

STEEL FORMING AND **HEAT TREATING HANDBOOK**

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- Austenite Formation Temperatures

. Grange

$$Ae_1 = 1333 - 25 Mn + 40 Si + 42 Cr - 26 Ni$$

Notation:

Ae₁: Equilibrium Temperature for Austenitization Start [°F]

Alloy Content: [weight %]

$$Ae_3 = 1570 - 323 C - 25 Mn + 80 Si - 3 Cr - 32 Ni$$

Notation:

Ae₃: Equilibrium Temperature for End of Austenitization [°F]

Alloy Content: [weight %]

Source: GRANGE, R.A. **Metal Progress**, April 1961, 73.

. Andrews

$$Ae_1 = 723 - 16.9 Ni + 29.1 Si + 6.38 W - 10.7 Mn + 16.9 Cr + 290 As$$

Notation:

Ae₁: Equilibrium Temperature of Austenitization Start [°C]

Alloy Content: [weight %]

$$Ae_3 = 910 - 203 \sqrt{C} + 44.7 Si - 15.2 Ni + 31.5 Mo + 104 V + 13.1 W - 30.0 Mn + 11.0 Cr + 20.0 Cu - 700 P - 400 Al - 120 As - 400 Ti$$

Notation:

A_e₃: Equilibrium Temperature for Austenitization End [°C]

Alloy Content: [weight %]

Notes:

- Both formulas are valid for low alloy steels with less than 0.6%C.

Source: ANDREWS, K.W. *Empirical Formulae for the Calculation of Some Transformation Temperatures*. **Journal of the Iron and Steel Institute**, 203, Part 7, July 1965, 721-727.

. Roberts

$$Ae_3 = 910 - 25 Mn - 11 Cr - 20 Cu + 60 Si + 700 P - 250 Al - F_n$$

Notation:

A_e₃: Equilibrium Temperature for End of Austenitization [°C]

Alloy Content: [weight %]

F_n: value defined according to the table below:

C	F_n
0.05	24
0.10	48
0.15	64
0.20	80
0.25	93
0.30	106
0.35	117
0.40	128

Source: ROBERTS, W.L.: **Flat Processing of Steel**; Marcel Dekker Inc., New York, 1988.

. ELDIS

$$Ae_1 = 712 - 17,8 \text{ Mn} - 19,1 \text{ Ni} + 20,1 \text{ Si} + 11,9 \text{ Cr} + 9,8 \text{ Mo}$$

Notation:

Ae₁: Equilibrium Temperature of Austenitization Start [°C]

Alloy Content: [weight %]

$$Ae_3 = 871 - 254,4 \sqrt{C} - 14,2 \text{ Ni} + 51,7 \text{ Si}$$

Notation:

Ac₃: Equilibrium Temperature for End of Austenitization [°C]

Alloy Content: [weight %]

Notes:

- Both formulas were proposed by ELDIS for low alloy steels with less than 0.6% C.

Source: BARRALIS, J. & MAEDER, G. *Métallurgie Tome I: Métallurgie Physique*. **Collection Scientifique ENSAM**, 1982, 270 p.

. Park

$$Ac_3 = 955 - 350 C - 25 \text{ Mn} + 51 \text{ Si} + 106 \text{ Nb} + 100 \text{ Ti} + 68 \text{ Al} - 11 \text{ Cr} - 33 \text{ Ni} - 16 \text{ Cu} + 67 \text{ Mo}$$

Notation:

Ac₃: Austenitization Start Temperature [°C]

Alloy Content: [weight %]

Notes:

- Formula specifically developed for TRIP steels.

Source: PARK, S.H. et al. *Development of Ductile Ultra-High Strength Hot Rolled Steels*. **Posco Technical Report**, 1996, 50-128.

. Lee & Lee

$$A_{cm} = 224.4 + 992.4 C - 465.1 C^2 + 46.7 Cr + 19.0 C Cr - 6.1 Cr^2 + 7.6 Mn + 10.0 Mo - 6.8 Cr Mo - 6.9 Ni + 3.7 C Ni - 2.7 Cr Ni + 0.8 Ni^2 + 16.7 Si$$

Notation:

A_{cm}: Austenitization Start Temperature [°C]

Alloy Content: [weight %]

Notes:

- Equation valid for the following alloy range: $0.2\% \leq C \leq 0.7$; $Mn \leq 1.5\%$; $Si \leq 0.3\%$; $Ni \leq 2.8\%$; $Cr \leq 1.5\%$; $Mo \leq 0.6\%$.

Source: LEE, S.J. & LEE, Y.K. *Thermodynamic Formula for the A_{cm} Temperature of Low Alloy Steels*. **ISIJ International**, 47:5, May 2007, 769-774.

- Austenite No-Recrystallization Temperature**. Boratto et al.**

$$T_{nr} = 887 + 464 C + (6445 Nb - 644 \sqrt{Nb}) + (732 V - 230 \sqrt{V}) + 890 Ti + 363 Al - 357 Si$$

Notation:

T_{nr}: Temperature of No-Recrystallization [°C]**Alloy Content**: [weight %]

Notes:

- Equation valid under the following alloy range: $0.04\% \leq C \leq 0.17\%$; $0.41\% \leq Mn \leq 1.90$; $0.15\% \leq Si \leq 0.50\%$; $0.002\% \leq Al \leq 0.650$; $Nb \leq 0.060\%$; $V \leq 0.120\%$; $Ti \leq 0.110\%$; $Cr \leq 0.67\%$; $Ni \leq 0.45$.

Source: BORATTO, F. et al.: *Effect of Chemical Composition on Critical Temperatures of Microalloyed Steels*. In: **THERMEC '88**. Proceedings. Iron and Steel Institute of Japan, Tokyo, 1988, p. 383-390.

- Austenite Solubility Products

. General

$$\log \frac{(a_A)^m (a_B)^n}{a_{A_m B_n}} = -\frac{A}{T} + B$$

Notation:

A_mB_n: Precipitate Considered for Calculation

a_x: Alloy Content [weight %]

T: Temperature [K]

A, B: Constants of the Solubility Product, given in the table below:

Precipitate	A	B	Source
AlN	7060	1.55	Narita
AlN	6770	1.03	
BN	13970	5.24	Fountain
Mo ₂ C	7375	5.00	
NbC	7900	3.42	Narita
NbC	7290	3.04	Meyer
NbC _{0.87}	7520	3.11	
NbC _{0.87}	7700	3.18	Mori
NbN	8500	2.80	Narita
NbN	10230	4.04	

Nb(CN)	5860	1.54	Meyer
TiC	7000	2.75	Irvine
TiN	15020	3.82	Narita
VC	9500	6.72	
VN	8330	3.46	

Notes:

- a_{AmBn} is equal to one if the precipitate is pure.
- $a_{AmBn} \leq 1$ if there is co-precipitation with another element.

Sources:

- IRVINE, K.J. et al. *Grain-Refined C-Mn Steels*. **Journal of the Iron and Steel Institute**, 205:2, Feb. 1967, 161-182.
- NARITA, K. et al. *Physical Chemistry of Ti/Zr, V/Nb/Ta and Rare Elements in Steel*. **Transactions of the ISIJ**, 15:5, May 1975, 145-51.
- FOUNTAIN, R. & CHIPMAN, J. *Solubility and Precipitation of Vanadium Nitride in Alpha and Gamma Iron*. **Transactions of the AIME**, Dec. 1958, 737-739
- Values compiled by Rajindra Clement Ratnapuli or Fúlvio Siciliano from assorted references when not specified above.

. Irvine

$$\log[Nb] \left[C + \frac{12}{14} N \right] = 2.26 - \frac{6770}{T}$$

Notation:

T: Temperature [K]

Alloy Content: [weight %]

Source: IRVINE, K.J. et al. *Grain-Refined C-Mn Steels*. **Journal of the Iron and Steel Institute**, 205:2, Feb. 1967, 161-182.

. Mori

$$\log[Nb][N]^{0.65}[C]^{0.24} = 4.09 - \frac{10400}{T}$$

Notation:

T: Temperature [K]

Alloy Content: [weight %]

Source: Equation compiled by Fúlvio Siciliano.

. Siciliano

$$\log[Nb]\left[C + \frac{12}{14}N\right] = 2.26 + \frac{838[Mn]^{0.246} - 1730[Si]^{0.594} - 6440}{T}$$

Notation:

T: Temperature [K]

Alloy Content: [weight %]

Source: SICILIANO JR., F.: *Mathematical Modeling of the Hot Strip Rolling of Nb Microalloyed Steels*. **Ph.D. Thesis**, McGill University, February 1999, 165 p.

. Dong

$$\log [Nb] \left[C + \frac{12}{14} N \right] = 3.14 + 0.35 [Si] - 0.91 [Mn] + \frac{1371 [Mn] - 923 [Si] - 8049}{T}$$

Notation:

T: Temperature [K]

Alloy Content: [weight %]

Source: DONG, J.X. et al.: *Effect of Silicon on the Kinetics of Nb(C,N) Precipitation during the Hot Working of Nb-bearing Steels.* **ISIJ International**, 40:6, June 2000, 613-618.

- Austenite Solubilization Temperatures

$$T_d(^0C) = \frac{A}{B - \log(a_A)^m(a_B)^n} - 273$$

Notation:

A_mB_n: Precipitate Considered for Calculation

T_d: Solubilization Temperature [K]

a_x: Alloy Content [weight %]

A, B: Constants of the Solubility Product, given in the table at the topic *Austenite Solubilization Products*.

- Austenite Transformation Temperatures

. Blás

$$Ar_3 = 903 - 328 C - 102 Mn + 116 Nb - 0.909 v$$

Notation:

Ar₃: Start Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Amount: [weight %]

v: Cooling Rate [°C/s]

Notes:

- This formula was determined using temperature data got from samples cooled directly from hot rolling experiments. Thus it includes the effects of hot forming over austenite decomposition.
- Useful range: 0.024-0.068% C, 0.27-0.39% Mn, 0.004-0.054% Al, 0.000-0.094% Nb, 0.0019-0.0072% N, 1.0-35°C/s
- r = 0.934; Standard Error of Deviation = 5°C

Source: BLÁS, J.G. et al.: *Influência da Composição Química e da Velocidade de Resfriamento sobre o Ponto Ar₃ em Aços de Baixo C Microligados ao Nb*. In: **Congresso Anual da Associação Brasileira de Metais**, ABM, São Paulo, Out. 1989, vol. 1, p 11-29.

. Choquet

$$Ar_3 = 902 - 527 C - 62 Mn + 60 Si$$

Notation:

Ar₃: Start Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Amount: [weight %]

Notes:

- This formula was determined using data got from samples cooled directly from hot rolling experiments. Thus it includes the effects of hot forming over austenite decomposition.

Source: CHOQUET, P. et al.: *Mathematical Model for Predictions of Austenite and Ferrite Microstructures in Hot Rolling Processes*. IRSID Report, St. Germain-en-Laye, 1985. 7 p.

. Unknown #1

$$Ar_3 = 879.4 - 516.1 C - 65.7 Mn + 38.0 Si + 274.7 P$$

Notation:

Ar₃: Start Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Content: [weight %]

$$Ar_1 = 706.4 - 350.4 C - 118.2 Mn$$

Notation:

Ar₁: Final Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Content: [weight %]

Notes:

- It is unknown the previous conditioning of the steel samples that supplied data for the deduction of this formula.
- Samples cooled at 20°C/s.

Source: Unknown.

. Unknown #2

$$Ar_3 = 901 - 325 C - 92 Mn + 33 Si + 287 P + 40 Al - 20 Cr$$

Notation:

Ar₃: Start Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Content: [weight %]

Notes:

- It is unknown the previous conditioning of the steel samples that supplied data for the deduction of this formula.

Source: Unknown.

. Ouchi

$$Ar_3 = 910 - 310 C - 80 Mn - 20 Cu - 15 Cr - 55 Ni - 80 Mo + 0,35(h - 8)$$

Notation:

Ar₃: Start Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Content: [weight %]

h: Plate Thickness [mm]

Notes:

- This formula was determined using temperature data got from samples cooled directly from hot rolling experiments. Thus it includes the effects of hot forming over austenite decomposition.

Source: OUCHI, C. et al. *The Effect of Hot Rolling Condition and Chemical Composition on the Onset Temperature of Gamma-Alpha Transformation After Hot Rolling*. **Transactions of the ISIJ**, March 1982, 214-222.

. Shiga

$$Ar_3 = 910 - 273 C - 74 Mn - 56 Ni - 16 Cr - 9 Mo - 5 Cu$$

Notation:

Ar₃: Start Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Content: [weight %]

Notes:

- This formula was determined using temperature data got from samples cooled directly from hot rolling experiments. Thus it includes the effects of hot forming over austenite decomposition.

Source: SHIGA, C. et al.: *Development of Large Diameter High Strength Line Pipes for Low Temperature Use*. **Kawasaki Steel Technical Report**, Dec. 1981, 97-109.

. Pickering

$$Ar_3 = 910 - 230 C - 21 Mn - 15 Ni + 32 Mo + 45 Si + 13 W + 104 V$$

Notation:

Ar₃: Start Temperature of the Transformation Austenite → Ferrite [°C]

Alloy Content: [weight %]

Notes:

- Applicable to Plain C Steels.

Source: PICKERING, F.B.: *Steels: Metallurgical Principles*. In: **Encyclopedia of Materials Science and Engineering**, vol. 6, The MIT Press, Cambridge, 1986.

. Steven & Haynes

$$B_s = 830 - 270 C - 90 Mn - 37 Ni - 70 Cr - 83 Mo$$

$$B_{50} = B_s - 50$$

$$B_{100} = B_s - 120$$

Notation:

B_s: Start Temperature of the Bainitic Transformation [°C]

Alloy Amount: [% em peso]

B_x: Temperature Required for the Formation of $x\%$ of Bainite [°C]

Source: STEVEN, W. & HAYNES, A.G. *The Temperature of Formation of Martensite and Bainite in Low Alloy Steels*. **Journal of the Iron and Steel Institute**, 183, 1956, 349-359.

. Suehiro

$$B_s = 718 - 425 C - 42.5 Mn$$

Notation:

B_s: Start Temperature of the Bainitic Transformation [°F]

Alloy Amount: [weight %]

Source: SUEHIRO, M. et al. *Kinetic Model for Phase Transformation of Low C Steel during Continuous Cooling.* **Tetsu-to-Hagané**, 73, 1987, 1026-1033.

. Kirkaldy

$$B_s = 656 - 58 C - 35 Mn - 75 Si - 15 Ni - 34 Cr - 41 Mo$$

Notation:

B_s: Start Temperature of the Bainitic Transformation [°F]

Alloy Amount: [weight %]

Source: KIRKALDY, J.S. et al. *Prediction of Microstructure and Hardenability in Low Alloy Steels.* In: **Phase Transformations in Ferrous Alloys**, AIME, Warrendale, 1983, 125-148.

. Lee

$$B_s = 984.4 - 361.9 C + 261.9 C^2 - 28.3 Mn + 43.7 Si$$

Notation:

B_s: Start Temperature of the Bainitic Transformation [K]

Alloy Amount: [weight %]

Notes:

- Formula specifically developed for TRIP steels.

Source: LEE, J.K. et al. *Prediction of Tensile Deformation Behaviour of Formable Hot Rolled Steels.* **Posco Technical Research Laboratories Report**, Pohang, 1999.

. Rowland & Lyle

$$M_s = 499 - 324 C - 32.4 Mn - 27 Cr - 16.2 Ni - 10.8 Si - 10.8 Mo - 10.8 W$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Amount: [% em peso]

Source: ROWLAND, E.S. et al. **Transactions ASM**, 37, 1946, 27.

. Steven & Haynes

$$M_s = 561 - 474 C - 33 Mn - 17 Cr - 17 Ni - 21 Mo$$

$$M_{10} = Ms - 18$$

$$M_{50} = Ms - 85$$

$$M_{90} = Ms - 185$$

$$M_{100} = Ms - 387$$

Notation:

M_x: Temperature Required for the Formation of $x\%$ of Martensite [°F]

Source: STEVEN, W. & HAYNES, A.G. *The Temperature of Formation of Martensite and Bainite in Low Alloy Steels*. **Journal of the Iron and Steel Institute**, 183, 1956, 349-359.

. Andrews

$$M_s = 539 - 423 C - 30.4 Mn - 17.7 Ni - 12.1 Cr - 11.0 Si - 7.0 Mo$$

$$M_s = 512 - 453 C - 16.9 Ni - 9.5 Mo + 217 C^2 - 71.5 C Mn + 15 Cr - 67.6 C Cr$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Content: [weight %]

Notes:

- Formula valid for low alloy steels with less than 0.6%C, 4.9% Mn, 5.0% Cr, 5.0% Ni and 5.4% Mo.

Source: ANDREWS, K.W. *Empirical Formulae for the Calculation of Some Transformation Temperatures*. **Journal of the Iron and Steel Institute**, 203, Part 7, July 1965, 721-727.

. Eldis

$$M_s = 531 - 391.2 C - 43.3 Mn - 21.8 Ni - 16.2 Cr$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Content: [weight %]

Notes:

- Equation valid for steels with chemical composition between the following limits: 0.1~0.8% C; 0.35~1.80% Mn; <1.50% Si; <0.90% Mo; <1.50% Cr; <4.50% Ni .

Source: BARRALIS, J. & MAEDER, G. *Métallurgie Tome I: Métallurgie Physique*. Collection Scientifique ENSAM, 1982, 270 p.

. Krauss

$$M_s = 561 - 474 C - 33 Mn - 17 Cr - 17 Ni - 21 Mo$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Amount: [weight %]

Source: KRAUSS, G. **Principles of Heat Treatment and Processing of Steels**, ASM International, 1990, p. 43-87.

. Sverdlin-Ness

$$M_s = 520 - 320 C - 50 Mn - 30 Cr - 20 (Ni + Mo) - 5 (Cu + Si)$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Amount: [weight %]

Source: SVERDLIN, A.V. & NESS, A.R. *The Effects of Alloying Elements on the Heat Treatment of Steel*. In: **Steel Heat Treatment Handbook**, Marcel Dekker, New York, 1997, p. 45-91.

. Payson & Savage

$$M_s = 499 - 308 C - 32.4 Mn - 27 Cr - 16.2 Ni - 10.8 Si - 10.8 Mo - 10.8 W$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Amount: [weight %]

Source: PAYSON, P. & SAVAGE, C.H. **Transactions A.S.M.**, 33, 1944, 261.

. Carapella

$$M_s = 496 (1 - 0.62 C) (1 - 0.092 Mn) (1 - 0.033 Si) (1 - 0.045 Ni) (1 - 0.07 Cr) (1 - 0.029 Mo) (1 - 0.018 W) (1 - 0.012 Co)$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Amount: [weight %]

Source: CARAPELLA, L.A. **Metal Progress**, 46, 1944, 108.

. Grange & Stewart

$$M_s = 538 - 350 C - 37.7 Mn - 37.7 Cr - 18.9 Ni - 27 Mo$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Amount: [weight %]

Source: GRANGE, R.A. & STEWART, H.M. **Transactions of the AIME**, 167, 1946, 467.

. Nehrenberg

$$M_s = 499 - 292 C - 32.4 Mn - 22 Cr - 16.2 Ni - 10.8 Si - 10.8 Mo$$

Notation:

M_s: Start Temperature of the Martensitic Transformation [°C]

Alloy Amount: [weight %]

Source: NEHRENBERG, A.E. **Transactions of the AIME**, 167, 1946, 494.

- Critical Diameter - Austenite Hardenability**. Dearden & O'Neill**

$$Di = 6 \times \exp \left[7.1 \times \left(C + \frac{Mn}{5.87} + \frac{Mo}{3.13} + \frac{Cr}{6.28} + \frac{Si}{18} + \frac{Ni}{15} \right) \right]$$

Notation:

D_i: Critical Diameter [mm]

Alloy Content: [weight %]

Source: DEARDEN, J & O'NEIL, H.: *A Guide to the Selection and Welding of Low Alloy Structural Steels.* **Transactions of the Institute of Welding**, 3, Oct. 1940, 203-214.

- Density

. Austenitic Steels

$$\rho_{\gamma} = \frac{1}{(1.231 Fe + 3.178 C_{sol} + 1.307 Mn + 2.436 Si + 1.431 Cr + 1.205 Cu + 1.018 Mo + 1.137 Ni + 1.890 Ti + 1.111 Co + 2.186 N + 2.032 TiC) \cdot 10^{-6}}$$

Notation:

ρ_{γ} : Austenite Density [kg/m³]

Alloy/TiC Content: [weight %]

Notes:

- C_{sol} is the content of this element not bound in TiC.
- Density calculated at 20°C.

Source: BOHNENKAMP, U. et al.: *Evaluation of the Density of Steels*. **Steel Research**, 71:3, March 2000, 88-93.

. Ferritic Steels

$$\rho_{\alpha} = \frac{1}{(1.270 Fe + 1.380 C + 1.524 Mn + 2.381 Si + 1.384 Cr + 0.8477 Cu + 1.076 Mo + 1.370 Ni + 2.012 V + 4.046 S) \cdot 10^{-6}}$$

Notation:

ρ_{α} : Steel Density [kg/m³]

Alloy Content: [weight %]

Notes:

- C is considered insoluble in ferrite (that is, all C has gone to cementite).
- The solubilities of the other alloy elements in cementite are zero.

- Density calculated at 20°C.

Source: BOHNENKAMP, U. et al.: *Evaluation of the Density of Steels*. **Steel Research**, 71:3, March 2000, 88-93.

. Liquid Iron

$$\rho_{Liquid\ Iron} = 1.99446 \times 0.22457 \left[1 - \frac{T}{9340} \right]^{0.7}$$

Notation:

$\rho_{Liquid\ Iron}$: Liquid Iron Density [g/ml]

T: Absolute Temperature, [K]

Source: YAWS, C.L.: *Liquid Density of the Elements*. **Chemical Engineering**, November 2007, 44-46.

. Steel Phases and Constituents

Phase/Constituent	C [weight %]	Specific Volume [cm³/g] at 20°C
Austenite	0.00 ~ 2.00	0.1212+0.0033 C
Martensite	0.00 ~ 2.00	0.1271+0.0025 C
Ferrite	0.00 ~ 0.02	0.1271
Cementite (Fe ₃ C)	6.7 ± 0.2	0.130 ± 0.001
ε Carbide	8.5 ± 0.7	0.140 ± 0.002
Graphite	100	0.451
Ferrite + Cementite	0.00 ~ 2.00	0.1271 + 0.0005 C
Low C Martensite + ε Carbide	0.25 ~ 2.00	0.1277 + 0.0015 (C - 0.25)
Ferrite + ε Carbide	0.00 ~ 2.00	0.1271 + 0.0015 C

Source: THELNING, K.E.: *Steel and its Heat Treatment – Bofors Handbook*. Butterworths, London, 1981, 570 p.

. Temperature Effect

$$\rho_{\alpha}^T = \rho_{\alpha}^{20^\circ C} - 0.33 T$$

$$\rho_{\gamma}^T = \rho_{\gamma}^{20^\circ C} - 0.47 T$$

Notation:

ρ_{α}^T : Ferrite Density at Temperature T [kg/m³]

$\rho_{\alpha}^{20^\circ C}$: Ferrite Density at 20°C [kg/m³]

ρ_{γ}^T : Austenite Density at Temperature T [kg/m³]

$\rho_{\gamma}^{20^\circ C}$: Austenite Density at 20°C [kg/m³]

T: Temperature[°C]

Source: FINK, K. et al.: *Physikalische Eigenschaften von Stählen, insbesondere von warmfesten Stählen. Thyssenforschung*, 2:2, 1970, 65-80.

- Dimensional Changes after Heat Treating

. After General Heat Treating

Transformation	ΔV [%]	Δl [mm/mm]
Spheroidized Pearlite \rightarrow Austenite	$-4.64 + 2.21 C$	$-0.0155 + 0.0074 C$
Austenite \rightarrow Martensite	$4.64 - 0.53 C$	$0.0155 - 0.0018 C$
Spheroidized Pearlite \rightarrow Martensite	$1.68 C$	$0.0056 C$
Austenite \rightarrow Lower Bainite	$4.64 - 1.43 C$	$0.0155 - 0.0048 C$
Spheroidized Pearlite \rightarrow Lower Bainite	$0.78 C$	$0.0026 C$
Austenite \rightarrow Upper Bainite	$4.14 - 2.21 C$	$0.0155 - 0.0074 C$
Spheroidized Pearlite \rightarrow Upper Bainite	0 (Zero)	0

Notation:

- C: Carbon Content [weight %].

Sources:

- THELNING, K.E.: *Steel and its Heat Treatment – Bofors Handbook*. Butterworths, London, 1981, 570 p.
- KRAUSS, G. *Steel: Processing, Structure and Performance*. ASM International, Metals Park, 2005, 420 p.

. After Quenching

$$\frac{\Delta V}{V} = \left(\frac{100 - V_C - V_A}{100} \right) 1.68 C_M + \frac{V_A}{100} (-4.64 + 2.21 C_A)$$

Notation:

- $\Delta V/V$: Volumetric Change after Quenching [%]

- V_C : Non-solubilized Cementite Volumetric Fraction [%]
- V_A : Austenite Volumetric Fraction [%]
- $100 - V_C - V_A$: Martensite Volumetric Fraction [%]
- C_M : Carbon Content Solubilized in Martensite [weight %]
- C_A : Carbon Content Solubilized in Austenite [weight %]

Source: THELNING, K.E.: *Steel and its Heat Treatment – Bofors Handbook*. Butterworths, London, 1981, 570 p.

- Equivalent Carbon – H.A.Z. Hardenability

. Dearden & O'Neill

$$C_{EQ_Dearden} = C + \frac{Mn}{6} + \frac{Mo}{4} + \frac{Cr+V}{5} + \frac{Cu}{13} + \frac{Ni}{15} + \frac{P}{2}$$

Notation:

C_{EQ_Dearden}: Equivalent Carbon (Dearden) [%]

Alloy Content: [weight %]

Source: DEARDEN, J & O'NEIL, H.: *A Guide to the Selection and Welding of Low Alloy Structural Steels*. **Transactions of the Institute of Welding**, 3, Oct. 1940, 203-214.

. IIW - International Institute of Welding

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

Notation:

C_{EQ_IIW}: Equivalent Carbon (IIW) [%]

Alloy Content: [weight %]

Source: HEISTERKAMP, F. et al.: *Metallurgical Concept And Full-Scale Testing of High Toughness, H₂S Resistant 0.03%*C* - 0.10%*Nb* Steel*. **C.B.M.M. Report**, São Paulo, February 1993.

. Bastien

$$C_{EQ_Bastien} = C + \frac{Mn}{4,4} + \frac{Mo}{7,7} + \frac{Cr}{15,4} + \frac{Ni}{10,3}$$

$$\ln(CR_m) = 13,9 - 10,6 C_{EQ_Bastien}$$

Notation:

C_{EQ_Bastien}: Equivalent Carbon (Bastien) [%]

Alloy Content: [weight %]

CR_m: Critical Cooling Rate at 700°C [°C/s], that is, minimum cooling rate that produces a fully martensitic structure)

Source: BASTIEN, P.G.: **Met. Constr. British Weld. J.**, 49, 1970, 9.

. Yurioka et al.

$$C_{EQ_Yurioka} = C + \frac{Mn}{6} + \frac{Mo}{4} + \frac{Cr}{8} + \frac{Ni}{12} + \frac{Si}{24} + \frac{Cu}{15}$$

$$\log(t_m) = 10,6 C_{EQ_Yurioka} - 4,8$$

Notation:

C_{EQ_Yurioka}: Equivalent Carbon (Yurioka) [%]

Alloy Content: [weight %]

t_m: Critical Cooling Time from 800 to 500°C [s] (that is, maximum cooling time that produces a fully martensitic structure)

Source: YURIOKA, N. et al.: **Met. Constr.**, 19, 1987, 217R.

. Kihara et al.

$$C_{EQ_Kihara} = C + \frac{Mn}{6} + \frac{Mo}{4} + \frac{Cr}{5} + \frac{V}{14} + \frac{Ni}{40} + \frac{Si}{24}$$

Notation:

C_{EQ_Kihara}: Equivalent Carbon (Kihara) [%]

Alloy Content: [weight %]

Source: KIHARA, H. et al. **Technical Report of JRIM**, 1, 1959, 93.

. Shinozaki et al.

$$C_{EQ_FBW} = C + \frac{Mn}{5} + \frac{Si}{15} + \frac{Cr}{9} + 7 Nb (1 - 10C) + \frac{V (50 C - 1)}{3} + 1.3 Ti (1 - 5 C) + \frac{Mo (1 - 6 C)}{2} + 29 B (11 C - 1)$$

Notation:

C_{EQ_FBW}: Equivalent Carbon Designed Specifically for Flash Butt Welding [%]

Alloy Content: [weight %]

Source: SHINOZAKI, M. et al.: *Effects of Chemical Composition and Structure of Hot Rolled High Strength Steel Sheets on the Formability of Flash Butt Welded Joints*. **Kawasaki Steel Technical Report**, 6, Sept. 1982, 21-30.

. Stout et al.

$$C_{EQ_Stout} = 1000 C \left(\frac{Mn}{6} + \frac{Cr + Mo}{10} + \frac{Ni}{20} + \frac{Cu}{40} \right)$$

Notation:

C_{EQ}_Stout: Equivalent Carbon (Kihara) [%]

Alloy Content: [weight %]

Source: STOUT, R.D. et al. **Welding Journal Research Supplement**, 55, 1976, 89s-94s.

- Equivalent Carbon – Hydrogen Assisted Cold Cracking

. DNV

$$C_{EQ_DNV} = C + \frac{Mn}{10} + \frac{Si}{24} + \frac{Ni + Cu}{40} + \frac{Cr}{5} + \frac{V}{10} + \frac{Mo}{4}$$

Notation:

C_{EQ_DNV}: Equivalent Carbon (DNV) [%]

Alloy Content: [weight %]

Source: HANNERZ, N.E.: *The Influence of Si on the Weldability of Mild and High Tensile Structural Steels.* **IIW Document IX-1169-80**, 1980.

. Uwer & Hohne

$$C_{EQ_Uwer} = C + \frac{Mn}{10} + \frac{Cu}{20} + \frac{Ni}{40} + \frac{Cr}{20} + \frac{Mo}{10}$$

Notation:

C_{EQ_Uwer}: Equivalent Carbon (Uwer & Hohne) [%]

Alloy Content: [weight %]

Source: UWER, D. & HOHNE, H.: *Determination of Suitable Minimum Preheating Temperature for the Cold-Crack-Free Welding of Steels.* **IIW Document IX-1631-91**, 1991.

. Mannesmann

$$C_{EQ_PLS} = C + \frac{Si}{25} + \frac{Mn+Cu}{16} + \frac{Cr}{20} + \frac{Ni}{60} + \frac{Mo}{40} + \frac{V}{15}$$

Notation:

C_{EQ_PLS}: Equivalent Carbon for Pipeline Steels [%]

Alloy Content: [weight %]

Notes:

- Formula deduced for pipeline steels
- A version of this formula divides V by 10

Sources:

- DUREN, C. & NIEDEROFF, K.: In: **Proc. on Welding and Performance of Pipeline**, TWI, London, 1986.
- HEISTERKAMP, F. et al.: *Metallurgical Concept And Full-Scale Testing of High Toughness, H₂S Resistant 0.03%C - 0.10%Nb Steel. C.B.M.M. Report*, São Paulo, February 1993.

. Graville

$$C_{EQ_HSLA} = C + \frac{Mn}{16} - \frac{Ni}{50} + \frac{Cr}{23} + \frac{Mo}{7} + \frac{Nb}{5} + \frac{V}{9}$$

Notation:

C_{EQ_HSLA}: Equivalent Carbon (Uwer & Graville) [%]

Alloy Content: [weight %]

Notes:

- Formula deduced for pipeline steels

Source: GRAVILLE, B.A.: In: **Proc. Conf. on Welding of HSLA Structural Steels**, ASM, Materials Park, 1976.

. Bersch & Koch (Hoesch)

$$C_{EQ_Bersch} = C + \frac{Mn + Si + Cr + Mo + V + Cu + Ni}{20}$$

Notation:

C_{EQ_Bersch}: Equivalent Carbon for Pipeline Steels [%]

Alloy Content: [weight %]

Notes:

- Formula deduced for pipeline steels

Source:

- BERSCH, B. et al. *Weldability of Pipe Steels for Low Operating Temperatures*. **3R International**, 1, 1977.
- PATCHETT, B.M. et al.: **Casti Metals Blue Book: Welding Filler Metals**. Casti Publishing Corp., Edmonton, February 1993, 608 p. (CD Edition).

. Ito & Bessyo (I)

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5 B$$

Notation:

P_{cm}: Cracking Parameter [%]

Alloy Content: [weight %]

Notes:

- Formula deduced for pipeline steels with C < 0.15%

- This is the most popular formula for this kind of material.
- Equation valid under the following conditions: $0.07\% \leq C \leq 0.22\%$; $0.40\% \leq Mn \leq 1.40\%$; $Si \leq 0.60\%$; $V \leq 0.12\%$; $Cr \leq 1.20\%$; $Ni \leq 1.20\%$; $Cu \leq 0.50\%$, $Mo \leq 0.7\%$, $B \leq 0.005\%$.

Source:

- ITO, Y. et al.: **Journal of the Japan Welding Society**, 37, 1968, 983.
- ITO, Y. & BESSYO, K. *Weldability Formula of High Strength Steels Related to Heat-Affected-Zone Cracking*. **The Sumitomo Search**, 1, 1969, 59-70.

. Ito & Bessyo (II)

$$P_c = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + \frac{d}{600} + \frac{H}{60}$$

Notation:

P_c: Cracking Parameter [%]

Alloy Content: [weight %], except

H: Hydrogen amount in the weld metal, [cm³/100 g]

d: Plate Thickness, [mm]

Source: ITO, Y. & BESSYO, K.: *Weldability Formula of High Strength Steels*. **I.I.W. Document IX-576-68**.

. Yurioka

$$C_{EQ_Yurioka} = C + A(C) \left(\frac{Mn}{6} + \frac{Si}{24} + \frac{Cr + Mo + V}{5} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Nb}{5} + 5B \right)$$

$$A(C) = 0.75 + 0.25 \tanh [20 (C - 0.12)]$$

Notation:

C_{EQ_Yurioka}: Equivalent Carbon for Pipeline Steels [%]

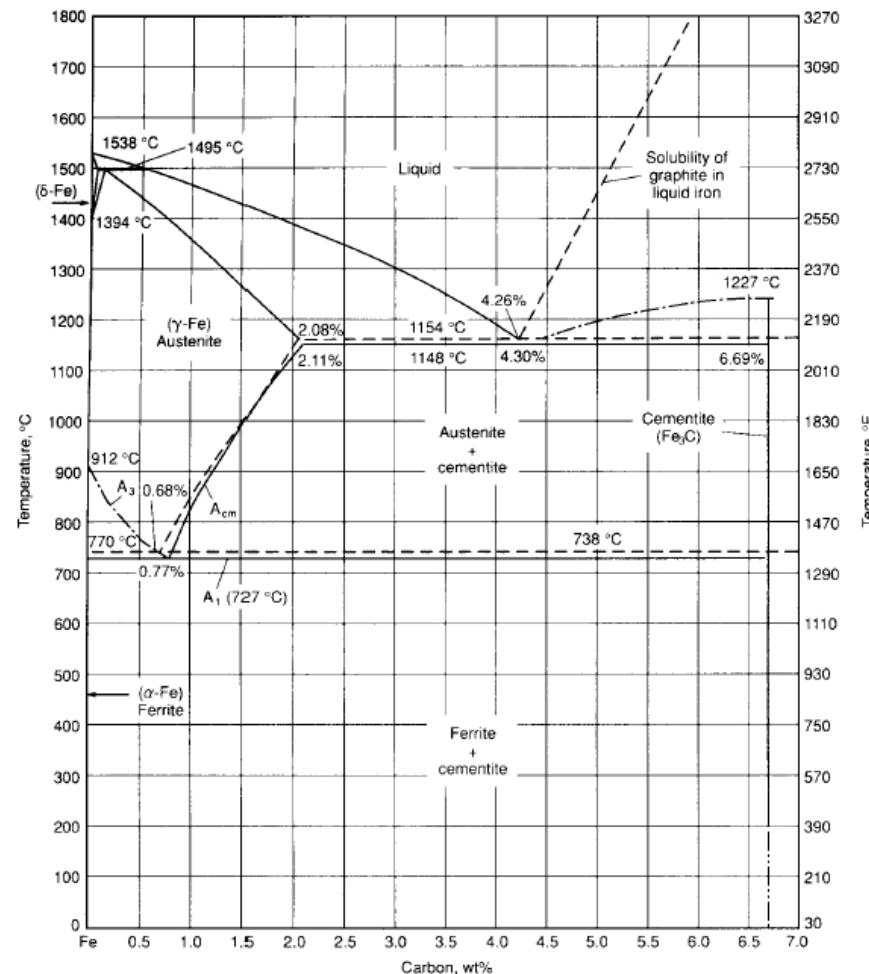
Alloy Content: [weight %]

Notes:

- Formula for C-Mn and microalloyed pipeline steels
- This formula combines Carbon Equivalent equations from IIW and P_{cm}

Sources:

- YURIOKA, N.: *Physical Metallurgy of Steel Weldability*. **ISIJ International**, 41:6, June 2001, 566-570.
- PATCHETT, B.M. et al.: **Casti Metals Blue Book: Welding Filler Metals**. Casti Publishing Corp., Edmonton, February 1993, 608 p. (CD Edition).

- Fe-C Diagram

Source: **ASM's Heat Treating One-Minute Mentor**,
<http://www.asminternational.org/pdf/HTSRefCharts/Vol4p4Fig1.pdf>.

- Ferrite Solubility Products

. General

$$\log_{10} \frac{(a_A)^m (a_B)^n}{a_{A_m B_n}} = -\frac{A}{T} + B$$

Notation:

A_mB_n: Precipitate Considered for Calculation

a_x: Alloy Content [weight %]

T: Temperature [K]

A, B: Constants of the Solubility Product, given in the table below:

Precipitate	A	B	Source
AlN	9595	2.65	Kunze & Reichert
BN	13560	4.53	Fountain & Chipman
MnS	8400	2.77	Ivanov
NbC	10990	4.62	Kunze
NbN	10650	3.87	Kunze
TiN	17640	6.17	Kunze
VC	12265	8.05	Taylor
VN	7830	2.45	Froberg
VN	8120	2.48	Roberts & Sandbert
ZrN	18160	5.24	Kunze

Notes:

- a_{AmBn} is equal to one if the precipitate is pure.
- $a_{AmBn} \leq 1$ if there is co-precipitation with another element.

Source:

- TAYLOR, K.A. et al. **Scripta Metallurgica**, 32, 1995, 7.
- FROBERG, M.G. & GRAF, H. **Stahl und Eisen**, 80, 1960, 539.
- KUNZE, J. **Nitrogen and Carbon in Iron and Steels – Thermodynamics**. Akademie Verlag, Berlin, 1991, p. 192.
- FOUNTAIN, R.W. & CHIPMAN, J. In: **Transactions of the Metallurgical Society of AIME**, 224, 1964, 599.
- KUNZE, J. & REICHERT, J. **Neue Hütte**, 26, 1981, 23.
- ROBERTS, W. & SANDBERG, A. **Report IM 1489**. Institute for Metallurgical Research, Stockholm, 1990.
- IVANOV, B.S. et al. **Stahl**, 8, 1996, 52.

- Hardness after Cooling**. LORENZ et al.**

$$HV = 2019 \left[C (1 - 0.5 \log t_{8/5}) + 0.3 \left(\frac{Si}{11} + \frac{Mn}{8} + \frac{Cu}{9} + \frac{Cr}{5} + \frac{Ni}{17} + \frac{Mo}{6} + \frac{V}{3} \right) \right] + 66 (1 - 0.8 \log t_{8/5})$$

Source: LORENZ, K. et al.: *Evaluation of Large Diameter Pipe Steel Weldability by Means of the Carbon Equivalent*. In: **International Conference on Steels for Linepipe and Fittings**, Metals Society, London, Oct. 1981, 322-332.

Notation:

HV: Maximum Hardness for a Martensitic-Bainitic HAZ Microstructure [Vickers, 10 kg Load]**Alloy Content**: [weight %]**t_{8/5}**: Cooling Time Between 800°C and 500°C [s]

- Hardness after Tempering

. Spies

$$HB = 2.84 HRC + 75 C - 0.78 Si + 14.24 Mn + 14.77 Cr + 128.22 Mo - 54.0 V - 0.55 T + 435.66$$

Notation:

HB: Brinell Hardness After Hardening and Tempering

HRC: Rockwell Hardness (C Scale) After Hardening

Alloy Content: [weight %]

T: Tempering Temperature [°C]

Notes:

- This equation is valid within the following ranges: **HRC**: 20~65; **C**: 0.20~0.54%; **Mn**: 0.50~1,90%; **Si**: 0.17~1.40%; **Cr**: 0.03~1.20%; **T**: 500~650°C.

Source: SPIES, H.J. et al.: *Möglichkeiten der Optimierung der Auswahl vergütbarer Baustähle durch Berechnung der Härt-und-vergütbarkeit*. Neue Hütte, 8:22, 1977, 443-445.

- Hardness after Welding

. Dearden & O'Neill

$$HV_{\max} = 1200 C_{EQ_Dearden} - 200$$

$$C_{EQ_Dearden} = C + \frac{Mn}{6} + \frac{Mo}{4} + \frac{Cr+V}{5} + \frac{Cu}{13} + \frac{Ni}{15} + \frac{P}{2}$$

Notation:

C_{EQ_Dearden}: Equivalent Carbon (Dearden) [%]

Alloy Content: [weight %]

HV_{max} = Maximum Hardness [Vickers]

Notes:

- This equation calculates maximum hardness after welding.

Source: DEARDEN, J & O'NEIL, H.: **Trans. Int. Weld.**, 3, 1940, 203.

. Shinozaki et al.

$$HV = 78 + 331 C_{EQ_FBW}$$

$$C_{EQ_FBW} = C + \frac{Mn}{5} + \frac{Si}{15} + \frac{Cr}{9} + 7 Nb (1 - 10C) + \frac{V (50 C - 1)}{3} + 1.3 Ti (1 - 5 C) + \frac{Mo (1 - 6 C)}{2} + 29 B (11 C - 1)$$

Notation:

C_{EQ_FBW}: Equivalent Carbon Designed Specifically for Flash Butt Welding [%]

Alloy Content: [weight %]

HV: Hardness at the Welding Interface [Vickers]

Source: SHINOZAKI, M. et al.: *Effects of Chemical Composition and Structure of Hot Rolled High Strength Steel Sheets on the Formability of Flash Butt Welded Joints.* **Kawasaki Steel Technical Report**, 6, Sept. 1982, 21-30.

- **Hot Strength of Steel**

. Tselikov

$$E = 308250 + 42924 C - 144000 C^2 + 20525 Si - 5289 Mn - 12000 P + 174000 S - 225,6 T + 0,01379 T^2$$

Notation:

E: Young Modulus [kgf/cm²]

C: C content [weight %]

Mn: Mn content [weight %]

Si: Si content [weight %]

P: P content [weight %]

S: S content [weight %]

T: Temperature [°C]

Note:

- Valid for carbon, alloy and stainless steels between 20 and 900°C.

Source: ROYZMAN, S.E. *Thermal Stresses in Slab Solidification*. **Asia Steel**, 1996, 158-162.

. Misaka

$$\sigma = \exp \left[0.126 - 1.75 C + 0.594 C^2 + \frac{(2851 + 2968 C - 1120 C^2)}{T} \right] \varepsilon^{0,21} \left(\frac{d\varepsilon}{dt} \right)^{0,13}$$

Notation:

σ: Steel Hot Strength [kgf/mm²]

C: C content [weight %]

T: Absolute Temperature [K]

ϵ : True Strain

t : Time [s]

Source: MISAKA, Y. et al. *Formulation of Mean Resistance to Deformation of Plain C Steels at Elevated Temperature.*
Journal of the Japan Society for the Technology of Plasticity, 8, 79, 1967-1968, 414-422.

. Shida

Calculation algorithm expressed in Visual Basic:

```
Function Shida(C, T, Def, VelDef)  
  
Dim nShida, Td, g, Tx, mShida, SigF As Single  
  
nShida = 0.41 - 0.07 * C  
Td = 0.95 * (C + 0.41) / (C + 0.32)  
T = (T + 273) / 1000  
If T >= Td Then  
    g = 1  
    Tx = T  
    mShida = (-0.019 * C + 0.126) * T + (0.075 * C - 0.05)  
    Else  
        g = 30 * (C + 0.9) * (T - 0.95 * (C + 0.49) / (C + 0.42)) ^ 2 + (C + 0.06) / (C + 0.09)  
        Tx = Td  
        mShida = (0.081 * C - 0.154) * T + (-0.019 * C + 0.207) + 0.027 / (C + 0.32)  
End If  
SigF = 0.28 * g * Exp(5 / Tx - 0.01 / (C + 0.05))  
Shida = 2 / Sqr(3) * SigF * (1.3 * (Def / 0.2) ^ nShida - 0.3 * (Def / 0.2)) * _  
    (VelDef / 10) ^ mShida
```

End Function

Notation:

σ: Steel Hot Strength [kgf/mm²]

C: C content [weight %]

T: Temperature [°C]

Def: True Strain

VelDef: Strain Rate [s⁻¹]

Source: SHIDA, S. *Empirical Formula of Flow Stress of C Steels - Resistance to Deformation of C Steels at Elevated Temperature*. **Journal of the Japan Society for Technology of Plasticity**, 10:103, 1969, 610-7.

- Liquid Steel Solubility Products

. General

$$\log \frac{(a_A)^m (a_B)^n}{a_{A_m B_n}} = -\frac{A}{T} + B$$

Notation:

A_mB_n: Precipitate Considered for Calculation

a_x: Alloy Content [weight %]

T: Temperature [K]

A, B: Constants of the Solubility Product, given in the table below:

Precipitate	A	B	Source
MnS	8236	5.03	
TiN	16586	5.90	
TiS	8000	4.00	
ZrN	17000	6.38	

Notes:

- $a_{A_m B_n}$ is equal to one if the precipitate is pure.
- $a_{A_m B_n} \leq 1$ if there is co-precipitation with another element.

Sources:

- Values compiled by Rajindra Clement Ratnapuli from assorted references.

- Liquidus Temperature of Steels

$$T_{Liq} = 1536 - [78 C + 7,6 Si + 4,9 Mn + 34 P + 30 S + 5 Cu + 3,1 Ni + 1,3 Cr + 3,6 Al + 2 Mo + 2 V + 18 Ti]$$

Notation:

T_{Liq}: Steel Melting Temperature [°C]

Alloy Content: [weight %]

Source: GUTHMANN, K. *Günstige Giesstemperatur im Vergleich zum Erstarrungspunkt von Eisen- und Stahlschmelzen.*
Stahl und Eisen, 71(1951), 8, 399-402.

- Poisson Ratio

$$E = 2 G (1 + \nu)$$

Notation:

E: Young Modulus

G: Shear Modulus

v: Poisson Ratio

. Elastic Range: 0.3

. Plastic Range: 0.5

Sources:

- WILSON, A.D. *Guidelines for Fabricating and Processing Plate Steel*. Bethlehem-Lukens Plate Report, Burns Harbor, 2000, 97 p.

- Precipitate Solubilization Kinetics

$$t = \frac{r_0^2}{2 c D}$$

Notation:

A_mB_n: Spheric Precipitate Considered for Calculation

r₀: radius of the precipitate [m], [cm] or [mm]

$$c = \frac{C_i - C_m}{C_p - C_i} \cong \frac{C_i}{C_p}$$

C_i: Solute concentration in the precipitate/matrix interface [%]

$$C_i = \frac{10^{\left(\frac{-A}{T} + B\right)}}{a_B}$$

T: Temperature [K]

A, B: Constants of the Solubility Product, given in the table at the topic *Austenite Solubilization Products*.

A_B: Alloy content [weight percent]

C_p: Solute content in the precipitate [%]

$$C_p = \frac{m M_A}{m M_A + n M_B}$$

M_x : Atomic mass of the element [g]

C_m: Solute content in a position far away from the precipitate [%]

D: Solute Diffusion Coefficient, calculated according the equations given in the table below:

Element	Phase	Equation
C	Ferrite	$D \text{ [cm}^2/\text{s}] = 0.02 * \text{Exp}(-20100/RT)$
C	Ferrite	$D \text{ [m}^2/\text{s}] = 0.62 * 10^{-6} * \text{Exp}(-80400/R_1 T)$
C	Austenite	$D \text{ [m}^2/\text{s}] = 0.10 * 10^{-4} * \text{Exp}(-135700/R_1 T)$
Mn	Austenite	$D \text{ [mm}^2/\text{s}] = 140 * \text{Exp}(-286000/R_1 T)$
Mn	Austenite	$D \text{ [cm}^2/\text{s}] = 0.65 * \text{Exp}(-276000/R_1 T)$
P	Austenite	$D \text{ [mm}^2/\text{s}] = 51 * \text{Exp}(-230120/R_1 T)$
P	Austenite	$D \text{ [cm}^2/\text{s}] = 2.90 * \text{Exp}(-55000/RT)$
N	Ferrite	$D \text{ [cm}^2/\text{s}] = 6.6 * 10^{-3} * \text{Exp}(-18600/RT)$
N	Ferrite	$D \text{ [m}^2/\text{s}] = 0.50 * 10^{-6} * \text{Exp}(-77000/R_1 T)$
N	Austenite	$D \text{ [m}^2/\text{s}] = 0.91 * 10^{-4} * \text{Exp}(-168600/R_1 T)$
B	Austenite	$D \text{ [m}^2/\text{s}] = 2 * 10^{-4} * \text{Exp}(-87864/R_1 T)$
Nb	Austenite	$D \text{ [mm}^2/\text{s}] = 5.9 * 10^4 * \text{Exp}(-343000/R_1 T)$
Nb	Austenite	$D \text{ [m}^2/\text{s}] = 5.30 * 10^{-2} * \text{Exp}(-344600/R_1 T)$
Ti	Austenite	$D \text{ [m}^2/\text{s}] = 1.5 * 10^{-5} * \text{Exp}(-251000/R_1 T)$
V	Ferrite	$D \text{ [cm}^2/\text{s}] = 3.92 * \text{Exp}(-57600/RT)$
V	Austenite	$D \text{ [cm}^2/\text{s}] = 0.25 * \text{Exp}(-63100/RT)$
V	Ferrite	$D \text{ [m}^2/\text{s}] = 0.61 * 10^{-4} * \text{Exp}(-267100/R_1 T)$
V	Austenite	$D \text{ [m}^2/\text{s}] = 0.25 * 10^{-4} * \text{Exp}(-264200/R_1 T)$

Cr	Ferrite	$D \text{ [cm}^2/\text{s}] = 8.52 * \text{Exp}(-59900/RT)$
Cr	Austenite	$D \text{ [cm}^2/\text{s}] = 10.80 * \text{Exp}(-69700/RT)$
Al	Ferrite	$D \text{ [m}^2/\text{s}] = 0.30 * 10^{-2} * \text{Exp}(-234500/R_1 T)$
Al	Austenite	$D \text{ [m}^2/\text{s}] = 0.49 * 10^{-4} * \text{Exp}(-284100/R_1 T)$

Notes:

- $R = 1.981 \text{ cal/mol.K}$
- $R_1 = 8.314 \text{ J/mol.K}$

Source: Formulas and values compiled by Rajindra Clement Ratnapuli from assorted references.

- Solidus Temperature of Steels

$$T_{\text{Sol}} = 1536 - [415,5 C + 12,3 Si + 6,8 Mn + 124,5 P + 183,9 S + 4,3 Ni + 1,4 Cr + 4,1 Al]$$

Notation:

T_{Sol}: Steel Solidus Temperature [°C]

Alloy Content: [weight %]

Source: TAKEUCHI, E. & BRIMACOMBE, J.K. *Effect of Oscillation-Mark Formation on the Surface Quality of Continuously Cast Steel Slabs*. **Metallurgical Transactions B**, 16B, 9, 1985, 605-25.

- Relationships Between Chemical Composition x Process x Microstructure x Properties

. C-Mn Mild Steels

$$YS = 53.9 + 32.3 Mn + 83.2 Si + 354.2 \sqrt{N_{sol}} + \frac{17.4}{\sqrt{d}}$$

$$TS = 294.1 + 27.7 Mn + 83.2 Si + 2.85 Pearl + \frac{7.7}{\sqrt{d}}$$

$$\frac{d\sigma}{d\varepsilon} = 370 + 120 C + 23.1 Mn + 116 Si + 554 P + 143 Sn + 1509 N_{sol} + \frac{15.4}{\sqrt{d}}$$

$$\varepsilon_{unif} = 0.28 - 0.20 C - 0.25 Mn - 0.044 Si - 0.039 Sn - 1.2 N_{sol}$$

$$\varepsilon_{tot} = 1.40 - 2.90 C + 0.20 Mn + 0.16 Si - 2.2 S - 3.9 P + 0.25 Sn + \frac{0.017}{\sqrt{d}}$$

$$50\% ITT = -19 + 44 Si + 700 \sqrt{N_{sol}} + 2.2 Pearl - \frac{11.5}{\sqrt{d}}$$

$$\Delta Y = 12.32 - 19250 N_{sol} + 162 Mn + 462 O$$

Notation:

YS: Yield Strength at 0.2% Real Strain [MPa]

TS: Tensile Strength [MPa]

dσ/dε: Strain Hardening Coefficient at 0.2% Real Strain [1/MPa]

εunif: Uniform Elongation, Expressed as Real (Logarithmic) Strain

ϵ_{tot} : Total Elongation, Expressed as Real (Logarithmic) Strain

Pearl: Pearlite Fraction in Microstructure [%]

50% ITT: Impact Transition Temperature for 50% Tough Fracture [°C]

ΔY : Strain Ageing After 10 Days at Room Temperature [MPa]

Alloy Content: [weight %]

d: Grain Size [mm]

Source: PICKERING, F.B.: **Physical Metallurgy and the Design of Steels**. Allied Science Publishers, London, 1978, 275 p.

. C-Mn Steels Processed at a Hot Strip Mill

$$d = 11.5 - 2.2 (6 C + Mn + 30 P + 35 S + 23 Al + 0.01 (723 - T_{coil}) + 0.01 e_{tot} - 0.002 T_{fin} - 100 N_{sol})$$

$$Pearl = \alpha \frac{C_{eq} - 0.06}{0.78} 100$$

$$S_0 = \frac{0.1}{723 - T_{coil}}$$

$$YS = 99.08 (38.2 + \frac{0.016 Pearl}{\sqrt{S_0}} + 5.5 Mn + 43 Si + 114 P - 45 S + 31 \sqrt{N_{sol}} + \frac{12.6}{\sqrt{d}} - 0.02 T_{fin})$$

$$TS = 130.47 (19.8 + \frac{0.004 Pearl}{\sqrt{S_0}} + 8.03 Mn + 41.4 Si + 57.7 P - 69 S + 262 \sqrt{N_{sol}} + \frac{11.5}{\sqrt{d}})$$

$$\varepsilon = 100 \left(0.000096 \text{Pearl } S_0 - 0.05 \text{Mn} - 4.23 \text{P} - 4.36 \text{S} + 2.37 \text{Sn} - 1.16 \sqrt{N_{sol}} + \frac{0.12}{\sqrt{d}} + 0.0006 T_{fin} \right)$$

Notation:

- YS:** Yield Strength at 0.2% Real Strain [MPa]
- TS:** Tensile Strength [MPa]
- ε :** Total Elongation [%]
- d:** Ferrite Grain Size [μm]
- Alloy Content:** [weight %]
- T_{coil}:** Coiling Temperature [°C]
- e_{tot}:** Total Hot Rolling Conventional Strain [%]
- T_{fin}:** Finishing Temperature [°C]
- N_{sol}:** Solubilized (Free) Nitrogen [%]
- Pearl:** Pearlite Fraction Present in Microstructure [%]
- S₀:** Pearlite Lamellar Spacing [mm]

$$C_{eq} = C + \frac{Mn}{6} + \frac{Si}{24} - S$$

$$\alpha = \frac{T_{fin} - T_{coil}}{T_{fin}}$$

Notes:

- These equations are valid under the following conditions: **Slab Reheating Temperature:** 1250°C; **T_{fin}:** 850~880°C; **T_{coil}:** 615~650°C; **Final Thickness:** 1.8~4.0 mm; **C:** 0.08~0.18%; **Mn:** 0.40~1.00%; **P** < 0.020%; **S** < 0.020%; **Si** < 0.030%; **Al:** 0.020~0.050%; **N:** 0.0030~0.0090%.

Source: ARTIGAS, A. et al.: *Prediction de Propiedades Mecánicas y Microestructurales em Aceros Laminados em Caliente. Revista Metalurgica CENIM*, 38, 2002, 339-347.

. Hot/Cold Rolled and Annealed Mild Steel

$$d_{CR} = 0.013 + 0.28 d_{HR} \quad (\text{after } 60\% \text{ cold rolling and annealing})$$

$$d_{CR} = 0.011 + 0.29 d_{HR} \quad (\text{after } 70\% \text{ cold rolling and annealing})$$

$$YS = 3.37 + \frac{2.72}{\sqrt{d_{CR}}}$$

$$YS = 28.16 - 154 d_{HR}$$

$$\varepsilon_{yield} = 6.27 - 78.5 d_{CR}$$

$$n = 0.33 - \frac{0.01}{\sqrt{d_{CR}}}$$

Notation:

d_{CR}: Grain Size of Cold Rolled Strip [mm]

d_{HR}: Grain Size of Hot Rolled Strip [mm]

YS: Yield Strength at 0.2% Real Strain [MPa]

ε_{yield}: Yield Elongation [%]

n: Strain Hardening Coefficient Measured during Tension Test

Notes:

- These equations are valid under the following conditions: **C**: 0.005~0,10%; **Mn**: 0.40%; **P** < 0.016%; **S** < 0.026%; **Si** < 0.010%; **Al**: < 0.040%; **N**: 0.0020~0.0040%.
- Cold rolled steel was box annealed at 700°C; the time of treatment, including heating of the samples, was equal to 32 hours, being followed by furnace cooling.

Source: LANGENSCHEID, G. et al.: *Untersuchungen über den Einfluß der Korngröße des Warmbandes auf die Kaltbandeigenschaften*. **Hoesch Berichte aus Forschung und Entwicklung unserer Werke**, 2, 1971, 64-70.

. Mild Steel, Full Annealed

$$n = \frac{5}{10 + \frac{1}{\sqrt{d}}}$$

Notation:

n: Strain Hardening Coefficient Measured during Tension Test

d: Grain Size [mm]

Source: MORRISON, W.: *The Effect of Grain Size on the Stress-Strain-Relationship in Low-Carbon Steel*. **Transactions of the ASM**, 59, 1966, 824-845.

. C-Mn Steels with Ferrite-Pearlite Structure (including HSLA Steels)

$$YS = 246 + 4.15 \text{ Pearl} + 44.6 \text{ Mn} + 138 \text{ Si} + 923 \text{ P} + 169 \text{ Sn} + 3754 \text{ N}_{sol} + \frac{14.9}{\sqrt{d}}$$

$$TS = 492 - 3.38 \text{ Pearl} + 246 \text{ Mn} + 277 \text{ Si} - 2616 \text{ S} + 723 \text{ P} + 246 \text{ Cr} + 6616 \text{ N}_{sol} + \frac{44.6}{\sqrt{d}}$$

$$\frac{d\sigma}{d\varepsilon} = 385 + 1.39 \text{ Pearl} + 111 \text{ Si} + 462 \text{ P} + 152 \text{ Sn} + 1369 \text{ N}_{sol} + \frac{15.4}{\sqrt{d}}$$

$$\varepsilon_{unif} = 0.27 - 0.016 \text{ Pearl} - 0.015 \text{ Mn} - 0.040 \text{ Si} - 0.043 \text{ Sn} - 1.0 \text{ } N_{sol}$$

$$\varepsilon_{tot} = 1,30 - 0.020 \text{ Pearl} + 0.30 \text{ Mn} + 0.20 \text{ Si} - 3.4 \text{ S} - 4.4 \text{ P} + 0.29 \text{ Sn} + \frac{0.015}{\sqrt{d}}$$

$$T_{trans} = 43 + 1.5 \text{ Pearl} - 37 \text{ Mn} - \frac{6.2}{\sqrt{d}}$$

Notation:

YS: Yield Strength at 0.2% Real Strain [MPa]

TS: Tensile Strength [MPa]

dσ/dε: Strain Hardening Coefficient at 0.2% Real Strain [1/MPa]

ε_{unif}: Uniform Elongation, Expressed as Real (Logarithmic) Strain

ε_{tot}: Total Elongation, Expressed as Real (Logarithmic) Strain

Pearl: Pearlite Fraction in Microstructure [%]

T_{trans}: Fracture Appearance Transition Temperature [°C]

Alloy Content: [weight %]

d: Grain Size [mm]

Source: PICKERING, F.B.: *The Effect of Composition and Microstructure on Ductility and Toughness*; in: **Towards Improved Ductility and Toughness**, Climax Molybdenum Company, Tokyo, 1971, p. 9-32

. Microalloyed Steels (Pickering)

$$YS = \sigma_0 + 37 \text{ Mn} + 83 \text{ Si} + 2918 \text{ } N_{sol} + \frac{15.1}{\sqrt{d}} + \Delta\sigma_{ppt}$$

Notation:

YS: Yield Strength at 0.2% Real Strain [MPa]

σ_0 : Friction Stress [MPa]

Alloy Content: [weight %]

d : Grain Size [mm]

$\Delta\sigma_{ppt}$: Precipitation Strengthening [MPa], for steels with Nb, Ti and/or V, defined by the formula below [MPa].

Notes:

- The Friction Stress σ_0 value depends on the previous treatment of the material and can be found in the table below:

Condition	σ_0 [MPa]
Mean	70
Air Cooled	88
Overaged	62

- The effect of solid solution strengthening from another alloy elements solubilized in ferrite can be included in this equation, using the following linear coefficients:

Element	MPa/weight %
Ni	33
Cr	-30
P	680
Cu	38
Mo	11
Sn	120
C	5000
N	5000

- The precipitation strengthening contribution is calculated according to the Ashby-Orowan model.

$$\Delta\sigma_{ppt} = \frac{5.9 \sqrt{f}}{\bar{x}} \ln \left(\frac{\bar{x}}{2.5 \times 10^{-4}} \right)$$

Notation:

$\Delta\sigma_{ppt}$: Precipitation Strengthening According to the Ashby-Orowan Model [MPa]

f: Volume Fraction of the Precipitate

x: Mean Planar Intercept Diameter of the Precipitate [μm]

Notes:

- Relationship adequate for the calculation of the precipitation strengthening of quench-aged carbides and precipitate carbonitrides in Nb, V and Ti steels.
- $\Delta\sigma_{ppt}$ can be calculated using a more simplified approach, multiplying the total content of the precipitating alloy by the factor **B** shown in the table below:

Alloy and Precipitate	B _{max} [MPa/weight %]	B _{min} [MPa/weight %]	Alloy Range [weight %]
V as V ₄ C ₃	1000	500	0,00 ~ 0,15
V as VN	3000	1500	0,00 ~ 0,06
Nb as Nb(CN)	3000	1500	0,00 ~ 0,05
Ti as TiC	3000	1500	0,03 ~ 0,18

Source: PICKERING, F.B. *Some Aspects of the Relationships between the Mechanical Properties of Steels and their Microstructures*. **TISCO**. Silver Jubilee Volume, Jan-Oct 1980, 105-132.

. Microalloyed Steels (Hodgson)

$$YS = 62.6 + 26.1 Mn + 60.2 Si + 759.0 P + 212.9 Cu + 3286.0 N_{sol} + \frac{19.7}{\sqrt{d}} + \Delta\sigma_{ppt}$$

$$TS = 164.9 + 634.7 C + 53.6 Mn + 99.7 Si + 651.9 P + 472.6 Ni + 3339.4 N_{sol} + \frac{11.0}{\sqrt{d}} + \Delta\sigma_{ppt}$$

$$\Delta\sigma_{ppt} = 57 \log CR + 700 V + 7800 N_{sol} + 19$$

Notation:

YS: Yield Strength at 0.2% Real Strain [MPa]

TS: Tensile Strength [MPa]

Alloy Content: [weight %]

d: Grain Size [mm]

$\Delta\sigma_{ppt}$: Precipitation Strengthening [MPa], only for steels with V [MPa]

CR: Cooling Rate [°C/s]

Source: HODGSON, P.D. & GIBBS, R.K. *A Mathematical Model to Predict the Mechanical Properties of Hot Rolled C-Mn and Microalloyed Steels.* **ISIJ International**, 32:12, December 1992, 1329-1338.

. V-Ti-N Steels Processed by Recrystallization Controlled Rolling

$$YS = 41.4 + 575.20 C_{eq} + (27401 N_{ef} - 2) \sqrt{V} + \frac{419.5}{\sqrt{h_f}}$$

$$TS = 74.1 + 985.1 C_{eq} + (31125 N_{ef} - 39) \sqrt{V} + \frac{181.5}{\sqrt{h_f}}$$

Notation:

YS: Yield Strength at 0.2% Real Strain [MPa]

TS: Tensile Strength [MPa]

Alloy Content: [weight %]

h_f: Plate Thickness [mm]

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

$$N_{ef} = N_{tot} - \frac{Ti}{3.42}$$

Notes:

- Formula Derived for Steels with Al Content over 0.010% and Si Content between 0.25 and 0.35%.
- Precision of the Formulas: ± 40 MPa.

Source: MITCHELL, P.S. et al.: *Effect of Vanadium on Mechanical Properties and Weldability of Structural Steels*. In: **Low Carbon Steels for the 90's**. Proceedings. American Society for Metals/The Metallurgical Society, Pittsburgh, Oct. 1993.

. Dual Phase Steels

$$YS = 203 + 855 \sqrt{\frac{1}{L_{\alpha\alpha}}}$$

$$TS = 266 + 548 \sqrt{\frac{1}{L_{\alpha\alpha}}} + 1741 \sqrt{\frac{f_\beta}{d_\beta}}$$

$$\frac{d\sigma}{d\varepsilon} = 266 + 548 \sqrt{\frac{1}{L_{\alpha\alpha}}} + 1741 \sqrt{\frac{f_\beta}{d_\beta}}$$

$$\varepsilon_{unif} = 32 - 64 \sqrt{\frac{1}{L_{\alpha\alpha}}}$$

Notation:

LE: Yield Strength [MPa]

LR: Tensile Strength [MPa]

dσ/dε: Strain Hardening Coefficient at Uniform Elongation [1/MPa]

a_{unif}: Uniform Elongation [%]

L_{αα}: Mean Ferritic Free Path [μm]

d_β: Mean Diameter of Martensite Islands [μm]

Sources:

- GORNI, A.A. & BRANCHINI, O.L.G. *Análise da Evolução do Encruamento de um Aço Bifásico*. In: **4º Simpósio de Conformação Mecânica**, EPUSP/UNICAMP/ABAL, São Paulo, Nov. 1990, 23-42.
- GORNI, A.A. & BRANCHINI, O.L.G. *Relações Microestrutura-Propriedades Mecânicas em um Aço Bifásico Laminado a Quente*. In: **1º Seminário sobre Chapas Metálicas para a Indústria Automobilística**, ABM/AEA, São Paulo, Set. 1992, 127-145.

. Acicular Ferrite/Low Carbon Bainite Steels

$$YS = 88 + 37 Mn + 83 Si + 2900 N_{sol} + \frac{15.1}{\sqrt{d_L}} + \sigma_{disc} + \sigma_{ppt}$$

$$TS = 246 + 1900 C + 230 (Mn + Cr) + 185 Mo + 90 W + 125 Ni + 65 Cu + 385 (V + Ti)$$

$$ITT = -19 + 44 Si + 700 \sqrt{N_{sol}} + 0.26 (\sigma_{disc} + \sigma_{ppt}) - \frac{11.5}{\sqrt{d}}$$

Notation:

YS: Yield Strength at 0.2% Real Strain [MPa]

TS: Tensile Strength [MPa]

ITT: Impact Transition Temperature for 50% Tough Fracture [°C]

Alloy Content: [weight %]

N_{sol}: Solubilized (Free) Nitrogen [%]

d_L: BainiteFerrite Lath Size [mm]

σ_{disc}: Strength Due to Dislocations [MPa]

σ_{ppt}: Precipitation Strengthening According to the Ashby-Orowan Model [MPa]

N_{sol}: Solubilized (Free) Nitrogen [%]

d: Mean Spacing between High Angle Boundaries (“Packet” or Prior Austenite Grain Boundaries)

$$\Delta\sigma_{disc} = \alpha \mu b \sqrt{\rho} = 1.2 \times 10^{-3} \sqrt{\rho} \text{ (PICKERING) or } 8 \times 10^{-4} \sqrt{\rho} \text{ (KEH)}$$

$$\Delta\sigma_{ppt} = \frac{5.9 \sqrt{f}}{\bar{x}} \ln \left(\frac{\bar{x}}{2.5 \times 10^{-4}} \right)$$

Notation:

α: Empirical Constant

μ: Shear Modulus [MPa]

b: Burger's Vector [cm]

ρ: Dislocation Density [lines/cm²]

f: Volume Fraction of the Precipitate

x: Mean Planar Intercept Diameter of the Precipitate [μm]

Sources:

- PICKERING, F.B. *Some Aspects of the Relationships between the Mechanical Properties of Steels and their Microstructures*. **TISCO**. Silver Jubilee Volume, Jan-Oct 1980, 105-132.

- KEH, A.S., *Work Hardening and Deformation Sub-Structure in Iron Single Crystals in Tension at 298K*, **Philosophical Magazine**, 12:115, 1965, 9-30.

. Medium C Steels

$$YS = \sqrt[3]{f_\alpha} \left(35 + 58 Mn + \frac{17.4}{\sqrt{d}} \right) + \left(1 - \sqrt[3]{f_\alpha} \right) \left(178 + \frac{3.8}{\sqrt{S_0}} \right) + 63 Si + 42 \sqrt{N_{sol}}$$

$$TS = \sqrt[3]{f_\alpha} \left(246 + 1140 \sqrt{N_{sol}} + \frac{18.2}{\sqrt{d}} \right) + \left(1 - \sqrt[3]{f_\alpha} \right) \left(720 + \frac{3.5}{\sqrt{S_0}} \right) + 97 Si$$

$$ITT = f_\alpha \left(-46 - \frac{11.5}{\sqrt{d}} \right) + \left(1 - f_\alpha \right) \left[-335 + \frac{5.6}{\sqrt{S_0}} - \frac{13.3}{\sqrt{p}} + 3.48 \times 10^6 t \right] + 48.7 Si + 762 \sqrt{N_{sol}}$$

Notation:

YS: Yield Strength at 0.2% Real Strain [MPa]

TS: Tensile Strength [MPa]

ITT: Impact Transition Temperature for 50% Tough Fracture [°C]

f: Volume Fraction of Ferrite

d: Ferrite Grain Size [mm]

Alloy Content: [weight %]

N_{sol}: Solubilized (Free) Nitrogen [%]

S₀: Pearlite Lamellar Spacing [mm]

p: Pearlite Colony Size [mm]

t: Pearlitic Carbide Lamellar Thickness [mm]

Sources:

- GLADMAN, T. e outros. *Some Aspects of the Structure-Property Relationships in High Carbon Ferrite-Pearlite Steels.* **Journal of the Iron and Steel Institute**, 210, Dec. 1972, 916-930.
- PICKERING, F.B. *Some Aspects of the Relationships between the Mechanical Properties of Steels and their Microstructures.* **TISCO**. Silver Jubilee Volume, Jan-Oct 1980, 105-132.

. Si Non-Oriented Electrical Steels

$$YS = 34.3 + \frac{22.0}{\sqrt{d}} + 258 P + 34.2 Mn + 52.8 Si$$

$$TS = 183 + \frac{11.2}{\sqrt{d}} + 506 P + 48.7 Mn + 109 Si + 48.8 Al + 2450 B$$

$$YR = 0.424 + \frac{0.0412}{\sqrt{d}} - 0.078 Si - 0.170 Al$$

Notation:

YS: Lower Yield Strength [MPa]

TS: Tensile Strength [MPa]

YR: Yield Ratio

d: Ferrite Grain Size [mm]

Alloy Content: [weight %]

Notes:

- These equations are valid under the following conditions: **ULC Steel**; **Mn**: 0.075~0.578%; **P** < 0.109%; **S**: 0.003~0.004%; **Si** < 0.34%; **Al**: < 0.432%; **N**: 0.0014~0.0020%; **B** < 0.0030%.
- Cold rolled steel was box annealed at 700°C; the time of treatment, including heating of the samples, was equal to 32 hours, being followed by furnace cooling.

Source: PINOY, L et al. *Influence of Composition and Hot Rolling Parameters on the Magnetic and Mechanical Properties of Fully Processed Non-Oriented Low-Si Electrical Steels.* **J. Phys. IV France**, 8, 1998, Pr2-487/Pr2-490.

$$P_T = 0.658 - 0.474 Si - 2.311 Al - 25.99 O + 12.51 C + 123.7 S_{init} + 130.2 \Delta S - 137.5 N + 5.266 h$$

Notation:

P_T: Core Loss [W/kg]

Alloy Content: [weight %]

h: Thickness [mm]

Notes:

- This equation is valid under the following conditions: **C**: 0.002~0.040%; **S**: 0.004~0.015%; **N**: 0.003~0.007%.
- Negative effects of O and N are in direct contradiction with specific experimental results.
- Adjusted Squared Multiple Correlation: 0.823; Residual Mean Square: 0.082 W²/kg²

$$P_T = 4.29 + 66.4 C + 0.0282 GBI + 16.2 \frac{h^2}{\rho r}$$

Notation:

P_T: Total Core Loss at 15 KG [W/kg]

Alloy Content: [weight %]

GBI: Number of Grain Boundary Intercepts per mm

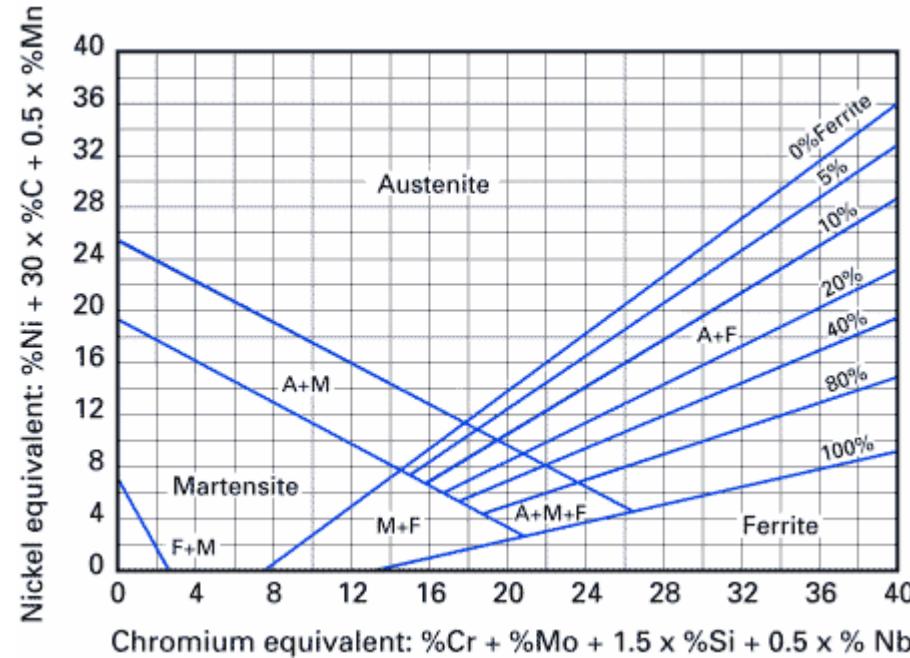
h: Thickness [mm]

ρ: Density [g/mm³]

r: Resistivity [μΩ.mm]

Source: LYUDKOVSKY, G. et al. *Non-Oriented Electrical Steels*. **Journal of Metals**, January 1986, 18-26.

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- Schaeffler Diagram

Source: Air Products Web Site

(<http://www.airproducts.com/maxx/software/UK/WeldingFaultFinder/wff22413.html>).

- Shear Modulus of Steel and its Phases**. Ferrite**

$$\mu = 64000 \left[1 - \frac{(T - 300)}{2235} \right] \quad (-273^{\circ}\text{C} < T < 300^{\circ}\text{C})$$

$$\mu = 64000 \left[1 - \frac{(T - 300)}{2235} \right] - 0.032 (T - 573)^2 \quad (300^{\circ}\text{C} \leq T < 700^{\circ}\text{C})$$

$$\mu = 64000 \left[1 - \frac{(T - 300)}{2235} \right] - 0.032 (T - 573)^2 - 0.024 (T - 923)^2 \quad (700^{\circ}\text{C} \leq T < 770^{\circ}\text{C})$$

$$\mu = 69200 \left[1 - \frac{(T - 300)}{1382} \right] \quad (770^{\circ}\text{C} \leq T < 911^{\circ}\text{C})$$

. Austenite

$$\mu = 81000 \left[1 - \frac{(T - 300)}{1989} \right] \quad (911^{\circ}\text{C} \leq T < 1392^{\circ}\text{C})$$

. Delta Ferrite

$$\mu = 39000 \left[1 - \frac{(T - 300)}{2514} \right] \quad (1392^{\circ}\text{C} \leq T < 1537^{\circ}\text{C})$$

Notation:

μ : Shear Modulus [MPa]

T : Temperature [K]

Source: FROST, H.J. & ASHBY, M.F.: *Pure Iron and Ferrous Alloys*. In: **Deformation-Mechanism Maps, The Plasticity and Creep of Metals and Ceramics**. Pergamon Press, Cambridge, 1982.

- **Thermal Properties of Steel**

. **Seredynski**

$$k = -58.6 \times 10^{-3} T + 72.5 \quad (T < 810^\circ\text{C})$$

$$k = 10.75 \times 10^{-3} T + 16.8 \quad (T > 810^\circ\text{C})$$

Notation:

k: Conductivity [J/m.°C.s]

T: Temperature [°C]

$$D = 0.15 \times 10^{-7} T - 0.07825 \times 10^{-4} \quad (700^\circ\text{C} < T < 875^\circ\text{C})$$

$$D = 0.02667 \times 10^{-7} T - 0.02966 \times 10^{-4} \quad (T > 875^\circ\text{C})$$

Notation:

D: Diffusivity [m²/s]

T: Temperature [°C]

$$\varepsilon = \frac{T}{1000} \left(0.12491 \frac{T}{1000} - 0.38012 \right) + 1.0948$$

Notation:

ε: Emissivity

T: Temperature [°C]

Note:

- Formulas specific for BS En 3 or SAE 1021 steel: 0.17-0.23% C; 0.60-0.90% Mn

Source: SEREDYNSKI, F.: *Performance Analysis and Optimization of the Plate-Rolling Process*. In: **Mathematical Process Models in Iron and Steelmaking**. Proceedings. Iron and Steel Institute, Amsterdam, 1973.

. Touloukian

$$\varepsilon = \frac{0,85}{[1 + \exp(42.68 - 0,02682 T_{\text{sup}})^{0,0115}]} \quad \boxed{\quad}$$

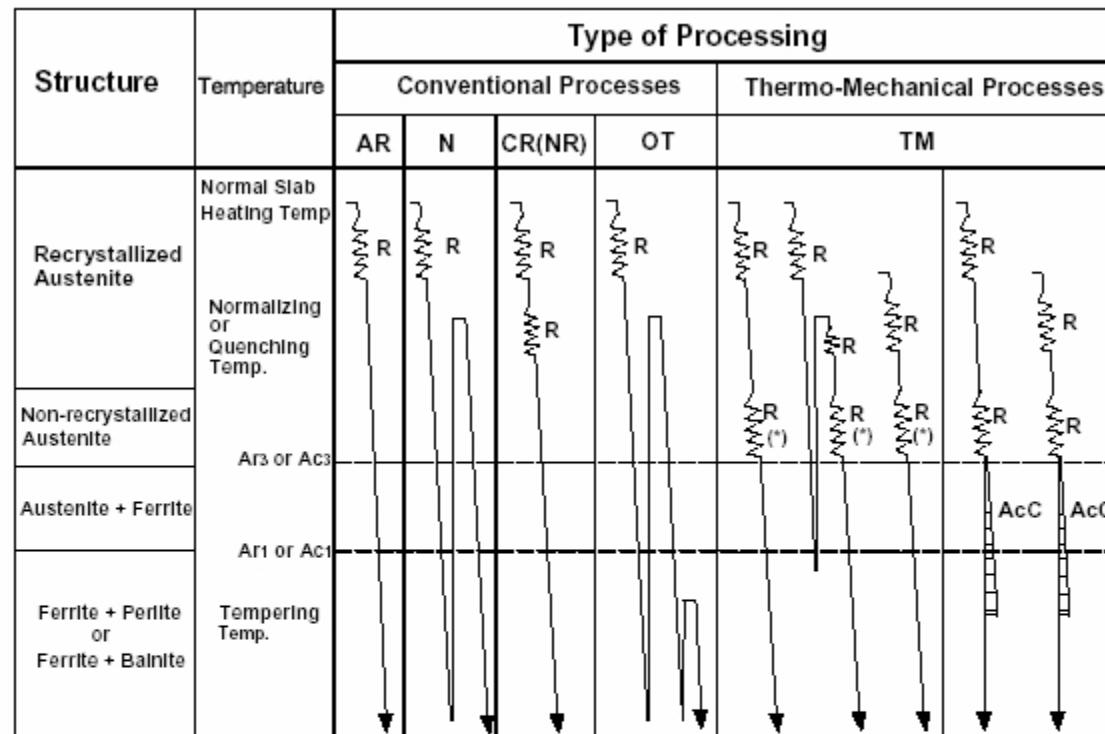
Notation:

ε : Emissivity

T_{sup} : Superficial Temperature [K]

Source: HARDIN, R.A. et al.: *A Transient Simulation and Dynamic Spray Cooling Control Model for Continuous Steel Casting*. **Metallurgical and Materials Transactions B**, 34B:6, June 2003, 297-306.

- Thermomechanical Processing of Steel



Notes:

- AR: As Rolled
- N: Normalizing
- CR(NR): Controlled Rolling (Normalizing Rolling)
- QT: Quenching and Tempering
- TM: Thermo-Mechanical Rolling (Thermo-Mechanical Controlled Process)
- R: Reduction
- (*): Sometimes rolling in the dual-phase temperature region of austenite and ferrite
- Acc: Accelerated Cooling

Source: *Requirements Concerning Materials and Welding. IACS - International Association of Classification Societies Requirement 1975*, Revision 2, 2004, 228 p.

- Time-Temperature Equivalency Parameters for Heat Treating

. Anisothermal Austenitizing

In this case the Austenitization Time-Temperature Equivalence Parameter in Terms of Grain Size, P_a , is the period of heating/cooling time between T_{\max} and T_{\min} , where

T_{\max} : Maximum Temperature during the Austenitizing Treatment [°C];

T_{\min} : Temperature Calculated According to the Following Equation [°C]:

$$T_{\min} = T_{\max} - \frac{R T_{\max}^2}{\Delta H_a}$$

Notation:

R : Molar Gas Constant, $8.314 \text{ JK}^{-1}\text{mol}^{-1}$

ΔH_a : Activation Energy of Austenitic Grain Coarsening, 460 kJmol^{-1} for low alloy steels

Source: BARRALIS, J. & MAEDER, G. *Métallurgie Tome I: Métallurgie Physique. Collection Scientifique ENSAM*, 1982, 270 p.

. Isothermal Austenitizing

$$P_a = \frac{1}{\left[\frac{1}{T_a} - \frac{2,3 R}{\Delta H_a} \log t_a \right]}$$

Notation:

P_a : Austenitization Time-Temperature Equivalence Parameter in Terms of Grain Size [K]

T_a: Austenitization Temperature [K]

R: Molar Gas Constant, 8.314 JK⁻¹mol⁻¹

t_a: Soaking time under **T_a**

ΔH_a: Activation Energy of Austenitic Grain Coarsening, 460 kJmol⁻¹ for low alloy steels

Source: BARRALIS, J. & MAEDER, G. *Métallurgie Tome I: Métallurgie Physique*. Collection Scientifique ENSAM, 1982, 270 p.

. Microstructural Banding Homogenization

$$t_{0.05} = \frac{0.3 l^2}{D_0 e^{\frac{-Q}{RT}}}$$

Notation:

t_{0.05}: Treatment Time Necessary to Achieve 5% Microstructure Banding [min]

l: Mean Spacing between Bands [mm]

D₀: Diffusion Constant for the Alloy Element being Considered [cm²/s]:

- P: 0.01 cm²/s
- Mn: 0.16 cm²/s

Q: Activation Energy for the Alloy Element Being Considered [cal/mol]:

- P: 43700 cal/mol
- Mn: 62500 cal/mol

R: Molar Gas Constant, 1.987 JK⁻¹mol⁻¹

T: Austenitization Temperature [K]

Source: YIMING, X. et al.: *A Metallographic Investigation of Banding and Diffusion of Phosphorus in Steels*. **Microstructural Science**, 20, 1993, 457-470.

. Tempering (Hollomon-Jaffe)

$$P = T (c + \log t)$$

$$c = 21.53 - 5.8 C$$

Notation:

P: Hollomon-Jaffe Parameter [K]

T: Tempering Temperature [K]

c: Constant Characteristic of the Steel Being Tempered

t: Soaking time under **T** [h]

C: Carbon Content [wt%]

Notes:

- Other values for the constant **c** were proposed by several authors for carbon, microalloyed and low alloy steels:
 - . 18 (Grange & Baughman)
 - . 20 (Larson & Miller, Irvine et al., Thelning)
- This expression was also deduced by Larson & Miller, which applied it to the study of metal creep. In that case **c** is equal to 20 and **P** is divided by 1000. Such relationship was also used for the study of hydrogen resistance and HAZ hardness of steels.

Sources:

- HOLLOWOM, J.H. & JAFFE, L.D. *Time-Temperature Relations in Tempering Steel*. **Transactions of the AIME**, 162, 1945, 223-249.
- LARSON, F.R. & MILLER, J. *A Time-Temperature Relationship for Rupture and Creep Stresses*. **Transactions of the American Society of Mechanical Engineers**, 74, 1952, 765-775.
- GRANGE, R.A. & BAUGHMAN, R.W. *Hardness of Tempered Martensite in Carbon and Low Alloy Steels*. **Transactions of the American Society for Metals**, 68, 1956, 165-197.
- THELNING, K.E.: *Steel and its Heat Treatment – Bofors Handbook*. Butterworths, London, 1981, 570 p.;

- IRVINE, K.J. et al. *Grain-Refined C-Mn Steels*. **Journal of the Iron and Steel Institute**, Feb. 1967, 161-182.

- Welding Effects

. Weld Interface Cracking Susceptibility during Flash Butt Welding

$$F_{eq} = (C - 0.03) \left[Si^2 + \left(\frac{Mn}{10} \right)^2 + (4 Al)^2 + \left(\frac{3 Cr}{2} \right)^2 \right]$$

Notation:

F_{eq}: Weld Interface Cracking Susceptibility during Flash Butt Welding (No Crack = Zero)

Alloy Content: [weight %]

Source: MIZUI, M. et al.: *Application of High-Strength Steel Sheets to Automotive Wheels*. **Nippon Steel Technical Report**, 23, June 1984, 19-30.

. Tensile Strength after Flash Butt Welding

$$TS_{eq} = 52 \left(C + \frac{Mn}{5} + \frac{Si}{7} + \frac{Cr}{9} + \frac{V}{2} \right) + 30$$

Notation:

TS_{eq}: Tensile Strength After Flash Butt Welding [kgf/mm²]

Alloy Content: [weight %]

Source: MIZUI, M. et al.: *Application of High-Strength Steel Sheets to Automotive Wheels*. **Nippon Steel Technical Report**, 23, June 1984, 19-30.

APENDIXES

USEFUL DATA AND CONSTANTS

Fuels and Combustion Gases:

- Density (Gas)

- . Natural Gas: 0.81 kg/Nm³
- . Butane: 2.44 kg/Nm³
- . Propane: 1.85 kg/Nm³
- . Liquified Petroleum Gas (LPG): 2.29 kg/Nm³
- . Air: 1.27 kg/Nm³

- Density (Liquid)

- . Butane: 0.58 kg/l
- . Propane: 0.51 kg/l
- . Liquified Petroleum Gas (LPG): 0.54 kg/Nm³
- . Water: 1.00 kg/Nm³

- Heat Capacity in Function of Temperature

- . Heat Capacity [kcal/°C m³] = a + bT [°C]. Values of **a** and **b** for some gases are seen below:

Gas	a	b
C ₂ H ₆	0.600	0.000540
C ₃ H ₈	0.871	0.001226
CH ₄	0.380	0.000210
CO	0.302	0.000022
CO ₂	0.406	0.000090

H ₂	0.301	0.000200
N ₂	0.302	0.000022
O ₂	0.320	0.000059

- **Net Heating Value**

- . Acetylene (C₂H₂): 13412 Kcal/Nm³
- . Basic Oxygen Steelmaking Off-Gas (OG Gas): 770 kcal/Nm³
- . Blast Furnace Gas: 770 Kcal/Nm³
- . Benzene (C₆H₆): 33,823 Kcal/Nm³
- . Butane (C₄H₁₀): 29,560 Kcal/Nm³
- . Butene/Butylene (C₄H₈): 27,900 Kcal/Nm³
- . Charcoal: 6,800 kcal/kg
- . Carbon Monoxide (CO): 3,019 Kcal/Nm³
- . Coke Oven Gas: 4,400 Kcal/Nm³
- . Diesel Oil: 10.200 kcal/kg
- . Electricity: 860 kcal/kW
- . Ethane (C₂H₆): 15,236 Kcal/Nm³
- . Ethene/Ethylene (C₂H₄): 14,116 Kcal/Nm³
- . Fuel Oil: 8,640~9,000 kcal/l or 9,600 ~ 10,000 kcal/kg
- . Hexane (C₆H₁₄): 41,132 Kcal/Nm³
- . Hydrogen (H): 2,582 Kcal/Nm³
- . Hydrogen Sulfide (H₂S): 5,527 Kcal/Nm³
- . i-Butane (C₄H₁₀): 28,317 Kcal/Nm³
- . i-Pentane (C₅H₁₂): 34,794 Kcal/Nm³
- . Liquified Petroleum Gas (LPG): 25,300 ~ 27,300 kcal/Nm³
- . Methane (CH₄): 8,557 Kcal/Nm³
- . Natural Gas: 9,000 ~ 9,400 Kcal/Nm³
- . Pentane (C₅H₁₂): 34,943 Kcal/Nm³
- . Propane (C₃H₈): 21,809 Kcal/Nm³
- . Propene/Propylene (C₃H₆): 20,550 Kcal/Nm³
- . Toluene (C₇H₈): 40,182 Kcal/Nm³

- . Xylene (C_8H_{10}): 46,733 Kcal/Nm³
- . Wood: 2,500 kcal/kg

- **Typical Chemical Compositions**

[% vol]	N₂	H₂	CH₄	C₂H₆	C₃H₈	CO	CO₂	O₂
Coke Oven Gas	3.09	61.55	24.54	0.42	0.06	8.04	0.00	0.26
Natural Gas	1.83	----	87.91	7.08	1.91	----	0.59	0.00

Mathematical Constants

- e: 2.718281828
- Pi: 3.141592654

Physical Constants

- Acceleration of gravity: $g = 9.805 \text{ m/s}^2$
- Avogadro constant: $N_A = 6.022 \times 10^{23} / \text{mol}$
- Boltzmann constant: $k = 1.381 \times 10^{-23} \text{ J/K}$
- Gas constant R:
 - . $1.98717 \text{ cal K}^{-1} \text{ mol}^{-1}$
 - . $82.056 \text{ cm}^3 \text{ atm K mol}^{-1}$
 - . $0.082056 \text{ atm K}^{-1} \text{ mol}^{-1}$
 - . $8.31433 \times 10^7 \text{ erg K}^{-1} \text{ mol}^{-1}$
 - . $8.31433 \text{ J K}^{-1} \text{ mol}^{-1}$

Physical Properties of Scale (Iron Oxide)

- Density: 4.86 g/cm³ (Source: Combustol)
- Hardness:
 - . Hematite (Fe₂O₃): 1000 HV
 - . Magnetite (Fe₃O₄): 320 ~ 500 HV
 - . Wustite (FeO): 270 ~ 350 HV
- Iron Content in Scale: 74.6% (Stoichiometric)
- Linear Coefficient of Thermal Contraction:
 - . Fe: 19 x 10⁻⁶ m/°C
 - . Wustite: 14 x 10⁻⁶ m/°C
- Melting Point:
 - . Fayalite (2FeO.SiO₂): 1177°C

Physical Properties of Steel and its Microstructural Constituents

- Densities:
 - . Bulk Steel: 7850 kg/m³
 - . Ferrite (Fe α): 7687 kg/m³
 - . Cementite (Fe₃C): 7882 kg/m³
 - . NbC: 7790 kg/m³
 - . VC: 5700 kg/m³
- Electrical Resistivity at 15.6°C: 17 x 10⁻⁸ ohm.m
- Emissivity of Polished Metal Surface:
 - . 0.07 @ 38°C
 - . 0.10 @ 260°C
 - . 0.14 @ 540°C
- Emissivity of Oxidized Steel Plate at 15.6°C: 0.80
- Linear Coefficient of Thermal Expansion: 11.7 x 10⁻⁶ 1/°C
- Melting Point: 1300 ~ 1450°C
- Modulus:
 - . Bulk: 159,000 MPa

- . Shear: 83,000 MPa
- . Young: 207,000 MPa
- Poisson's Ratio:
 - . Elastic Range: 0.3
 - . Plastic Range: 0.5
- Specific Heat: 0.12 cal/g. $^{\circ}$ C
- Speed of Sound through Steel: 5490 m/s
- Thermal Conductivity at 15.6 $^{\circ}$ C: 58.9 W/m.K
- Volumetric Coefficient of Thermal Expansion: $35.1 \times 10^{-6} \text{ } 1/\text{ } ^{\circ}\text{C}$

Sources:

- ANON.: *Practical Data for Metallurgists*. The Timken Company, Canton, September 2006, 130 p.
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- METNUS, G.E. et al. **Comparing CO₂ Emissions and Energy Demands for Alternative Ironmaking Routes**. *Steel Times International*, March 2006, 32-36.
- WILSON, A.D. *Guidelines for Fabricating and Processing Plate Steel*. Bethlehem-Lukens Plate Report, Burns Harbor, 2000, 97 p.

UNIT CONVERSIONS

From	Multiply by	To
A	10^{-10}	m
bar	1.019716	kg/cm ²
BTU	1058.201058	J
cal	4.184	J
F	5/9 ($^{\circ}\text{F}-32$)	$^{\circ}\text{C}$
ft	12	inch
ft	0.30485126	m
ft.lb	1.356	J ou N.m
ft.lb	0.324	cal
ft.lb	1.355748373	J
ft.lb/s	1.355380862	W
ft.lbf	1.355818	J ou N.m
ft.lbf	0.1382	kg
ft ²	92.90×10^{-3}	m ²
ft ³	0.02831685	m ³
HP	0.7456999	kW
HP	745,7121551	W
in	25.4	mm
in ²	645.2	mm ²
in ³	16387.064	mm ³
inch	25.4	mm
J	9.45×10^{-4}	BTU
J	0.2390	cal
J	0.7376	ft.lb
kg	2.205	lb
kgf	9.80665	N
kgf.m	9.80665	J

From	Multiply by	To
kgf/mm ²	9.80665	MPa
kN	224.8	lbf
kN/mm	5.71×10^3	lbf/ft
ksi	6.894757	MPa
ksi	1000	psi
Ksi. $\sqrt{\text{in}}$	1.098901099	MPa. $\sqrt{\text{m}}$
kW	1.341022	HP
lb	0.4535924	kg
lb.in	0.1129815	J ou N.m
lb/ft ³	0.016020506	g/cm ³
lb/in ³	27.67783006	g/cm ³
lbf	4.448222	N
lbf/in ²	1	psi
long ton	1016.047	kg
M	10^{10}	A
m	3.281	ft
m ²	10.76	ft ²
mm	0.0394	in
mm ²	1.550×10^{-3}	in ²
MPa	1	N/mm ²
MPa	0.145	ksi
MPa	145	lbf/in ²
MPa $\sqrt{\text{m}}$	0,920	ksi $\sqrt{\text{in}}$
N.m	1	J
oz	0.028352707	kg
Pa	1	N/m ²
Pa	$1,449 \times 10^{-4}$	Psi

From	Multiply by	To
Pa	$1,020 \times 10^{-7}$	Kg/mm ²
pct (%)	10000	ppm
ppm	0.0001	%
psi	0.001	Ksi
psi	0.0068947573	MPa
psi	0.0007030697	kgf/mm ²

From	Multiply by	To
Rad	57.2958	°
Short Ton	907.1847	Kg
W	1	J/s
W	0,001341	HP

GENERAL STATISTICAL FORMULAS

- Correlation Coefficient

$$r = \pm \sqrt{\frac{\sum (Y_{est} - \bar{Y})^2}{\sum (Y - \bar{Y})^2}}$$

Notation:

r: Correlation Coefficient

Y: Raw Data

Y_{est}: Estimated Data Calculated by the Fitted Equation

\bar{Y} : Mean of the Raw Data

Source: SPIEGEL, M.R. **Estatística**, Editora McGraw-Hill do Brasil Ltda., São Paulo, 1976, 580 p.

- Standard Error of Estimation

$$\sigma = \sqrt{\frac{\sum (Y_{est} - \bar{Y})^2}{n}}$$

Notation:

σ: Standard Error of Estimation

Y_{est}: Estimated Data Calculated by the Fitted Equation

\bar{Y} : Mean of the Raw Data

n: Number of Points of Data

Source: SPIEGEL, M.R. **Estatística**, Editora McGraw-Hill do Brasil Ltda., São Paulo, 1976, 580 p.