2E14

Design of aluminium and stainless steel structures

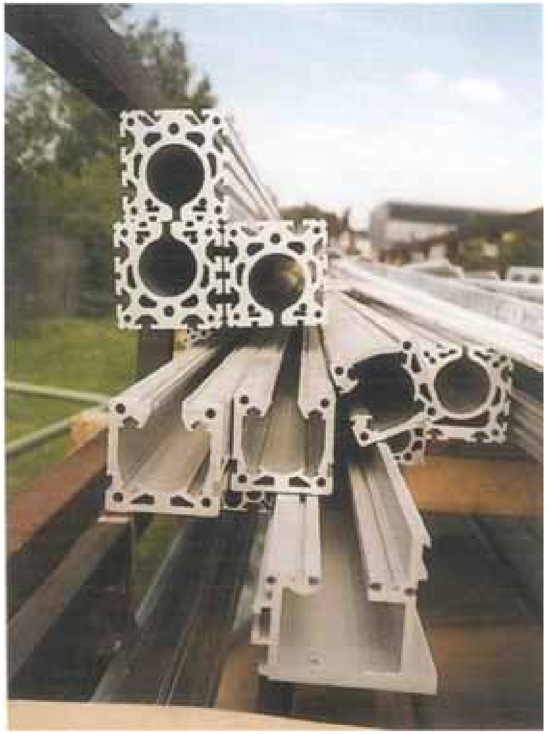
František Wald

List of lessons

1) Aluminium structures
2) HAZ softening
3) Design of aluminium elements
4) Design of aluminium connections
5) Design beyond the elastic limit
6) Aluminium advanced design
7) Stainless steel structures
8) Stainless steel material and material properties
9) Specialty in design of stainless steel structural elements
10) Connection design
11) Erection and installation of stainless steel structures
12) Stainless steel advanced design

Objectives of the lecture

- Introduction to aluminium design
- References
- Examples
- Material selection
- Eurocodes for aluminium design



Advantages

– Weight (2700 kg\m^3)

– Corrosion

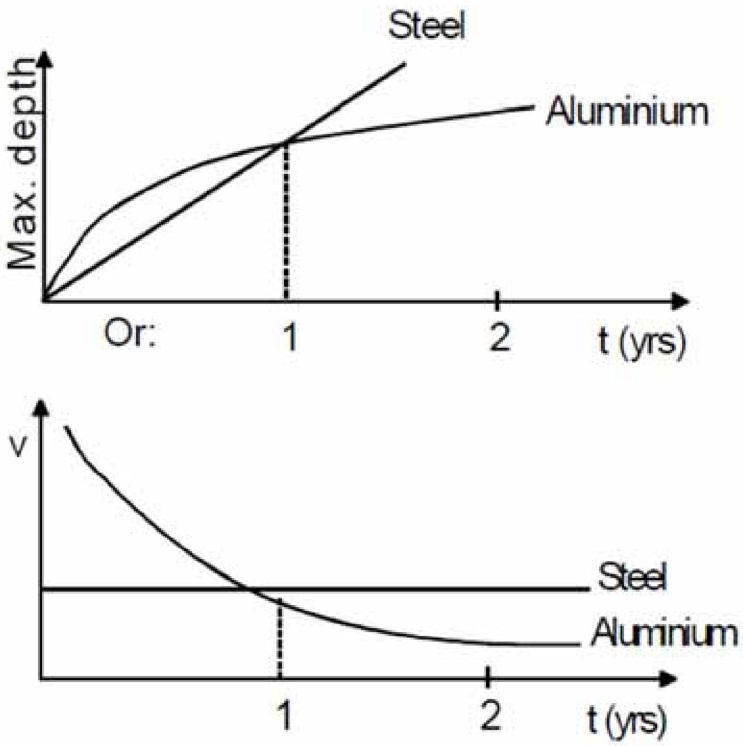
– Mon magnetic and low toxic

– Fatigue, low ductility transaction temperature

Corosion

Rate of corrosion in a marine environment:

Steel: $v_{St} = k_{St} \cdot t$
Aluminium: $v_{Al} = k_{Al} \cdot t^{1/3}$



<u>Consequence:</u>

Virtually maintenance free construction

After 20 years in sea water:
Average corrosion rate/year: St52/Al 10-40/1

References

European recommendation for aluminium alloy structures, ECCS publication, No. 26, Brusel, 1978.

Bulíček V.: Rules for design, production and erection,**Směrnice pro navrhování**, výrobu a montáž konstrukcí z hliníkových slitin, Technický zpravodaj r.11 č.4, Vítkovice, 1975.

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Kosteas D.: European Recommendation for fatigue design of Aluminium Structures, v Proceeding of the 5th International conference on aluminium weldments, INACO, Munich, 1992.

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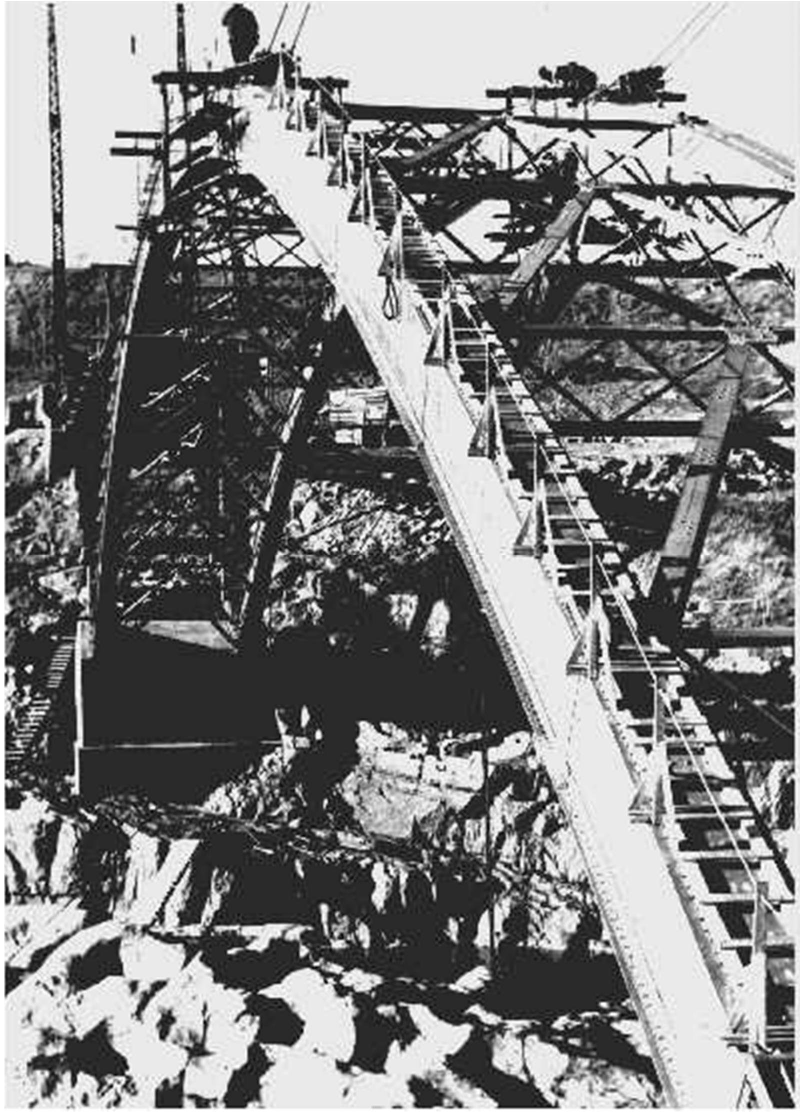
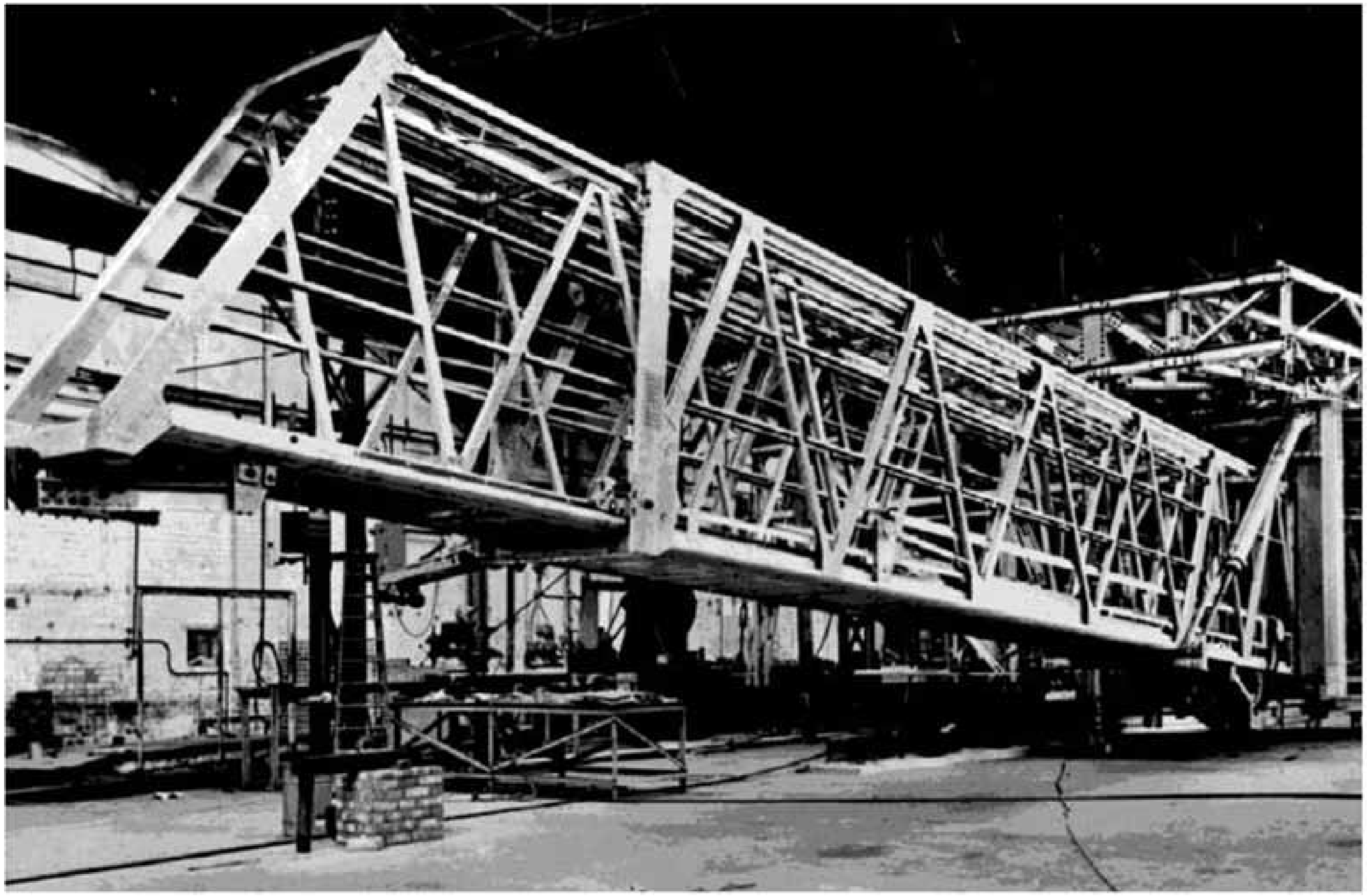
Educational program TALAT ww.eaa.net/eaa/education/TALAT

History – Bridge Quebec 1947



History – Bridge for airport terminal 1948



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Examples of structures
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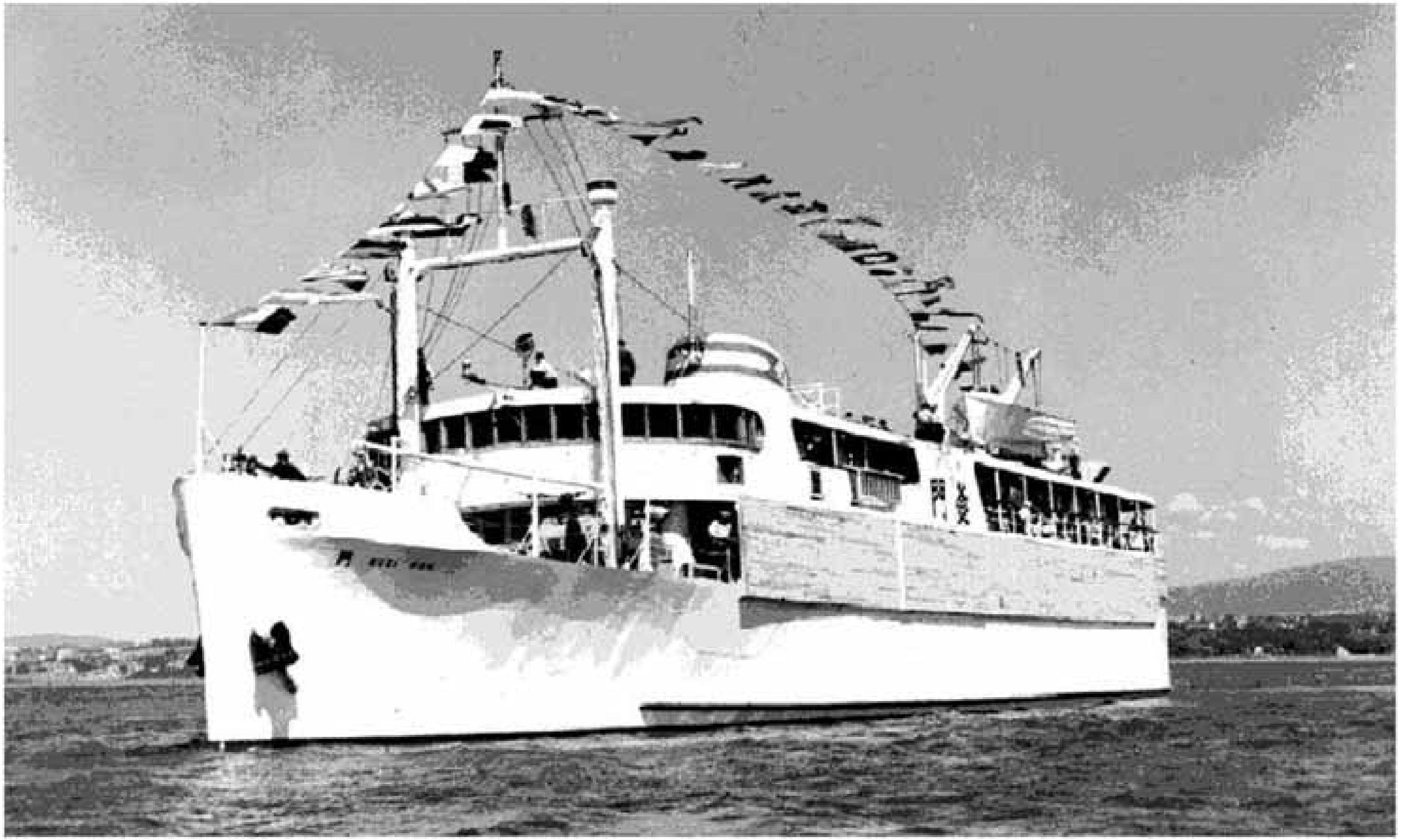
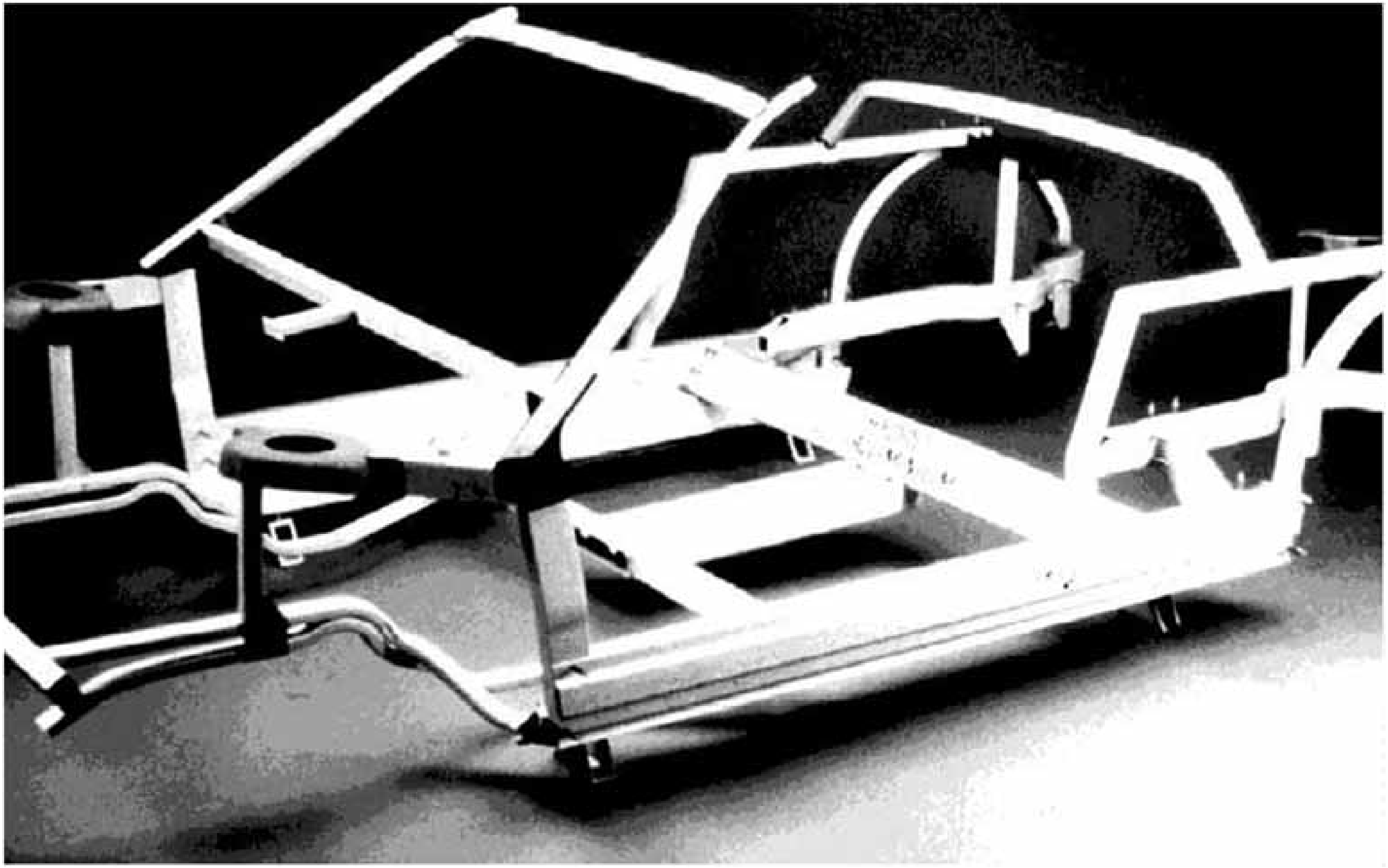
History – Aluminium ship 1948



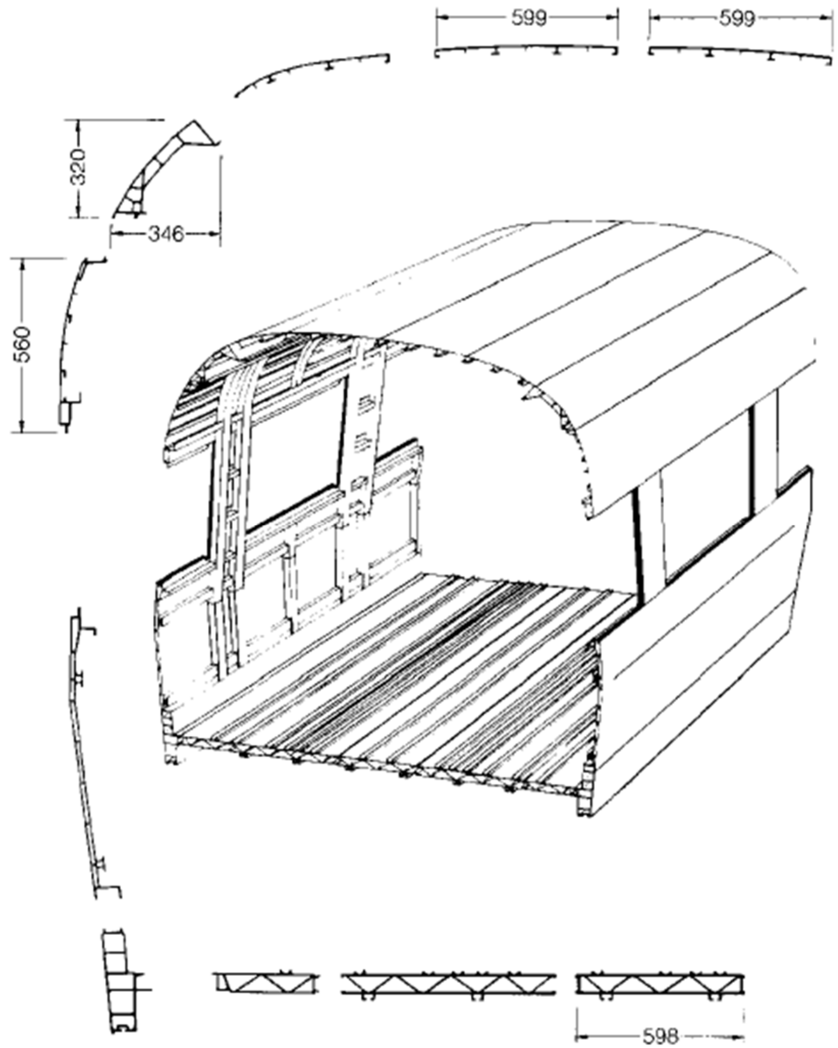
History – Sceleton of car, Landover 1990



History – Offshore helimodule, 1986

Helideck, Helihangar, Stairtowers and Support Structure

History – Couch for subway 1992



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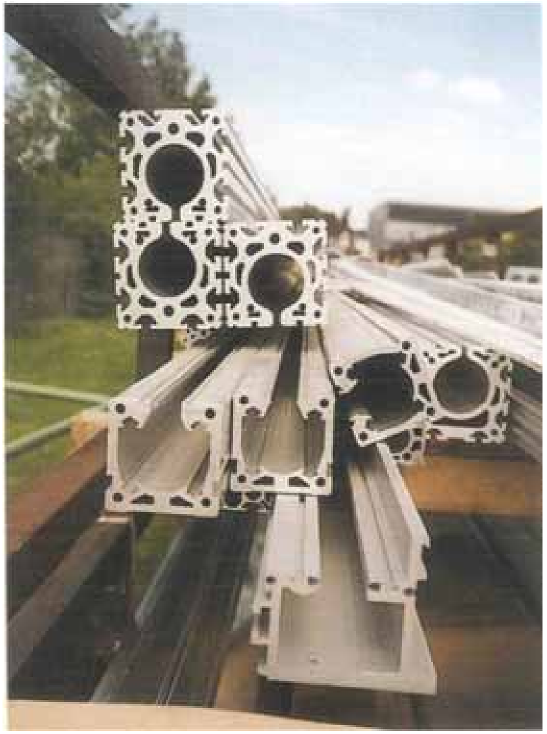
Examples of application

- Scaffolds
- Platforms
- Roofing
- Mobil structures

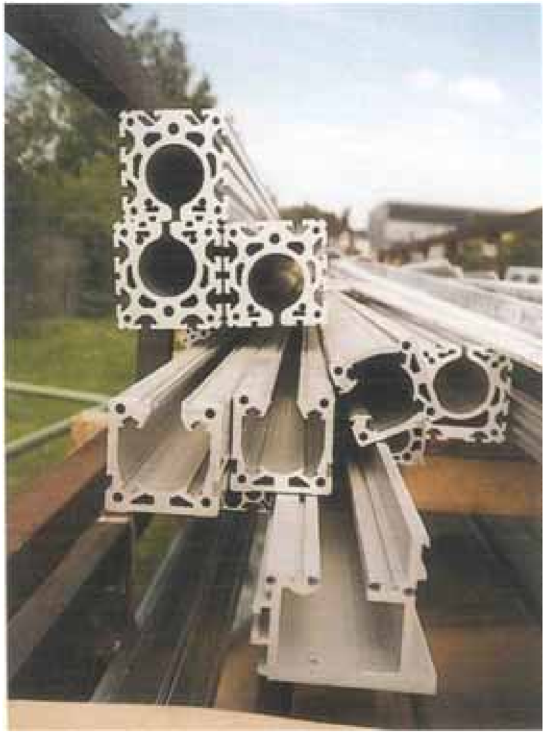


Aluminium and its alloys

- Pure Aluminium

- Aluminium Alloys
  - Wrought alloys
  - Casting alloys

  - Non-heat treatable alloys
  - Heat treatable alloys



Pure aluminium

- Electrolytic smelters
- Cast into different shapes or forms suitable for manufacturing of semifinished products
- Level of purity a distinction is made between
  - commercial purity (99,5 - 99,8% aluminium) and
  - high purity (up to 99,98% aluminium)

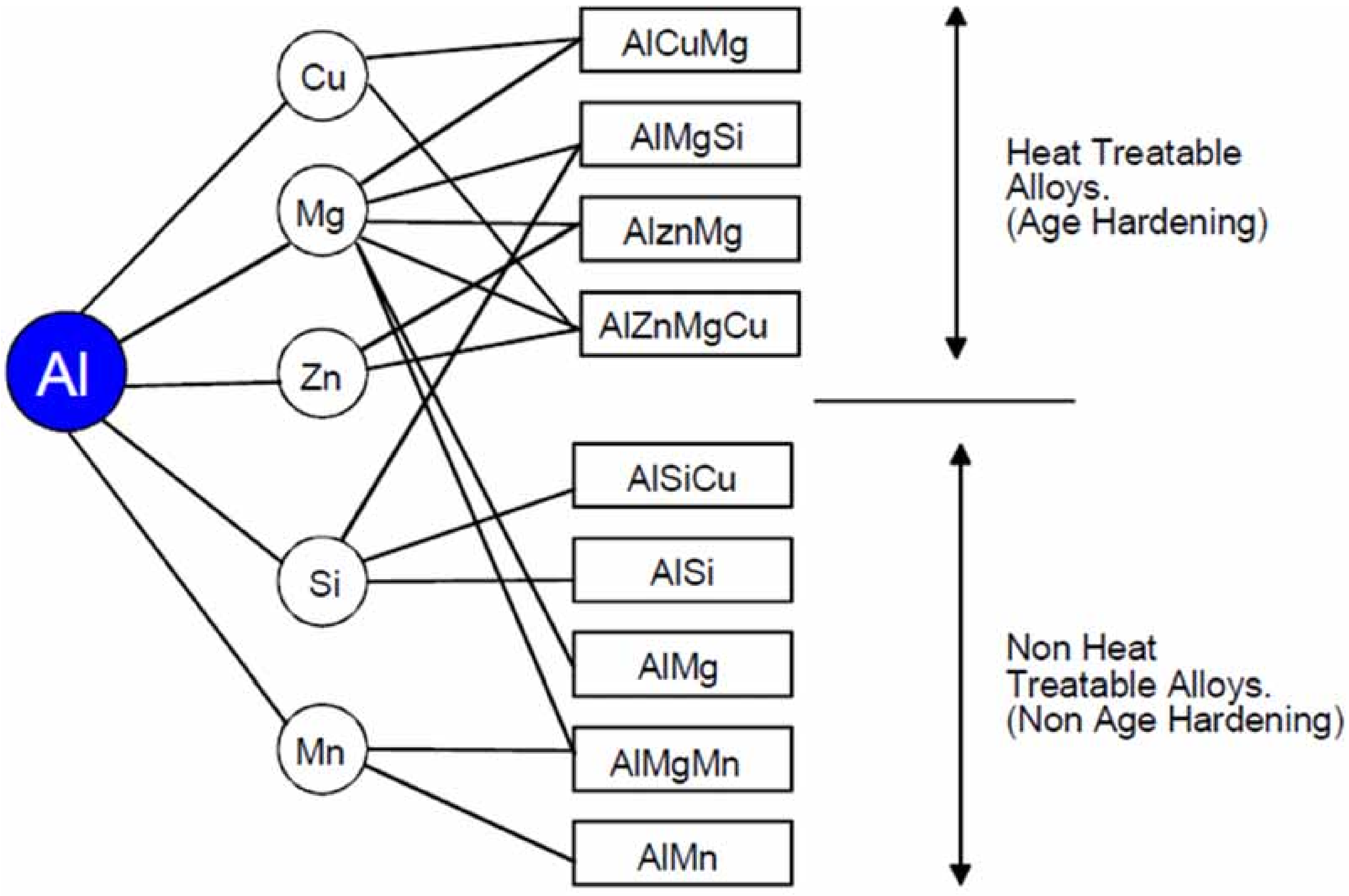
Alloying elements

- Improve its strength (from 20 MPa to 350 MPa)
- Commonly used
  - Copper (Cu)
  - Magnesium (Mg)
  - Zinc (Zn)
  - Silicon (Si)
  - Manganese (Mn)
- Other alloying elements
  - bismuth (Bi), boron (B), chromium (Cr), lithium (Li), iron (Fe), lead (Pb), nickel (Ni), titanium (Ti), zirconium (Zr), strontium (Sr) and sodium (Na)
  - in small quantities to achieve special metallurgical effects or properties, e.g. grain refining, machinability etc.

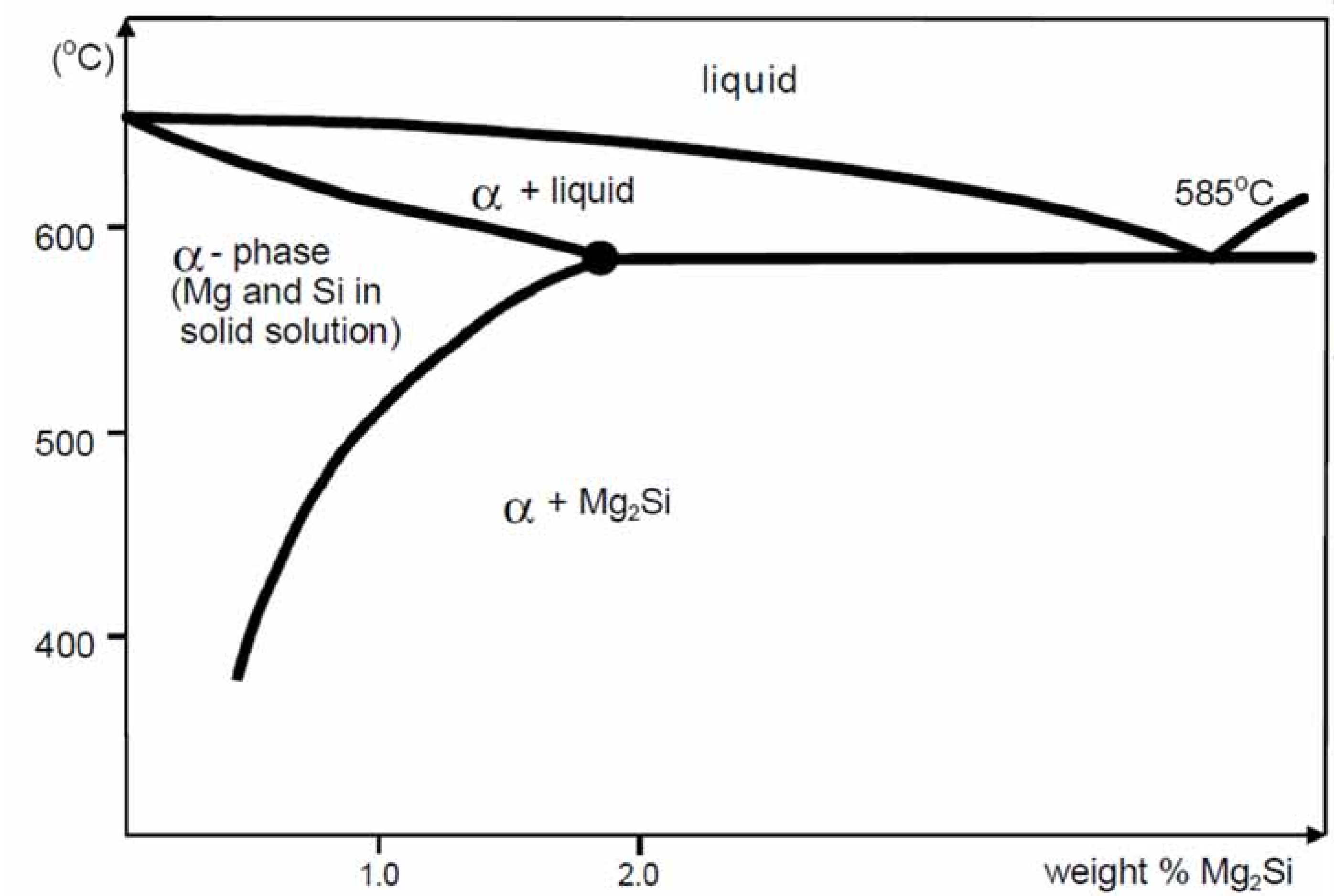
Adding lithium (Li)

- Quantities of 3 to 5%
  - Improves the elastic modulus
  - Decreases the density.
- Structural aluminium-lithium alloys
  - restricted to aerospace applications
  - special care and attention at
    - casting,
    - fabrication,
    - use
    - scrap recycling stages

Heat treatable and not treatable alloys



Heat treatment



The nature of heat treatment

- Heating for a prescribed period
  - at a prescribed temperature, then cooling rapidly from this temperature,
  - usually by quenching (solution heat-treatment).
- Ageing
  - spontaneously at ordinary temperatures (natural ageing)
  - by heating for a prescribed period at a prescribed low temperature (artificial ageing).

The application of both solution heat-treatment and artificial ageing is often termed “full heat treatment“

Solution treatment

Heating, quenching, artificial ageing, re-heat treatment

- **Heating**

Specified temperature range and heating length. Alloying constituents tend to diffuse from the core into the aluminium cladding. Cast aluminium alloys need to be solution heat-treated for longer periods than wrought aluminium alloys.

- **Quenching**

Plate, extrusions and strip may be discharged from a furnace horizontally and quenched by water sprays to minimise distortion. Distortion can also be reduced by decreasing the cooling rate using hot water or oil as a quenching medium and this is often helpful with castings and forgings.

Solution treatment

Heating, quenching, artificial ageing, re-heat treatment

- ## Artificial ageing

Hardening can be accelerated by heating the solution heat-treated alloy in the range 100 - 200 °C for a suitable period.

Maximum strength is generally achieved by prolonged ageing at low temperature rather than by rapid ageing at high temperature.

- ## Re-heat treatment

Alloys which have been incorrectly heat-treated can be re-solution treated and then precipitation treated again to enable optimum properties to be achieved.

Clad material should not be re-heat treated.

Heat treatment

- Non heat treatable (Non-age hardening) alloys
  - AlMg
  - AlMn
  - AlMgMn
  - AlSiCu
  - AlSi
- Heat treatable (Age hardening) alloys
  - AlMgSi (6000 series)
  - AlZnMg(Cu) (7000 series)
  - AlCuMg (2000 series)
  - AlLi (8000 series)

Four digit alloy designation system

- The first digit indicates the alloy group as follows:
- The second digit indicates modifications of the original alloy or impurity limits.
- The last two digits identify the aluminium alloy or indicate the aluminium purity.
  - A letter used as a prefix indicates an experimental alloy.
  - A letter used as a suffix indicates national variations.

The first digit indicates the alloy group

• Al. 99,00 % purity and above	1xxx
• Copper (Cu)	2xxx
• Manganese (Mn)	3xxx
• Silicon (Si)	4xxx
• Magnesium (Mg)	5xxx
• Magnesium and Silicon (MgSi)	6xxx
• Zinc (Zn)	7xxx
• Other element (eg. Li, Fe)	8xxx
• Unused series	9xxx

Classification examples of commonly used alloys

Int. reg. record EN 573	ISO
1050A	Al 99,5
1070A	Al 99,7
2017A	AlCu4MgSi
3103	AlMn1
5052	AlMg2,5
5454	AlMg2,7Mn
5083	AlMg4,5Mn
6060	AlMgSi
6063	AlMg0,5Si
6082	AlSiMgMn
7020	AlZn4,5Mg1

Temper Designation

F as-fabricated

Fabricated products without special control

O annealed

Wrought products which are annealed to obtain the lowest strength temper

H strain hardened

Wrought products which have been cold worked

W solution heat treated

Unstable temper applicable only to alloys which spontaneously age at room temperature

T thermally treated to produce stable tempers other than F, O, and H

Products which are thermally treated, with or without supplementary strain hardening.

The T is always followed by one or more digits.

H-temper - strain hardened

H1 strain hardened only

The number following this designation indicates the degree of strain hardening

.

H2 strain hardened and partially annealed

Applies to products that are strain hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing.

H3 strain hardened and stabilized

Applies to products which are strain hardened and whose mechanical properties are stabilized by a low temperature thermal treatment which results in slightly lower tensile strength and improved ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age-soften at room temperature.

H-temper - strain hardened

Three-digit H temper designation

H111 to products strain hardened less than the amount required for a controlled H11

H112 acquire some temper from shaping processes

H311 to products which are strain hardened less than the amount required for a controlled H31 temper.

H321 to products which are strain-hardened less than the amount required for a controlled H32 temper

H323/H343 to products which are specially

T temper - thermally treated

T4 solution heat treated and naturally aged to a substantially table condition

to products which are not cold worked after solution heat treatment, or in which the effect of cold work in flattering or straightening

T5 cooled from an elevated temperature shaping process and then artificially aged

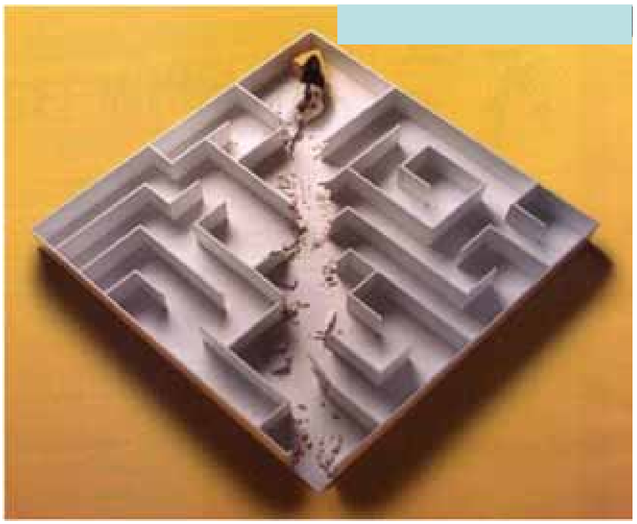
to products which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattering or straightening

T6 solution heat treated and then artificially aged

to products which are not cold worked after solution heat treatment, or in which the effect of cold work in flattering or straightening may not be recognized in mechanical property limits.

Assessment 1

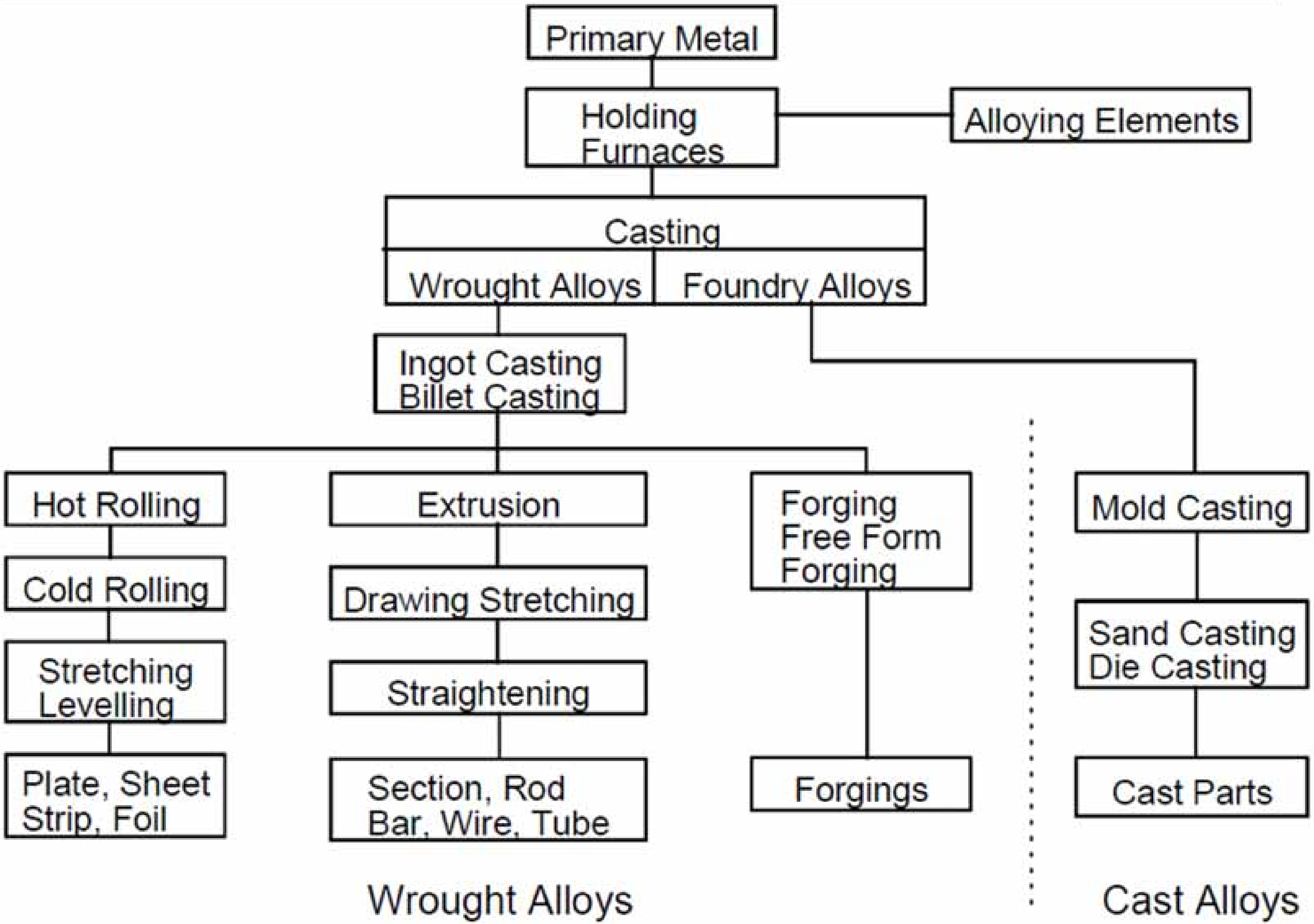
- What are the advantages of aluminium structures?
- What is nature of heat treatment?
- How is indicated the heat treatment?



Aluminium products for structural applications

- **Extrusions**
  - The extrusion process
  - Direct extrusion
  - Indirect and hydrostatic extrusion
  - Extrusions for structural applications
- **Sheet and plate**
  - The cold rolling process
  - Hot rolling
  - Alloys for rolled products
- **Casting alloys**

Processing aluminium alloys



Wrought alloys

- For fabrication by hot and cold forming processes
  - rolling, forging and extrusion.
- Principal aloying elements
  - Magnesium strengthening element
    - added up to 5% by weight.
  - Zinc, copper and/or silicon + magnesium
    - very high strength alloys special heat treatments.
  - Lead and bismuth
    - The machinability is increased by adding.
  - Copper and/or nickel, manganese or iron
    - High temperature strength properties

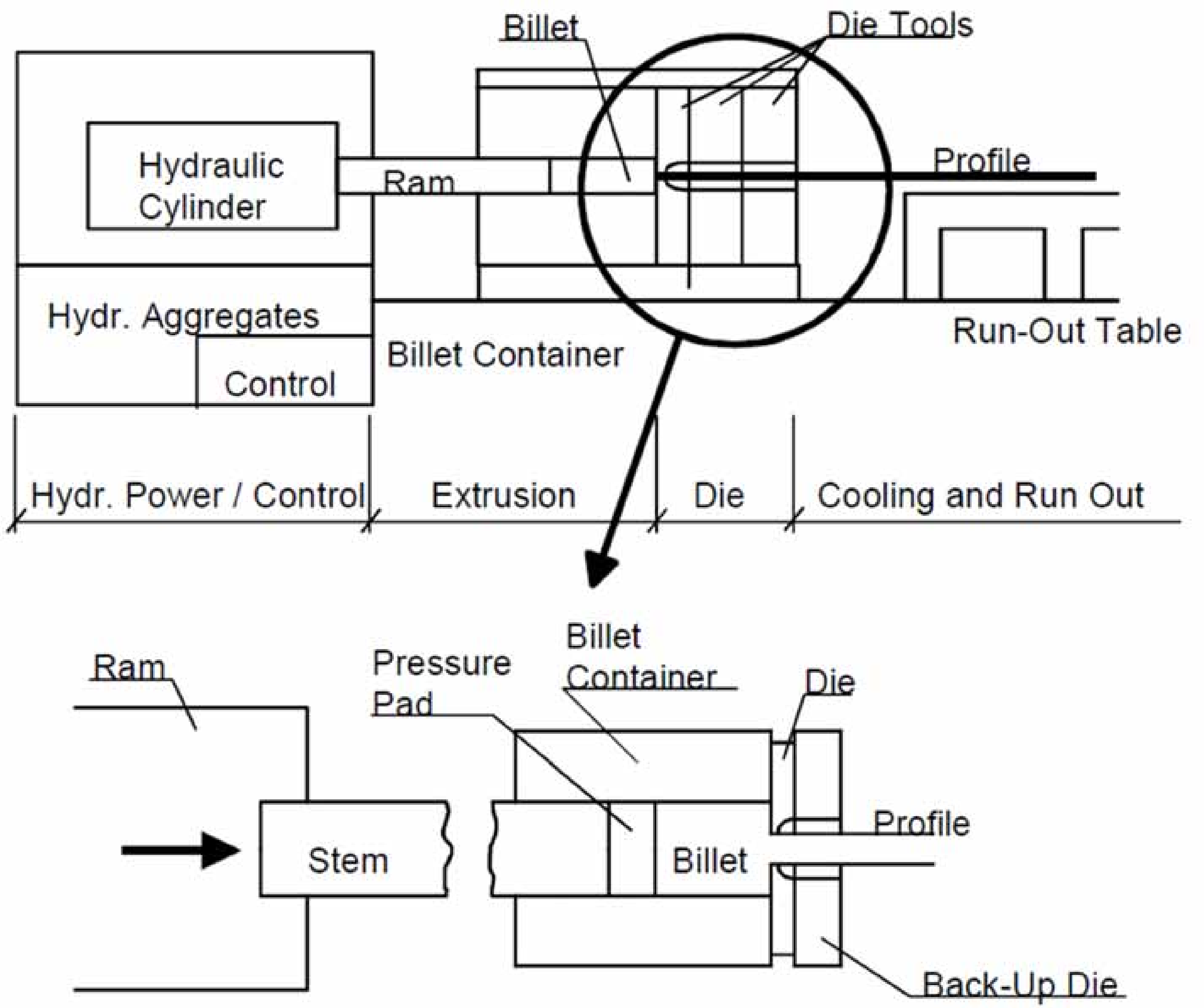
Casting alloys

- For the fabrication of cast parts
- High fluidity in the liquid state
- Good resistance to hot cracking during solidification.
- Castability
  - addition of silicon (7 to 13% Si)
  - the silicon content further up to 25% reduces the thermal expansion down to levels of iron and steel

Extrusion process

- At temperatures 400° - 500° C
  - using a pre-heated billet
- Direct Extrusion
- Indirect and Hydrostatic Extrusions
- Extrusion alloys
  - 6000-series (AlMgSi), and the
- Extrusion speed for the 6063 alloy
  - between 20 and 70 m/min.

Extrusion process



Extrusion - examples

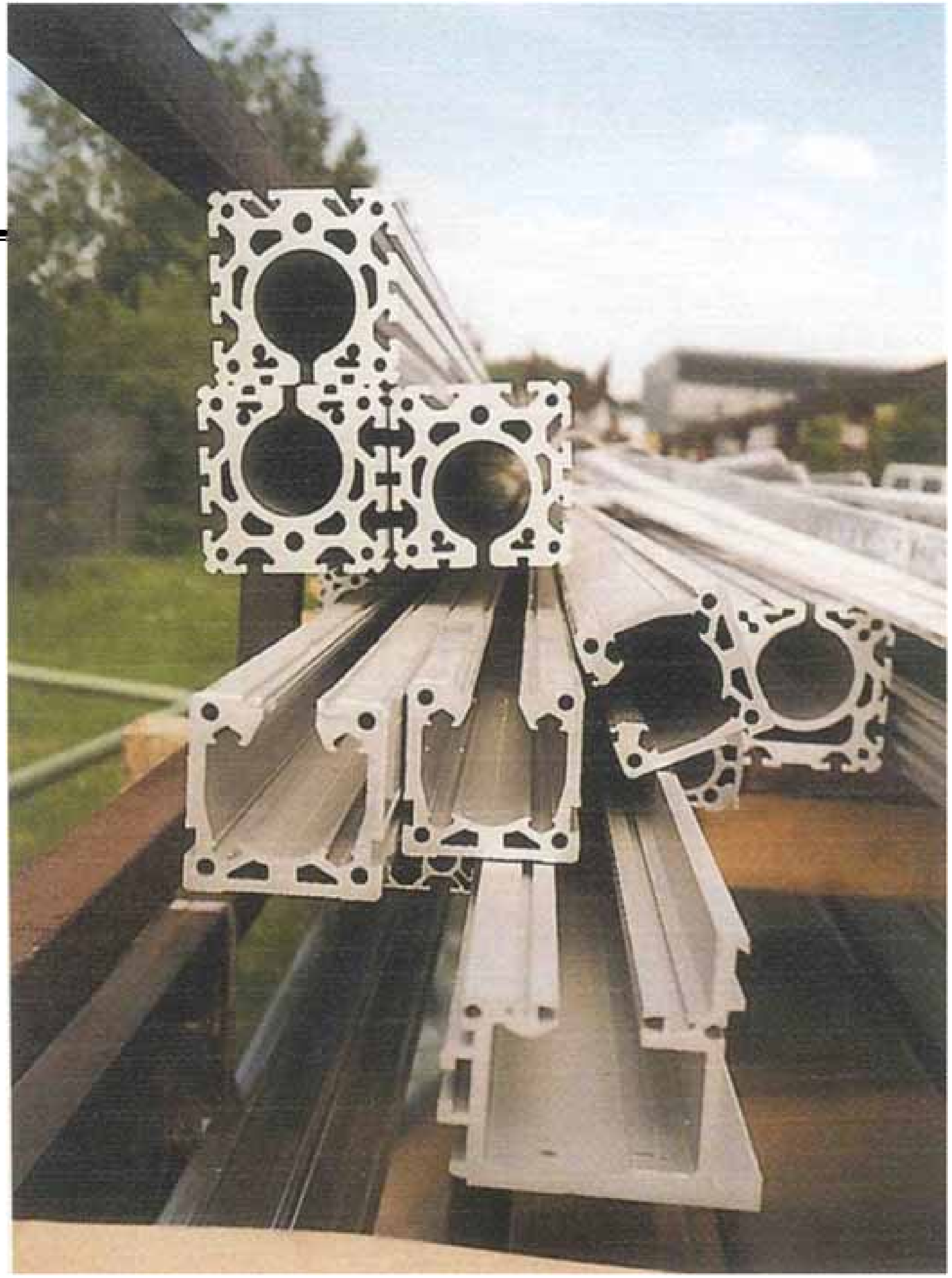
- AlMn - 3000-series for drawn tubes
    - due to very high formability
    - excellent dimensional tolerance abilities
- 2000-series or the 7000 series
    - trength performance
    - no weldability (Cu alloys)
    - potential danger of stress corrosion (Zn alloys).
- AlMgSi 6000-serie
    - majority of extrusions good overall performance i.e.
        - relatively easy to extrude
        - medium to high strength in the T6 condition
        - good corrosion resistance in marine and industrial environments
        - good weldability by all welding methods
        - good availability on the market, both as standard and special sections

6082 (AlMgSi1Mn) T6 In Europe normal

Sections

- Extrusion
- Extrusion
- Extrusion

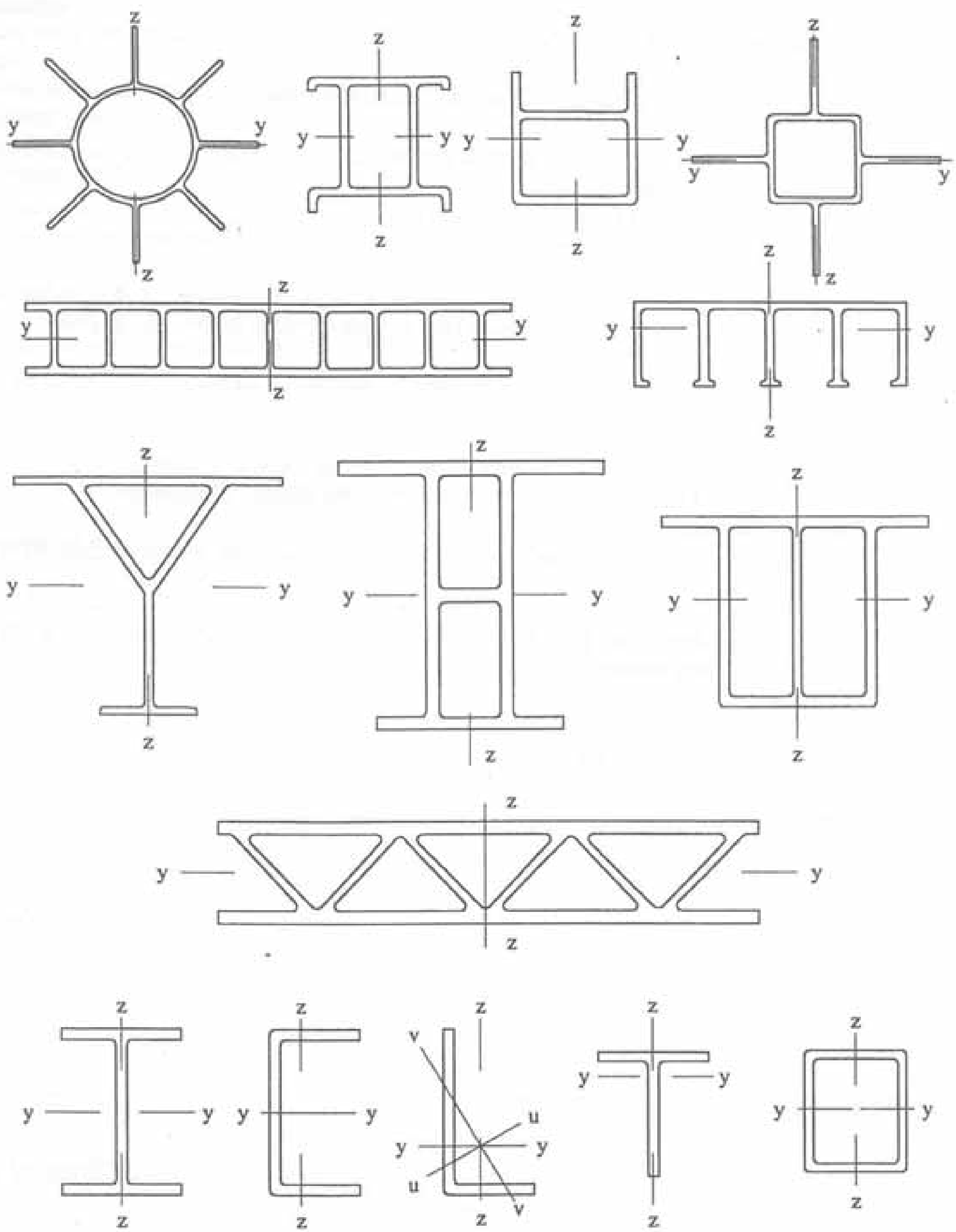
- Casting
- Cold forming
- Hot rolling



Sections

- Extrusion
- Extrusion
- Extrusion

- Casting
- Cold forming
- Hot rolling



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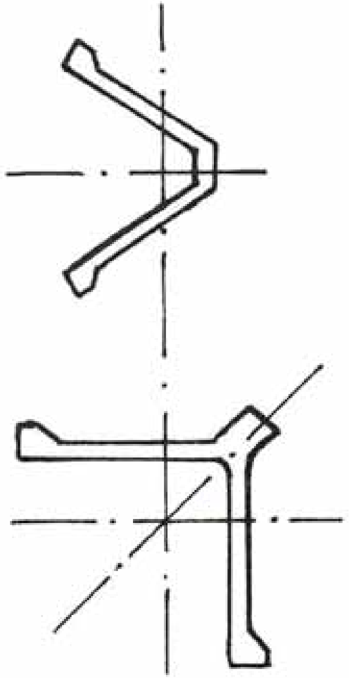
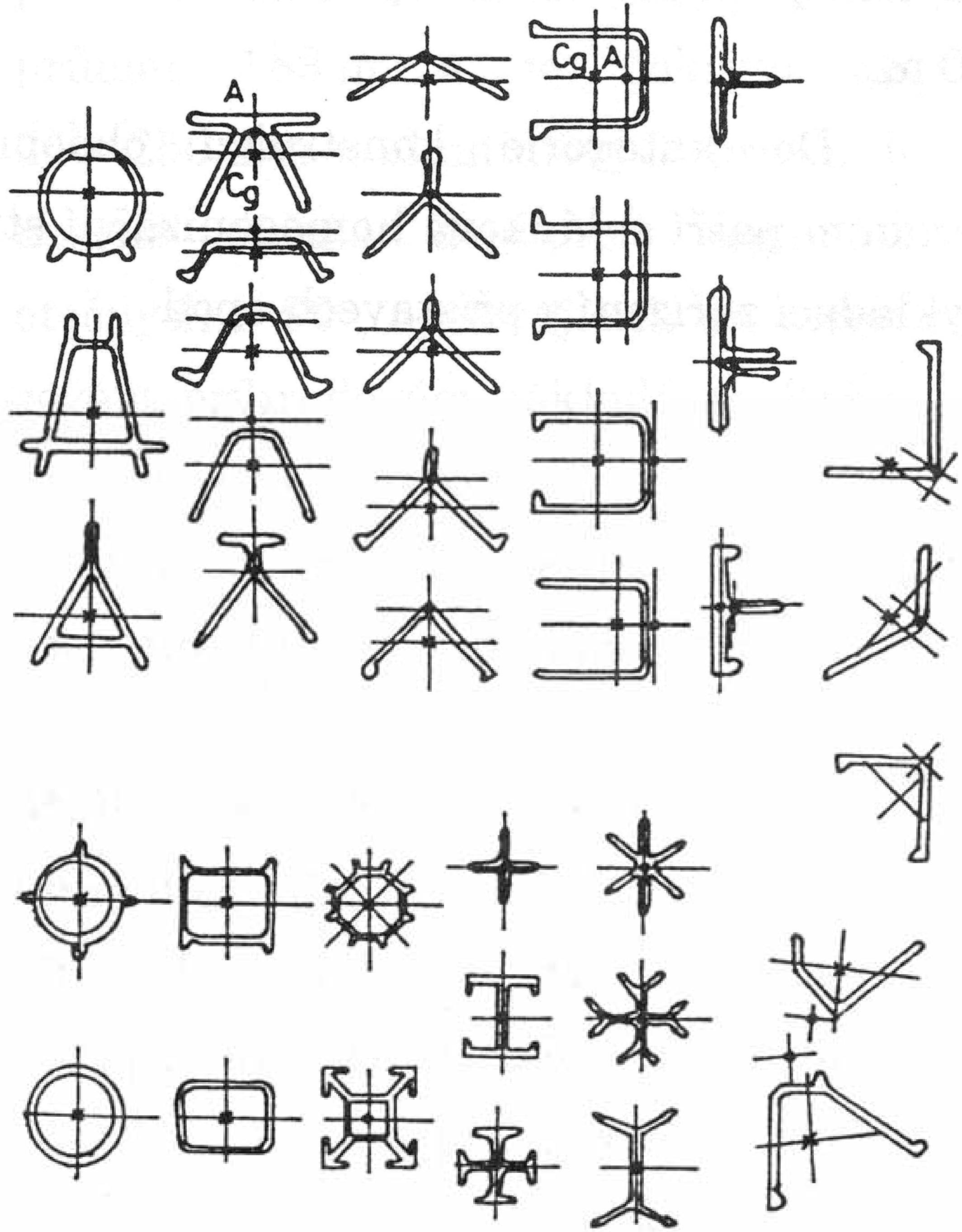
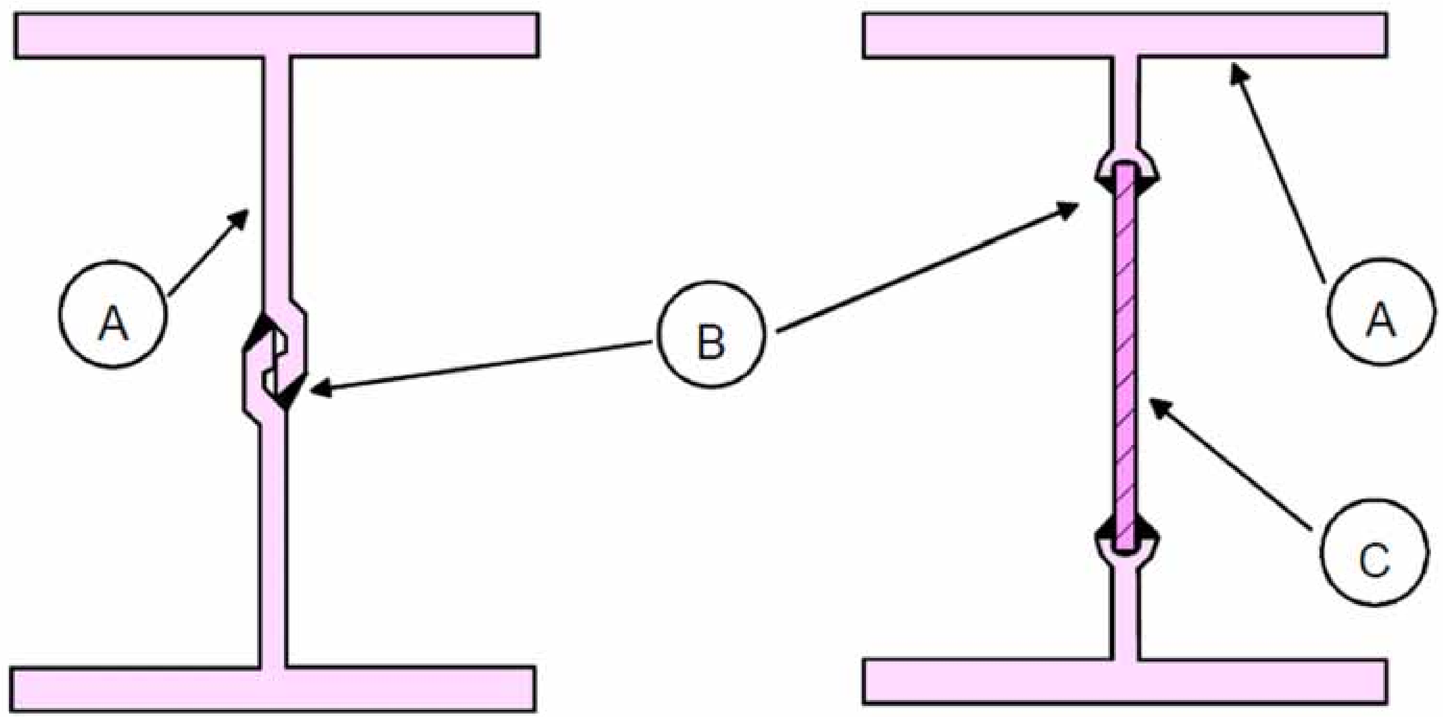
Extrusion

- Bulbs
- Stiffners
- Locks





Extrusion – preparation for welding



A: Extruded profiles
B: Fillet welds
C: Extruded flat bar or rolled plate

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Extrusion - thicknesses

Min. possible wall thickness for extrusion presses 10 - 80 MN.

Alloy	Profile type	25	50	75	100	150	200	250	300	350	400	450
Al 99-99,9	a	0,8	1	1,2	1,5	2	2,5	2,5	3	4	4	5
AlMgSi 0,5	b	0,8	1	1,2	1,5	2	2,5	2,5	3	4	4	5
AlMn 1	c	1	1	1,5	2	2,5	2,5	2,5	4	5	5	6
AlMg 1												
AlMgSi 1	a	1	1,2	1,2	1,5	2	2,5	3	4	4	5	6
	b	1	1,2	1,5	2	2	2,5	3	4	4	5	6
	c	2	1,5	2	2	3	4	4	5	5	6	6
AlMg 3	a	1	1	1,2	1,5	2	2,5	3	4	4	5	6
AlMg 5	b	1	1	1,2	1,5	2	2,5	3	4	4	5	6
AlCuMg 1	a	1,2	1,2	1,2	1,5	2	3	5	5	6	7	8
AlCuMg 2												
ALZnMgCu	a	2	2	2,5	3	3	5	6	8	12	12	14

Press capacity (MN) 10 → 25 → 35 → 50 → 80 →

a: Solid / semi-hollow sections

b: Hollow sections with equal wall thicknesses

c: Hollow sections with unequal wall thicknesses

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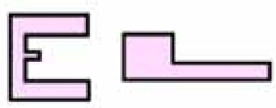
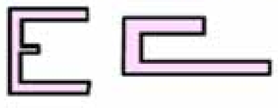
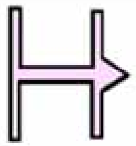
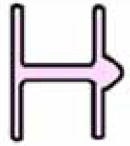
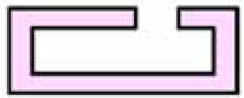
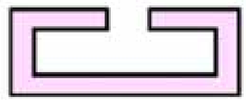
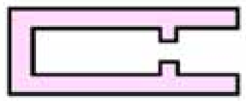
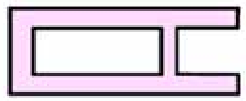
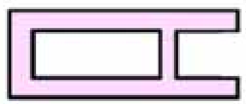
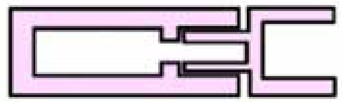
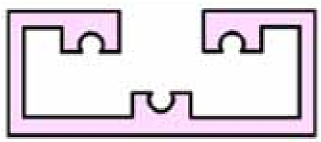
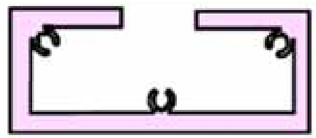
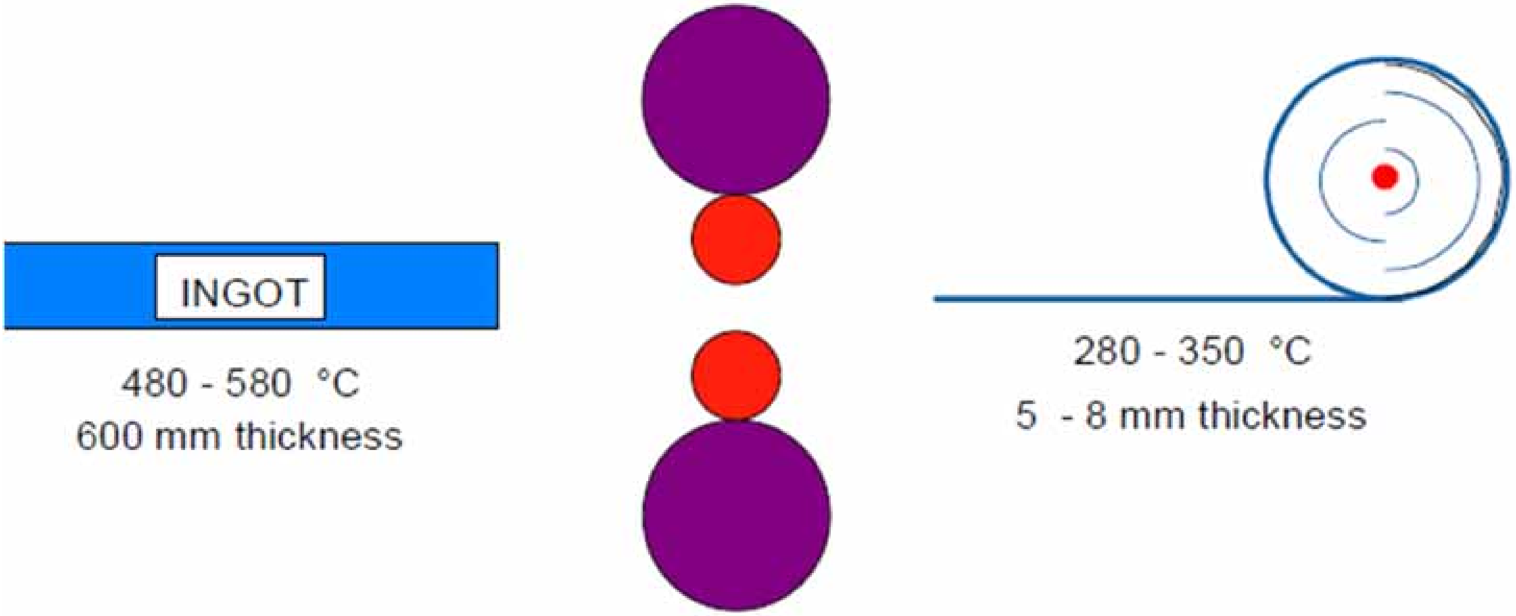
Extrusion – reccomended shapes

	Insteads of this	This is recommended
Equal wall thickness		
Sharp edges		
Profile symmetrie		
Better dimensional control		
Avoid hollow sections if possible		
Increased strength of weak points		

Hot rolling

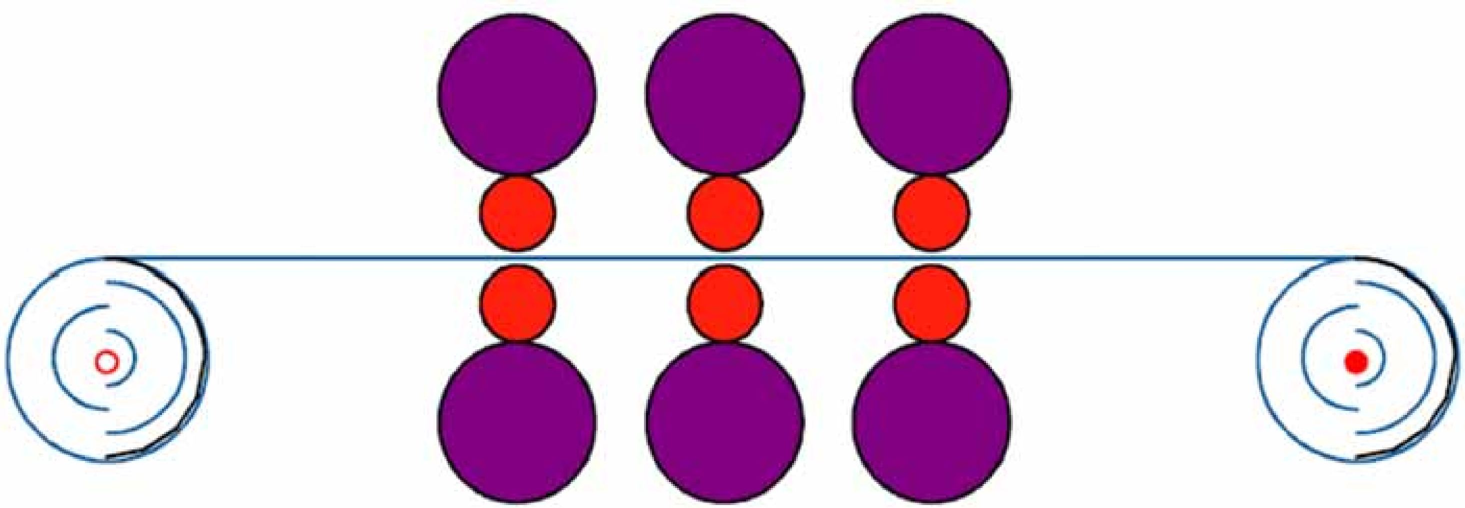


- Thick sheetings

Hot rolling

- Non heat treatable alloys
  - 5052 (AlMg2.5)
  - 5083 (AlMg4.5Mn)
  - 5054 (AlMg2.7Mn)
- Heat treatable alloys
  - 6082 (AlMgSi1)
  - 7020 (AlZn4.5Mg1)

Reverze hot rolling

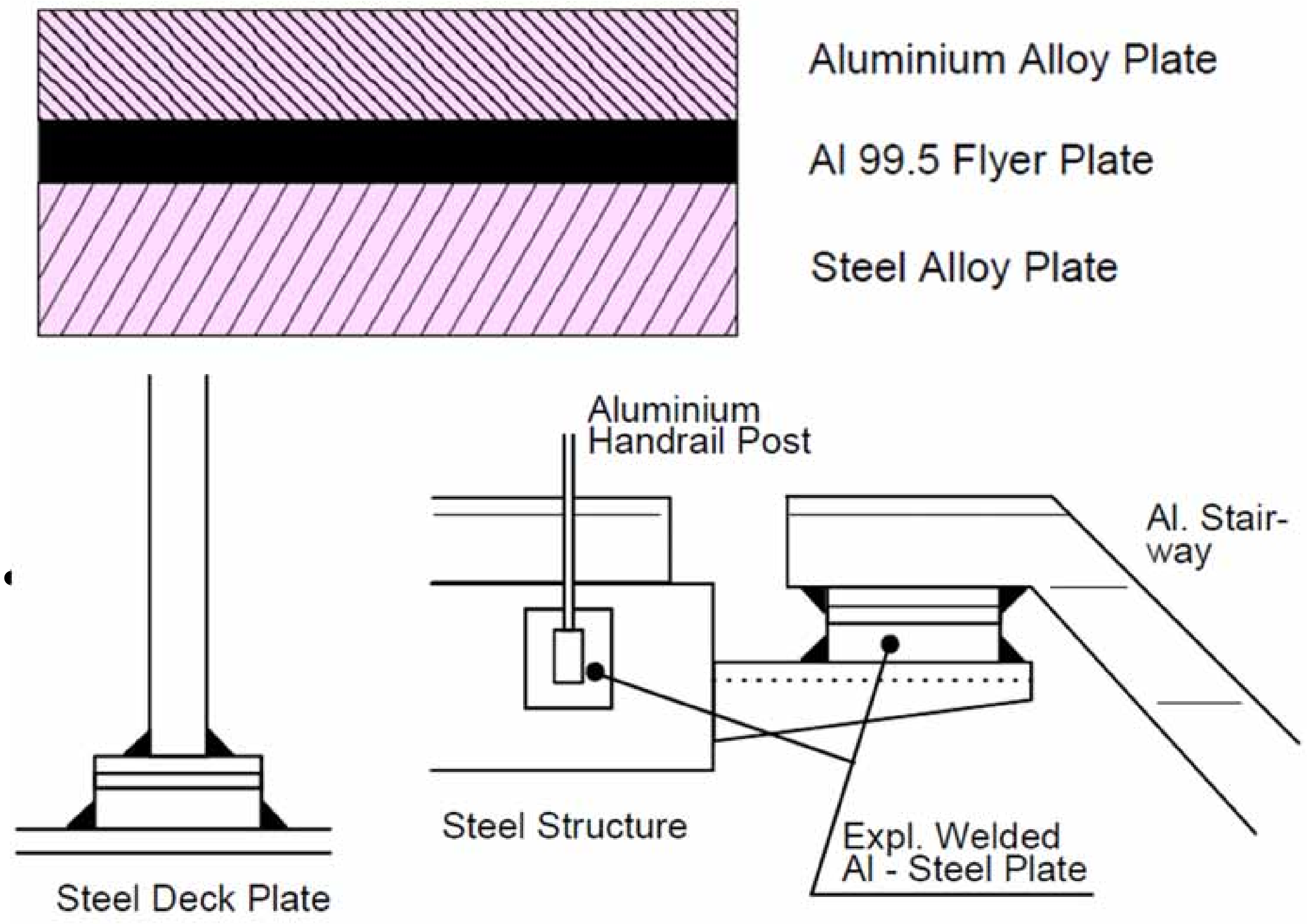


- Thin sheetings

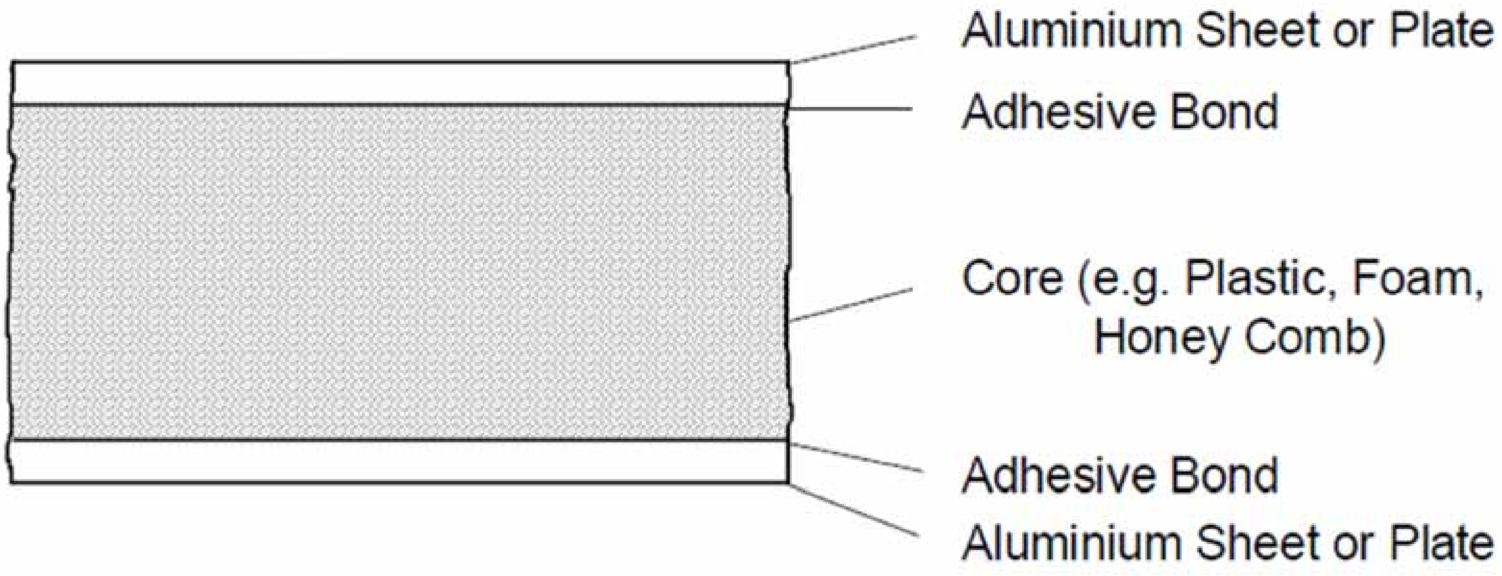
Casting Alloys for Structural Applications

- The typical alloys AlSiMg, AlSiCu, AlMg, AlCuTi and AlZnMg,
    - AlSi-alloys are preferred with respect to castability.
- **Sand casting**
    - produced by pouring molten metal into a sand mold and allowing it to solidify.
- **Permanent mold casting**
    - produced by feeding molten metal by force of gravity or low pressure into a mold constructed of durable material (iron or steel), and allowing it to solidify.
- **Die casting**
    - produced by injecting molten metal under high pressure into a metal mold or die and allowing it to solidify.

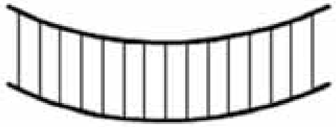
Advanced sheetings



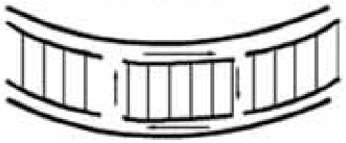
Sandwitch panels - priciple



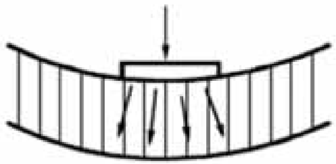
Sandwitch panels - advantages



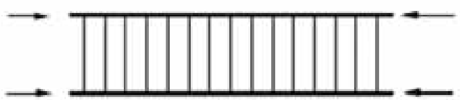
Normal stresses are taken by the faces.



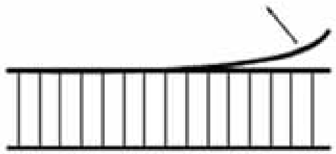
Transverse shear stress is taken by the core.



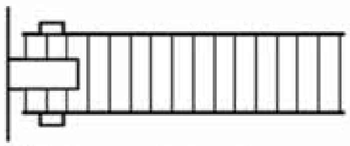
The core must have sufficient resistance against compression.



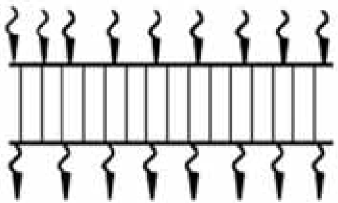
The panel must resist compression loading without buckling.



The adhesive joint must resist tension and peeling stresses.



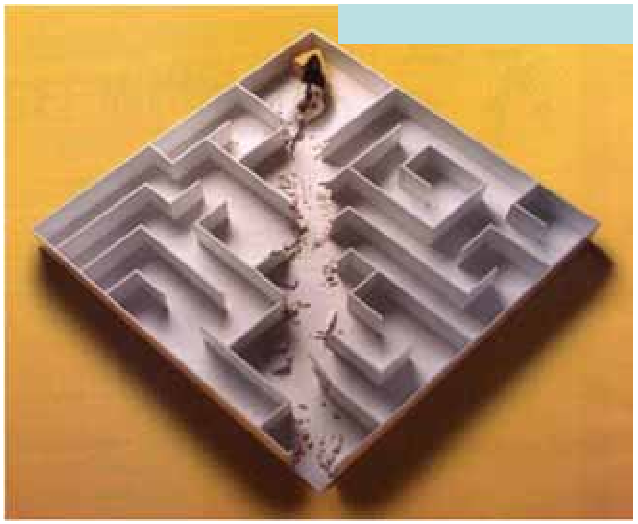
Adequate load transfer joints between different structures to be considered.



Thermal insulation capacity for the complete panel construction.

Assessment

- What are the major proceses for aluminium products?
- What sre the advantages of extrusion?
- What is the reason for limits of size and thickness in extrusion?



Choice of alloy and temper

- The available semi product range
- Delivery time from stock or plant
- Prices, etc

Costs

- Main relevant factors,
  - type of alloy
  - quantity and price
  - material dimensions
  - delivery time/eventual need for own internal stock
  - demands for special material control/certificates and traceability

- Type of Alloy

AlMn1 < AlMg2,5 < AlMg4,5Mn < AlMgSi1

Design

- Steel as a reference material
- Material property

  E = 70 000 MPa

  ρ = 2 700 kg / m^3

  ρ ductility 0,1 % to 12 % (structural abow 4 %)

  (steel min 15 %, commonly 40 % and more)

Standards

Eurocode 9 - Design of Aluminium Structures

Pre-standars	Eurocode	Title
ENV 1999-1-1	**EN 1999-1-1**	General structural rules.
ENV 1999-1-2	**EN 1999-1-2**	Structural fire design
ENV 1999-2	**EN 1999-1-3**	Structures susceptible to fatigue
	EN 1999-1-4	Cold-formed structural sheeting
	EN 1999-1-5	Shell structures.

Structure of EN 1999-1-1
Chapters

1. General
2. Basis of design
3. Materials
4. Durability
5. Structural analysis
6. Ultimate limit states for members
7. Serviceability limit states
8. Design of joints

Annexes to EN 1999-1-1

A. Execution classes
B. Equivalent T-stub in tension
C. Materials selection
D. Corrosion and surface protection
E. Analytical models for stress strain relationship
F. Behaviour of cross section beyond elastic limit
G. Rotation capacity
H. Plastic hinge method for continuous beams
I. Lateral torsional buckling of beams and torsional or flexural-torsional buckling of compression members
J. Properties of cross sections
K. Shear lag effects in member design
L. Classification of connections
M. Adhesive bonded connections

Material
EN 1991-1-1 Chapter 3

Table 3.2b - Characteristic values of 0,2% proof strength f_o and ultimate tensile strength f_u (unwelded and for HAZ), min elongation A, reduction factors $r_{o,haz}$ and $r_{u,haz}$ in HAZ, buckling class and exponent n_p for wrought aluminium alloys –
Extruded profiles, extruded tube, extruded rod/bar and drawn tube

Alloy EN-AW	Product form	Temper	Thick-ness t mm 1) 3)	f_o 1)	f_u 1)	A 5) 2)	$f_{o,haz}$ 4)	$f_{u,haz}$ 4)	HAZ-factor 4)		BC 6)	n_p 7)
				N/mm²		%	N/mm²		$\rho_{o,haz}$	$\rho_{u,haz}$		
6082	EP,ET,ER/B	T4	$t \leq$ **25**	110	205	14	100	160	0,91	0,78	B	8
	EP/O, EP/H	T5	$t \leq 5$	230	270	8	125	185	0,54	0,69	B	28
	EP/O,EP/H ET	T6	$t \leq 5$	250	290	8	125	185	0,50	0,64	A	32
			$5 < t \leq$ **15**	260	310	10			0,48	0,60	A	25
	ER/B	T6	$t \leq 20$	250	295	8			0,50	0,63	A	27
			$20 < t \leq 150$	260	310	8			0,48	0,60	A	25
	DT	T6	$t \leq 5$	255	310	8			0,49	0,60	A	22
			$5 < t \leq 20$	240	310	10			0,52	0,60	A	17

Objectives

Introduction

Examples
of structures

Structural alloys

Designation
system

Assessment 1

Products

Assessment 2

Material selection

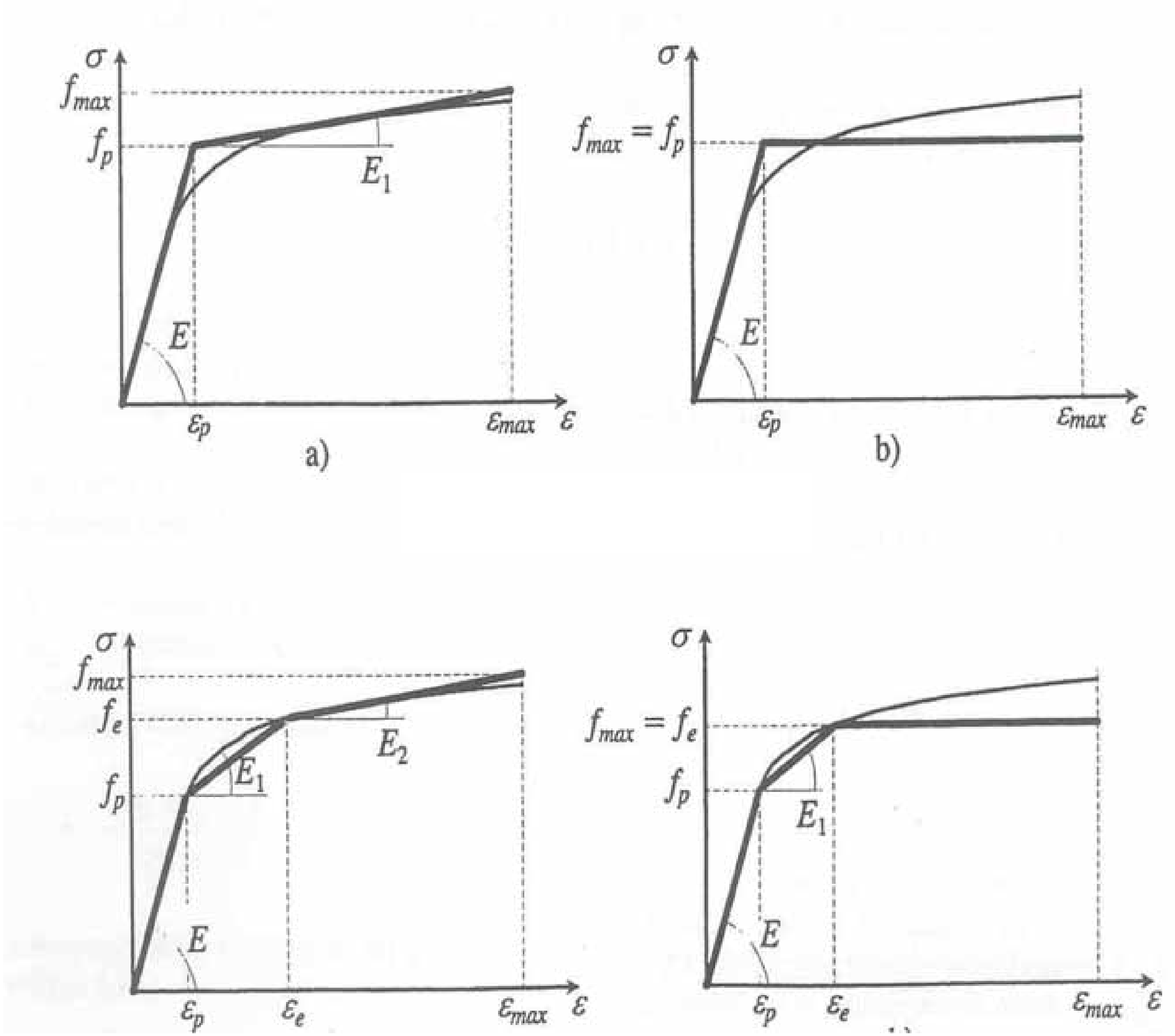
Eurocodes

Assessment 2

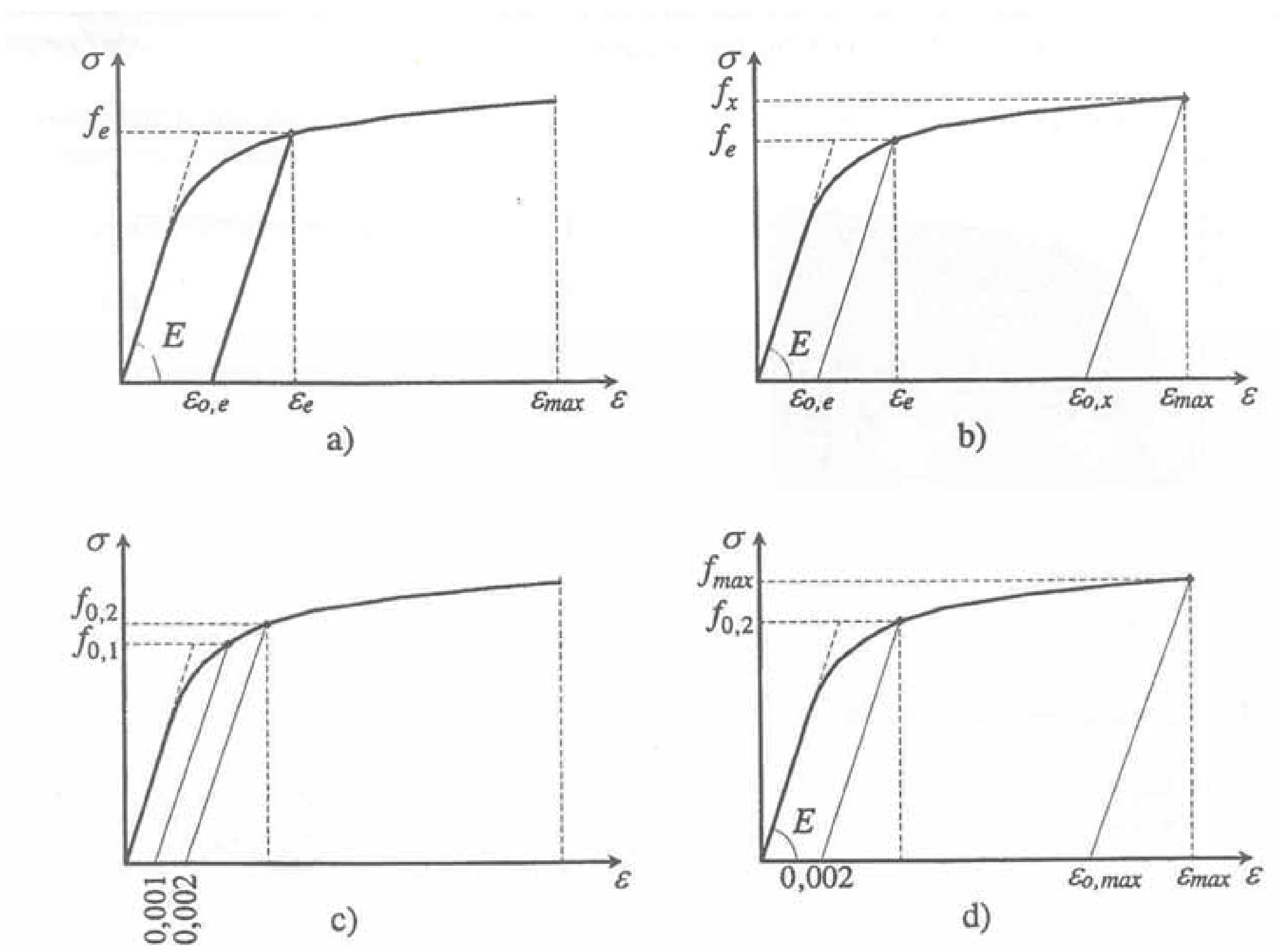
Summary

Notes

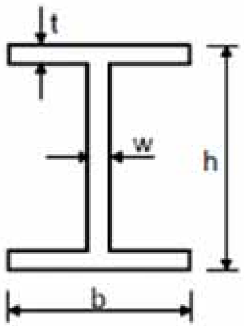
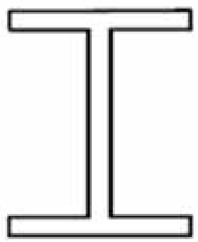
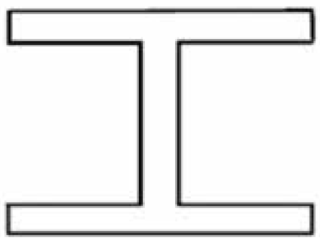
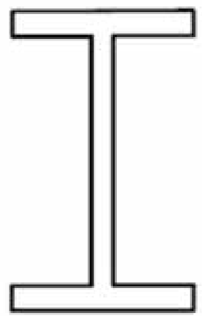
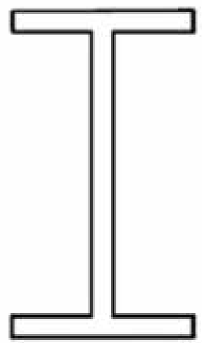
Linear/multi-linear model of material



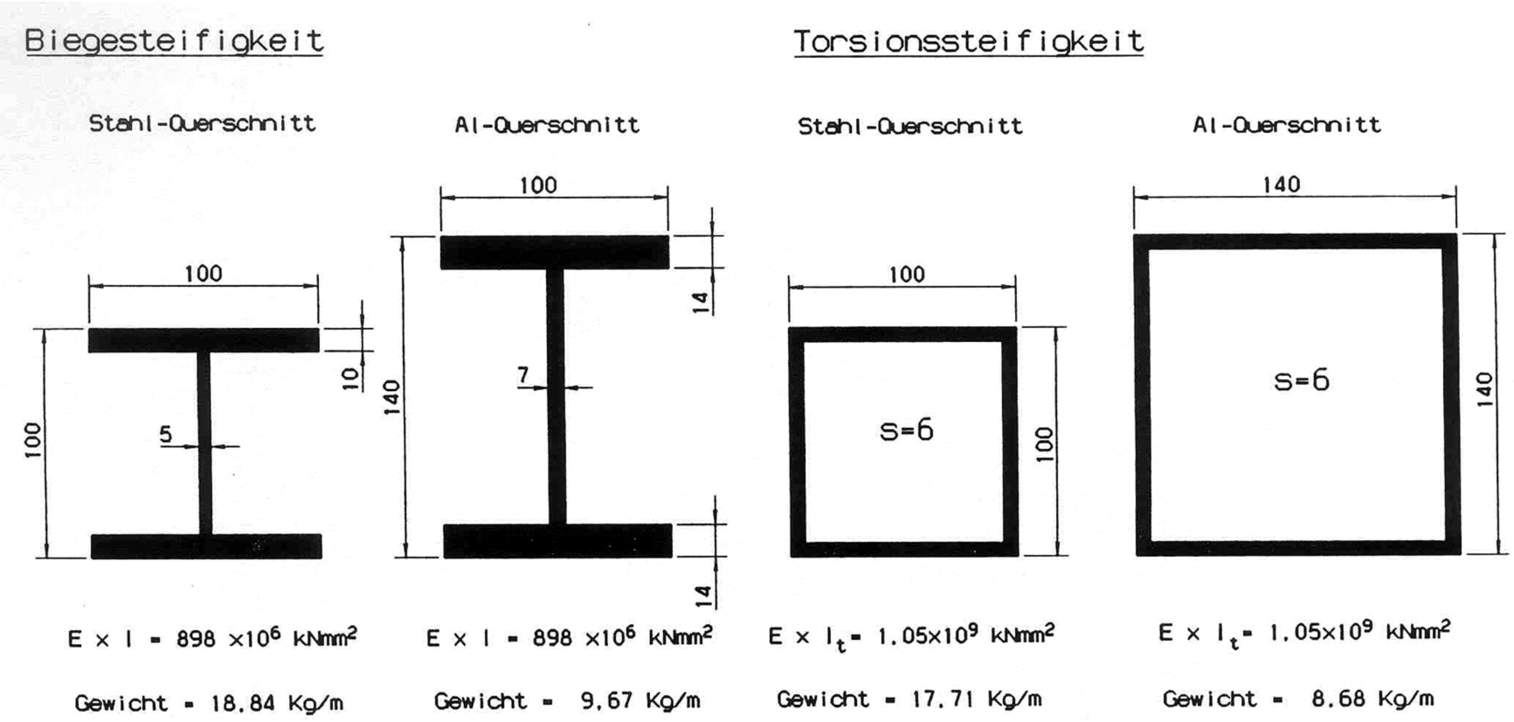
Nonlinear model of material



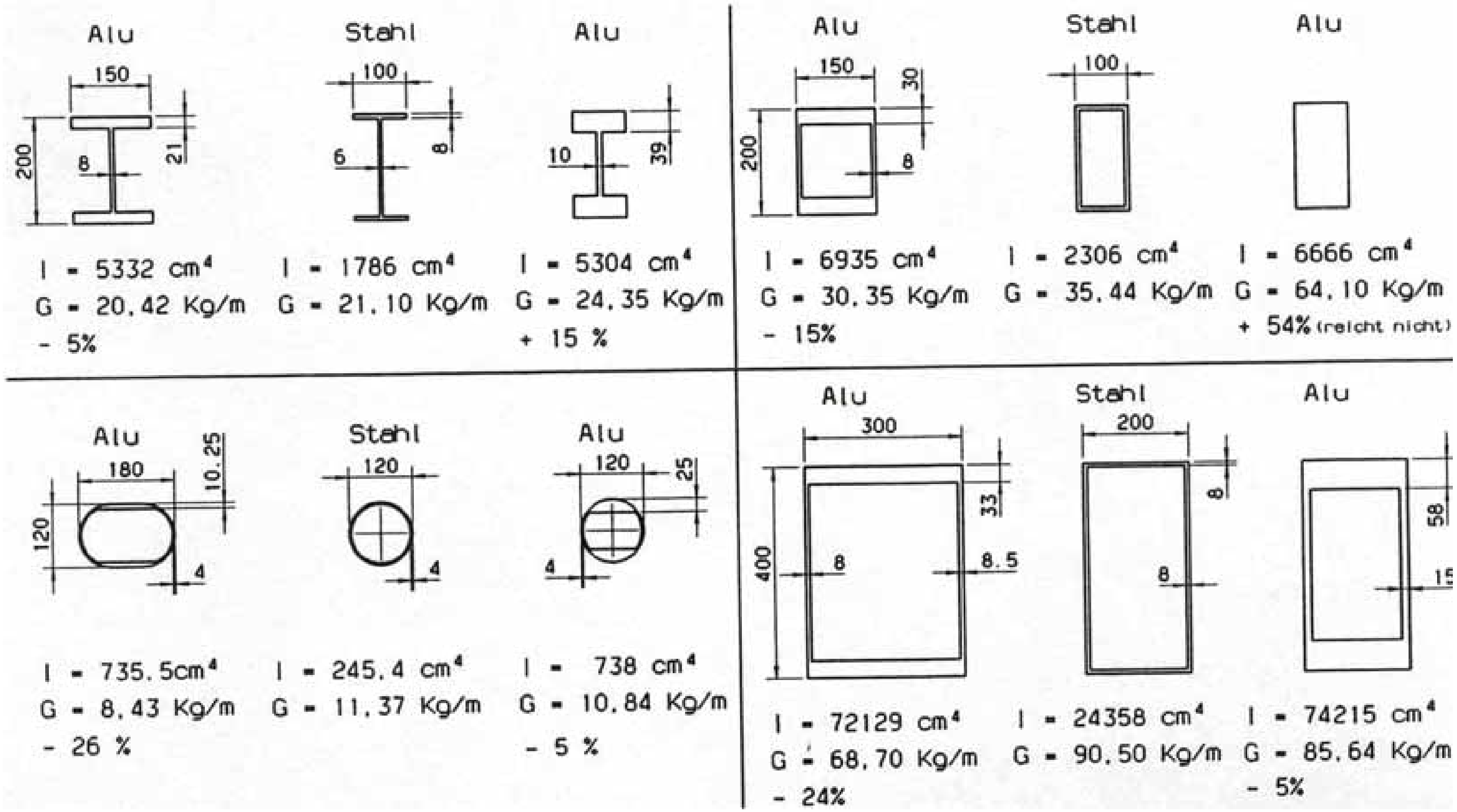
Steel and aluminium sections

	Steel	Aluminium Alloy	Aluminium Alloy	Aluminium Alloy
				
Moment of inertia in mm^4	38,9 E 6	116,6 E6	116,7 E6	117,3 E6
EI (N/mm^2)	8,17 E12	8,16 E12	8,17 E12	8,21 E12
h (mm)	240	240	300	330
b (mm)	120	240	200	200
t (mm)	9,8	18,3	12,9	10
w (mm)	6,2	12	6	6
g (kg/m)	30,7	30,3	18,4	15,8

Aluminium and steel

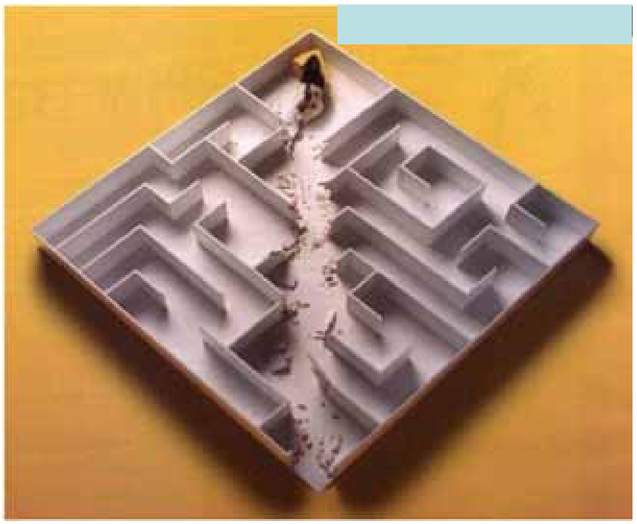


Aluminium and steel



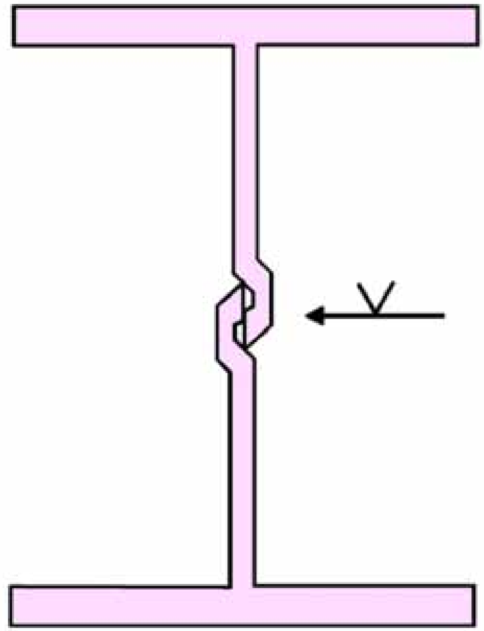
Assessment

- What affest the cost of aluminium structures?
- What knowledge in EN 1999-1-1 supports the other Eurocodes ?
- How are described the material properties of aloys?



Summary

- Weight (2700 kg/m^3)
- Corrosion
- Mon magnetic and low toxic
- Fatigue, low ductility transaction temperature

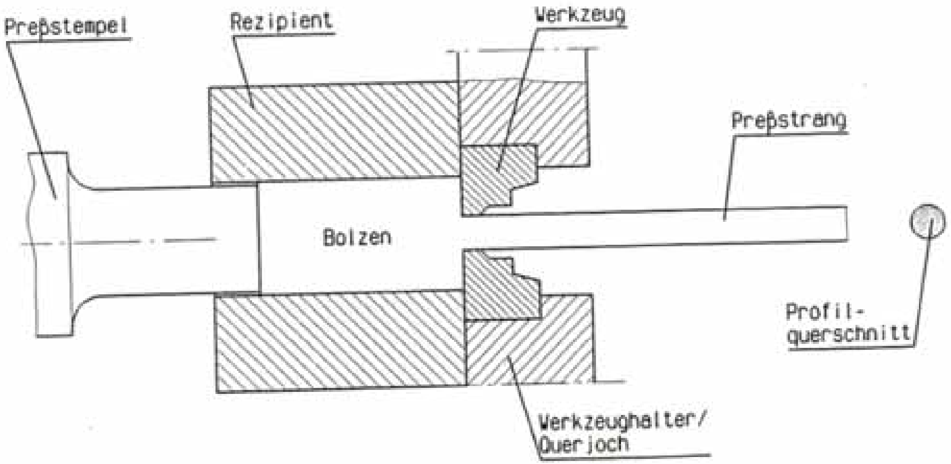


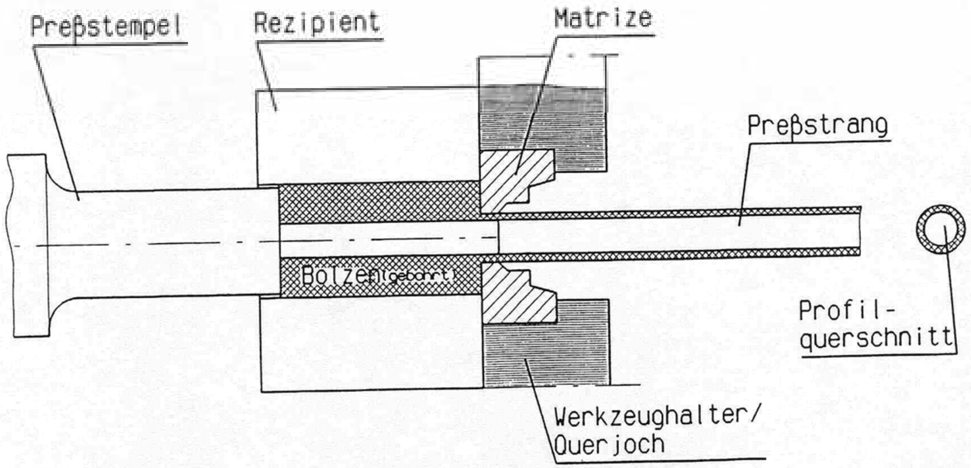
Extrusion - examples

- AlMgSi 6000-serie
  - majority of extrusions good overall performance i.e.
    - relatively easy to extrude
    - medium to high strength in the T6 condition
    - good corrosion resistance in marine and industrial environments
    - good weldability by all welding methods
    - good availability on the market, both as standard and special sections

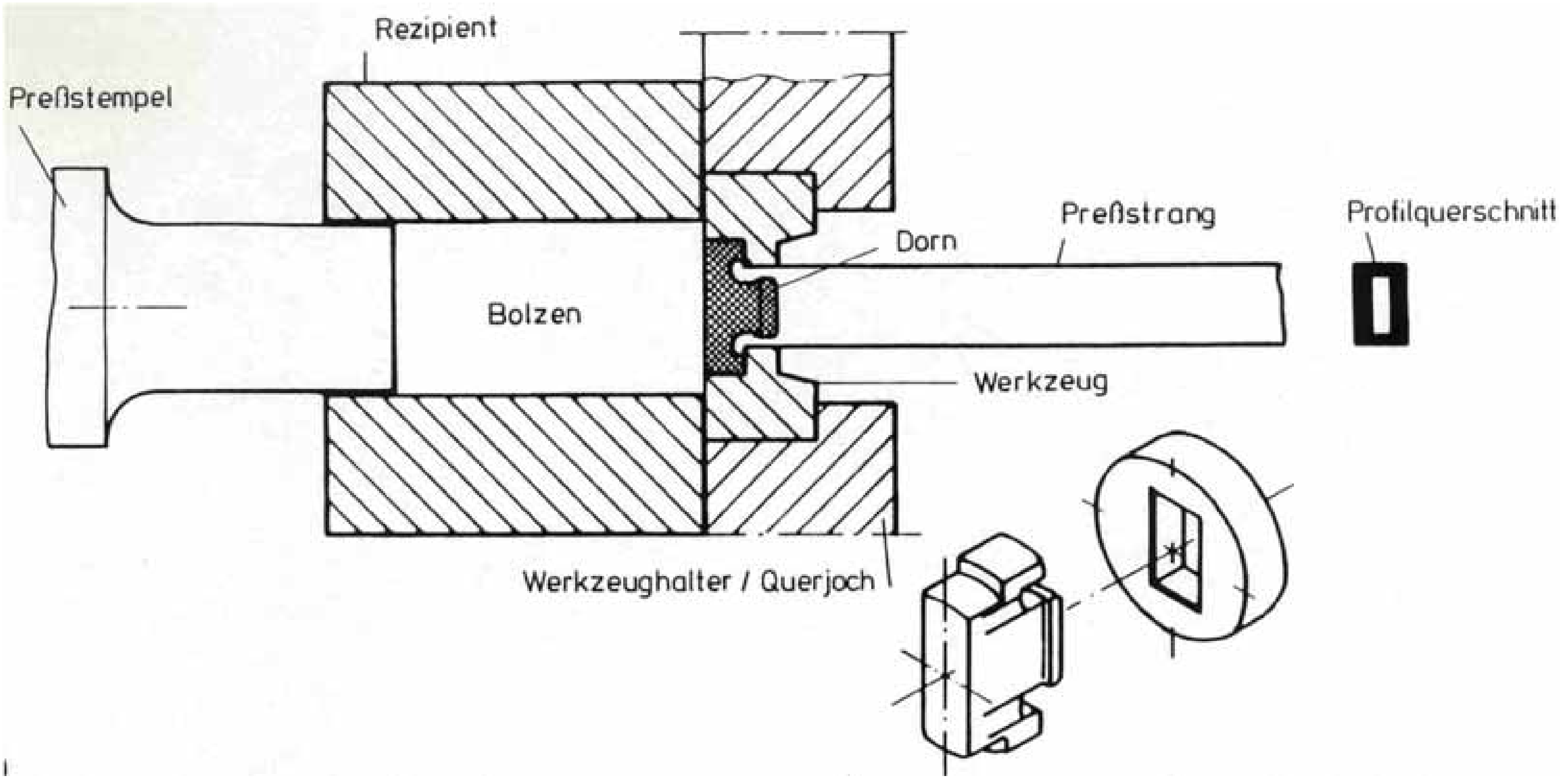
6082 (AlMgSi1Mn) T6 In Europe normal

Extrusion


Preßstempel
Rezipient
Werkzeug
Preßstrang
Bolzen
Profil-
querschnitt
Werkzeughalter/
Querjoch


Preßstempel
Rezipient
Matrize
Preßstrang
Bolzen
Profil-
querschnitt
Werkzeughalter/
Querjoch

Extrusion


Rezipient
Preßstempel
Preßstrang
Profilquerschnitt
Dorn
Bolzen
Werkzeug
Werkzeughalter / Querjoch

Thank you for your kind attention

Notes to users of the lecture

- This session is a basic information about the fire design and requires about 90 min lecturing.
- Further readings on the relevant documents from website of ww.eaa.net/eaa/education/TALA.
- The use of relevant standards of national standard institutions are strongly recommended.
- Formative questions should be well answered before the summative questions completed within the tutorial session.
- Keywords for the lecture:

  aluminium structures, material, production, examples, Eurocodes.