Metal Structures

Lecture II

Physical, chemical and mechanical properties

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The most important properties

	Steel	Aluminum
dead weight [kN/m^3], d	78,5	27,0
melting point [^{o}C], T_m	1 538	660
boiling point [^{o}C], T_b	2 861	2 060
Young modulus [GPa], E	210	70
Kirchhoff modulus [GPa], G	81	27
Poisson ratio, ν	0,30	0,33
thermal expansion [10^{-6}/ ^{o}C], α_T	11,8	23,0

Young and Kirchhoff modulus

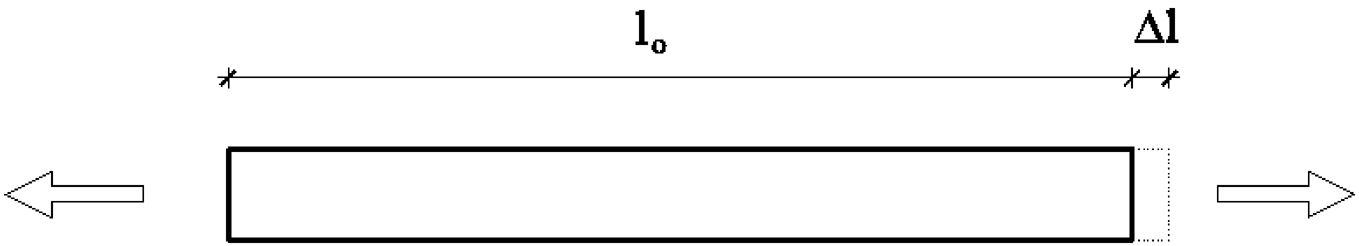


Photo: Author

$\varepsilon E = \sigma$ (Hooke's law; true for linear elastic deformations only)

$$\varepsilon = \Delta l / l_o$$

$$\Delta l\, E / l_o = \sigma$$

$$\Delta l = l_o \rightarrow \Delta l + l_o = 2\, l_o \rightarrow \varepsilon = \Delta l / l_o = 1 \rightarrow E = \sigma$$

Young modulus = theoretical stress, when the element is 2 times longer

$$G = E / (2 + 2\, \nu)$$

Poisson ratio

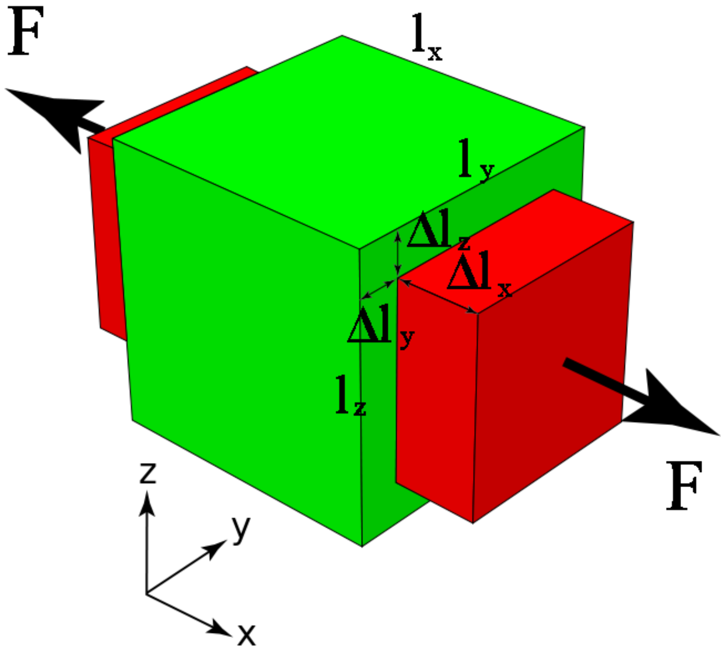


Photo: wikipedia

$$\varepsilon_x = \Delta l_x / l_x$$

$$\varepsilon_y = \Delta l_y / l_y = \varepsilon_z = \Delta l_z / l_z$$

$$\nu = \varepsilon_y / \varepsilon_x = \varepsilon_z / \varepsilon_x$$

Thermal expansion

$$T_0 \rightarrow l_0$$

$$T_0 \text{ +/- } \Delta T \rightarrow l_0 \text{ +/- } \Delta l$$

$$\Delta l / l_0 = \Delta T \, \alpha_T$$

Example:

IPE 500 ($A = 116\ cm^2$); $l_0 = 20{,}0\ m$; $\Delta T = 20^oC$

$$\Delta l = l_0 \, \Delta T \, \alpha_T = 0{,}4\ mm$$

The same effect for axial force:

$$N_{Ed} / (E\,A) = \Delta l / l_0$$

$$N_{Ed} = E\,A\,\Delta l / l_0 = 48{,}720\ kN \;\; ; \;\; \sigma(N_{Ed}) = 4{,}200\ MPa$$

Homogenous, isotropic

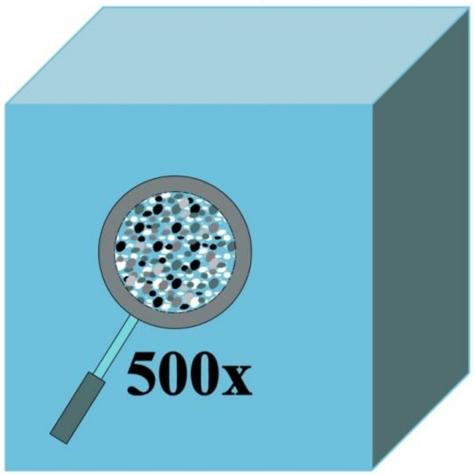


Photo: Author

Strength

f (tension) = f (compression)

f the same in each direction

<u>Universal testing machine</u>

EN 10 002-1

Photo: Author

Photo: feiplar.com.br

Shapre of specimen

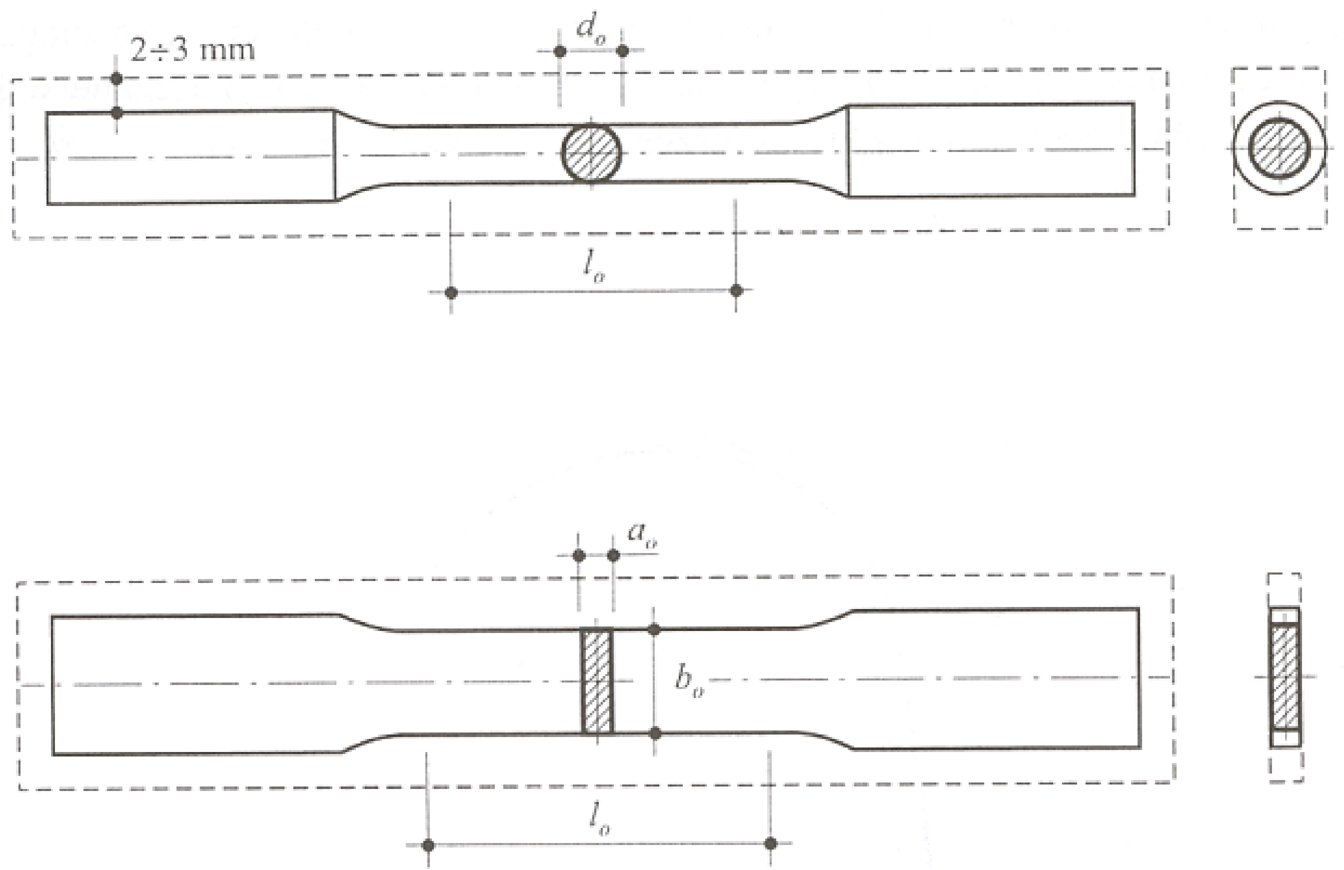


Photo: Konstrukcje stalowe, K. Rykaluk,
Dolnośląskie Wydawnictwo Edukacyjne
Wrocław 2001

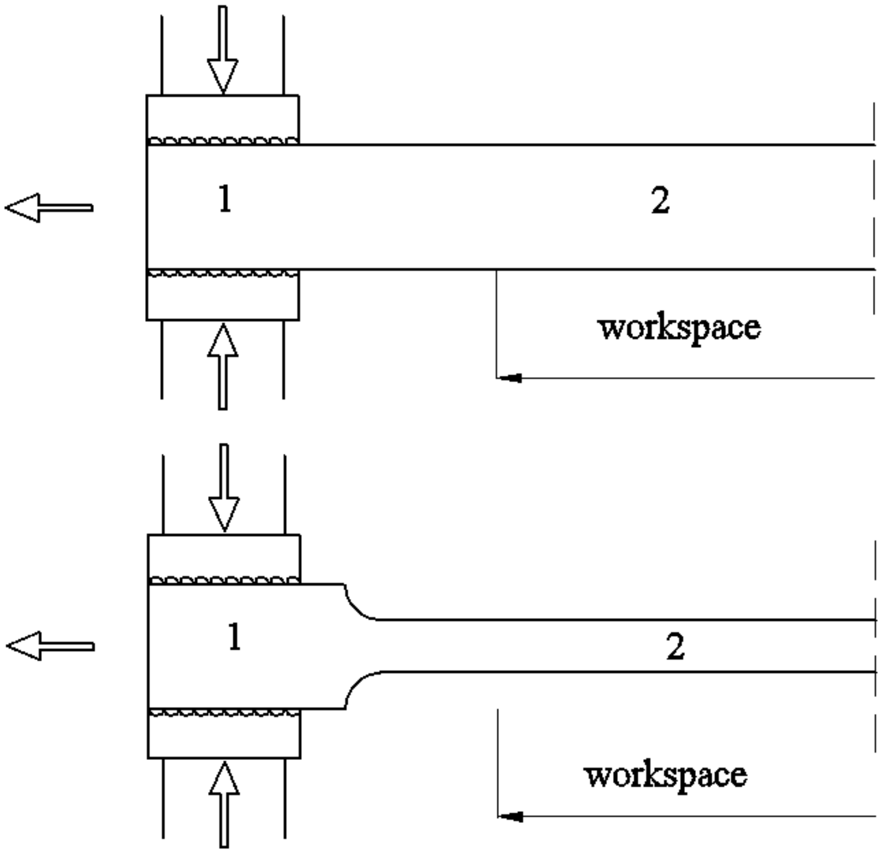


Photo: Author

$A = const$

$\sigma_{HMH,1} \geq \sigma_{HMH,2}$

possible destruction outside the workspace

$A \neq const$

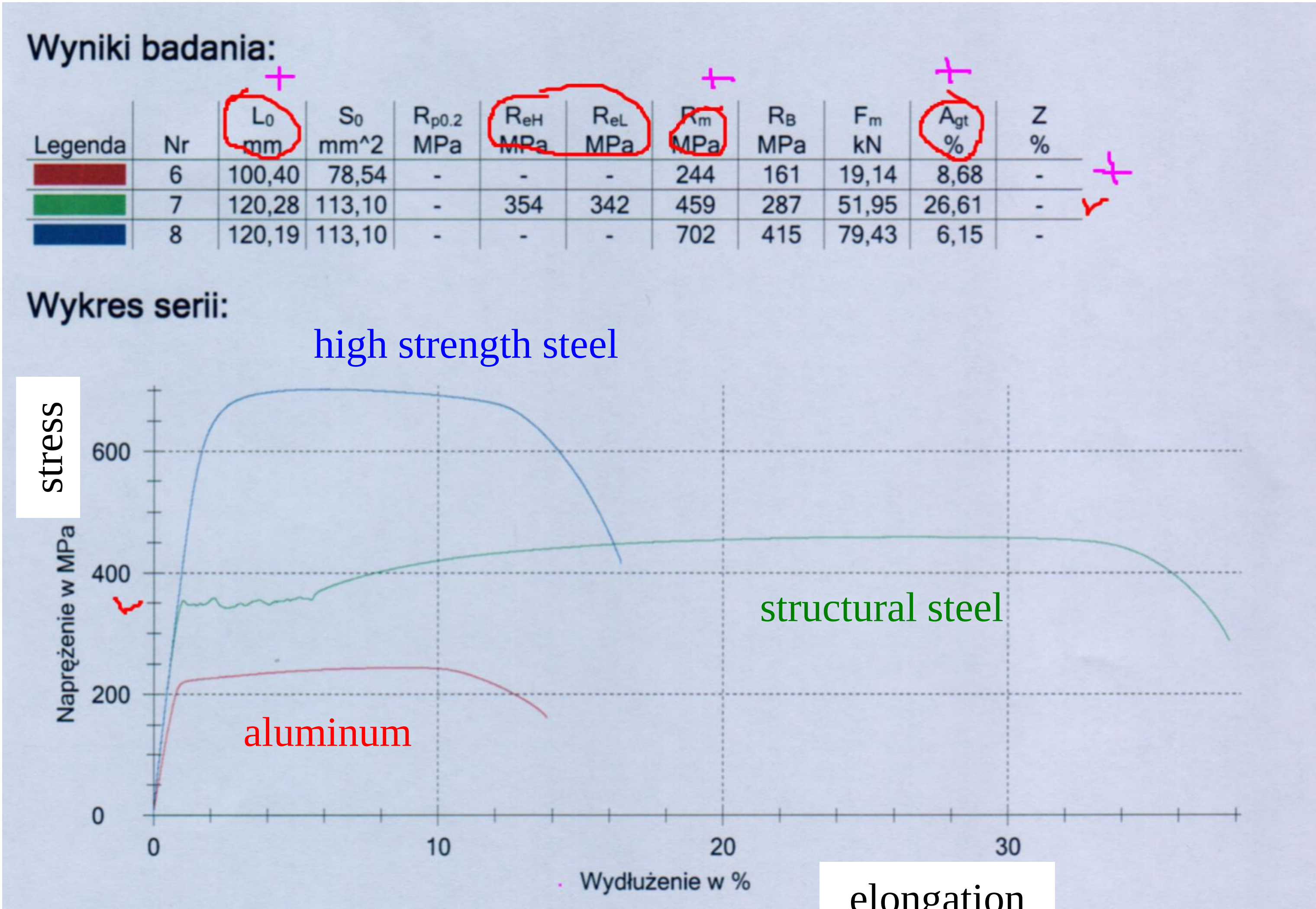
$\sigma_{HMH,1} \leq \sigma_{HMH,2}$

destruction within the workispace

Speciment is put into jaws of U.T.M and stretched

Photo: paragonsystems.ca

The results for structural steel, alumnium and special steel (non-structural steel):



Wyniki badania:

Legenda	Nr	L_0 mm	S_0 mm^2	$R_{p0.2}$ MPa	R_{eH} MPa	R_{eL} MPa	R_m MPa	R_B MPa	F_m kN	A_{gt} %	Z %
	6	100,40	78,54	-	-	-	244	161	19,14	8,68	-
	7	120,28	113,10	-	354	342	459	287	51,95	26,61	-
	8	120,19	113,10	-	-	-	702	415	79,43	6,15	-

Wykres serii:

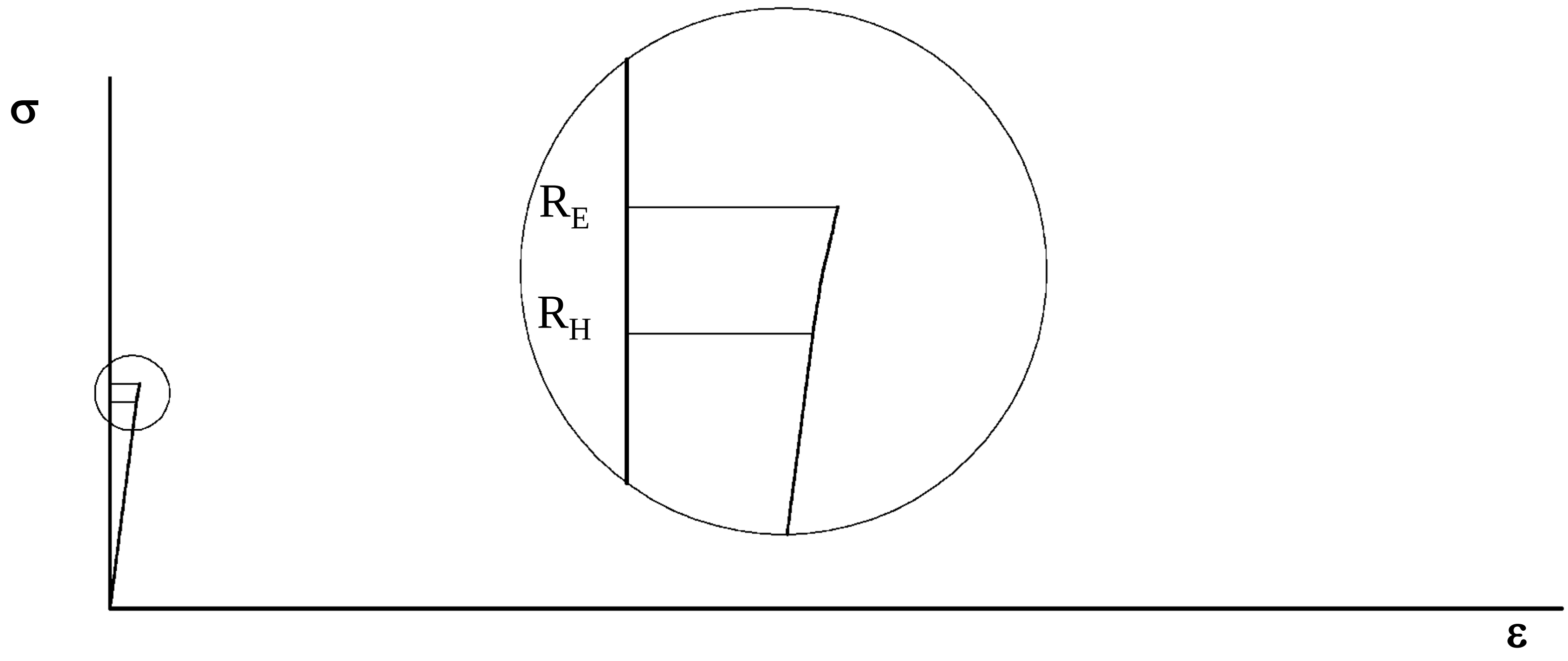
Photo: Author

Structural steel

Linear elastic part of relationship **σ–ε**. For this part E = const. Hooke's law is true.

Photo: Author

Nonlinear elastic part (between R_H and R_E) of relationship **σ–ε**. For this part E ≠ const. Hooke's law is true, but there is trouble wiht measure of Young modulus. There are no special measurable phenomenons for R_H. Value of R_H depends only on accuracy of test - for low accuracy we can miss that E ≠ const.



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Plastic (nonlinear) part of relationship **σ–ε** - plastic shelf. Deformations increase for nearly constant value of load.

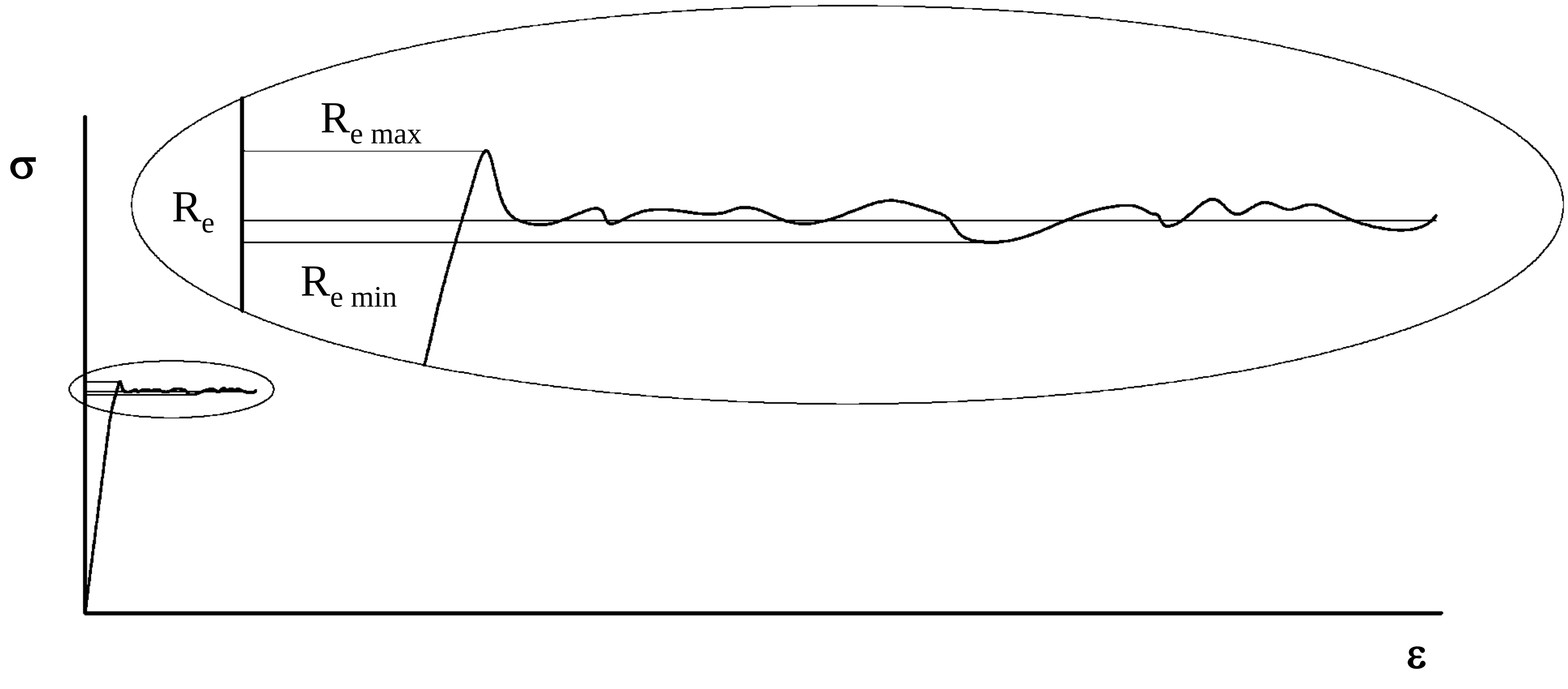


Photo: Author

Idealization:

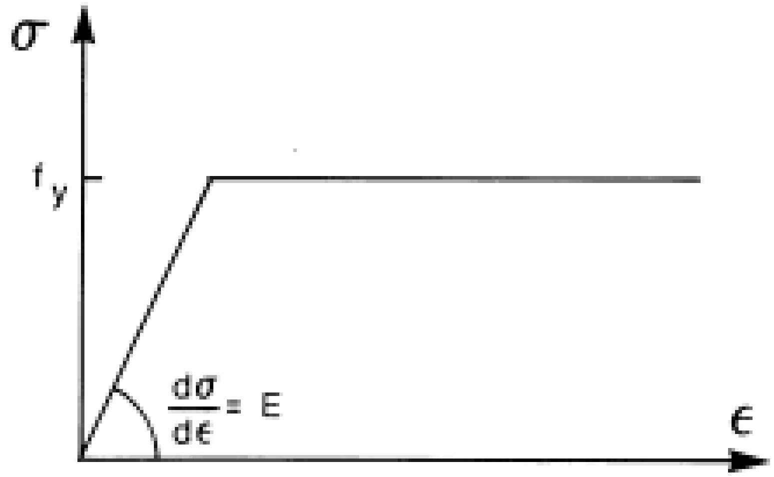
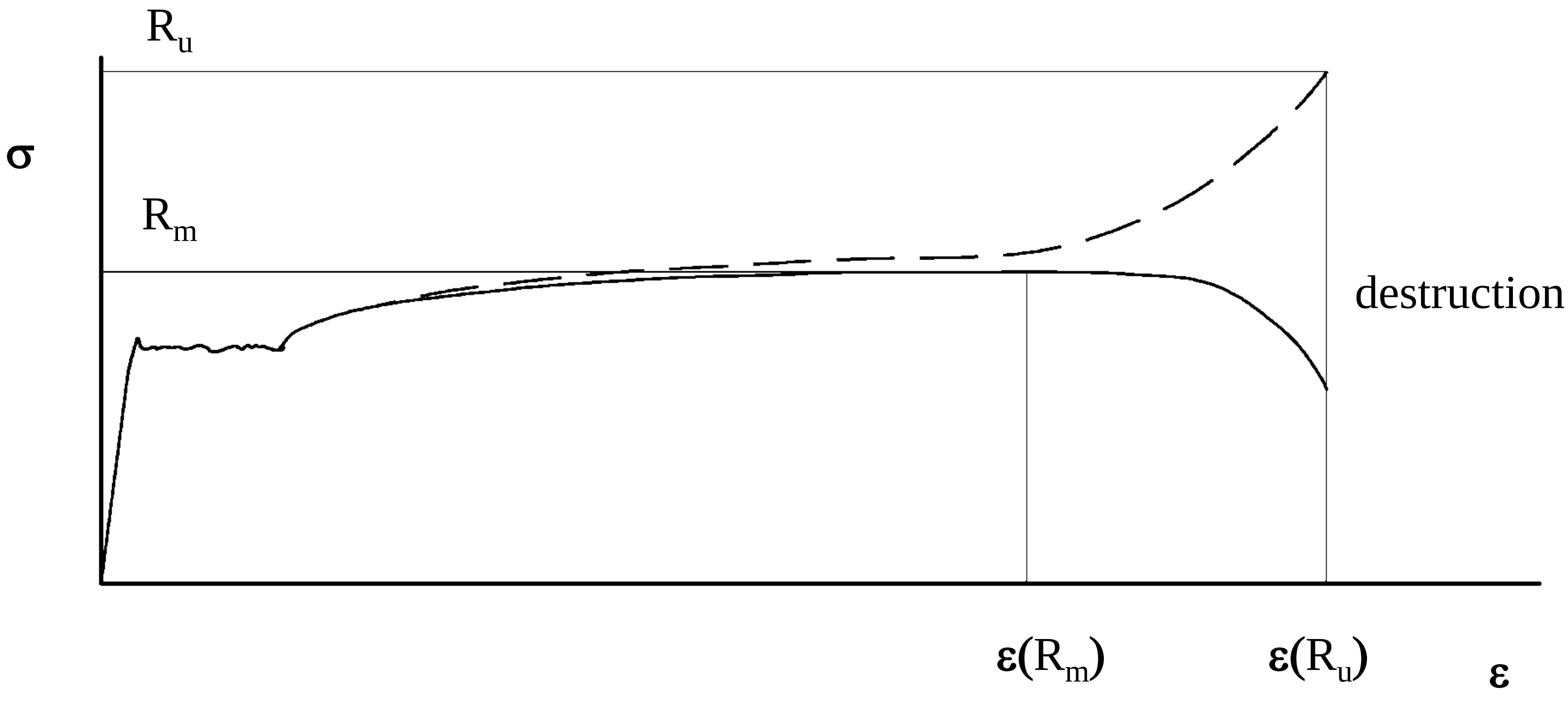


Figure 5.3: Bi-linear stress-strain relationship

Photo: EN 1993-1-1 fig. 5.3

Plastic (nonlinear) part of relationship **σ–ε** after plastic shelf. There are two possibilities of relationships:

- continued line; **σ** = F / $A_{initial}$
- dashed line; **σ** = F / $A_{present}$



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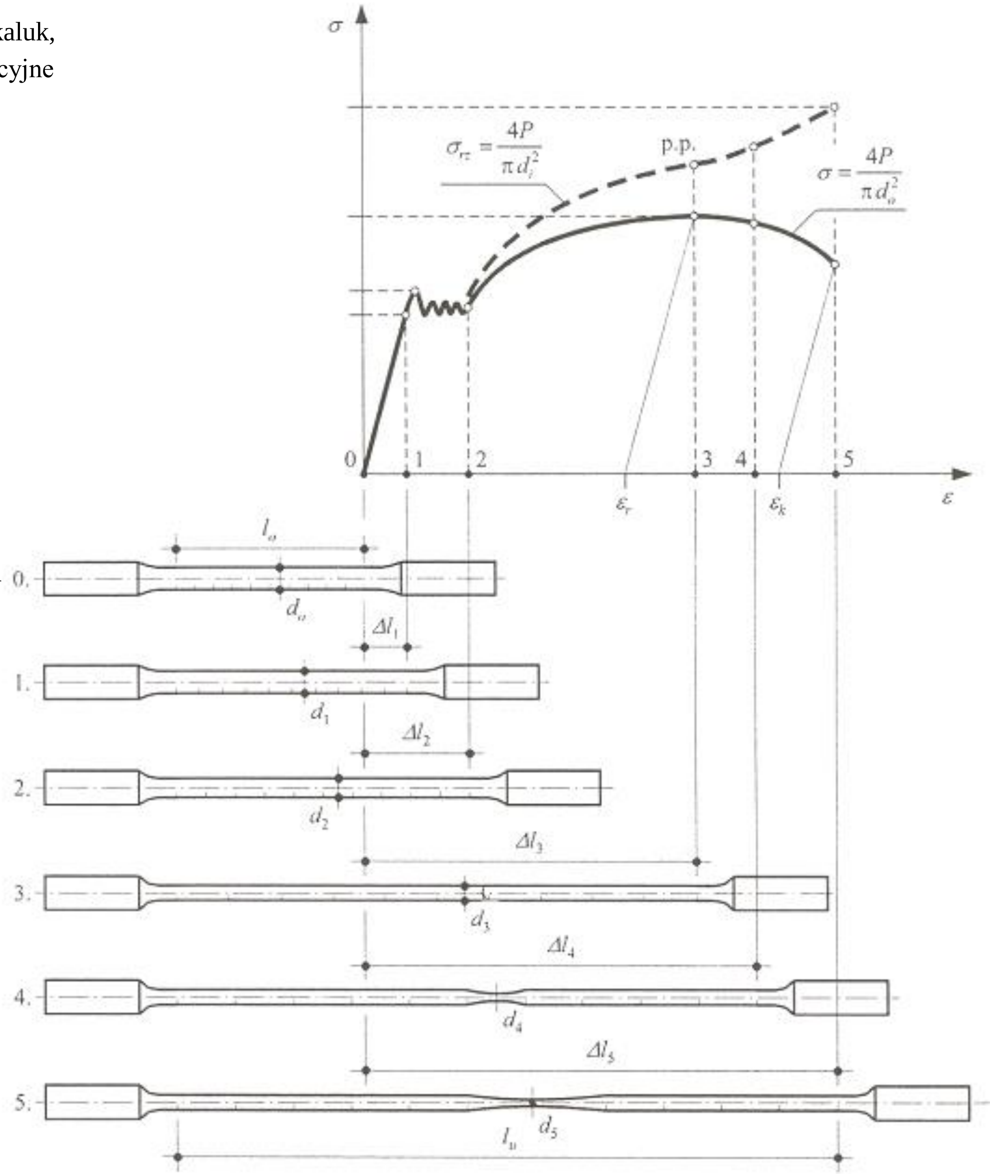


$A_{initial}$

$A_{present}$ (reduction of area during testing)

Speciment after testing - tension

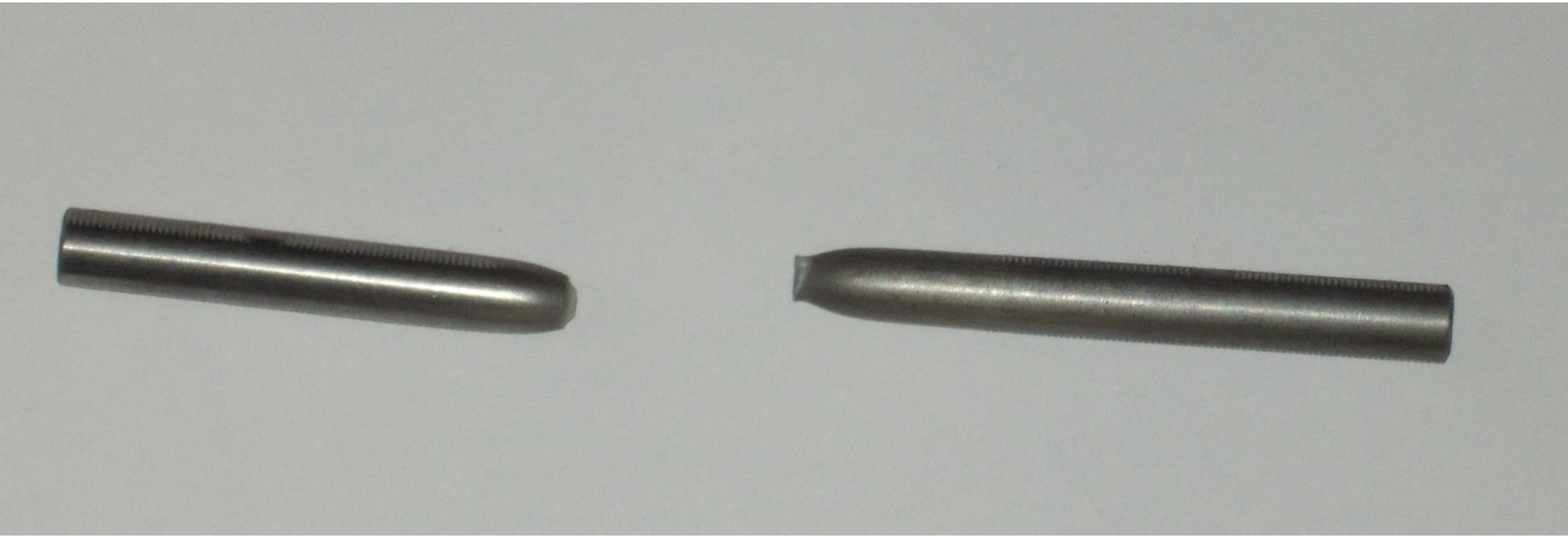


Photo: Author

(informal speciment, A = const)

Increase and decrease value of load: if $\boldsymbol{\sigma} \le R_E$ (elastic range), there is still the same line on diagram.

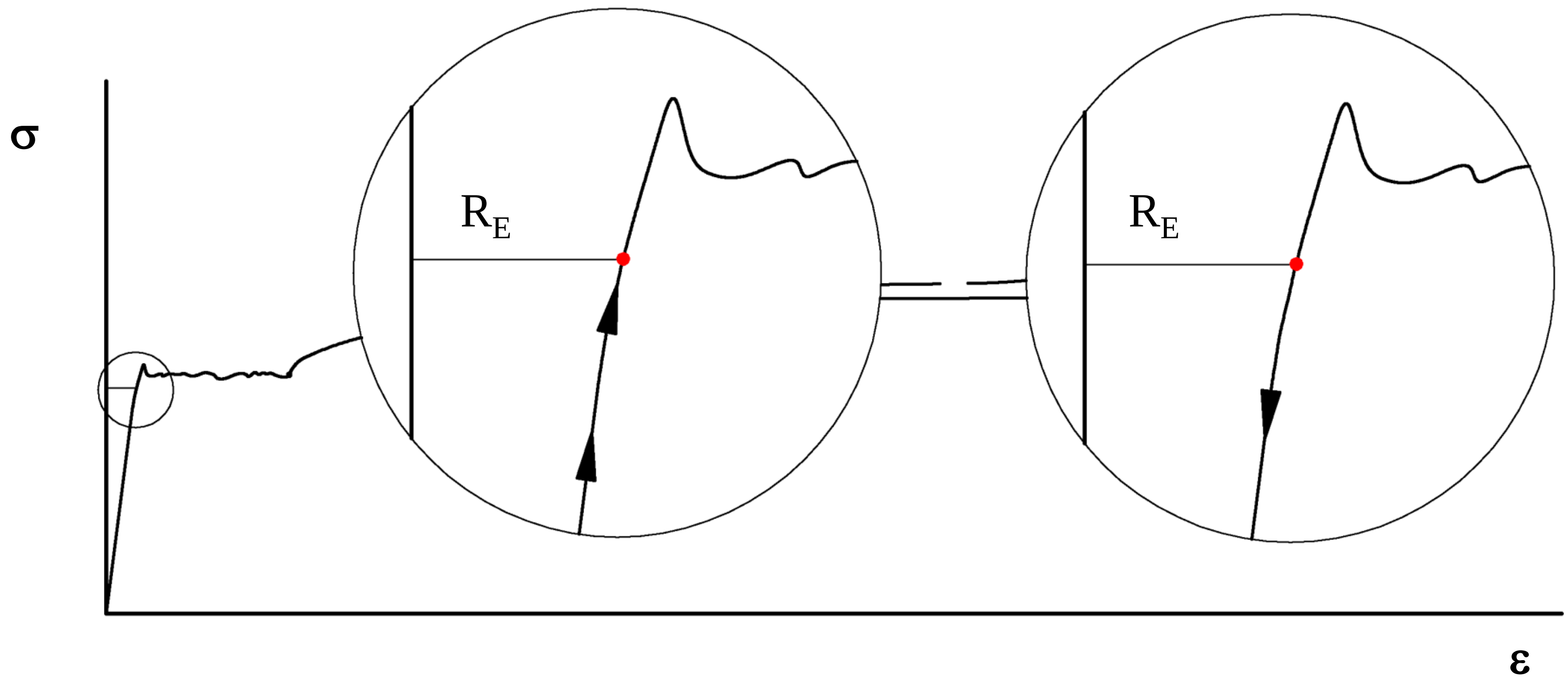


Photo: Author

Increase and decrease value of load: if $\boldsymbol{\sigma} > R_E$ (plastic range), there is other line for decreasing; parallel to linear elastic part. There is non-zero value of plastic deformation $\boldsymbol{\varepsilon}_{pl}$ after cycle of increase-decrease of loads.

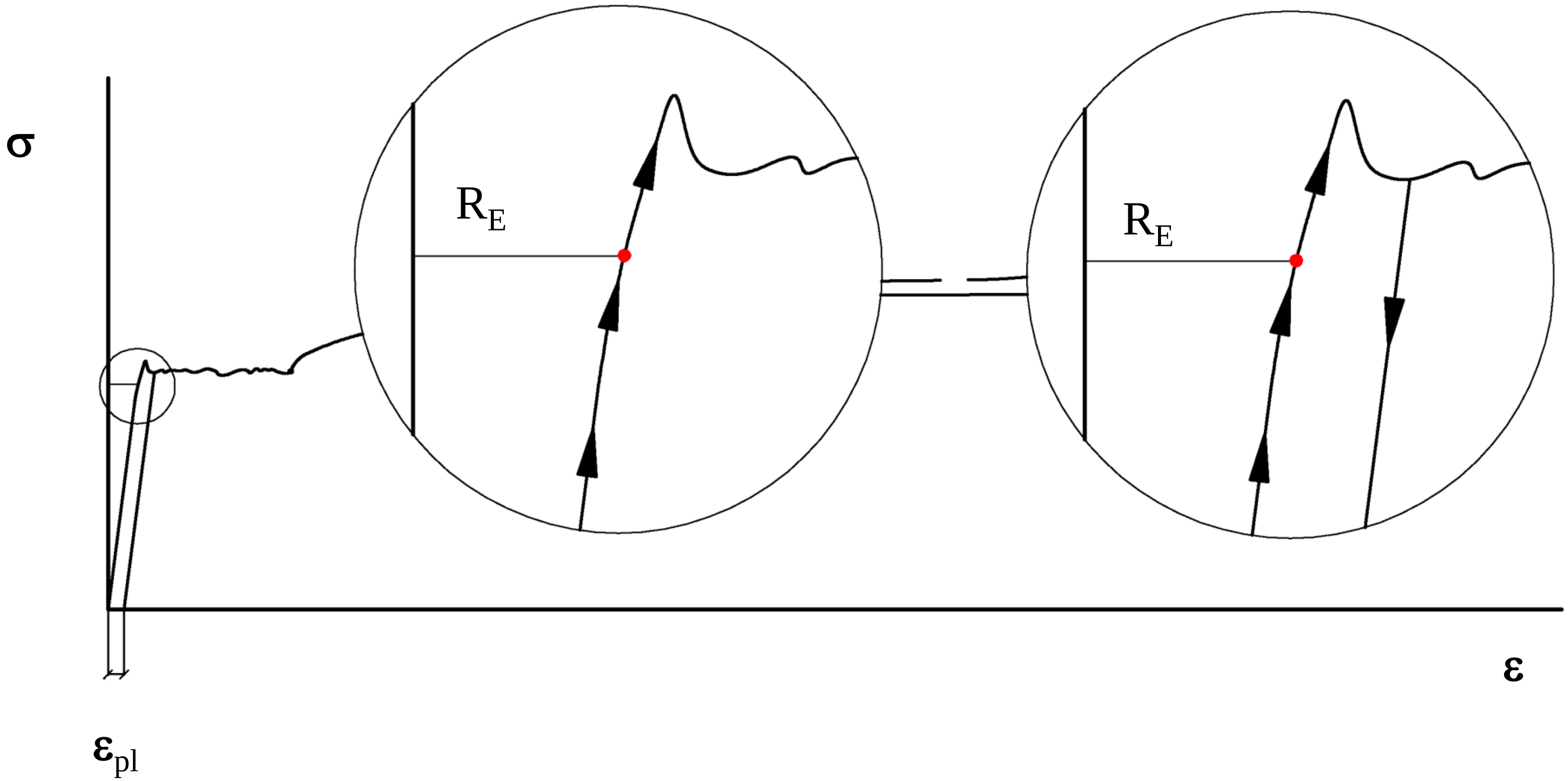
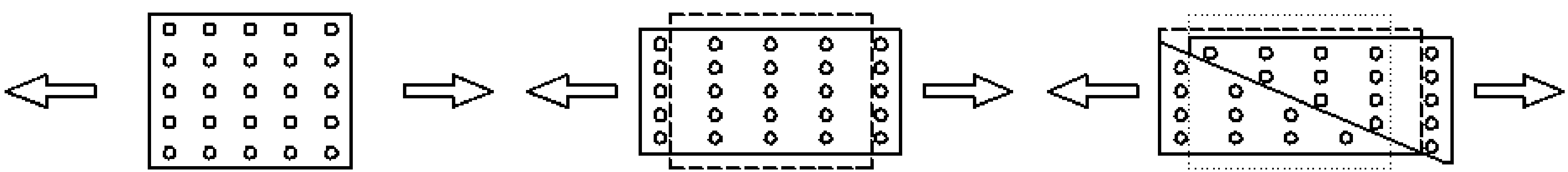


Photo: Author

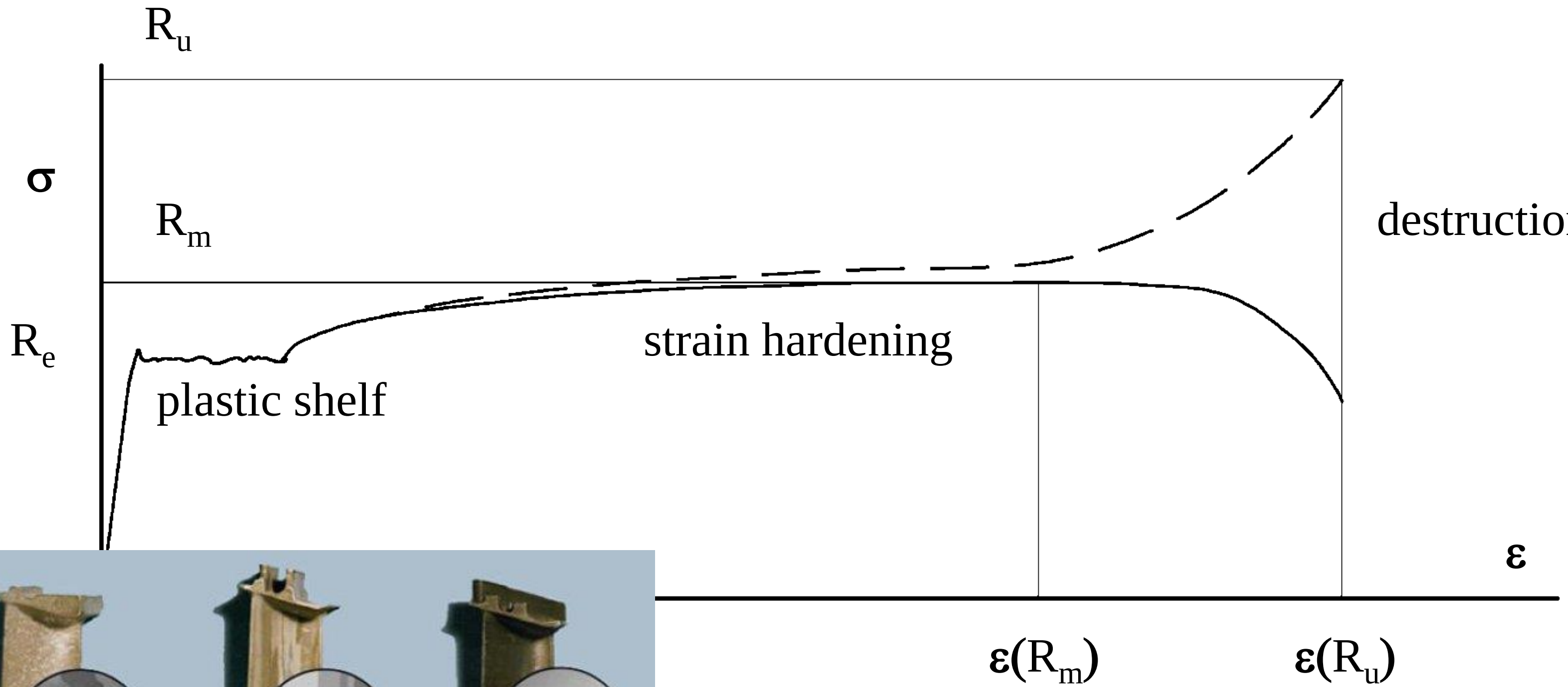
For elastic range of behaviour, deformations are effects of change of distance between molecules. This type of deformation is reversible - after elliminating of loads, molecules return to initial positions.



For plastic range of behaviour, deformations are effects of shearing of cristals. This type of deformation is irreversible - there is need compression to eliminate deformations.

Photo: Author

Photo: Author



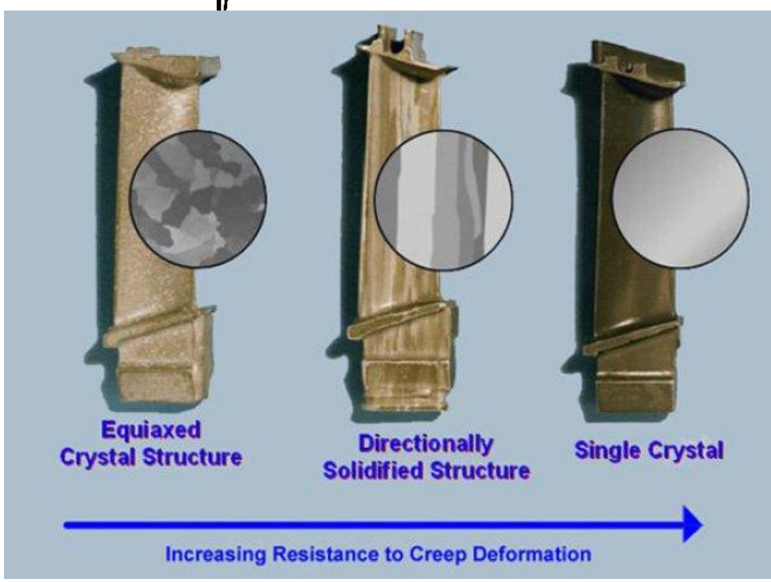


Photo: makezine.com

There is, as the effect of tension, change of crystals shape. Directionally structure of cristals has bigger strength in direction of force, than equalized structure. Because of this, after plastic shelf (R_e), occurs increasing of strength (R_m, R_u)named strain hardening.

Return to the zero value of plastic deformation is possible only after compression to plastic range of deformation.

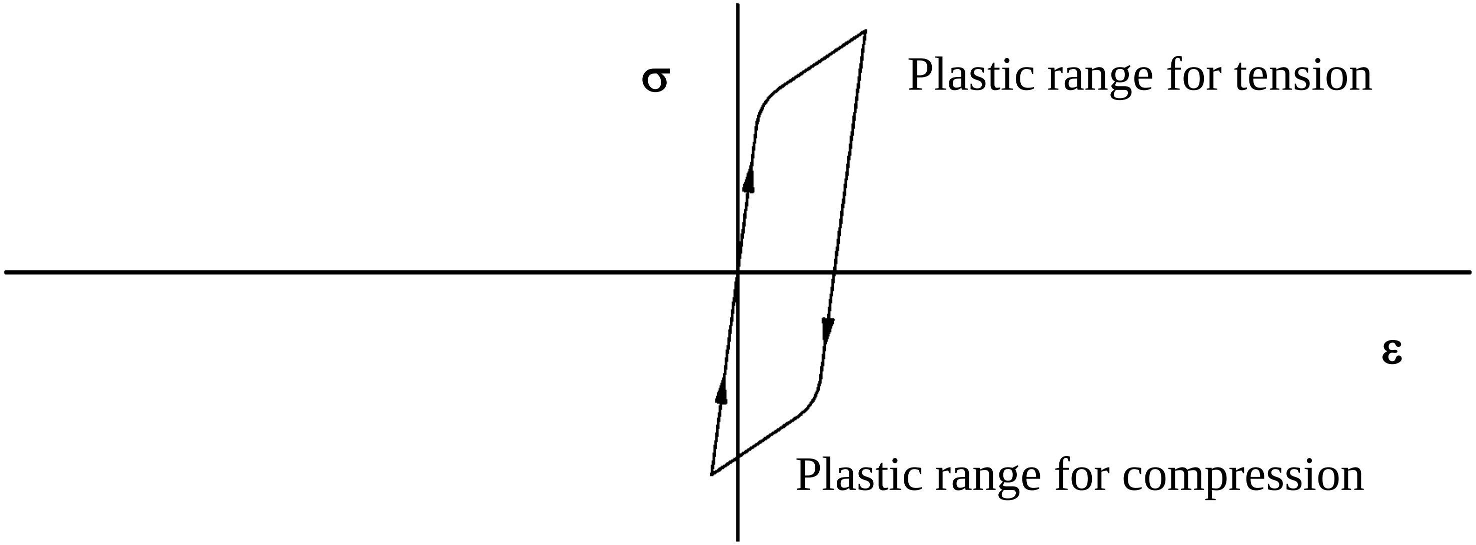


Photo: Author

There is no plastic shelf for alumnium and special steel. There are no special phenomenons for R_e

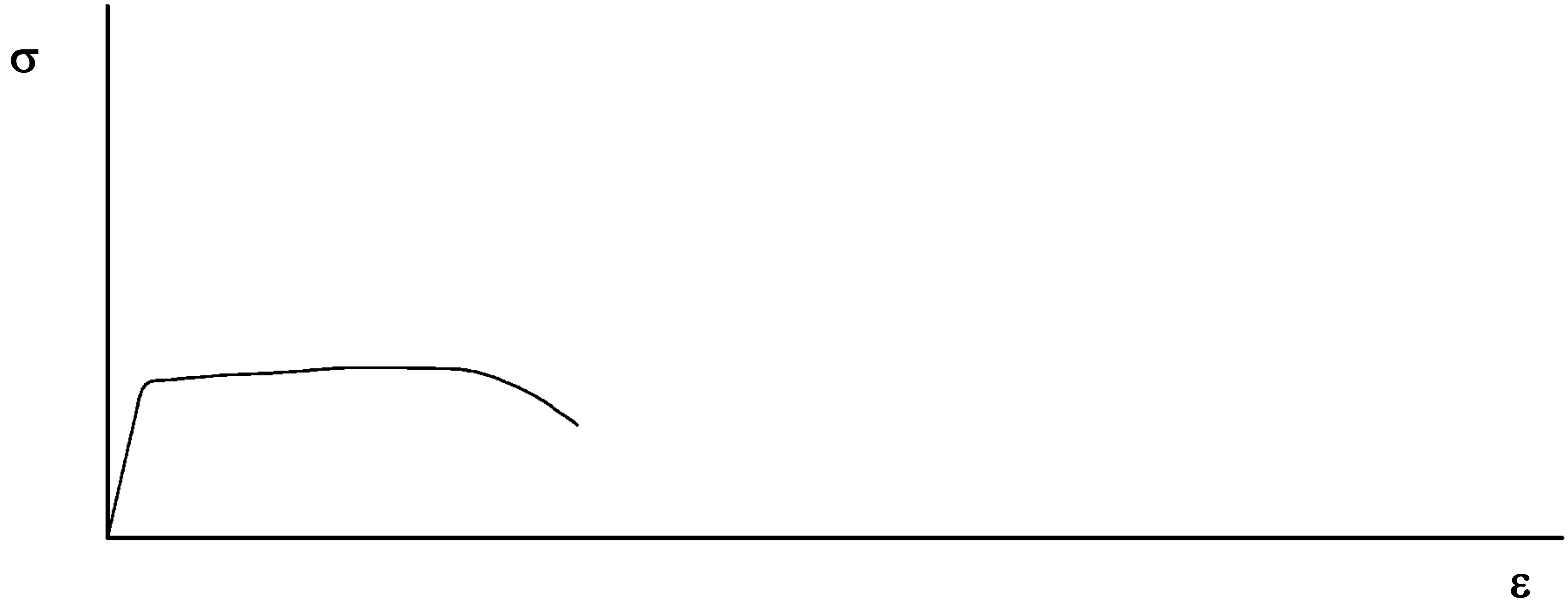


Photo: Author

On this situation as R_e is taken value of $\boldsymbol{\sigma}$ for which plastic deformation is equal 0,2%.

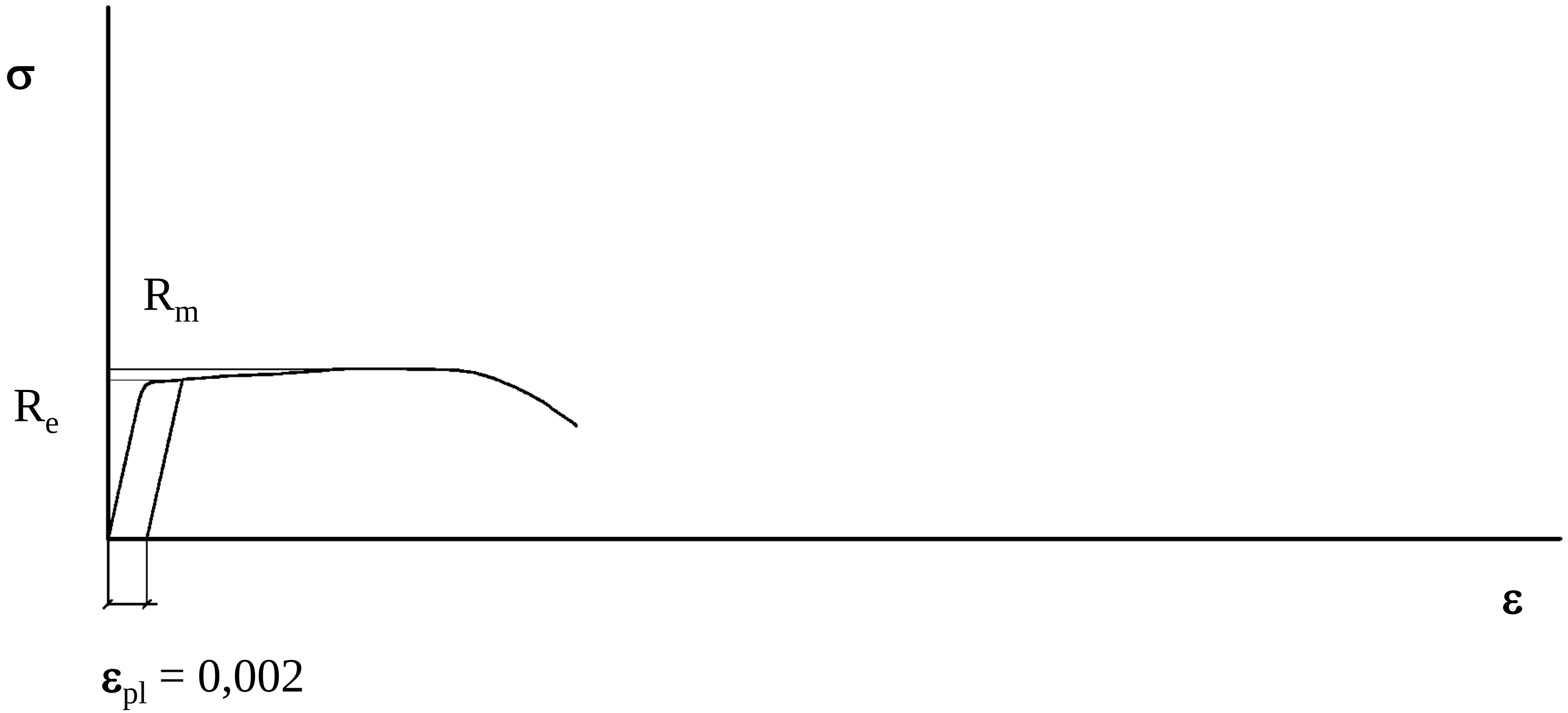


Photo: Author

There is buckling for compression test.

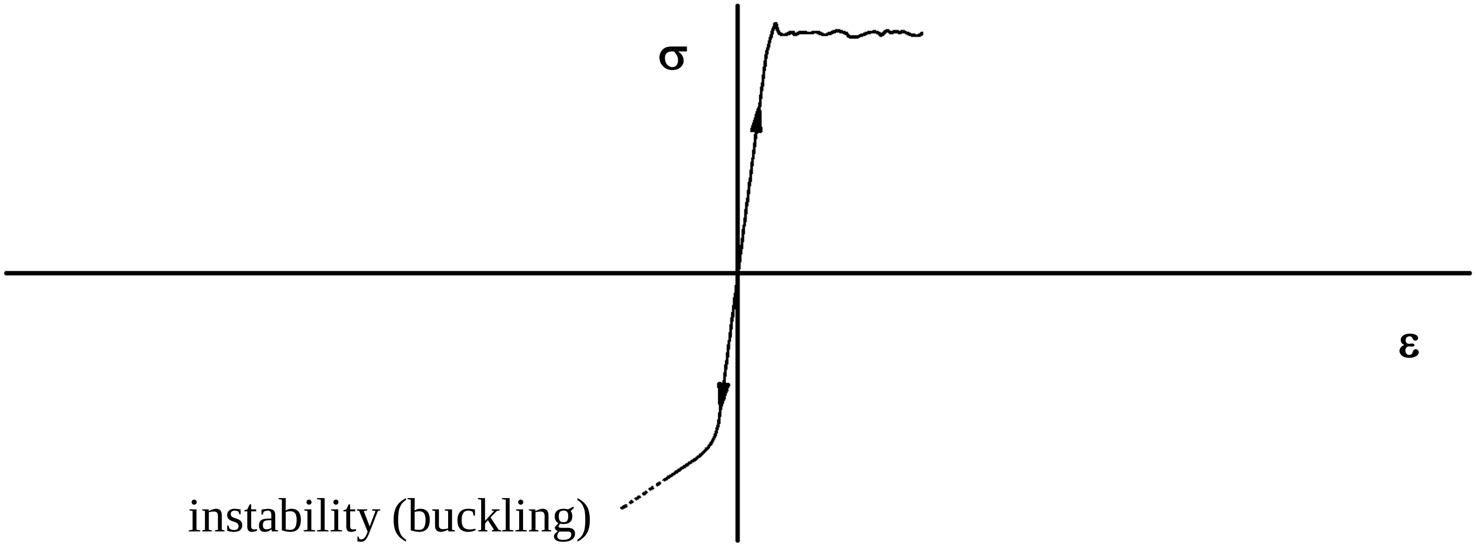


Photo: Author

Speciment after testing - compression

Photo: Author

(no information about the mechanical properties from this type of test)

When increase of load is made immediately after decrease, there is no change for relationship **σ–ε**.

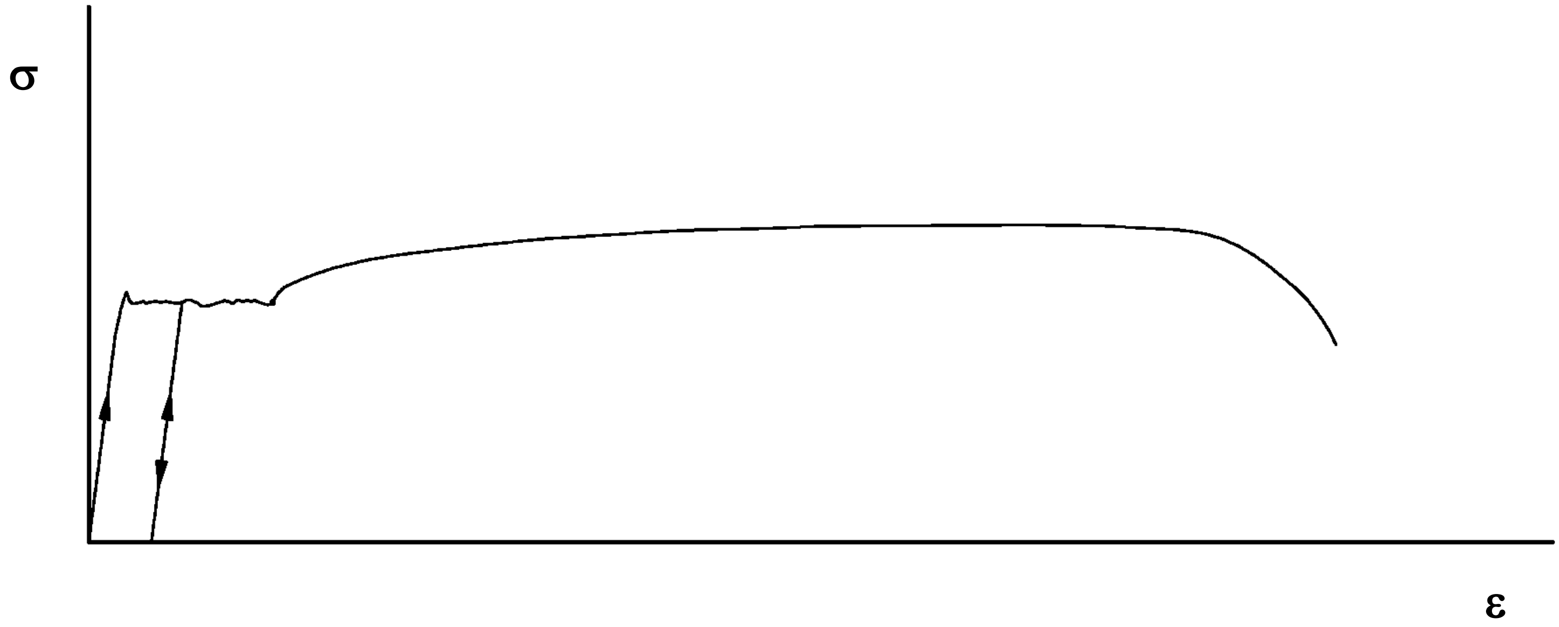


Photo: Author

When increase of load is made few days after decrease, there is recrystallisation in analysed sample. The effect is completely change of mechanical parameters of steel and new relationship **σ–ε**, for new axis of **σ**. There is no plastic shelf, R_e (stress for which ε_{pl} = 0,2%) and R_m have much more higher values, max deformation is smaller. These phenomenons are very important for steel for tension components.

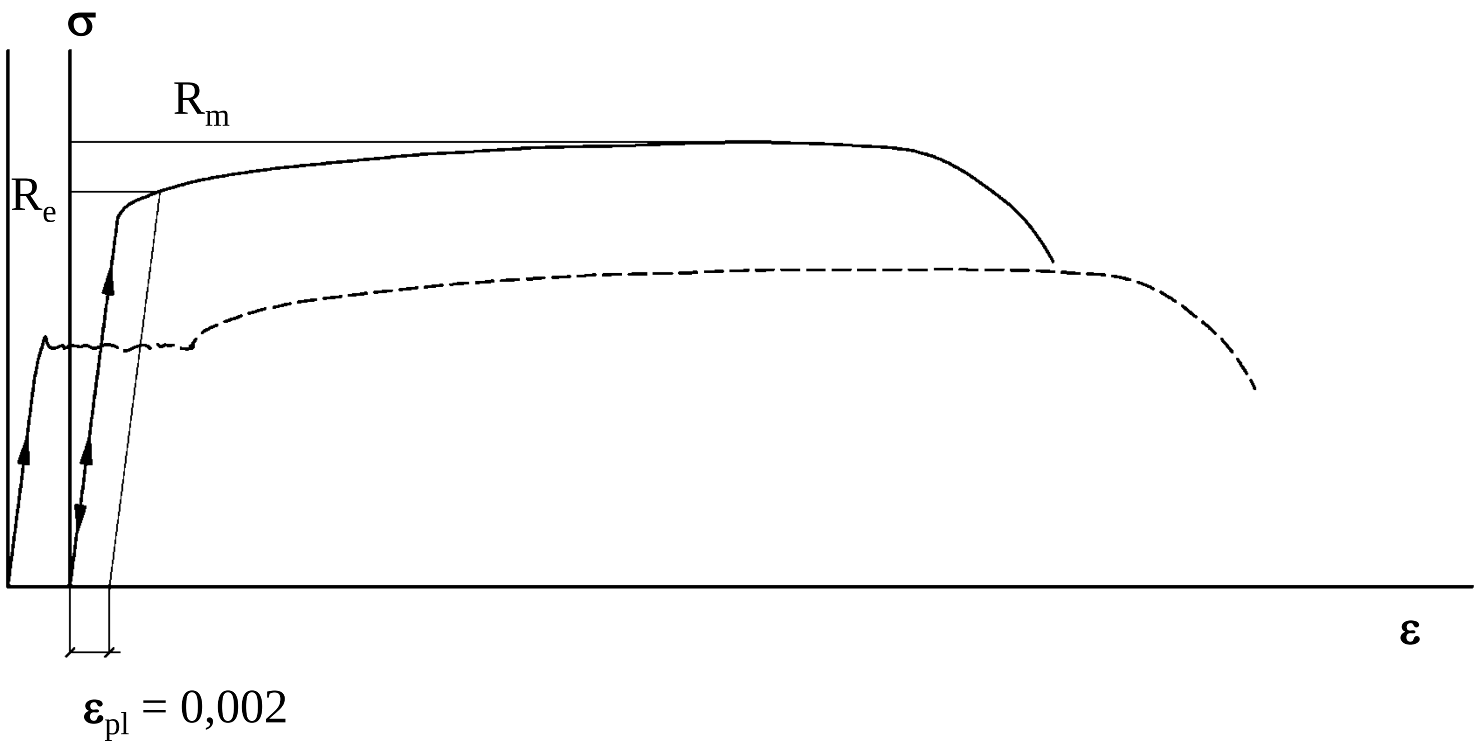


Photo: Author

Analysis of results

$R_e \rightarrow f_y$ yeld strength

$R_m \rightarrow f_u$ ultimate tensile strength

For example:

$R_e = 285$ MPa

$R_m = 400$ MPa

$f_y =?$

$f_u = ?$

Results – for example 60 specimens

#	R_e [MPa]
1	294,8
2	268,9
3	255,6
4	255,9
5	279,2
...	...
60	274,8

$$(R_1 , R_2 , R_3 \ldots R_{60}) = (294{,}8 ; 268{,}9 ; 255{,}6 ; 255{,}9 ; 279{,}2 \ldots 274{,}8)$$

Change the order of the results:

$$R_{min} \leq R_a \leq R_b \leq R_c \leq \ldots \leq R_{max} \rightarrow 229{,}2 ; 231{,}1 ; 237{,}7 ; 245{,}1 \ldots 326{,}3$$

$$R_{min} = 229{,}2 \text{ MPa}$$

$$R_{max} = 326{,}3 \text{ MPa}$$

Grouping the results into categories:

Limits [MPa] (Δ_R = 20 MPa)	220-240	240-260	260-280	280-300	300-320	320-340
Number of results	3	12	20	14	10	1

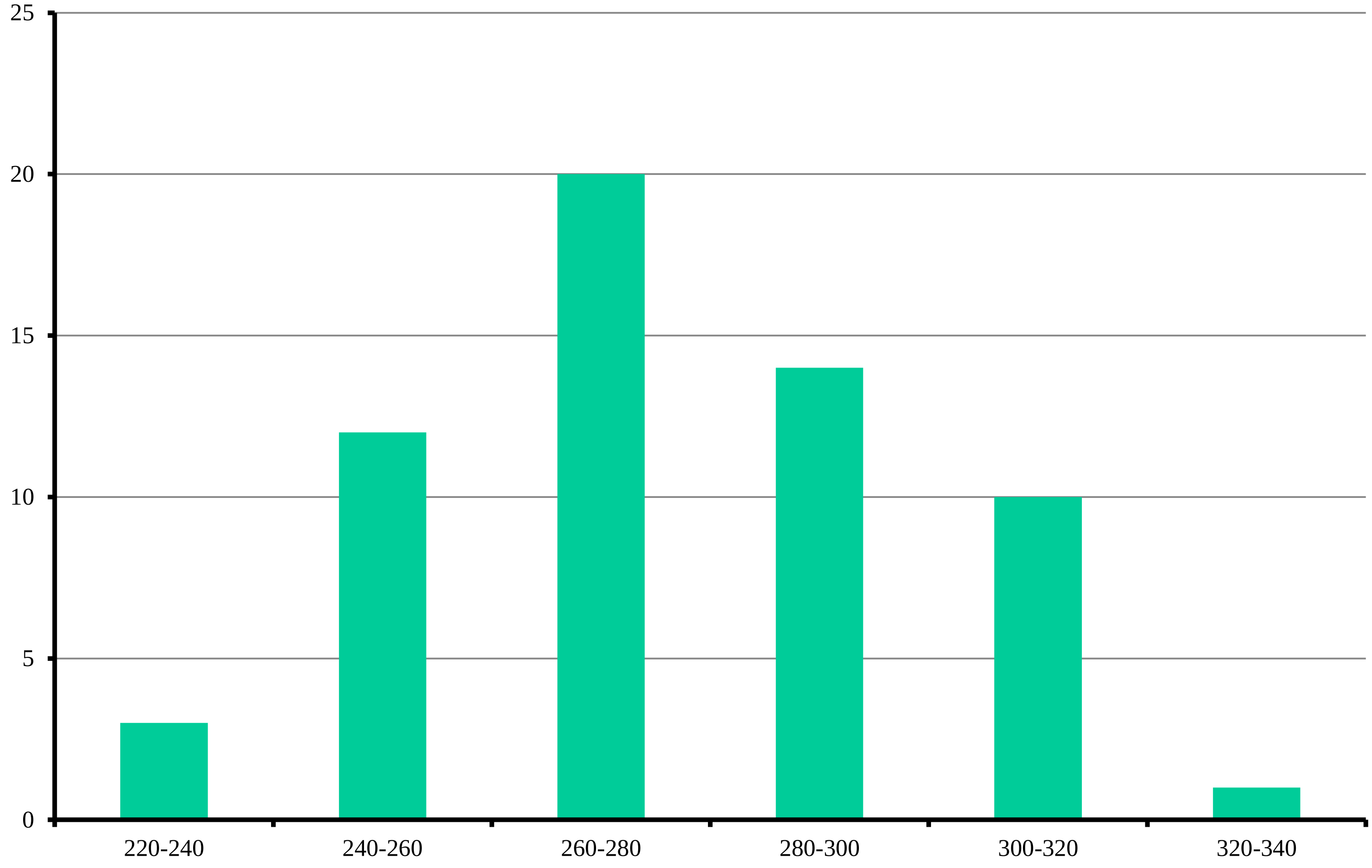


Photo: Author

Normalisation: number of results in cathegory / total number of results

Sum of height of the bars = 1

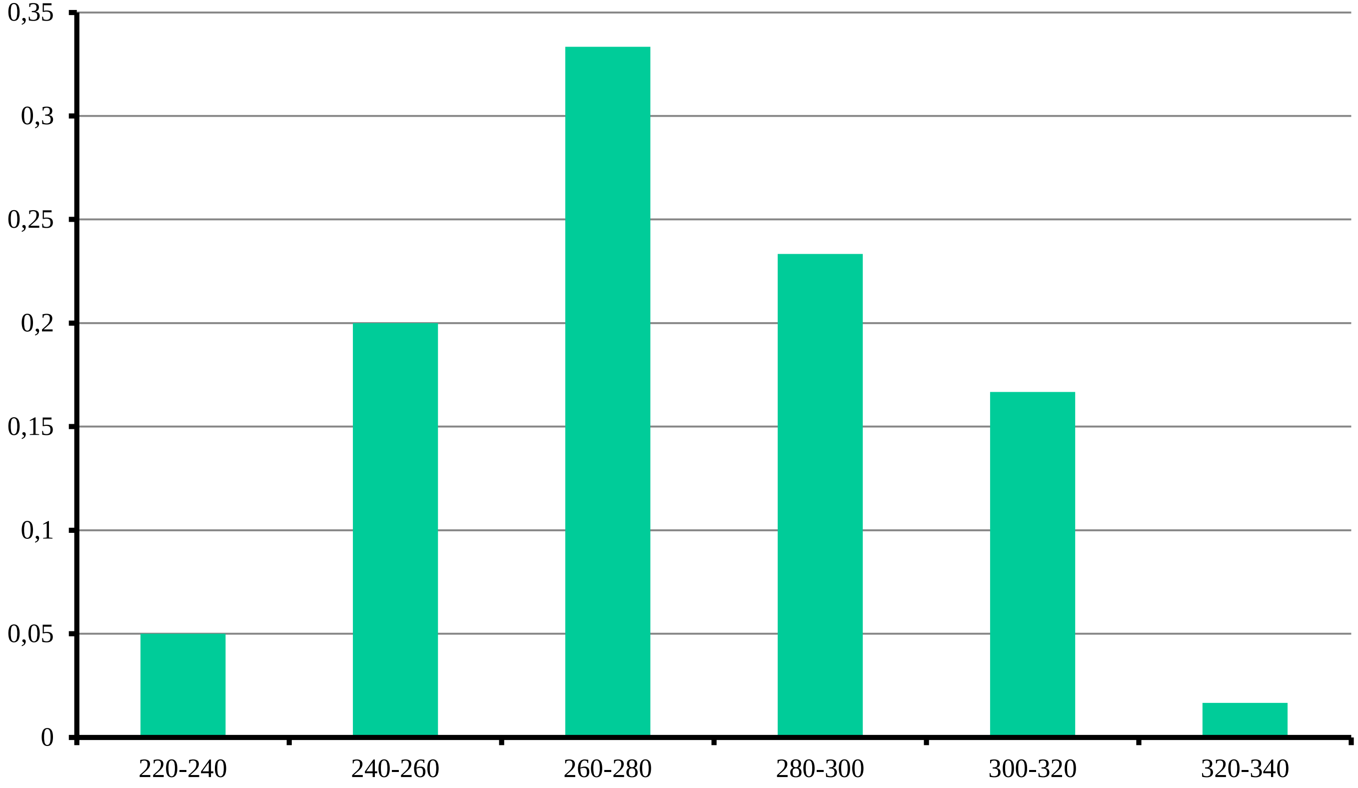


Photo: Author

This type of results we can described by a normal distribution $\phi(x)$:

$$\phi(x) = \frac{1}{\sigma_{Re}\sqrt{2\pi}} \exp\left(-\frac{(x-\mu_{Re})^2}{2\sigma_{Re}^2}\right)$$

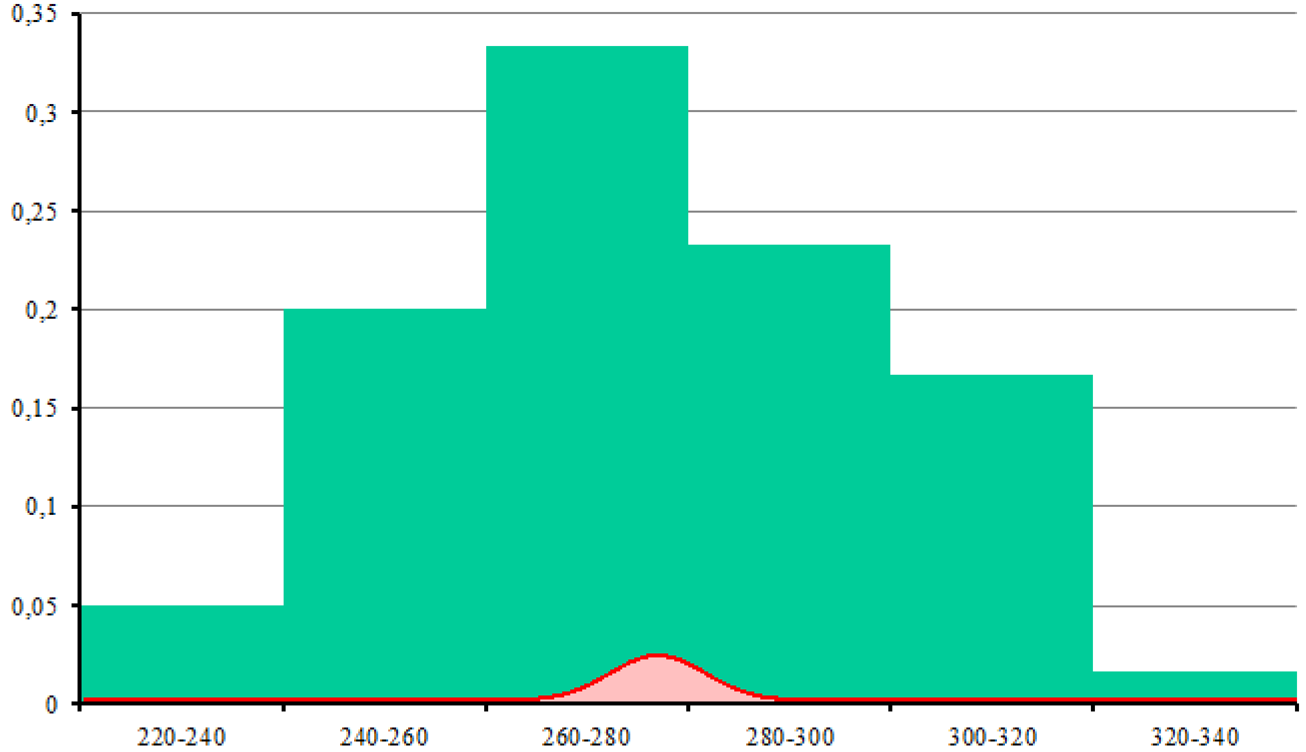
$$x = R_{e,i}$$

$$\mu_{Re} = (\Sigma R_{e,i}) / n \quad \text{(average)}$$

$$\sigma_{Re} = \sqrt{\{[\Sigma (R_{e,i} - \mu_{Re})^2] / n\}} \quad \text{(standard deviation)}$$

The same way of recalculations for R_m

Photo: Author



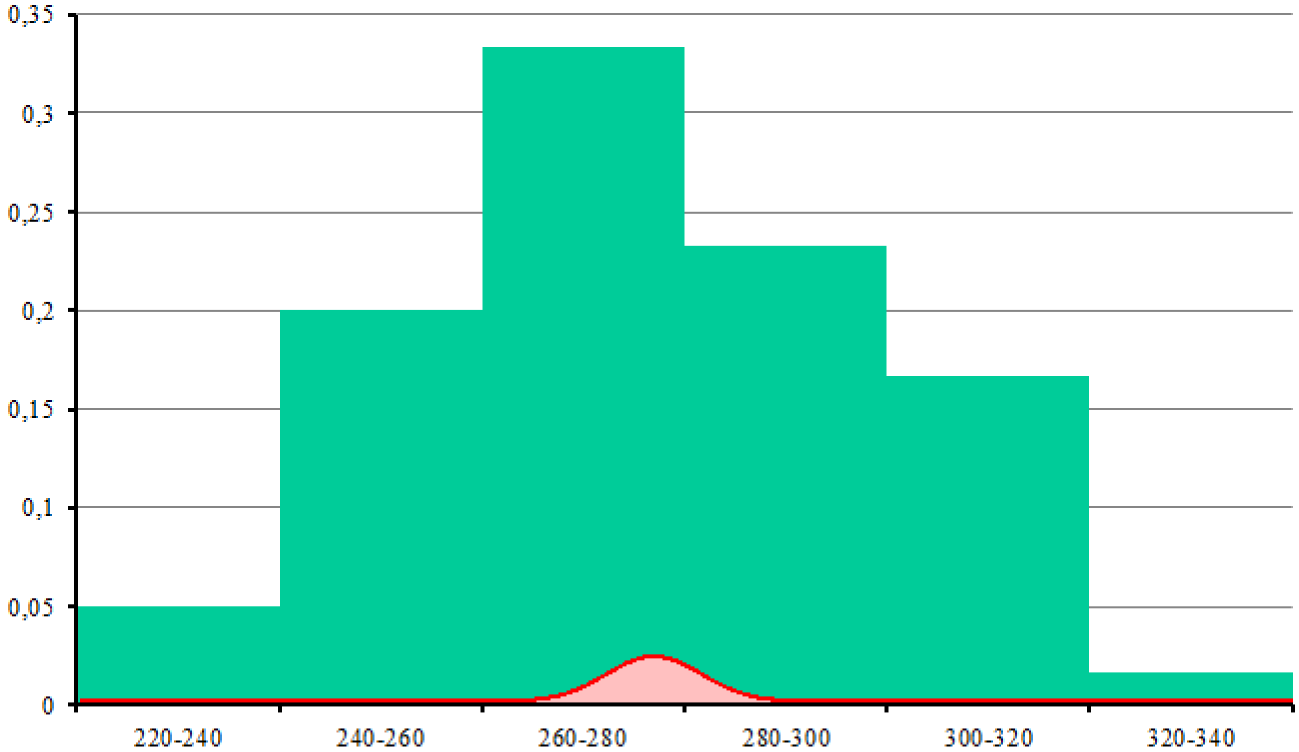
μ_{Re} = 276,8 MPa

σ_{Re} = 21,9 MPa

Area under red curve = 1

Total height of the bars = 1

Photo: Author



Bar diagram: for any number of results n and any value of Δ_R (for this case n = 60, Δ_R = 20 MPa)

Normal distribution: theoretical result for $n \rightarrow \infty$ and $\Delta_R \rightarrow 0$

What do you think – this is a good idea to take into calculation:

$$f_y = R_{e,\ average}$$

$$f_u = R_{m,\ average}$$

?

NO!

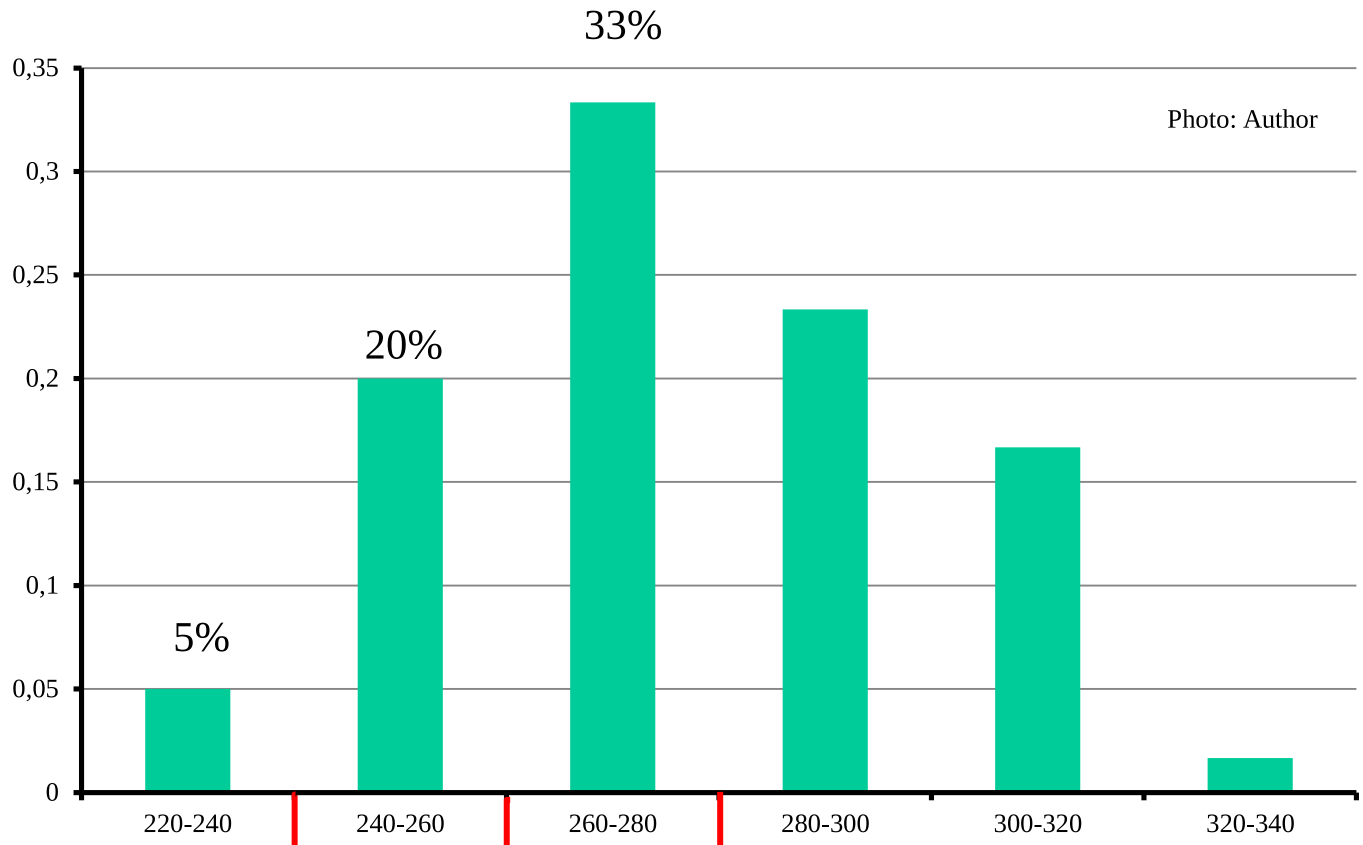
Photo: rcnkonstantynow.pl

Average → for 50% elements $f < f_{average}$

50% of structures woud have strength less than we assume in calculations!

Photo: wiadomosci.wp.pl

Photo: biznes.newsweek.pl



<u>X% quantile</u>: such strength value, that smaller values occur only for x% of samples

Below 240 MPa: 5% results

Below 260 MPa: 5+20 = 25% results

Below 280 MPa: 5+20+33 = 58% results

240 MPa → 5% quantile

260 MPa → 25% quantile

Average (276,8 MPa) → 50% quantile

280 MPa → 58% quantile

Calculation of quantile is much more accurate, when we base on normal distribution, not bar diagram:

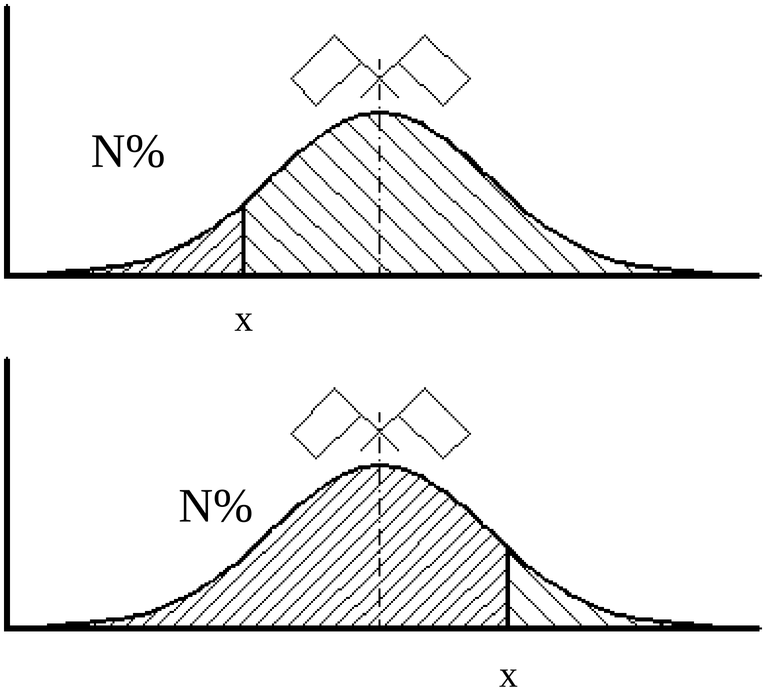


Photo: Author

Value x is N% quantile, when:

$$\text{N\% of total area} = \int_{-\infty}^{x} \phi(\xi)\, d\xi$$

Area under curve on left side of x.

(There is dξ no dx to avoit of symbols conflict)

We analysed this problem as function for curve and area under curve.

But, generally, there are special definitions in maths for this problem:

$\phi(x)$ - distribution (here: normal distribution)

$$\Phi(x) = \int_{-\infty}^{x} \phi(\xi)\, d\xi \text{ - cumulative distribution}$$

$$d / dx\, [\Phi(x)] = \Phi(x)' = \phi(x)$$

We can draw curve for $\phi(x)$, and, of course, we can draw curve for $\Phi(x)$.

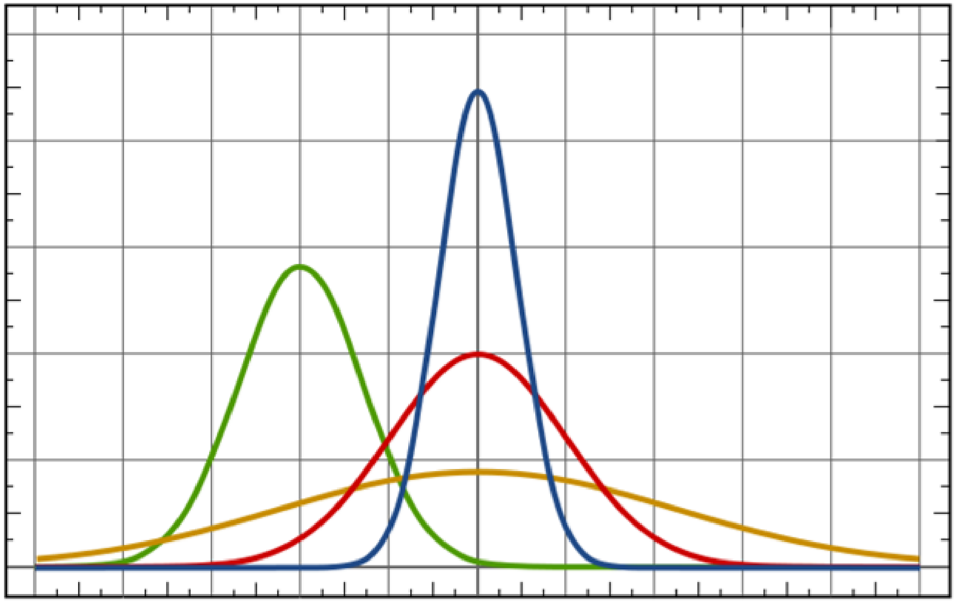


Photo: wikipedia

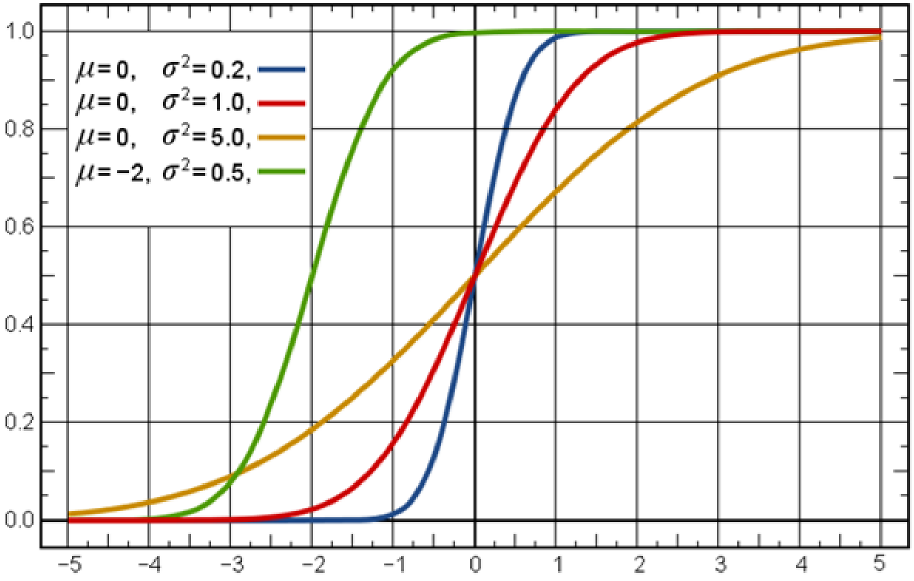
← Examples of normal distribution $\phi(\xi)$:

$$\phi(-\infty) \rightarrow 0{,}0$$

$$\phi(x_{average}) = max$$

$$\phi(\infty) \rightarrow 0{,}0$$

Photo: wikipedia



Examples of cumulative distribution $\Phi(x)$ for normal distribution $\phi(x)$ →

$$\Phi(-\infty) \rightarrow 0{,}0$$

$$\Phi(x_{average}) = 0{,}5$$

$$\Phi(\infty) \rightarrow 1{,}0$$

In analysed case, area under line and cumulative distribution is the same object:

$$N\% = A(x) = \int_{-\infty}^{x} \phi(\xi)\, d\xi = \Phi(x)$$

$$0{,}0 \leq \Phi(x) \leq 1{,}0$$

Relation $\Phi(x) = \int_{-\infty}^{x} \phi(\xi)\, d\xi$ can be analised:

- from x to $\Phi(x)$ (calculation of function);
- from F(x) to x (calculation of inverse of function $[F(x)]^{[-1]}$);

For example:

$$\Phi(x) = x^2 \quad ; \quad x = 5 \rightarrow \Phi(x) = 5^2 = 25$$

$$x = [\Phi(x)]^{[-1]} = \sqrt{[\Phi(x)]} \quad ; \quad \Phi(x) = 49 \rightarrow x = \sqrt{49} = 7$$

- data: x ; finding value: **Φ** = N%
- data: **Φ** = N% ; finding value: x

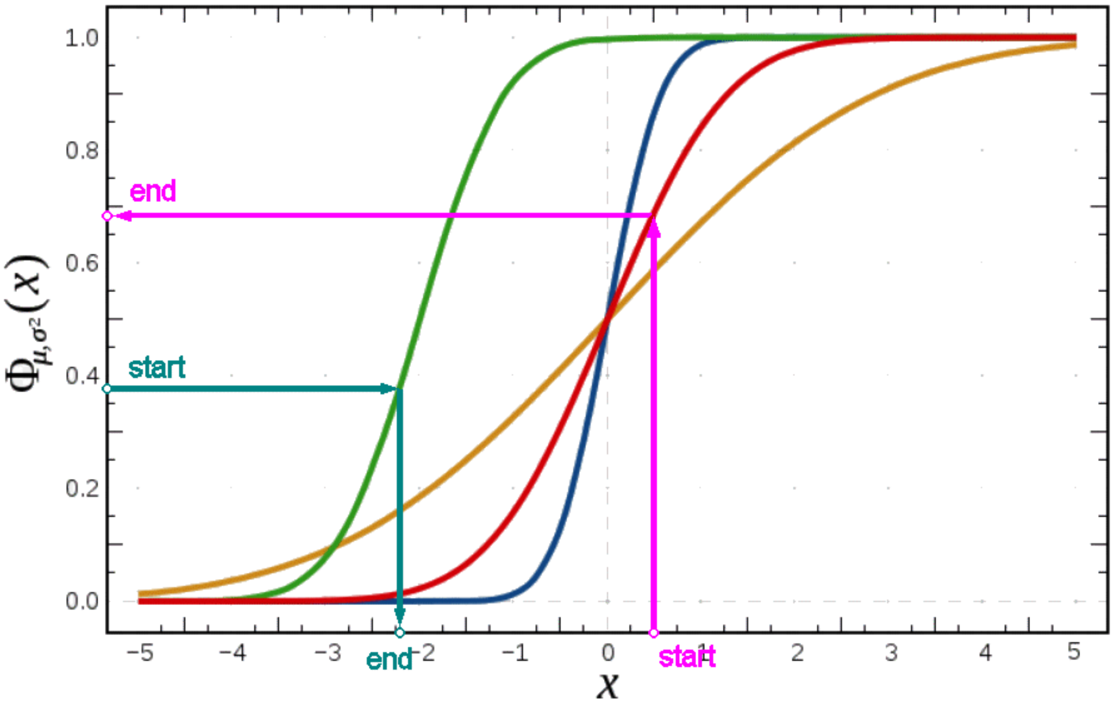


Photo: Author

First case is calculation of cumulative distribution.

Second case is finding value of quantile.

Characteristic value of strength is equal 5% quantie from test.

Calculation of N%-quantile is provided based on μ_{Re} (average) and σ_{Re} (standard deviation). Way of calculations will be presented on Laboratory #3. For data presented on #t / 32, when μ_{Re} = 276,8 MPa and σ_{Re} = 21,9 MPa, lower 5% quantile = 240,8 MPa.

$$f_{y,\,k} = 240{,}8 \text{ MPa}$$

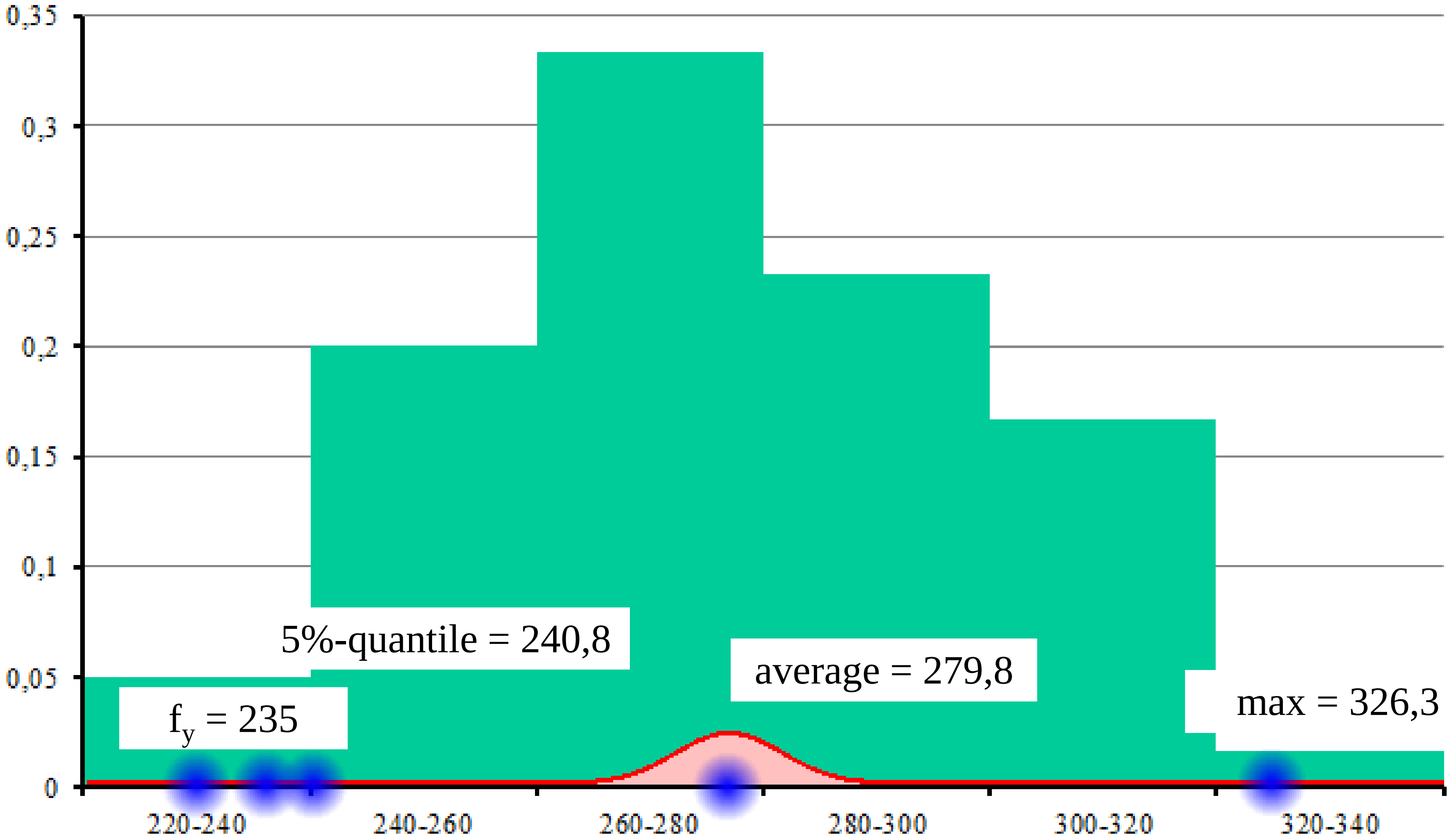
This means, analised steel is steel S235 ($f_{y,\,k}$ = 235 Mpa)

For design value of strength of material, we must use safety factor.

$$f_{y,\,d} = f_{y,\,k} / \gamma_M$$

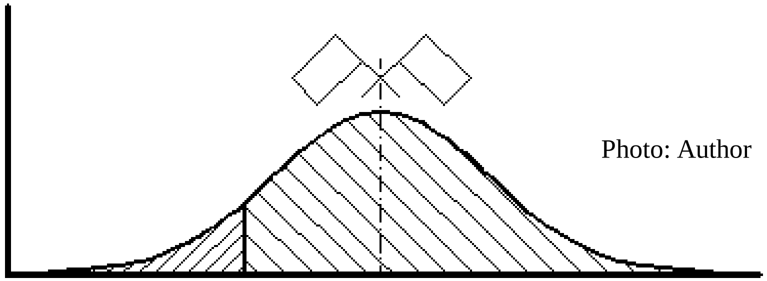
According to EN 1990, γ_M = 1,0.

Photo: Author



min = 229,2

A_{left} = 5% of total area



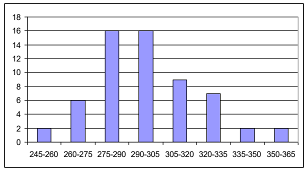
$q_{5\%}$

In the analyzed situation, 5% of 60 results are 3 results. Less than the 240,8 quantile are: 229,2; 231,2; 237,7. In this case, exactly 5% of the results are lower than the quantile.

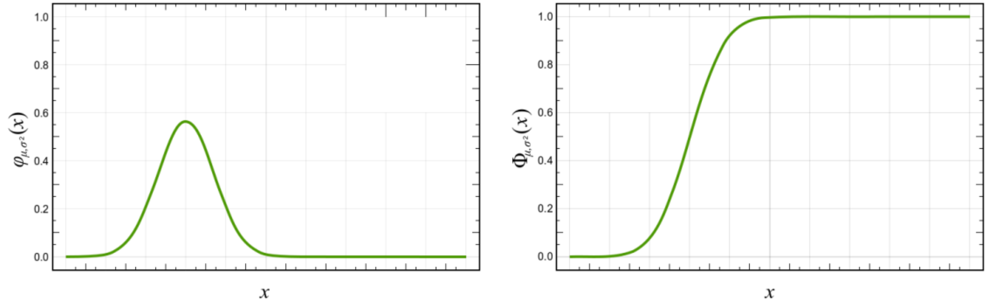
Algorithm:

Normal Distribution (μ_{Re} , σ_{Re})

Test in Universal Testing Machine



μ_{Re} , σ_{Re}

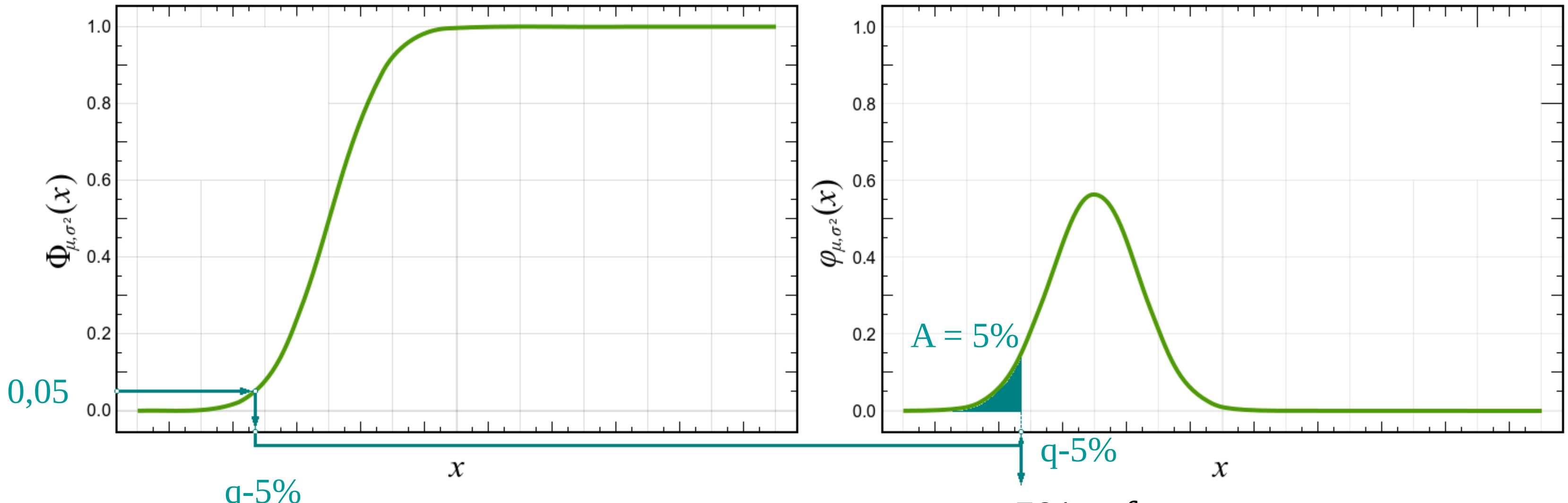


Cumulative Distribution (μ_{Re} , σ_{Re})

Photo: Author

Cumulative Distribution (μ_{Re} , σ_{Re})

Normal Distribution (μ_{Re} , σ_{Re})



$$q\text{-}5\% = f_{y,\,k}$$

Few words about economy:

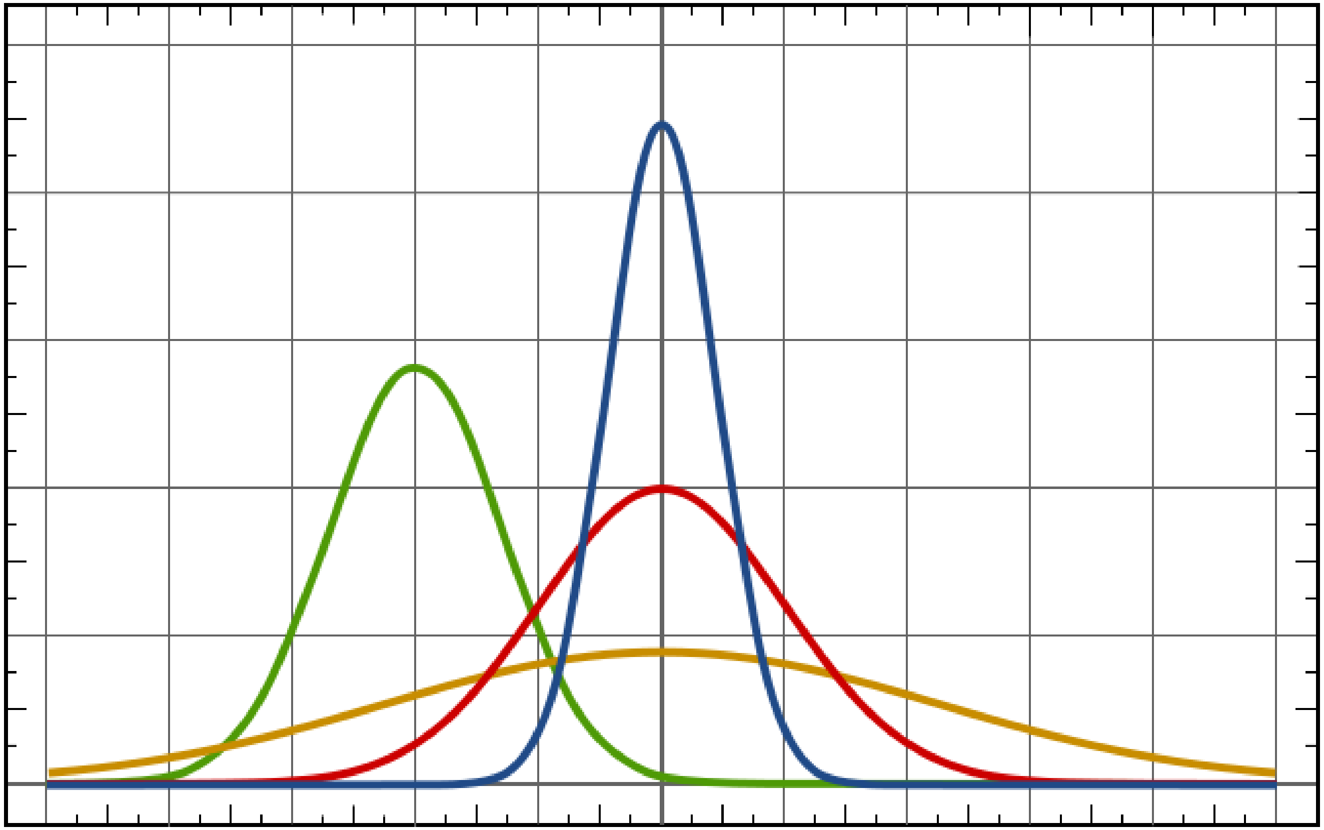


Photo: wikipedia

average = average = average

standard deviation < standard deviation < standard deviation

area = area = area = area = 1,0

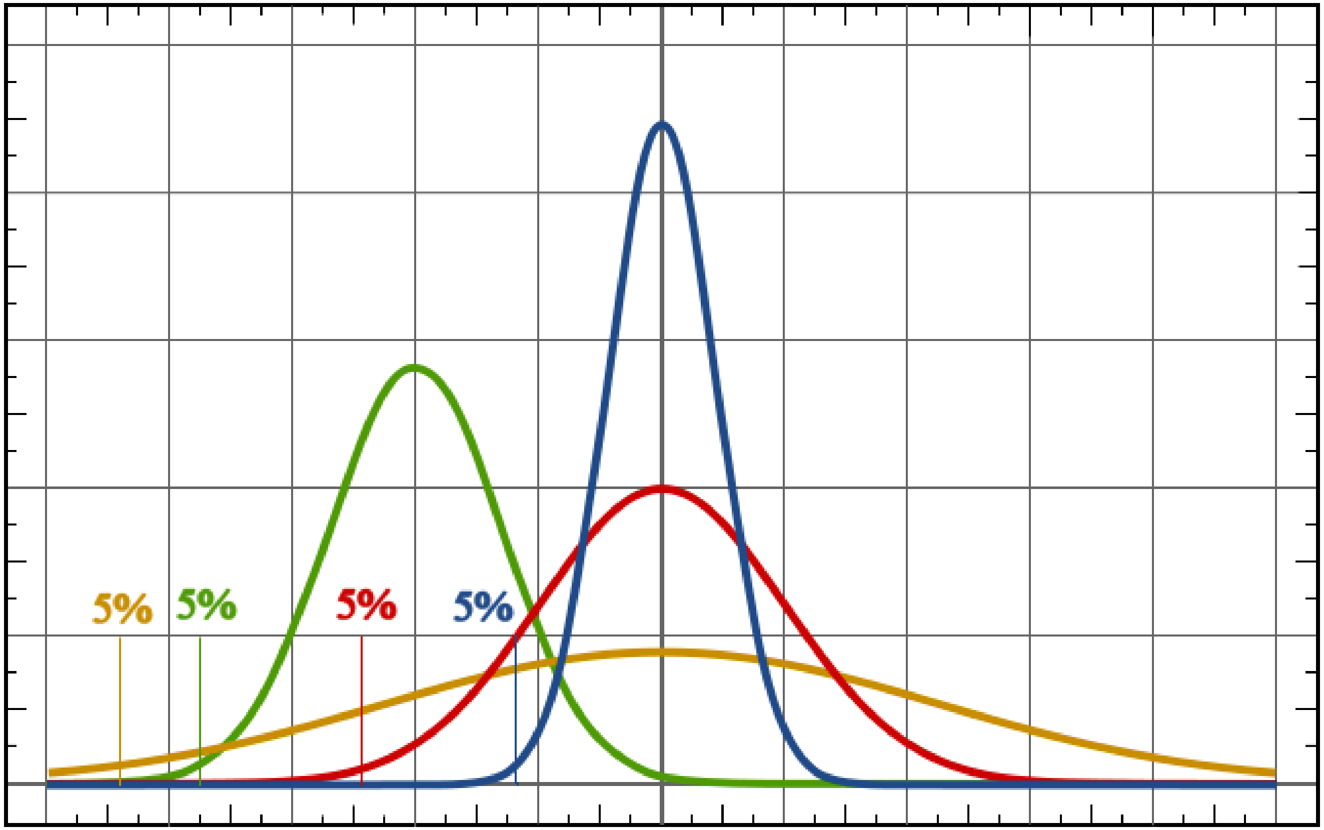


Photo: wikipedia

production costs < production costs ≈ production costs ≈ production costs ≈ average

$f_y < f_y < f_y < f_y \approx$ price

price < price < price < price

Profit = price – production cost; the bigest for bule one or green one

Summation:

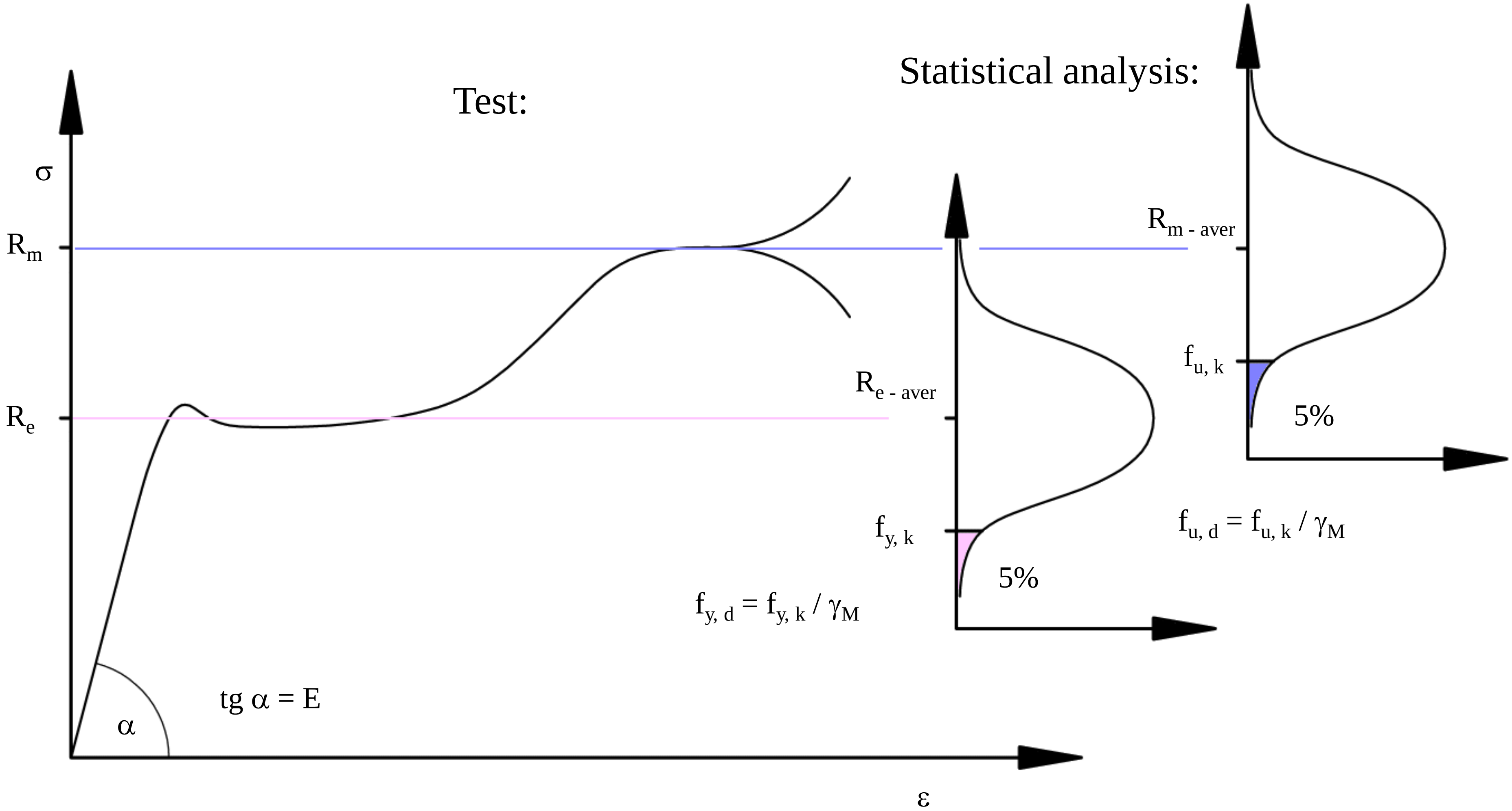


Photo: Author

EN 1993-1-1 tab 3.1

Standard and steel grade	Nominal thickness of the element t [mm]			
	$t \leq 40$ mm		40 mm $< t \leq 80$ mm	
	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
EN 10025-2				
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	490	335	470
S 450	440	550	410	550
EN 10025-3				
S 275 N/NL	275	390	255	370
S 355 N/NL	355	490	335	470
S 420 N/NL	420	520	390	520
S 460 N/NL	460	540	430	540
EN 10025-4				
S 275 M/ML	275	370	255	360
S 355 M/ML	355	470	335	450
S 420 M/ML	420	520	390	500
S 460 M/ML	460	540	430	530
EN 10025-5				
S 235 W	235	360	215	340
S 355 W	355	490	335	490
EN 10025-6				
S 460 Q/QL/QL1	460	570	440	550

Wyniki badania:

Legenda	Nr	L_0 mm	S_0 mm^2	$R_{p0.2}$ MPa	R_{eH} MPa	R_{eL} MPa	R_m MPa	R_B MPa	F_m kN	A_{gt} %	Z %
	6	100,40	78,54	-	-	-	244	161	19,14	8,68	-
	7	120,28	113,10	-	354	342	459	287	51,95	26,61	-
	8	120,19	113,10	-	-	-	702	415	79,43	6,15	-

Wykres serii:

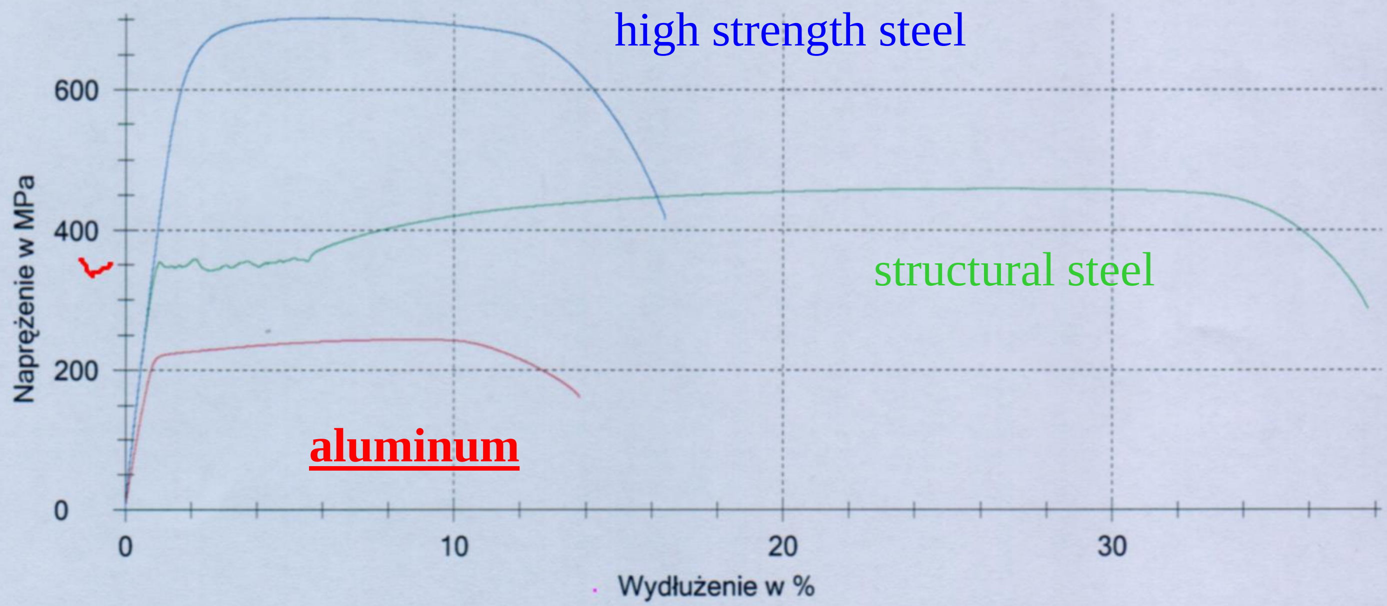


Photo: Author

Aluminum: other symbols, the same way of analysis

$$R_{02} \rightarrow f_o$$
$$R_m \rightarrow f_u$$

EN 1999-1-1 tab 3.2

Alloy EN-AW	Temper [1)]	Thick-ness mm [1)]	f_o [1)]	f_u	A_{50} [1) 6)]	$f_{o,haz}$ [2)]	$f_{u,haz}$ [2)]	HAZ-factor [2)]		BC 4)	n_p 1), 5)
			N/mm²		%	N/mm²		$\rho_{o,haz}$ [1)]	$\rho_{u,haz}$		
3004	H14 | H24/H34	≤ 6 | 3	180 | 170	220	1 | 3	75	155	0,42 | 0,44	0,70	B	23 | 18
	H16 | H26/H36	≤ 4 | 3	200 | 190	240	1 | 3			0,38 | 0,39	0,65	B	25 | 20
3005	H14 | H24	≤ 6 | 3	150 | 130	170	1 | 4	56	115	0,37 | 0,43	0,68	B	38 | 18
	H16 | H26	≤ 4 | 3	175 | 160	195	1 | 3			0,32 | 0,35	0,59	B	43 | 24
3103	H14 | H24	≤ 25| 12,5	120 | 110	140	2 | 4	44	90	0,37 | 0,40	0,64	B	31 | 20
	H16 | H26	≤ 4	145 | 135	160	1 | 2			0.30 | 0,33	0,56	B	48 | 28
5005/ 5005A	O/H111	≤ 50	35	100	15	35	100	1	1	B	5
	H12 | H22/H32	≤ 12,5	95 | 80	125	2 | 4	44	100	0,46 | 0,55	0,80	B	18 | 11
	H14 | H24/H34	≤ 12,5	120 | 110	145	2 | 3			0,37 | 0,40	0,69	B	25 | 17
5052	H12 | H22/H32	≤ 40	160 | 130	210	4 | 5	80	170	0,50 | 0,62	0,81	B	17 | 10
	H14 | H24/H34	≤ 25	180 | 150	230	3 | 4			0,44 | 0,53	0,74	B	19 | 11
5049	O / H111	≤ 100	80	190	12	80	190	1	1	B	6
	H14 | H24/H34	≤ 25	190 | 160	240	3 | 6	100	190	0,53 | 0,63	0,79	B	20 | 12
5454	O/H111	≤ 80	85	215	12	85	215	1	1	B	5
	H14|H24/H34	≤ 25	220 | 200	270	2 | 4	105	215	0,48 | 0,53	0,80	B	22 | 15
5754	O/H111	≤ 100	80	190	12	80	190	1	1	B	6
	H14|H24/H34	≤ 25	190 | 160	240	3 | 6	100	190	0,53 | 0,63	0,79	B	20 | 12
5083	O/H111	≤ 50	125	275	11	125	275	1	1	B	6
		50<t≤80	115	270	14 [5)]	115	270			B	
	H12|H22/H32	≤ 40	250 | 215	305	3 | 5	155	275	0,62 | 0,72	0,90	B	22 | 14
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]

Other mechanical properties

Hardness #t / 59

Impact resistance #t / 67

Elasticity #t / 74

Ductility / plasticity #t / 75

Forgeability #t / 76

Grindability #t / 77

Fatigue resistance #t / 78

Weldability #t / 84

Fragility #t / 85

Hardness

measure of how resistant solid matter is to various kinds of permanent shape change when a force is applied

- Brinell
- Vickers
- Rockwell

- Poldi

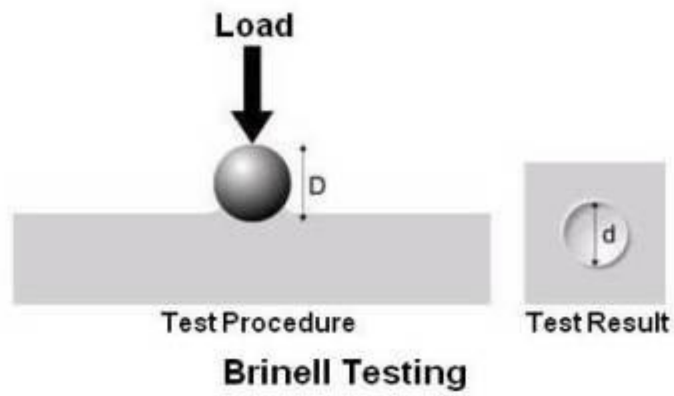


Photo: practicalmaintenance.net

Brinell (EN ISO 6506)

$$HB = 0{,}204\, F / \{\pi D [\, D - \sqrt{(D^2 - d^2)}]\}$$

$$d = (d_1 + d_2) / 2$$

$[N/m^2]$ $R_m \approx 3{,}33$ HB $(125 < HB < 175)$

$[N/m^2]$ $R_m \approx 3{,}53$ HB $(HB > 175)$

We can identify the grade of steel in non-destructive test

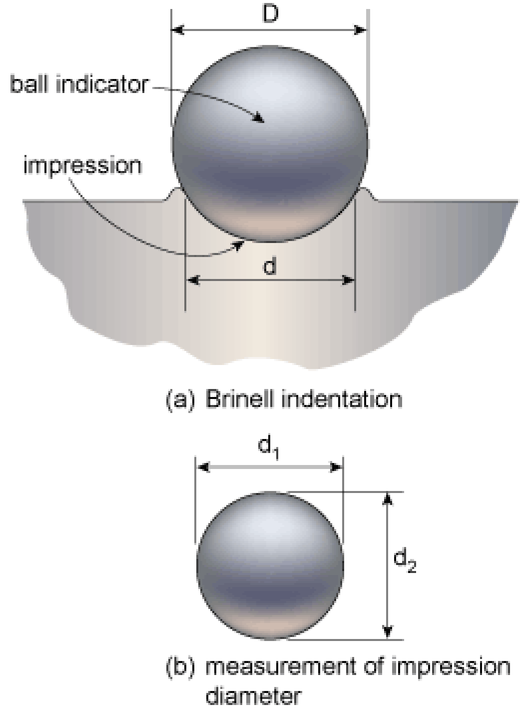


Photo: twi-global.com

Vickers (EN ISO 6507)

$HV = 0,189 F / d^2$

$d = (d_1 + d_2) / 2$

$R_m \approx 95,5 [\sqrt{(149 + 0,122 HV)} -12,2]$

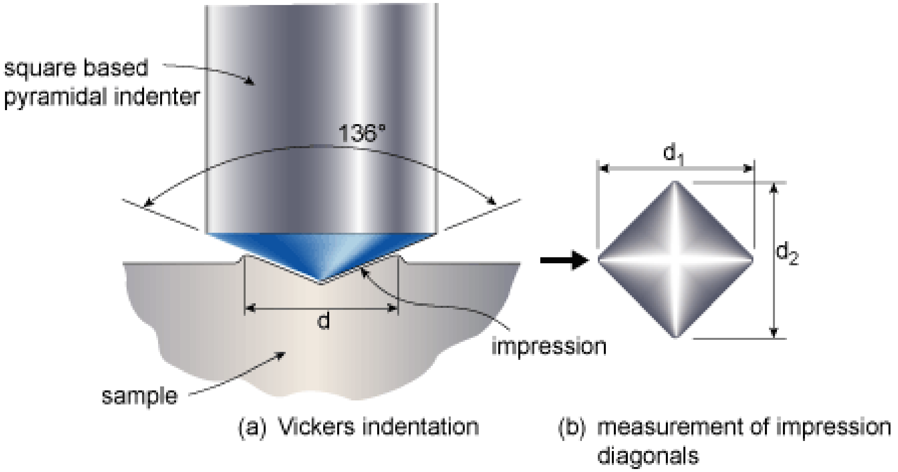


Photo: twi-global.com

Rockwell (EN ISO 6508)

$HR = 100 – e / 0,002$

e [mm] = plastic deformation only

Forces depend on type of material

HR could be recalculated to R_m in dependence on type of material (applicated force).

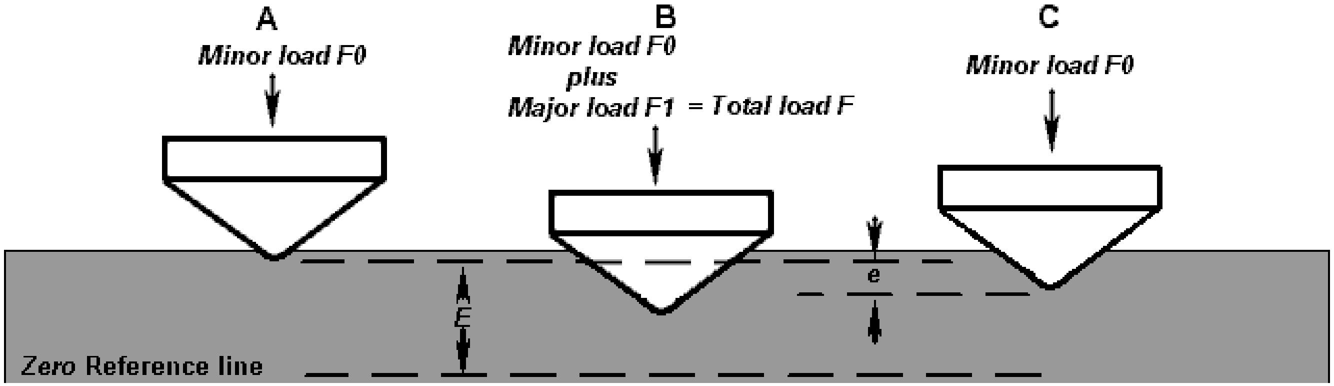


Fig. 1.Rockwell Principle

Photo: gobanengineeringnotes.com

Poldi

spherical probe, calculations the same as for Brinell

Photo: metale24.pl

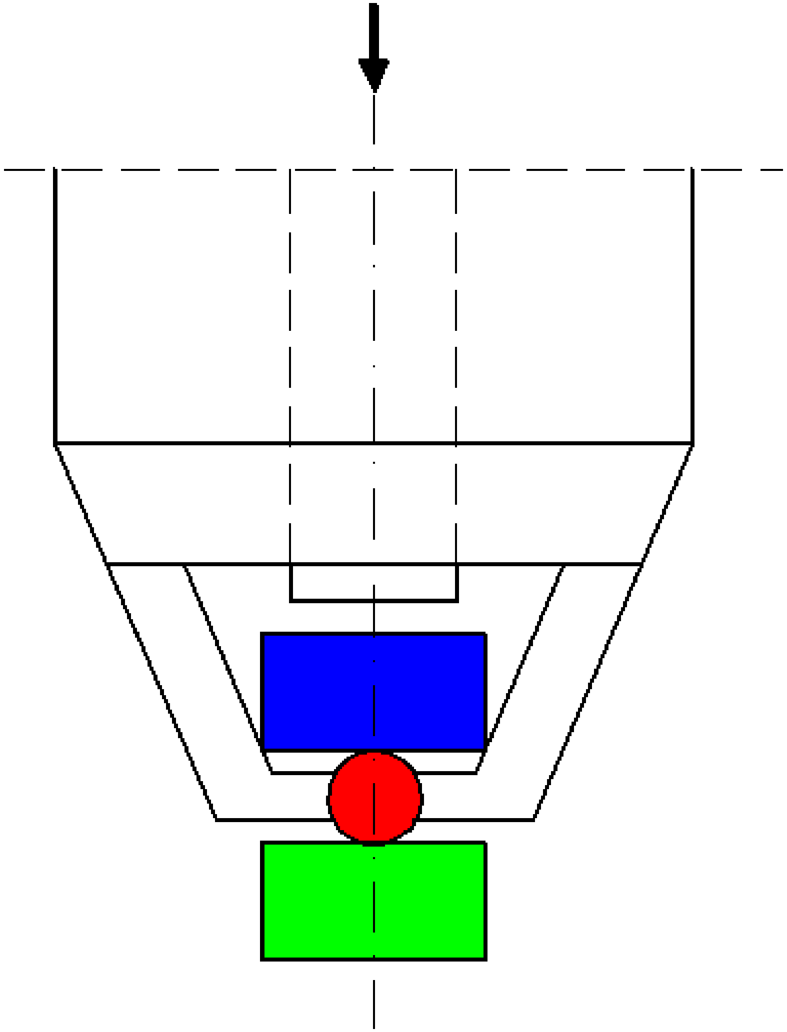


Photo: Author

Pattern

Probe

Test material

Main idea: test holes are formed in the pattern and the test material under the influence of the same force

$$HB = HB_p \, [\, D - \sqrt{(D^2 - d_p^2)}\,] \,/\, [\, D - \sqrt{(D^2 - d^2)}\,]$$

HB_p - HB of the pattern (known)

D - diameter of the probe (known)

d - diameter hole in the test material (measured)

d_p - diameter hole in the test pattern (measured)

$HB \rightarrow R_m \rightarrow$ grade of steel

We no need to know value of force

Very old steel strucures, no documentation on steel grade:

Photo: wikipedia

Photo: oceanmachinery.com

Cutting part of structure and testing in UTS; very accurate results, but destruction of part of the structure.

Photo: ndtteknik.com

In situ testing with a Poldi hammer; approximate results, but undamaged construction.

Impact resistance

the ability of a material to absorb energy and plastically deform without fracturing

Shapre of specimen

(notch U or V)

EN 10 045-1

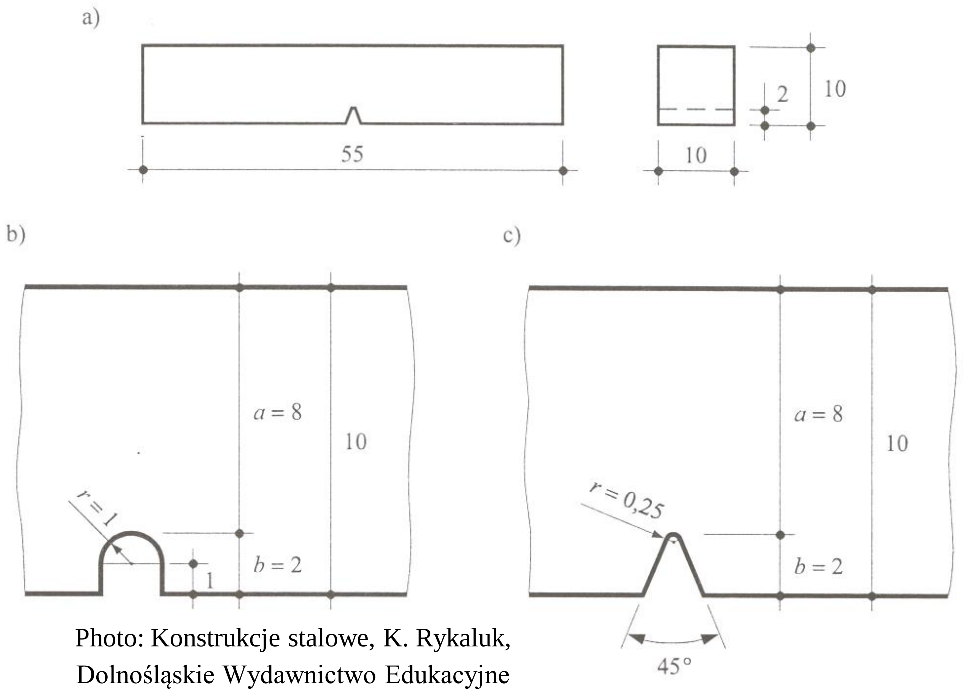


Photo: Konstrukcje stalowe, K. Rykaluk, Dolnośląskie Wydawnictwo Edukacyjne Wrocław 2001

Photo: ccsi-inc.com

Energy of hammer at the start position: G h

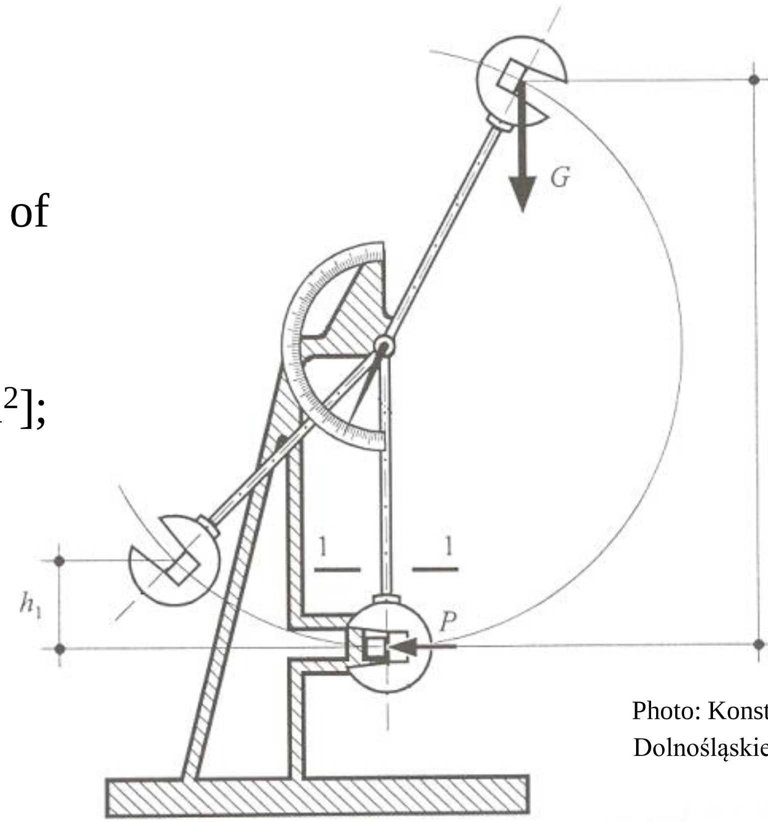
Energy of hammer at the end position: G h_1

Energy absorbed by a material during fracture for notch U or V:

KCU (KCV) = G (h - h_1) [J]

There are two alternative measures of impact resistance:

- energy [J];
- energy / area of speciment [J / cm^2];



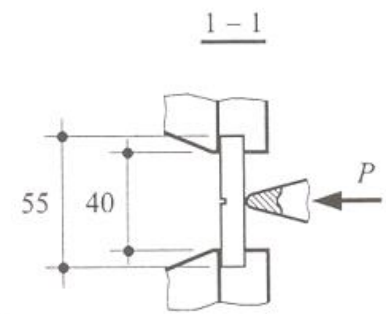


Photo: Konstrukcje stalowe, K. Rykaluk, Dolnośląskie Wydawnictwo Edukacyjne Wrocław 2001

Results of tests:

1. fracture without separation (left)
2. fracture with separation (right)

KC(1) > KC(2)

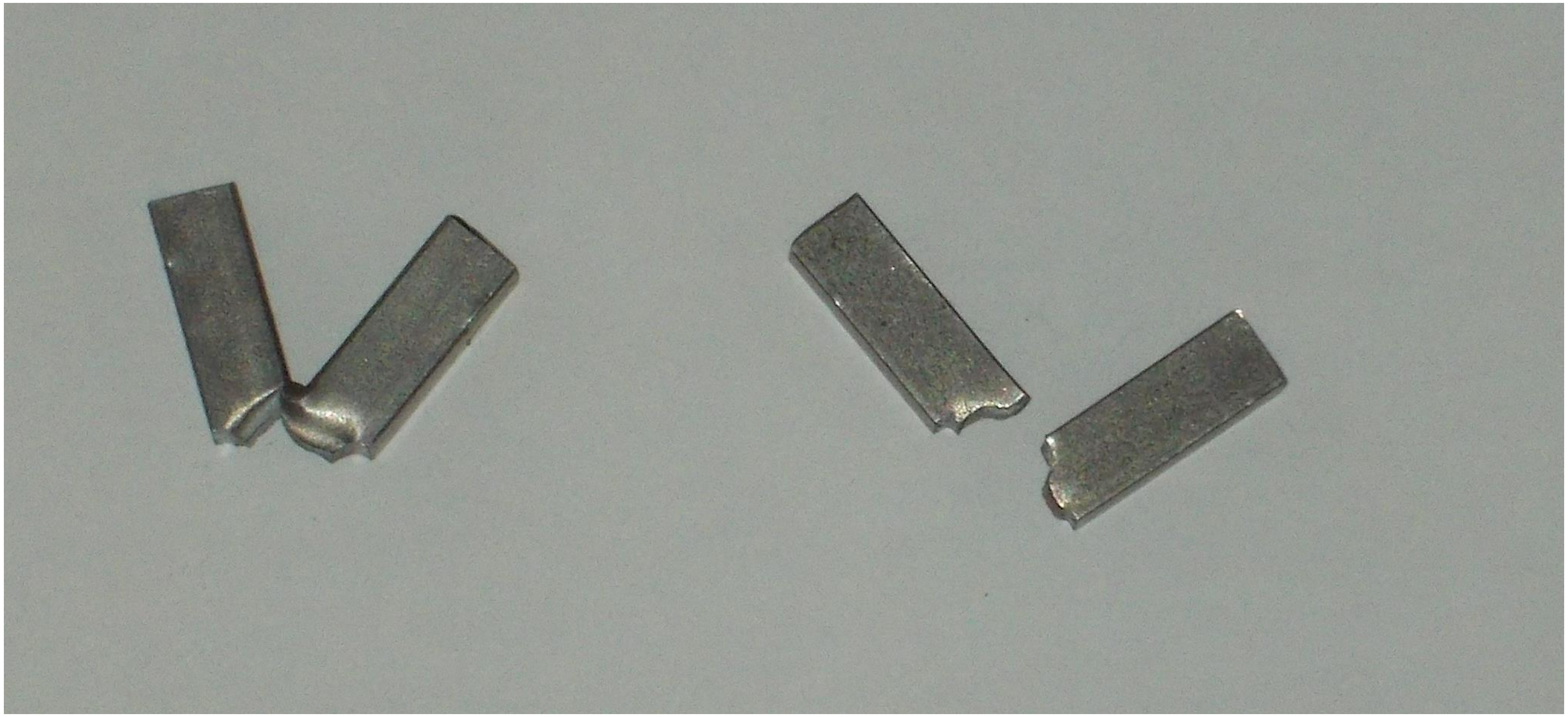


Photo: Author

Symbols of different subrages of steel

EN 10025-2 tab. 9

T [^{o}C]	KV [J]		
	27	40	60
+20	JR	KR	LR
0	J0	K0	L0
-20	J2	K2	L2
-30	J3	K3	L3
-40	J4	K4	L4
-50	J5	K5	L5
-60	J6	K6	L6

Why impact resistance is important?

Photo: inspectioneering.com

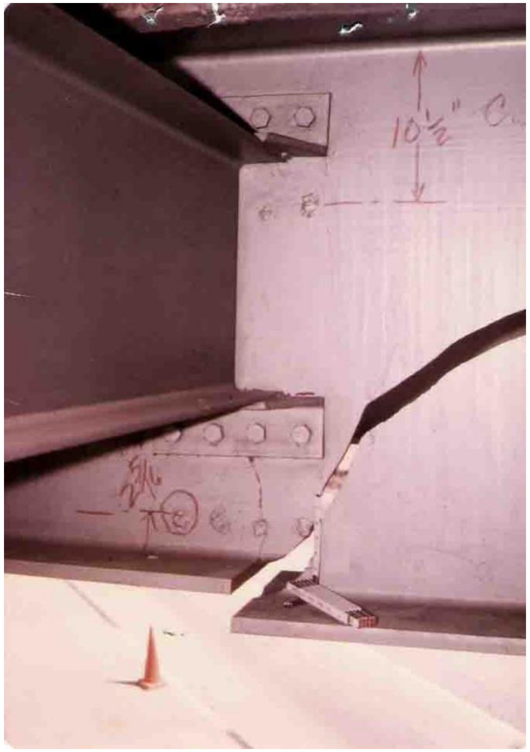


Photo: rebar.ecn.purdue.edu

Photo: civildigital.com

Result of Charpy hammer test shows susceptibility to brittle cracking of various grades of steel.

Photo: globalnpsolutions.com

Photo: wikipedia

Susceptibility to brittle cracking increases when:

- ↓ temperature;
- ↑ stresses;
- ↑ thickness of elements;

EN 1993-1-10 tab 2.1

Steel grade	Sub-grade	KV at T [°C]	KV J_{min}	Reference temperature T_{Ed} [°C]: 10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50	10	0	-10	-2
				$\sigma_{Ed} = 0{,}75\, f_y(t)$							$\sigma_{Ed} = 0{,}50\, f_y(t)$							$\sigma_{Ed} = 0.$			
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	135	115	100	8
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	175	155	135	11
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	200	200	175	15
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	40	35	30	125	110	95	8
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	55	50	40	165	145	125	11
	J2	-20	27	110	95	75	65	55	45	35	155	130	115	95	80	70	55	200	190	165	14
	M,N	-20	40	135	110	95	75	65	55	45	180	155	130	115	95	80	70	200	200	190	16
	ML,NL	-50	27	185	160	135	110	95	75	65	200	200	180	155	130	115	95	230	200	200	2
S355	JR	20	27	40	35	25	20	15	15	10	65	55	45	40	30	25	25	110	95	80	7
	J0	0	27	60	50	40	35	25	20	15	95	80	65	55	45	40	30	150	130	110	9

Low temperature + big values of stresses → too thick elements are prohibited

Elasticity

the ability to recover its original shape and dimensions

f_y , E

High f_y = high resistance of elements. High E means small deformations of structure and smal suscebility to instability.

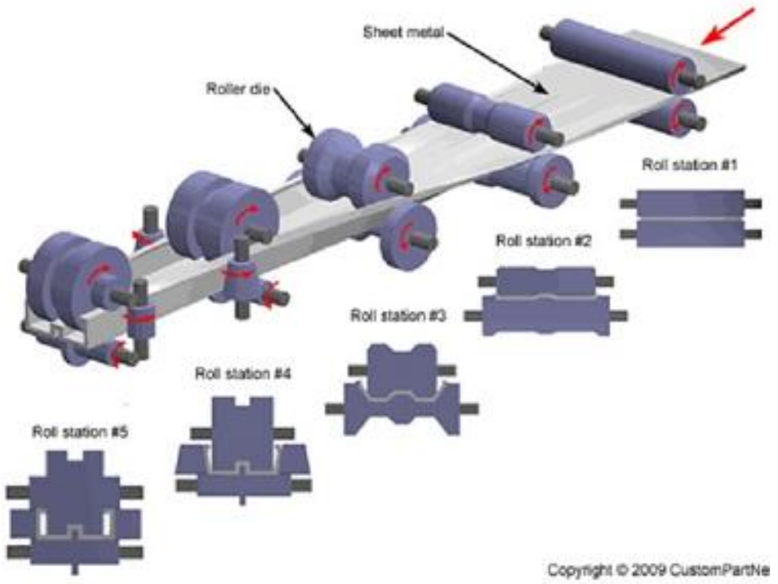


Photo: cnc.info.pl

Ductility / plasticity

ability to permanent deform

f_y

Important for cold forming of cross-sections. This type of cross-sections is formed in low temperature by permanent deformations of material.

Forgeability

ability to change shape by hammered or under pressure

Important for hot-rolling of cross-sections. This type of cross-sections is formed in high temperature by pressure of rollers.

Photo: wd-bearing.com

Grindability

susceptibility to abrasion

Important for structures exposed to abrasion (for example internal surfaces of silos).

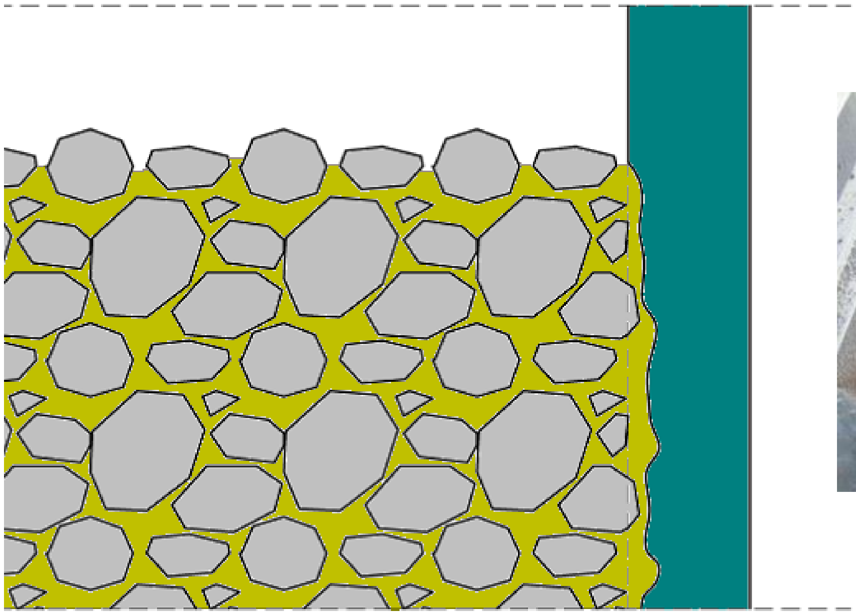


Photo: Author

Photo: mining-report.de

Fatigue resistance

the amplitude or range of cyclic stress that can be applied to the material without causing fatigue failure

This is not the same as strength of material

Strength → static load

Fatigue resistance → cyclic (dynamic) load

This phenomenon is important for structures exposed to dynamic and cyclic loads. There is possible, that even little loads, but in many cycles (> 10 000) can destroy structure.

On each elements exist imperfections and notches (holes, welds, micro-cracks). There is concentration of stress around each notches.

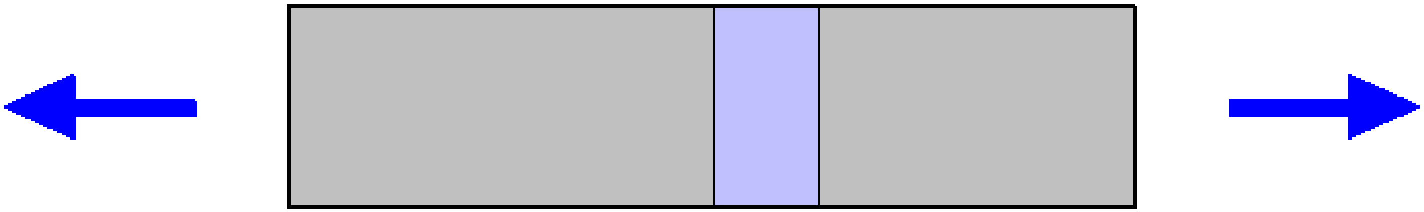
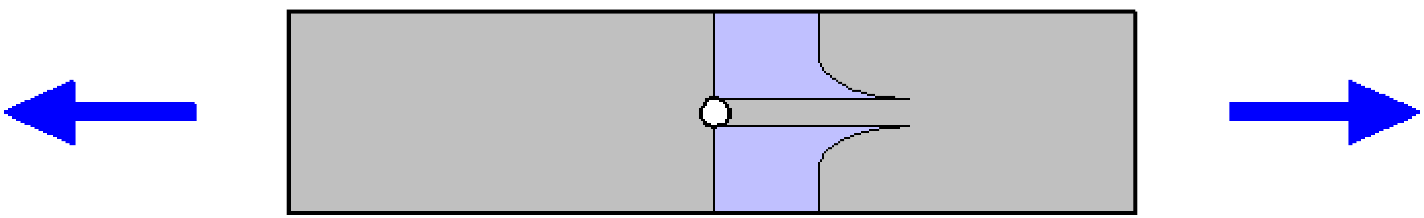


Photo: Author



$$\mu \, \sigma_{Ed} \leq f_y$$

μ stress concentration factor
σ_{Ed} stress as for ideal cross-section

For many cycles of loads, notches increase and can destroy member.

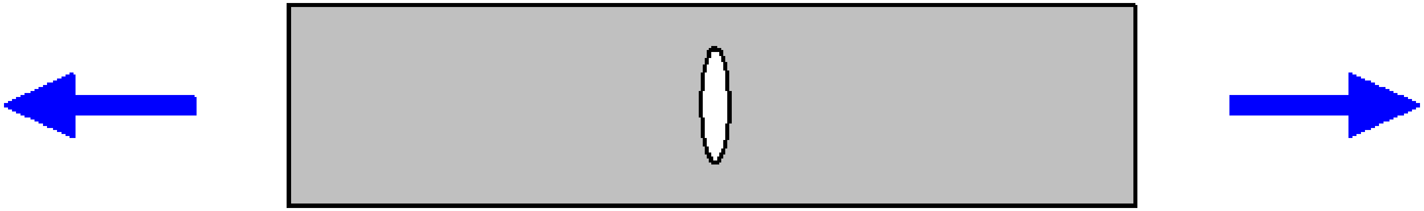
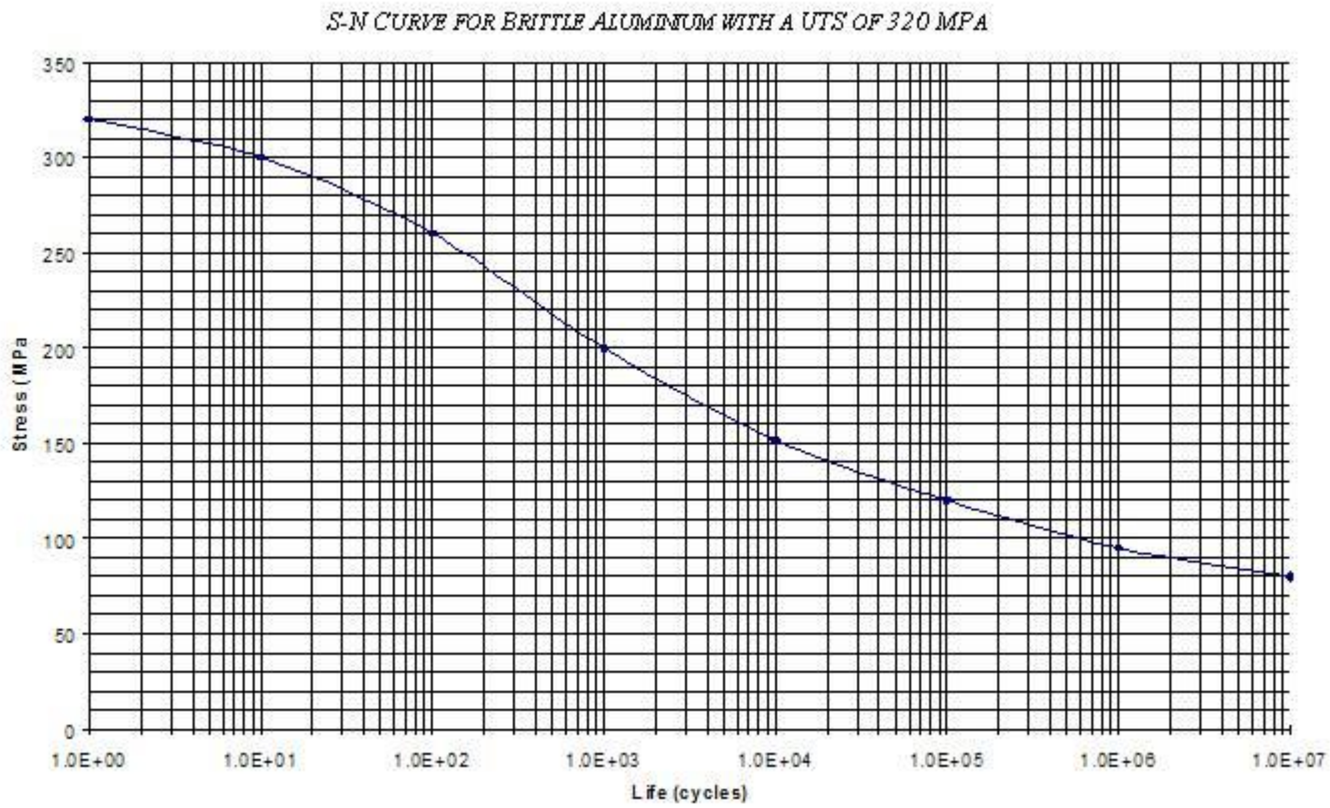


Photo: Author

General relationship (Wöhler Diagram):

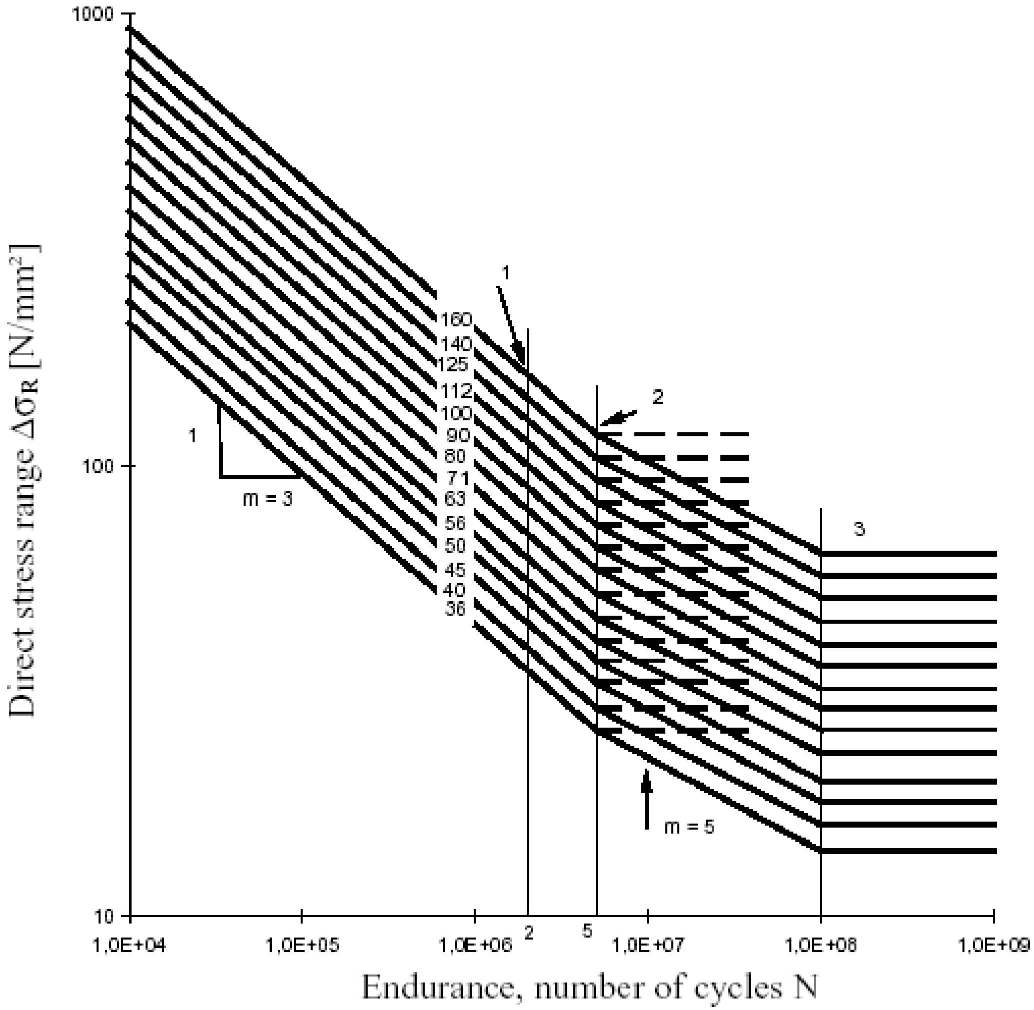
Fatigue resistance



Number of cycles

Photo: wikipedia

Photo: EN 1993-1-9 fig 7.1

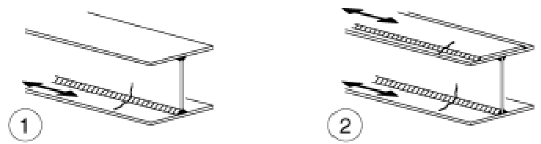
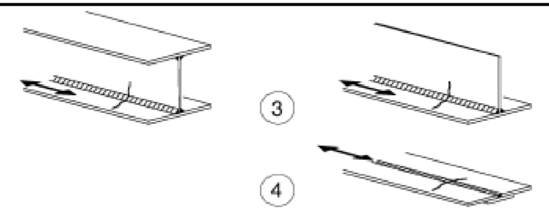
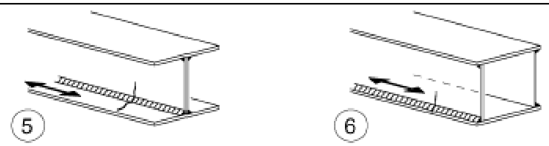
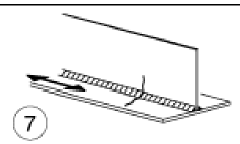


1 *Detail category $\Delta\sigma_C$*

2 *Constant amplitude fatigue limit $\Delta\sigma_D$*

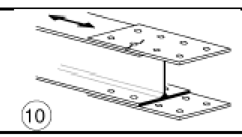
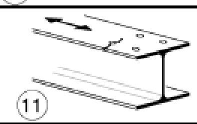
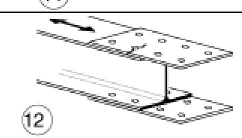
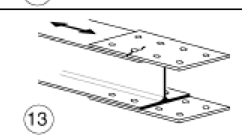
3 *Cut-off limit $\Delta\sigma_L$*

Various value for various notches

125		<u>Continuous longitudinal welds:</u> 1) Automatic butt welds carried out from both sides. 2) Automatic fillet welds. Cover plate ends to be checked using detail 6) or 7) in Table 8.5.
112		3) Automatic fillet or butt weld carried out from both sides but containing stop/start positions. 4) Automatic butt welds made from one side only, with a continuous backing bar, but without stop/start positions.
100		5) Manual fillet or butt weld. 6) Manual or automatic butt welds carried out from one side only, particularly for box girders
100		7) Repaired automatic or manual fillet or butt welds for categories 1) to 6).

EN 1993-1-9 tab. 8.1 - 8.10

EN 1993-3-2 tab. C-1

		9) Double covered joint with fitted bolts. 9) Double covered joint with non preloaded injection bolts.	9) ... net cross-section. 9) ... net cross-section.
		10) One sided connection with preloaded high strength bolts. 10) One sided connection with preloaded injection bolts.	10) ... gross cross-section. 10) ... gross cross-section.
		11) Structural element with holes subject to bending and axial forces	11) ... net cross-section.
80		12) One sided connection with fitted bolts. 12) One sided connection with non-preloaded injection bolts.	12) ... net cross-section. 12) ... net cross-section.
50		13) One sided or double covered symmetrical connection with non-preloaded bolts in normal clearance holes. No load reversals.	13) ... net cross-section.

Weldability

ability to be welded

Carbon equivalent:

$C_E = C + (Cr + V + Mo) / 5 + Mn / 6 + (Ni + Cu) / 15$

$C_E < 0{,}42\%$ good weldability

$0{,}42\% < C_E < 0{,}60\%$ average weldability

$C_E > 0{,}60\%$ bad weldability

Not every kind of steel can be wleded (risk of **cracking**)

More information → (Lecture #16)

Fragility

different types of cracking under load

Important for few mechanical properties:

fragility ↑ → impact resistance ↓ and forgeability ↓ and weldability ↓

Chemical composition

Steel:

Fe ≈ 96 - 98%

Ingredients ≈ 2 - 4%

Aluminum:

Al ≈ 85,0% - 98,5%

Ingredients ≈ 1,5% - 15,0%

Element		Steel	Aluminum
Oxygen O	☠	Corrosion, reduction of C, S, P	Corrosion
Hydrogen H	☠	Fragility, cracking	Fragility, cracking
Nitrogen N	☠	Fragility, cracking	Fragility, cracking
Sulfur S	☠	Fragility, corrosion	
Phosphorus P	☠	Fragility, corrosion	
Iron Fe	👍	**Main component**	
Aluminum Al	👍	Reduction of O	**Main component**
Carbon C	👍	Hardness 👍 strength 👍 impact 👎 weldability 👎	
Chrome Cr	👍	Hardness 👍 strength 👍 grindability 👍 weldability 👎	
Copper Cu	👍	Corrosion resistance 👍	second essential ingredient
Magnesium Mg	👍		second essential ingredient
Manganese Mn	👍	Reducion of O and S	second essential ingredient
Molybdenum Mo	👍	Strength 👍 weldability 👎	second essential ingredient
Nickel Ni	👍	Hardness 👍 strength 👍 impact 👍	
Niobium Nb	👍	Weldability 👍	
Silicon Si	👍	Reduction of O hardness 👍 strength 👍	second essential ingredient
Titanium Ti	👍	Strength 👍	
Vanadium V	👍	Strength 👍 impact 👍 weldability 👎	
Zinc Zn	👍		second essential ingredient

Examples of chemical composition for diferent grades of steel (the most often used):

Steel	C [%]			Si_{max} [%]	Mn_{max} [%]	P_{max} [%]	S_{max} [%]	N_{max} [%]	Cu_{max} [%]
	t ≤ 16 mm	16 < t ≤ 40 mm	t > 40 mm						
S235 JR	0,170	0,170	0,200	0,000	1,400	0,035	0,035	0,012	0,550
S235 J0	0,170	0,170	0,170	0,000	1,400	0,030	0,030	0,012	0,550
S235 J2	0,170	0,170	0,170	0,000	1,400	0,025	0,025	0,000	0,550
S275 JR	0,210	0,210	0,220	0,000	1,500	0,035	0,035	0,012	0,550
S275 J0	0,180	0,180	0,180	0,000	1,500	0,030	0,030	0,012	0,550
S275 J2	0,180	0,180	0,180	0,000	1,500	0,025	0,025	0,000	0,550
S355 JR	0,240	0,240	0,240	0,550	1,600	0,035	0,035	0,012	0,550
S355 J0	0,200	0,200	0,220	0,550	1,600	0,035	0,035	0,012	0,550
S355 J2	0,200	0,200	0,220	0,550	1,600	0,030	0,030	0,000	0,550

Conclusions:

- S235 → S275 → S355: increasing of strength ↔ increasing of amount of C, Si, Mn
- JR → J0 → J2: increasing of resistance for low temperatures (#t /67 - 73) ↔ decreasing of amount of pollutions P, S, N

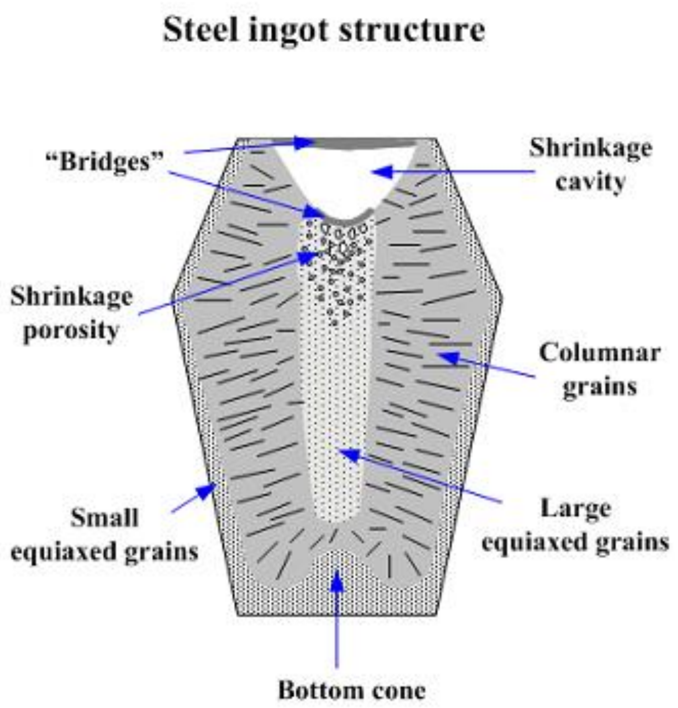


Photo: substech.com

Relationship: mechanical properties ↔ amount of C [%]

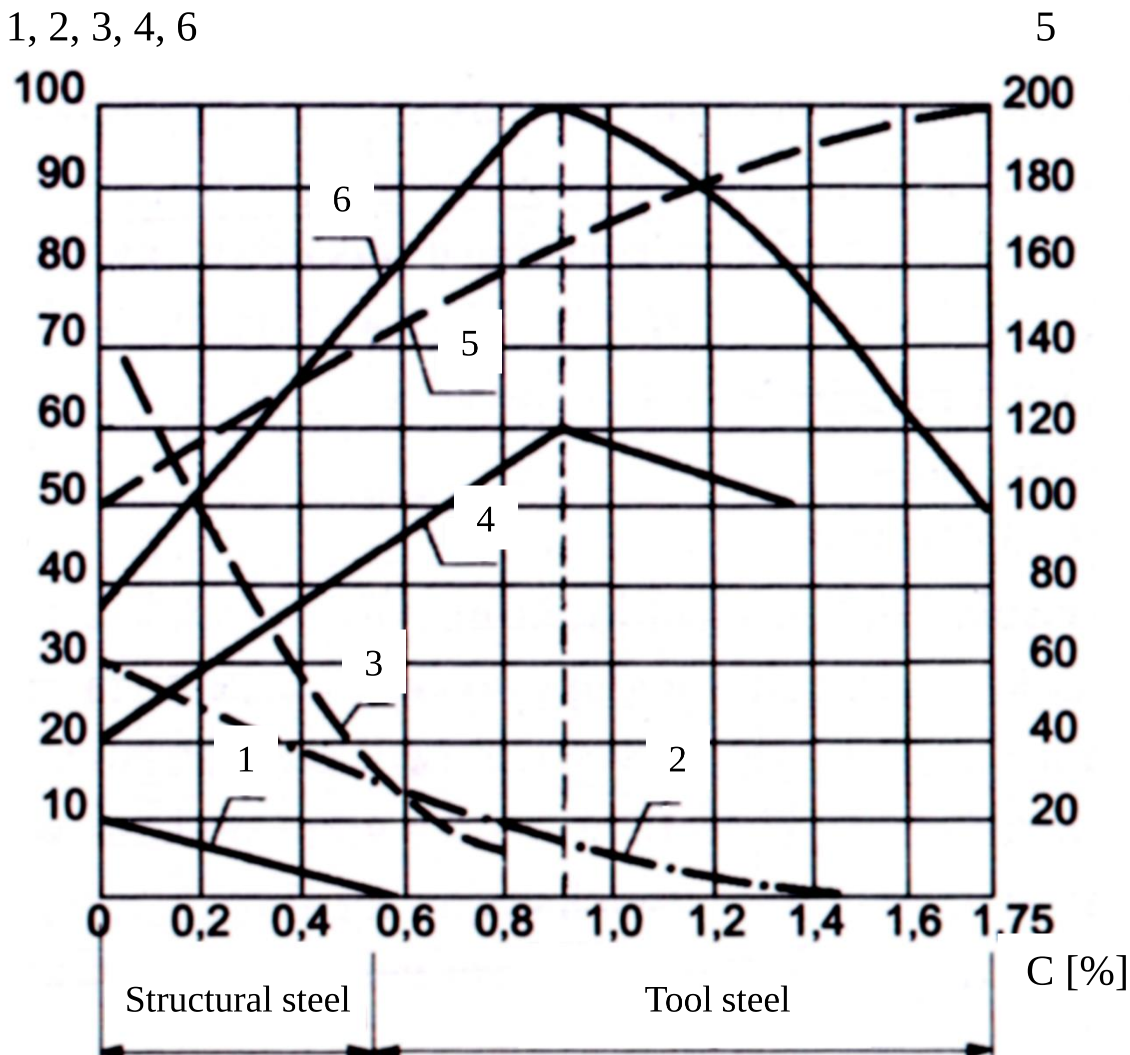


Photo: Łubiński M, Filipowicz A, Żółtowski W, "Konstrukcje metalowe", Arkady 2000

1. Impact resistane / 100 (left scale, [kJ / m^2]);

2. Elongation during testing, #t / 12 (left scale, [%]);

3. Reduction of area during testing, #t /18 (left scale, [%]);

4. f_y / 10 (left scale, [MPa]);

5. Brinell hardness (right scale, [MPa]);

6. f_u / 10 (left scale, [MPa]);

<u>**Symbol of steel**</u>

Four parts of symbol:

A	B	C	D

A:

S - structural steel

L - pipes for pipelines

B - for reinforcement of concrete

G - cast iron

C:

Symbols of subgrade, result from Charpy test (for structural steel)

B:

Grade of steel = f_y [MPa]

For example 235 $\rightarrow$ f_y = 235 [MPa]

D:

Additional information on steelmaking processes (for structural steel)

For example:

S 235 JR G2

Aluminum alloys

1xxx Technical aluminum Al > 99 %
2xxx Alloys Al + Cu
3xxx Alloys Al + Mn
4xxx Alloys Al + Si
5xxx Alloys Al + Mg
6xxx Alloys Al + Mg + Si
7xxx Alloys Al + Zn
8xxx Alloys Al + other
9xxx Special alloys (not used)

As in the case of steel, alloying elements are added to aluminum alloys.

Alloying elements → Lec. #2

There is very important type of "heat treating" for aluminium: precipitation hardening (age hardening). The effect of process is increasing of strength and decreasing of plasticity. Increasing of aluminum strength can be up to few dozens %.

Precipitation hardening is devastated during welding. Because of this, heat affected zones (HAZ) must be analysed during calculation of aluminum welding.

HAZ → Lab. #2

→ #1 / 93

Strength of aluminum alloys comes mainly from special heat treating. High temperatures - for example during welding - devastate this effect.

Heat affected zones (HAZ) for aluminum - reduction of strength parameters as a result of welding.

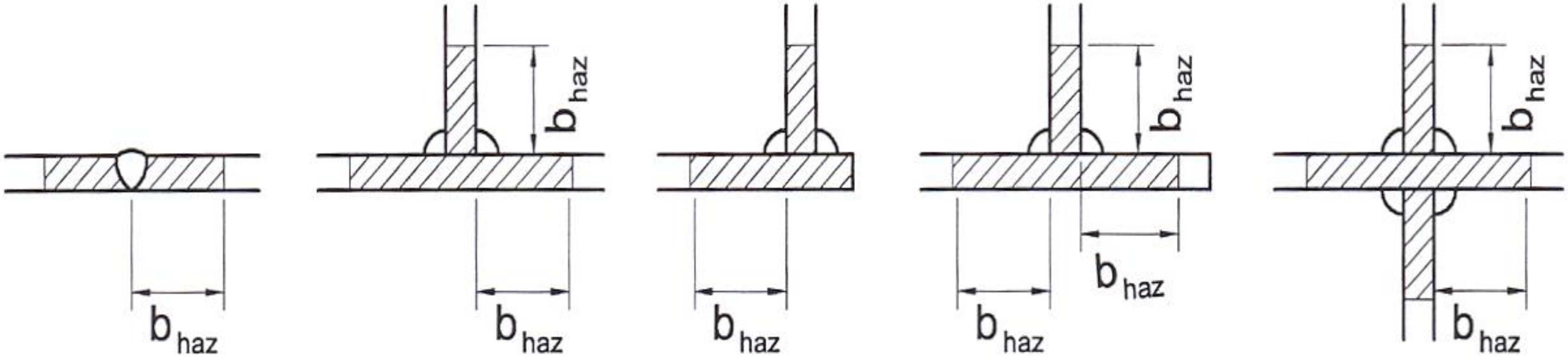


Photo: Author

Reduction factor

$$1,0 \geq \rho_{haz} \geq 0,28$$

More information → (Laboratory #2)

Examination issues

Relationship $\boldsymbol{\sigma}$–$\boldsymbol{\varepsilon}$, value of E , R_e , R_m , $f_{y,k}$, $f_{y,d}$

The importance of hardness test

The importance of Charpy test

The importance of weldability

Influence of welding in aluminum

Universal testing machine - maszyan wytrzymałościowa

Yeld strength - granica plastyczności

Ultimate tensile strength - granica wytrzymałości (na rozciąganie)

Buckling - wyboczenie

Standard deviation - odchylenie standardowe

Normal distribution - rozkład normalny

Hardness - twardość

Impact resistance - udarność

Ductility - ciągliwość

Forgeability - kowalność

Grindability - ścieralność

Weldability - spawalność

Fragility - kruchość

Fatigue resistance - wytrzymałość zmęczeniowa

Thank you for attention

tmichal@pk.edu.pl