sprue channel into cavity; Plunger transfer molding – plunger injects charge from a heated well through channels into cavity Compression VS Transfer Molding: Both: scrap is produced each cycle as leftover material, called cull; thermoset scrap cannot be recovered; transfer molding capable of molding more intricate part shapes than compression molding, but not as intricate as injection molding (e.g. IC package) ;Transfer and compression molding both use thermosets and elastomers; Transfer and injection molding – the charge is preheated in a separate chamber before being injected into the mold; Blow Molding: Air pressure is used to inflate soft plastic into a mold cavity; impt for making one-piece hollow plastic parts with thin walls, such as bottles; production is typically organized for very high quantities; Blow Molding Process: 1. Fabrication of a starting tube (parison), 2. Inflation of the tube to desired final shape - forming the parison accomplished by either extrusion/injection molding; Stretch Blow Molding: like injection blow molding; blowing rod stretches the soft parison for a more favorable stressing of polymer than conventional blow molding; resulting structure is more rigid, more transparent, and more impact resistant; used for polyethylene terephthalate (PET) which has very low permeability and is strengthened by stretch blow molding, combination of properties makes it ideal as container for carbonated beverages, produce hollow, seamless containers such as bottles Materials & Products in Blow Molding: only thermoplastics; materials: high density polyethylene, polypropylene (PP), polyvinylchloride (PVC), and polyethylene terephthalate, e.g. disposable containers, large shipping drums for liquids & powders, large storage tanks, gasoline tanks, toys, & hulls for sail boards & small boats; Thermoforming: flat thermoplastic sheet/film is heated & deformed into desired shape using mold; Heating usually accomplished by radiant electric heaters located on one or both sides of starting plastic sheet or film; used in packaging of products & to fabricate large items such as bathtubs, contoured skylights, and internal door liners for refrigerators; types: Vacuum/Pressure/Mechanical (Better dimensional control, surface details on both sides, Two mold halves: more costly) Thermoforming Materials for Thermoforming: Only thermoplastics (Extruded sheets of thermosetting/ elastomeric polymers have been cross-linked & cannot be softened by reheating), common TP polymers: polystyrene, ABS, PVC, acrylic, polyethylene, and polypropylene; Applications of Thermoforming: Thin films: blister packs and skin packs for packaging commodity products such as cosmetics, toiletries, small tools, and fasteners (nails, screws, etc.), Thicker sheet stock: boat hulls, shower stalls, advertising displays and signs, bathtubs, certain toys, contoured skylights, internal door liners for refrigerators

5 – Welding – >=2 parts coalesced at contacting surfaces by application of heat and/or pressure; sometimes a filler material added to facilitate coalescence; essentially atomic bonding; Fusion Welding – joining process that melt the base metals; filler metal added to molten pool to facilitate process & provide bulk & added strength to welded joint; e.g. arc welding(AW): melting metals by electric arc, Oxyfuel gas welding (OFW): melting by oxyfuel gas (acetylene, etc) autogenous weld: no filler metal used; Solid State Welding (SSW): Joining processes where coalescence results from application of pressure alone or combination of heat & pressure; if heat used, temp should be < melting pt of metals being welded; no filler metal is added in SSW, e.g. Friction Welding(FRW): coalescence by heat of friction between two surfaces, Ultrasonic welding (USW): coalescence by ultrasonic oscillating motion in a direction parallel to contacting surfaces of two parts held together under pressure, Resistance welding: melting is accomplished by heat from resistance to an electrical current between faying surfaces held together by pressure; Power Density (PD): PD = P/A, PD: power density, W/mm²,P: power entering surface, A = Surface Area over which energy is entering, mm²; Unit Energy for Melting*: $U_m = kT_m^2$, U_m (j/mm³), T_m = melting pt of material, k = 3.33 × 10^{-6} for T_m in Kelvin (K) (K = °C + 273); Heat Available for Welding: $H_w = f_1f_2H$; H_w = net heat available for welding; f_1 = heat transfer efficiency; f_2 = melting efficiency; H = total heat generated by welding process (Joules); Heat Transfer Efficiency f_1 - Proportion of heat received at work surface relative to total heat generated at source; Depends on welding process & capacity to convert power source (e.g. electrical energy) into usable heat at work surface: Oxyfuel gas welding - relatively inefficient; Arc welding - relatively efficient Melting Efficiency f_2 - Proportion of heat received at work surface used for melting, rest conducted into work metal; Depends on welding process, also influenced by thermal properties of metal, joint configuration, & work thickness; Metals with high thermal conductivity (e.g. Al, Cu) present a problem in welding because of rapid dissipation of heat away from heat contact area. Energy Balance Equation
H_w = net heat energy delivered to operation, J
U_m = unit energy required to melt the metal, J/mm³
V = volume of metal melted, mm³

$$H_w = U_m V \qquad H_w = f_1 f_2 H$$

If time factor (rate) is considered:
HR_w = rate of heat energy delivered
WVR = Welding Volume Rate (mm³/min)
A_w = weld area; v = welding speed

$$HR_w = U_m(WVR) \qquad HR_w = f_1f_2HR = U_mA_wv$$

Mechanical assembly: No atomic bonding; Oxyfuel Gas Welding (OFW): Fusion welding operations that burn fuels mixed with oxygen; OFW employs several types of gases; Oxyfuel gas also used in flame cutting torches to cut and separate metal plates and other parts; Most important: oxyacetylene welding; Torch Used in OAW: The acetylene valve is opened first -> gas is lit with a spark lighter -> then O_2 valve opened and flame adjusted; Basic equipment used - For safety, all threads on acetylene fittings are lefthanded, those for O_2 are right-handed. Oxygen regulators are painted green, acetylene regulators red. Acetylene (C_2H_2):Most popular fuel -> capable of higher temp. (up to 3,480°C); chemical reaction of C2H2 and O2 - First stage reaction (inner cone of flame): $C_2H_2 + O_2$ –exothermic-> $2CO + H_2$; Second stage reaction (outer envelope): $2CO + H_2 + 1.5O_2$ –exothermic-> $2CO_2 + H_2O$; Arc Welding (AW) – (fusion) coalescence of metals achieved by heat from electric arc between an electrode & work; Electric energy from the arc produces temperatures ~ 5,500°C, hot enough to melt any metal; Most AW processes add filler metal to increase volume and strength of weld joint; Same basic process also used in arc cutting; Electric Arc - Discharge of electric current across a gap in a circuit; Sustained by an ionized column of gas (plasma) through which current flows; To start the arc in AW, electrode is brought into contact with work and then quickly separated from it by a short distance; Air Welding - pool of molten metal formed near electrode tip -> As electrode is moved along joint, molten metal pool solidifies in its wake

Power Source - DC / AC

$$HR_w = f_1f_2 I\,E = U_mA_wv \quad \text{OR} \quad v = \frac{(f_1f_2)EI}{U_mA_w}$$

- Power HR = voltage × current = E I
f_1, f_2: heat transfer and melting efficiency respectively; U_m: unit energy required to melt metal; A_w: weld cross-sectional area; v: travel velocity, HR_w : rate of heat generation; At high temp. in AW, metals are chemically reactive to O_2, N_2, and H_2 in air; Mechanical properties of joint can be seriously degraded by these reactions; To protect operation, arc must be shielded from surrounding air in nearly all AW processes; Accomplished by: shielding gases (inert gas: Argon, helium, CO_2); flux; "joint not strong if any oxidation" Role of Flux - substance that prevents formation of oxides and other contaminants in welding, or removes them; Provides protective atmosphere for welding; Stabilizes arc; Reduces spattering; Application Methods of Flux - Pouring granular flux onto welding operation; Stick electrode coated with flux material that melts during welding to cover operation; Tubular electrodes where flux is contained in core & released as electrode is consumed; AW Electrodes – Consumable: consumed during welding process (Source of filler metal in arc welding); Non-consumable: not consumed during welding process (Any filler metal must be added separately); Consumable Electrodes - Types: 1. Welding rods/sticks are ~30 cm long and ~8 mm in diameter & must be changed often, 2. Weld wire can be continuously fed from spools with long wires,avoid frequent interruptions; In both, electrode consumed by arc & added to weld joint as filler metal; Nonconsumable Electrodes - Made of tungsten which resists melting; Gradually depleted during welding (vaporization is principal mechanism); Any filler metal must be supplied by a separate wire fed into weld pool; AW Processes that use Consumable Electrodes: Shielded Metal Arc/Gas Metal Arc/Flux-Cored Arc/ Submerged Arc Welding; AW Processes that use Nonconsumable Electrodes: Gas Tungsten Arc/Plasma Arc/Carbon Arc/Stud Welding; Shielded Metal Arc Welding (SMAW) - Uses consumable electrode -> filler metal rod coated with chemicals that provide flux & shielding; "stick welding"; Gas Tungsten Arc Welding (GTAW) - Uses nonconsumable tungsten electrode & inert gas for arc shielding; Melting pt of tungsten = 3,410°C; aka Tungsten Inert Gas welding; Used with/without a filler metal; When used, filler metal added to weld pool from separate rod or wire; Applications: aluminum and stainless steel; Other Fusion Welding Processes - FW processes that can't be classified as arc/ resistance/ oxyfuel welding; Electron beam welding, Laser beam welding; Solid State Welding (SSW) - Coalescence of part surfaces achieved by: Pressure alone, or Heat & pressure; If both heat and pressure are used, heat by itself is not sufficient to cause melting of work surfaces; time maybr a factor; Filler metal not added; Success Factors in SSW - two faying surfaces must be very clean & In very close physical contact with each other to permit atomic bonding; SSW Pros over Fusion Welding Processes: If no melting -> no heat affected zone ->metal around joint retains original properties; Many produce welded joints that bond entire contact interface between two parts rather than at distinct spots/seams; Some can be used to bond dissimilar metals, without concerns about relative melting points, thermal expansions, & other problems that arise in FW; Solid State Welding Processes: Forge/Friction/ Ultrasonic/Resistance/Explosive/Diffusion welding; Roll Bonding/Cladding: Rolls thin out base metal with cladding metal outer surface; Ultrasonic Welding (USW): two components are held together, & oscillatory shear stresses of ultrasonic frequency applied to interface cause coalescence; Oscillatory motion breaks down any surface films to allow intimate contact & strong metallurgical bonding between surfaces; Although heating of surfaces occurs, temps are well below T_m; No filler metals, fluxes, or shielding gases; Generally limited to lap joints on soft materials like alum & copper; (Rotational)Friction Welding (FRW) - coalescence is achieved by frictional heat combined with pressure; no melting occurs at faying surfaces; No filler metal, flux, or shielding gases normally used; Process yields a narrow HAZ; Can be used to join dissimilar metals; Used for automation & mass production; Size of weld zone depends on: Amt of heat generated, Thermal conductivity of materials, Mechanical properties of materials at elevated temperatures.