HARDNESS OF THE HEAT AFFECTED ZONE

MAT E 481/681
FALL 2020

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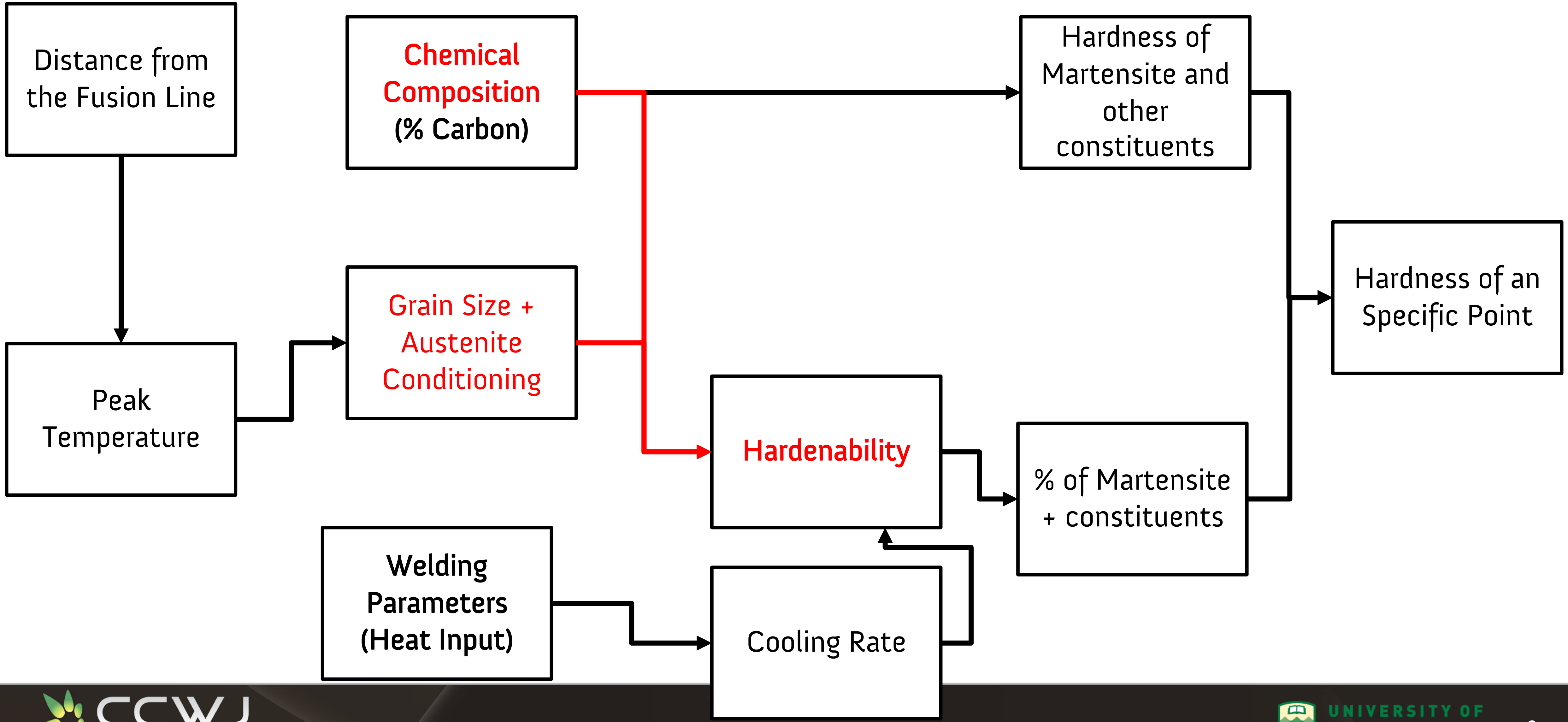
Hardness after the Heat Affected Zone



Hardenability

ASM Handbook Volume 4 A

Hardenability refers to the ability of steel to obtain satisfactory hardening to some desired depth when cooled under prescribed conditions. Hardening is achieved by transformation of austenite to martensite, and the extent of martensite formation depends on the necessary cooling rate to rapidly cool austenitized steel below the martensite-start temperature without significant transformation of austenite into pearlite or other transformation products (see the preceding article, "Introduction to Steel Heat Treatment," in this Volume). Thus, steels that exhibit deep hardening (martensite formation) are considered to have high hardenability, while those that exhibit shallow martensitic hardening are of low hardenability.

- Austenite Chemical Composition
- Austenite Grain Size
- Second Phases present

Prediction of the Hardness after the Heat Affected Zone

Experimental

Empirical Formulas

Computational Calculations

- CCT diagrams for Welding.
    - You will not always find the right diagram for your material.
- Experiments (*weld coupons, dilatometry, Gleeble®, etc*) cost more time and money but it's the most accurate approach.
    - Each experiment is unique chemical composition, minimal addition of certain alloying elements can have a significant effect on the hardenability.

Prediction of the Hardness after the Heat Affected Zone

Experimental

Empirical Formulas

Computational Calculations

- **Simple and free Formulas** derived from the statistical evaluation of experiments. Can be used in a spreadsheet to have an **immediate estimation** of the **HAZ**
- Several models available in literature. Usually designed for specific range of chemical composition and cooling rates. They **requires knowledge** and **criteria** from the user. Carelessly use of the equation can lead to erroneous estimations.

Prediction of the Hardness after the Heat Affected Zone

Experimental

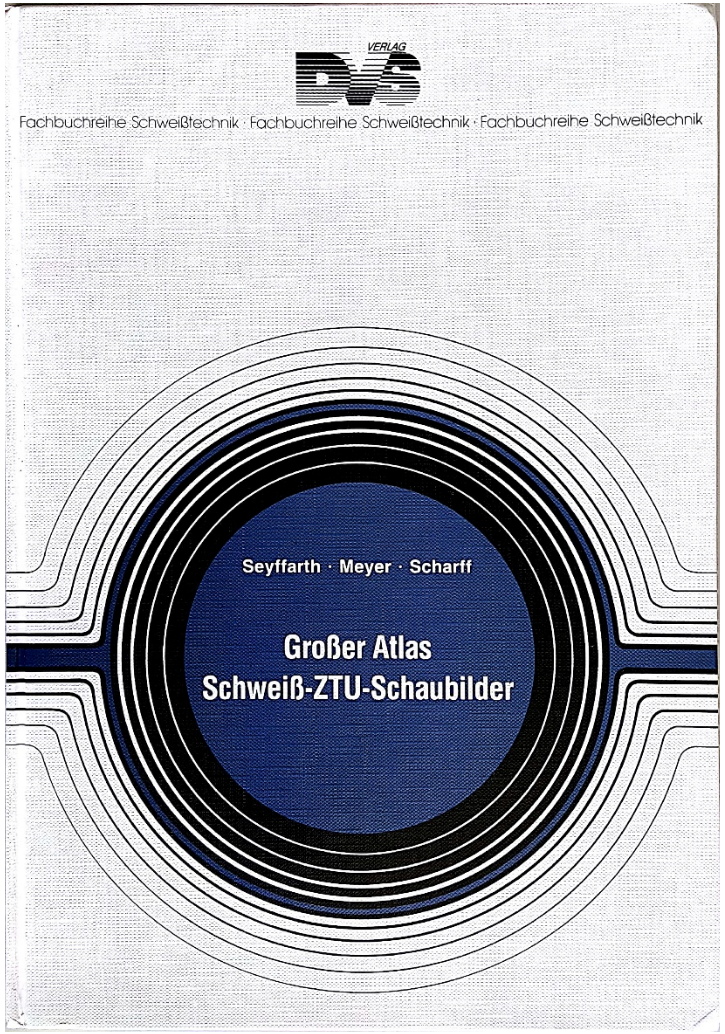
Empirical Formulas

Computational Calculations

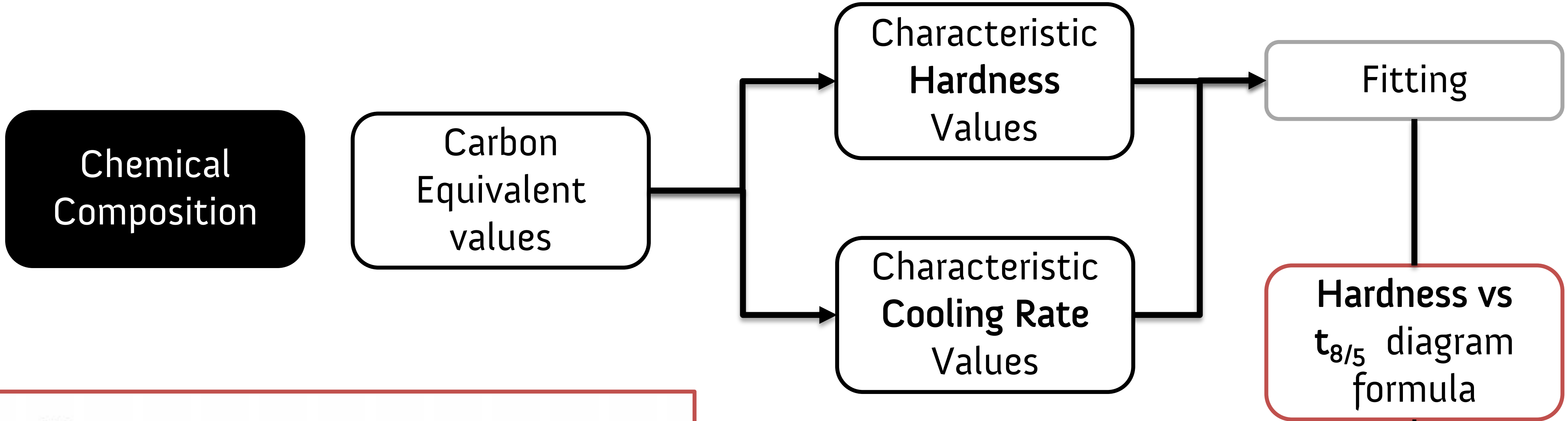
- Physical Metallurgical Models of phase transformation require enormous calculation power and knowledge.
- Neural Networks or Deep Learning models are based on treatment of experimental data but requires a software algorithm.
  - Designed for specific range of composition and cooling rates.
- Commercial Software they are simpler to use but they are expensive.
  - They are not much more accurate than empirical formulas used correctly.

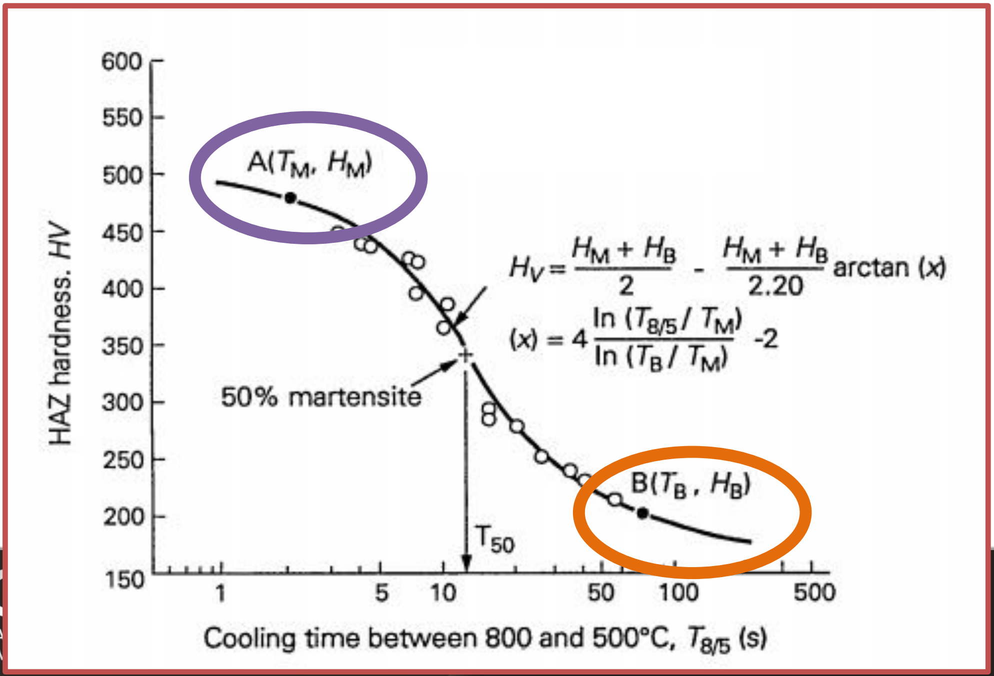
Hardness prediction models

- Experimental:
  - CCT Diagrams for Welding (e.g *Grosse Atlas*)
- Empirical:
  - Beckert (1973)
  - Le Creusot (1975 – 1978)
  - Arata (1979)
  - Terasaki (1979)
  - Lorenz & Duren (1981)
  - Suzuki (1984)
  - Cotrell (1984)
  - Ion (1984)
  - Boothby (1985)
  - Yurioka (1981, 1987)
  - Abson (2008)
- Computational
  - Modeling Phase Trans: Kirkaldy/Bhadeshia
  - Neural Networks, Deep Learning: Bhadeshia/Chan
  - Commercial Software (Jmat Pro, MatCal, etc)



Yurioka's model to predict the maximum hardness in the HAZ





Carbon Equivalent values

$C_P = C$ when $C \leq 0.3\%$;

$C_P = C/6 + 0.25$ when $C > 0.3\%$

$$CE_I = C_P + Si/24 + Mn/6 + Cu/15 + Ni/12 + Cr(1-0.16\sqrt{Cr})/8 + Mo/4 + \Delta H$$

$$CE_{II} = C + Si/24 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3$$

$$CE_{III} = C_P + Mn/3.6 + Cu/20 + Ni/9 + Cr/5 + Mo/4$$

Effect of Boron on hardenability

$\Delta H = 0$ when $B \leq 1$ppm;

$\Delta H = 0.03\ f_N$ when $B = 2$ppm;

$\Delta H = 0.06\ f_N$ when $B = 3$ppm;

$\Delta H = 0.09\ f_N$ when $B \geq 4$ppm;

where: $f_N = (0.02 - N)/0.02$

Characteristic **Hardness** Values

$$T_M = \exp(10.6\ CE_I - 4.8)$$

$$H_M = 884C(1-0.3C^2) + 294$$

Characteristic **Cooling Rate** Values

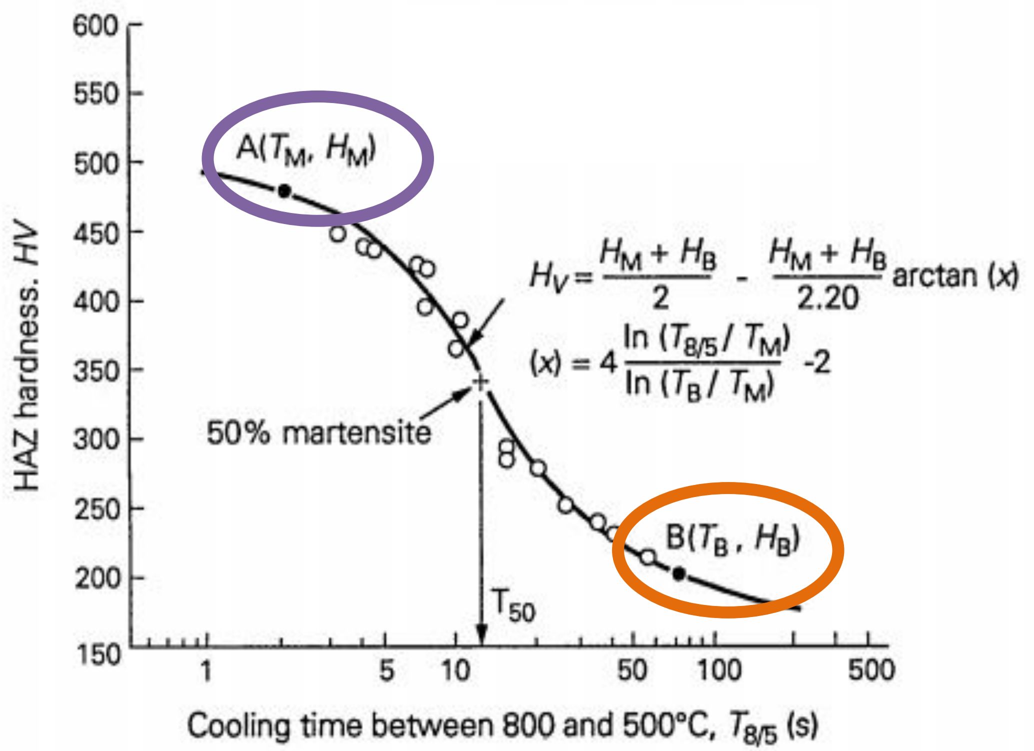
$$T_B = \exp(6.2CE_{III} + 0.74)$$

$$H_B = 145 + 130\tanh(2.65CE_{II} - 0.69)$$

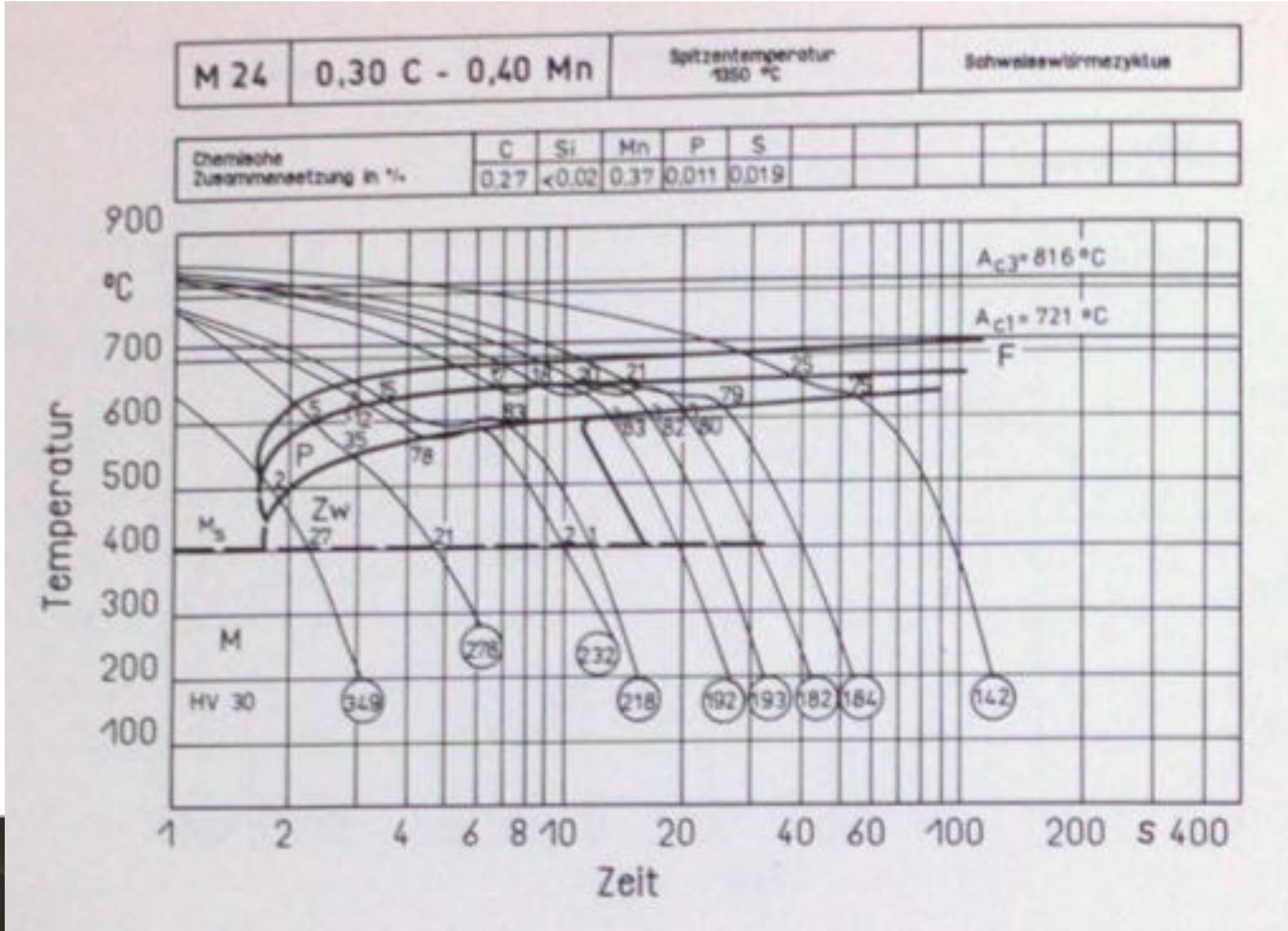
Hardness vs $t_{8/5}$ diagram formula

$$H_V = \frac{H_M + H_B}{2} - \frac{H_M - H_B}{2.20}\arctan(x)$$

$$(x) = 4\frac{\ln(T_{8/5}/T_M)}{\ln(T_B/T_M)} - 2$$



Problem 1. Determine from the CCT the maximum hardness of the heat affected zone for a $t_{8/5}$ of 8 s. Then estimate using Yuruioka's model the hardness.

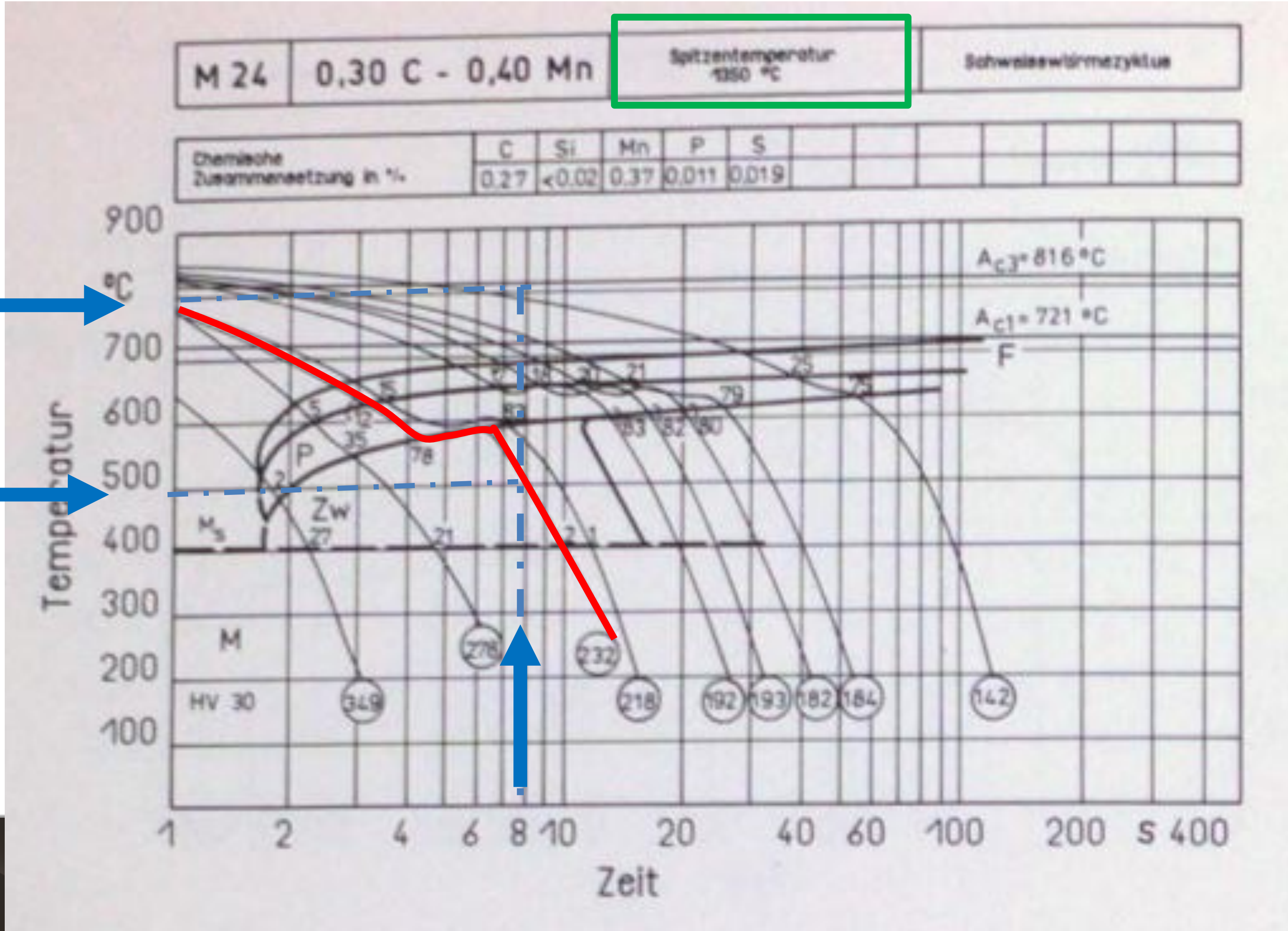


How do we know is the maximum hardness?

Which cooling curve represents a $t_{8/5}$ of 8 s?

Problem 1. Determine from the CCT the maximum hardness of the heat affected zone for a $t_{8/5}$ of 8 s. Then estimate using Yuruioka's model the hardness.

Peak temperature 1350 C



0.27C-0.02Si-0.37Mn

Carbon Equivalent values

$C_P = C$ when $C \leq 0.3\%$;

$C_P = C/6 + 0.25$ when $C > 0.3\%$

$CE_I = C_P + Si/24 + Mn/6 + Cu/15 + Ni/12 + Cr(1 - 0.16\sqrt{Cr})/8 + Mo/4 + \Delta H$

$CE_{II} = C + Si/24 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3$

$CE_{III} = C_P + Mn/3.6 + Cu/20 + Ni/9 + Cr/5 + Mo/4$

Characteristic **Hardness** Values

$T_M = \exp(10.6\, CE_I - 4.8)$

$H_M = 884C(1 - 0.3C^2) + 294$

Characteristic **Cooling Rate** Values

$T_B = \exp(6.2 CE_{III} + 0.74)$

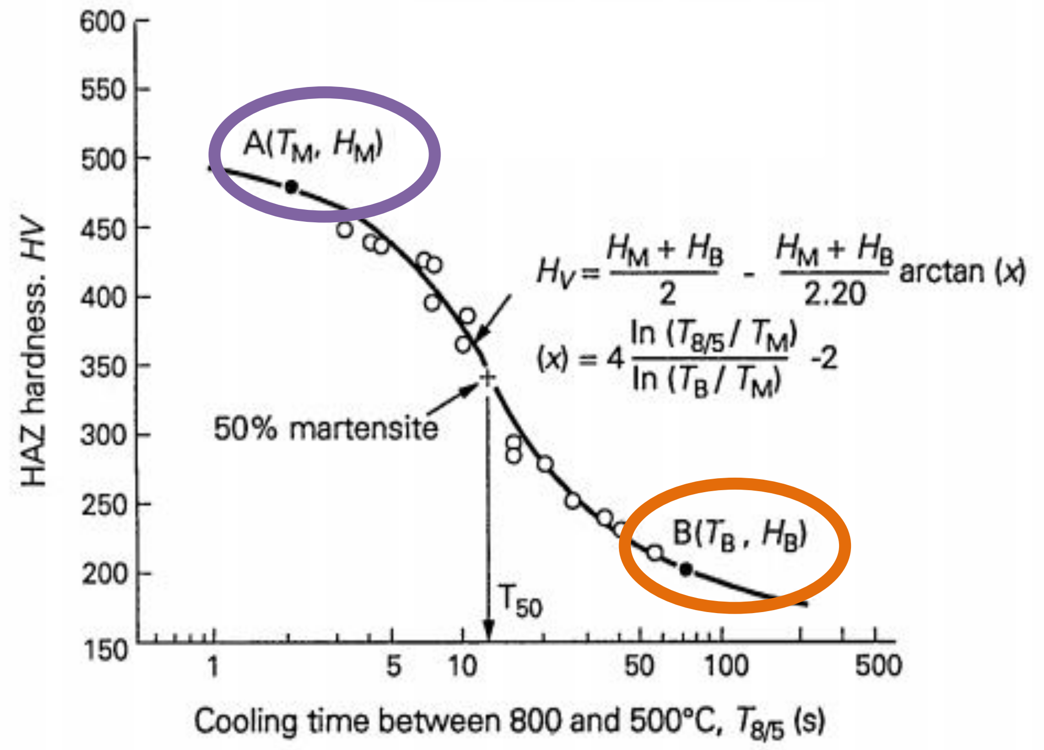
$H_B = 145 + 130 \tanh(2.65 CE_{II} - 0.69)$

Hardness vs $t_{8/5}$ diagram formula

$t_{8/5} = 8\text{s}$

$$H_V = \frac{H_M + H_B}{2} - \frac{H_M - H_B}{2.20} \arctan(x)$$

$$(x) = 4 \frac{\ln(T_{8/5}/T_M)}{\ln(T_B/T_M)} - 2$$



0.27C-0.02Si-0.37Mn

Carbon Equivalent values

$C_P = C$ when $C \leq 0.3\%$;

$C_P = C/6 + 0.25$ when $C > 0.3\%$

0.27

$CE_I = C_P + Si/24 + Mn/6 + Cu/15 + Ni/12 + Cr(1 - 0.16\sqrt{Cr})/8 + Mo/4 + \Delta H$

0.33

$CE_{II} = C + Si/24 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3$

0.34

$CE_{III} = C_P + Mn/3.6 + Cu/20 + Ni/9 + Cr/5 + Mo/4$

0.37

Characteristic **Hardness** Values

$T_M = \exp(10.6\,CE_I - 4.8)$

0.27 s

$H_M = 884C(1 - 0.3C^2) + 294$

516

Characteristic **Cooling Rate** Values

$T_B = \exp(6.2\,CE_{III} + 0.74)$

21 s

$H_B = 145 + 130\tanh(2.65\,CE_{II} - 0.69)$

182

Hardness vs $t_{8/5}$ diagram formula

$t_{8/5} = 8s$

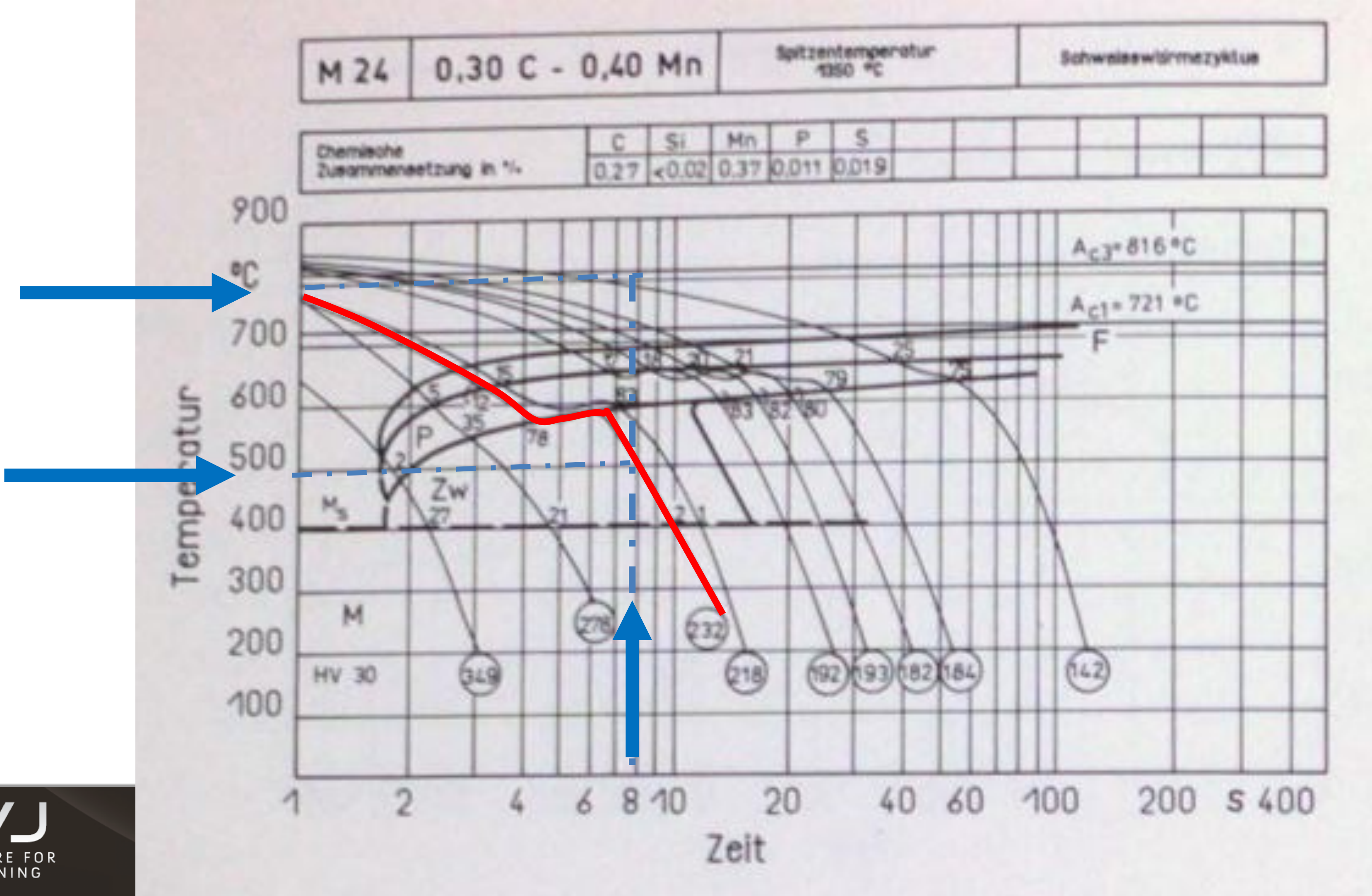
$$H_V = \frac{H_M + H_B}{2} - \frac{H_M - H_B}{2.20}\arctan(x)$$

$$(x) = 4\frac{\ln(T_{8/5}/T_M)}{\ln(T_B/T_M)} - 2$$

1.10

320

Problem 2. According to Yurioka's model, maximum hardness with a $t_{8/5}$ of 8 s is 320 HV.



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Problem 2. Estimate the maximum hardness for a process which $t_{8/5}$ is 1, 4, and 10 s for a steel with the given composition: 0.1C-0.23Si-0.35Mn-1.97Cr. Where is located this point of maximum hardness?

0.1C-0.35Mn-0.23Si-1.97Cr

Carbon Equivalent values

Characteristic **Hardness** Values

Characteristic **Cooling Rate** Values

Hardness vs $t_{8/5}$ diagram formula

$C_P = C$ when $C \leq 0.3\%$;

$C_P = C/6 + 0.25$ when $C > 0.3\%$

$$CE_I = C_P + Si/24 + Mn/6 + Cu/15 + Ni/12 + Cr(1-0.16\sqrt{Cr})/8 + Mo/4 + \Delta H$$

$$CE_{II} = C + Si/24 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3$$

$$CE_{III} = C_P + Mn/3.6 + Cu/20 + Ni/9 + Cr/5 + Mo/4$$

$$T_M = \exp(10.6\,CE_I - 4.8)$$

$$H_M = 884C(1-0.3C^2) + 294$$

$$T_B = \exp(6.2CE_{III} + 0.74)$$

$$H_B = 145 + 130\tanh(2.65CE_{II} - 0.69)$$

$t_{8/5}$= 1 s

$t_{8/5}$= 4 s

$t_{8/5}$= 10 s

$$H_V = \frac{H_M + H_B}{2} - \frac{H_M - H_B}{2.20}\arctan(x)$$

$$(x) = 4\frac{\ln(T_{8/5}/T_M)}{\ln(T_B/T_M)} - 2$$

Problem 2. Estimate the maximum hardness for a process which $t_{8/5}$ is 1, 4, and 10 s for a steel with the given composition: 0.1C-0.23Si-0.35Mn-1.97Cr. Where is located this point of maximum hardness?

0.1C-0.35Mn-0.23Si-1.97Cr

Carbon Equivalent values

$C_P = C$ when $C \leq 0.3\%$;

$C_P = C/6+0.25$ when $C>0.3\%$

0.1

$CE_I = C_P+Si/24+Mn/6+Cu/15+Ni/12 +Cr(1-0.16\sqrt{Cr})/8+Mo/4+\Delta H$

0.36

$CE_{II} = C+Si/24+Mn/5+Cu/10+Ni/18 +Cr/5+Mo/2.5+V/5+Nb/3$

0.57

$CE_{III} = C_P+Mn/3.6+Cu/20+Ni/9+Cr/5 +Mo/4$

0.59

Characteristic Hardness Values

$T_M = \exp(10.6\ CE_I-4.8)$

0.37 s

$H_M = 884C(1-0.3C^2)+294$

378

Characteristic Cooling Rate Values

$T_B = \exp(6.2CE_{III}+0.74)$

81 s

$H_B = 145+130\tanh(2.65CE_{II}-0.69)$

236

Hardness vs $t_{8/5}$ diagram formula

$t_{8/5}$= 1 s — 365

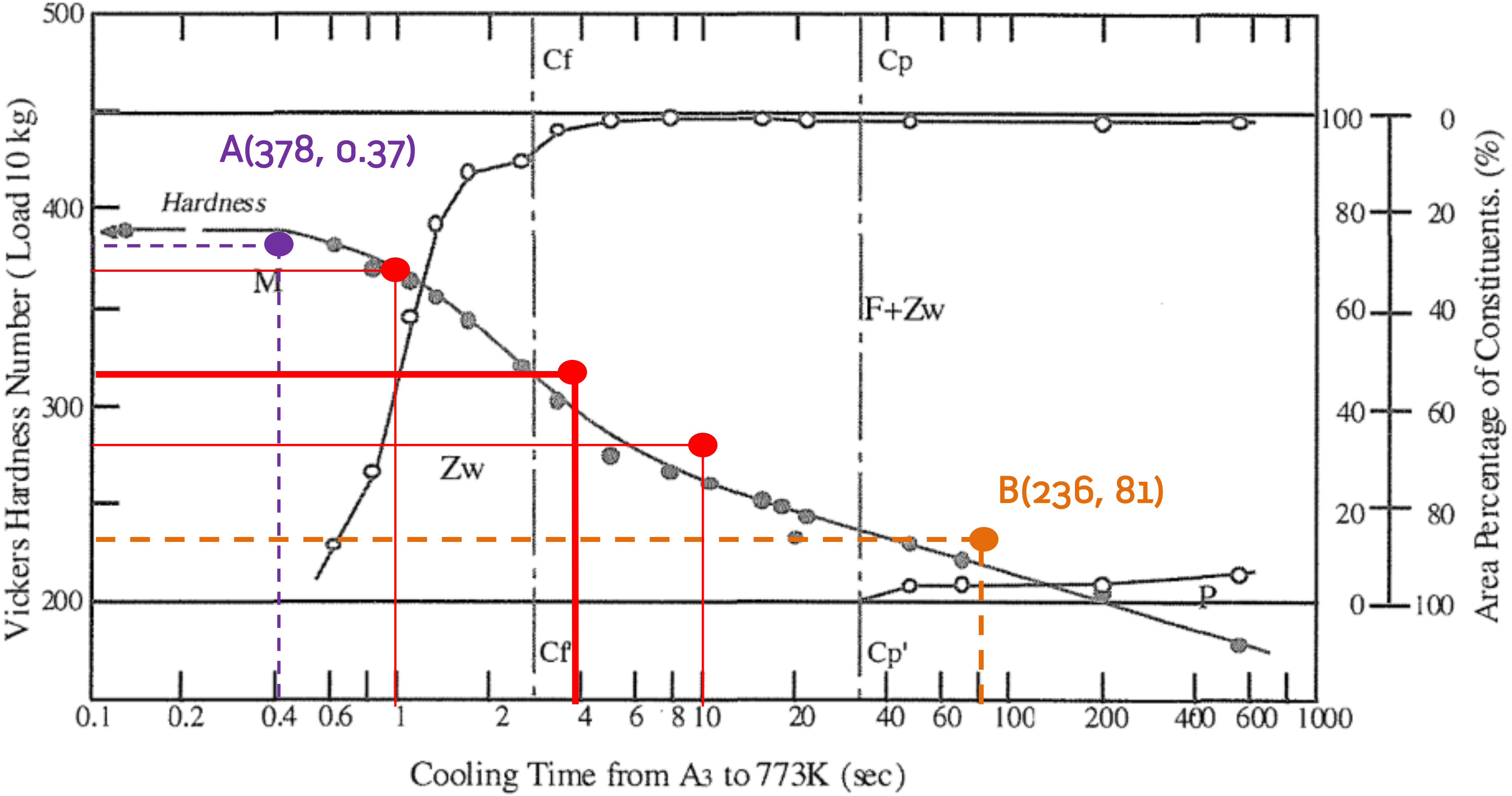
$t_{8/5}$= 4 s — 322

$t_{8/5}$= 10 s — 280

$$H_V = \frac{H_M + H_B}{2} - \frac{H_M - H_B}{2.20}\arctan(x)$$

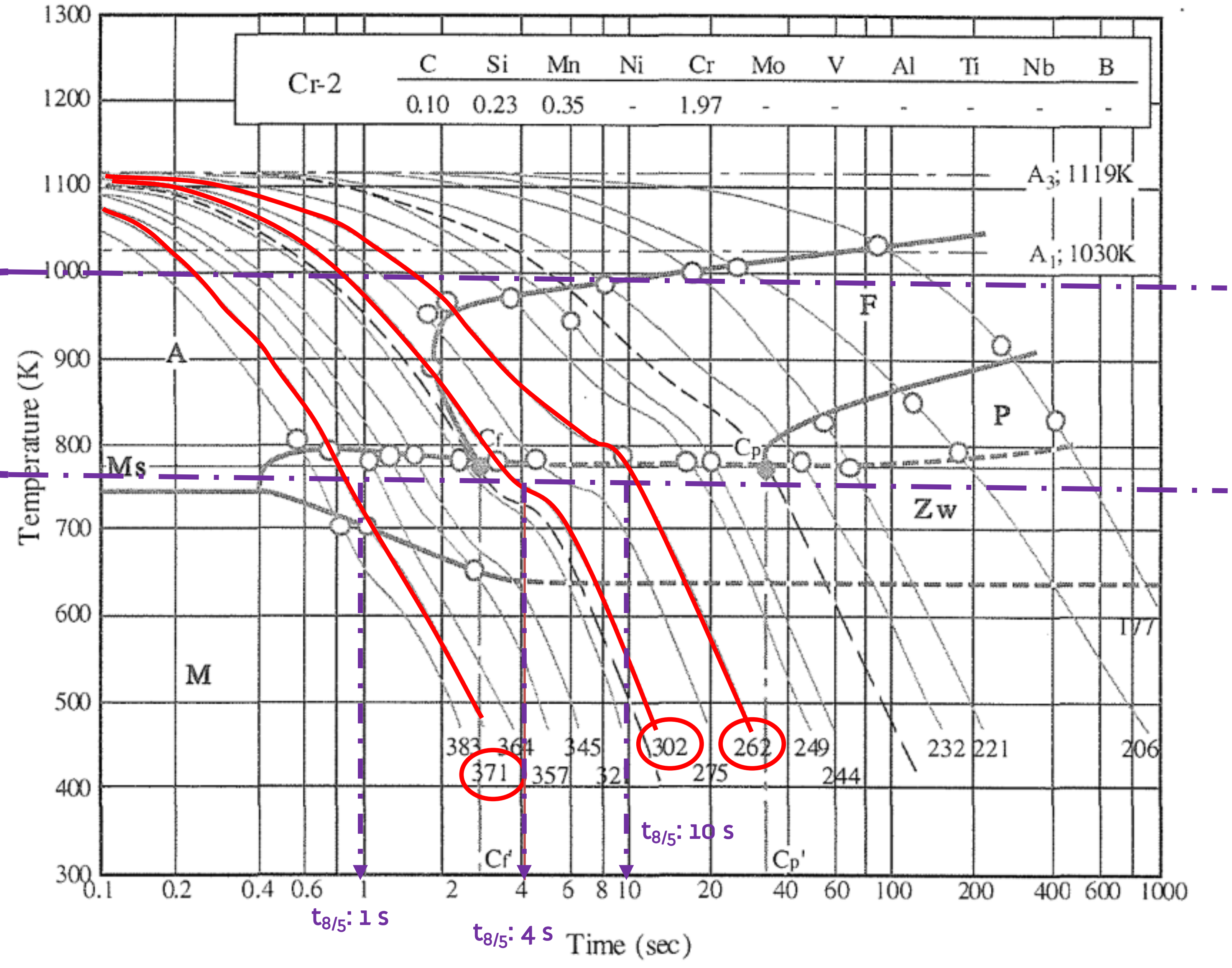
$$(x) = 4\frac{\ln(T_{8/5}/T_M)}{\ln(T_B/T_M)} - 2$$

Comparing Yurioka's model vs Experimental



Continuous Cooling Transformation Diagram

From
800 °C to 500 °C



Can we predict hardness of any specific point of the HAZ? Not necessarily the Maximum?

Different points of the HAZ will have associated different peak temperatures and hence different austenite grain sizes. This will affect the hardenability.

Some models available in literature, estimates the HAZ hardness by splitting the problem into three parts. This allow us to use these models to estimate not only the maximum hardness of the HAZ.

1. First **determine the amount of phases formed during cooling** as a function of the **chemical composition** and the **peak temperature**. An "austenization parameter" *(which is intimately related to the grain growth of austenite at high temperatures)* is used to evaluate the effect of different peak temperatures
2. Second **predicts the hardness of each constituent** as a **function** of the **chemical composition** and the **cooling rate**.
3. Using a **rule of mixtures**, the hardness of any point is given by the **combination** of the **hardness and** the **volume fraction** of each constituent.

[21] Ph Maynier, B Jungmann, and J Dollet. Creusot-loire system for the prediction of the mechanical properties of low alloy steel products. Hardenability concepts with applications to steel, pages 518–545, 1977.

[22] Ph Maynier, J Dollet, and P Bastien. Prediction of microstructure via empirical formulas based on cct diagrams. Metallurgical Society AIME,, pages 163–178, 1978.

[23] R Blondeau, Ph Maynier, J Dollet, and B Viellard-Baron. Mathematical model for the calculation of mechanical properties of low alloy steel metallurgical products: A few examples of its applications. Heat Treatment, 76:6–7, 1976.

[24] JC Ion, Kenneth E Easterling, and MF Ashby. A second report on diagrams of microstructure and hardness for heat-affected zones in welds. Acta Metallurgica, 32(11):19491957–19551962, 1984.

[25] MF Ashby and Kenneth E Easterling. A first report on diagrams for grain growth in welds. Acta metallurgica, 30(11):1969–1978, 1982.