Introduction to Aerospace Engineering

Lecture slides

Introduction to Aerospace Engineering

13 & 14. Materials & Exploring the limits

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Materials

Contents

3 main topics:

- What are MATERIALS?

- OVERVIEW of materials

- Relationship
  – MATERIAL
  – DESIGN/STRUCTURE
  - MANUFACTURING?

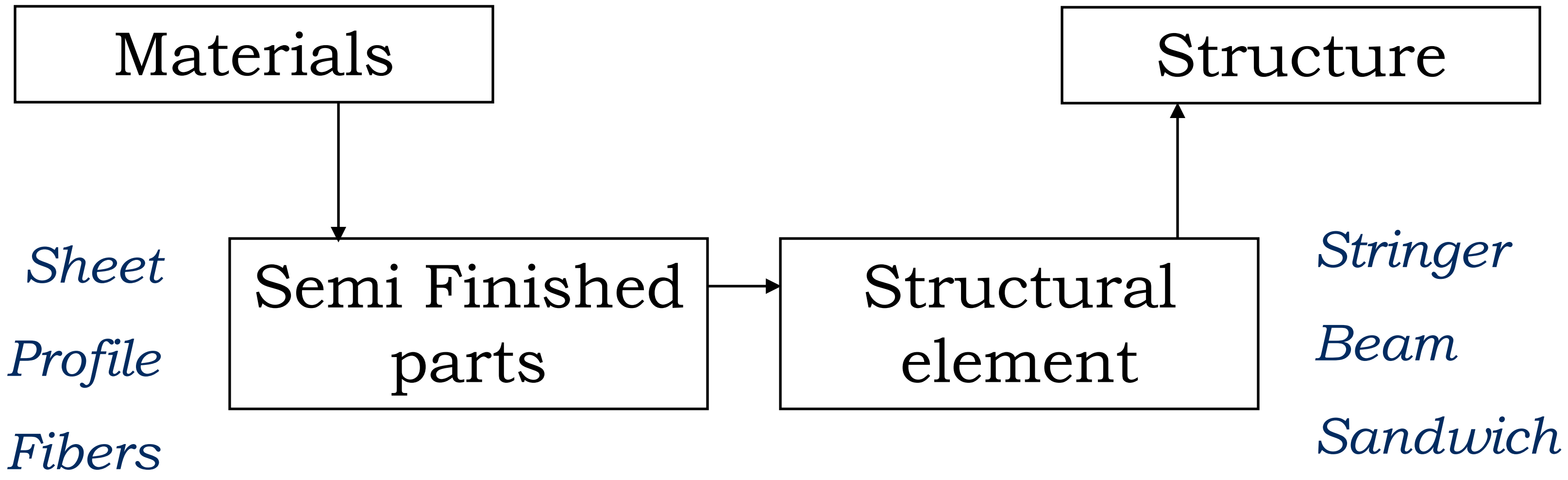
What is a MATERIAL?

Could you give a brief definition? Features?

- Approximated by: “Substances” and “matter”
- Having specific properties, but without shape

Relation "structures" and "materials"

Structures are made of these "substances", these materials. ***How?***



OVERVIEW of materials

Most important materials for Aerospace applications:

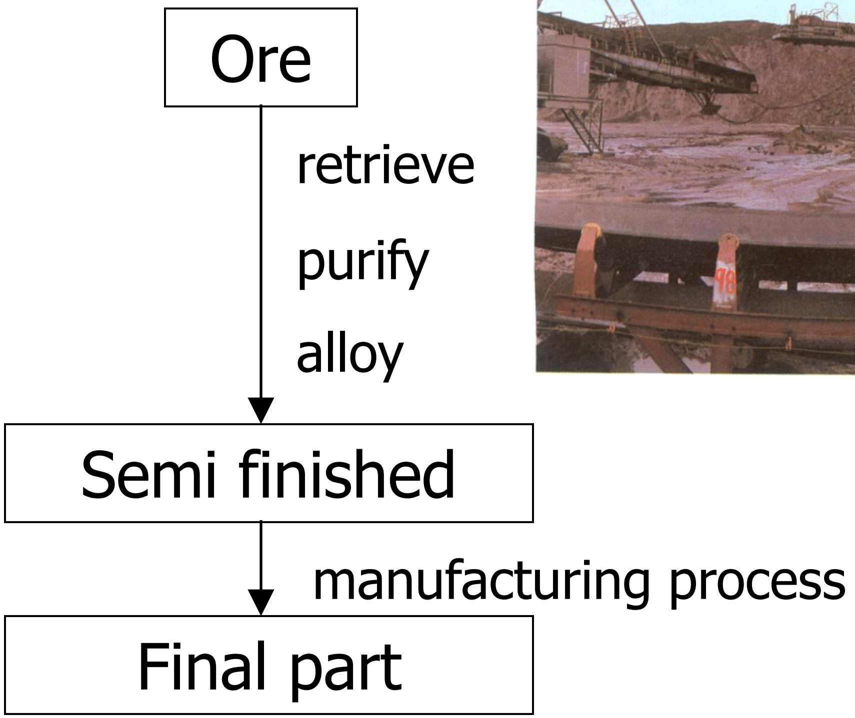
- Metal alloys
- Composites

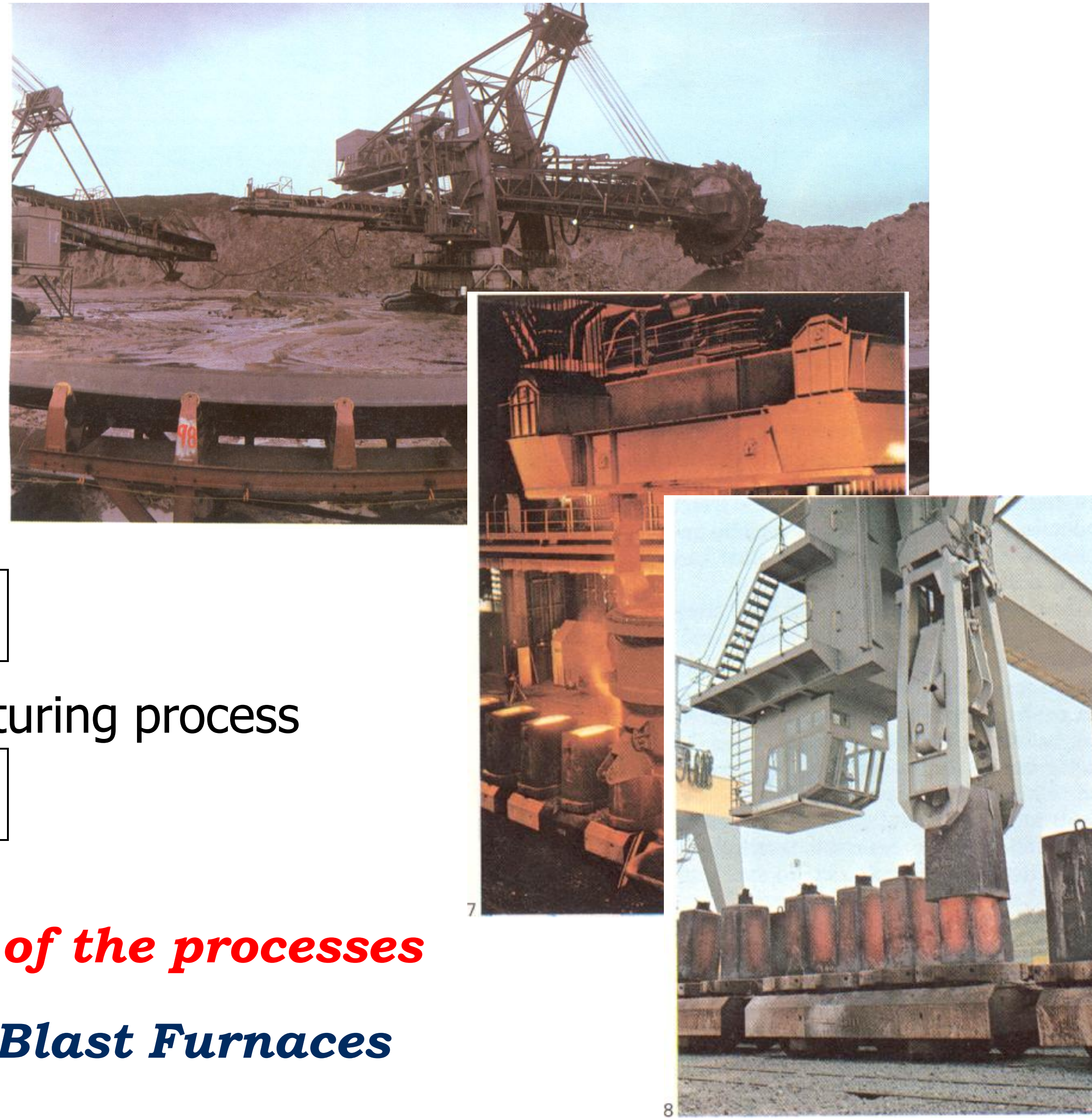
  Composed materials (fibers, resin, metal)

Structurally not relevant

- Pure polymers: properties not good enough (strength, stiffness, etc.)
- Ceramics: too brittle

Metals

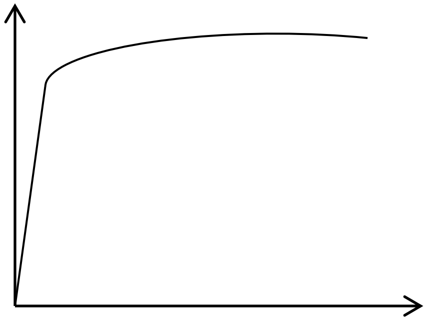




What are the names of the processes for Al and Fe?

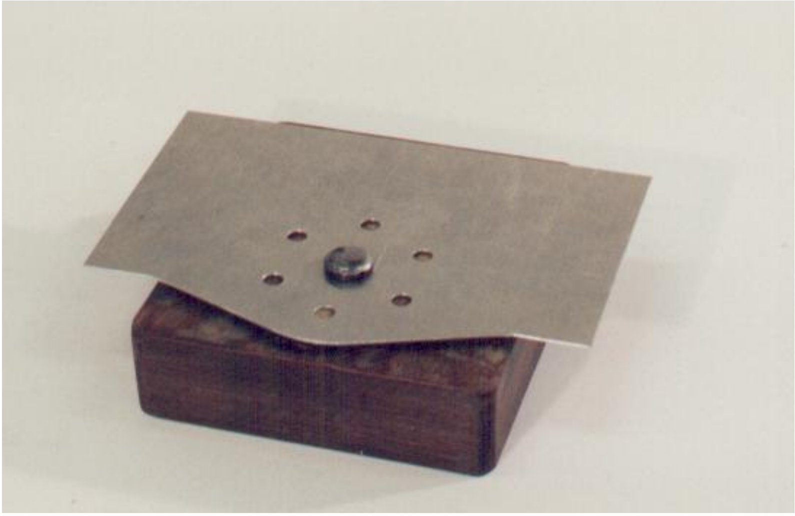
Electrolysis (Al) and Blast Furnaces (Fe)

Metals & metal alloys

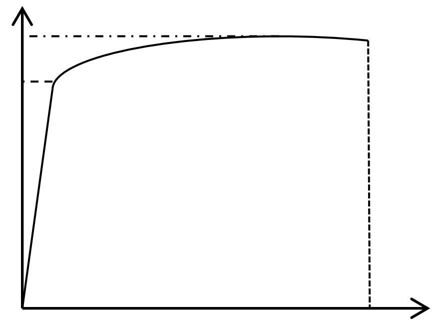


Characteristics:

- Isotropic ***(what does it mean?)***
- Metal to be strengthened (alloying, heat treatment)
- ***Plastic behavior*** & Melting (recycling, welding)
- Good processibility
- Low costs (often)



Metals and Metal alloys



Huge diversity in (**<u>tension</u>**) properties
(why stresses & strains)

Metal (alloy)	Density	spec. E-modulus	spec. yield strength	spec. Fail. strength	Maximum strain
	[kg/dm^3]				[%]
Carbon steel (Norm.)	7.8	**26.5**	**48**	**76**	28
HS Steel (OQ-Temp)	7.8	**26.5**	**208**	**226**	12
pure Aluminum (O)	2.7	**25.5**	**13**	**33**	40
Al-2024-alloy (T351)	2.8	**25.7**	**116**	**168**	20
Al-7075-alloy (T6)	2.8	**25.3**	**180**	**204**	11
pure Titanium (An.)	4.5	**22.9**	**38**	**53**	30
Ti-6Al-4V alloy (An)	4.5	**25.3**	**184**	**200**	14

Specific: in this case (property/density - e.g. E/ρ - applicable for tension only!) ***Why Specific?***

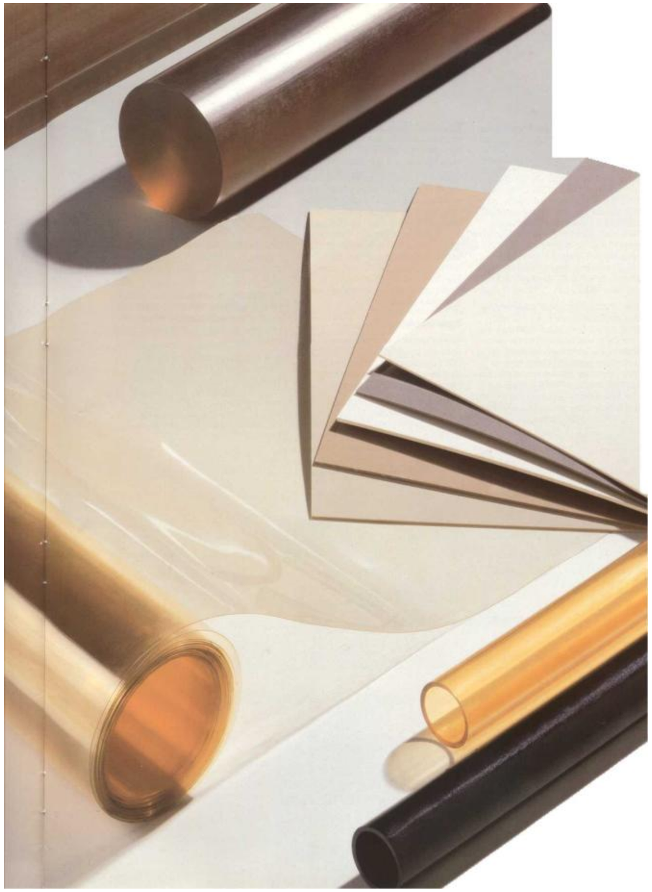
Polymers

As pure materials: Structurally not interesting

Macro-molecular substances

Two major types: *thermoplastic and thermoset polymers*

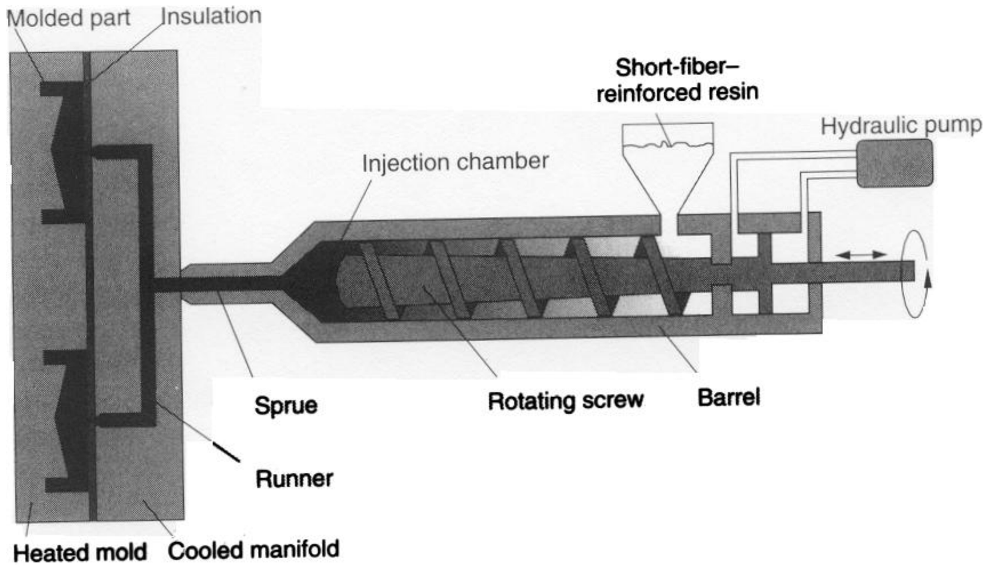
- Thermoplastics: softening reversible, one component
- Thermoset: curing irreversible, often more components



Polymers

Characteristics:

- Isotropic
- Low strength & stiffness
- Huge variety
- ***Plastic flow*** & Melting (recycling, welding)
- Good processibility
- Low costs (often)



Composites

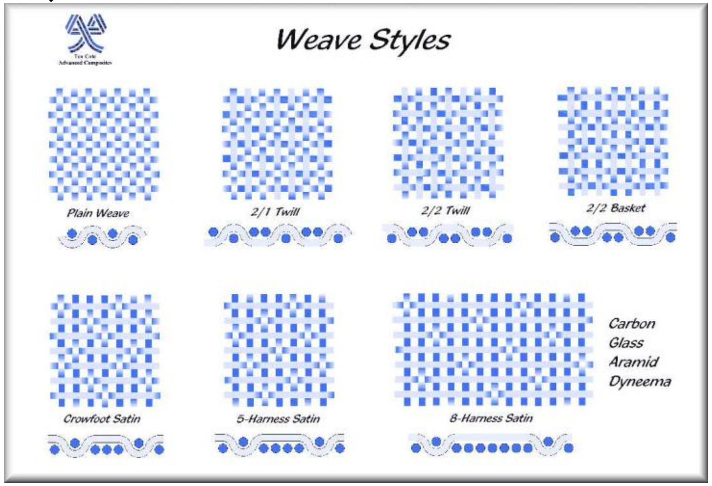
Fiber reinforced polymers

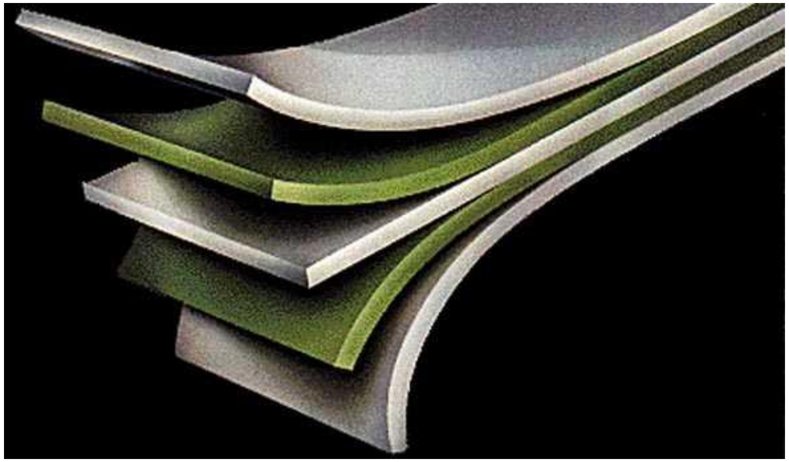
- Polymers + fibers
- Fibers: glass, carbon, aramid, Dyneema
- Short, long, “continuous” fibers

Hybrid materials:

- GLARE: composite- and metal layers

Composites (examples)

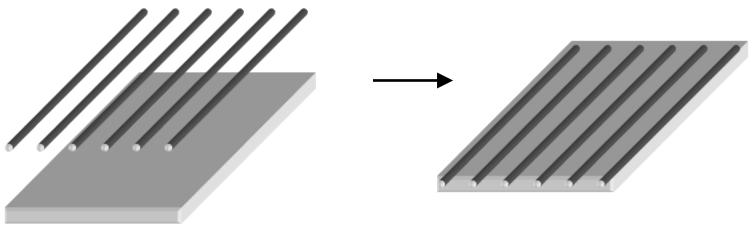




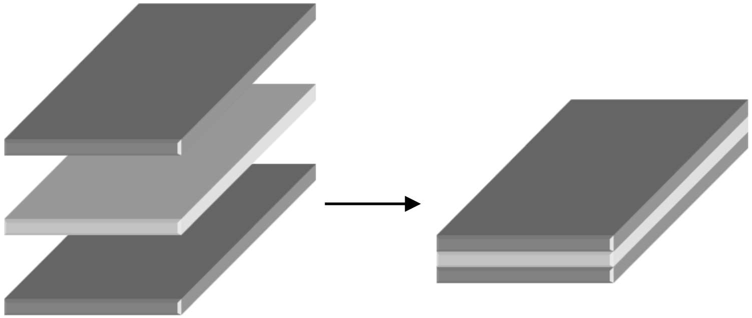
Composites

Principles of composite materials ("continuous" fibers)

fibers (strong & stiff) embedded in resin (support & protect)
fibers: strong and stiff in one direction only!
anisotropic (direction dependent) behavior



Continuous fibers in resin



Layers (laminate)

Composites (cont.)

Features:

- Anisotropic (orientation) – ***Benefit? When?***
- Layered structure (laminate)
- High strength & stiffness
- Low density but often costly
- No plasticity
- Good processibility
  - Prepregs
  - Draping in moulds - curing

Composites

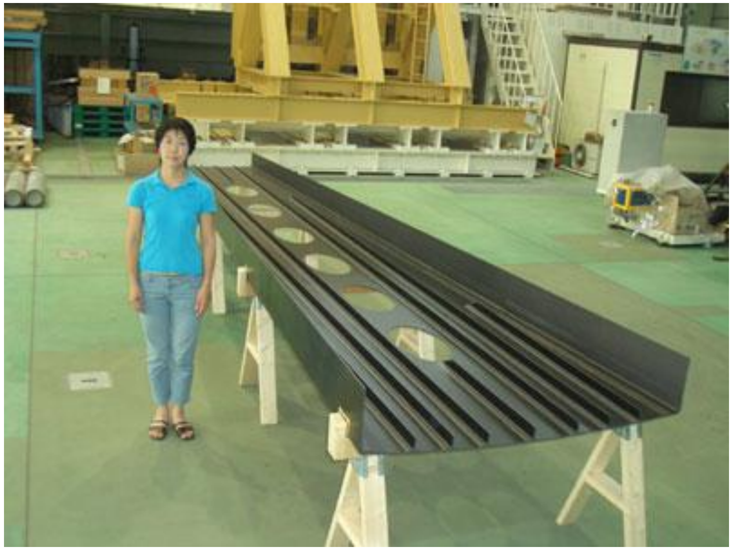
Composite structures made of

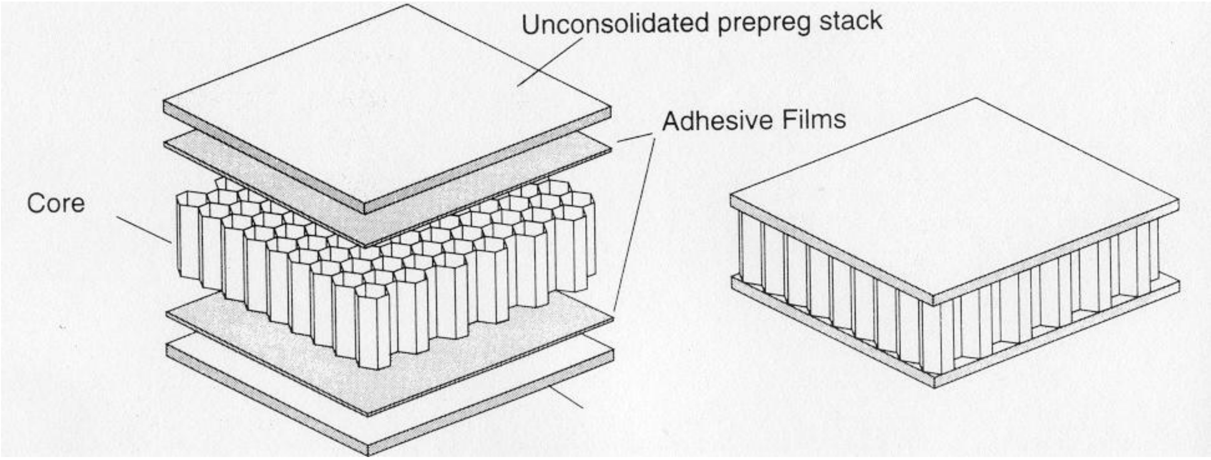
laminates – shell structure

thin-walled

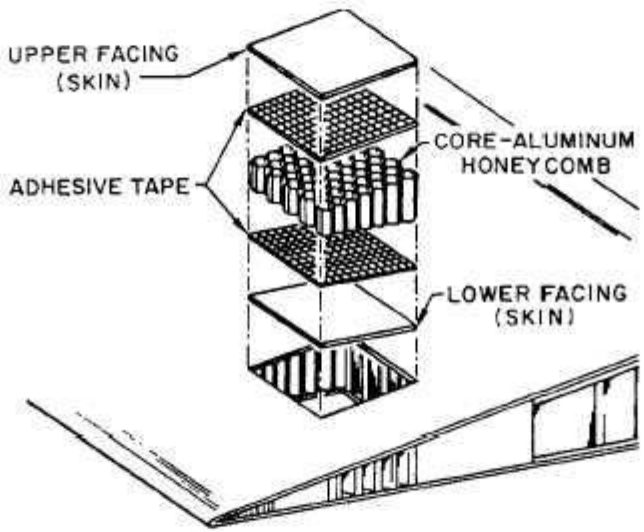
sandwich

- two laminates – facings
- lightweight core





Composites - sandwiches



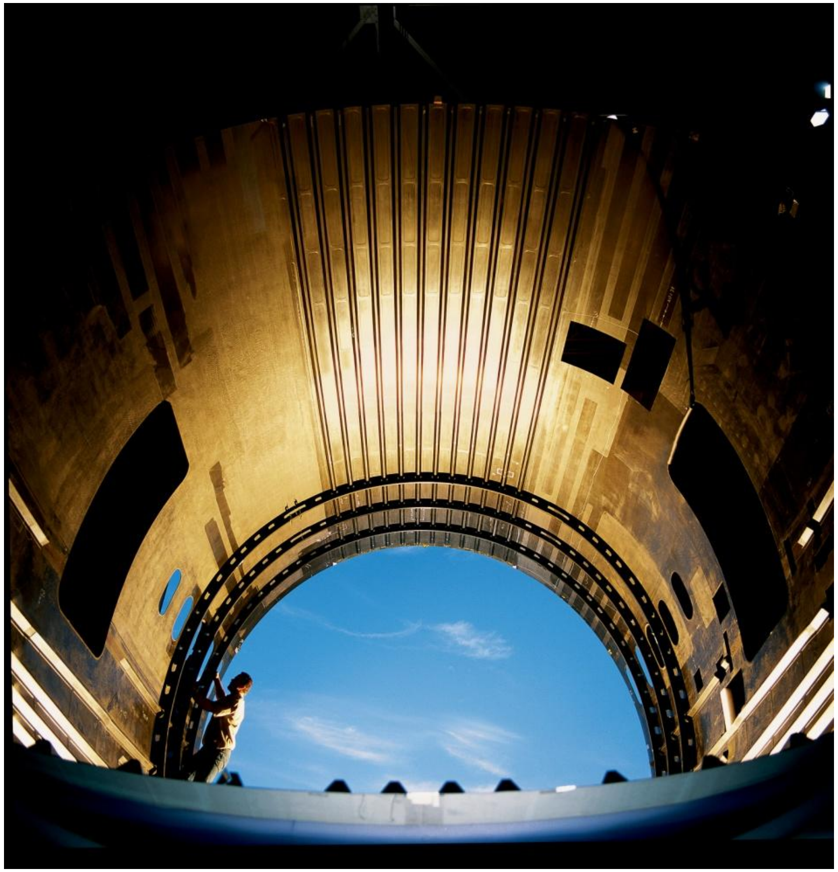
Boeing 787

New Aircraft

Material – more than 50% composites
Composites in primary structures

Boeing 787

Shell structures



Polymers & composites and Metal alloys

Also a huge diversity in (**<u>tension</u>**) properties

Material Density E- yield Failure Maximum

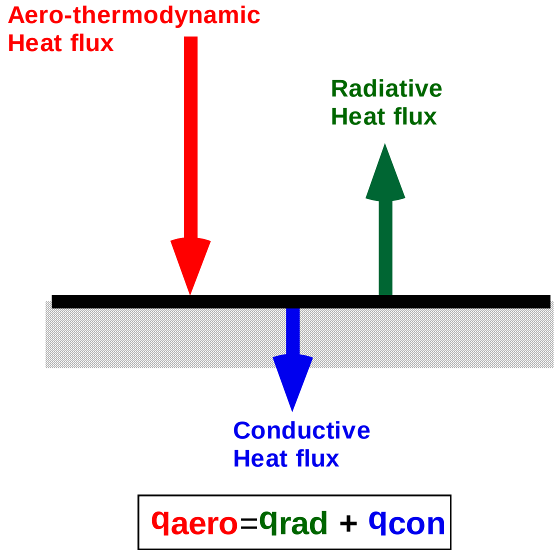
Material	Density	E-modulus	yield strength	Failure strength	Maximum strain
	[kg/dm^3]	[kN/mm^2]	[N/mm^2]	[N/mm^2]	[%]
Epoxy (TS)	1.25	**1.9**	**---**	**48**	4.5
Polyetheretherketone (PEEK) (TP)	1.31	**0.8**	**69**	**76**	75
Polypropene (PP)	0.91	**1.5**	**38**	**42**	300
E-glass epoxy UD-60%	2.1	**21**	**---**	**486**	2.3
HM carbon epoxy UD 60%	1.7	**129**	**---**	**447**	0.3
Al-2024-alloy (T351)	2.8	**25.7**	**116**	**168**	20
Ti-6Al-4V alloy (An)	4.5	**25.3**	**184**	**200**	14

Specific: in this case (property/density - e.g. E/ρ - applicable for tension only!)

Space Materials

Have to fulfill ***special requirements***

- High temperature loading
- Specific atmospheres (Oxygen, radiation, chemical reactions – i.c.w. high T)



Will be continued

Link between Materials & Structures

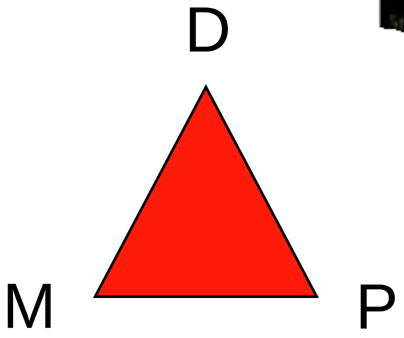
Load carrying capacity of a structure depends on:

- Design, shape
- **Materials**
- Production techniques

Examples?

Note: Not every random combination (D, M, P) is possible! - There is interaction!!

Examples?



Materials – DESIGN & MANUFACTURE

Manufacturing techniques

Casting
Machining
Forming
Forging
Joining

Materials

Metal alloys
Polymers
Fiber-reinforced polymers
Ceramics
Hybrid materials

Performance (concept)

Design/shape

<u>Structural level</u>	<u>part level</u>
Tubes and truss structures	flat
(stiffened) skin structure	single curved
Sandwich structure	double curved

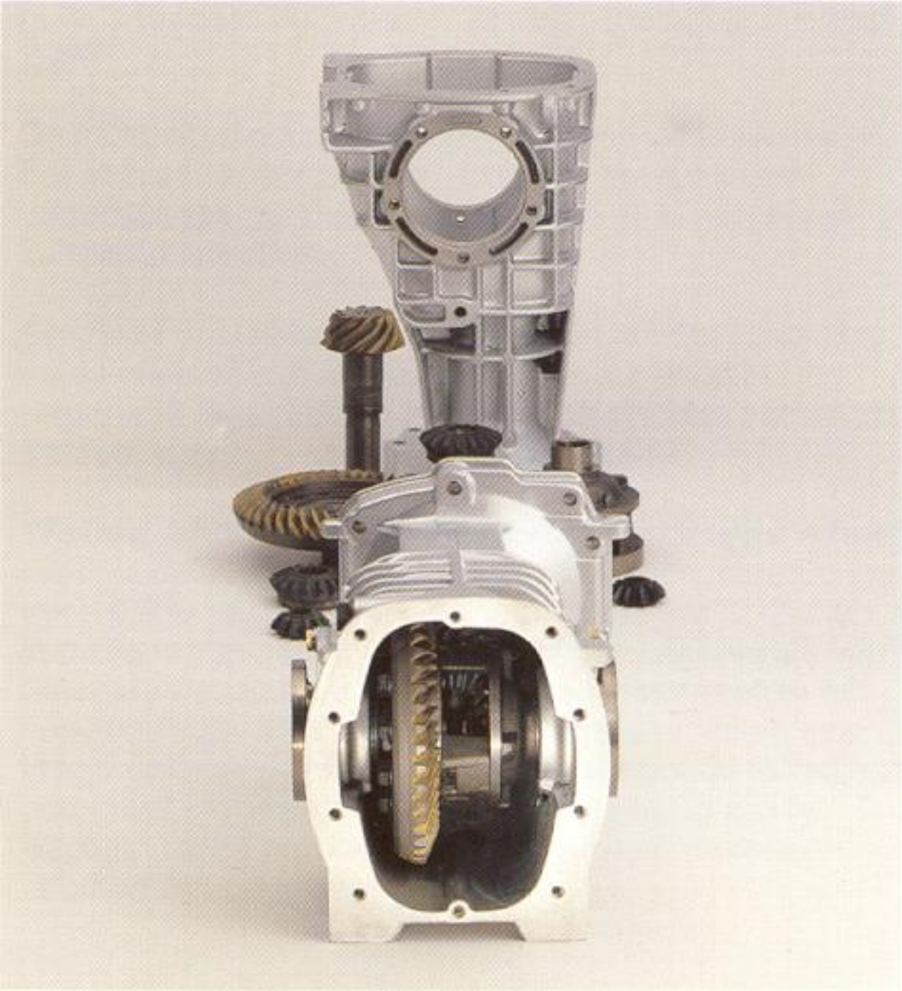
Metals - Manufacturing

- Liquid: Casting
- Solid High temperature: Forging
- Solid Room temperature: Forming (sheet); machining.
- Assembly - joining

Metals - casting

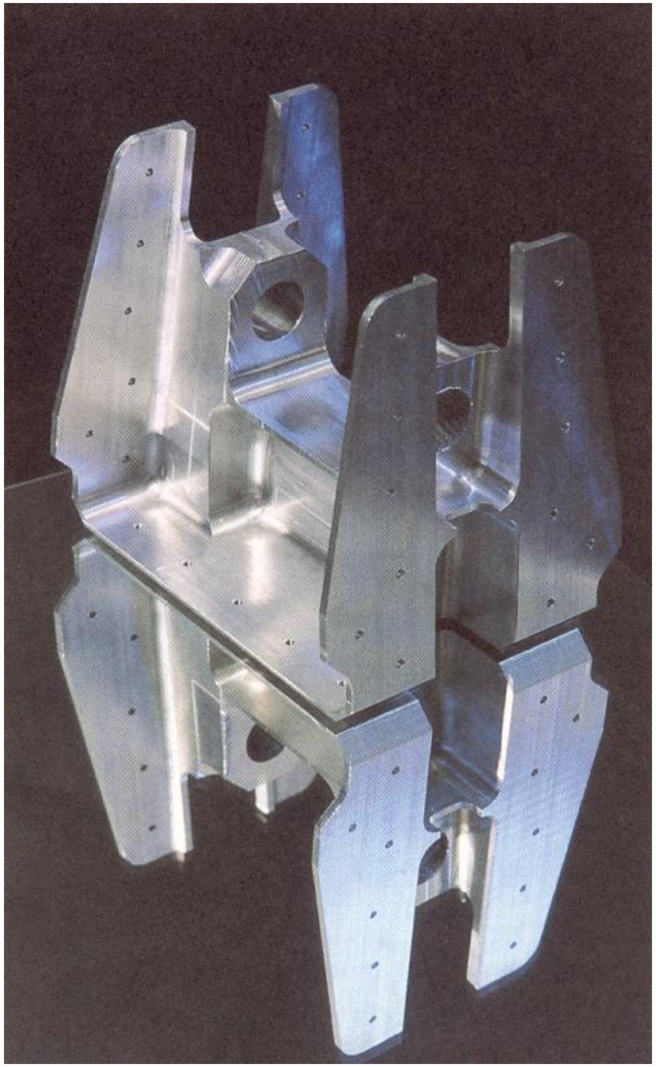
Solid ⇔ Liquid

Injection molding



Metals - machining

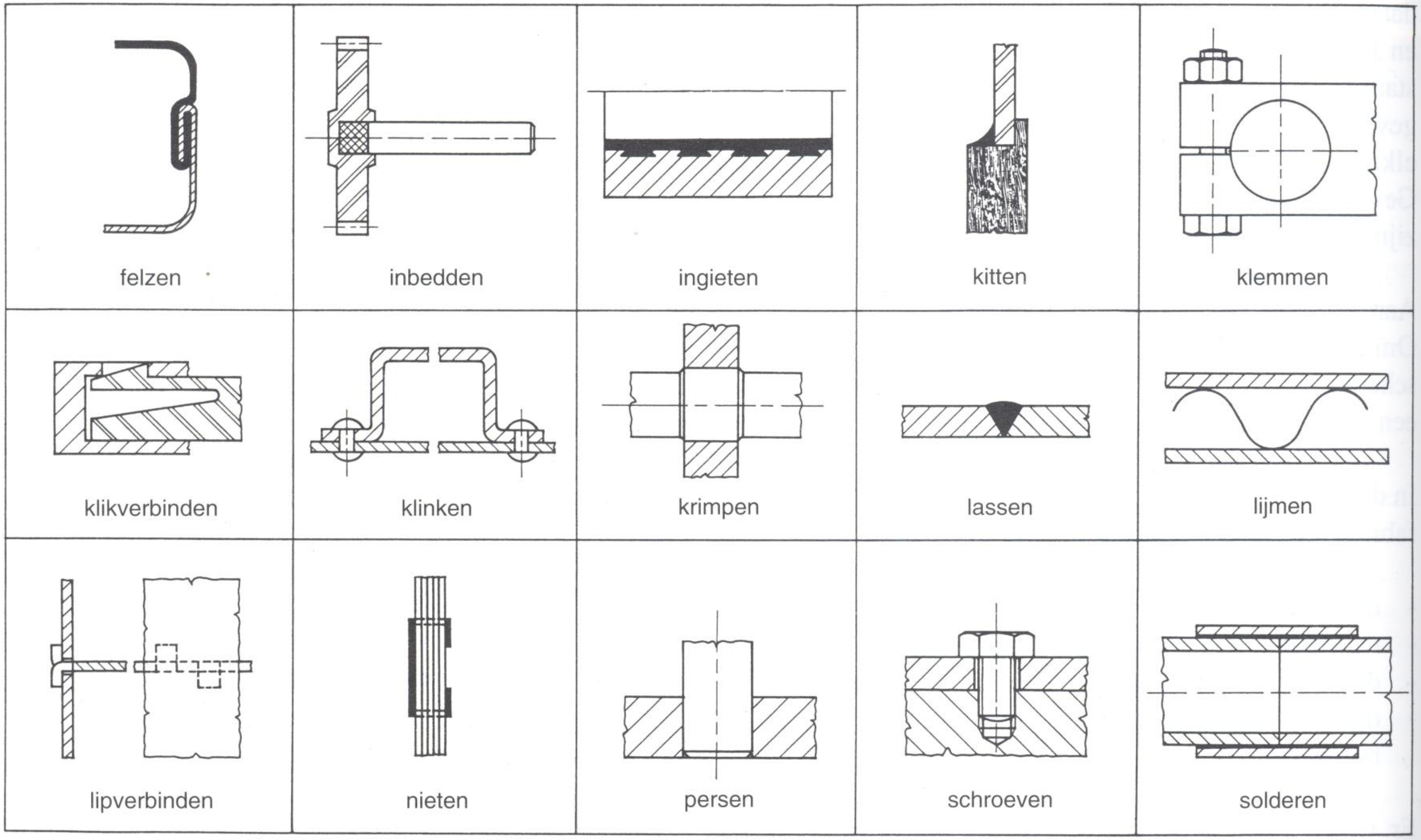
Solid - cutting



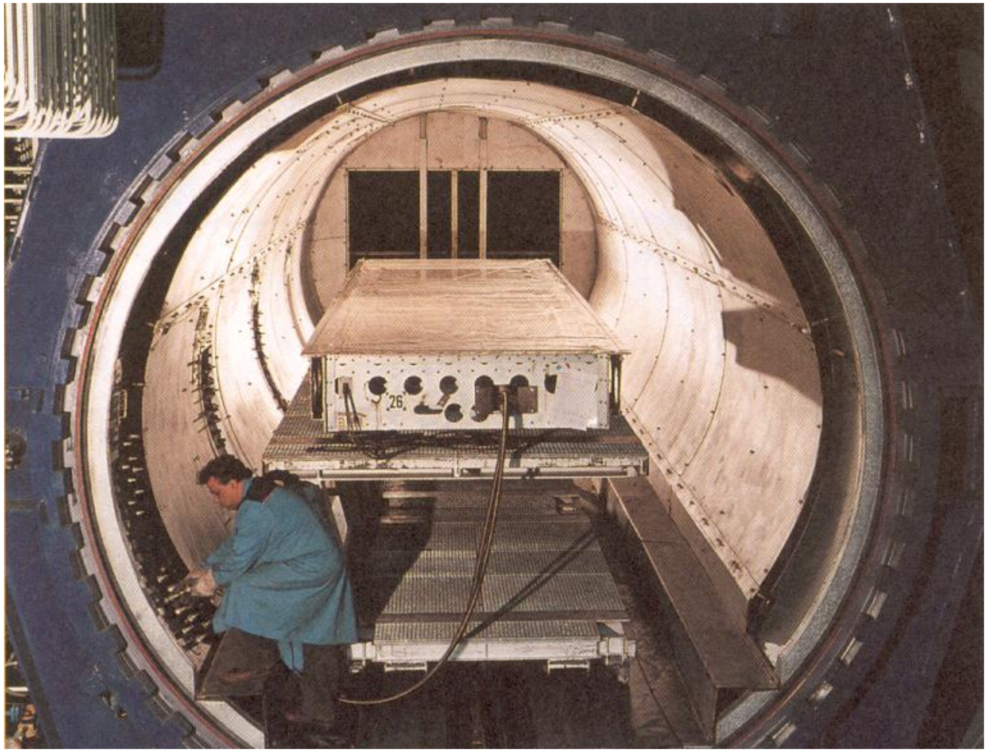
Metals – forming

Sheet

Metals - joining



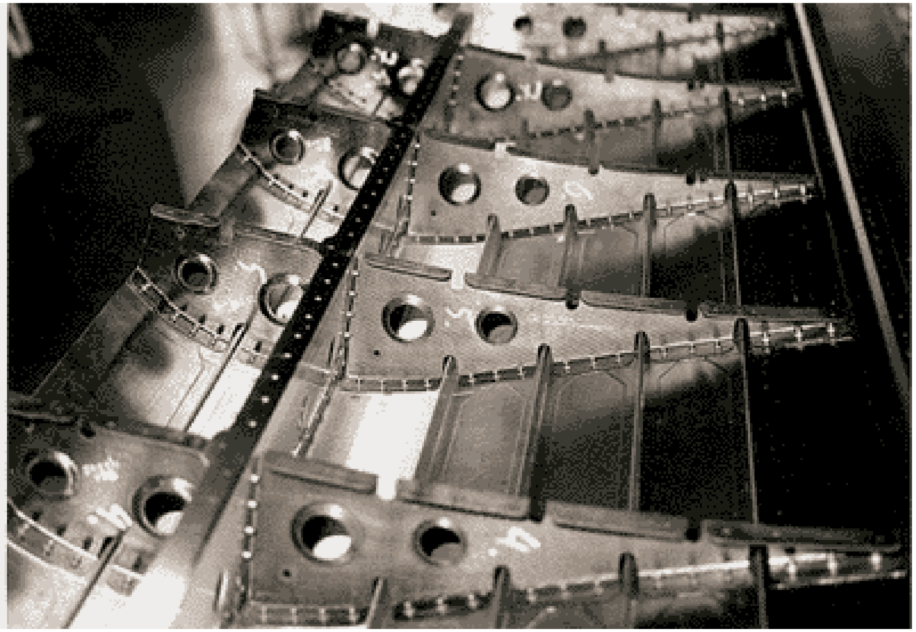
Composites – Lay-up and curing



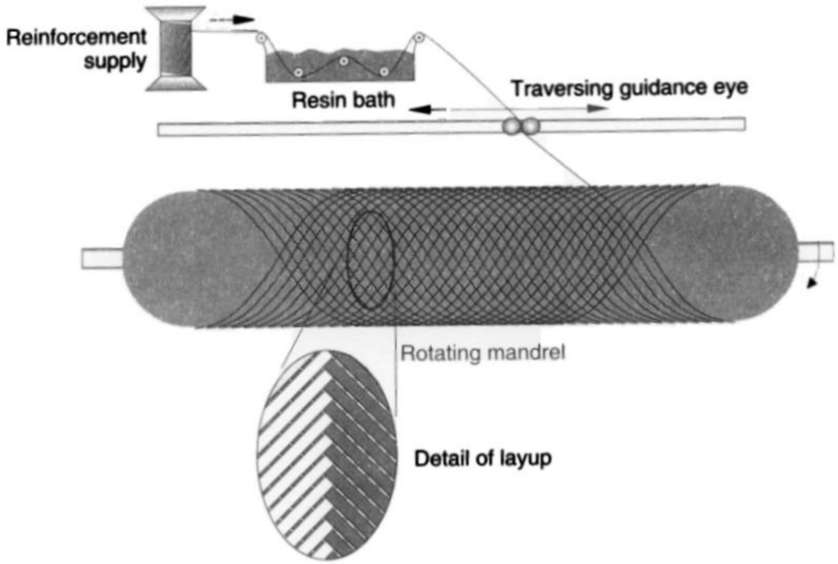
Composites – forming

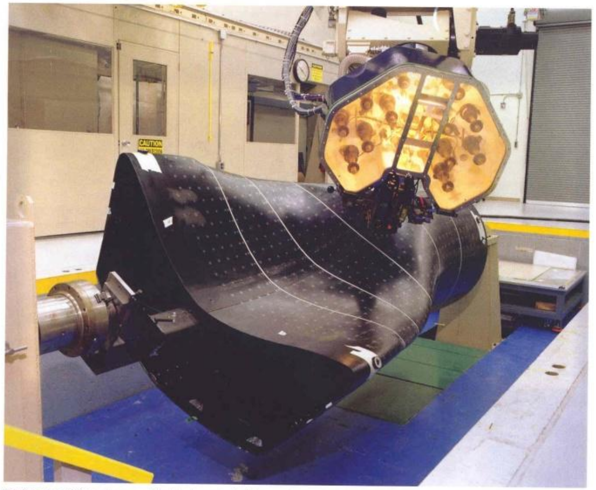
press forming

“Black” Metal??



Composites – filament winding/tape laying




Boeing used fiber placement technology to build complex parts for the X-32s, such as this one-piece inlet duct assembly. Fiber placement is an automated process in which a narrow band of continuous carbon-fiber "tow" is laid up around a male form or mandrel in a precise, computer-defined pattern. It allows complex parts with compound curvature to be produced in one piece. Boeing

Summary: composites vs. metal

Different Properties

Metals

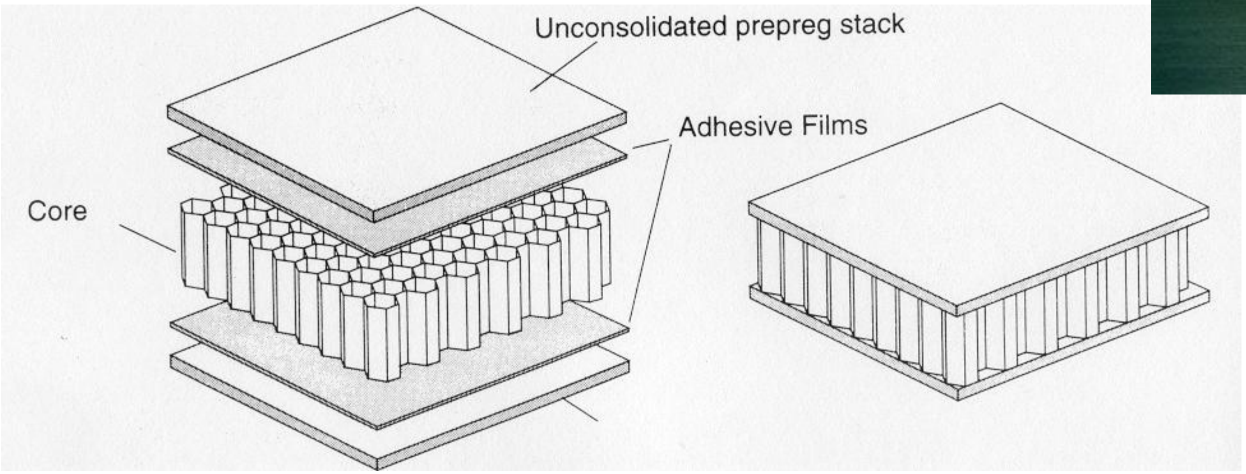
+ Plastic behavior – damage tolerant - joining
+ Cheap materials – easy processing
- Labor intensive

Composites

+ High spec. strength & stiffness ***(specific?)*** – low weight
+ High integration possible
- Expensive materials → compensated by production

Summary: composites vs. metal

- ***Different manufacturing*** techniques
  - Laminating, filament winding (composites)
  - Plastic deformation, forging, casting (metals)
- ***Different designs***
  - Sandwich (composites)
  - Stiffened shell structure (metal)



14.

Exploring the limits

Contents

X-planes

Flight regimes: From subsonic to hypersonic

High Temperature Materials

X-planes : Exploring the limits

X-plane – “X” stands for eXperimental

1^{st} was Bell X1
Objective:
  fly supersonic
  sound “barrier”

Charles “Chuck” Yeager
October 14, 1947
1078 km/h (M = 1,015)

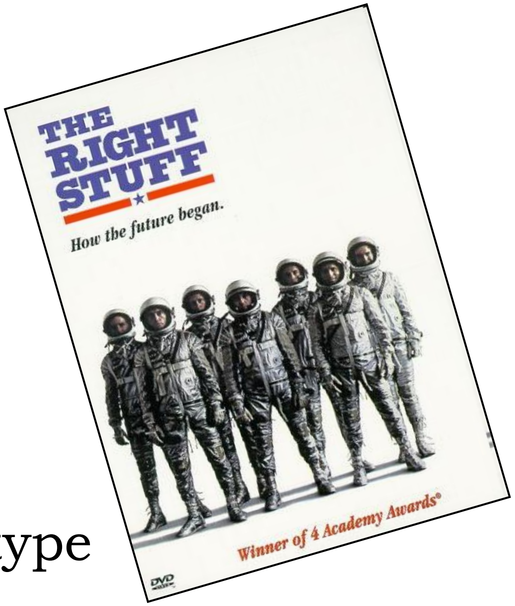
X-planes

A large number of experimental planes followed
(see *en.wikipedia.org/wiki/**X-plane*** for complete overview)

Latest is the X-53

Main purpose for X-planes:
Test specific features, phenomena, etc.
e.g. scramjet, reentry from space, supersonic and hypersonic speeds, tailless aircraft

X-planes



Risky business: many test pilots died

In general only a few aircraft were build of a type
Number of flights was also very limited

E.g. Bell X-1A and 1B;
flew in 1953/54
Speed exceeding Mach 2;
15 and 27 flight resp.

X-planes

Few typical examples: X-15 (1959)

Objective: hypersonic flight/high altitude
Achieved: Mach 6,72 & altitude of 107,9 km

Aerodynamic heating:
Temperatures > 650^0 C

Titanium, Stainless steel
Ablative material

X-planes

X-29 (1984)

Testbed for
Effectiveness of forward
swept wings
+ canards

Structural composites

Advanced avionics

X-planes

X-31 (1990)

Trust vectoring
& maneuverability

Maintain controlled
at high angles of attack

Break the “stall barrier”

Computer controlled canards

X-planes

X-32 and X-35 (JSF) (2000)
STOVL in one airframe: Short (Vertical) Take Off & Landing
Competition between Boeing (X-32) & Lockheed Martin (X-35)
 X-35 won and becomes JSF (Air Force, Navy & Marine Corps)

X-planes

X-45 (2002)
Unmanned Combat Air Vehicle (UCAV)

UAV with attack missions

Aerodynamics: from subsonic to hypersonic

Regimes of aerodynamic flow

subsonic	$M < 1$		subsonic	$M < 0.8$
sonic	$M = 1$	or	transsonic	$0.8 < M < 1.2$
supersonic	$M > 1$		supersonic	$1.2 < M < 5$
			hypersonic	$M > 5$

M is the Mach number

M is defined as: $M = V/a$

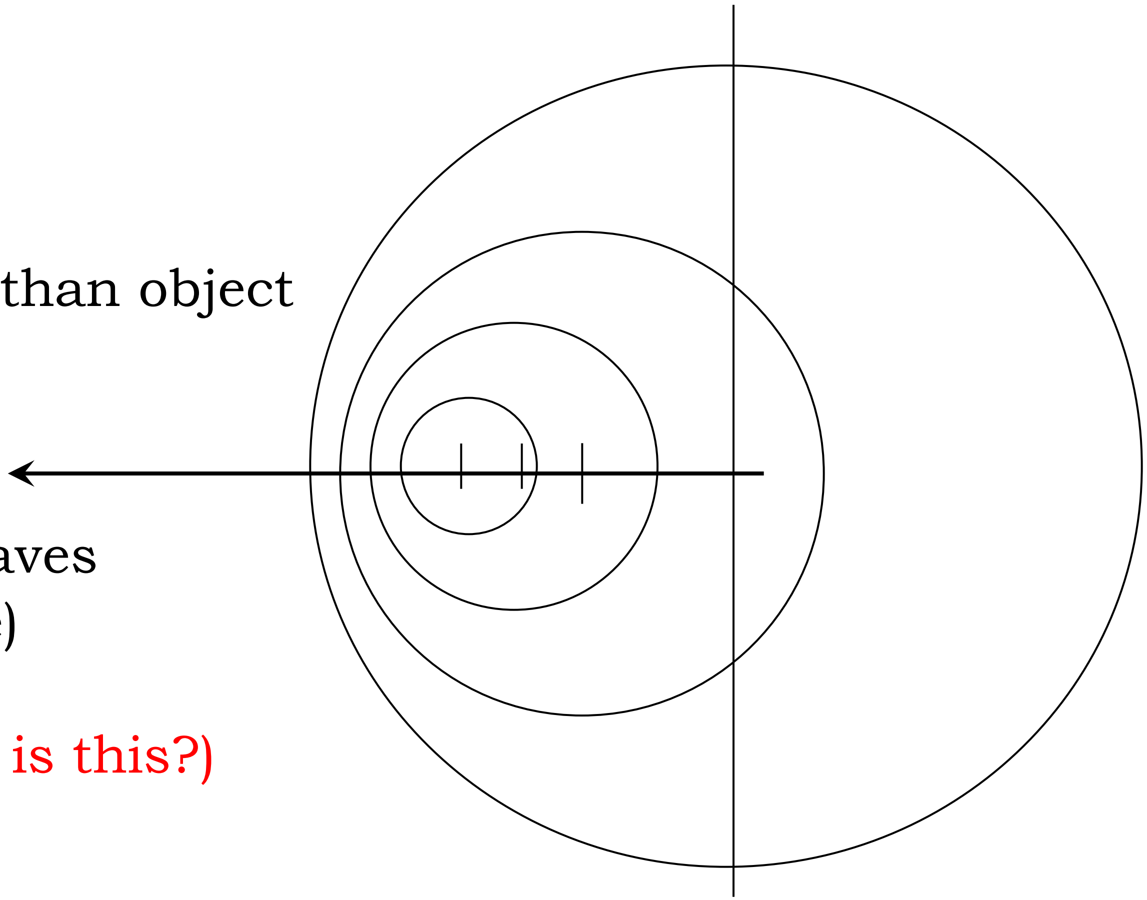
a is the speed of sound **(how large?)**

Aerodynamics

Subsonic

Sound moves faster than object

$a > V$



No coalescence of waves
(sound or pressure)

Doppler-effect (what is this?)

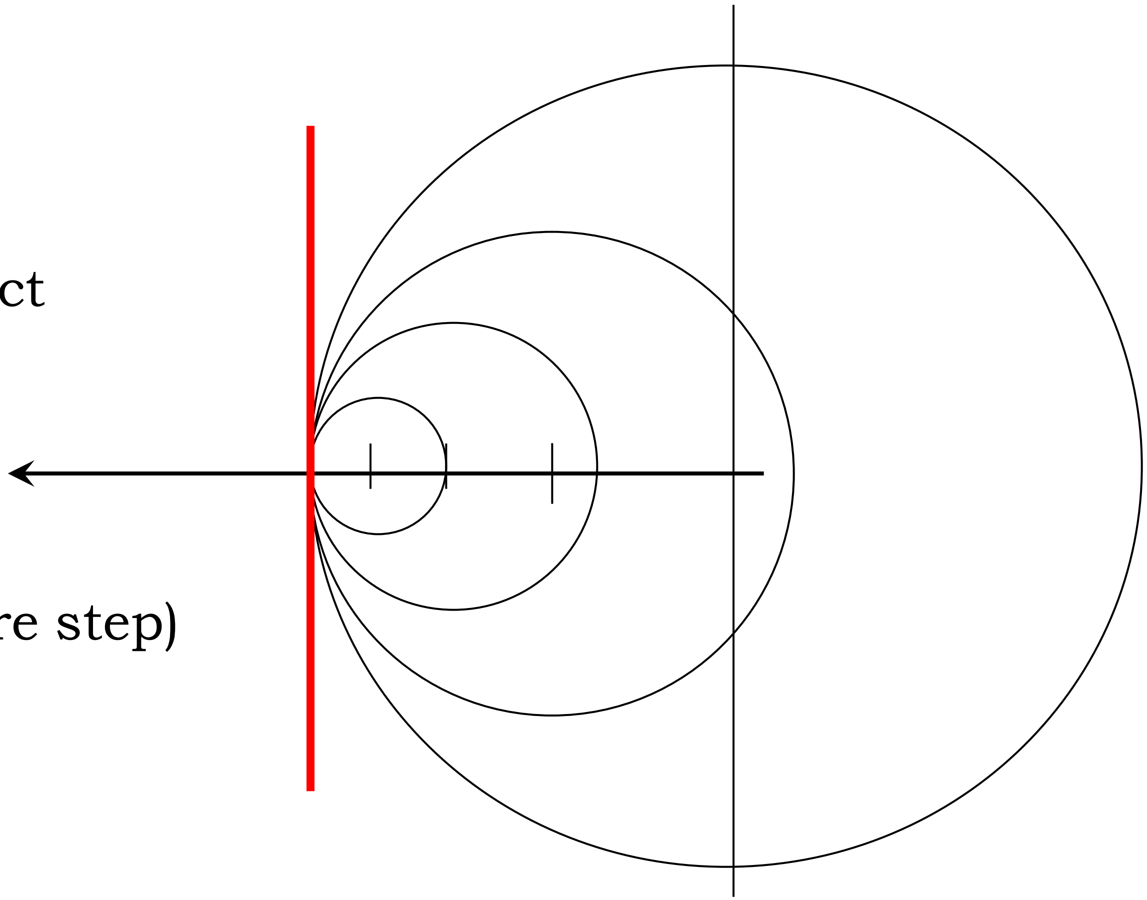
Aerodynamics

Sonic

Sound as fast as object

$a = V$

Coalescence of waves
shock wave (pressure step)
"barrier"

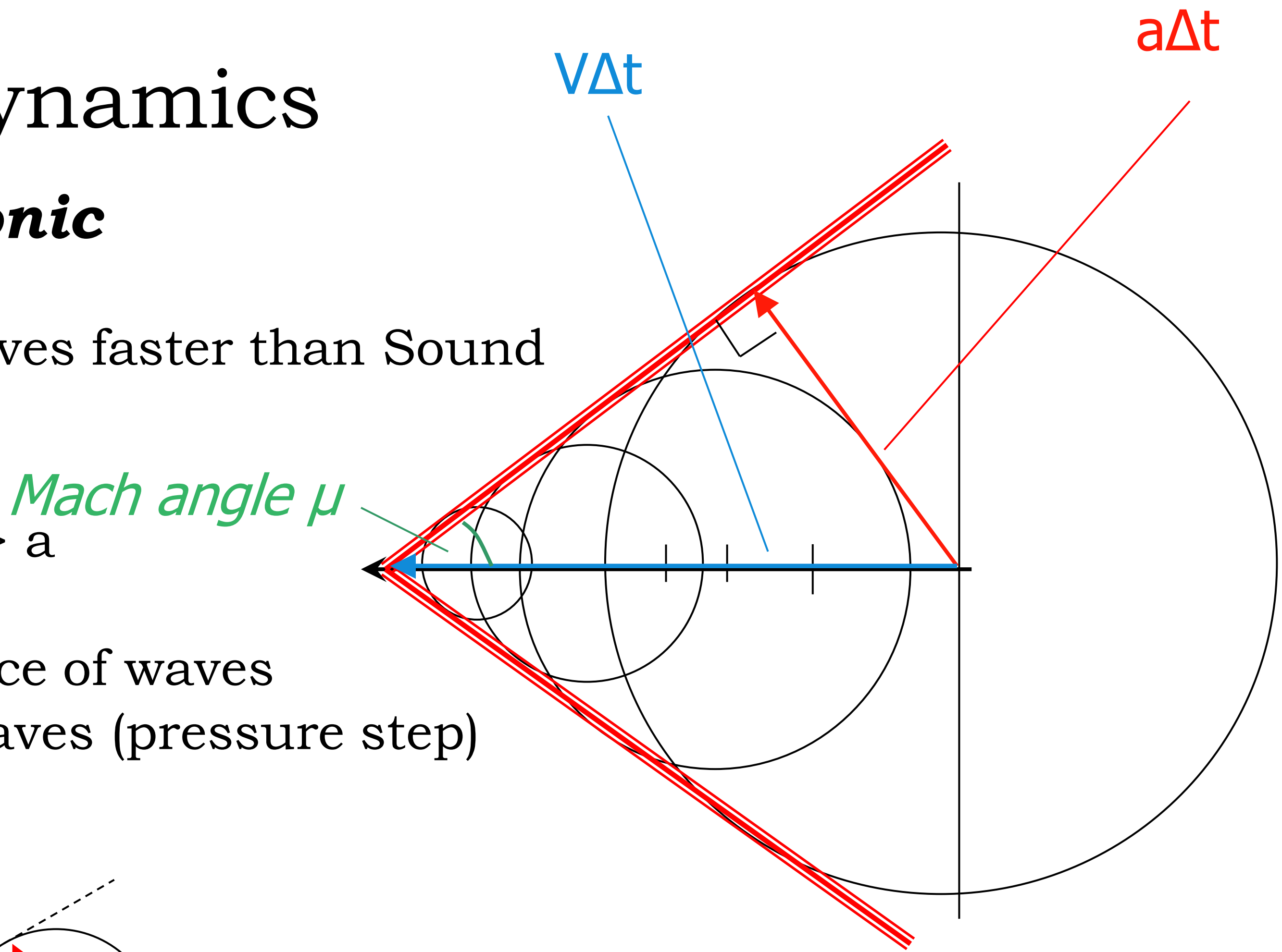


Aerodynamics

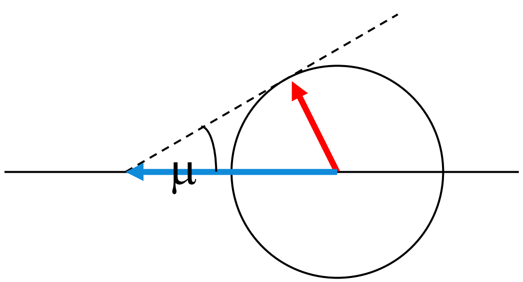
Supersonic

Object moves faster than Sound

V > a

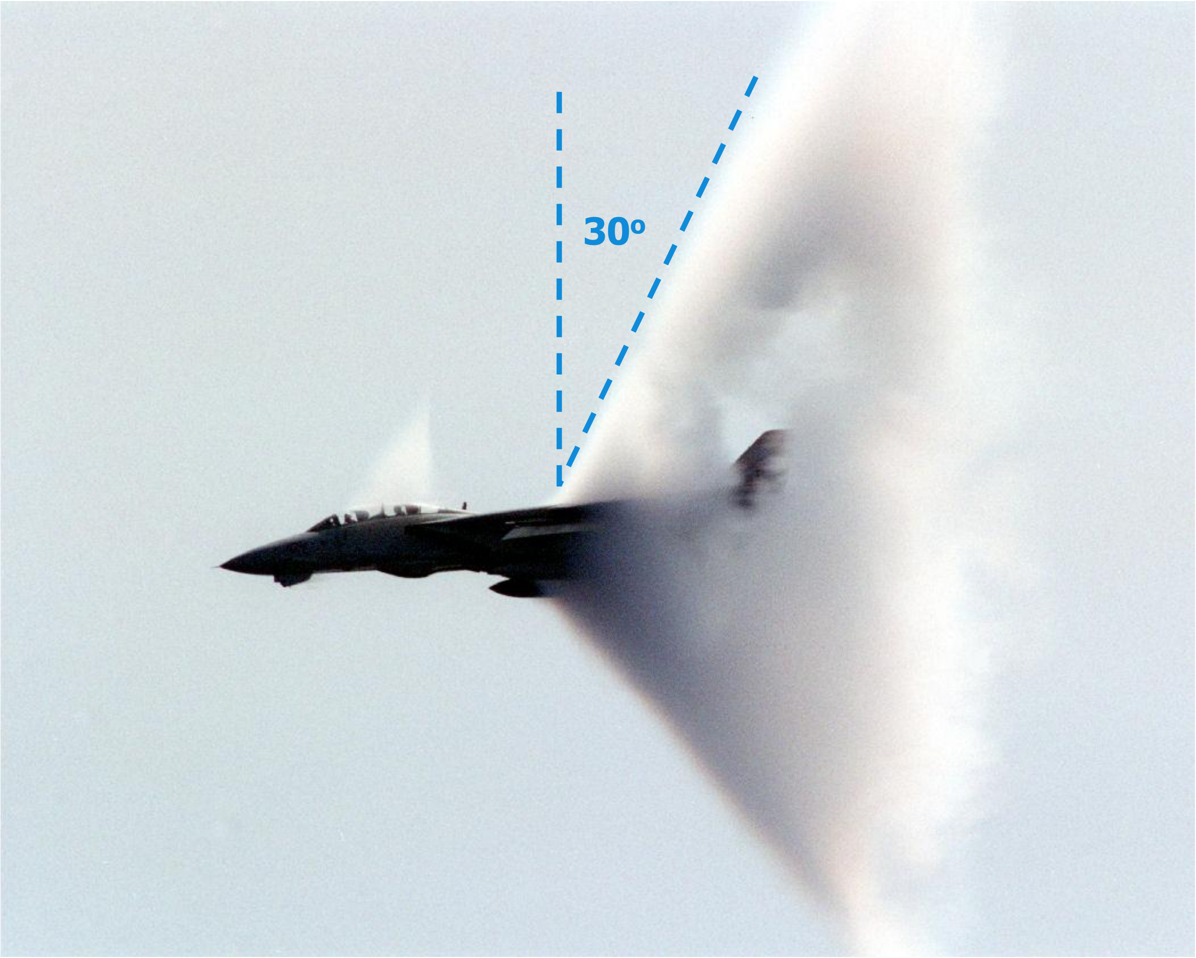


Coalescence of waves
  shock waves (pressure step)



μ (Mach angle) $\rightarrow$ $\sin\mu = a/V = 1/M$

What is the speed of this F-14?



$\mu = 90^o - 30^o = 60^o$

$\sin \mu = \frac{1}{2}\sqrt{3} = 0.87$

$M = 1/\sin \mu = 1.15$

a = 340 m/s (S.L.)

V = 391 m/s
= 1409 km/hr
= 761 kts

Note:

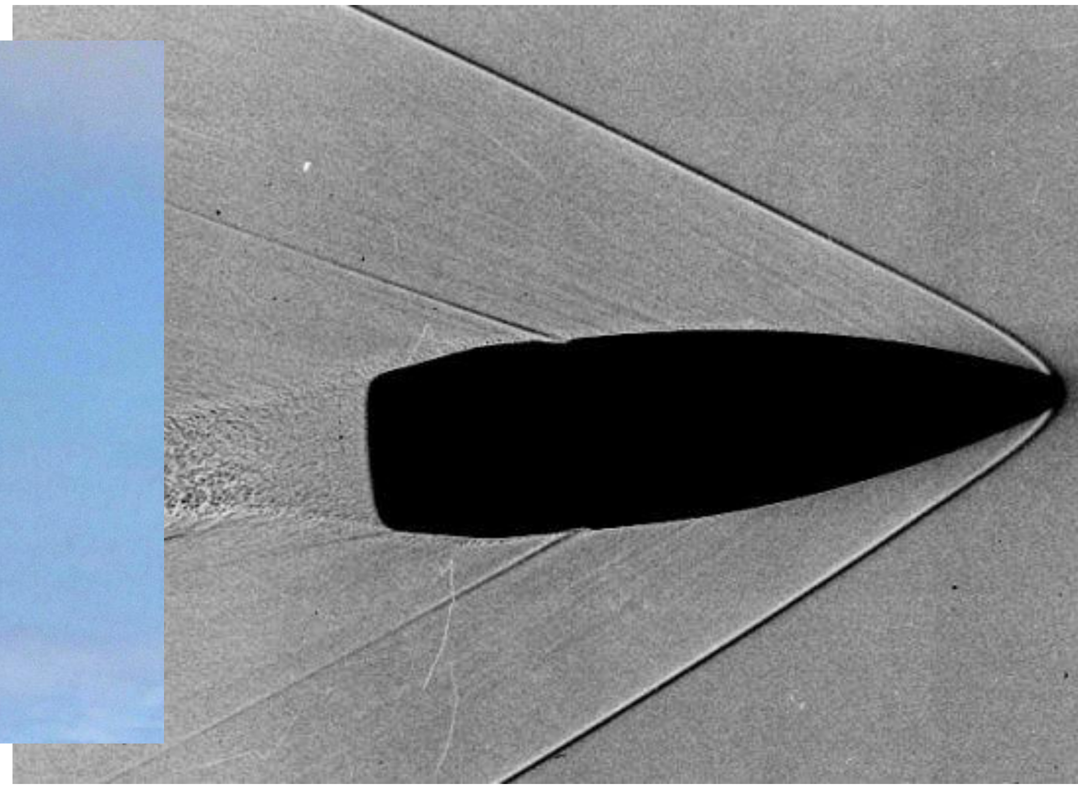
$a = \sqrt{\gamma R T}$

$= \sqrt{1.4 \cdot 287 \cdot T}$

Aerodynamics

Visualization of shock waves

http://www.youtube.com/watch?v=5UrW3swSMs4

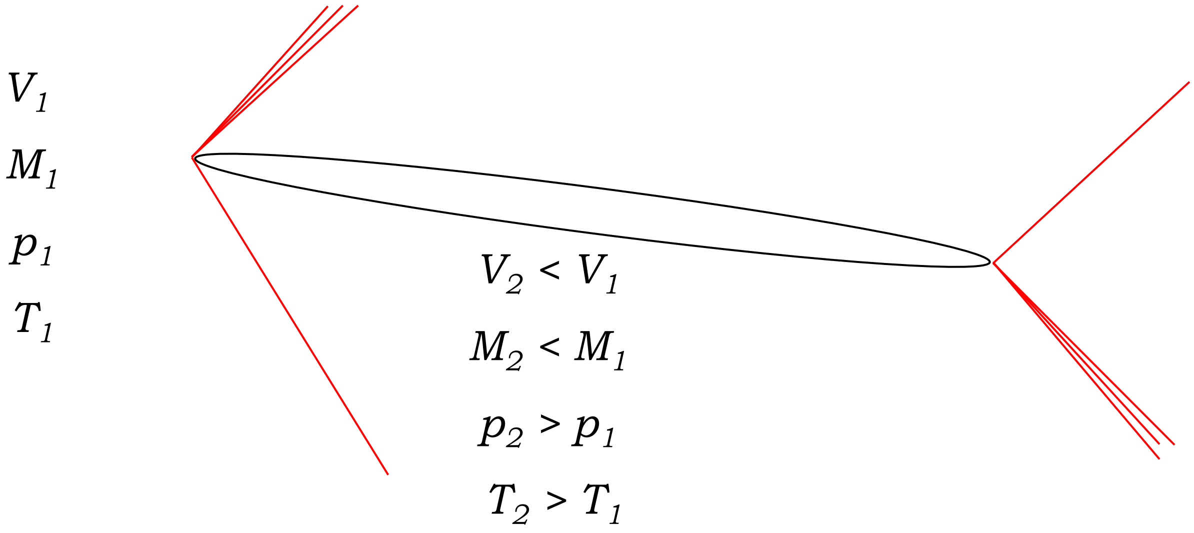


Aerodynamics

Incompressible: until M = 0.3 (arbitrary – 5% decline)

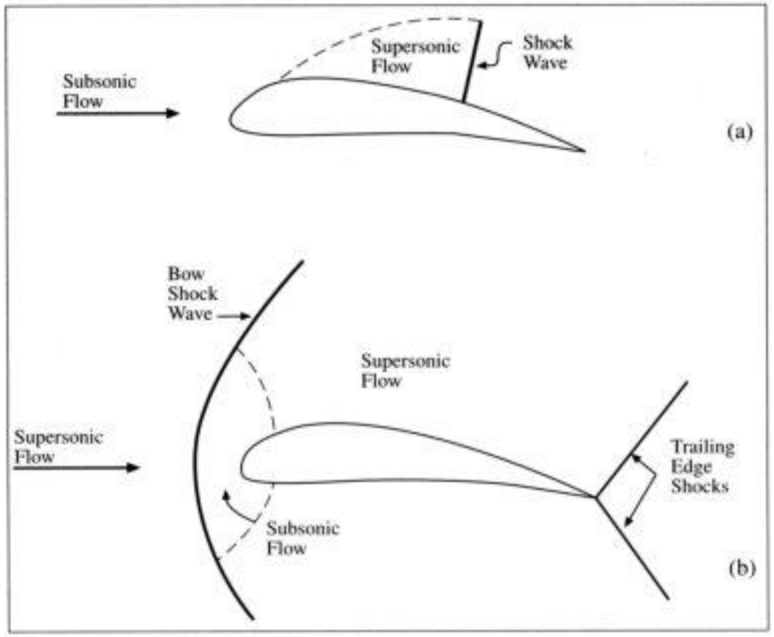
Compressible: for M > 0.3

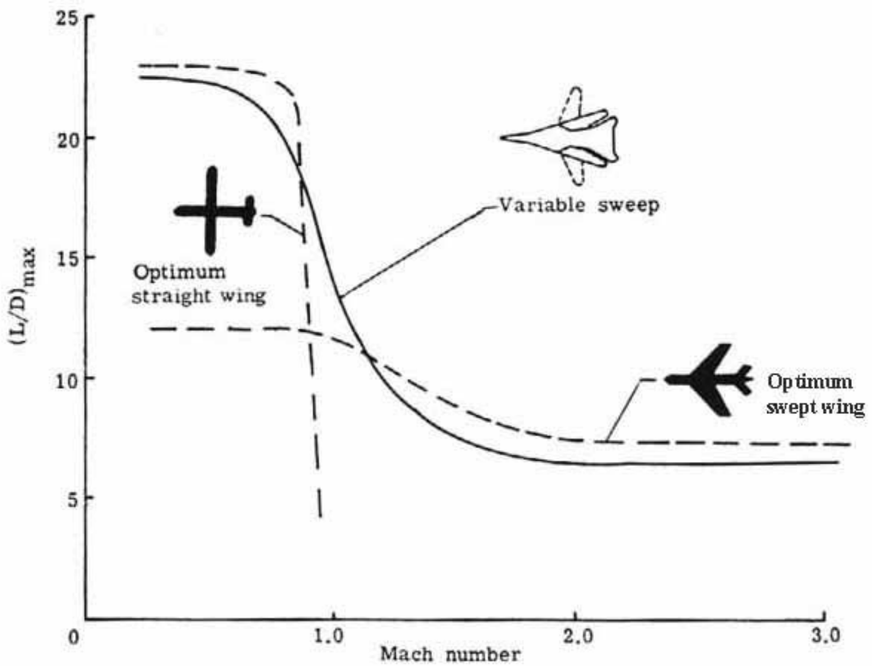
supersonic: complex



Aerodynamics

Shock waves induce - reduction of lift
- increase in drag (wave drag)



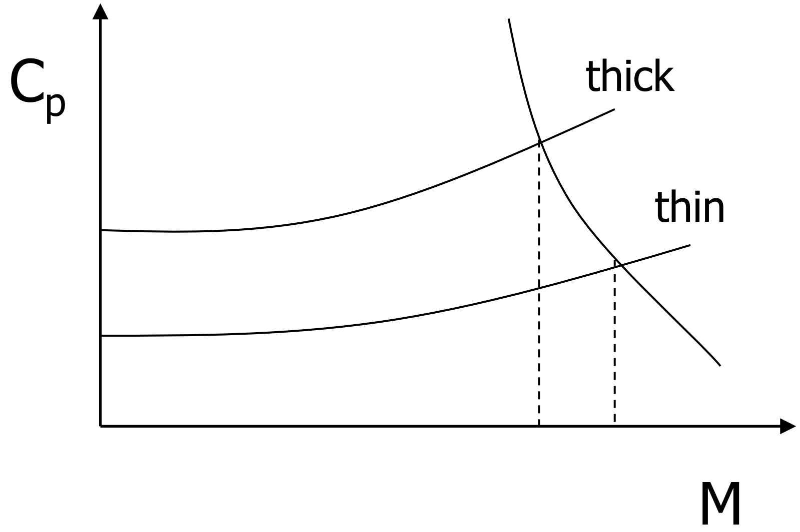


Aerodynamics

Reducing drag in supersonic flight

Option 1: Thin wing profiles:
extending subsonic flow over profile
increasing critical Mach number (M_{cr})

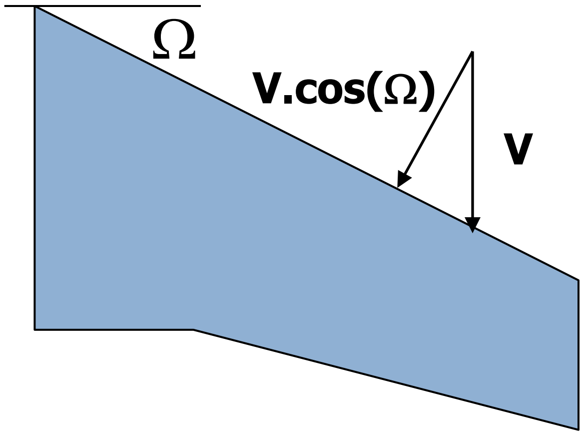
C_p (-) pressure coefficient at minimum pressure point of the airfoil

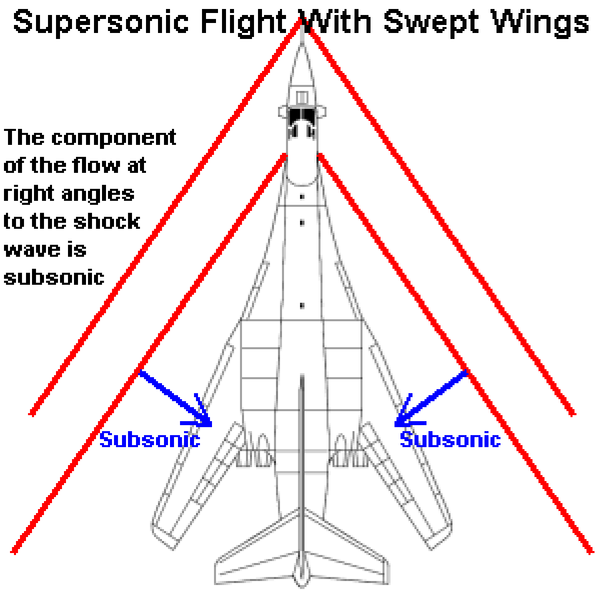


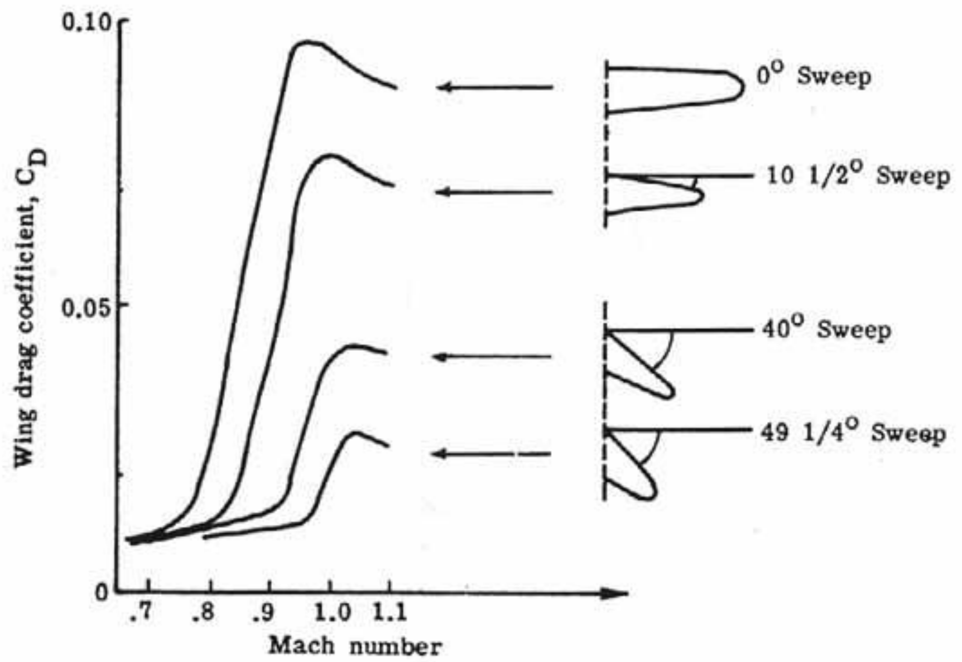
Aerodynamics

Reducing drag in supersonic flight

Option 2: Swept wings

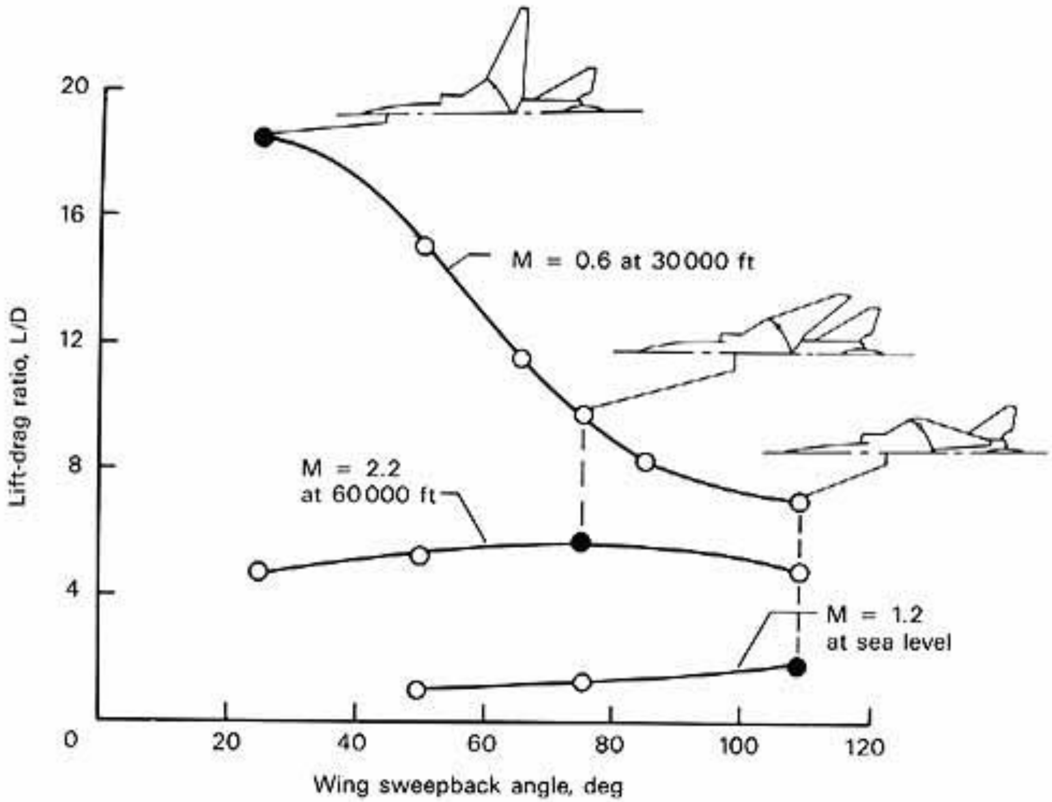






Aerodynamics

Effect of sweep angle Ω on L/D ratio for swept-wing AC



Aerodynamics

Transonic flight — High drag – "sound barrier"

Supersonic flight — Lower L/D ratio, but compensated by dynamic pressure q ($q = \frac{1}{2}\rho V^2$)

Note: Starfighter F-104 (M = 2+); S = 19.5 m^2; b = 6.9 m; Aspect Ratio = 2.45; t/c = 0.05

What about take-off and landing speeds?

Aerodynamics

Hypersonic speeds – M > 5

Example X-15: “thermal barrier”

Very high skin (and stagnation) temperatures: T > 650^0 C

Special materials required:
Stainless steel, Titanium alloys; Special steel alloys like Inconel

Special Materials – high speed

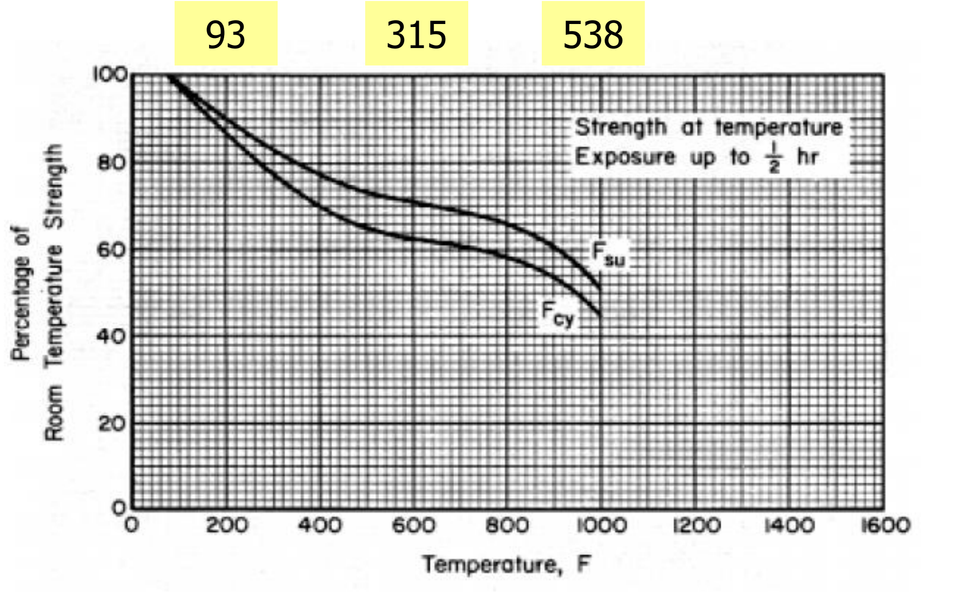
		Alu 2024 T351	Ti-6Al-4V	Stainless 316	Inconel
Max. strength	N/mm2	470	950	515	1110
Yield strength	N/mm2	325	880	205	634
Max. elongation	%	19	14	40	20
Density	kg/dm3	2,73	4,43	8	8,3
Modulus	kN/mm2	70	114	193	210

Conventional: Aluminum

HT materials:

- Ti-6Al-4V (see graph)
- RVS 316
- Inconel

Maintain properties at higher temperatures!



Special Materials - Blackbird

First flight in 1964

Fastest (non-Exp.) aircraft (M3+)
Reconnaissance

Titanium (>90%)

Leading edge > 400^0 C

Cool down time half hour

Note Concorde <M2,02 (127^0 C)

because of Aluminum structure

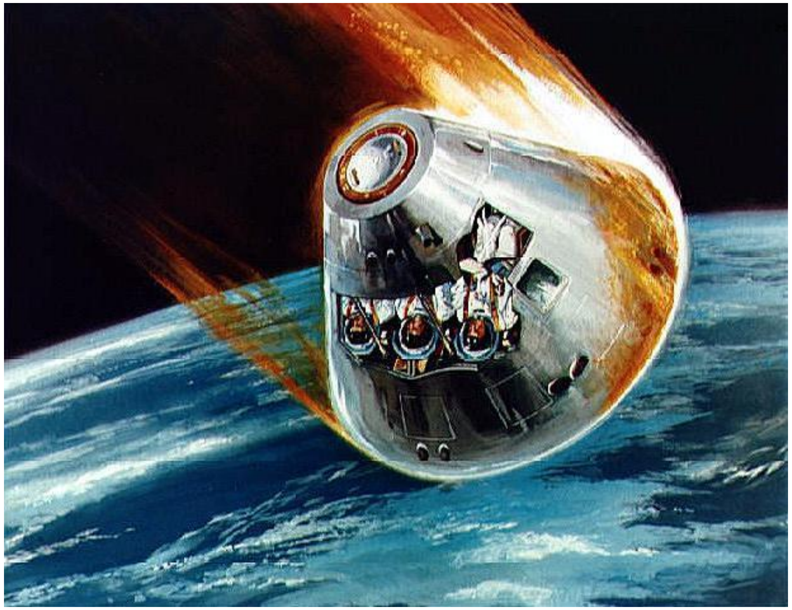
Reentry from space

Mercury, Apollo programs

Capsules with ablative shields

Slowly sublimating surface

Dissipation of energy

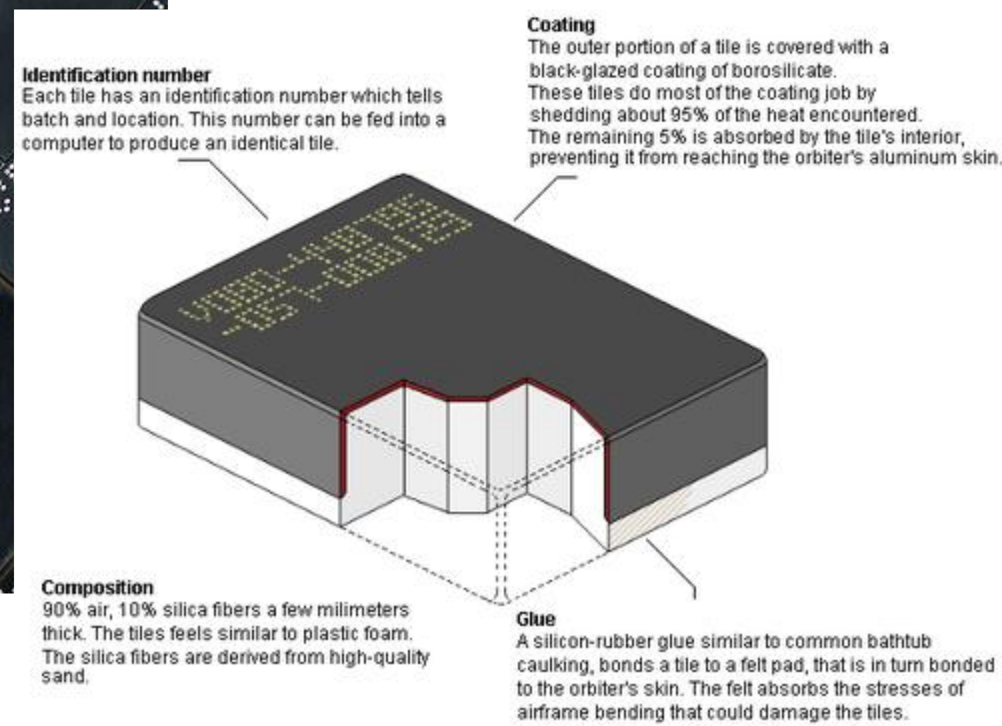


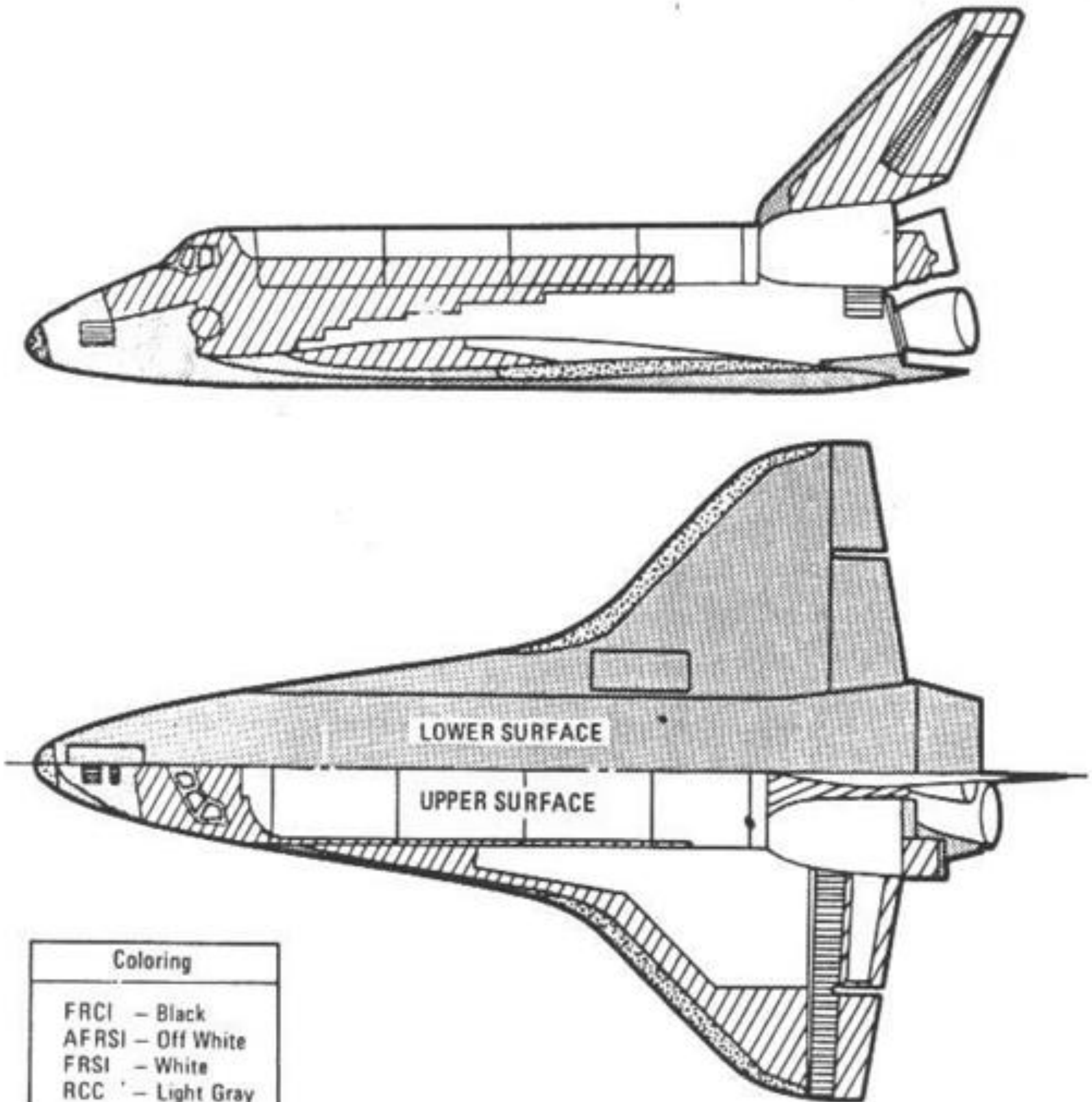
Space Shuttle

TPS – Thermal Protection System
Up to 1650^0 C during reentry phase

- Reinforced Carbon-Carbon (RCC), nose cap, wing leading edges. Where temperature exceeds 1260 °C
- High-temperature reusable surface insulation (HRSI) tiles, used on the orbiter underside. Made of coated Silica ceramics. Used where temperature is below 1260 °C.
- Flexible Insulation Blankets (FIB), a quilted, flexible blanket-like surface insulation. Used where reentry temperature is below 649 °C (1200 °F).

Space Shuttle - TPS





Coloring
FRCI – Black
AFRSI – Off White
FRSI – White
RCC – Light Gray

- Reinforced Carbon-Carbon (RCC)
- High-Temperature, Reusable Surface Insulation (HRSI)
  Fibrous Refractory Composite Insulation (FRCI)
- Low Temperature, Reusable Surface Insulation (LRSI)
  Advanced Flexible Reusable Surface Insulation (AFRSI)
- Coated Nomex Felt Reusable Surface Insulation (FRSI)
- Metal or Glass

Element*	Area, sq m (sq ft)	Weight Kg (lb)
FRSI	332.7 (3581)	532.1 (1173)
LRSI**	TBD	TBD
AFRSI**-***	TBD	TBD
HRSI**	TBD	TBD
FRCI**-***	TBD	TBD
RCC	38.0 (409)	1697.3 (3742)
Miscellaneous		918.5 (2025)
Total	TBD	TBD

*Includes bulk insulation, thermal barriers, and closeouts
**Possibly some of Orbiter -099
***Orbiter 103 and subsequent
TBD - To Be Determined

Summary

Limits: speed – record is M = 6,72

altitude – record is 103 km

High temperatures – special materials

– during supersonic/hypersonic flights

- during reentry from space