Metal Structures

Lecture XVI

Welding technology

Contents

Welding process

Welding: in high temperature two elements locally transform from solid to liquid. We need **source of heat**. Liquid steel can react with oxygen in air – we need **source of shielding gas** to remove oxygen. Welds must have enough quality – we need **source of alloying additives** for proper chemical composition of welds (special types of electrodes).

After all, welds transform from liquid to solid – we have uniform material.

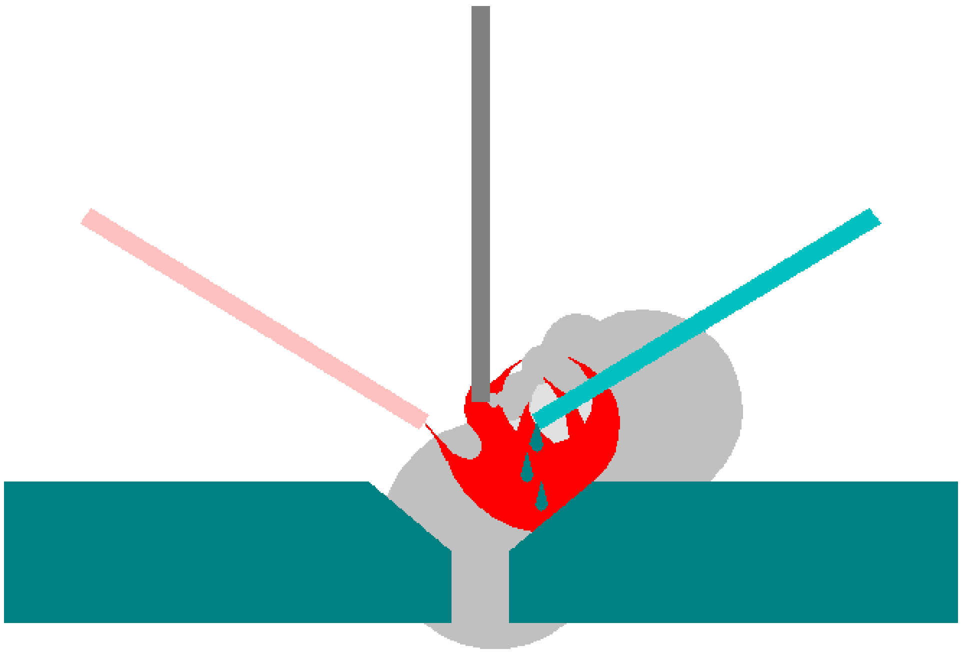


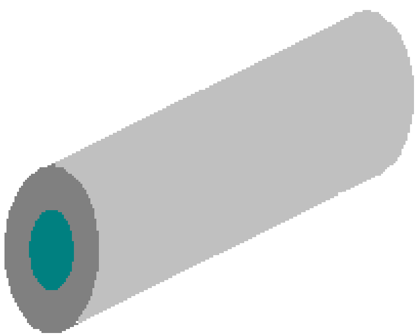
Photo: Author

Covered electrode:

core wire is the source of alloying additives;

flux coating is the source of shielding gas

Photo: ua.all.biz



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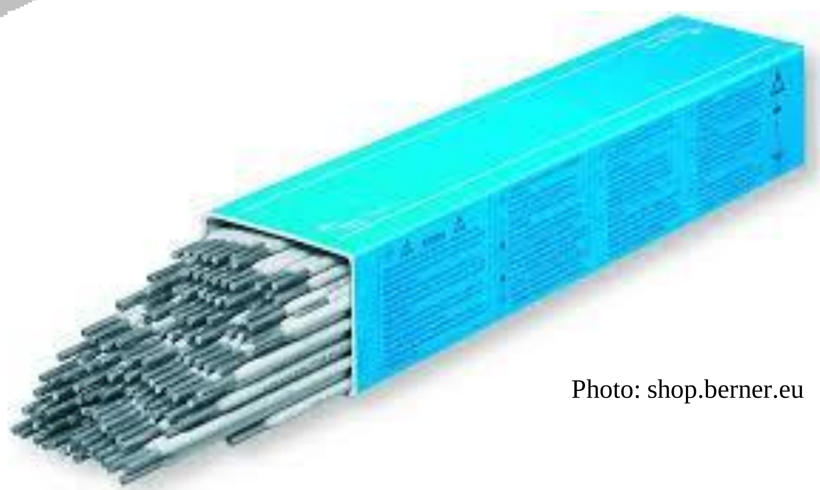


Photo: shop.berner.eu

Types of welding processes:

- gas welding;
- electro-welding (many subtypes);
- thermit welding;
- laser welding;

Gas welding

Photo: plomien-zgorzelec.pl

Photo: elektroda.pl

- mixture of oxygen + acetylene
- temperature ~ 3 000° C
- two separated elements: source of heat (burner) and source of alloying additives + shielding gas
- cheap method, but not for each type of steel, not very precise, not very safe, cause of hydrogen embrittlement (→ #t / 60)

Electro-welding

Photo: hak.com.pl

- electro-power makes very high temperature
- details depend on method (MIG, MAG, TIG, plasma etc)
- the most often situation - only one element: source of heat + alloying additives + shielding gas
- expensive method, for each type of steel, precise

Thermit welding

Photo: wikipedia

- thermite: mixture of Fe_2O_3 + Al (~75% + 25%)
- $Fe_2O_3 + 2\,Al \rightarrow 2\,Fe + Al_2O_3$ + energy
- temperature to 4 000^o C
- not very precise method, usually used to welded pipes and rails

Photo: pl.all.biz

Laser welding

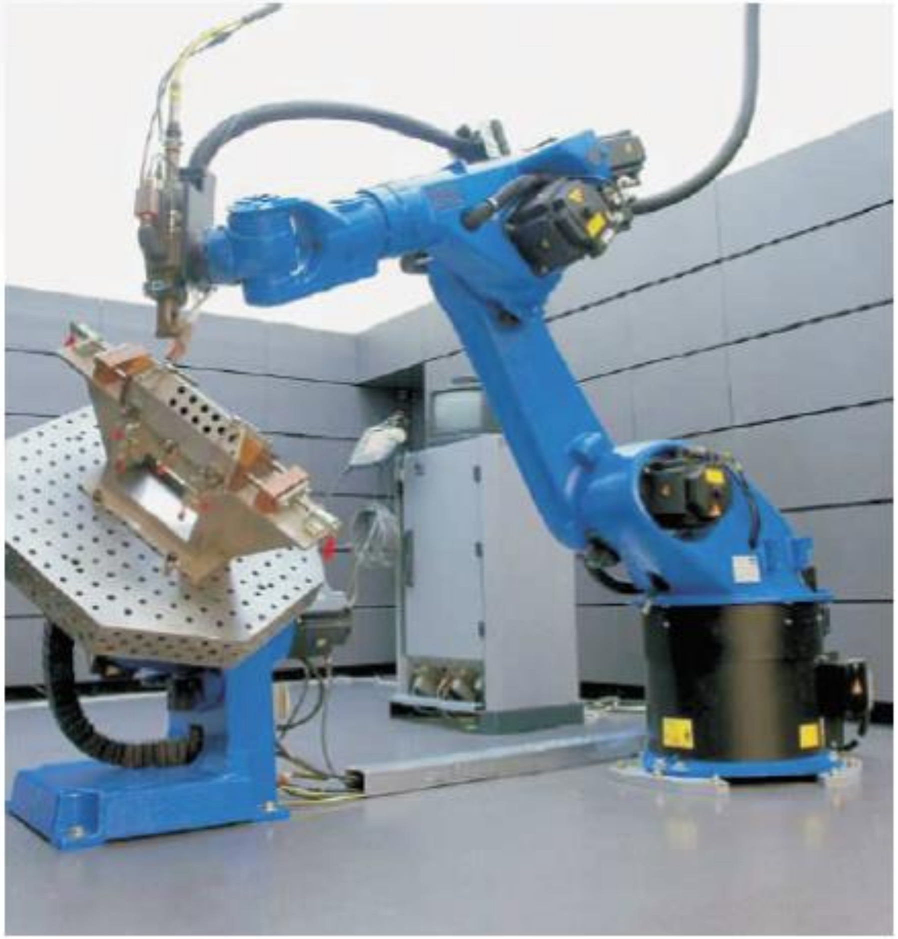


Photo: spawanielaserowe.pl

• expensive and very precise method
• rather not used in civil engineering

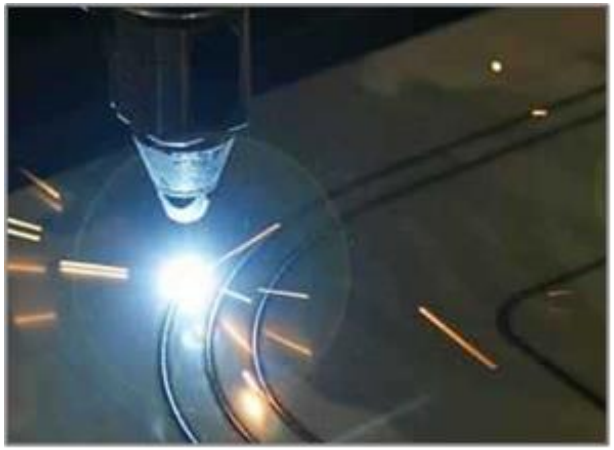


Photo: ciecie-laserowe.co.pl

Standards

EN 1090-2 Technical requirements

EN 12345 Welding; terms for welding joints

EN ISO 6520-1 Welding; classification of imperfections

EN 1991-1-8 Design of joints $t_{min} \geq 4$ mm

EN 1993-1-3 Supplementary rules for cold-formed members and sheeting $t_{min} \geq 2,5$ mm

EN 1993-1-9 Fatigue

EN 1993-1-10 Material toughness and through-thickness properties

Few standards ISO for welding electrodes

ISO 2560 Welding consumables - Covered electrodes for manual metal arc welding of non-alloy and fine grain steels - Classification

ISO 3580 Welding consumables - Covered electrodes for manual metal arc welding of creep-resisting steels - Classification

ISO 3581 Welding consumables - Covered electrodes for manual metal arc welding of stainless and heat-resisting steels - Classification;

ISO 18275 Welding consumables - Covered electrodes for manual metal arc welding of high-strength steels - Classification

ISO 2560 Welding consumables - Covered electrodes for manual metal arc welding of non-alloy and fine grain steels - Classification

Table 8B — Mechanical test requirements
(classification by tensile strength and 27 J impact energy)

Classification	Tensile strength [a] N/mm²	Yield strength [a] N/mm²	Elongation [a] A_5 %	Charpy V-notch temperature [b] °C
E4303	430	330	20	0
E4310	430	330	20	– 30
E4311	430	330	20	– 30
E4312	430	330	16	NS [b]
E4313	430	330	16	NS
E4316	430	330	20	– 30
E4318	430	330	20	– 30
E4319	430	330	20	– 20
E4320	430	330	20	NS
E4324	430	330	16	NS
E4327	430	330	20	– 30
E4340	430	330	20	0
E4903	490	400	20	0
E4910	480 to 650	400	20	– 30
E4911	480 to 650	400	20	– 30
E4912	490	400	16	NS
E4913	490	400	16	NS
E4914	490	400	16	NS
E4915	490	400	20	– 30

EN 10025-2 Hot rolled products for structural steel; technical delivery conditions for non-alloy structural steel

Table 7 - Mechanical properties at ambient temperature for flat and long products of steel grades and qualities with values for the impact strength

Designation		Minimum yield strength R_{eH} [a] MPa[b] Nominal thickness mm									Tensile strength R_m [a] MPa[b] Nominal thickness mm				
According EN 10027-1 and CR 10260	According EN 10027-2	≤ 16	> 16 ≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100	> 100 ≤ 150	> 150 ≤ 200	> 200 ≤ 250	> 250 ≤ 400[c]	< 3	≥ 3 ≤ 100	> 100 ≤ 150	> 150 ≤ 250	> 250 ≤ 400[c]
S235JR	1.0038	235	225	215	215	215	195	185	175	-	360 to 510	360 to 510	350 to 500	340 to 490	-
S235J0	1.0114	235	225	215	215	215	195	185	175	-	360 to 510	360 to 510	350 to 500	340 to 490	-
S235J2	1.0117	235	225	215	215	215	195	185	175	165	360 to 510	360 to 510	350 to 500	340 to 490	330 to 480
S275JR	1.0044	275	265	255	245	235	225	215	205	-	430 to 580	410 to 560	400 to 540	380 to 540	-
S275J0	1.0143	275	265	255	245	235	225	215	205	-	430 to 580	410 to 560	400 to 540	380 to 540	-
S275J2	1.0145	275	265	255	245	235	225	215	205	195	430 to 580	410 to 560	400 to 540	380 to 540	380 to 540
S355JR	1.0045	355	345	335	325	315	295	285	275	-	510 to 680	470 to 630	450 to 600	450 to 600	-
S355J0	1.0553	355	345	335	325	315	295	285	275	-	510 to 680	470 to 630	450 to 600	450 to 600	-
S355J2	1.0577	355	345	335	325	315	295	285	275	265	510 to 680	470 to 630	450 to 600	450 to 600	450 to 600
S355K2	1.0596	355	345	335	325	315	295	285	275	265	510 to 680	470 to 630	450 to 600	450 to 600	450 to 600
S450J0[d]	1.0590	450	430	410	390	380	380	-	-	-	-	550 to 720	530 to 700	-	-

[a] For plate, strip and wide flats with widths ≥ 600 mm the direction transverse (t) to the rolling direction applies. For all other products the values apply for the direction parallel (l) to the rolling direction.

[b] 1 MPa = 1 N/mm^2.

[c] The values apply to flat products.

[d] Applicable for long products only.

(*To be continued*)

Table 7 - Mechanical properties at ambient temperature for flat and long products of steel grades and qualities with values for the impact strength (*concluded*)

Designation		Position of test pieces [a]	Minimum percentage elongation after fracture [a] %										
			L_0 = 80 mm Nominal thickness mm					$L_0 = 5,65 \sqrt{S_0}$ Nominal thickness mm					
According EN 10027-1 and CR 10260	According EN 10027-2		≤ 1	> 1 ≤ 1,5	> 1,5 ≤ 2	> 2 ≤ 2,5	> 2,5 < 3	≥ 3 ≤ 40	> 40 ≤ 63	> 63 ≤ 100	> 100 ≤ 150	> 150 ≤ 250	> 250[c] ≤ 400 only for J2 and K2
S235JR	1.0038	l	17	18	19	20	21	26	25	24	22	21	-
S235J0	1.0114												-
S235J2	1.0117	t	15	16	17	18	19	24	23	22	22	21	21 (l and t)
S275JR	1.0044	l	15	16	17	18	19	23	22	21	19	18	-
S275J0	1.0143												-
S275J2	1.0145	t	13	14	15	16	17	21	20	19	19	18	18 (l and t)
S355JR	1.0045	l	14	15	16	17	18	22	21	20	18	17	-
S355J0	1.0553												-
S355J2	1.0577												17 (l and t)
S355K2	1.0596	t	12	13	14	15	16	20	19	18	18	17	17 (l and t)
S450J0[d]	1.0590	l	-	-	-	-	-	17	17	17	17	-	-

[a] For plate, strip and wide flats with widths ≥ 600 mm the direction transverse (t) to the rolling direction applies. For all other products the values apply for the direction parallel (l) to the rolling direction.

[c] The values apply to flat products.

[d] Applicable for long products only.

Electrode: yield strength, tensile strength, elongation and result of Charpy test;

Steel: yield strength, tensile strength, elongation and result of Charpy test;

These four parameters should be as similar as possible.

Types of welds

Welds						
Fillet			Butt		Plug	Flare groove
„Normal”	Intermittent	All round	Full penetration	Partial penetration		
#t / 17, 18, 23, 24, 28	#t / 17, 18, 19, 23, 24, 28	#t / 17, 18, 20, 23, 24, 27, 28	#t / 17, 18, 21, 25, 26, 28	#t / 17, 18, 21, 25, 26, 28	#t / 20, 27	#t / 22

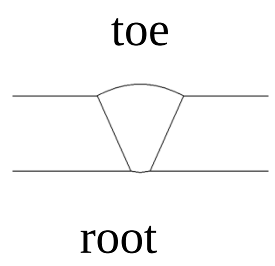
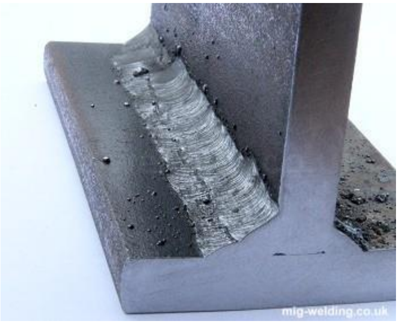


Photo: Author

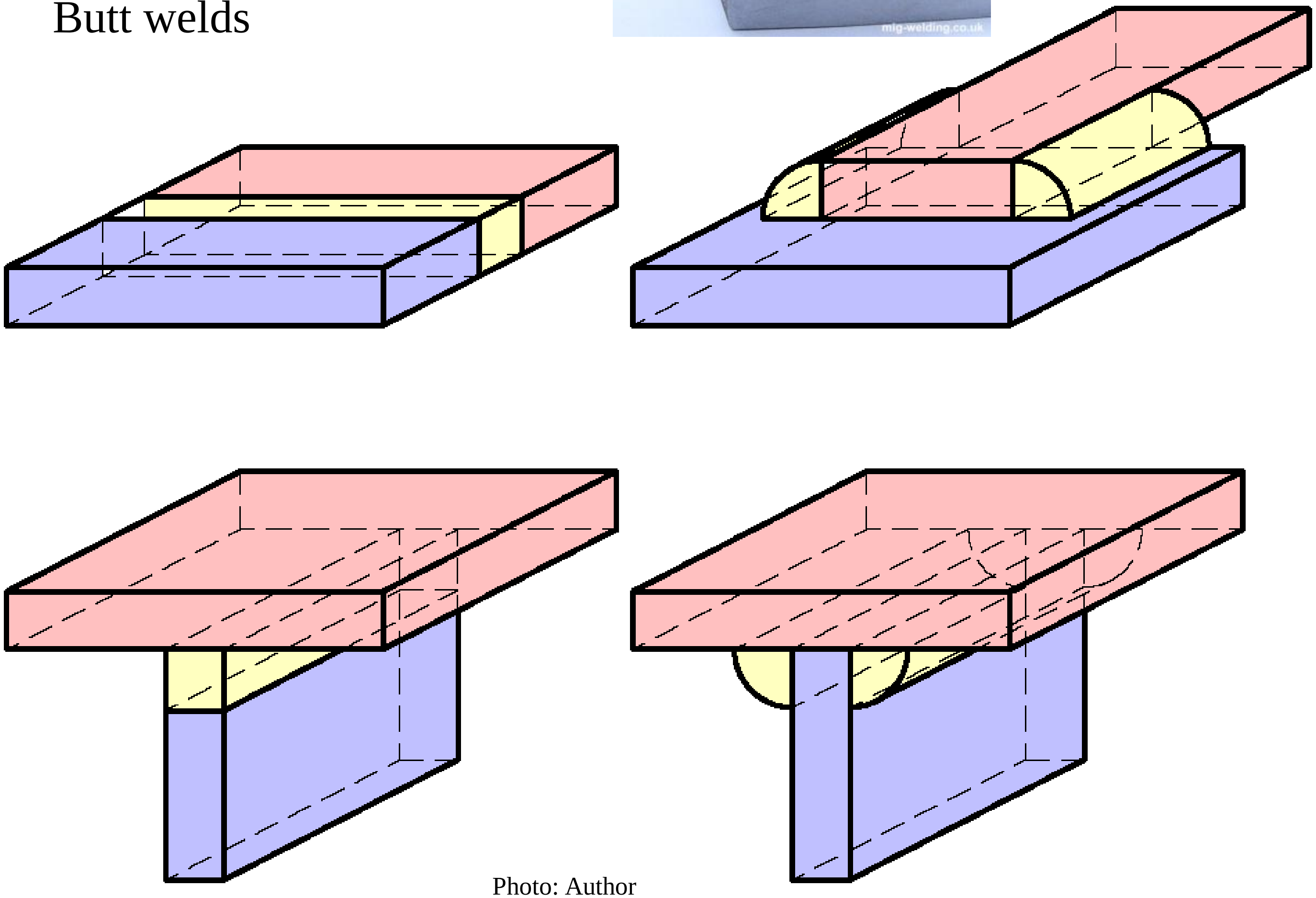
Photo: mig-welding.co.uk



Filled welds

Photo: mig-welding.co.uk

Butt welds



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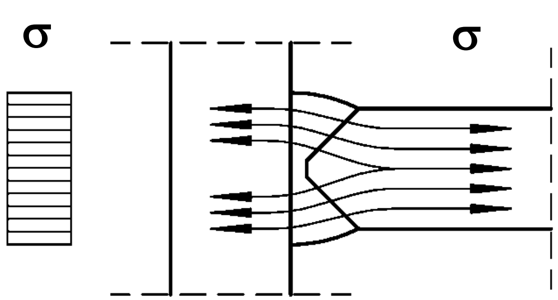
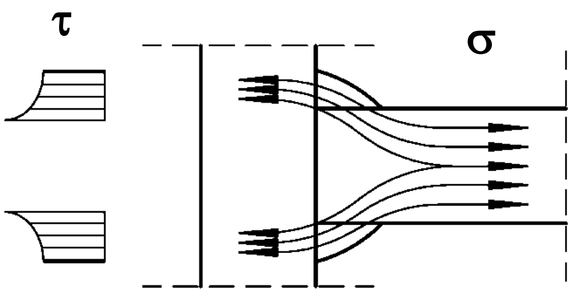




Butt welds – the same stresses in elements and weld

Filled welds – completely another stresses in elements and weld

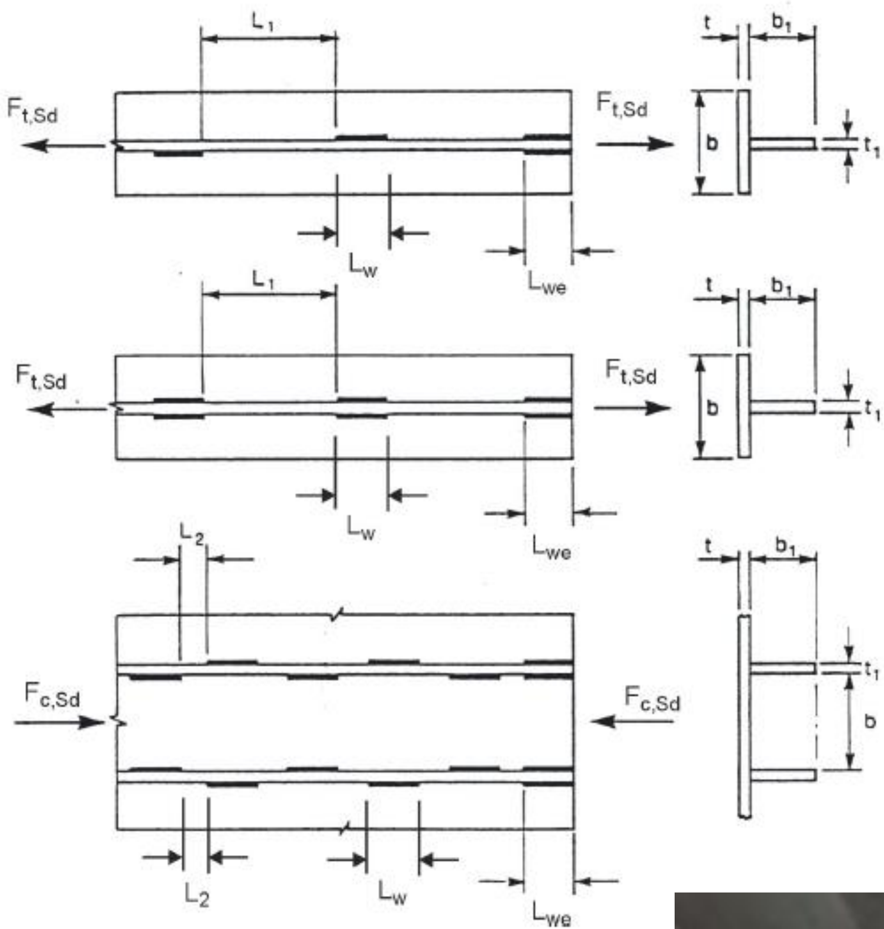


Photo: EN 1993-1-8 fig 4.1

Filled intermittent welds

$L_{we} \geq \min(\ 0{,}75\ b \quad ; \quad 0{,}75\ b_1)$

tension:

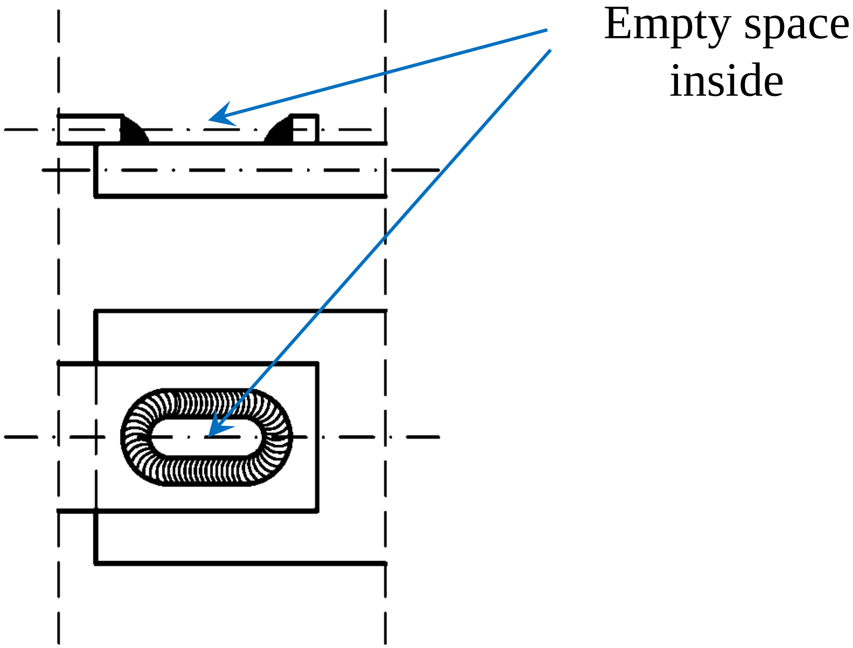
$L_1 \leq \min(\ 16\ t \quad ; \quad 16\ t_1 \quad ; \quad 200\ mm)$

compression or shear:

$\leq \min(\ 12\ t \quad ; \quad 12\ t_1 \quad ; \quad 0{,}25\ b \quad ; \quad 200\ mm)$

Photo: resources.arcmachines.com

Photo: Author



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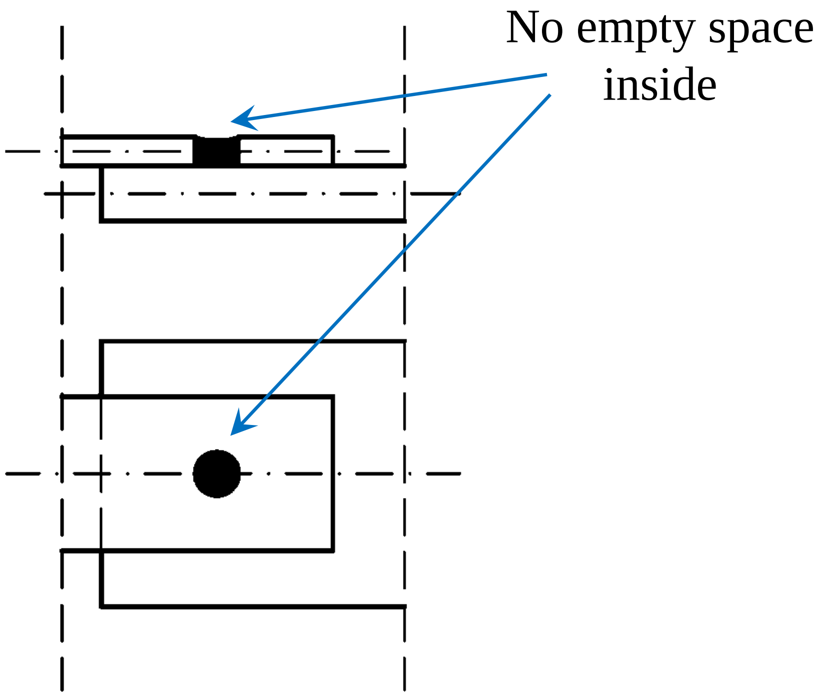


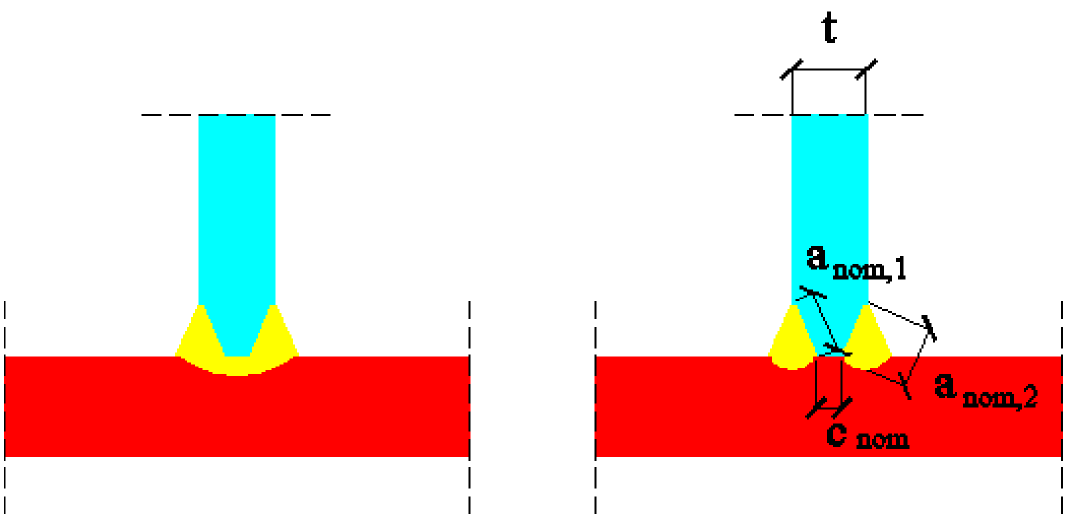
Filled all round welds (slot welds)

Plug welds

Photo: dirtydragonfabrication.com

Photo: Experimental Fatigue Evaluation of Welded Connections in Cantilevered Steel Sign Structures, Sim H-B, Uang C-M, Journal of Structural Engineering, 139 / 12

Butt full penetration welds

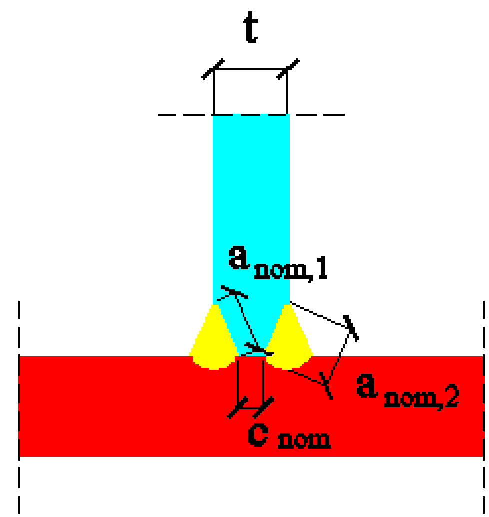


$$a_{nom,\,1} + a_{nom,\,1} \geq t$$

and

$$c_{nom} = \min\,(3\text{ mm} \quad ; \quad t / 5)$$

Butt partial penetration welds



$$a_{nom,\,1} + a_{nom,\,1} < t$$

or

$$c_{nom} > \min\,(3\text{ mm} \quad ; \quad t / 5)$$

Photo: Author

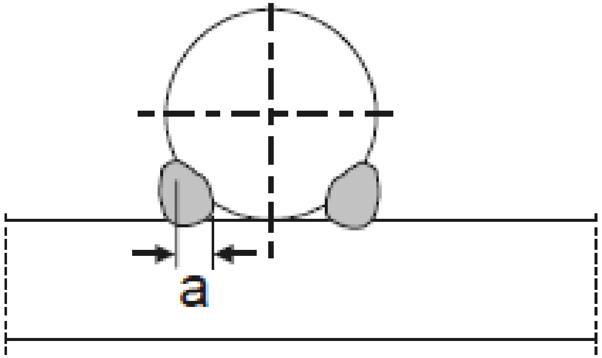


Photo: scottmetals.com.au

Flare groove welds – round surfaces

Photo: EN 1993-1-8 fig 4.2

Photo: steeltubeinstitute.org

Geometry of filled welds

$a \geq 3$ mm $\quad\quad l_{min} = \max(\,6a;\ \ 30\ \text{mm})$

(EN 1993-1-8)

$0{,}2\ t_2 \leq a \leq 0{,}7\ t_1$

$t_2 \geq t_1$

(PN-B 3200)

$150\ a \geq\ l$

(EN 1993-1-8)

Filled welds – acceptable angles between elements (EN 1993-1-9 p.4.3.2.1)

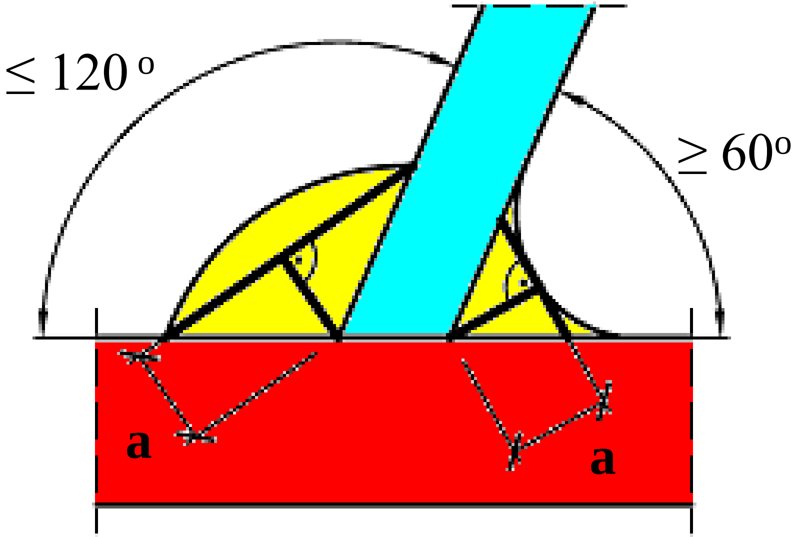


Photo: Author

Butt welds – geometry

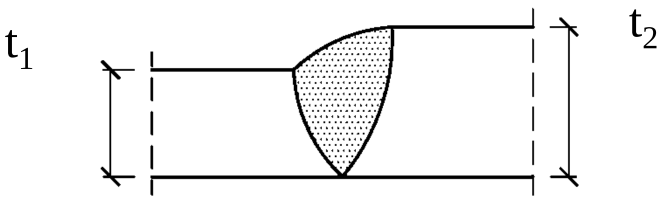
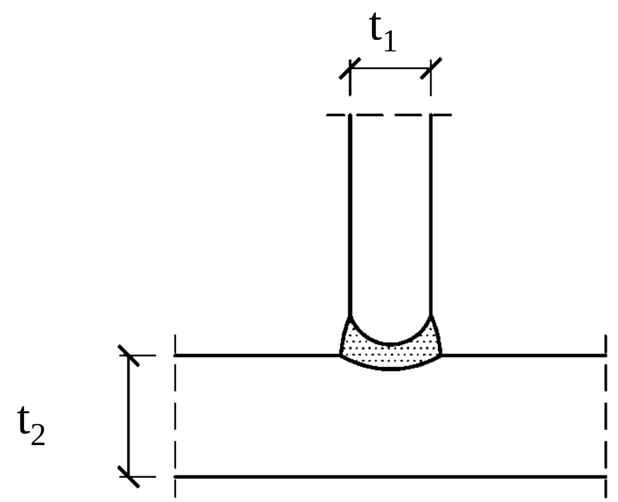
	
$a = \min(t_1; t_2)$	$a = t_1$

Photo: Author

Butt welds – bevelling

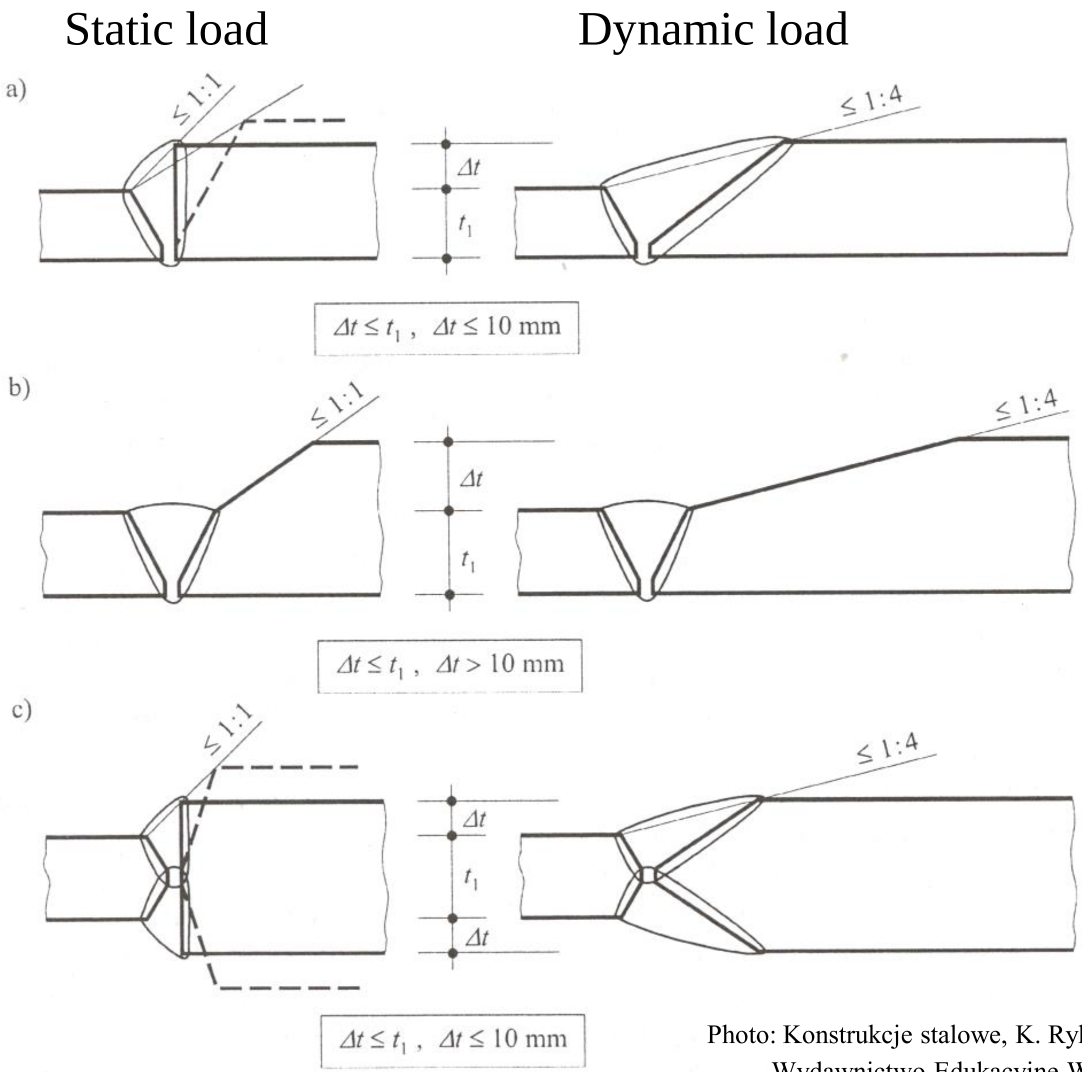
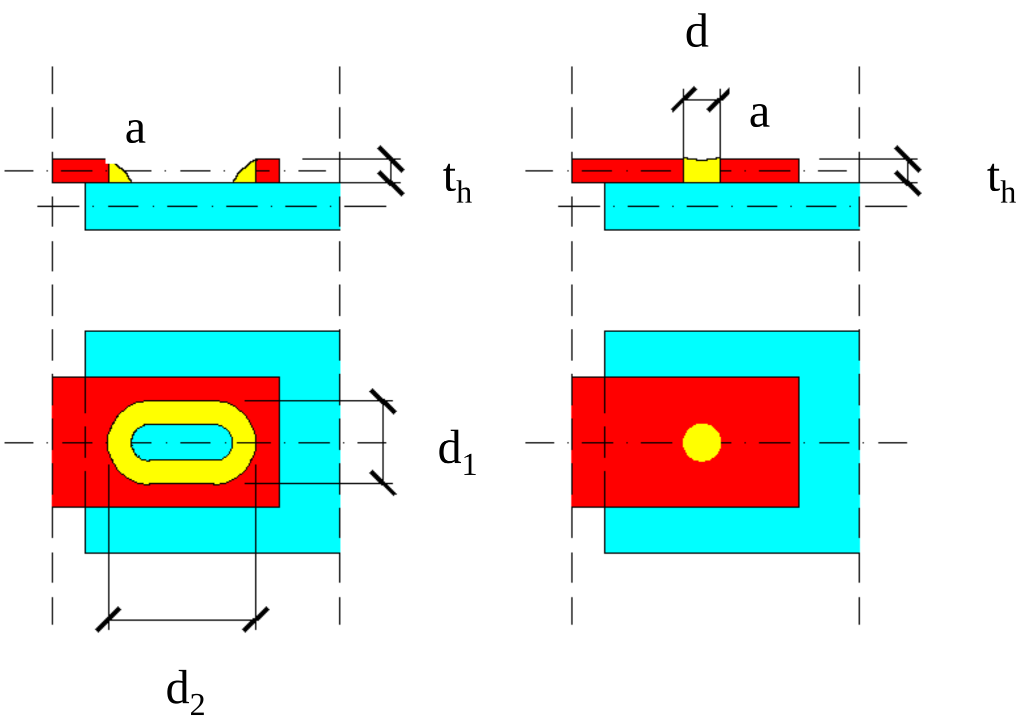


Photo: Konstrukcje stalowe, K. Rykaluk, Dolnośląskie Wydawnictwo Edukacyjne Wrocław 2001

Photo: Author

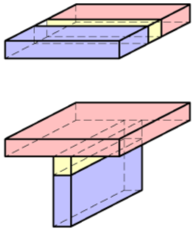
All round and plug welds – geometry



EN 1993-1-8
4.3.3
4.3.5

Dimensions	Filled all round welds	Plug welds
min (d ; d_1 ; d_2)	> 4 t_h	> t_h + 8mm
a	→ filled welds	= t_h (t_h < 16 mm)
		= max (16mm; t_h / 2) (t_h > 16 mm)

Comparison



Butt welds	Filled welds
No calculations for resistance of weld; it is the same as weaker element	Additional calculation for resistance of welds; it is different that resistance of elements
Possible between elements on only few relative positions (for example - impossible between flange and flange plate)	Possible between elements on each relative position
There are need additional preparation for elements (bevelling)	No need additional preparation of elements

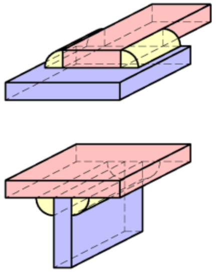


Photo: Author

Requirements and recommendations

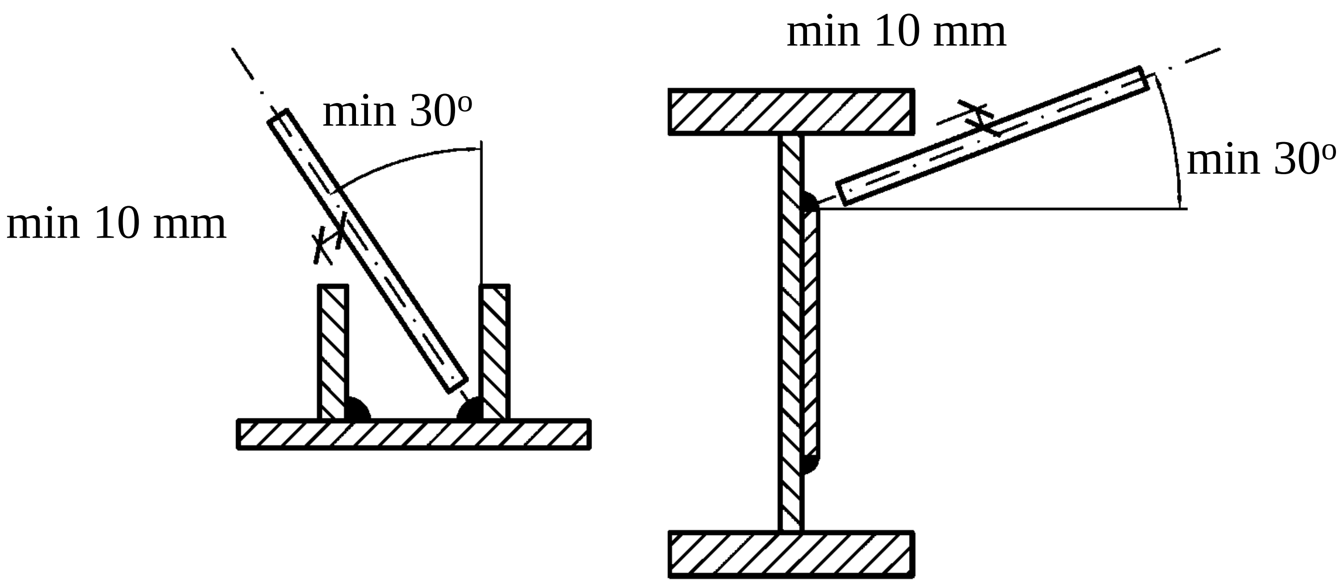
Surfaces:

- Degreased
- Dry
- No rust
- No galvanized
- No paint
- No cracks

Baked impurities and coatings may cause weld imperfections

Cracking of welds means destruction of joint; crack in element will cause a crack in weld.

Therma decomposition of water is source of hydrogen. Hydrogen cracking is one of many types od welds destruction.



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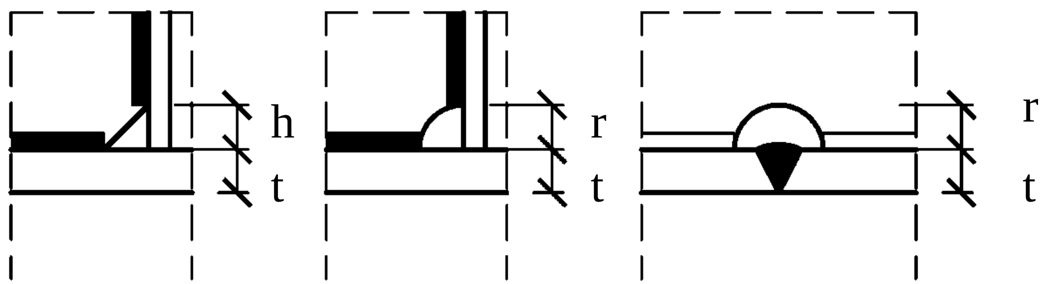
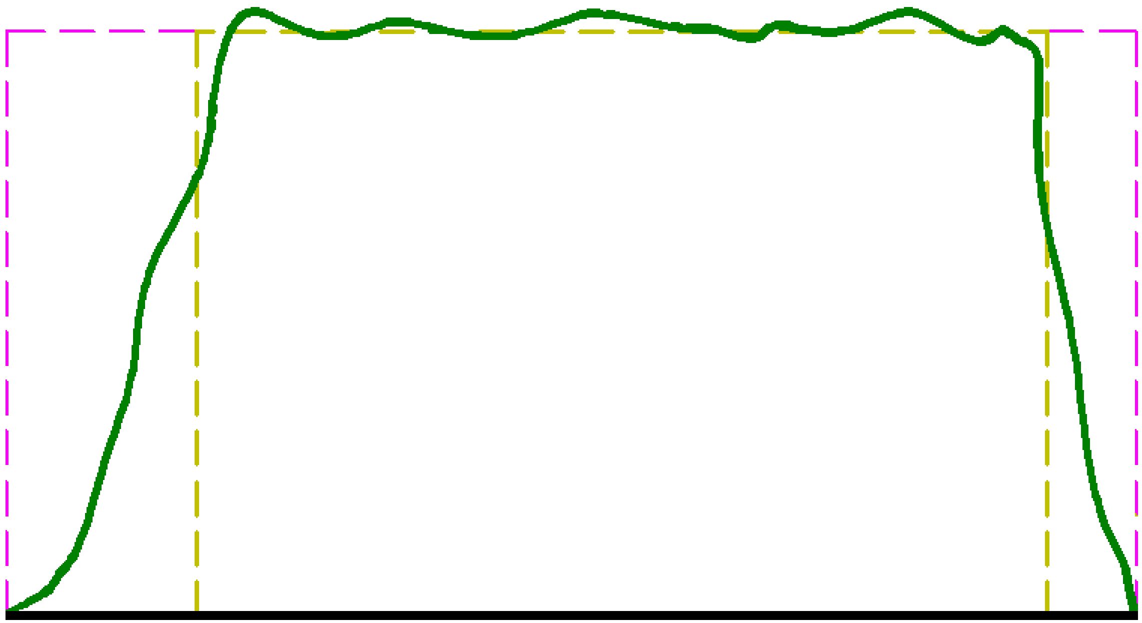


$h \geq 25$ mm; $h \geq 3$ t

$r \geq 25$ mm; $r \geq 3$ t

Weld quality

→ #6 / 65



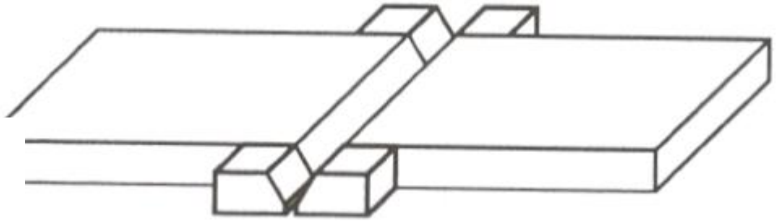
Initial part - launch of the welding machine

Final part - possibility of premature shutdown

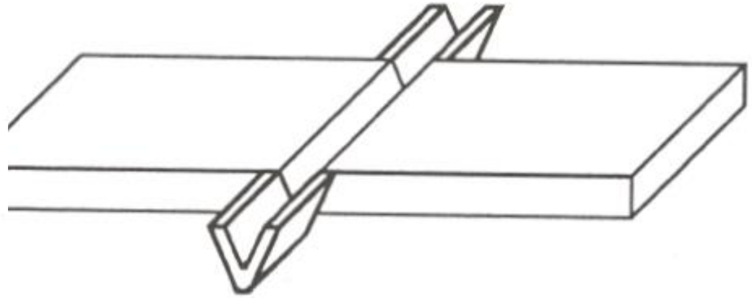
Theoretical weld quality by mathematical model

Real weld quality

Real weld quality by mathematical model - too short weld in comparison to load a)



b)



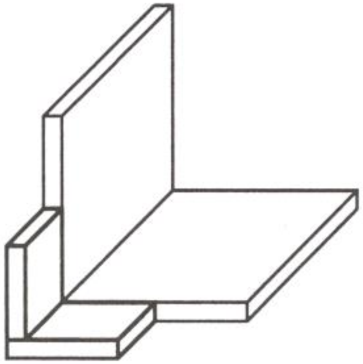
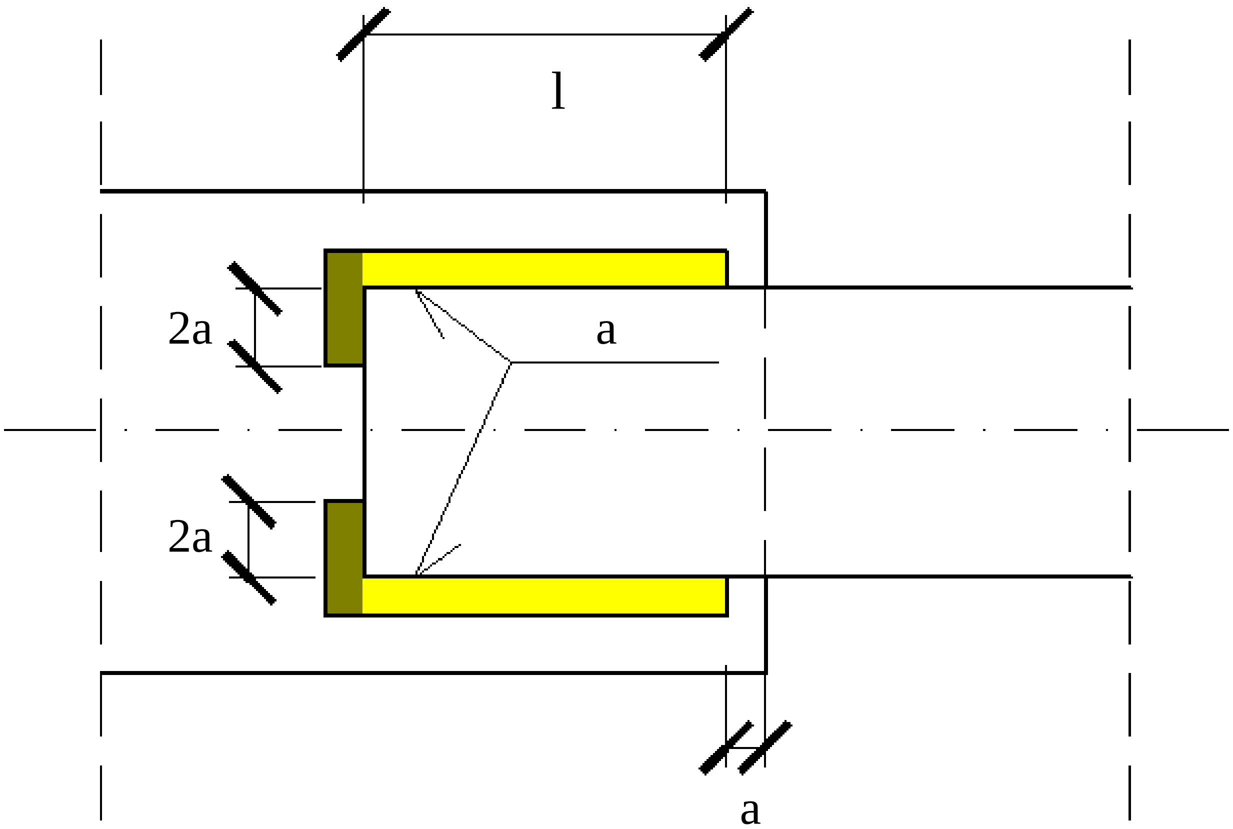


Photo: Konstrukcje stalowe, K. Rykaluk, Dolnośląskie
Wydawnictwo Edukacyjne Wrocław 2001

Run-off plates – initial and final section of the weld are removed

Filled welds – length of welds without run-off plates



$l_{(calculations)} = l$ or $l - 2a$ or $l + 2a - 2a$

Photo: Author

Limitations

We should avoid of welds in „sensitive" parts of cross-sections

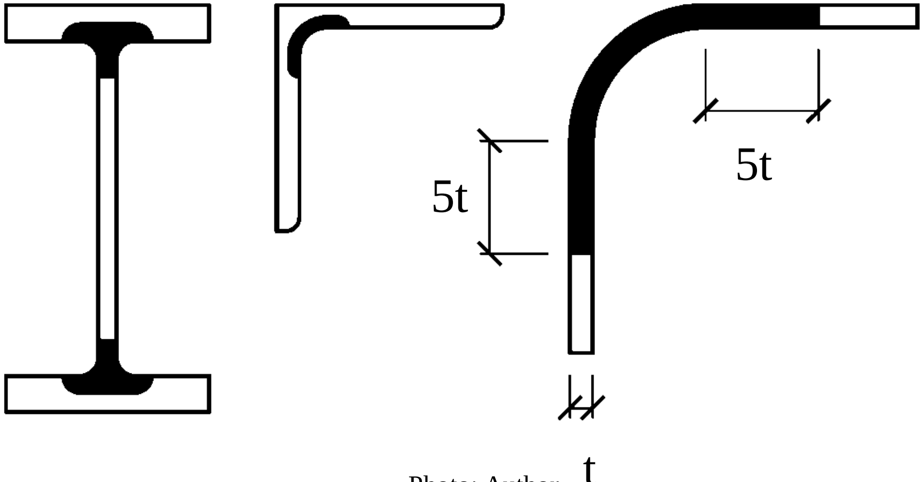
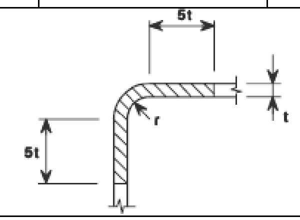


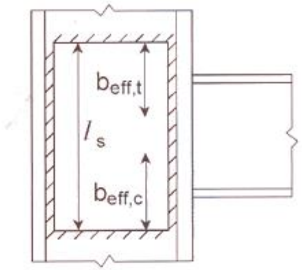
Photo: Author

For cold-formed cross-sections, welding is possible when:

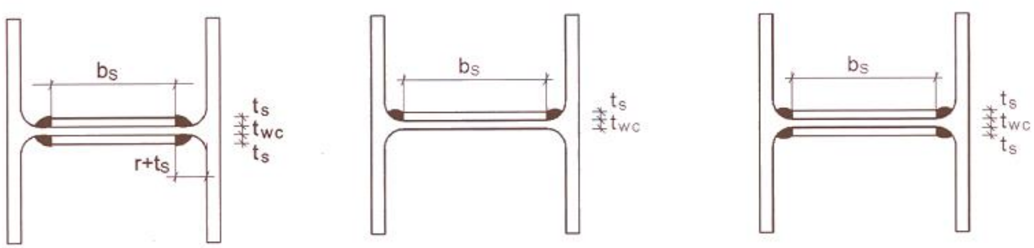
(EN 1993-1-8 tab. 4.2)

r/t	Strain due to cold forming (%)	Maximum thickness (mm)		
		Generally		Fully killed Aluminium-killed steel (Al ≥ 0,02 %)
		Predominantly static loading	Where fatigue predominates	
≥ 25	≥ 2	any	any	any
≥ 10	≥ 5	any	16	any
≥ 3,0	≥ 14	24	12	24
≥ 2,0	≥ 20	12	10	12
≥ 1,5	≥ 25	8	8	10
≥ 1,0	≥ 33	4	4	6



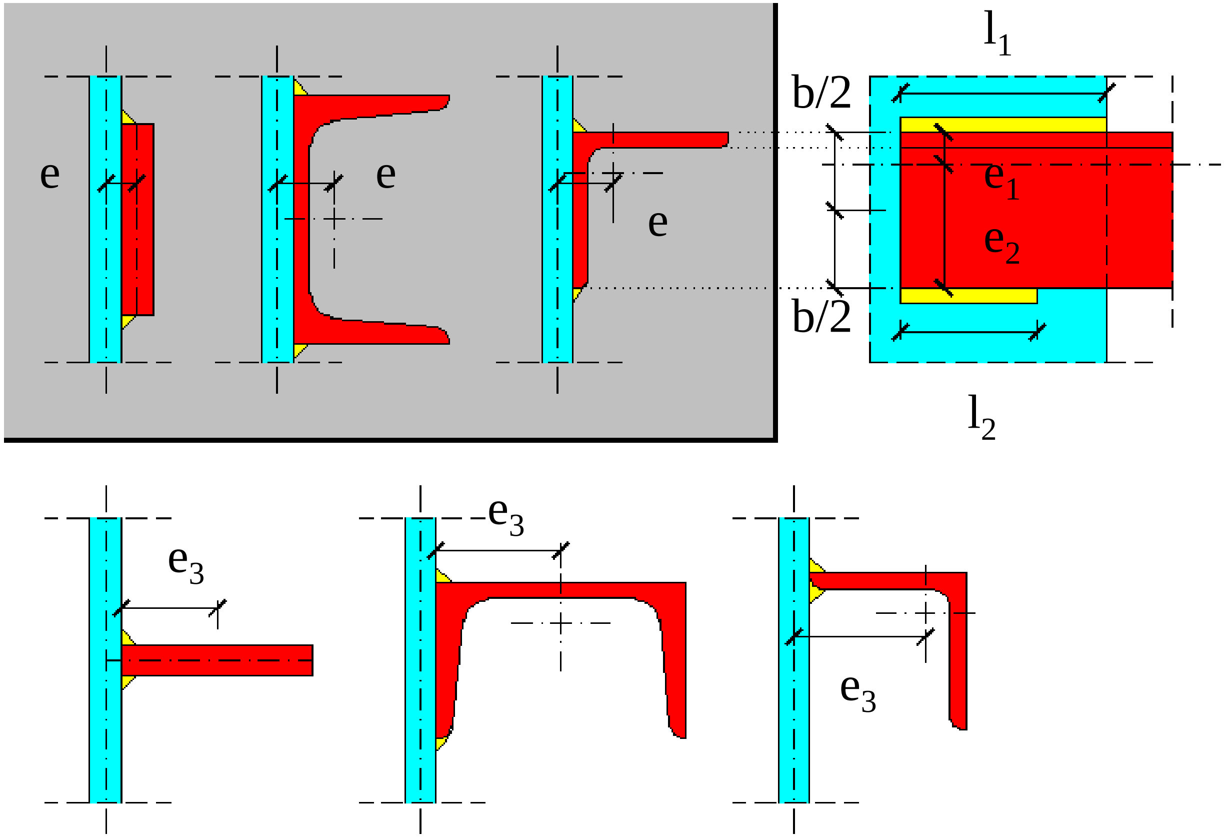


Supplementary web plates for node reinforcement - weldability at the corner should be taken into account (EN 1993-1-8 fig. 6.5)



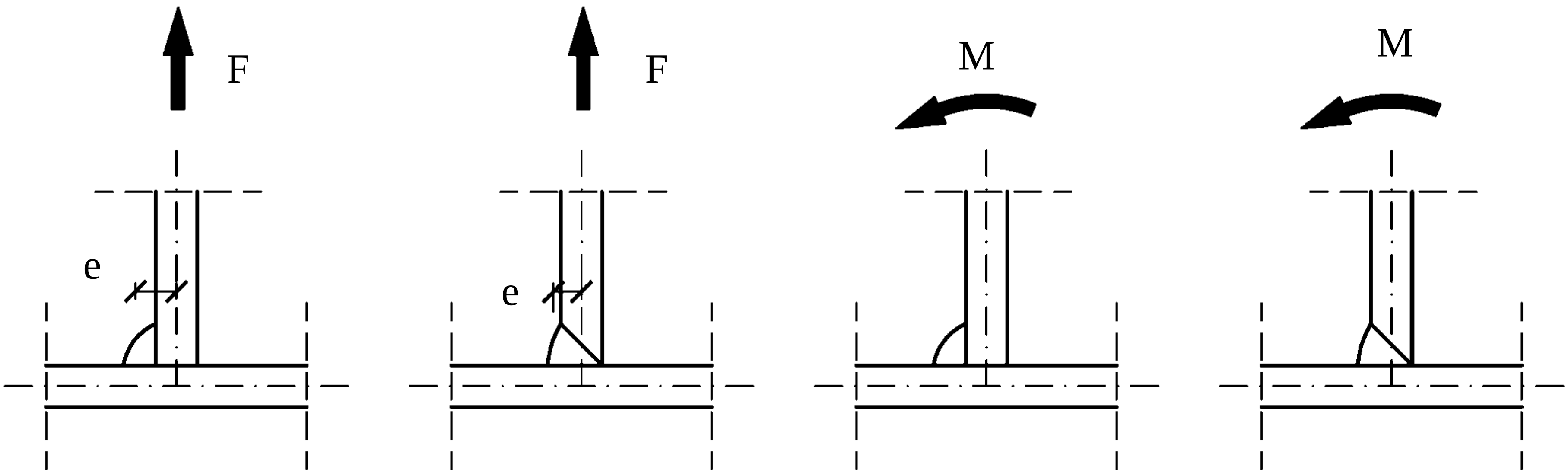
Eccentricities

Photo: Author



e can be neglected
e_1 , e_2 , e_3 can’t be neglected → additional bending moment

Eccentricities should be taken into account when force or bending moment produce tension at the root of the weld.



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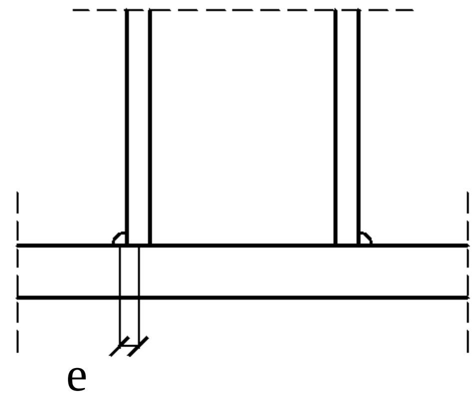

Local eccentricity need not be taken into account if a weld is used as part of a weld group around the perimeter of a structural hollow section.

Types of cracks

There are many types of cracking and similar phenomenons in steel structures. Part of them is associated with welding, part not.

Main idea: weldability

Time		Type of cracking
Before exploatation (technological problems)	Preparations for welding	stress-relief cracking;
	During welding	hot cracking; lamellar tearing;
	After welding	stress-relief cracking; cold cracking;
During exploatation	Associated with welding	fatigue cracking; hydrogen embrittlement;
	Not associated	hydrogen embrittlement; brittle cracking; ductile fracture;

There are no clear requirements for calculations and avoidance many types of cracking. There are many models for each types of cracking in literature.

Type of cracking	Calculation		Information
	according to literature	according to EN	
weldability;		EN 1011-2	#t / 41-44
stress-relief cracking;	+		#t / 45
hot cracking;	+		#t / 46
lamellar tearing;		EN 1993-1-10 EN 10 164	#t / 47-50
cold cracking;	+		#t / 51
fatigue cracking;		EN 1993-1-9	#t / 52-59
hydrogen embrittlement	+		#t / 60
brittle cracking;		EN 1993-1-10	#t / 61-63
ductile fracture;	$E / R \leq 1{,}0$		#t / 64

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

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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

Weldability

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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)

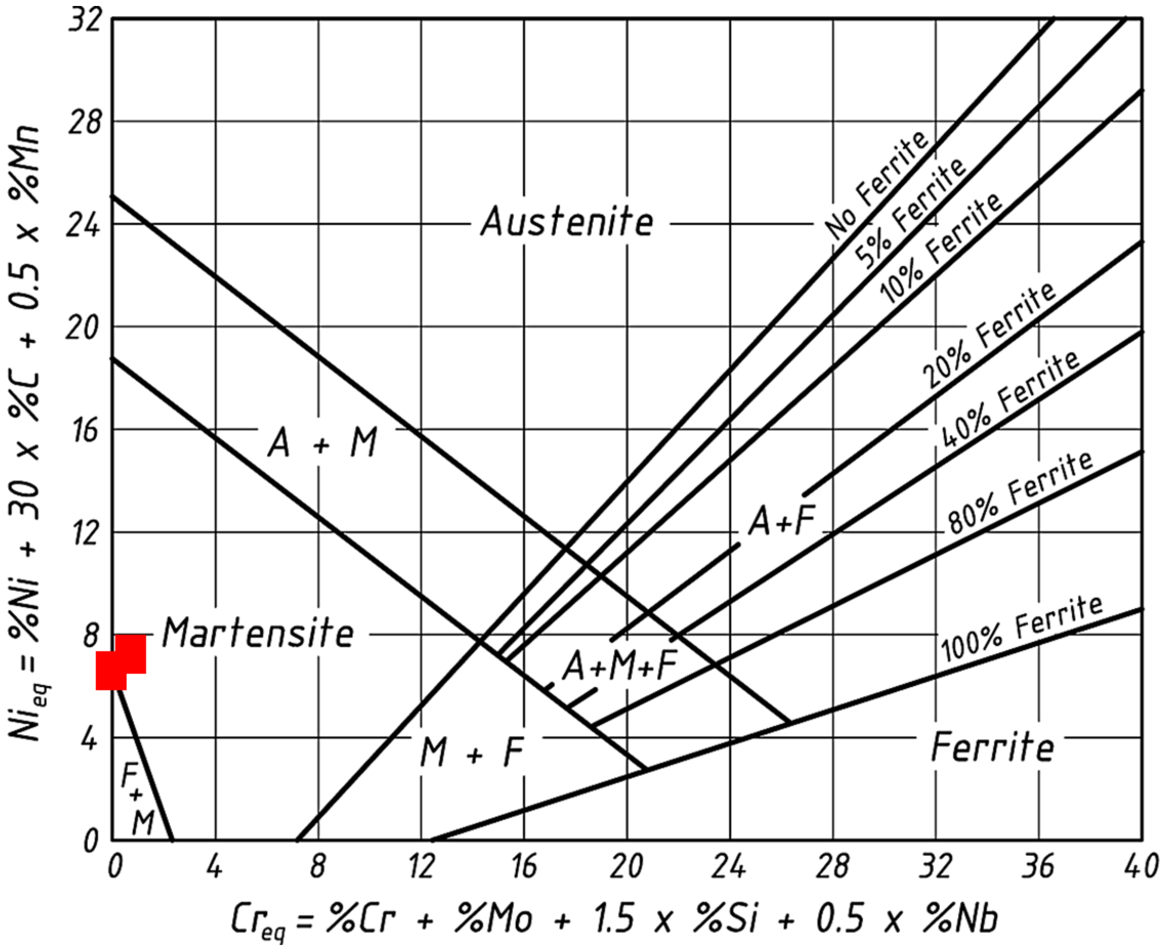


Photo: I. Tylek, K. Kuchta, Physical and technological properties of structural stainless steel, Technical Transactions 4-B / 2014

Chemical composition of structural steel S235, S275 and S355 places it in group of martensitic steels. This means a potentially high tendency to uncontrolled martensitic transformation and weldability problems.

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

Steel	t ≤ 16 mm	16 < t ≤ 40 mm	t > 40 mm
S235 JR	0,170 + 1,400 / 6 + 0,550 / 15 = **0,440**		0,220 + 1,400 / 6 + 0,550 / 15 = **0,490**
S235 J0	0,170 + 1,400 / 6 + 0,550 / 15 = **0,440**		
S235 J2	0,170 + 1,400 / 6 + 0,550 / 15 = **0,440**		
S275 JR	0,210 + 1,500 / 6 + 0,550 / 15 = **0,497**		0,220 + 1,500 / 6 + 0,550 / 15 = **0,507**
S275 J0	0,180 + 1,500 / 6 + 0,550 / 15 = **0,467**		
S275 J2	0,180 + 1,500 / 6 + 0,550 / 15 = **0,467**		
S355 JR	0,240 + 1,600 / 6 + 0,550 / 15 = **0,543**		
S355 J0	0,200 + 1,600 / 6 + 0,550 / 15 = **0,503**		
S355 J2	0,200 + 1,600 / 6 + 0,550 / 15 = **0,503**		

0,42% < C_E < 0,60% average weldability

Prevention:

preliminary heating (T_W) (not alvays possible);
heat treatement after welding (not alvays possible);

Preliminary heating: increasing temperature of members before welding process, recommended temperature:

$$T_W = 350 \{[1 + 0{,}005\ t / (1mm)]C_E – 0{,}25\}^{0{,}5}\ [^oC]$$

About 160-230°C in presented cases

Stress-relief cracking

Thermal stresses during preheating or post-weld heat treatment, superimposed on recrystallizing weld; gaps are formed between microcrystals in which carbides precipitate. This leads to grain boundary hardening, increased brittleness and cracking. A case in which influence of welding technology on recrystallization should be examined in more detail.

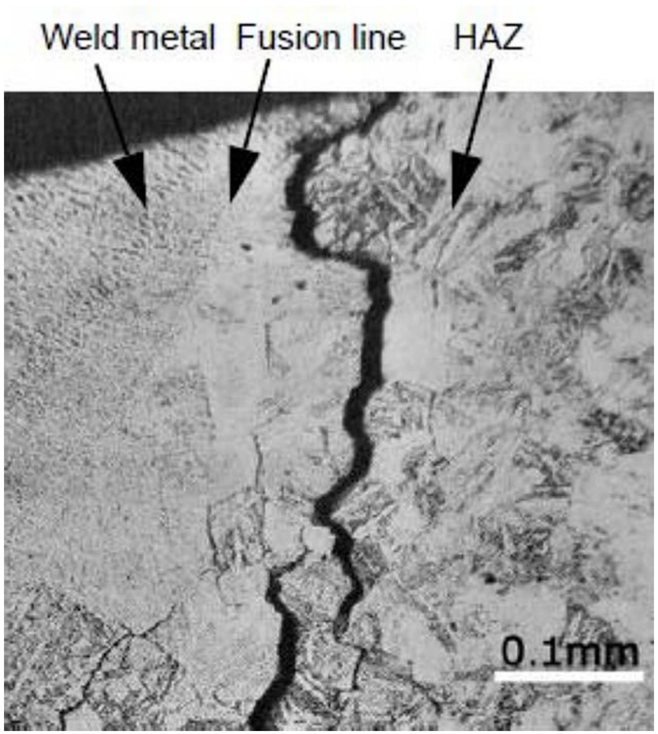
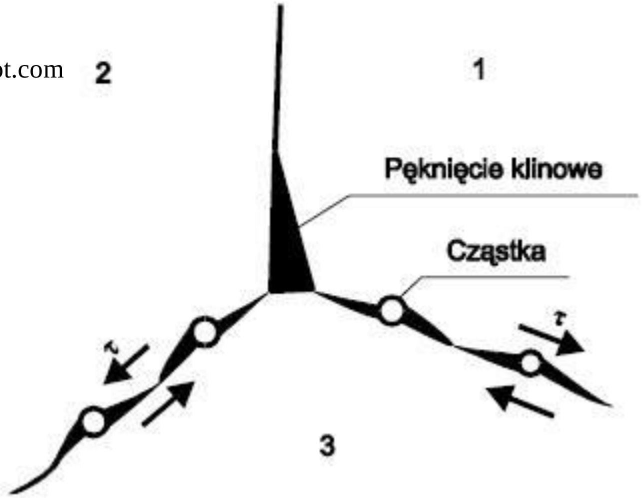


Photo: weldingengineers.co.nz

Photo: spawalnictwo.blogspot.com



Steel **S355** is the most vulnerable.

Hot cracing

Thermal stresses during welding, "frozen" in the solidifying material. Here, too, influence of welding technology on recrystallizing weld should be examined more closely.

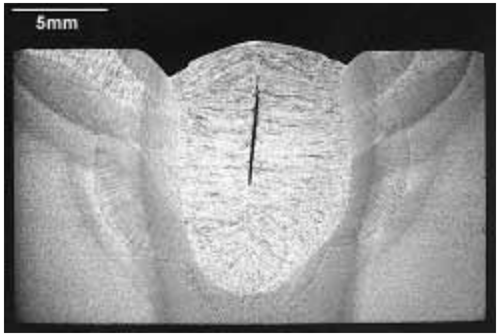


Photo: twi-global.com

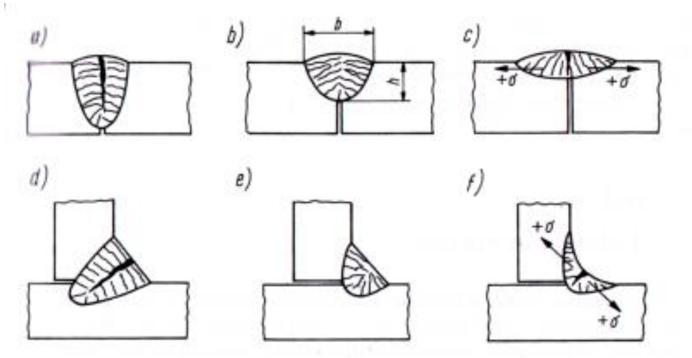


Photo: K. Ferenc, J. Ferenc, Konstrukcje spawane, połączenia, WNT 2003

Steel **S355** is the most vulnerable.

Lamellar tearing

Contamination; mainly sulphides and hydrogen + thermal deformations. Described in EN 1993-1-10 and EN 10 164. Eurocode 1993-1-10 application of a limitation on permissible thickness of welded elements in order to reduce risk of lamellar tearing.

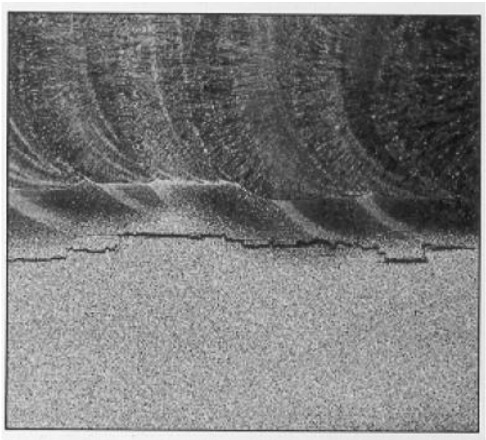


Photo: pipingengineer.org

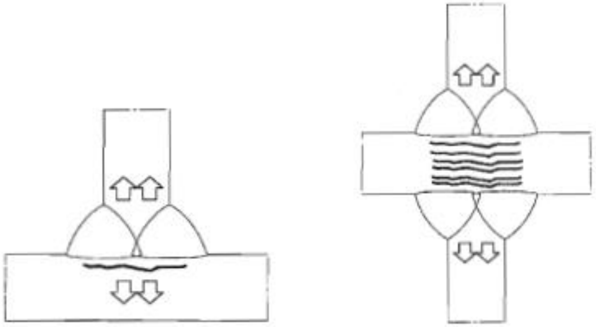


Photo: EN 1993-1-10

Steel **S355** is the most vulnerable.

Thorough analysis
According to EN 1993-1-10 and EN 10 164

General formula
(EN 1993-1-10 (3.1):

$$Z_{Ed} = Z_a + Z_b + Z_c + Z_d + Z_e \leq Z_{Rd}$$

Z_a - according to weld depth (EN 1993-1-10 tab 3.2);
Z_b - shape and position of weld (EN 1993-1-10 tab 3.2);
Z_c - material thickness (EN 1993-1-10 tab 3.2);
Z_d - shrinkage (EN 1993-1-10 tab 3.2);
Z_e - preheating (EN 1993-1-10 tab 3.2);

Z_{Rd} - quality class (EN 10 164 tab 1); value: 15 or 25 or 35
Quality class is defined in forth part of symbol of steel

Symbol of steel

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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 → f_y = 235 [MPa]

D:

Additional information on steelmaking processes (for structural steel)

For example:

S 235 JR G2

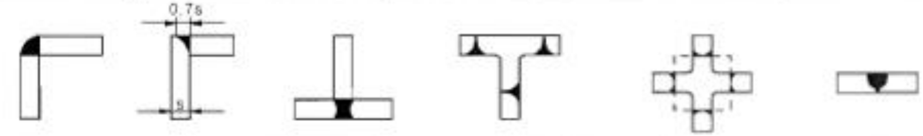
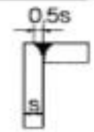
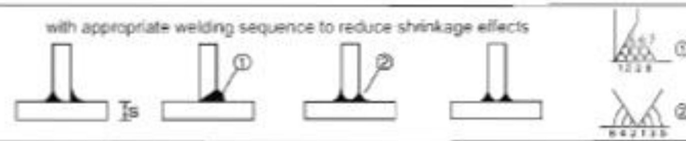
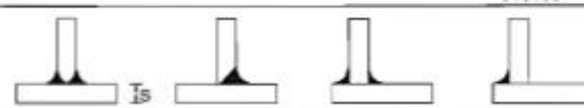
		$20 < a_{eff} \leq 30mm$	$a = 21$ mm	$Z_a = 9$
		$30 < a_{eff} \leq 40mm$	$a = 28$ mm	$Z_a = 12$
		$40 < a_{eff} \leq 50mm$	$a = 35$ mm	$Z_a = 15$
		$50 < a_{eff}$	$a > 35$ mm	$Z_a = 15$
b)	Shape and position of welds in T- and cruciform- and corner-connections			$Z_b = -25$
		corner joints		$Z_b = -10$
		single run fillet welds $Z_a = 0$ or fillet welds with $Z_a > 1$ with buttering with low strength weld material		$Z_b = -5$
		multi run fillet welds		$Z_b = 0$
		partial and full penetration welds		$Z_b = 3$
		partial and full penetration welds		$Z_b = 5$
		corner joints		$Z_b = 8$
c)	Effect of material	$s \leq 10mm$		$Z_c = 2^*$
		$10 < s \leq 20mm$		$Z_c = 4^*$

Photo: EN 1993-1-10 tab 3.2

Cold cracking

Appearance of unimproved (brittle) martensite as a result of welding + presence of hydrogen in weld; cracks appear approx. 48 hours after welding.

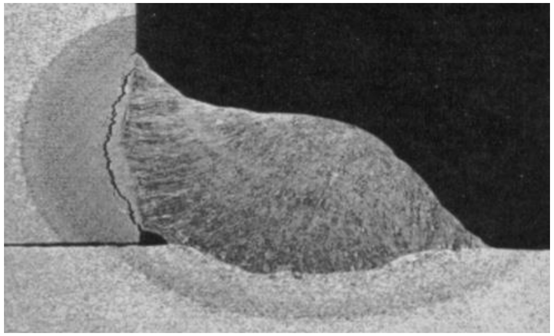


Photo: welderdestiny.com

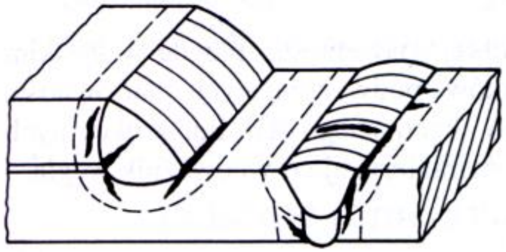
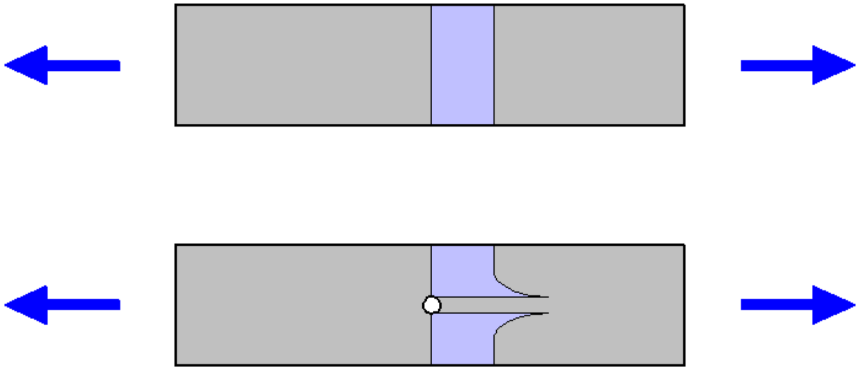


Photo: K. Ferenc, J. Ferenc, Konstrukcje spawane, połączenia, WNT 2003

Steel **S355** is the most vulnerable.

Fatigue cracking

Dynamic and cyclic actions

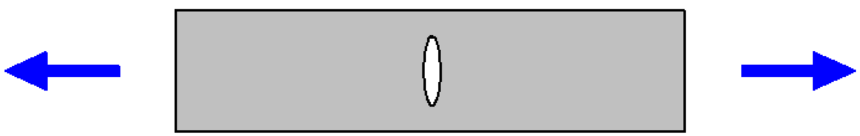


$\mu\ \sigma_{Ed}$

There are many microimperfections in weld as the effect of welding process (gas poroes, inclusions, microcracks etc), which not exist in native steel. Each of imperfection is a type of notch. There is concentration of stress around each notches.

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

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

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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.

Photo: scottmetals.com.au

Photo: Author

Bar bracing with gusset plate

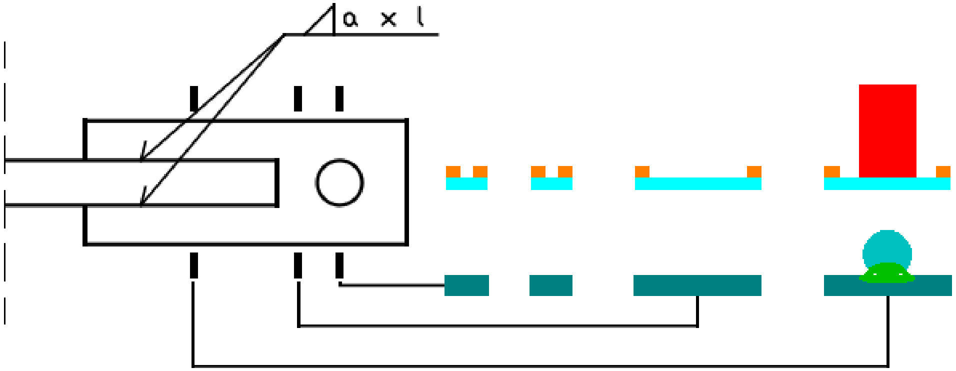

Photo: Author

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Approximation: average number of imperfections:

„normal” structural imperfections in steel plate

effect of material processing (cuting, making holes…)

effect of welding process

Structural imperfections in steel plate (#6 / 12 – 17)

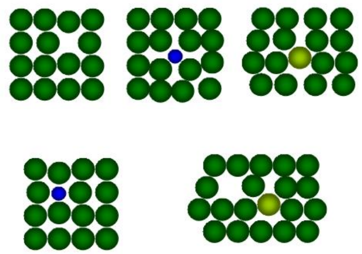


Photo: wikipedia

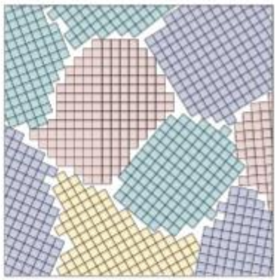


Photo: zasoby.open.agh.edu.pl

Additional effects of material processing (#6 / 18 – 25): plastic deformations, local hardening of steel, local cracking…

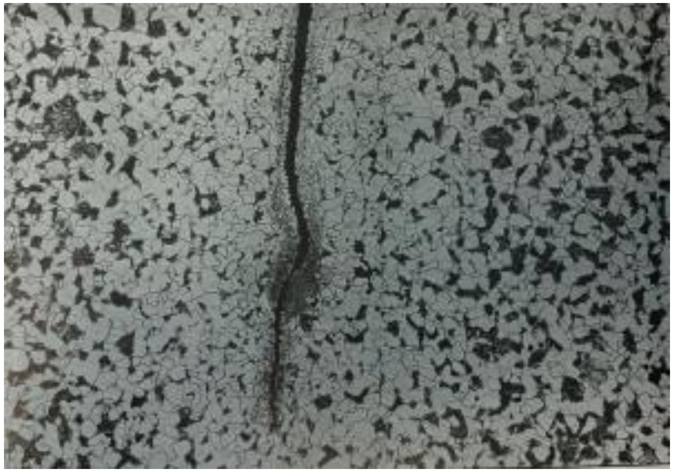
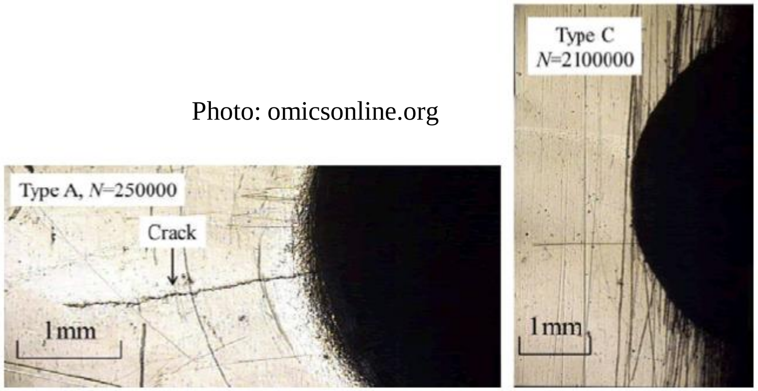


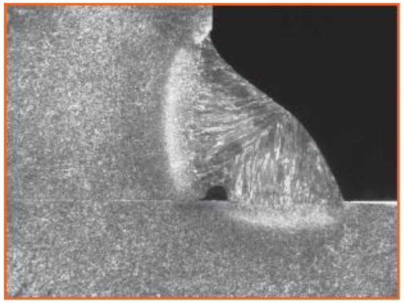
Photo: pmpaspeakingofprecision.com

→ #6 / 31

Photo: omicsonline.org



Additional effects of welding process (#6 / 26 – 29): secondary pollutions (gas bubbles, ash) introduced during welding, local deformation of plates, cracks as effect of thermal shrinkage...

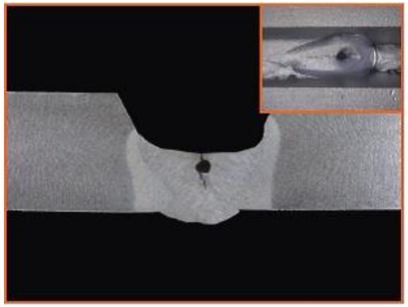


Photo: figel.pl

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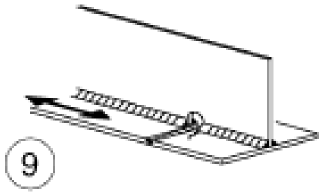
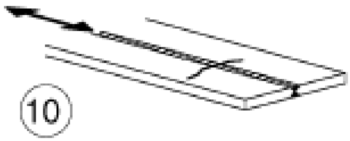
Ability and experience of worker ↓ → number of welding imperfection ↑ → quality level of welds ↓

Accepted number of welding imperfection is limited by Execution Class. (→ #6 / 47).

Calculations

Each type of welds is presented in EN 1993-1-9 table 8.2 - 8.10. First column in table means detail category = basic value of fatigue resistance [MPa].

71		9) Longitudinal butt weld, fillet weld or intermittent weld with a cope hole height not greater than 60 mm. For cope holes with a height > 60 mm see detail 1) in Table 8.4	9) Δσ based on d flange.
125		10) Longitudinal butt weld, both sides ground flush parallel to load direction, 100% NDT	
112		10) No grinding and no start/stop	
90		10) with start/stop positions	
140		11) Automatic longitudinal seam weld without stop/start positions in hollow sections	11) Free from de tolerances of EN Wall thickness t
125		11) Automatic longitudinal seam weld without stop/start positions in hollow sections	11) Wall thickne
90		11) with stop/start positions	

Fatigue resistance depends on number of cycles and its basic value. Fatigue resistance $\Delta\sigma_{Rd}$ decreases with increases of number of cycles.
For calculation important is amplitude of dynamic loads $\Delta\sigma_{Ed}$.

$$\Delta\sigma_{Ed} / \Delta\sigma_{Rd} \leq 1,0$$

Fatigue resistance

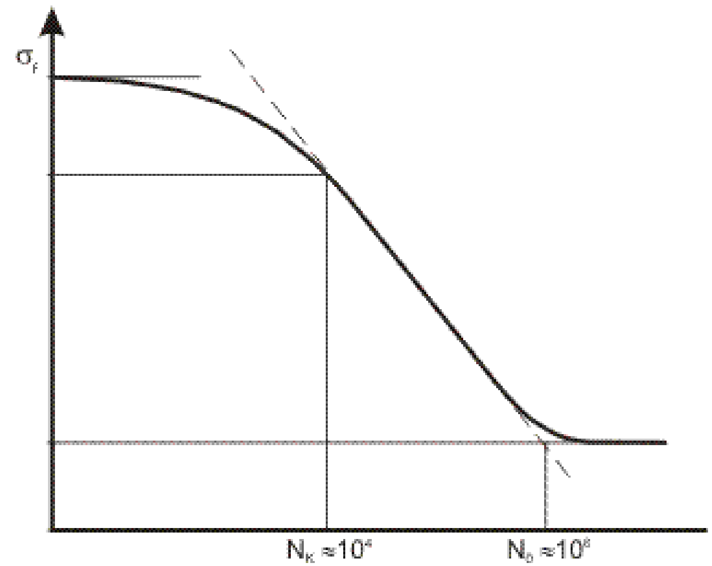


Photo: Author

Number of cycles

More information about fatigue will be presented on IInd step of study.

Impact of dynamic and cyclic actions:

Non-welded structures

↓

Fatigue resistance comes from cuting of members and drilling of holes only

↓

EN 1993-1-9, tab 8.1, 8.10

Welded structure

↙

Level of weld's imperfection **accepted** by EXC (Lec #6 / 47-58 ; Lab #6)

↓

Fatigue resistance comes from cuting of members and drilling of holes and from weld's imperfection

↓

EN 1993-1-9, tab 8.1 – 8.10 (**generally fatigue resistance lower than for non-welded structure**)

↘

Level of weld's imperfection **over limit** accepted by EXC (Lec #6 / 47-58 ; Lab #6)

↓

Welds must be removed and made again (**always**, **not only in case of dynamic and cyclic actions**)

Hydrogen embrittlement

Global name for many different types of cracking, which are the effect of presence of free hydrogen in welds. Mechanism of growth of cracks in presence of hydrogen is not completely clear. There are many different models for different phenomenons.

Sources of hydrogen can be:

- pollutions from furnace process;
- moisture of welding materials;
- not completely dry surfaces of steel during welding;
- hydrogen from welding gas;
- chemical pollutions during exploatation;

Photo: boltscience.com

Prevention is adherence to technology (dry, no moisture) and corrosion protection of structures.

Steel **S355** is the most vulnerable.

Brittle cracking

Effect of impurities (mainly P, N, S) in steel. These chemical elements increase corrosion and fragility. Brittle cracking is very dangerous - in opposite to "normal" destruction (big deformations before collapse), there are no signals before collapse.

Susceptibility to brittle cracking in measured in Charpy Hammer test.

Susceptibility to brittle cracking increases when:

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

Why impact resistance is important?

Photo: inspectioneering.com

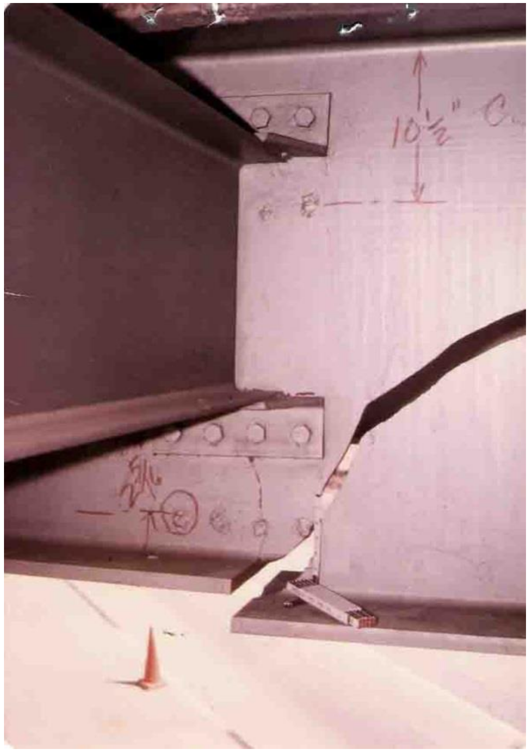


Photo: rebar.ecn.purdue.edu

Photo: civildigital.com

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

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

Table 2.1: Maximum permissible values of element thickness t in mm

Steel grade	Sub-grade	Charpy energy CVN at T [°C]	Charpy energy CVN J_{min}	Reference temperature T_{Ed} [°C] $\sigma_{Ed} = 0,75\ f_y(t)$: 10	0	-10	-20	-30	-40	-50	$\sigma_{Ed} = 0,50\ f_y(t)$: 10	0	-10	-20	-30	-40	-50	$\sigma_{Ed} = 0,25\ f_y(t)$: 10	0	-10	-20	-30	-40	-50
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	135	115	100	85	75	65	60
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	175	155	135	115	100	85	75
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	200	200	175	155	135	115	100
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	40	35	30	125	110	95	80	70	60	55
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	55	50	40	165	145	125	110	95	80	70
	J2	-20	27	110	95	75	65	55	45	35	155	130	115	95	80	70	55	200	190	165	145	125	110	95
	M,N	-20	40	135	110	95	75	65	55	45	180	155	130	115	95	80	70	200	200	190	165	145	125	110
	ML,NL	-50	27	185	160	135	110	95	75	65	200	200	180	155	130	115	95	230	200	200	200	190	165	145
S355	JR	20	27	40	35	25	20	15	15	10	65	55	45	40	30	25	25	110	95	80	70	60	55	45
	J0	0	27	60	50	40	35	25	20	15	95	80	65	55	45	40	30	150	130	110	95	80	70	60
	J2	-20	27	90	75	60	50	40	35	25	135	110	95	80	65	55	45	200	175	150	130	110	95	80
	K2,M,N	-20	40	110	90	75	60	50	40	35	155	135	110	95	80	65	55	200	200	175	150	130	110	95
	ML,NL	-50	27	155	130	110	90	75	60	50	200	180	155	135	110	95	80	210	200	200	200	175	150	130
S420	M,N	-20	40	95	80	65	55	45	35	30	140	120	100	85	70	60	50	200	185	160	140	120	100	85
	ML,NL	-50	27	135	115	95	80	65	55	45	190	165	140	120	100	85	70	200	200	200	185	160	140	120
S460	Q	-20	30	70	60	50	40	30	25	20	110	95	75	65	55	45	35	175	155	130	115	95	80	70
	M,N	-20	40	90	70	60	50	40	30	25	130	110	95	75	65	55	45	200	175	155	130	115	95	80
	QL	-40	30	105	90	70	60	50	40	30	155	130	110	95	75	65	55	200	200	175	155	130	115	95
	ML,NL	-50	27	125	105	90	70	60	50	40	180	155	130	110	95	75	65	200	200	200	175	155	130	115
	QL1	-60	30	150	125	105	90	70	60	50	200	180	155	130	110	95	75	215	200	200	200	175	155	130
S690	Q	0	40	40	30	25	20	15	10	10	65	55	45	35	30	20	20	120	100	85	75	60	50	45
	Q	-20	30	50	40	30	25	20	15	10	80	65	55	45	35	30	20	140	120	100	85	75	60	50
	QL	-20	40	60	50	40	30	25	20	15	95	80	65	55	45	35	30	165	140	120	100	85	75	60
	QL	-40	30	75	60	50	40	30	25	20	115	95	80	65	55	45	35	190	165	140	120	100	85	75
	QL1	-40	40	90	75	60	50	40	30	25	135	115	95	80	65	55	45	200	190	165	140	120	100	85
	QL1	-60	30	110	90	75	60	50	40	30	160	135	115	95	80	65	55	200	200	190	165	140	120	100

EN 1993-1-10 tab. 2.1

Ductile fracture

Specific name for effect of exceeding resistance

$$E / R > 1,0$$

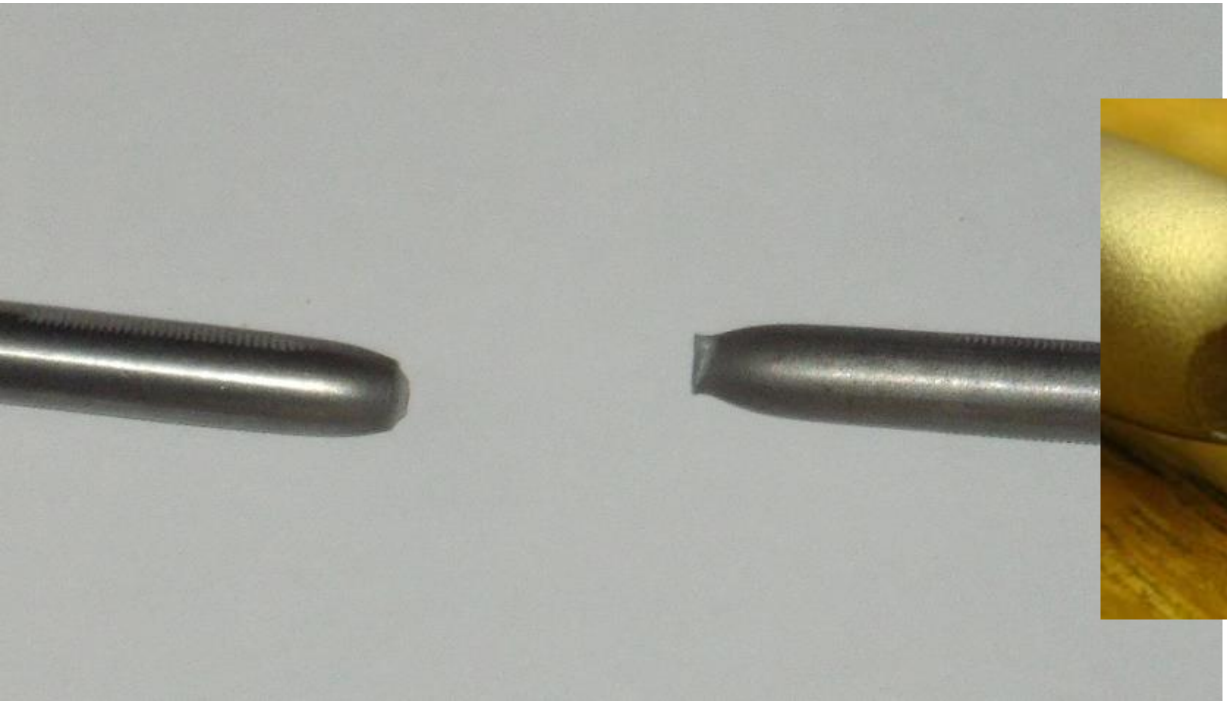


Photo: Author

Photo: wikipedia

Examples

Photo: wikipedia

Atlantic, MS Titanic, 1912 – brittle cracking

Atlantic, several ships type „Liberty”,
II World War – hydrogen embittment

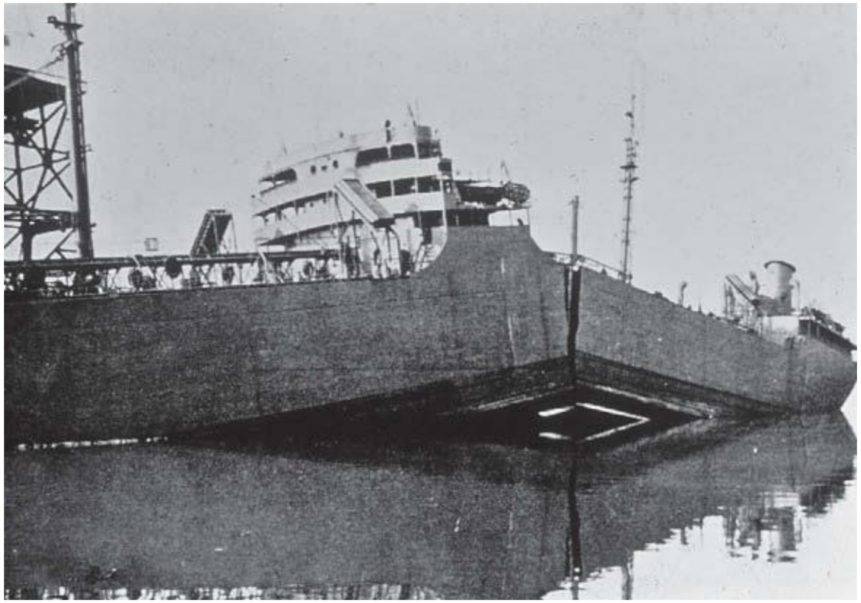


Photo: tmetallurgyandmaterials.wordpress.com

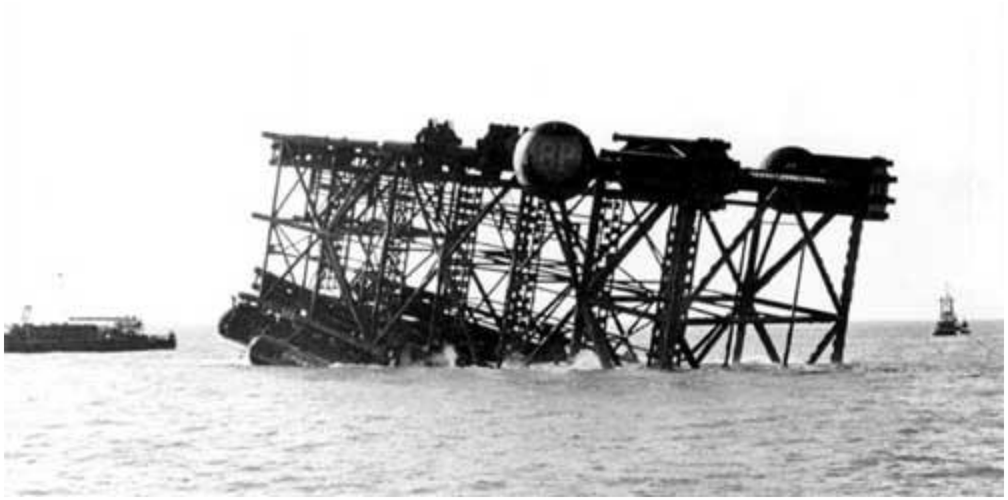


Photo: twi-global.com

North Sea, PB oli platform, 2001 – lamellar tearnig

USA, Memphis, , Hernando De Soto bridge over Mississippi, 2021 – hydrogen embittment

Photo: washingtonpost.com

Conclusions

We can't avoid different types of cracking during / after welding in many cases. Because of this, analysis of welding imperfections (among others – cracks) is very important. They serve the non-destructive testing. Range is determined on the basis of execution class of structure.

We can only minimize the risk of cracking by appropriate selection of steel grade and welding techniques.

Imperfections

Photo: weldreality.com

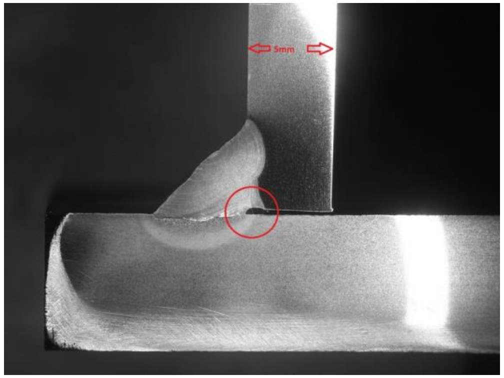


Photo: weldingtipsandtricks.com

Photo: weldreality.com

Photo: bbs.homeshopmachinist.net

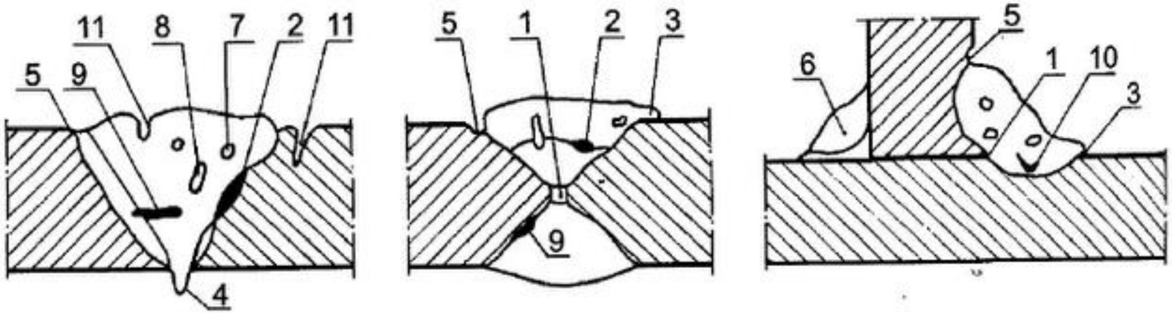


Photo: Łubiński M, Filipowicz A, Żółtowski W, "Konstrukcje metalowe", Arkady 2000

Execution class

There are two classes of imperfections for functional geometrical imperfections. They depend on execution class.
What is the way to determine type of execution class?

Consequences classes		CC1		CC2		CC3	
Service categories		SC1	SC2	SC1	SC2	SC1	SC2
Production categories	PC1	EXC1	EXC2	EXC2	EXC3	EXC3	EXC3
	PC2	EXC2	EXC2	EXC2	EXC3	EXC3	EXC4
Class of imperfection		1			2		

EN 1090-2 tab B.3

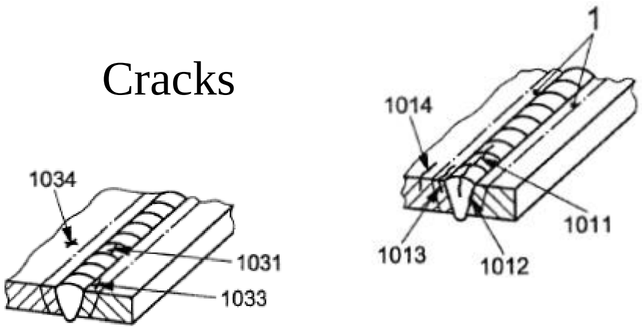
If we can't make accurate analysis, we assume EXC2.

Execution class are very important for quality of welds (EN 1090-2 tab. 7.6)

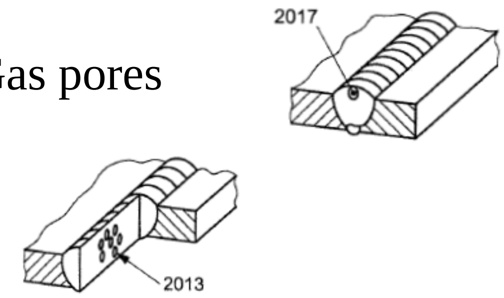
Execution classes	Quality level for weldings
EXC1	D
EXC2	C (generally) D (undercut, overlap, stray arc, end crater pipe)
EXC3	B
EXC4	B+

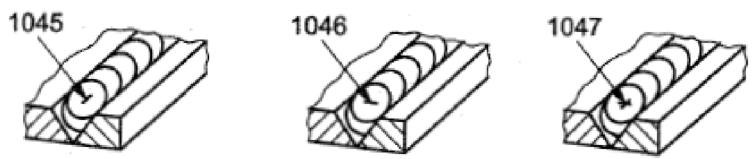
EN ISO 6520-1 Welding; classification of imperfections Table 1

Cracks



Gas pores

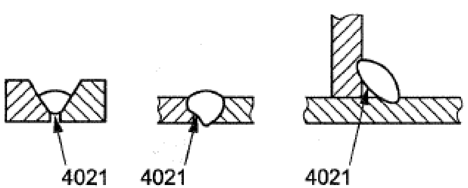


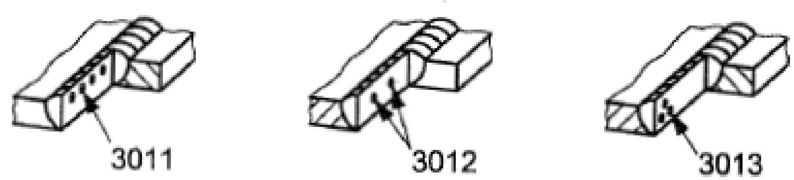


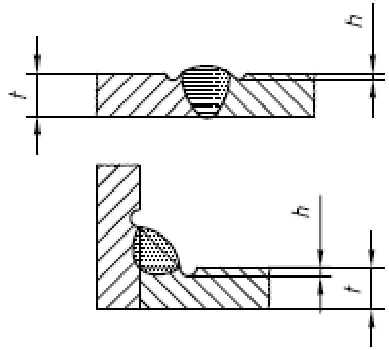
Craters

Inclusions

Incomplete penetrations





No.	ISO 6520-1 reference	Imperfection designation	Remarks	t mm	Limits for imperfections for quality levels		
					D	C	B
1.7	5011 5012	Continuous undercut Intermittent undercut	Smooth transition is required. This is not regarded as a systematic imperfection. 	0,5 to 3	Short imperfections: $h \leqslant 0,2\ t$	Short imperfections: $h \leqslant 0,1\ t$	Not permitted
				> 3	$h \leqslant 0,2\ t$, but max. 1 mm	$h \leqslant 0,1\ t$, but max. 0,5 mm	$h \leqslant 0,05\ t$, but max. 0,5 mm

EN ISO 5817 tab. 1 - limits of imperfections for quality level

Type of weld	Shop and site welds		
	EXC2	EXC3	EXC4
Transverse butt welds and partial penetration welds in butt joints subjected to tensile stress:			
$U \geq 0,5$	10 %	20 %	100 %
$U < 0,5$	0 %	10 %	50 %
Transverse butt welds and partial penetration welds:			
in cruciform joints	10 %	20 %	100 %
in T joints	5 %	10 %	50 %
Transverse fillet welds in tension or shear:			

EN 1090-2 tab. 24 – range of non-destructive tests (NDT), for example X-ray, made for determining the real level of imperfections.

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For good-quality weld: real level of imprerfections ≤ limit.

Otherwise weld must be deleted and made once again.

Because of this non-destructive tests (NDT) of welds after welding process are important. We can use few different methods:

- visual testing (VT);
- magnetic parting testing (MT);
- penetrant testing (PT);
- ultrasonic testing (UT);
- radiographic testing (RT);

Information about range of tests, different levels of quality and acceptable limits of imperfections is presented on Laboratory #6.

Weather

Work quality for welded joints is much more important, than for bolted joints.

Photo: polskiekrajobrazy.pl

Photo: kobieta.onet.pl

Photo: pytamy.wp.pl

Photo: blog-medyczny.pl

Bad weather can significantly decreases ability of workers → and quality of welded joints. Bolted joints are not such susceptible.

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Bad weather conditions or an uncomfortable position of welder significantly reduce his concentration during work. This increases probability of poorly-made welds and number of imperfections.

Photo: blog-medyczny.pl

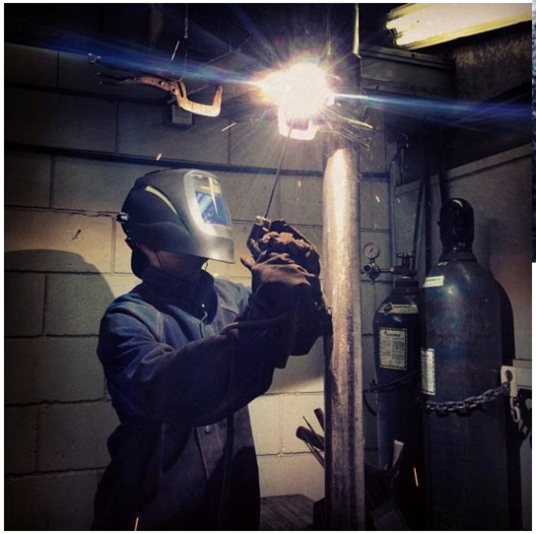


Photo: jamietilson.ca

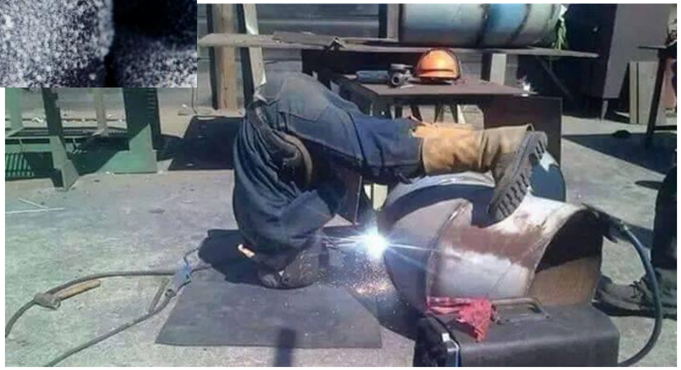


Photo: cnc.info.pl

Eurocode assumes perfect technical control of welding imperfections. It does not allow for possibility of weak welds. It does not introduce any additional parameters to formulas EN 1993-1-8 (4.1) for weld strength, taking into account influence of position or weather. This type of coefficients were defined by old Polish Standard.

PN-B 3200, tab. 18

Condition	α_R
Welds on construction site	0,9
Overhead welds	0,8
Overhead welds on construction site	0,7

Unofficially, these issues can also be taken into account today.

$$\sqrt{[(\sigma_\perp)^2 + 3(\tau_\parallel^2 + \tau_\perp^2)]} \leq \alpha_R \, [f_u / (\beta_w \, \gamma_{M2})]$$

and

$$\sigma_\perp \leq \alpha_R \, [0{,}9 \, f_u / \gamma_{M2}]$$

Preferring bolted joints for joining elements on construction site is way to avoid problems with influence of weather on quality of welds.

Photo: tboake.com

Photo: tboake.com

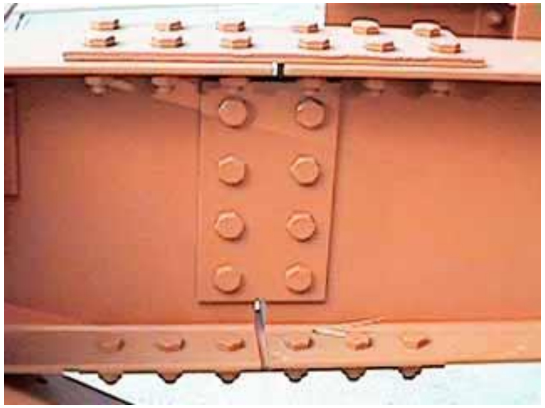
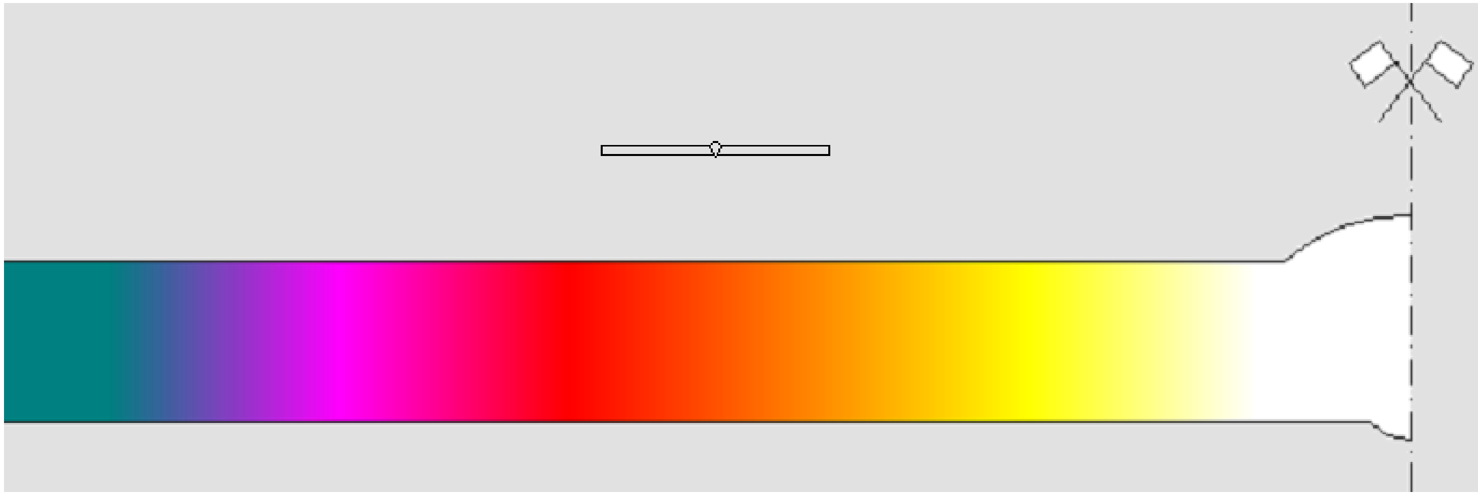


Photo: amsd.co.uk

Photo: moellerengineering.com

Photo: Author

Residual stresses and strains



Solid steel			Liquid steel
No change values of E, f_y, f_u	Decrease values of E, f_y, f_u	Values of E, f_y, $f_u \approx 0$	Liquid - no E, f_y, f_u
„Normal” diagram for $\sigma - \varepsilon$	Change diagram for $\sigma - \varepsilon$	No dependence $\sigma - \varepsilon$	
Different temperatures and different volumes of iron crystals – different values of deformations			
„Full” streses during deformations	„Reduced” stresses during deformations	No stresses during deformations	

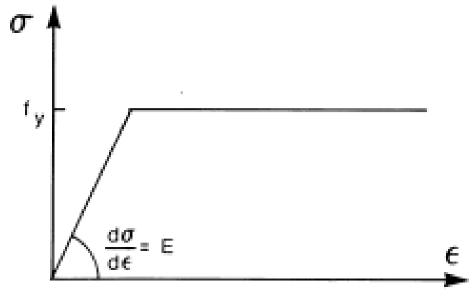
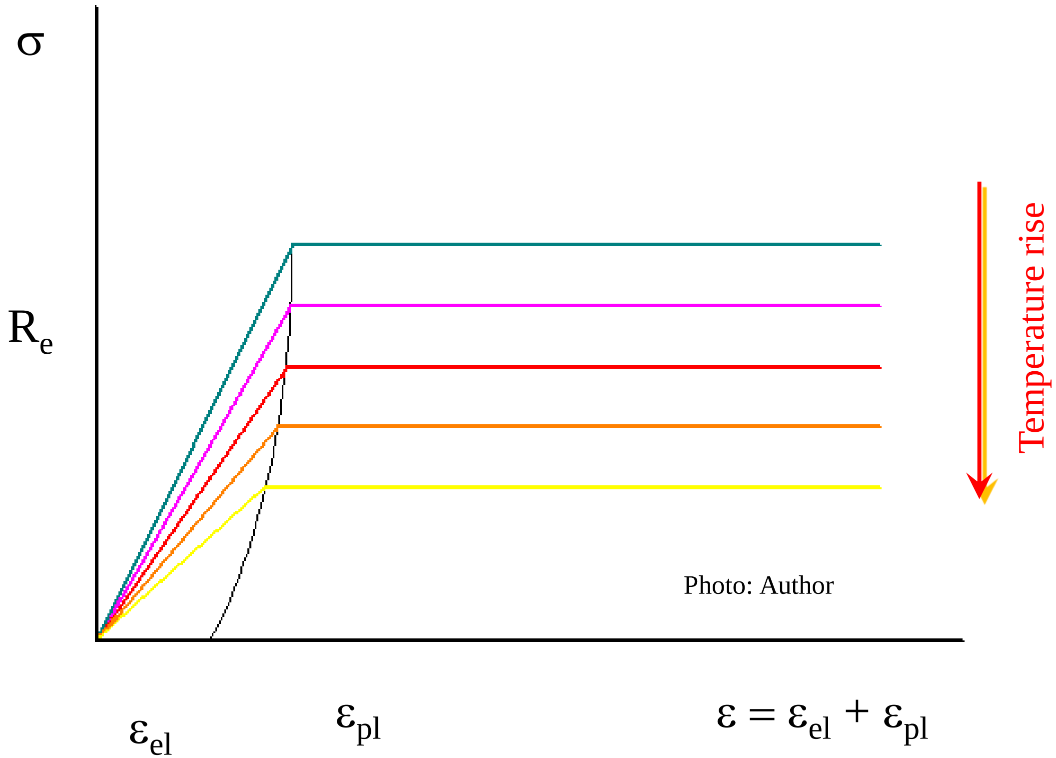


Figure 5.3: Bi-linear stress-strain relationship

„Normal" relationship between σ and ε

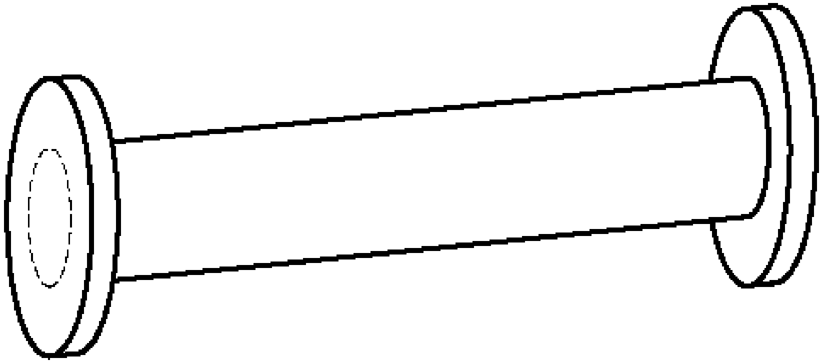
Photo: EN 1993-1-1 fig. 5.8



Change relationship between σ and ε for increasing temperature:

- reduction value R_e (plastic shelf lower and lower)
- reduction value E (reduction angle for elastic range)
- reduction elastic range

Model for analysis residual stresses and strains – round bar with two plates in both ends and special supports.



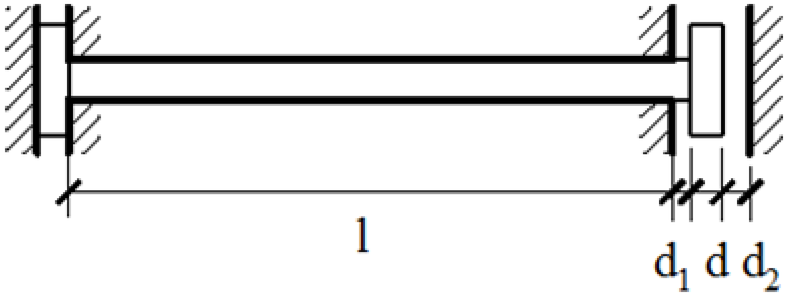


Photo: Author

Gap d_2 - the susceptibility model of the material liquid part during heating.

Gap d_1- the susceptibility model of the material liquid part during cooling.

Photo: Author

Parameters are depend on temperature:

$\varepsilon = \alpha_T \, \Delta T$

$\sigma = \varepsilon \, E$

$\alpha_T \neq \alpha_T \, (\Delta T)$

$E = E \, (\Delta T) \rightarrow \sigma = \sigma \, (\Delta T)$

$R_e = R_e \, (\Delta T)$

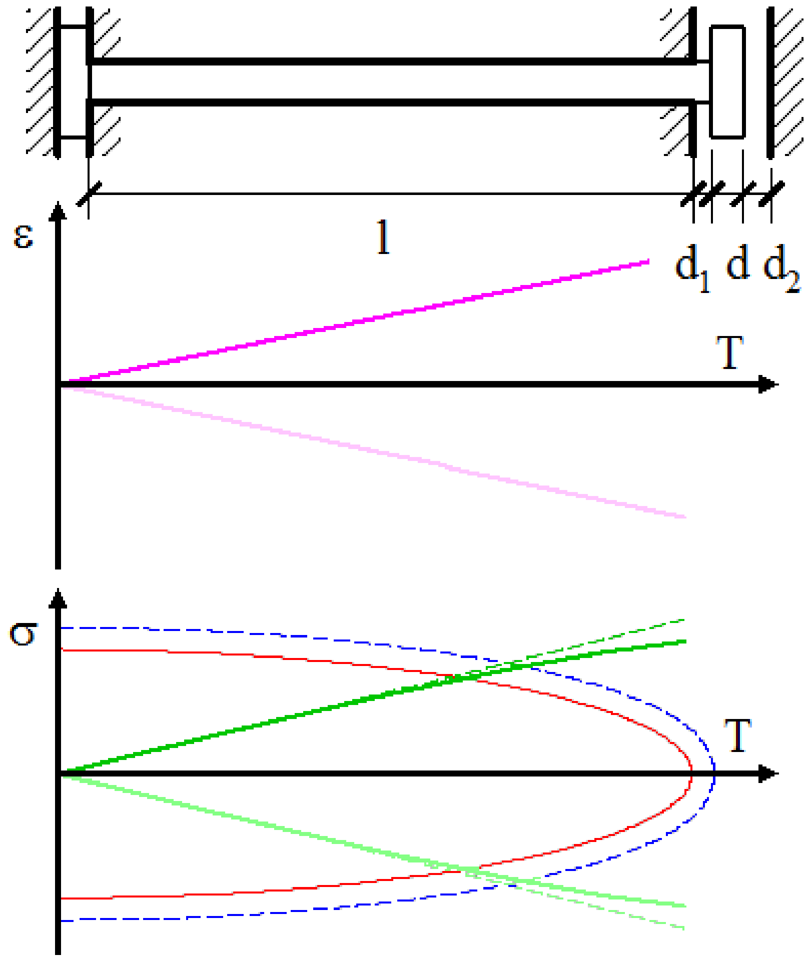
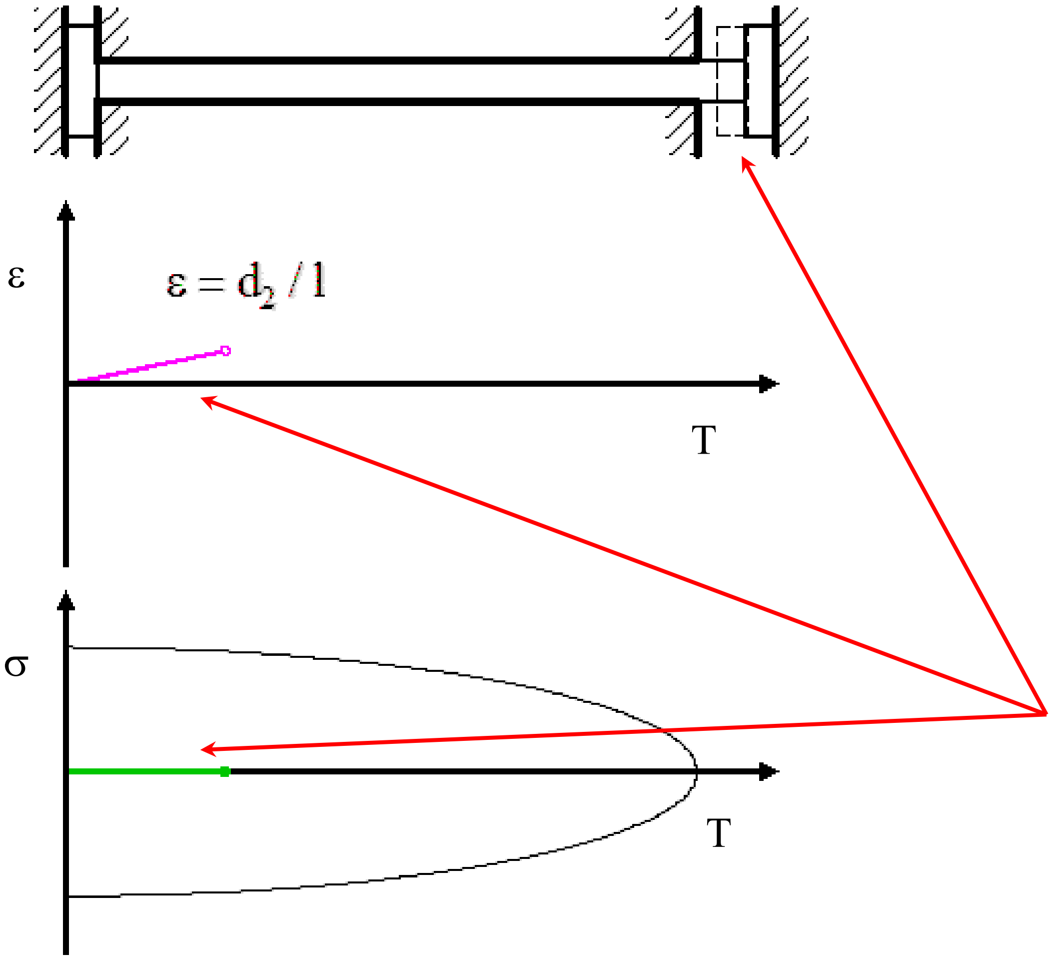


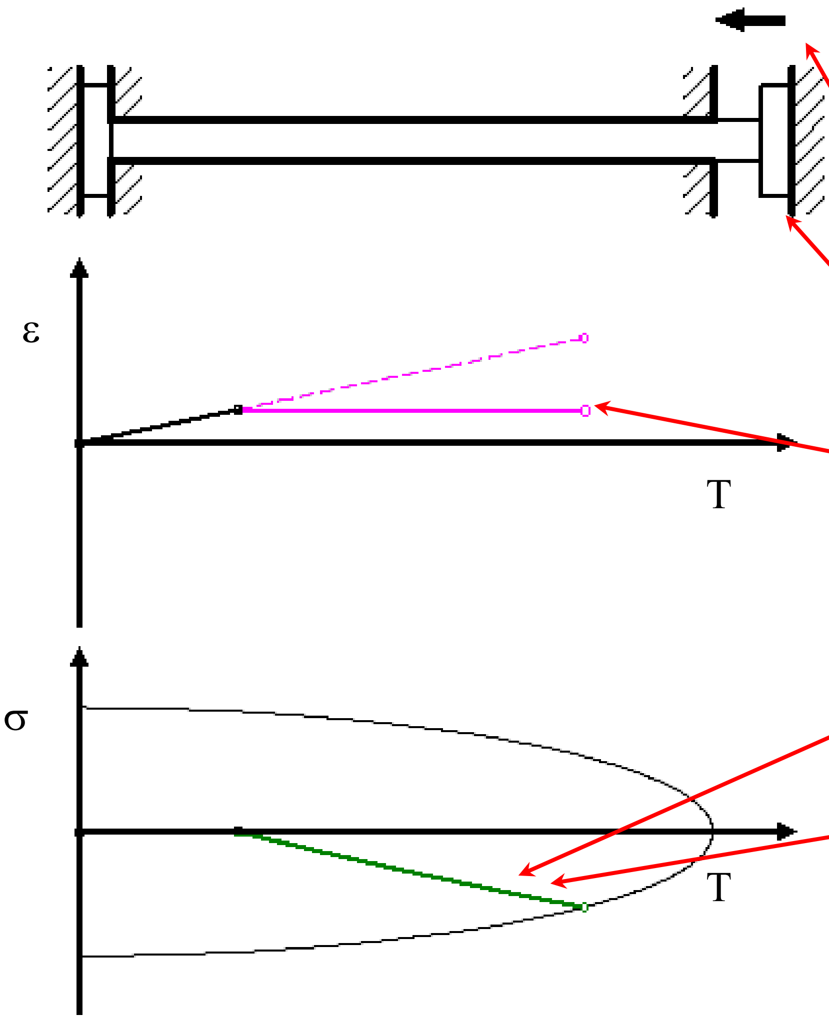
Photo: Author



Temperature increaes:

For $\Delta \leq d_2 \rightarrow$ unfettered displacement; no stresses

Photo: Author



Temperature increaes:

Elastic range of relation σ – ε;

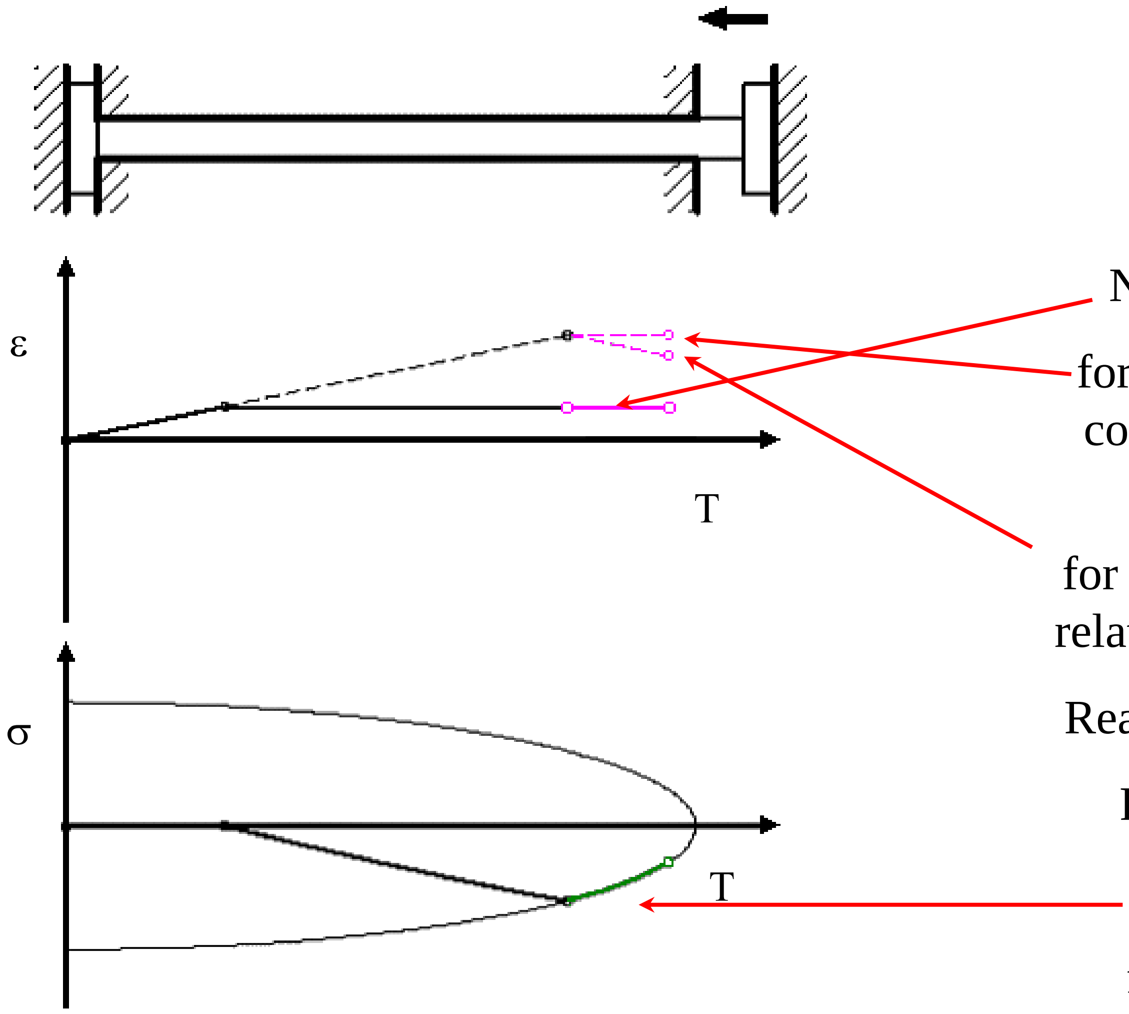
Reaction on right support increases;

No possibility of deformations;

Stress increases;

Non-linear dependence stress-temperature (change mechanical characteristics of steel due to temperature, E decreases)

Photo: Author



Temperature increaes:

No possibility of deformations:

for "normal" relationship (support, constant temperature) - horizontal dashed line;

for temperature increases (nonlinear relation σ – ε) - inclined dashed line;

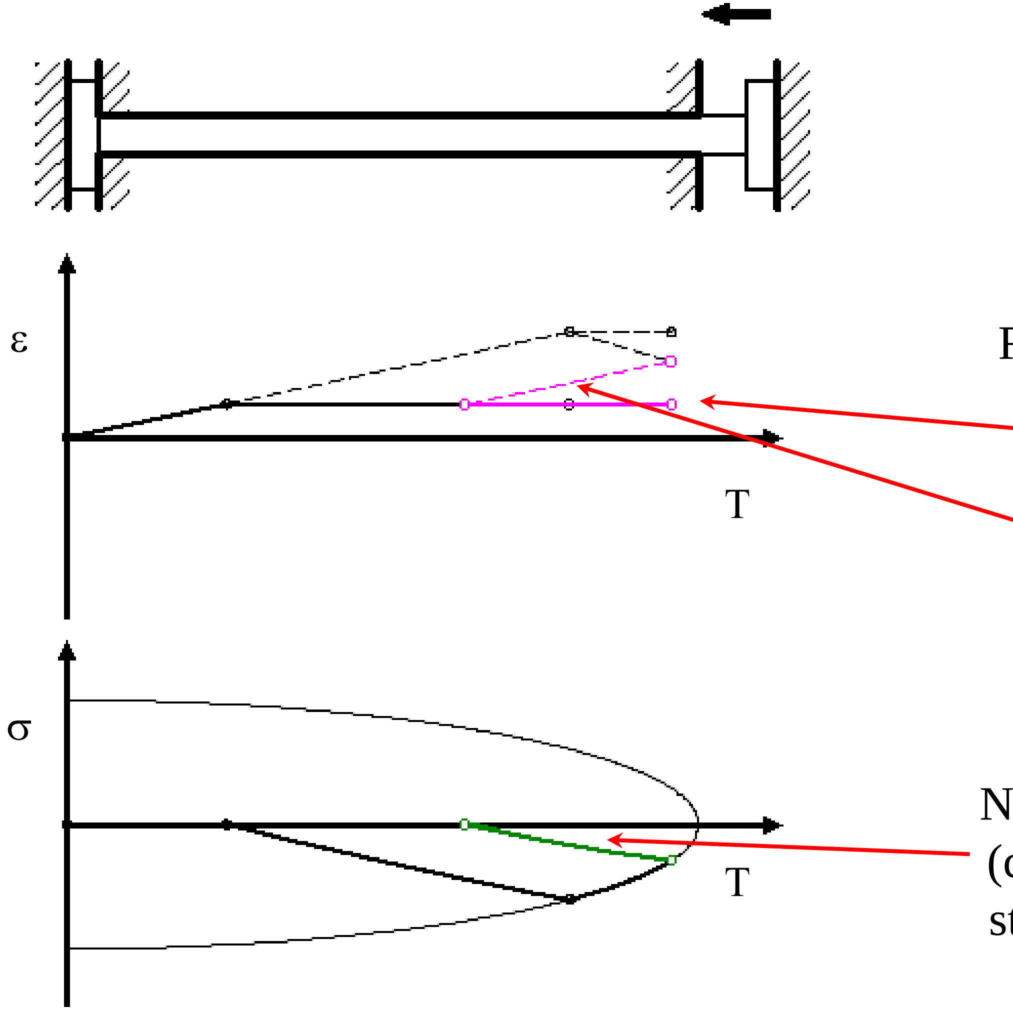
Reaction on right support increases;

Plastic range of relation σ – ε:

plastic shelf, $\sigma = f_y$;

f_y decreases with temperature increasing;

Photo: Author



Temperature decreases:

Elastic range of relation σ – ε;

Reaction on right support decreases;

No possibility of deformations:

for "normal" relationship (witout support, constant temperature) - inclined dashed line;

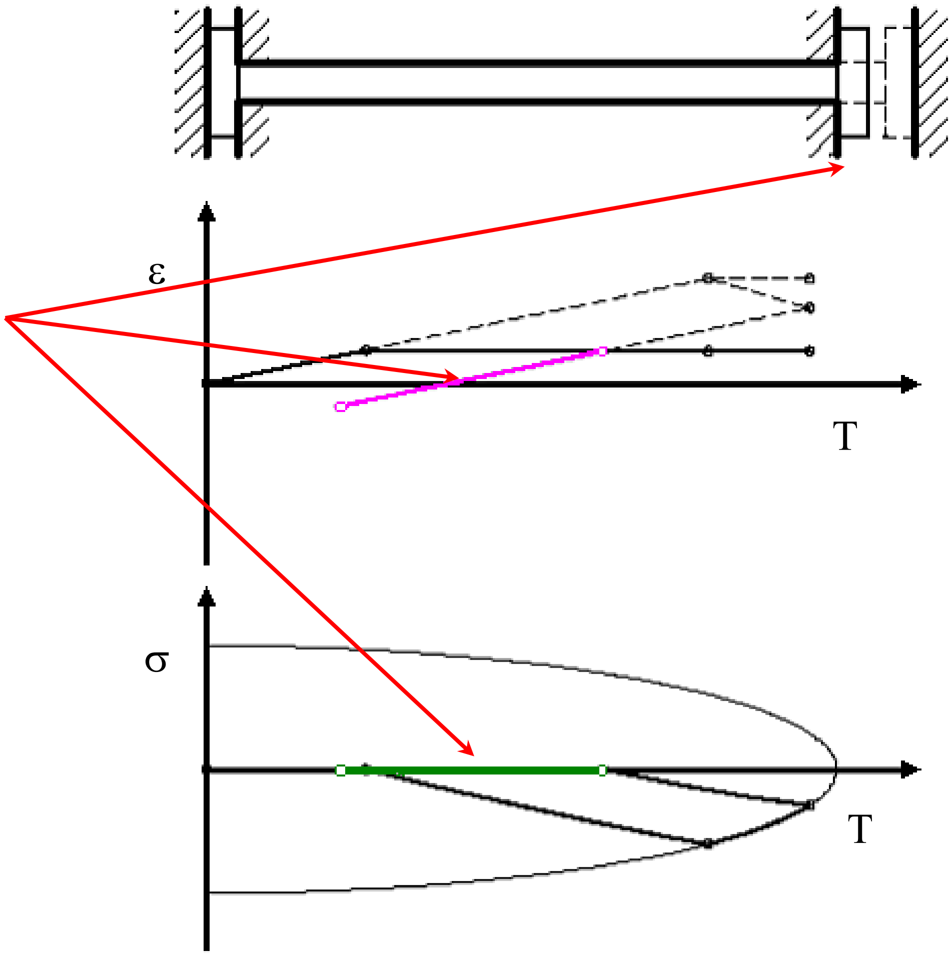
Stress decreases;

Non-linear dependence stress-reaction (change mechanical characteristics of steel due to temperature, E increases)

Photo: Author

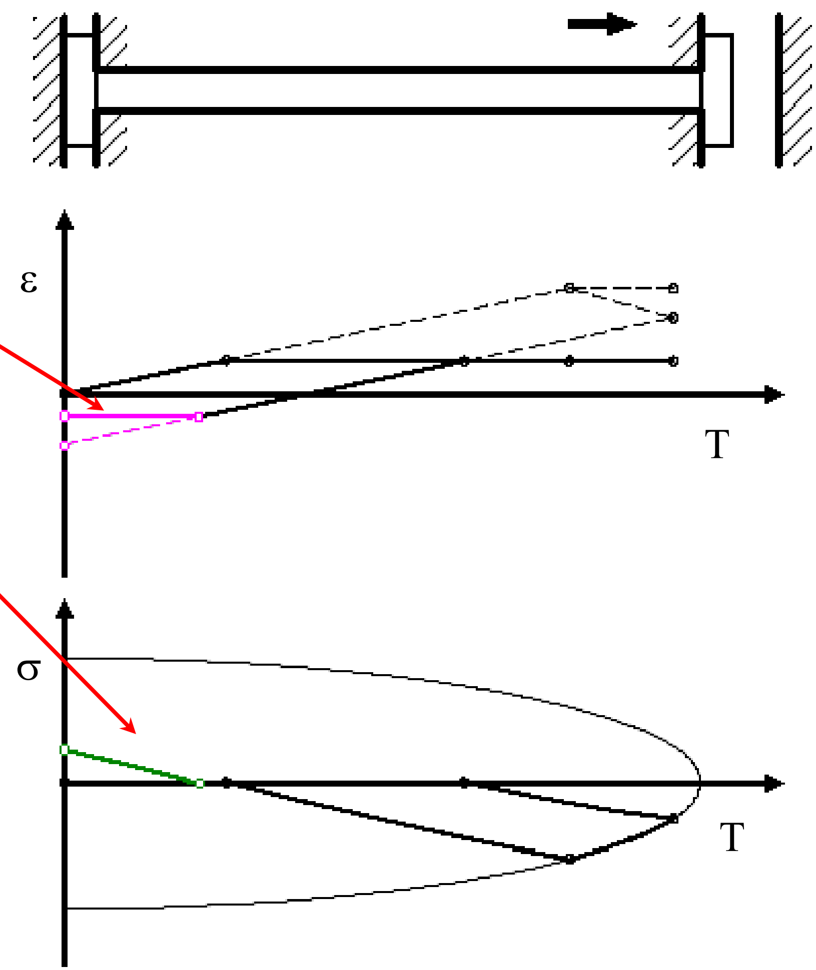
Temperature decreases:

Unfettered displacement; no stresses;



Temperature decreases:

Photo: Author



Elastic range of relation σ – ε;

Reaction on left support increases;

No possibility of deformations;

Stress increases;

Non-linear dependence stress-reaction (change mechanical characteristics of steel due to temperature, E increases)

Temperature - the same as at the start of process;

Non-zero value of ε;

Non-zero value of σ.

Residual stresses and strains

Calculations of residual stresses and deformations are rather complicated. Their values depend on geometry of elements and welds, type of welding process ant its parameters (for example amperage, voltage, velocity of making welds), velocity of increase and decrease temperature, range of heat affected zone, grade and subgrade of steel.

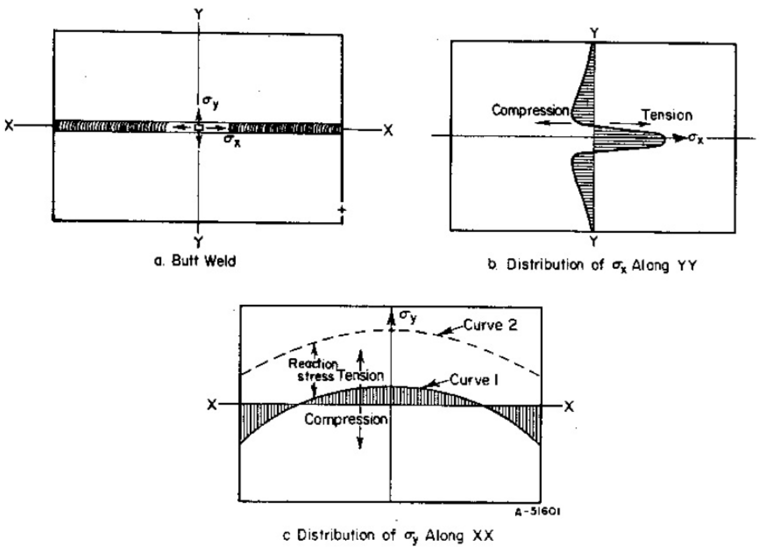


Photo: intechopen.com

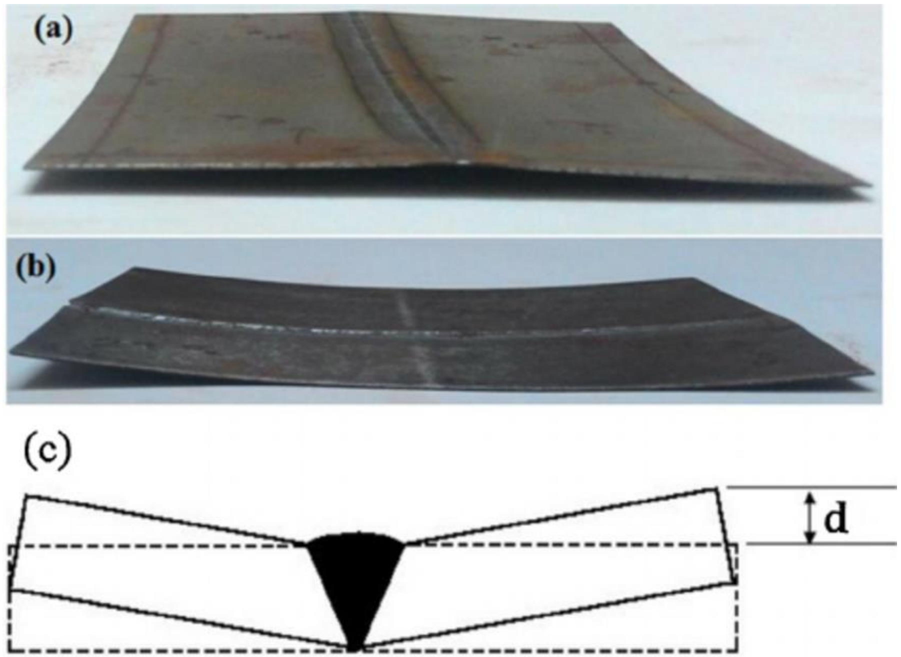
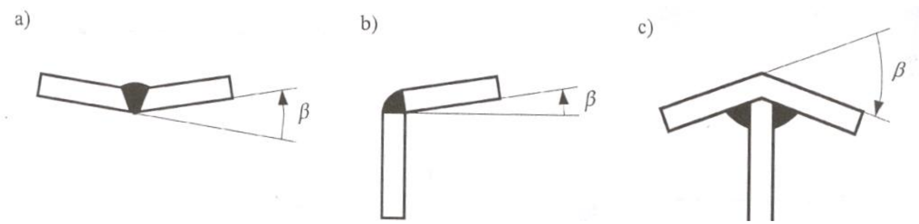
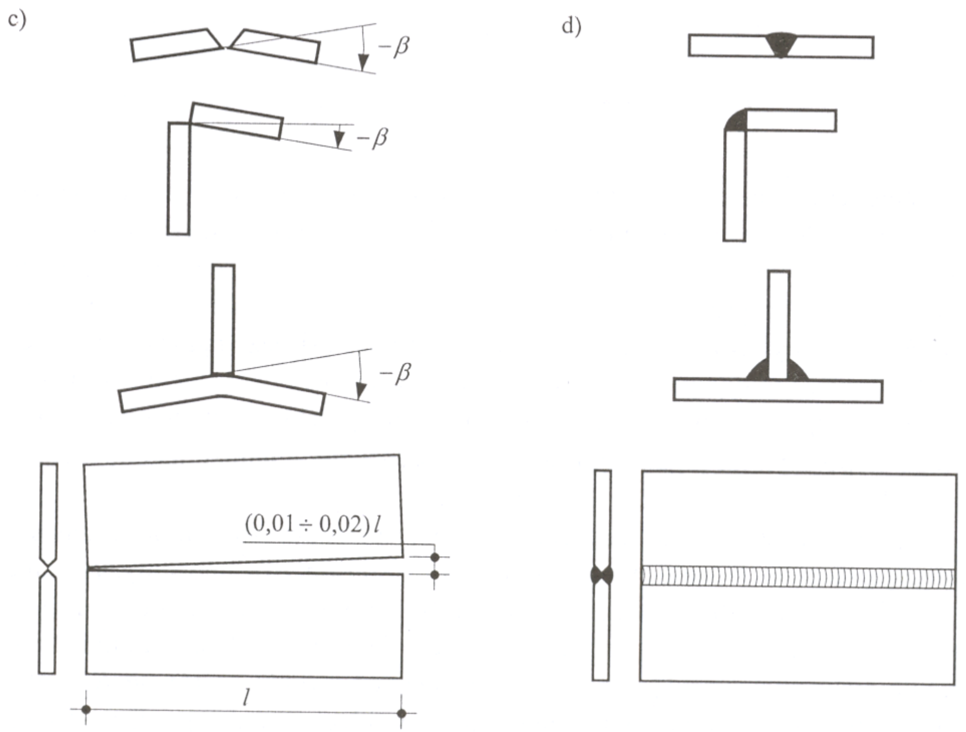


Photo: Influence of heat input in microwelding of titanium alloy by micro plasma arc, M. Baruah, S. Bag





We try to minimalise values of residual stresses by heat treatment after welding and minimalise values of deformation by welding elements with initial anti-deformation.

Photo: M. Łubiński, W. Żółtowski, Konstrukcje Metalowe t. II, Arkady, Warszawa 2004

Examination issues

Types of welds
Differences between filled and butt welds
Types of cracks
Impact of dynamic and cyclic actions on welded structure

Rust - rdza
Fragility - kruchość
Carbon equivalent - równoważnik węglowy
Weldability - spawalność
Preliminary heating - podgrzanie wstępne
Hot cracking - pękanie na gorąco
Cold cracking - pękanie na zimno
Lamellar tearing - pękanie lamelarne
Stress-relief cracking - pękanie relaksacyjne
Fatigue cracking - pękanie zmęczeniowe
Shielding gas - gaz osłonowy
Alloying additives - domieszki stopowe
Butt weld - spoina czołowa
Filled weld - spoina pachwinowa
Plug weld - spoina otworowa
Flare groove weld - spoina szerokobruzdowa
Run off plate - płytka wybiegowa
Toe - lico spoiny
Root - grań spoiny
Crater - otwarty por gazowy
Inclusion - wtrącenie innego ciała stałego
Lack - przyklejenie, brak wtopienia
Undercut - podtopienie
Excess - nadlew, wyciek
Bevelling - ukosowanie

Thank you for attention

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