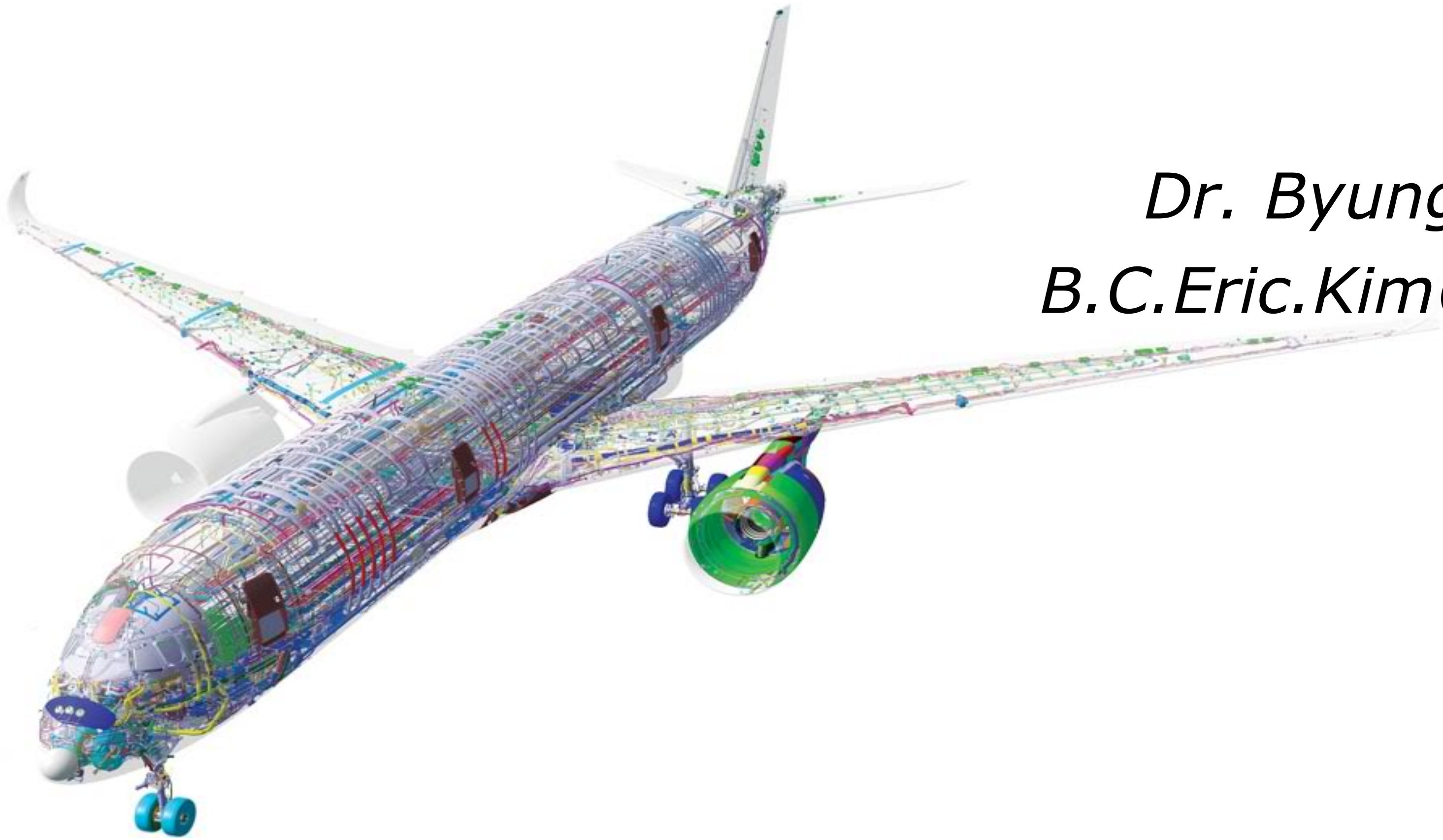
University of BRISTOL

StM3. Aircraft manufacture

Part 1



Dr. ByungChul Eric Kim

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Case study – Aircraft wings

Reverse Engineering approach for learning

- ***What materials are used and how they change the manufacturing methods***
- ***What key manufacturing processes are used***
- ***How the components are joined together***

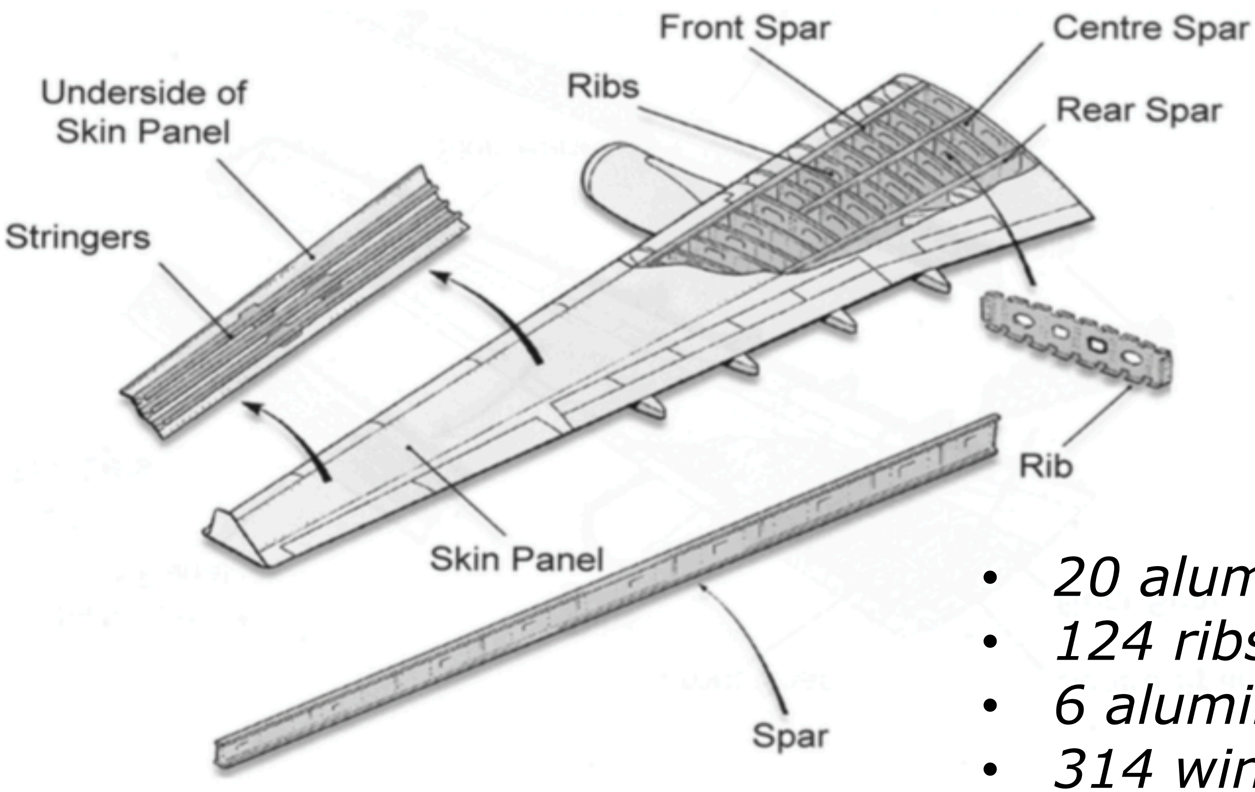
Case study – Aircraft wings

Case study – Aircraft wings

	Metallic ***A340, A380***	***Composite*** ***A350XWB, A400M***
Main raw material	2000 and 7000 series Aluminium alloys	Carbon/epoxy composite
Raw material processing	Hot rolling	Prepreging
Key Manufacturing Processes	1. Metal cutting 2. Forming - Creep age forming - Die forging - Sheet metal forming	1. Automated Fibre/Tape Placement 2. Drape forming 3. Autoclave curing 4. Composite machining
Assembly Process	Mechanical joining + Welding	Adhesive + Mechanical joining

Metallic wing

Aircraft wing structure – A380



- *20 aluminium alloy panels (skins)*
- *124 ribs (76 metallic, 48 CFRP)*
- *6 aluminium alloy spars*
- *314 wing stringers or stiffeners (124 for the top skins, 190 for the bottom skins)*
- *16 leading edge, 6 trailing edge devices*
- *22 flying control surfaces*
- *360,000 metres of wiring, piping and ducting*
- *750,000 fasteners (nuts, bolts, rivets)*

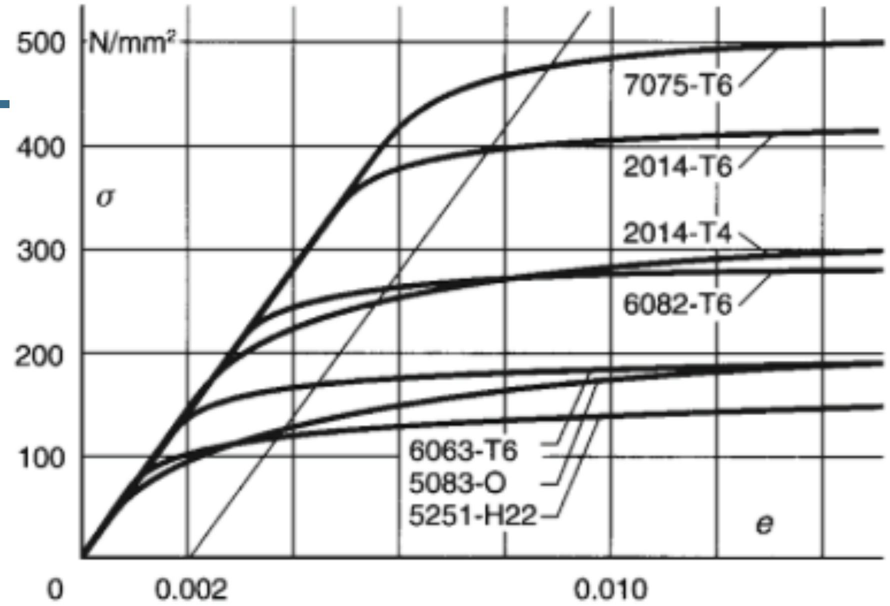
http://www.cadinfo.net/s6-mechanical-engineering/c69-aerospace/building-the-worlds-largest-passenger-aircraft-wings/

Aluminium alloys

- Material designation

7075 – T6

Material designation



Ref. Aluminium Design and Construction

Material designation	Major alloying element	Advantage
1xxx	99% Al	Electrical, thermal conductivity
2xxx	Cu	Strength
3xxx	Mn	Formability
4xxx	Si	Castability (Fluidity), machinability
5xxx	Mg	Strength, corrosion resistance
6xxx	Mg + Si	Strength, extrudability, corrosion resistance
7xxx	Zinc	Very high strength
8xxx	Other	Very high strength

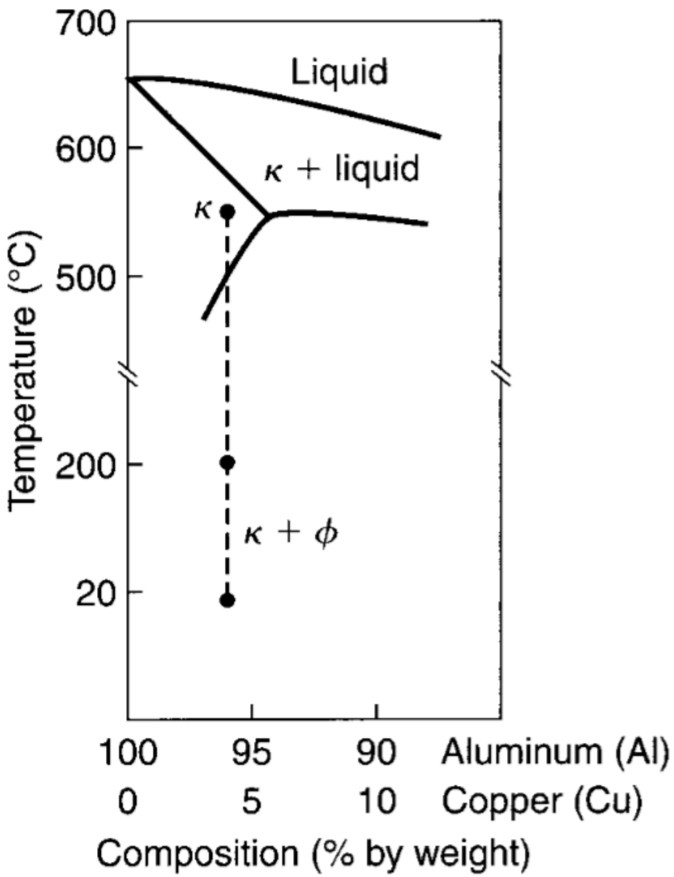
AENG31200 Structures and Materials 3

Aluminium alloys

Ref. Handbook of Aluminium (volume1)

Temper designation

7075 – T6



"F"	*As Fabricated*: Applies to products of forming processes in which no special control over thermal or work hardening conditions is employed. Mechanical property limits are not assigned to wrought alloys in this temper, but are assigned to cast alloys in "as cast," F temper.
"O"	*Annealed*: Applies to wrought products that have been heated to effect re-crystallization, produce the lowest strength condition, and cast products that are annealed to improve ductility and dimensional stability.
"H"	*Strain-Hardened*: Applies to wrought products that are strengthened by strain hardening through cold working. The strain hardening may be followed by supplementary thermal treatment, which produces some reduction in strength. The H is always followed by two or more digits (see Table 4).
"W"	*Solution Heat-Treated*: Applies to an unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is specified. For example, W $\frac{1}{2}$ hour solution heat treatment involves heating the alloy to approximately 1000°F to bring the alloying elements into solid solution, followed by rapid quenching to maintain a supersaturated solution to room temperature.
"T"	*Thermally Treated*: Applies to products that are heat-treated, sometimes with supplementary strain-hardening, to produce a stable temper other than F or O. The T is always followed by one or more digits (see Table 5).

First digit indicates sequence of treatments:	
T1	Naturally aged after cooling from an elevated temperature shaping process
T2	Cold worked after cooling from an elevated temperature shaping process and then naturally aged
T3	Solution heat-treated, cold worked and naturally aged
T4	Solution heat-treated and naturally aged
T5	Artificially aged after cooling from an elevated temperature shaping process
T6	Solution heat-treated and artificially aged
T7	Solution heat-treated and stabilized (over-aged)
T8	Solution heat-treated, cold worked, and artificially aged
T9	Solution heat-treated, artificially aged, and cold worked
T10	Cold worked after cooling from an elevated temperature shaping process and then artificially aged

Aluminium alloys

Properties of Selected Aluminum Alloys at Room Temperature

Alloy (UNS)	Temper	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)
1100 (A91100)	O	90	35	35–45
1100	H14	125	120	9–20
2024 (A92024)	O	190	75	20–22
2024	T4	470	325	19–20
3003 (A93003)	O	110	40	30–40
3003	H14	150	145	8–16
5052 (A95052)	O	190	90	25–30
5052	H34	260	215	10–14
6061 (A96061)	O	125	55	25–30
6061	T6	310	275	12–17
7075 (A97075)	O	230	105	16–17
7075	T6	570	500	11

Non-heat treatable

Heat treatable

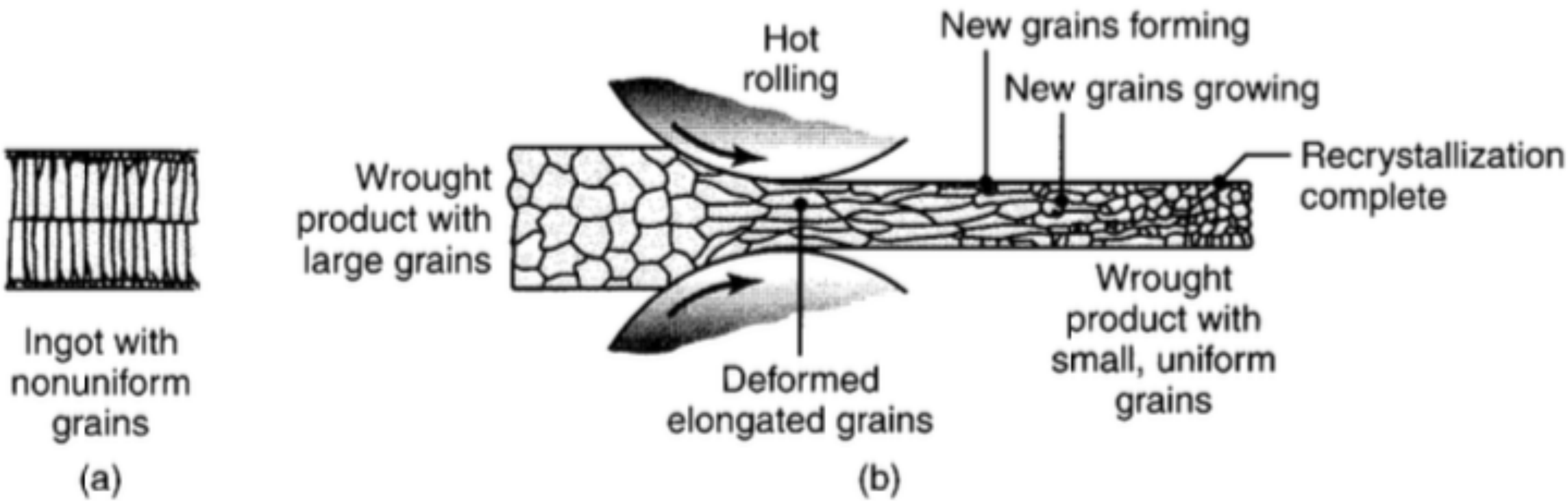
Ref. Manufacturing Engineering and Technology

Forming - Rolling

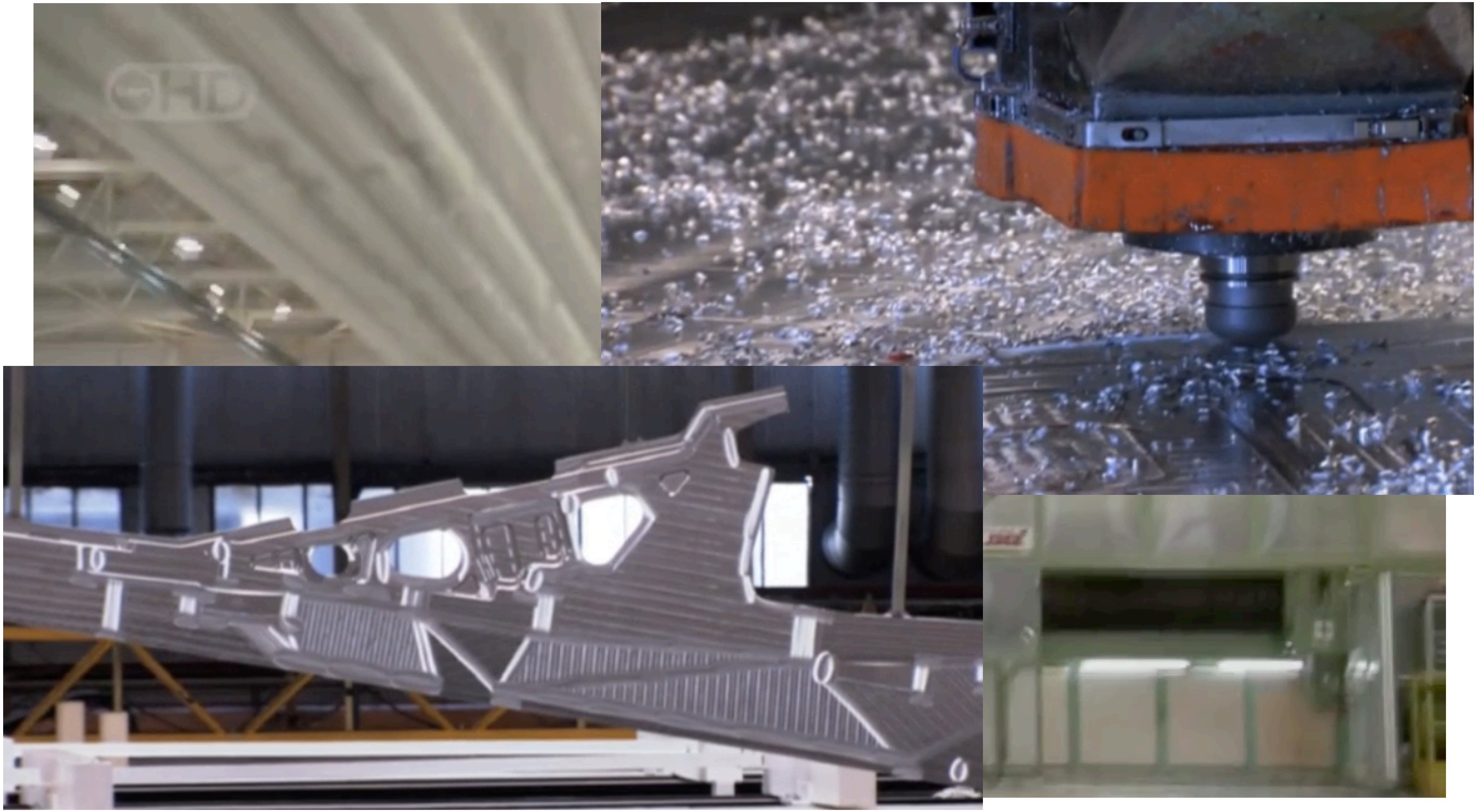
https://youtu.be/RQusr1f4S7c?t=29s
https://youtu.be/yZMtBMBt_SU?t=3m6s

Hot rolling

- Cast structure ➔ a wrought structure with finer grains and enhanced ductility, breaking up of brittle grain boundaries and the closing up of internal defects (e.g. porosity).
- Typical temperature range
  - Aluminium alloys: 450°C
  - Steel alloys: 1250°C

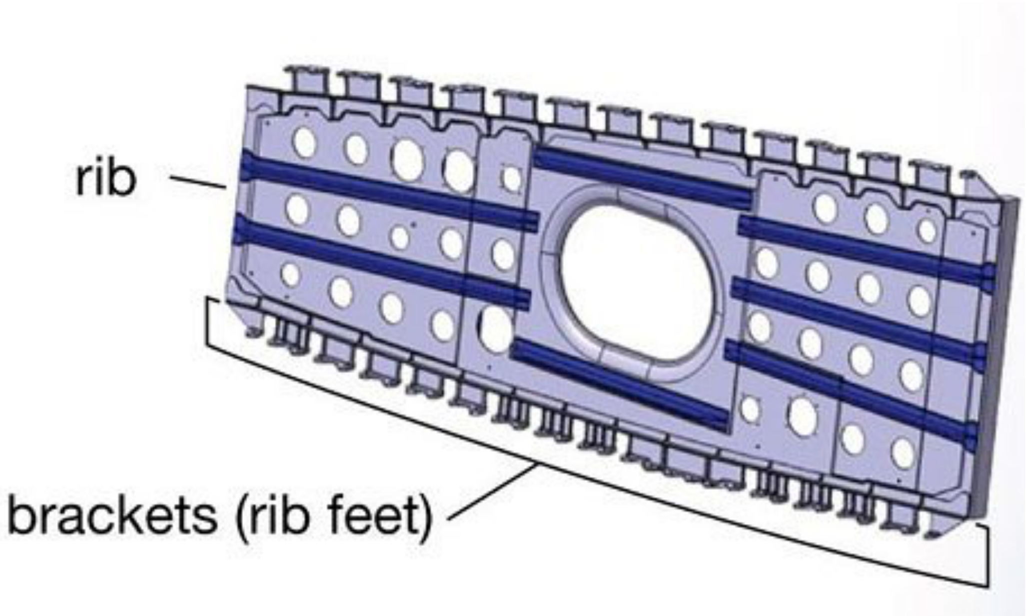


Metal cutting - Milling



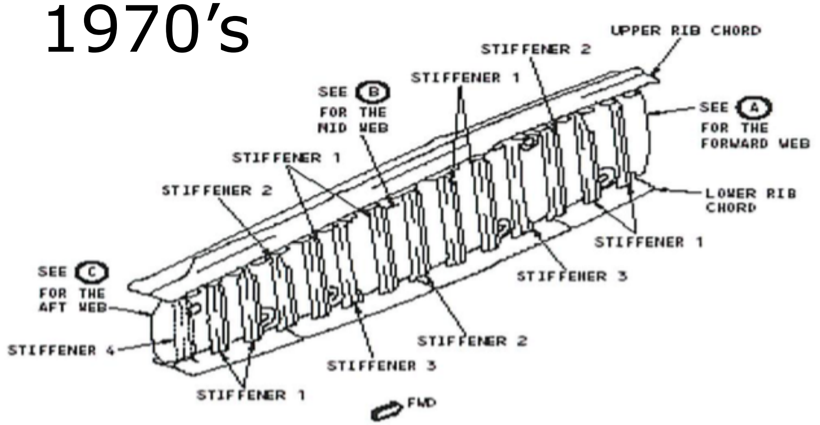
BBC How to build a super jumbo wing

Metal cutting - Milling



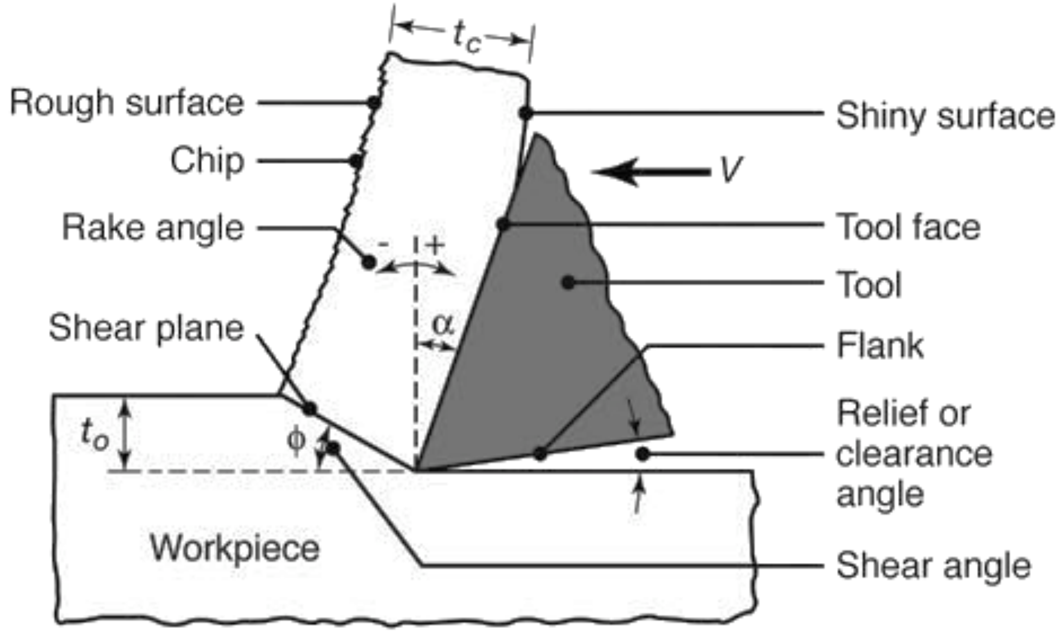
https://youtu.be/y89M0dhoLh4

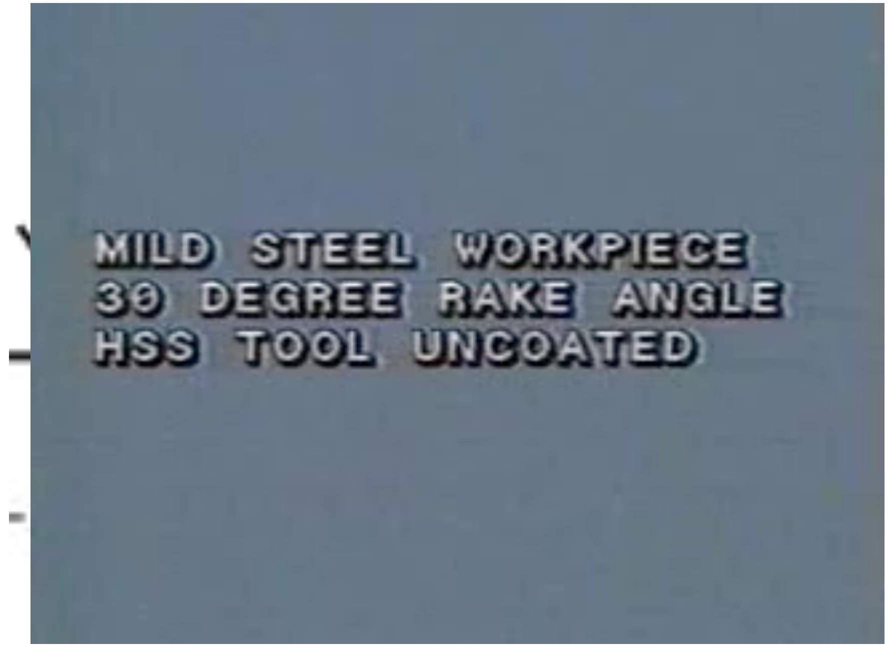
1970's



- Sub-assembled ➔ Single piece component
  - Higher dimensional tolerance (Elimination of the assembly error)
  - Cost reduction

Fundamentals of Machining

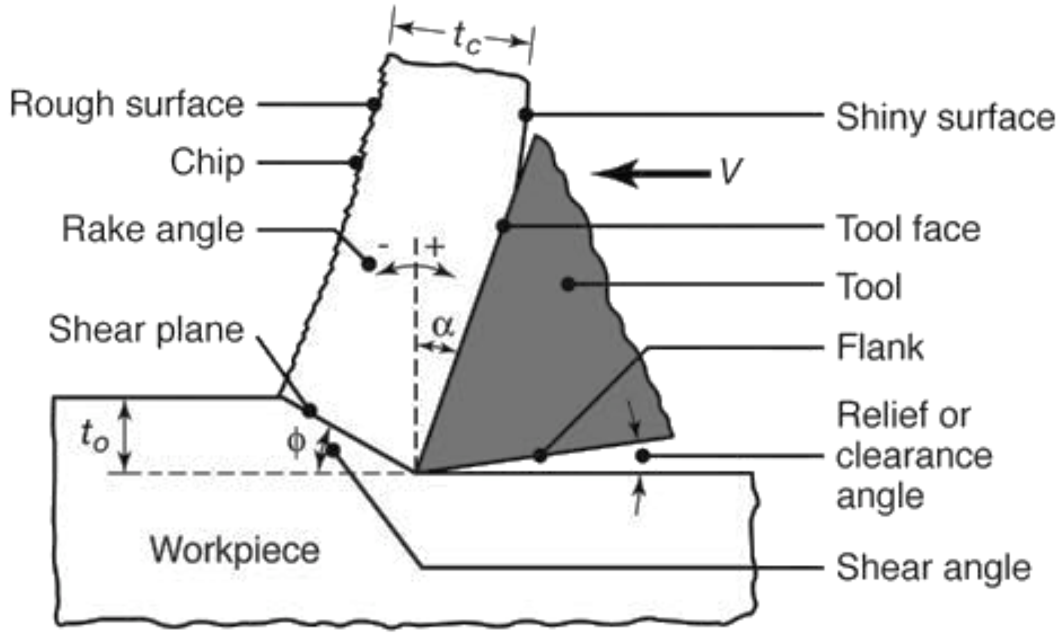


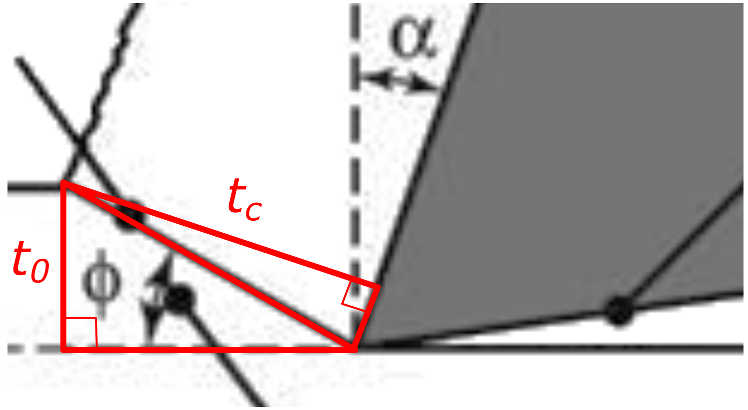


Parameter	Influence
Cutting speed Depth of cut Feed Tool angle Tool wear Machinability of the work peice	Cutting force, power, temperature rise, tool life, type of chip, surface finish, chip flow direction, resistance to tool wear and chipping

Fundamentals of Machining

- Chip formation





$$r = \frac{t_o}{t_c} = \frac{\sin\phi}{\cos(\phi - \alpha)}$$

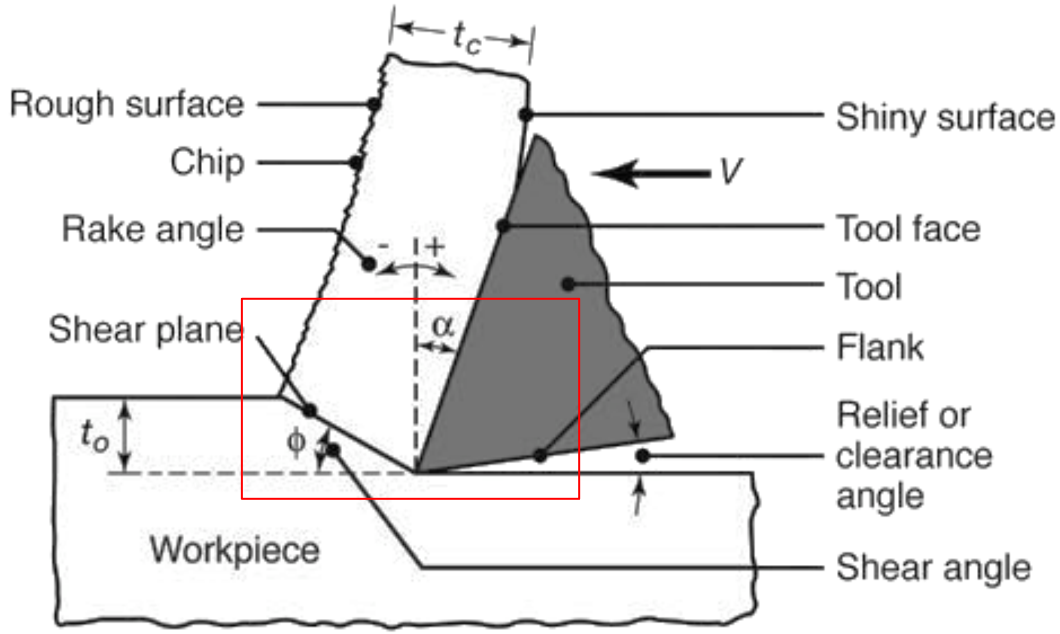
t_c: chip thickness
t_o: depth of cut
$r = (t_o/t_c)$: cutting ratio

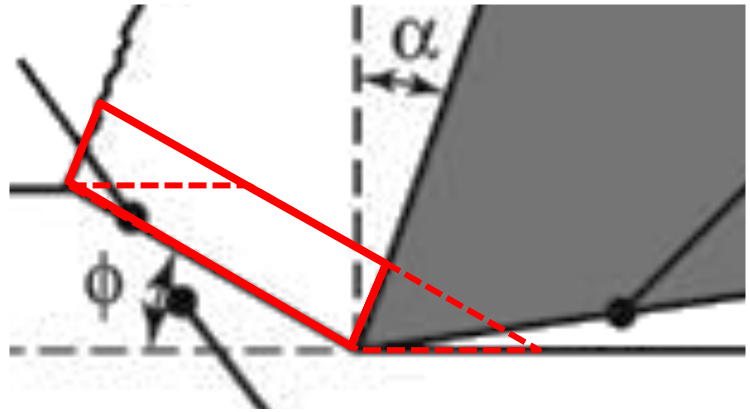
The cutting ratio, r, is a useful parameter for evaluating cutting conditions. Since ***the rake angle, α,*** is known, ***r*** can be easily calculated by measuring the chip thickness with a micrometre.

Then it allows us to calculate ***the shear angle, ϕ***, which influences the cutting force and power requirements, and temperature rise, and so on.

Fundamentals of Machining

- Shear strain & Velocities

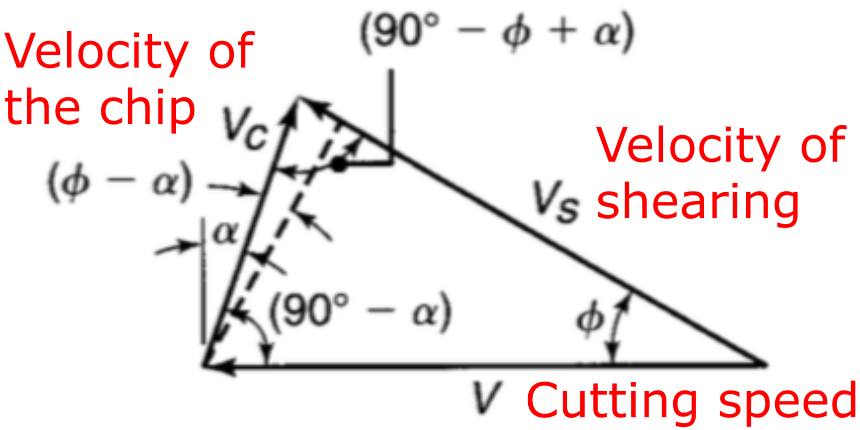




$$\gamma = \cot\phi + \tan(\phi - \alpha)$$

$$\phi = 45° + \alpha - \beta$$ Merchant's equation

$$\mu = \tan\beta$$ Friction angle (tool-chip interface)

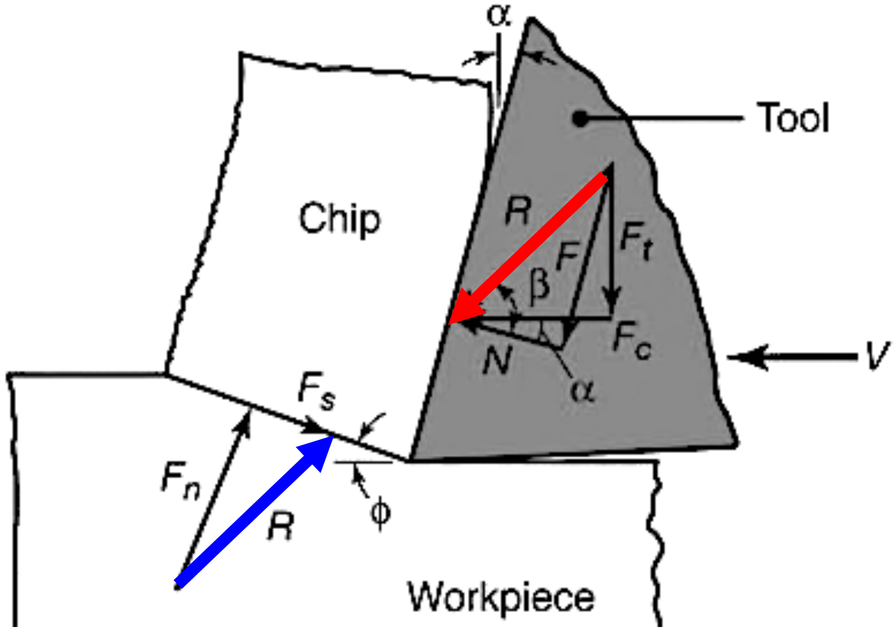


$$Vt_o = V_c t_c$$: Mass continuity

$$\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos\alpha} = \frac{V_c}{\sin\phi}$$

Fundamentals of Machining

- Cutting force and power



< Forces on workpiece >

Shear $$F_s = F_c \cos\phi - F_t \sin\phi$$

Normal $$F_n = F_c \sin\phi + F_t \cos\phi$$

Friction coeff. $$\mu = \frac{F}{N} = \frac{F_t + F_c \tan\alpha}{F_c - F_t \tan\alpha}$$

< Forces on the tool >

Friction $$F = R\sin\beta$$

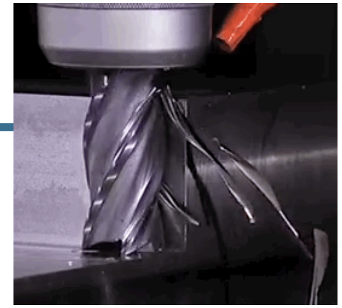
Normal $$N = R\cos\beta$$

Thrust (+ or -) : *Stability issue*

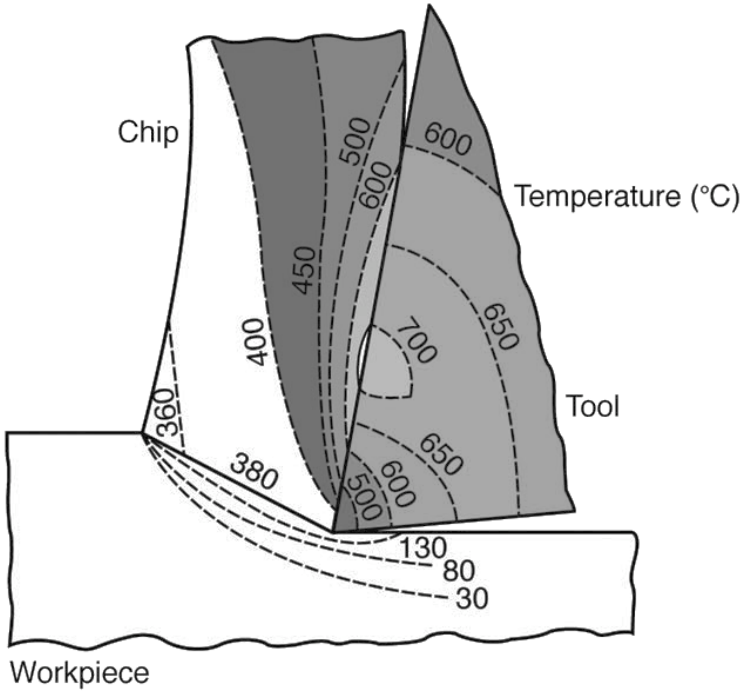
$$F_t = R\sin(\beta - \alpha) = F_c \tan(\beta - \alpha)$$

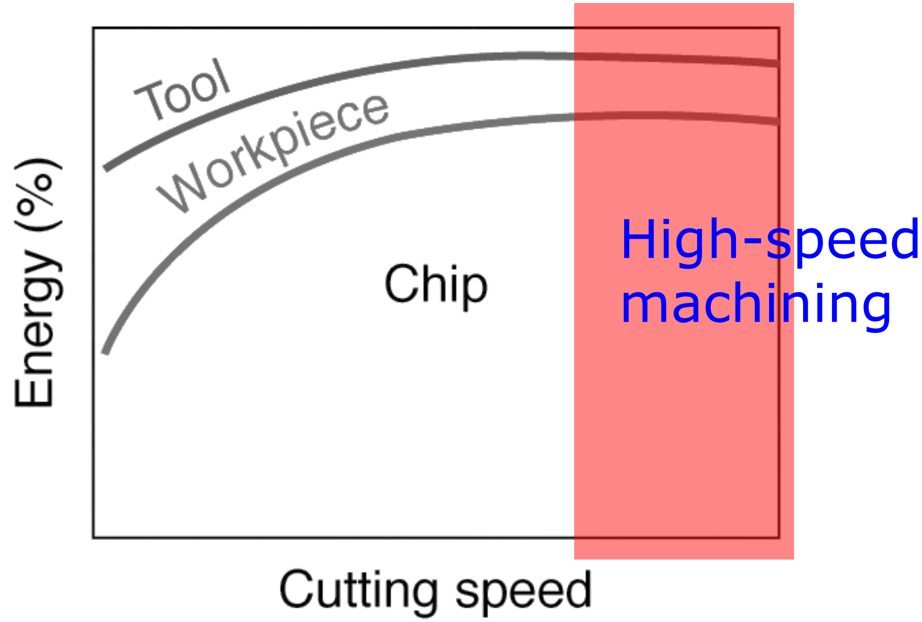
Material	Specific energy $W \cdot s/mm^3$
Aluminum alloys	0.4–1
Cast irons	1.1–5.4
Copper alloys	1.4–3.2
High-temperature alloys	3.2–8
Magnesium alloys	0.3–0.6
Nickel alloys	4.8–6.7
Refractory alloys	3–9
Stainless steels	2–5
Steels	2–9
Titanium alloys	2–5

Fundamentals of Machining



- Heat generation and the effect





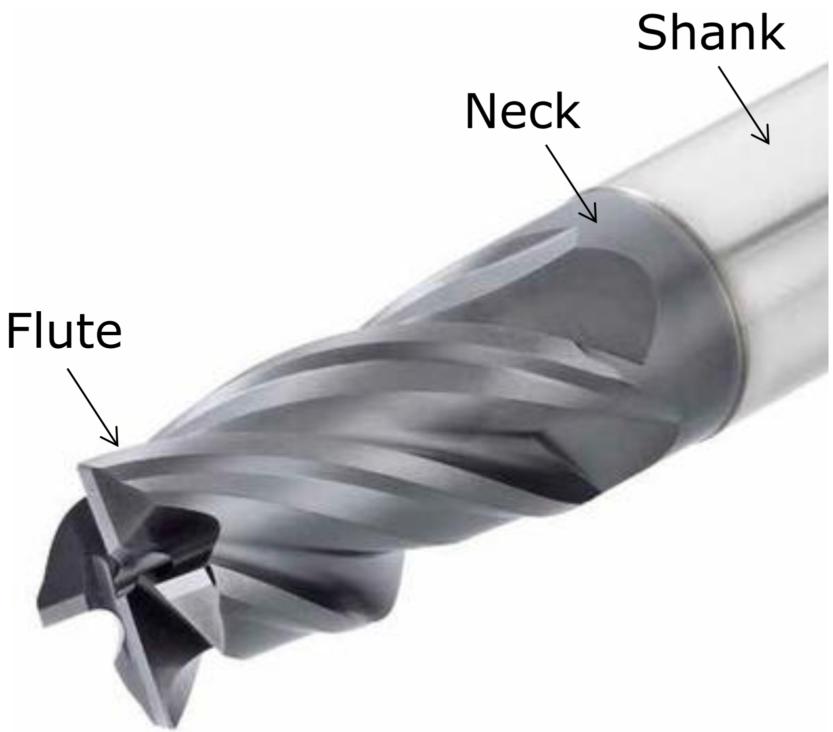
Main sources of heat generation

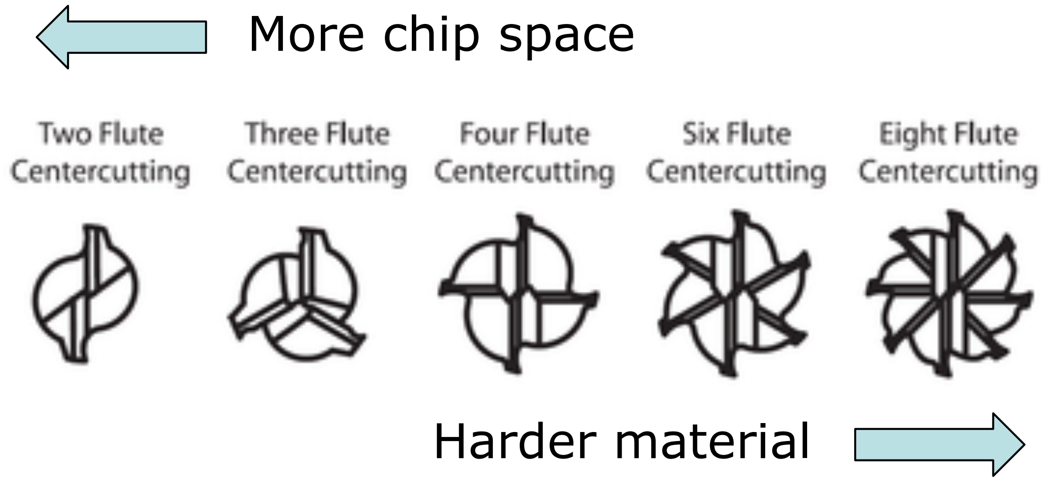
1. Work done in shearing
2. Energy dissipated by friction at the tool-chip interface
3. Friction between the tool and the machined surface

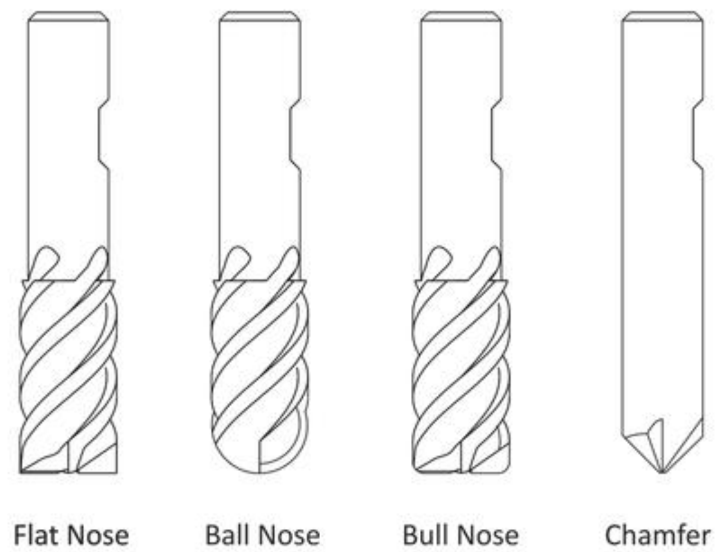
Tool wear
Dimension change
Thermal damage

Metal cutting - Milling

- End Mill



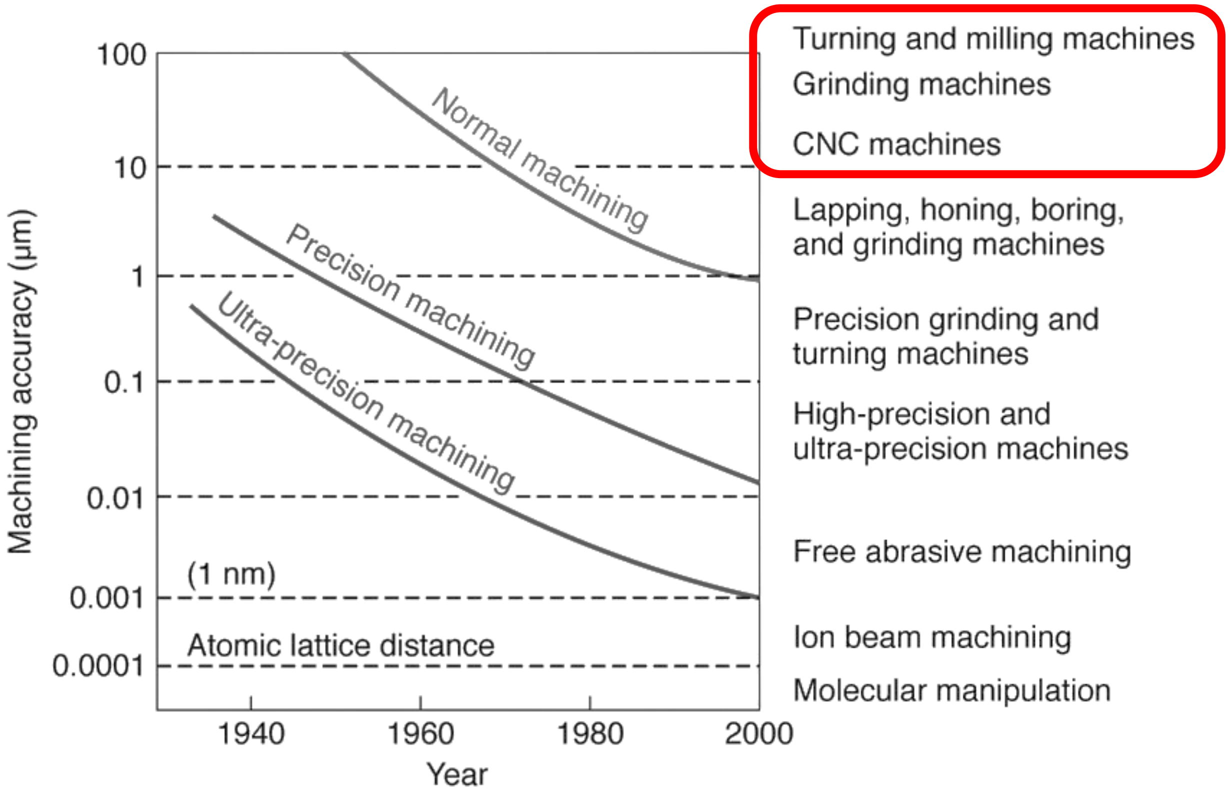


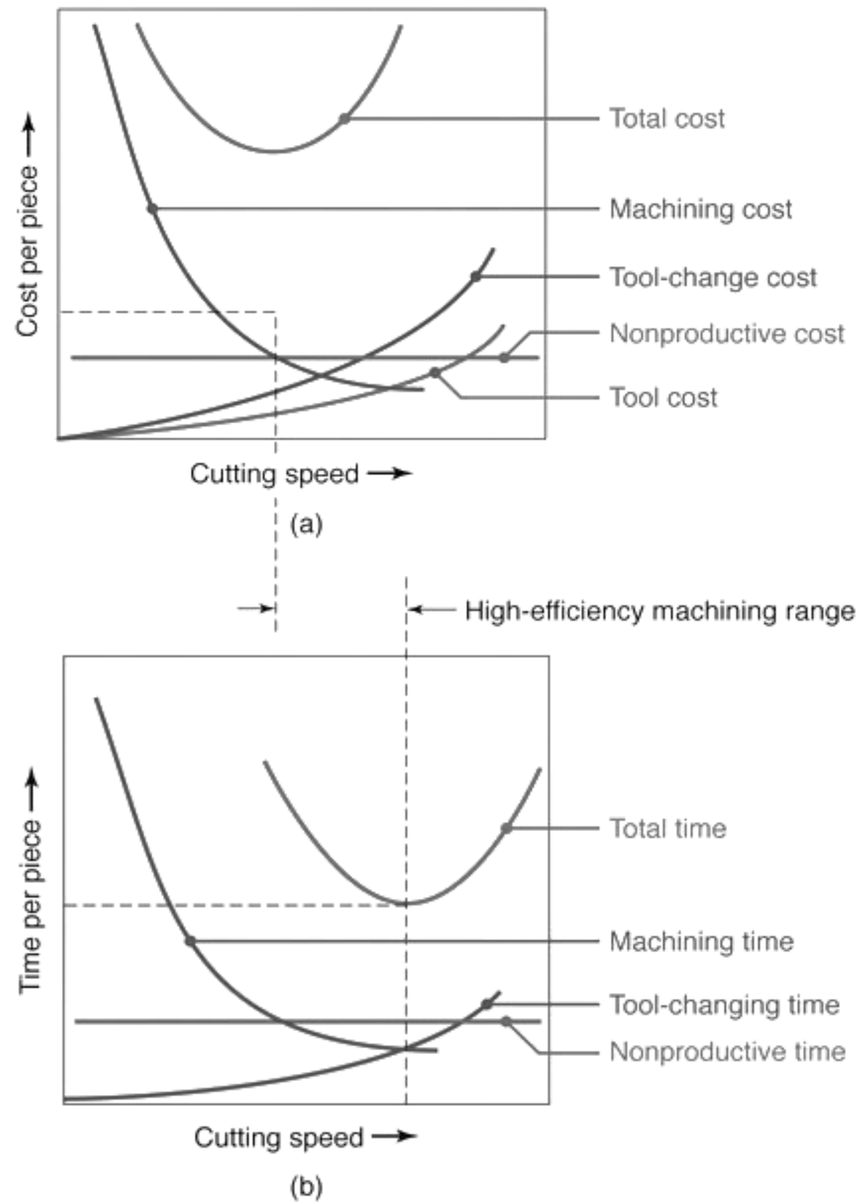


https://youtu.be/HfIaISnqHOk

Metal cutting - Milling

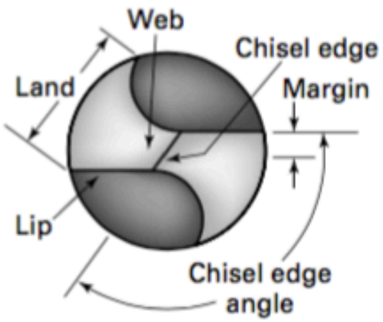
- Tolerance and speed

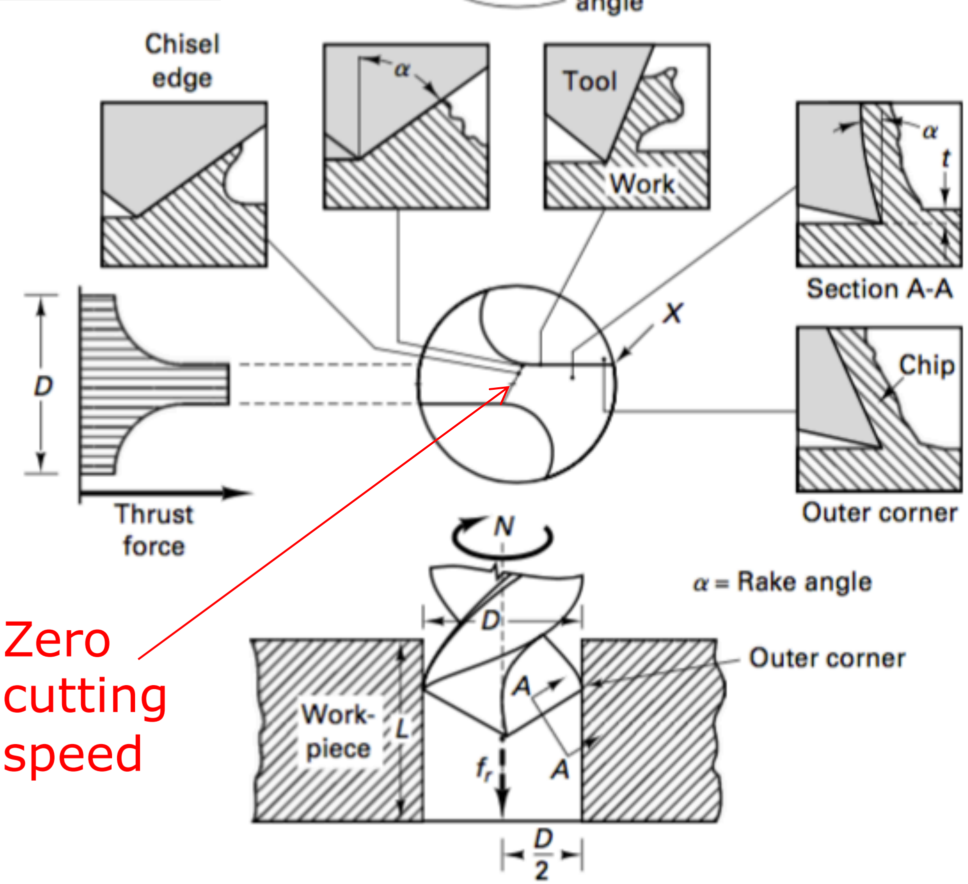




- Machining accuracy using metal cutting is about 10 μm.
- Small change in cutting speed can have a significant effect on the minimum cost or time per piece.

Metal cutting - Drilling





Zero cutting speed

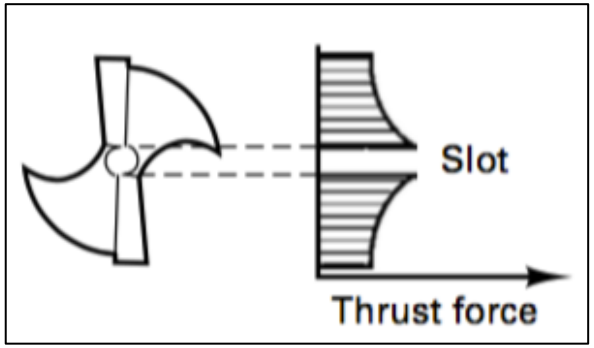
rpm of the drill $$N = \frac{12V}{\pi D}$$

Material removal rate

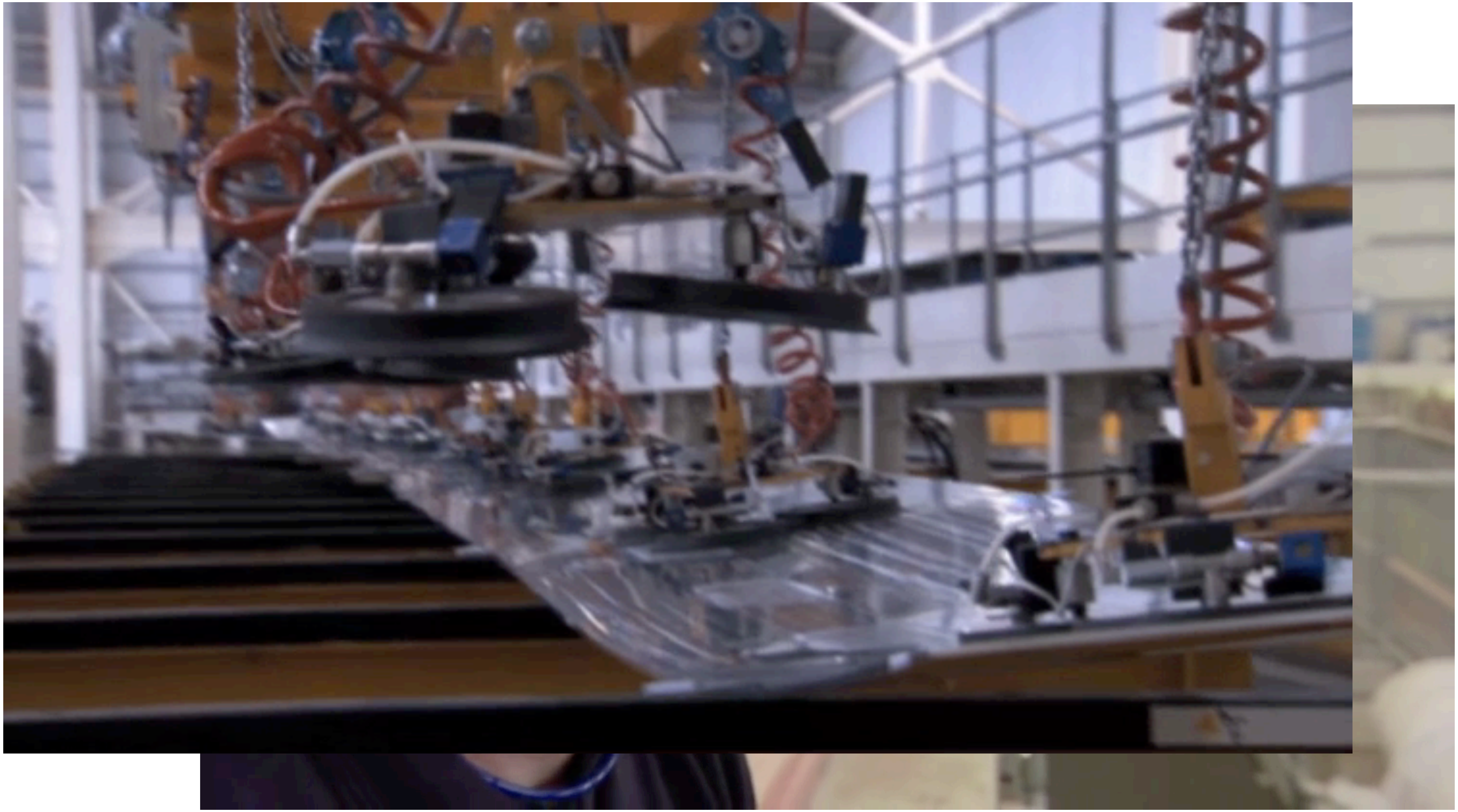
$$\mathrm{MMR} = \left(\frac{\pi D^2}{4}\right) f_r N$$

f_r: distance the drill penetrates per unit revolution

Centre core drill



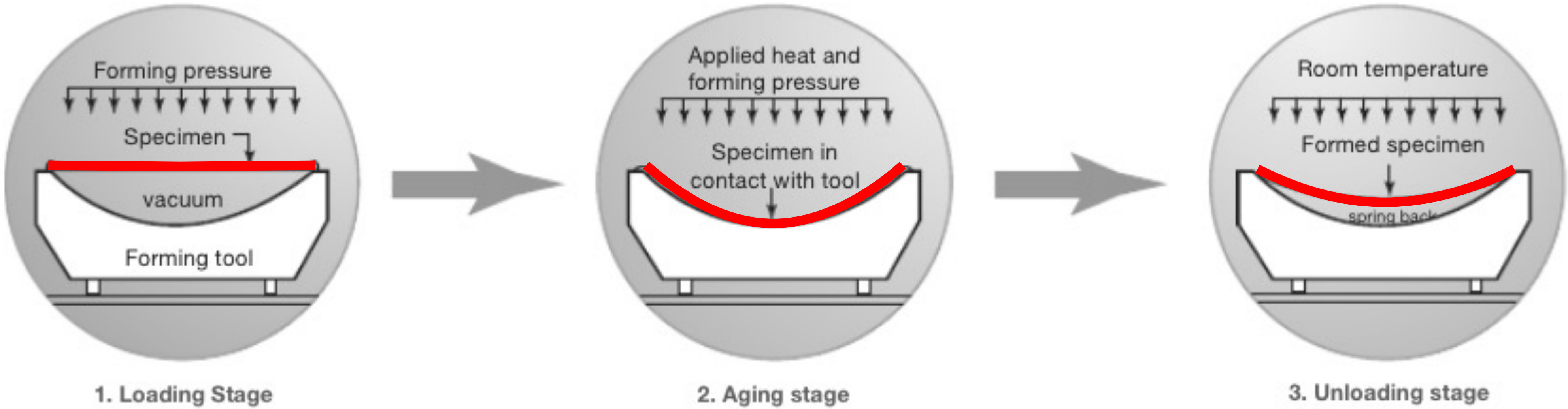
Creep age forming (CAF)



BBC How to build a super jumbo wing

Creep age forming (CAF)

- Al 2xxx (lower skin) & 7xxx (Upper skin) alloys, at 120-180°C, 10-48 hours

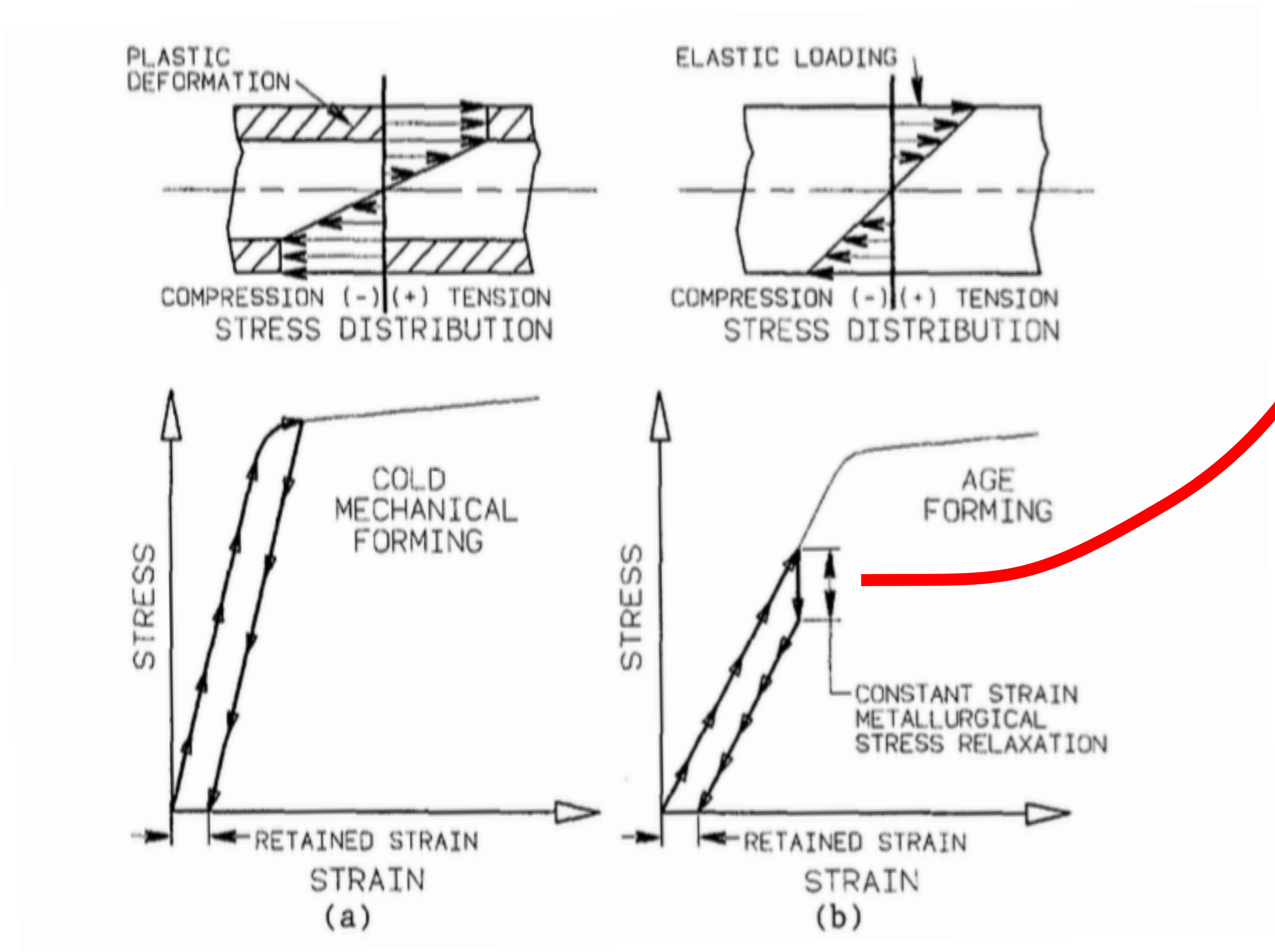


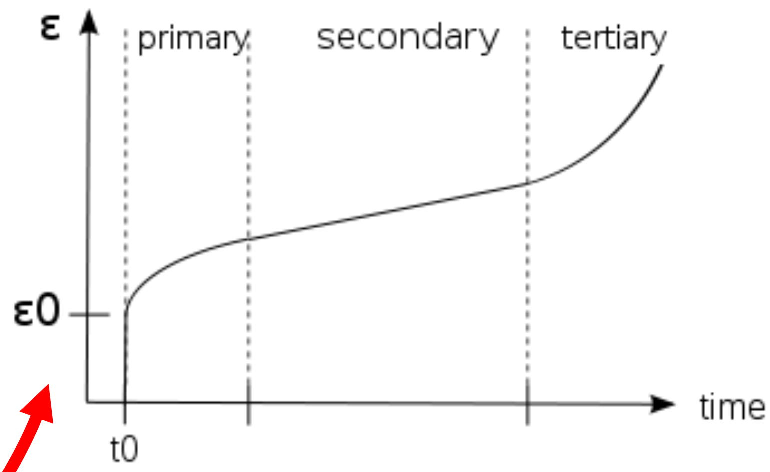
http://www.technology-licensing.com/etl/int/en/What-we-offer/Technology-videos.html

Advantages	Disadvantages
• Low residual stresses ➔ High fatigue resistance, shape stability • Low forming stress • Low forming equipment cost • Simultaneous age-hardening process	• Usually for 2xxx, 6xxx, 7xxx Al alloys (still under development for others) • Long process time • Springback ➔ difficult mould design • Reduction of yield strength (2xxx)

Creep age forming (CAF)

Cold forming vs. CAF





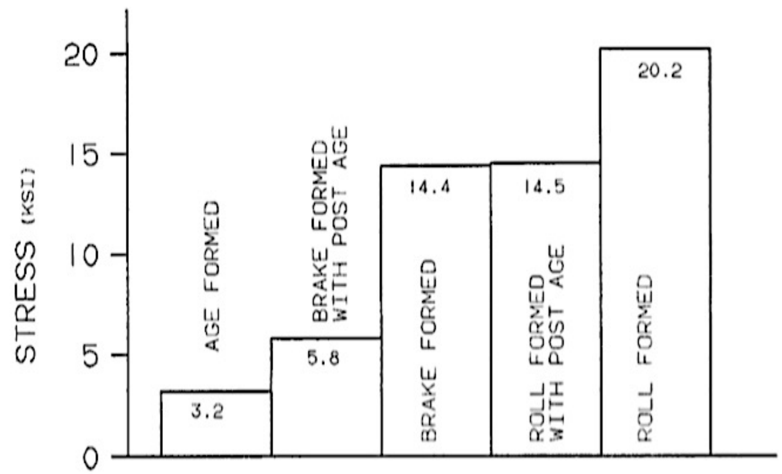
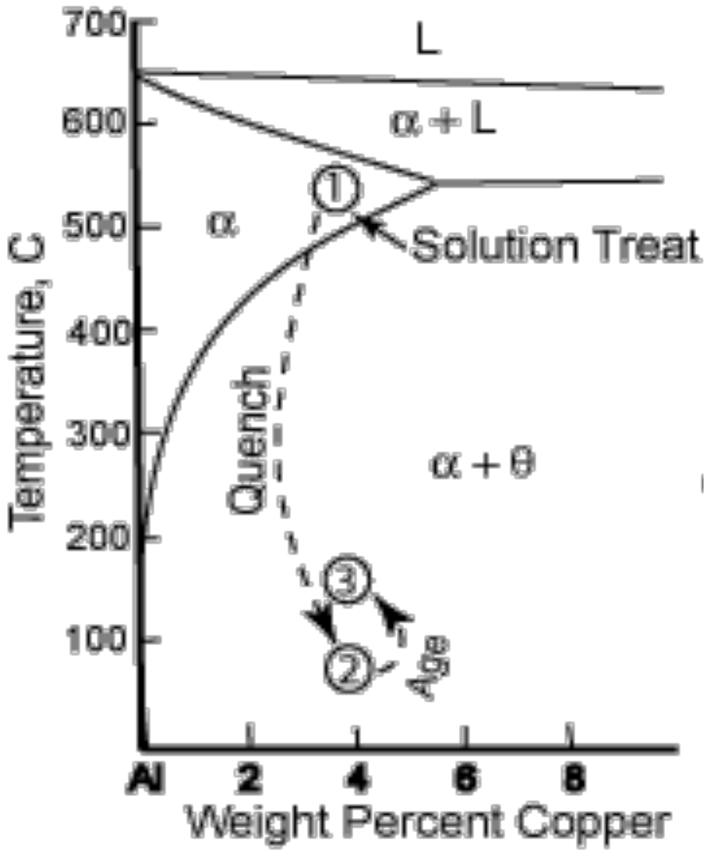


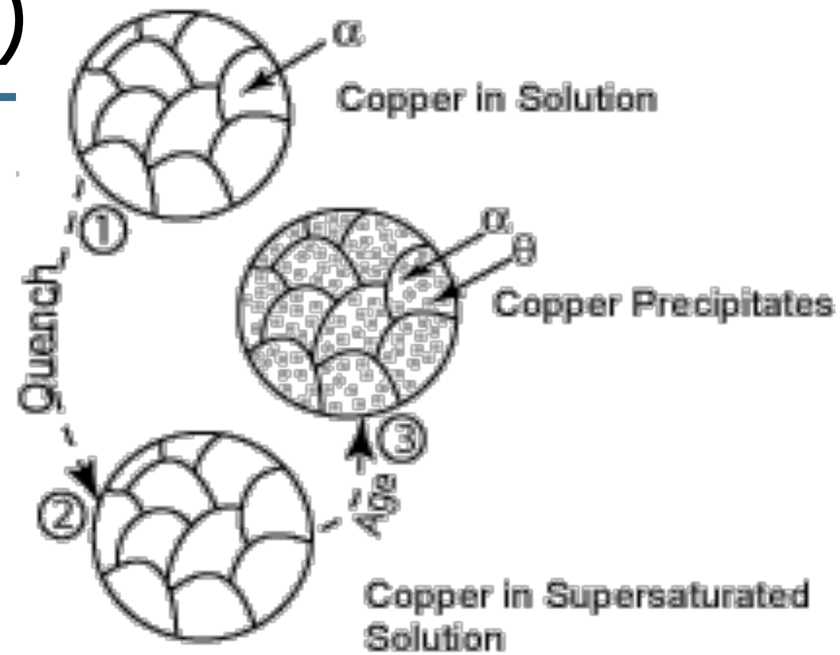
Figure 3. Tensile residual stress measurements of aluminum alloy 7075 specimens formed to the same radius of curvature.

Ref. MC Holman, Autoclave age forming large aluminum aircraft panels, Journal of Mechanical Working Technology, 20 (1989) 477-488.

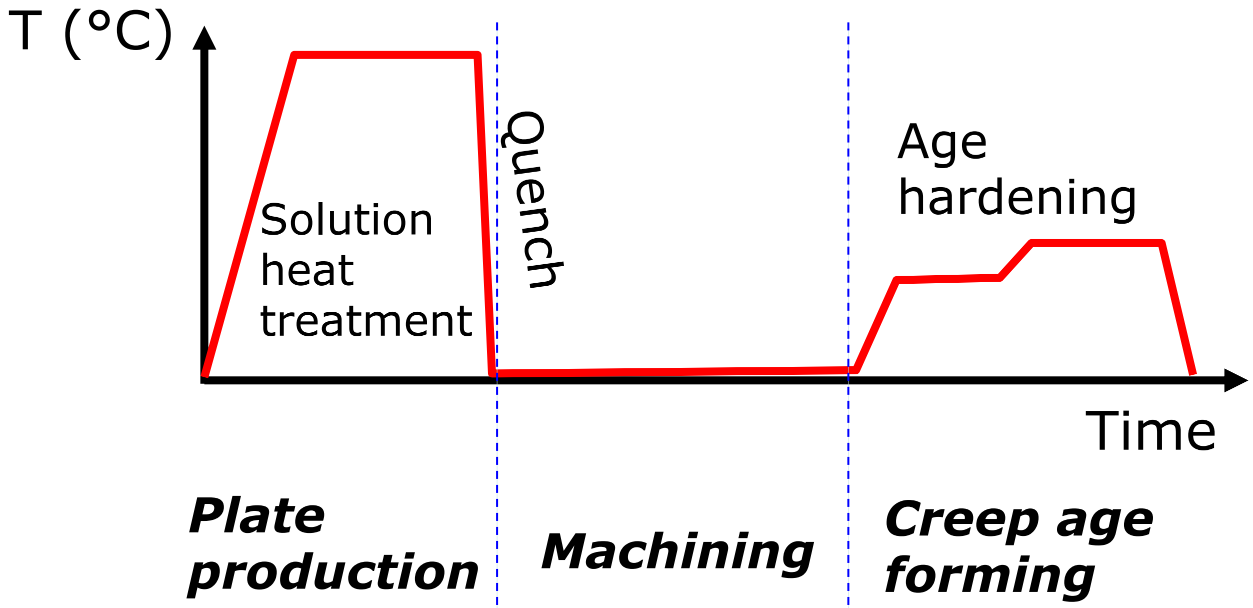
Creep age forming (CAF)

- Age hardening (precipitation hardening)





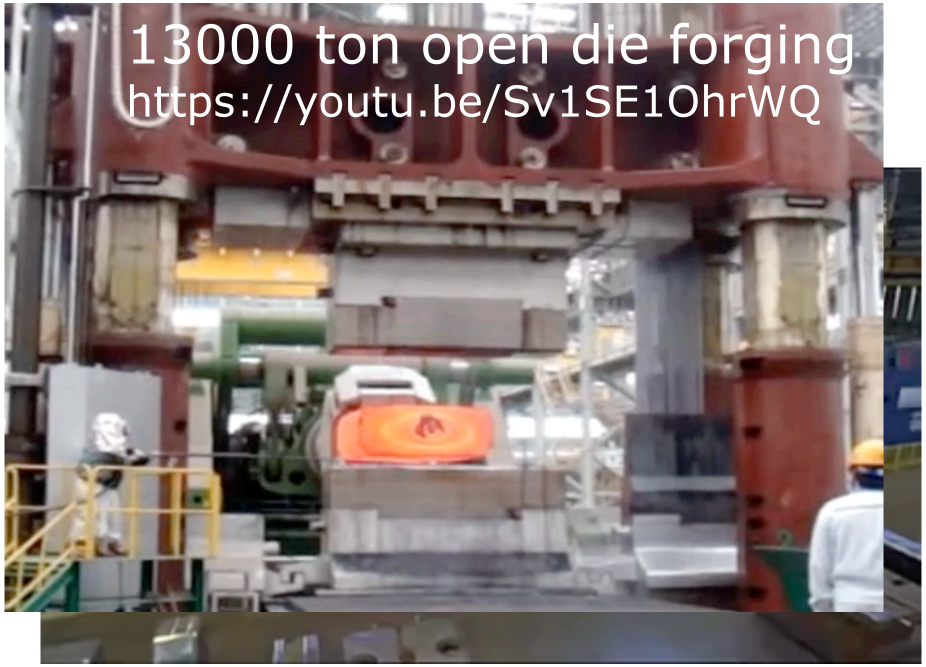
< Example of Al 2xxx alloy >

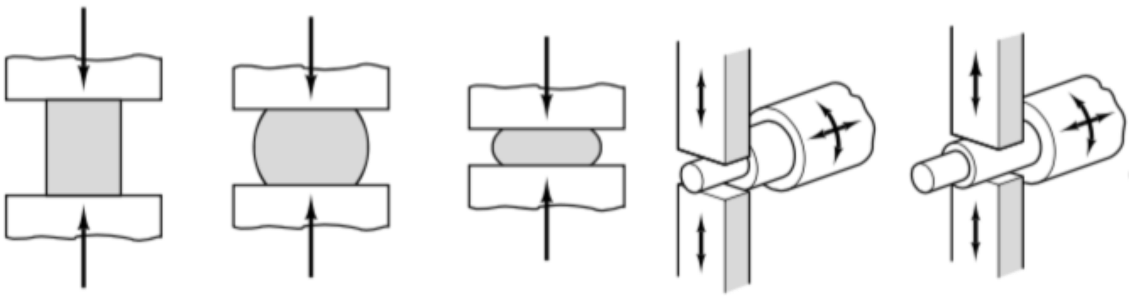


Forming – Die forging

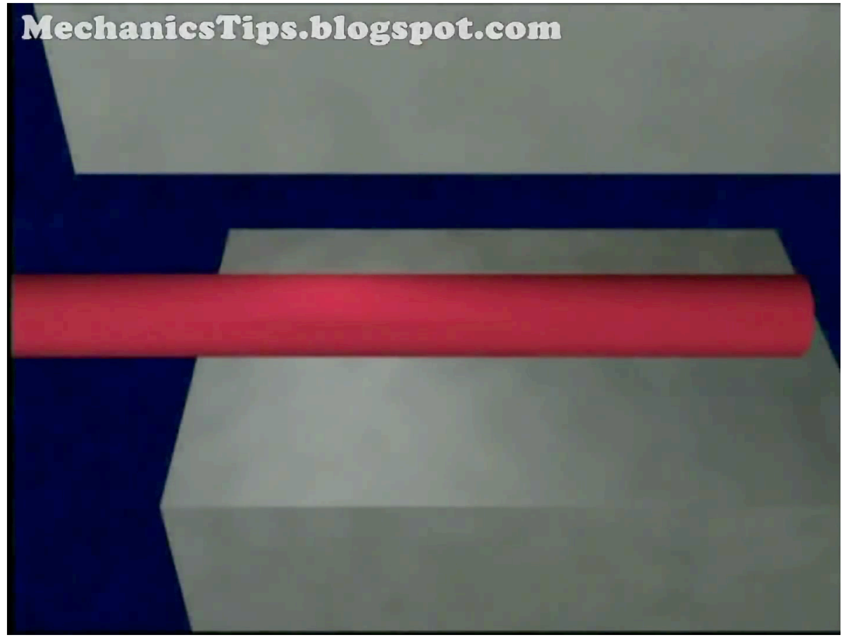
Forming – Die forging

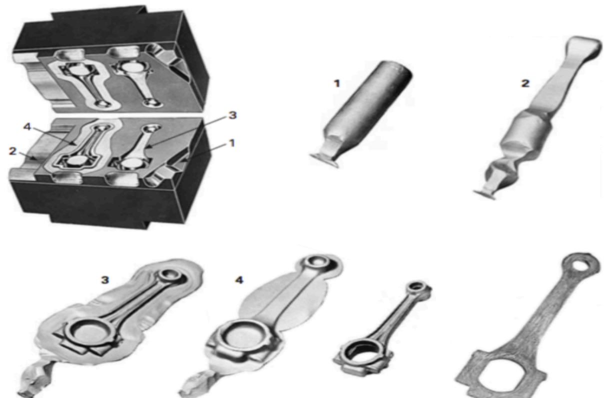
- Open die forging





- Closed die forging





https://youtu.be/YobXFODkp50?t=3m58s

Forming – Die forging

- Why forging rather than casting or machining?
  - Continuity of the grain structure
  - Reduction of material waste (compared to machining)
  - High production rate
  - Improvement of static and fatigue strengths (strain hardening, pore reduction), toughness, grain refinement

CASTING
No grain flow

BAR STOCK
Grain flow broken by machining

FORGING
True grain flow

Forgeability of Metals, in Decreasing Order

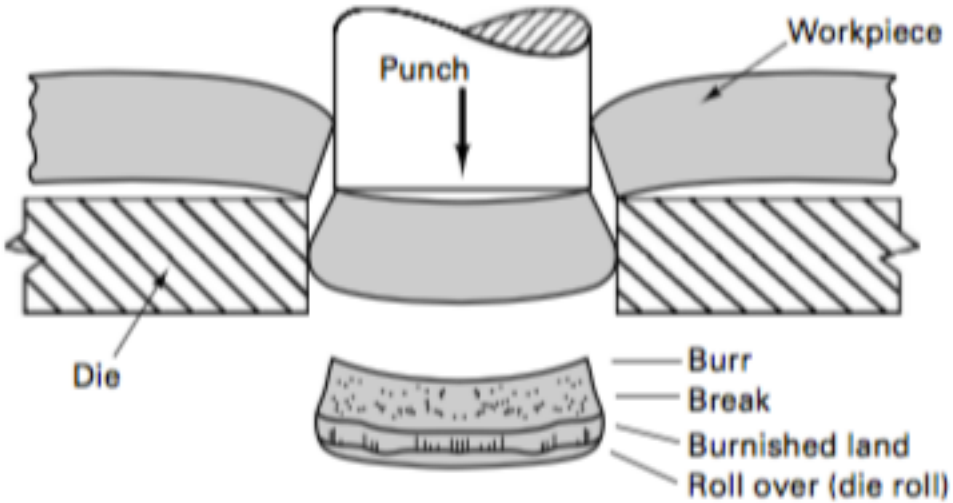
Metal or alloy	Approximate range of hot-forging temperatures (°C)
Aluminum alloys	400–550
Magnesium alloys	250–350
Copper alloys	600–900
Carbon- and low-alloy steels	850–1150
Martensitic stainless steels	1100–1250
Austenitic stainless steels	1100–1250
Titanium alloys	700–950
Iron-based superalloys	1050–1180
Cobalt-based superalloys	1180–1250
Tantalum alloys	1050–1350
Molybdenum alloys	1150–1350
Nickel-based superalloys	1050–1200
Tungsten alloys	1200–1300

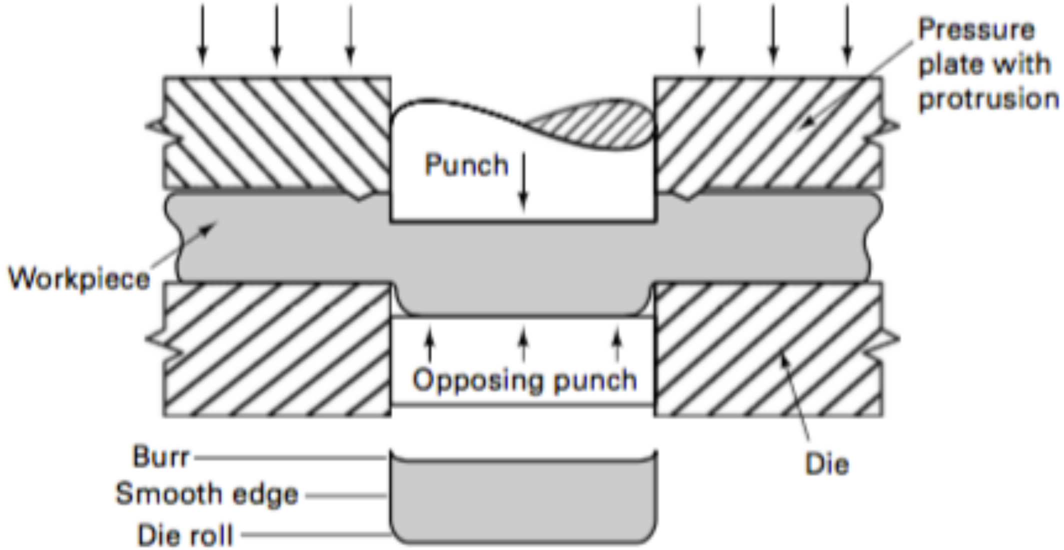
Sheet metal forming

For small-sized aircraft, sheet metal materials are more popular since they are easy to cut and deform.

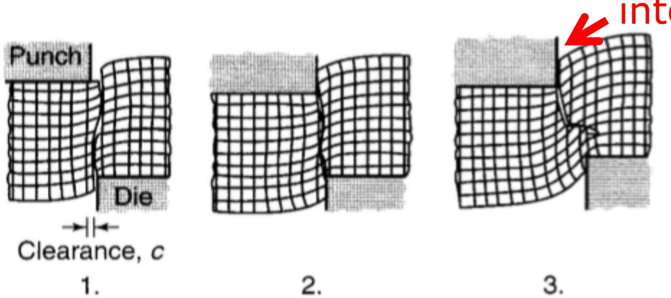
- Punching
- Forming with rubber tooling
- Bending

Sheet metal forming – Punching/blanking





The material pulls into the die.



Sheet metal forming - Bending

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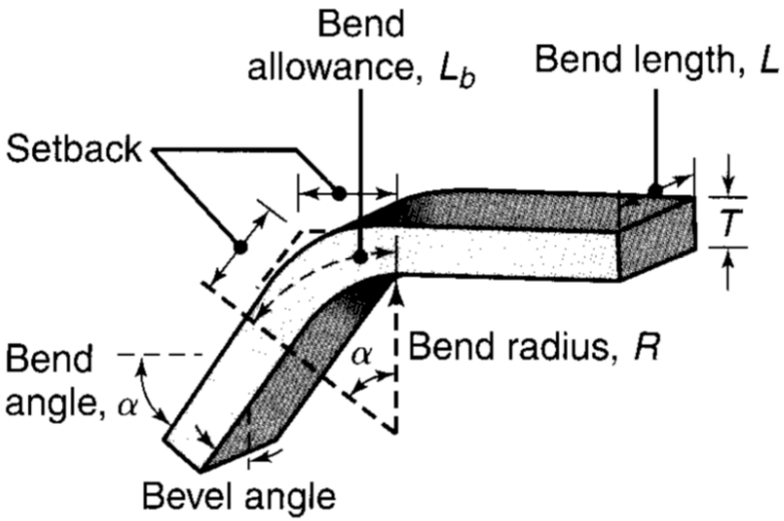
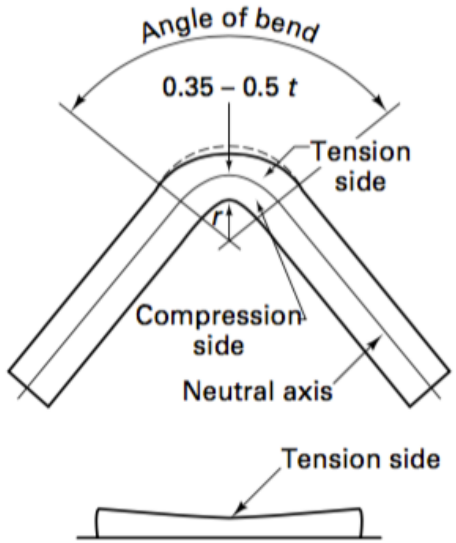




- Bend allowance, L_b
  Length of neutral axis in bending

$$L_b = \alpha(R + kT)$$

k = 0.33~0.5 (R < 2T)
k = 0.5 (neutral axis = the centre of the sheet)

- Min. bend radius

Surface strain $$e = 1/(2R/T + 1)$$

$$\min .R = T(50/r - 1)$$

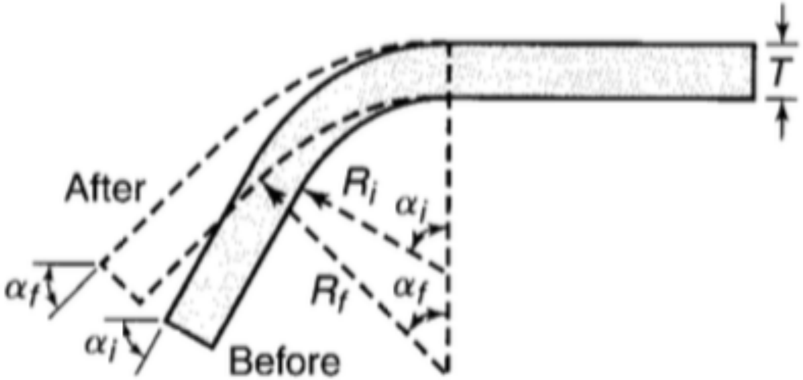
r: Tensile reduction of area

Minimum Bend Radius for Various Metals at Room Temperature

Material	Condition: Soft	Condition: Hard
Aluminum alloys	0	$6T$
Beryllium copper	0	$4T$
Brass (low-leaded)	0	$2T$
Magnesium	$5T$	$13T$
Steels		
Austenitic stainless	$0.5T$	$6T$
Low-carbon, low-alloy, and HSLA	$0.5T$	$4T$
Titanium	$0.7T$	$3T$
Titanium alloys	$2.6T$	$4T$

Sheet metal forming - Bending

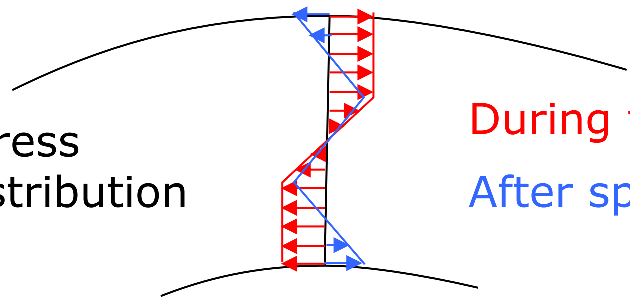
- Spring-back



Approx. solution (Y: yield strength)

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1$$

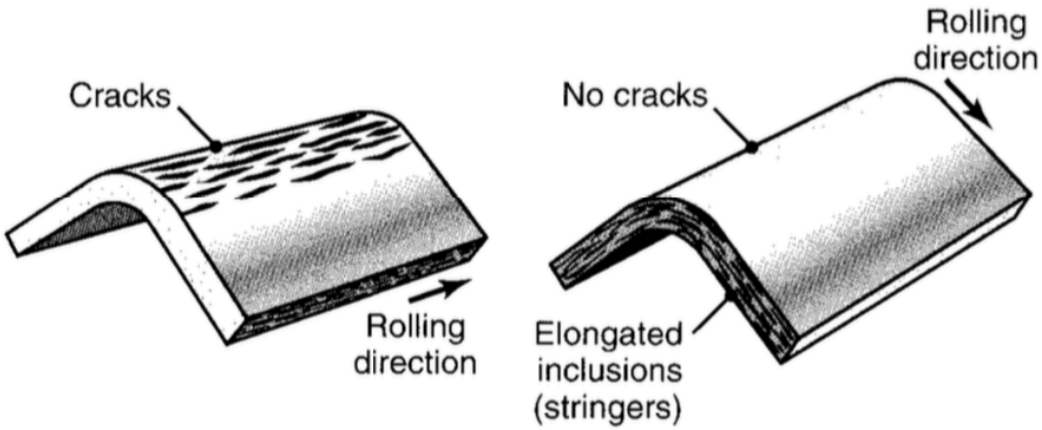
Stress distribution

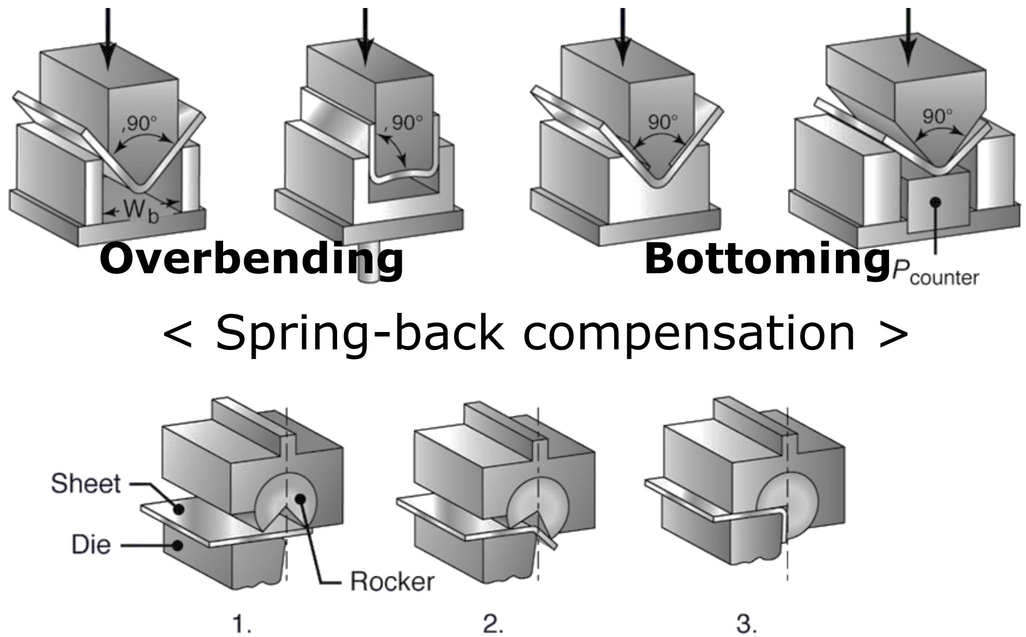


During forming

After spring-back

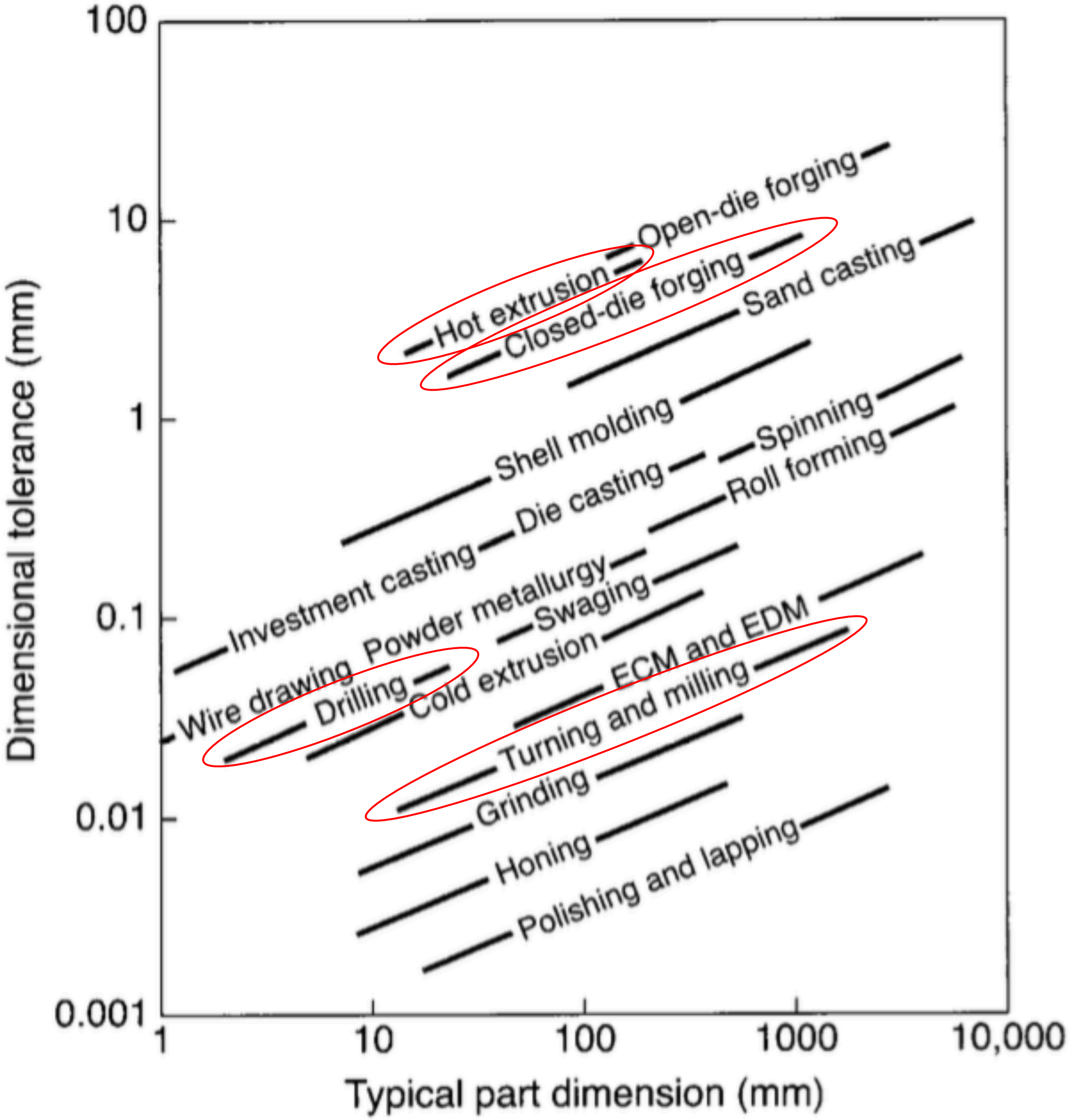
- Material anisotropy

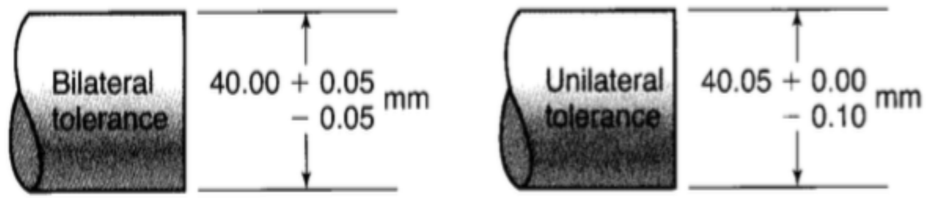




< Spring-back compensation >

Managing tolerance





- The required dimensional tolerance may determine the manufacturing process ➔ Cost & productivity
- All dimensions should be considered as statistical distributions.
- Measurement methods also have different measurement accuracy. (e.g. Venire calliper, micrometre, coordinate measurement machine, laser sensors)

Wing assembly

Automated riveting of the wing skin stringers

Assembly of spars, ribs, and wing panels

Wing assembly

- Due to the size of the components (large machining tolerance, distortion during assembly), it is impossible to pre-machine the holes on each component and bolt/rivet them together at once.
  - e.g. thermal expansion of the 36 m long aluminium skin panel
    $= 24 \times 10^{-6}$ mm/mm°C x 36,000 mm = 0.86 mm/°C

- Drilling and fastening processes are carried out during the assembly process after clamping the components together.
- On the contact surfaces among the components, sealing material is applied to liquid-tighten the fuel storage space.

Next Lecture

<u>***Composites wing***</u>