Aalto University
School of Engineering

Welding Technology and Design

Formulae Support

☞ Heat Input for different processes:

$$\boxed{HI[J/mm]=\eta_1 \frac{P[J/s]\cdot 60}{v[mm/\min]}}$$

Sample of power determination for several welding processes:

$$P_{\text{EletricArc}}[W]=V[V]\cdot I[A]$$
$$P_{\text{Laser}}[W]=P_{Beam}[W]$$
$$P_{\text{ElectronBeam}}[W]=\begin{cases} n_e\left[\dfrac{\text{N}^{\text{o}}\,\text{Electrons}}{\text{s}}\right]\cdot\dfrac{1}{2}\cdot m_e[kg]\cdot\left(v_e\left[\dfrac{mm}{\min}\right]\cdot\dfrac{1}{1000\cdot 60}\right)^2 \\ or \\ V_a\times I \end{cases}$$

$$P_{\text{FSW}}[W]=T[N.m]\cdot\Omega[rpm]\cdot\frac{2\pi}{60}+F_x[N]\cdot v[mm/\min]\cdot\frac{1}{1000\cdot 60}$$

☞ Residual stress due to uniform thermal expansion of a component:

Note: Considering that, the component is in adiabatic condition, with uniform temperature distribution ($T_0+\Delta T$), e.g. long time after the weld procedure.

$$\Delta \text{T}=\frac{\text{HI}\times \text{L}_{\text{Total}}}{\rho\times \text{C}_{\text{p}}\times \text{Vol}}$$
$$\varepsilon_{\text{Thermal}}=\alpha\times\Delta\text{T}$$
$$\sigma_{\text{Thermal}}=\text{E}\times\varepsilon_{\text{Thermal}}\ (\text{if }\sigma_{\text{Thermal}}\le\sigma_{\text{Yield}})$$

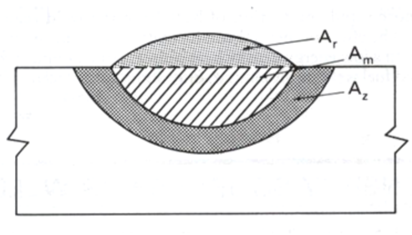
Where:

- Vol – Volume of the component;
- L_{total} – Total length of the weld joint)

☞ **Dilution Rate (BM - Base Material; FM – Filler Metal):**

$$DR = \frac{(BM)_{Melt}}{(BM + FM)_{Melt}}$$

☞ **Estimative of fusion area in a cross section of the weld bead, Aw:**



$A_w = A_m + A_R$

$V_w = A_w \times L \rightarrow$ Volume of melted metal in weld bead (where: L – Weld bead length)

$$Q = \frac{(T_f + 273)^2}{300\,000} \quad (\mathrm{J/mm^3})$$

$$\eta_2 = \frac{Q \cdot A_w}{E_c}$$

Q – Amount of heat energy to melt one unit of volume of metal

T_f – Fusion temperature [ºC]

$$\boxed{A_w = \frac{\eta_1 \eta_2 P}{Q \cdot v_s}}$$

η_1 – Energetic transference efficiency

η_2 – Fusion efficiency

☞ **Empirical expressions for determination of relevant thermal cycle information:**

$$\frac{1}{T_p - T_0} = \frac{4.13 \times \rho \times c_p \times t \times Y}{HI} + \frac{1}{T_f - T_0}$$

Note: expression valid for fusion welding of steels with 1 pass and full penetration - heat flow quasi-parallel to plate surface)

Where:
Y – Distance from weld line into the HAZ, [mm]
t – Thickness of the workpiece, [mm]
T_f – Fusion temperature, [K]
T_0 – Pre-heat temperature, [K]
T_p – Peak/maximum temperature at distance Y from weld line, [K]
HI – Heat Input, [J/mm]
$\rho \times c_p$ – Specific heat capacity per un. of volume, [J/(mm^3.K)]

☞ Determination of cooling rate, R:

$$\left.\begin{aligned}\tau \le 0.75 &\Rightarrow R = 2\pi\cdot k\cdot\rho\cdot C_p\cdot\left(\frac{t}{HI}\right)^2 (T_p - T_o)^3\\ \tau > 0.75 &\Rightarrow R = \frac{2\pi\cdot k\cdot(T_p - T_o)^2}{HI}\end{aligned}\right. ;\left[\tau = t\sqrt{\frac{\rho\cdot C_p\cdot(T_p - T_o)}{HI}}\right]$$

$$\text{Where}: [\tau], \text{ corresponds to relative thickness. Adimensional}$$

$[HI] = J/mm$

$[\rho\times c_p] = J/mm^{3\,\circ}C$

$[T_p] = [T_0] = {}^{\circ}C$

$[t] = [Y] = mm$

$[R] = {}^{\circ}\mathrm{C/s}$

$[\mathrm{k}] = J/mm.s.{}^{\circ}C$

$$\boxed{R_{540}\left[{}^{0}C/s\right] = 300\,{}^{0}C/t_{8/5}}$$

☞ Equivalent Carbon content (IIW expression):

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}$$

Note:

- Ceq lower 0.35, no special precautions are needed (e.g. no preheat temperature)
- Ceq higher 0.42, special precautions are needed (e.g. preheat temperature is mandatory)

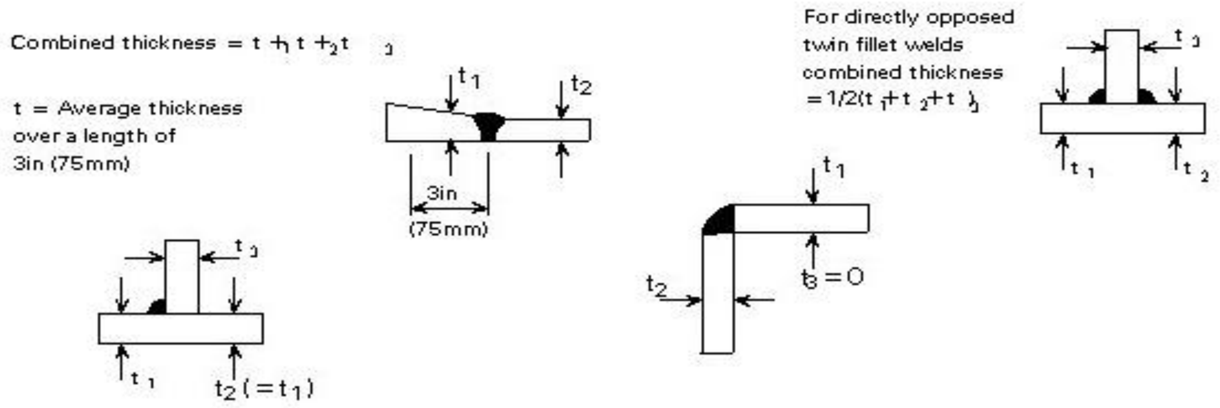
☞ Procedure for the determination of Pre-Heat Temperature

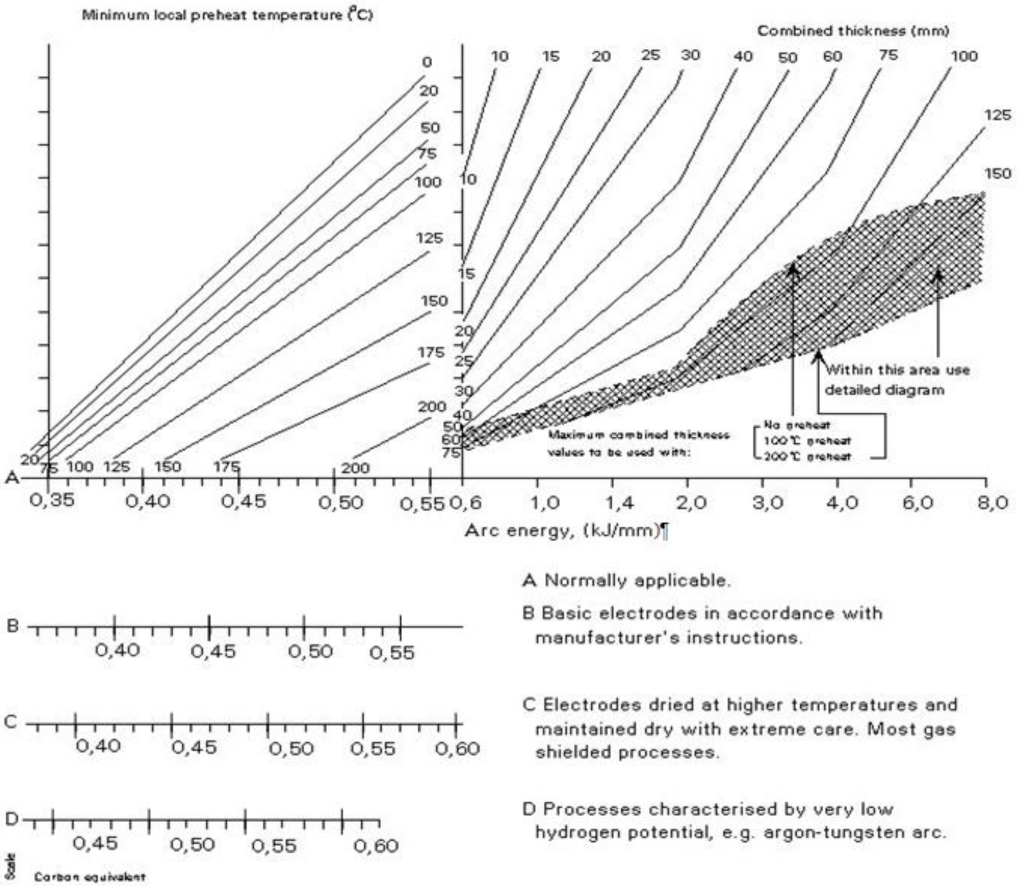
Determination of the Scale of Equivalent Carbon content:

Weld Hydrogen Level	Examples of corresponding processes and consumables	Carbon Equivalent Scale								
		Bead on plate		Butts				Fillets		
		Continuous surface	Abutting surfaces	Normal	Misalignment	Partial penetration, high constraint	Full penetration, high constraint	Normal structural fit	Machined fit	High constraint
High	Shielded Metal Arc Welding (SMAW) Submerged Arc Welding (SAW) Flux Cored Arc Welding (FCAW) **(electrodes with non-dry basic flux)**	A	A	A	A	A	A	A	A	A
Medium	Shielded Metal Arc Welding (SMAW) Submerged Arc Welding (SAW) Flux Cored Arc Welding (FCAW) **(electrodes dry to 250ºC and above)**	C	B	B	B	A	A	B	C	A
Low	Shielded Metal Arc Welding (SMAW) Submerged Arc Welding (SAW) Flux Cored Arc Welding (FCAW) **(electrodes dry to 350ºC and above)** GMAW with solid dirty wires	D	C	C	C	A	B	C	D	B
Very Low	Shielded Metal Arc Welding (SMAW) Submerged Arc Welding (SAW) Flux Cored Arc Welding (FCAW) **(electrodes dry to 450ºC and above)** TIG and GMAW with solid clean wires	D	D	D	D	A	C	D	D	C

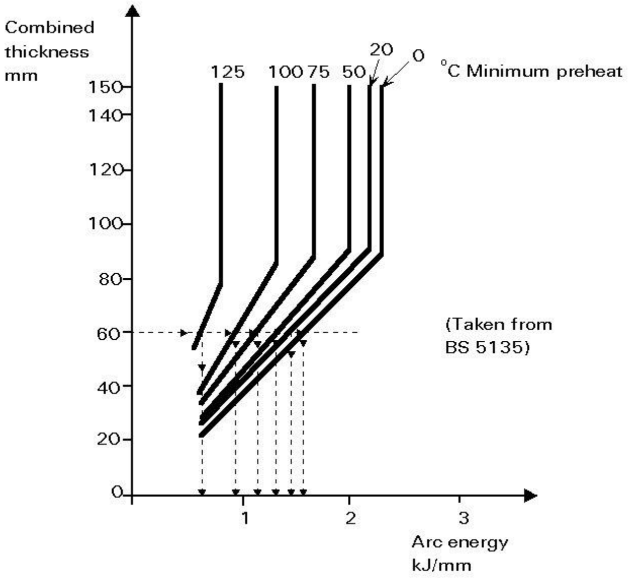
Where: Combined thickness, $t_c = \sum_{i=1}^{n} t_i$

t_i – corresponds to the thickness of the component *i*, adjacent to the weld bead
n – number of components adjacent to weld bead





☞ Alternative simplified procedure for the determination of Pre-Heat Temperature based on British Standard: BS 5135:



☞ **Hot Cracking Susceptibility index:**

$$H.C.S. = \frac{\%C \times \left(\%S + \%P + \frac{\%Si}{25} + \frac{\%Ni}{100} \right) \times 10^3}{3 \times \%Mn + \%Cr + \%Mo + \%V}$$

Limit values of Hot Cracking Susceptibility (H.C.S.), are:

- ✓ H.C.S $\leq$ 4 (or 3.6, for low alloy steels)

Nakamura and Ito:

$$\Delta G = \%Cr + 3.3\%Mo + 8.1\%V - 2 \leq 0$$

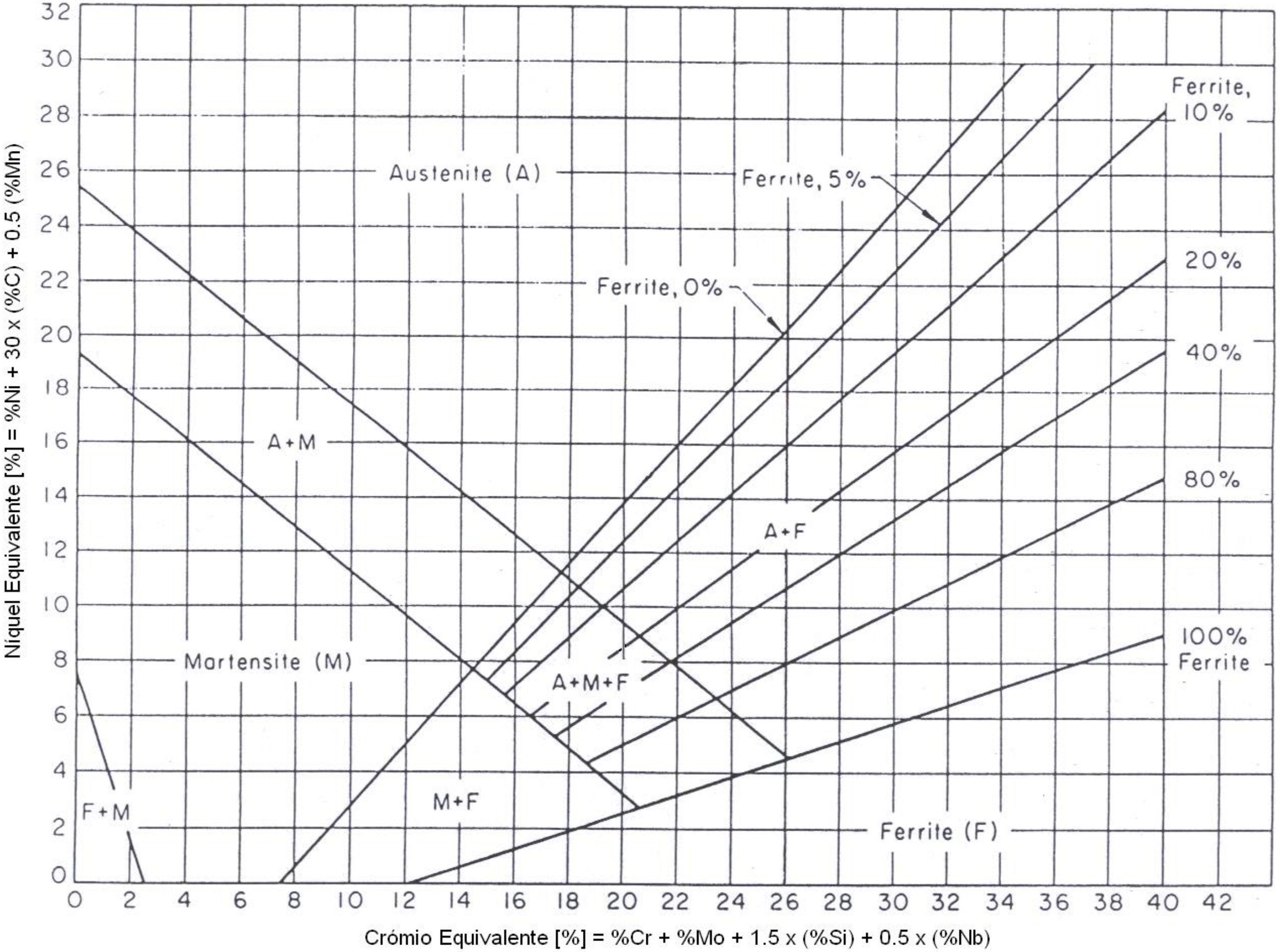
$$P_{SR} = \%Cr + \%Cu + 2Mo + 10\%V + 7\%Nb + 5\%Ti - 2 \leq 0$$

☞ The formula for Avesta Ferrite Number FNA assumes parallel lines of constant ferrite numbers. These are the formulas for FNA:

↳Creq = Cr + 1.5 Si + Mo + 2 Ti + 0.5 Nb
↳Nieq = Ni + 30 (C + N) + 0.5 Mn + 0.5 Cu + 0.5 Co
↳FNA = 3.34 Creq - 2.46 Nieq - 28.6

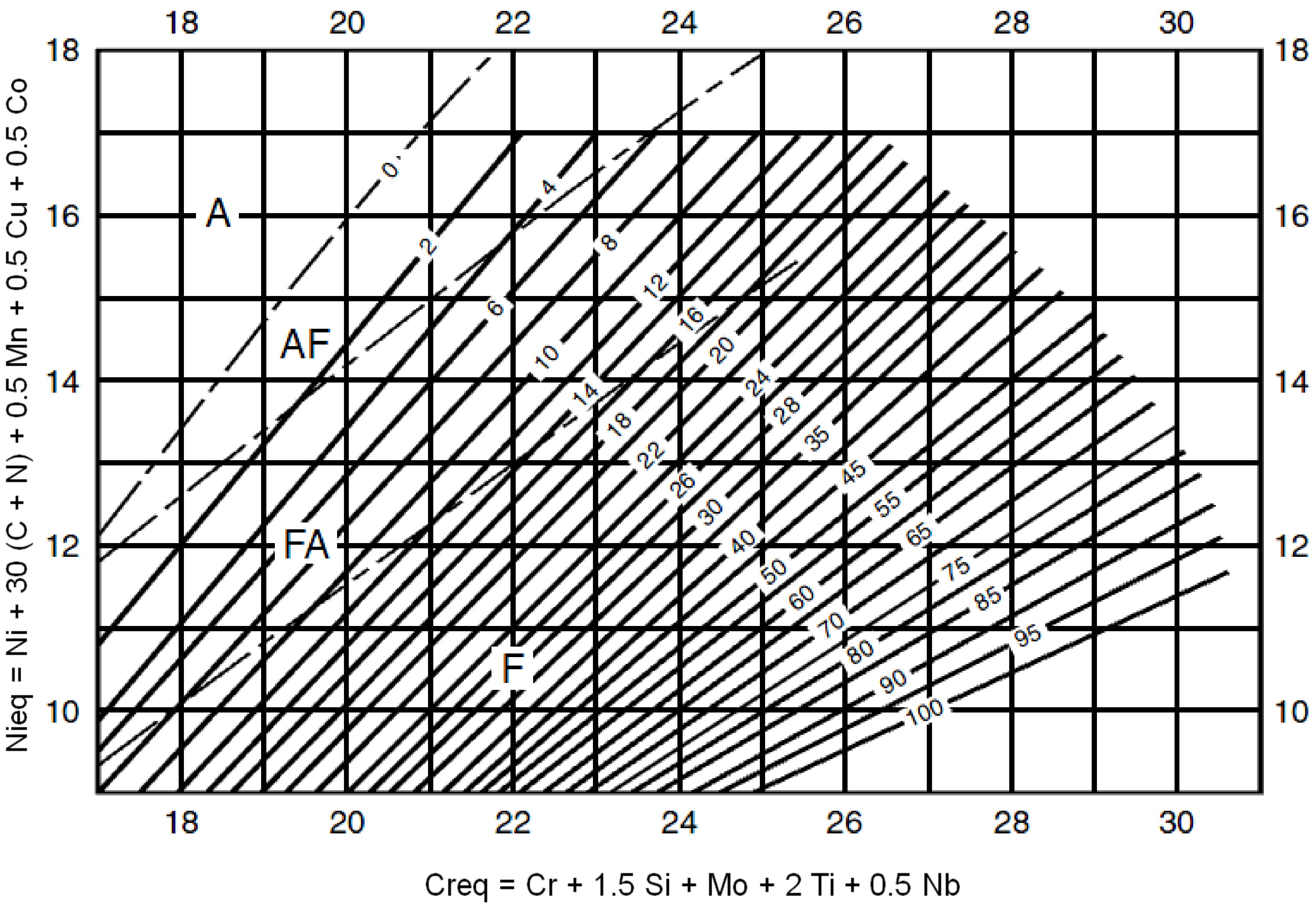
Diagrama de Schaeffler (1948): Prevision of the Microstructure in Weld Zone of Stainless Steels

Identification: Name:____________________________________ Number:_________



WRC – 92 (1992): Prevision of the Microstructure in Weld Zone of Stainless Steels

Identification: Name:_______________________________________ Number:__________



☞ Static design of welds: Design method

(5) The normal stress $\sigma_{\parallel}$ parallel to the axis is not considered when verifying the design resistance of the weld.

(6) The design resistance of the fillet weld will be sufficient if the following are both satisfied:

$$[\sigma_{\perp}^2 + 3(\tau_{\perp}^2 + \tau_{\parallel}^2)]^{0,5} \le f_u / (\beta_w \gamma_{M2}) \quad \text{and} \quad \sigma_{\perp} \le f_u / \gamma_{M2} \qquad \text{... (4.1)}$$

where:

f_u is the nominal ultimate tensile strength of the weaker part joined;

β_w is the appropriate correlation factor taken from Table 4.1.

(7) Welds between parts with different material strength grades should be designed using the properties of the material with the lower strength grade.

Simplified Method
(conservative design):

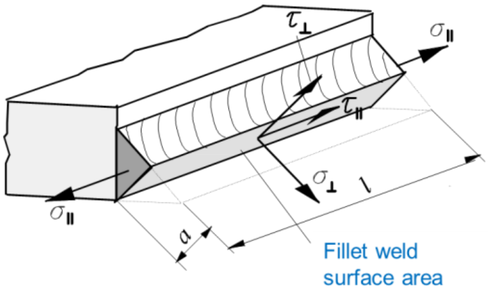
$$\sigma_w = \frac{F}{al} \le f_{vw,d} = \frac{f_u}{\sqrt{3}\beta_w \gamma_{M2}}$$

Weld stress is computed as force divided by total area

Directional Method
(more exact design)

$$\frac{\sigma_{eq}}{\sqrt{3}} \le f_{vw,d} = \frac{f_u}{\sqrt{3}\beta_w \gamma_{M2}} \Leftrightarrow \sigma_{eq} \le \frac{f_u}{\beta_w \gamma_{M2}}$$

Equivalent von Mises stress is computed from the stress components

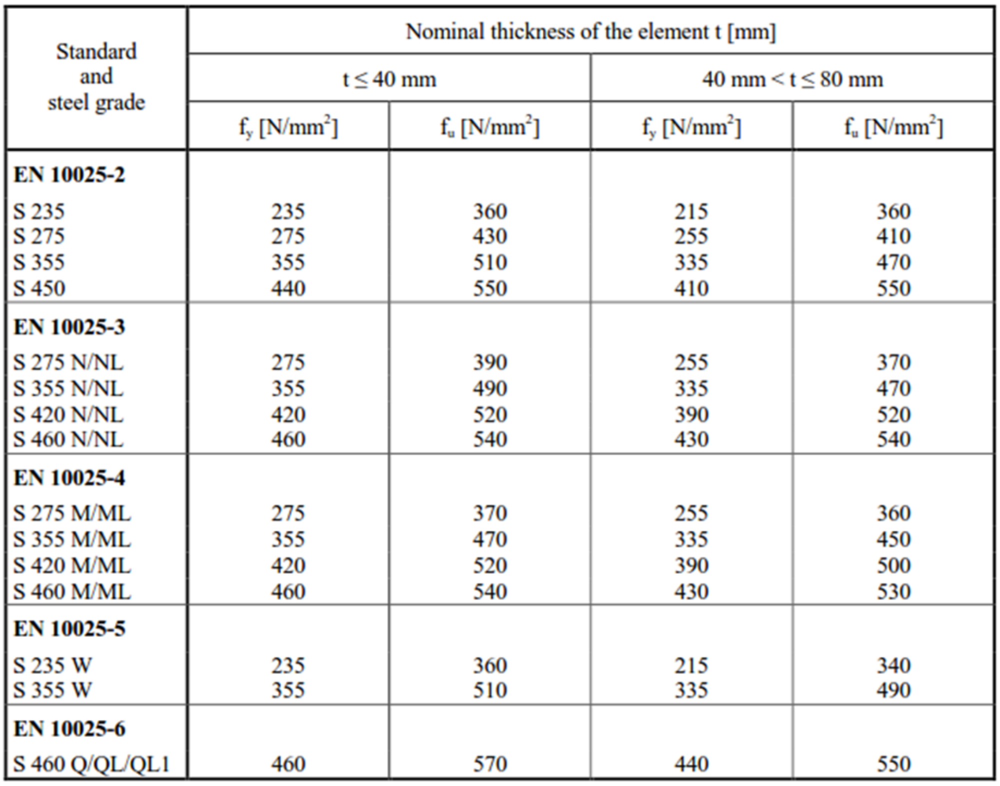


Fillet weld surface area

Correlation factor β_w for fillet welds

Standard and steel grade			Correlation factor β_w
EN 10025	**EN 10210**	**EN 10219**	
S 235 S 235 W	S 235 H	S 235 H	0,8
S 275 S 275 N/NL S 275 M/ML	S 275 H S 275 NH/NLH	S 275 H S 275 NH/NLH S 275 MH/MLH	0,85
S 355 S 355 N/NL S 355 M/ML S 355 W	S 355 H S 355 NH/NLH	S 355 H S 355 NH/NLH S 355 MH/MLH	0,9
S 420 N/NL S 420 M/ML		S 420 MH/MLH	1,0
S 460 N/NL S 460 M/ML S 460 Q/QL/QL1	S 460 NH/NLH	S 460 NH/NLH S 460 MH/MLH	1,0

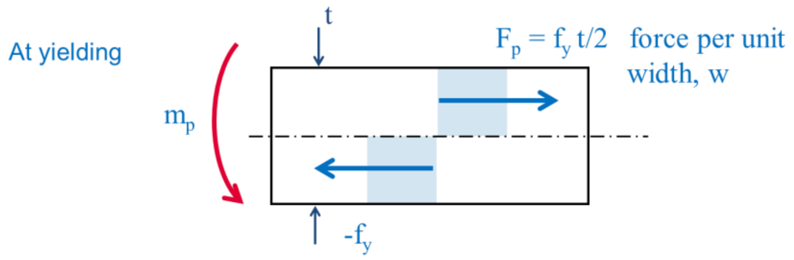
Nominal values of yield strength f_y and ultimate tensile strength f_u for hot rolled structural steel



Standard and steel grade	Nominal thickness of the element t [mm]			
	t ≤ 40 mm		40 mm < t ≤ 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	510	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	510	335	490
EN 10025-6				
S 460 Q/QL/QL1	460	570	440	550

☞ Static design of welds: Plastic Bending Momentum

- Considering uniform distribution of the bending loading along the plate width, w, and neutral axis coincident with mid-thickness (pure uniform bending with no migration of neutral axis)

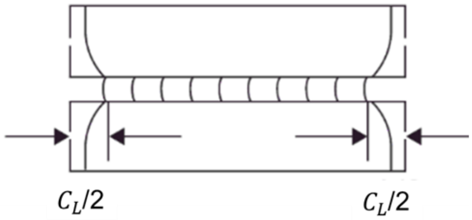


$m_p = (\, f_y\, t^2\,)/4$ moment per unit width (w) of plate

$M_p = m_p * w$

☞ Estimative of longitudinal shrinkage in butt joints:

Longitudinal Shrinkage of continuous groove welds in butt-joint (C_{L_grove}):



$$C_{L\_groove} = \frac{0.12 \times I \times L}{100000 \times t}$$

Longitudinal Shrinkage (C_{L_groove}) = [mm]

Current, I= [A]

Length of joint, L=[mm]

Thickness, t=[mm]

☞ Estimative of longitudinal shrinkage in fillet joints:

Longitudinal Shrinkage of continuous fillet welds in “T” joint (C_{L_fillet}):

$$C_{L\_fillet} = \frac{A_w}{A_T} \text{ x } 25$$

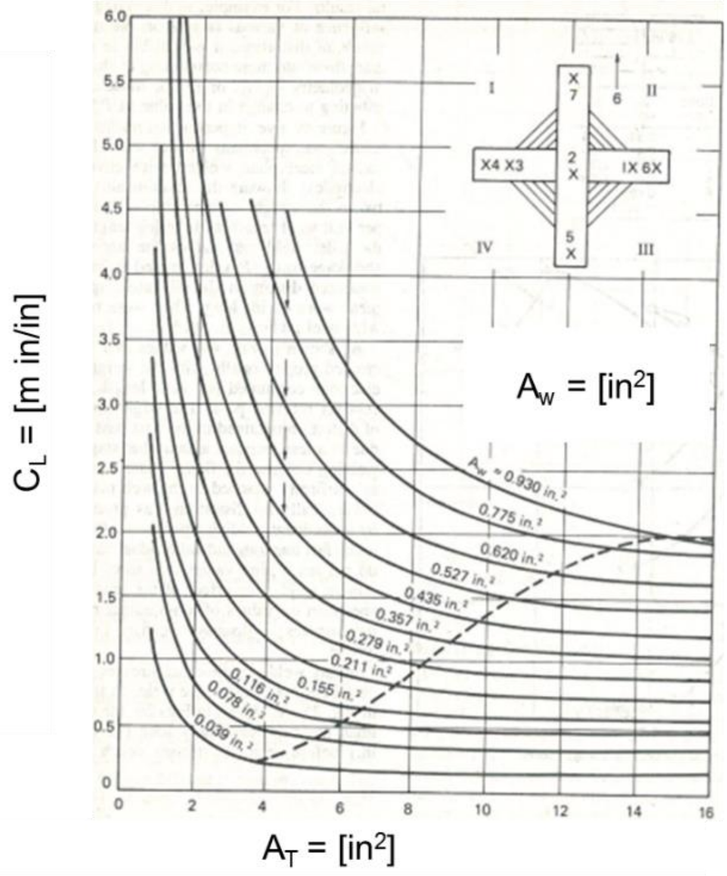
Longitudinal Shrinkage (C_{L_fillet}) = [mm/m]

Area of weld cross section (A_w) = [mm^2]

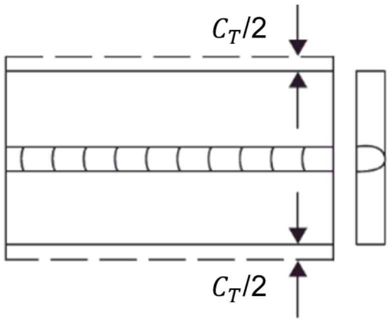
Area of total cross section (A_T) = [mm^2]

Note: When $A_T > 20 \text{ x } A_w$ then use table in next slide

When $A_T > 20 \times A_w$



Estimative of transversal shrinkage in butt joints:



(a) Transverse shrinkage

$$C_T = 0.2\,\frac{A_w}{t} + 0.05\ \mathrm{g}$$

Transversal Shrinkage (C_T) = [mm]
Area of weld cross section (A_w) = [mm^2]
Thickness of plate (t) = [mm]
Gap at weld root (g) = [mm]

Note: Estimation valid for thickness, t ≥ 6mm

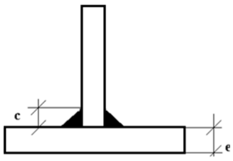
☞ Estimative of longitudinal and transversal shrinkage in fillet joints:

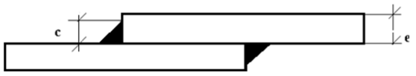
Transversal Shrinkage of 2 continuous fillet welds in “T” joint (C_{T_fillet}):

$$C_{T\_fillet} = \frac{c}{t} \times 0.04$$

Transversal Shrinkage of fillet welds (C_{T_fillet}) = [mm]
Leg of fillet weld (c) = [mm]
Thickness of flange plate (t) = [mm]

Note: For intermittent welding the C_{T_fillet} should be affected by the ratio of the total weld length versus total joint length





Transversal Shrinkage of 2 continuous fillet welds in overlap joint (C_{T_fillet}):

$$C_{Overlap\_fillet} = \frac{c}{t} \times 0.06$$

☞ Estimative of Angular Rotation in free joints:

$$\theta_0 = arctg\,\frac{0.4\,c^{1.3}}{t^2}$$

θ_0 - Angular rotation due to weld cycle [°]
c - Leg of fillet weld or penetration in butt joints [mm]
t - Thickness of the components [mm]