Transformation barriers for growth of WS-ferrite and bainitic ferrite

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Acknowledgements
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1. Introduction - the diffusional growth model

The ALEMI group started as a consequence of the bainite controversy;

does bainite form as a diffusional decomposition product from austenite or does it form diffusionless as martensite with carbon redistribution between bainitic ferrite and parent austenite afterwards?

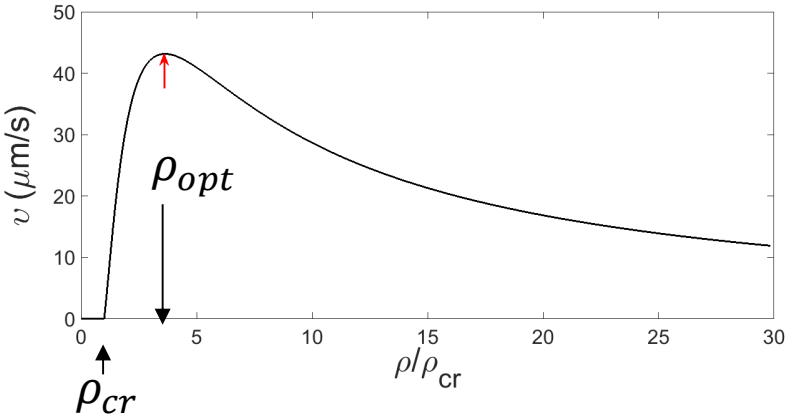
The diffusional growth model

- Growth of the ferritic component of bainite is essentially similar to the growth of Widmanstätten ferrite at higher temperatures, i.e.
  - The rate is essentially controlled by the rate of carbon diffusion in the austenite.
  - The interface is essentially in local equilibrium for Fe-C alloys (PARA equilibrium for alloy steels).
  - There are certain crystallograpfic orientation relationships, i.e. KS leading to shape changes and relief effects on a surface as in martensite.
  - Deviation from local equilibrium is expected at low temperatures.
  - Effect of stresses and plastic deformation may be important at lower temperatures.

The Zener-Hillert model

Approximations

- Diffusion controlled growth of a ferrite plate under local equilibrium
- Steady-state diffusion problem
- Effect of interfacial energy and edge curvature by the Gibbs-Thomson equation
- Dilute solution approximation
- Maximum growth rate selection of edge curvature



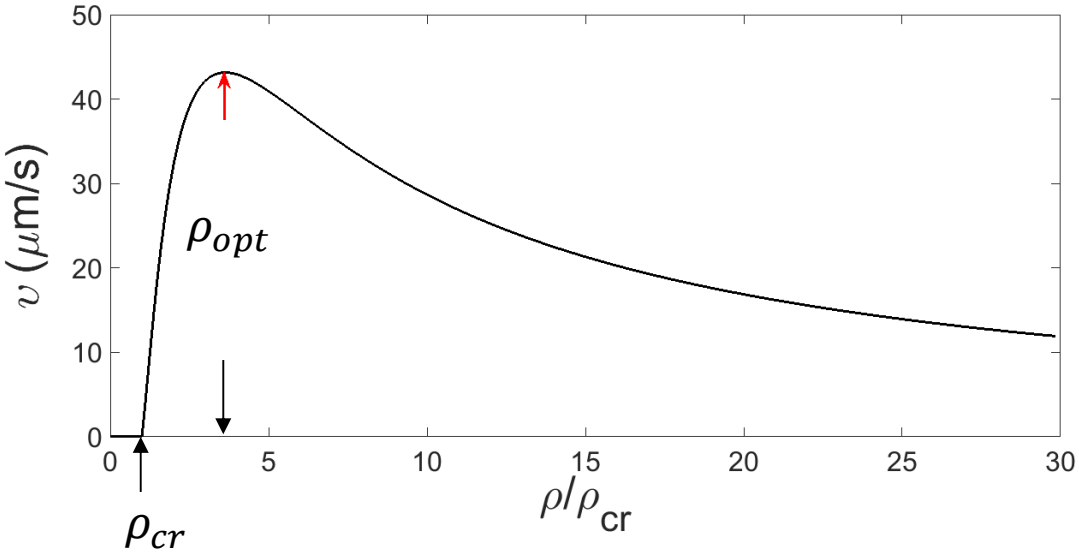
The Zener-Hillert model - cont

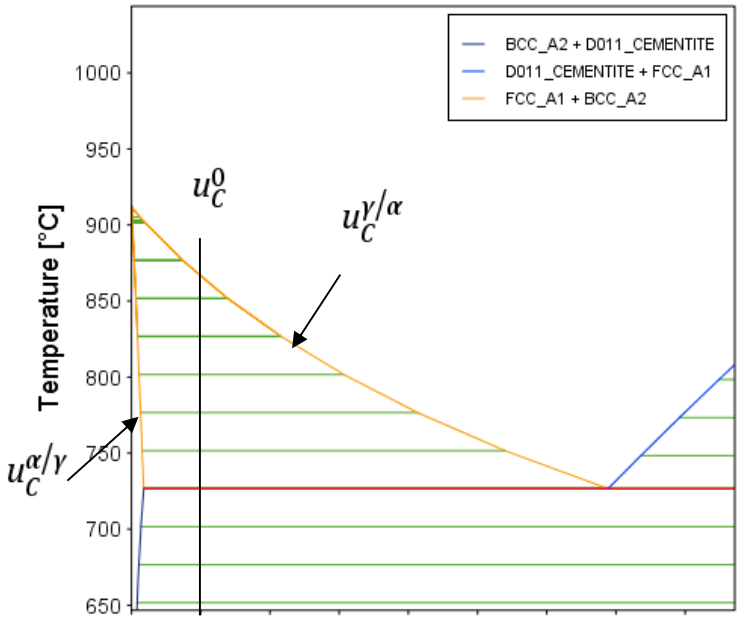
- Plates having a tip radius larger than a critical radius, ρ_{cr} grow
- The modified Zener-Hillert equation gives velocities over varying plate tip radii
- v_{max} is the maximum velocity at the optimal curvature, ρ_{opt}

From Gibbs-Thomson

$$v = \frac{D}{2\rho}\frac{u_C^{\gamma/\alpha} - u_C^0}{u_C^0 - u_C^{\alpha/\gamma}}(1-\rho_{cr}/\rho)$$

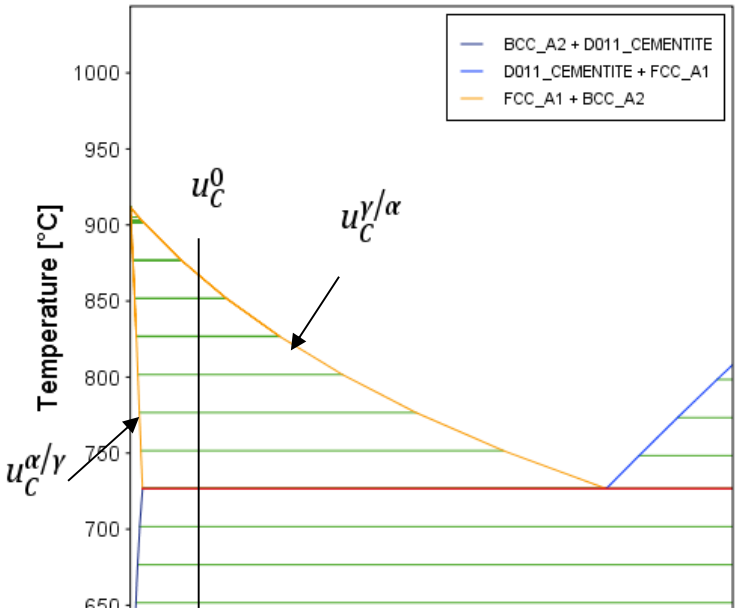
$$\rho_{cr} = \frac{\sigma^{\alpha/\gamma}}{-\Delta G_m^0 / V_m}, \quad \rho_{opt} = 2\rho_{cr}$$





$$u_C = x_C/(1-x_C)$$

The Zener-Hillert model - cont



u_C

$$v = \frac{D}{8\rho_{cr}} \frac{u_C^{\gamma/\alpha} - u_C^0}{u_C^0 - u_C^{\alpha/\gamma}}$$

$$\rho_{cr} = \frac{\sigma^{\alpha/\gamma}}{-\Delta G_m^0 / V_m}$$

$$-\Delta G_m^0 \cong RT(u_C^{\gamma/\alpha} - u_C^0)$$

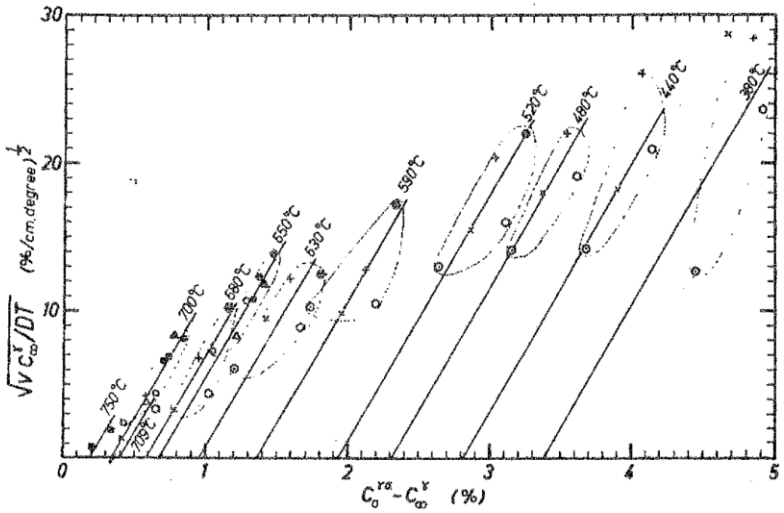
$$v \cong \frac{D}{8\sigma^{\alpha/\gamma} V_m} \frac{RT(u_C^{\gamma/\alpha} - u_C^0)^2}{u_C^0 - u_C^{\alpha/\gamma}}$$

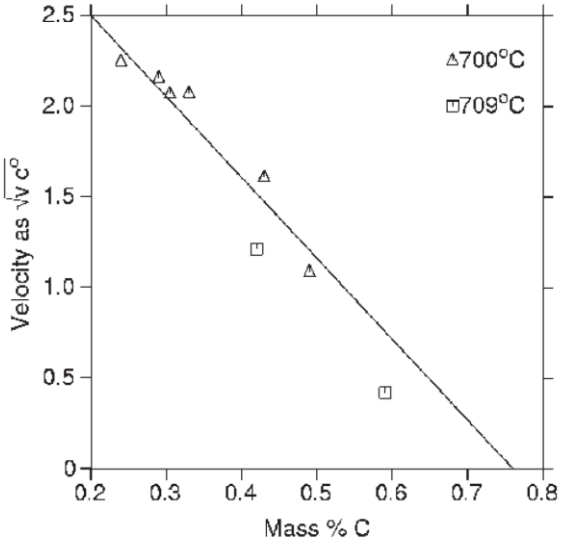
$$\Rightarrow$$

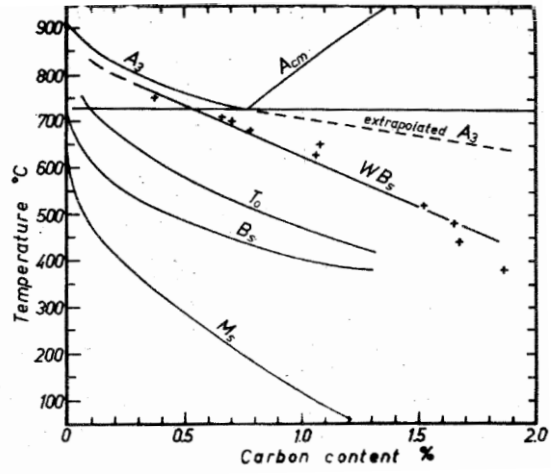
$$\sqrt{vu_C^0 / TD} \propto (u_C^{\gamma/\alpha} - u_C^0)$$

The WB_s temperature

$$\sqrt{vu_C^0 / TD} \propto (u_C^{\gamma/\alpha} - u_C^0)$$

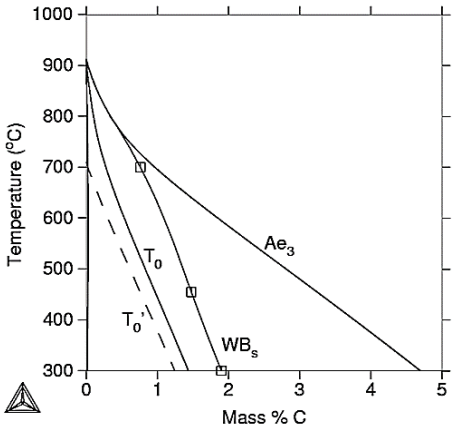






Hillert 1960

Need for thermodynamic barriers



- If there were full local equilibrium the growth rate would always become zero when the initial carbon content of austenite falls on the austenite-ferrite phase boundary, Ae_3.
- 1960 Hillert found that the experimental data on growth rates extrapolated to a much lower carbon content see WB_s.
- I.e. it seems as an extra driving force is needed for onset of the ferrite growth.
- A thermodynamic barrier was introduced to represent this behaviour.

2. Improvements of Zener-Hillert model – thermodynamic barriers

- Avoid the Gibbs-Thomson approximation by adding the effect of curvature and interfacial energy directly to the Gibbs energy of ferrite and calculate the modified equilibria using;

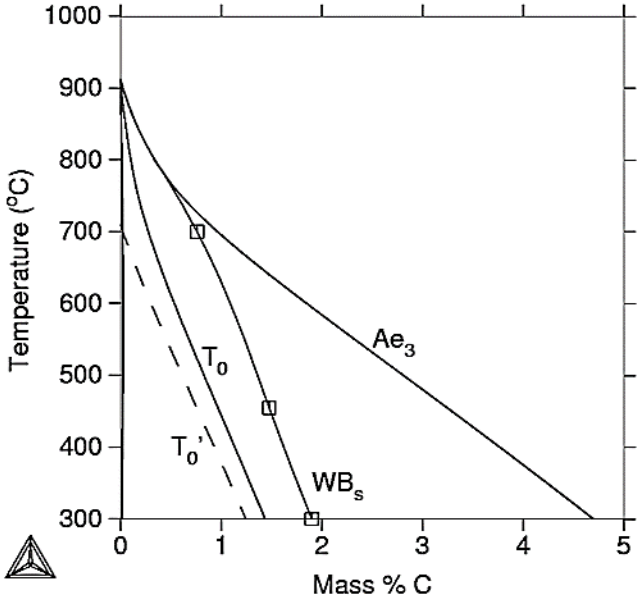
$$G_m^{\alpha}(\rho, B_m) = G_m^{\alpha} + V_m \sigma^{\alpha/\gamma} / \rho$$

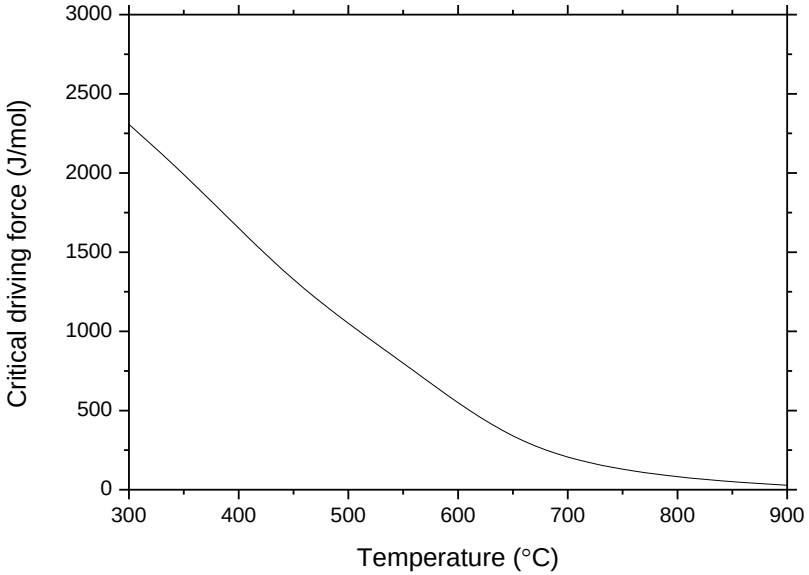
$$v = \frac{D}{2\rho} \frac{u_{C\rho}^{\gamma/\alpha} - u_C^0}{u_C^0 - u_{C\rho}^{\alpha/\gamma}}$$

- At $\rho = \rho_{cr}$ and $u_{C\rho}^{\gamma/\alpha} = u_C^0$ and $v = 0$
- The interfacial energy assumed constant and taken from Hillert 1960.

Hillert et al. 2004

One needs to cool below a temperature WB_s lower than the A_{e3} line but higher than T_0 in order for the WS or bainitic ferrite to grow. This undercooling is represented by a critical driving force i.e. A ”thermodynamic barrier”.





Calculation of growth rate with a barrier

- The equations modified with the barrier and the interfacial energy then reads

$$G_m^{\alpha}(u_j^{\alpha},T,\rho,B_m) = G_m^{\alpha}(u_j^{\alpha},T) + V_m\sigma^{\alpha/\gamma}/\rho + B_m(v,u_j,T)$$

$$v = \frac{D}{2\rho}\frac{u_{C\rho B}^{\gamma/\alpha} - u_C^0}{u_C^0 - u_{C\rho B}^{\alpha/\gamma}}$$

- At each temperature and content of original austenite the growth rate is calculated as a function of radius of curvature and the maximal value is chosen and compared with the experimental value.

3. Inverse calculation – evaluation of the barrier

- For each piece of experimental information one may thus calculate the barrier that gives the best agreement with the experimental growth rate provided that
  - the thermodynamic properties
  - the diffusivity
  - the interfacial energy

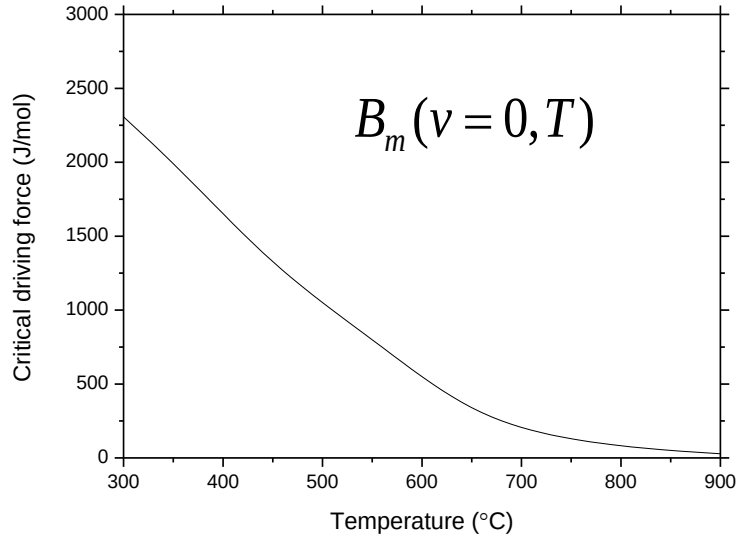
  are known.
- The diffusivity depends on temperature and carbon content but the theory uses only a single number. We have chosen the maximum value in each experiment i.e. the value for the carbon content closest to the interface, i.e. $u_{C\rho B}^{\gamma/\alpha}$

We evaluate the barrier

$B_m(v, u_j, T)$

For binary Fe-C: $B_m(v, T)$

- The barrier for zero growth rate thus is the barrier for onset of growth and gives the WB_s temperature.



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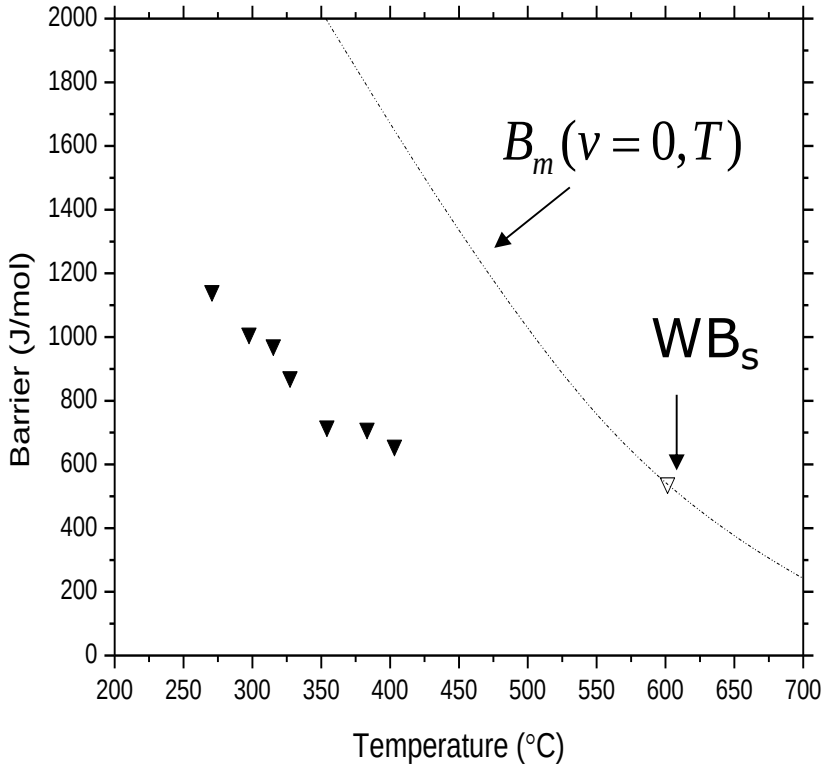
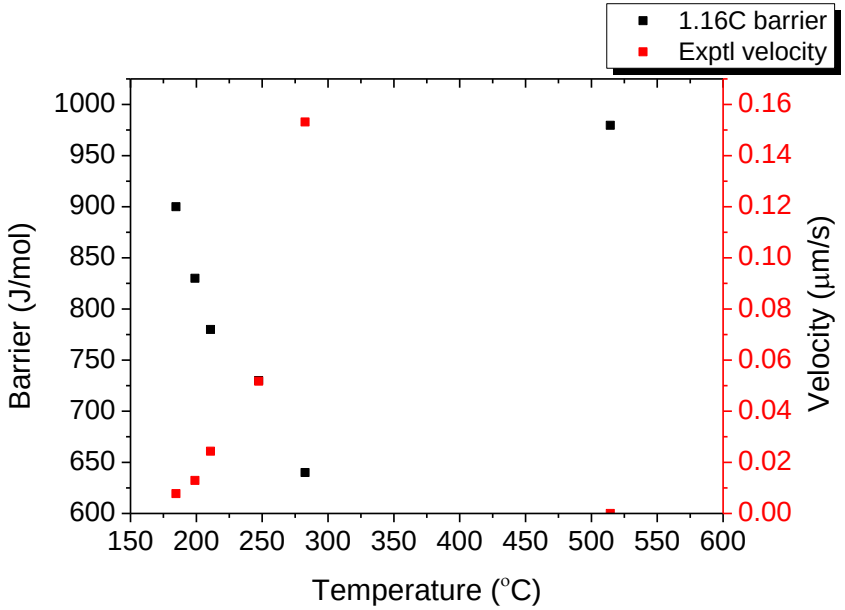
Example Fe - 0.9 mass% C



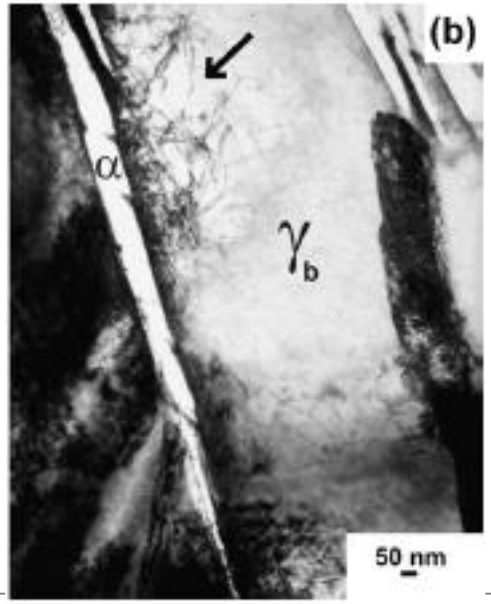
Relation between barrier and growth rate



- At the start the barrier is highest – largest resistance to be overcome
- At the highest velocity (nose), barrier is lowest – smallest resistance to a rapidly growing plate

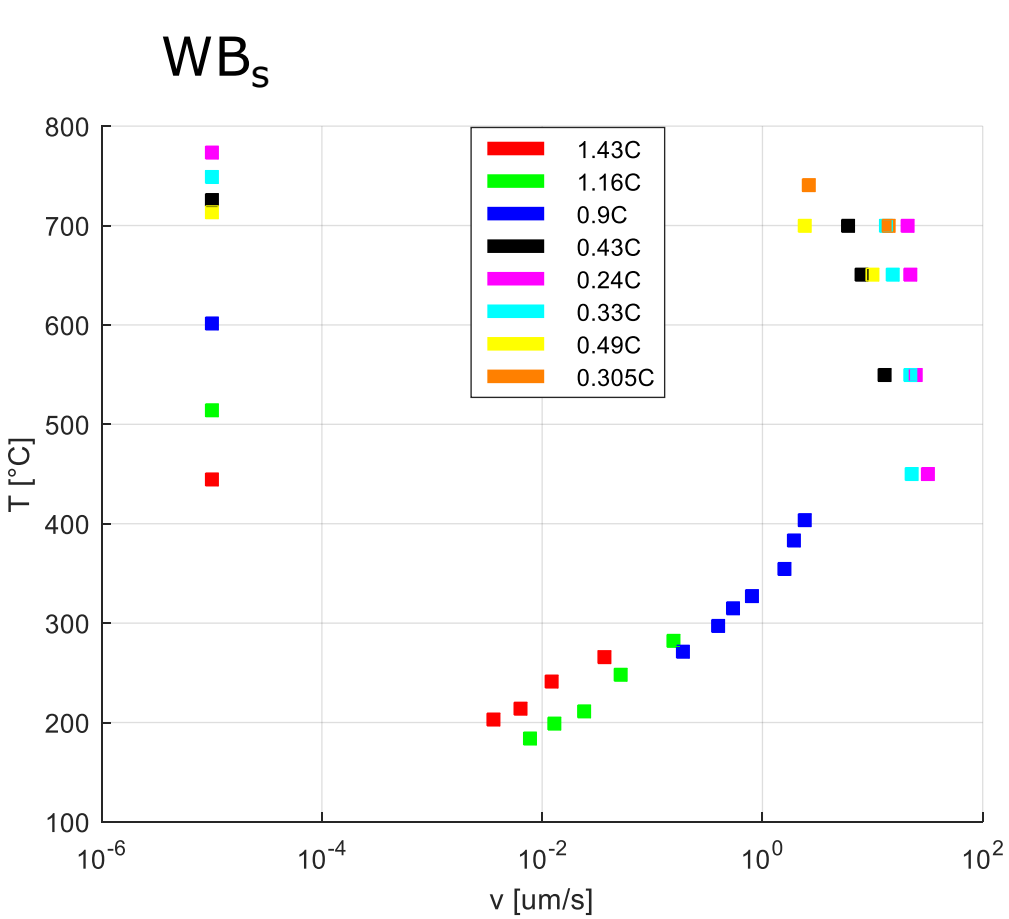
Physical interpretation?
Resistance to movement of austenite/ferrite interface due to:

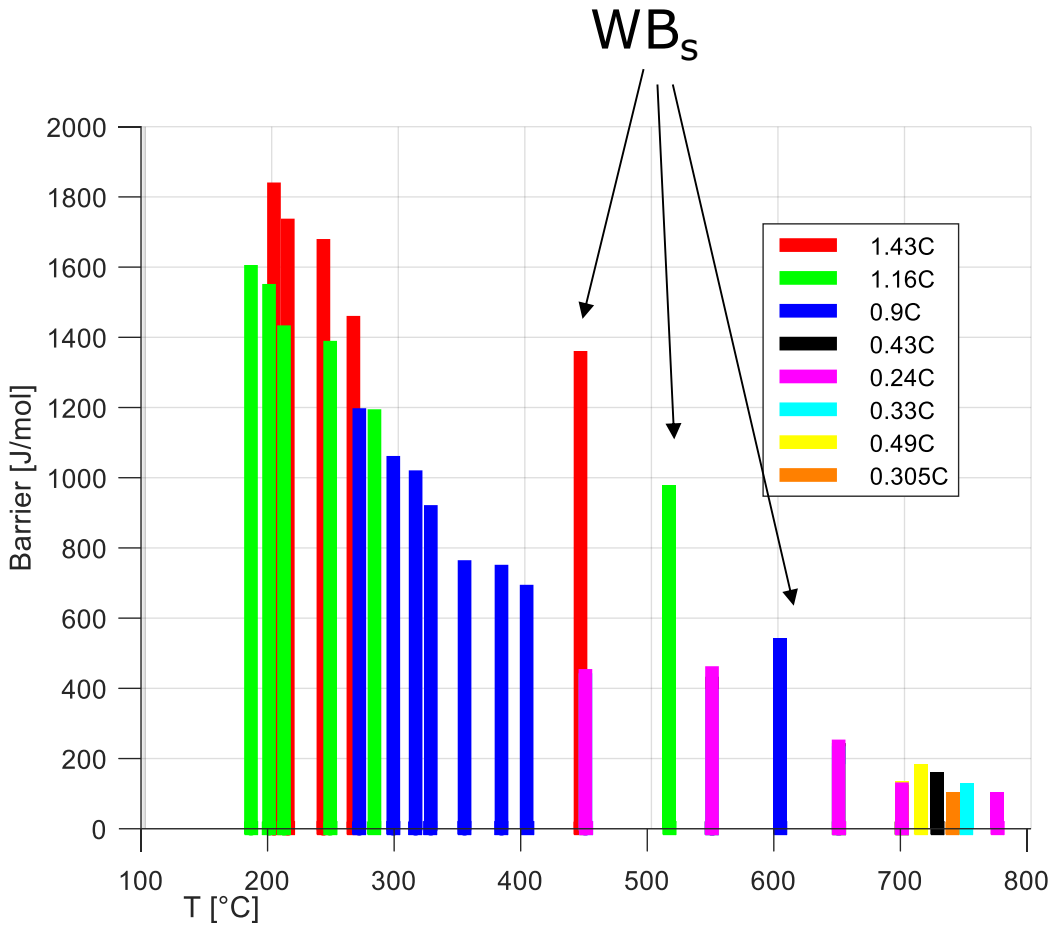
- ➢ Friction at the interface
- ➢ Strain due to volume misfit
- ➢ Accumulation of dislocations



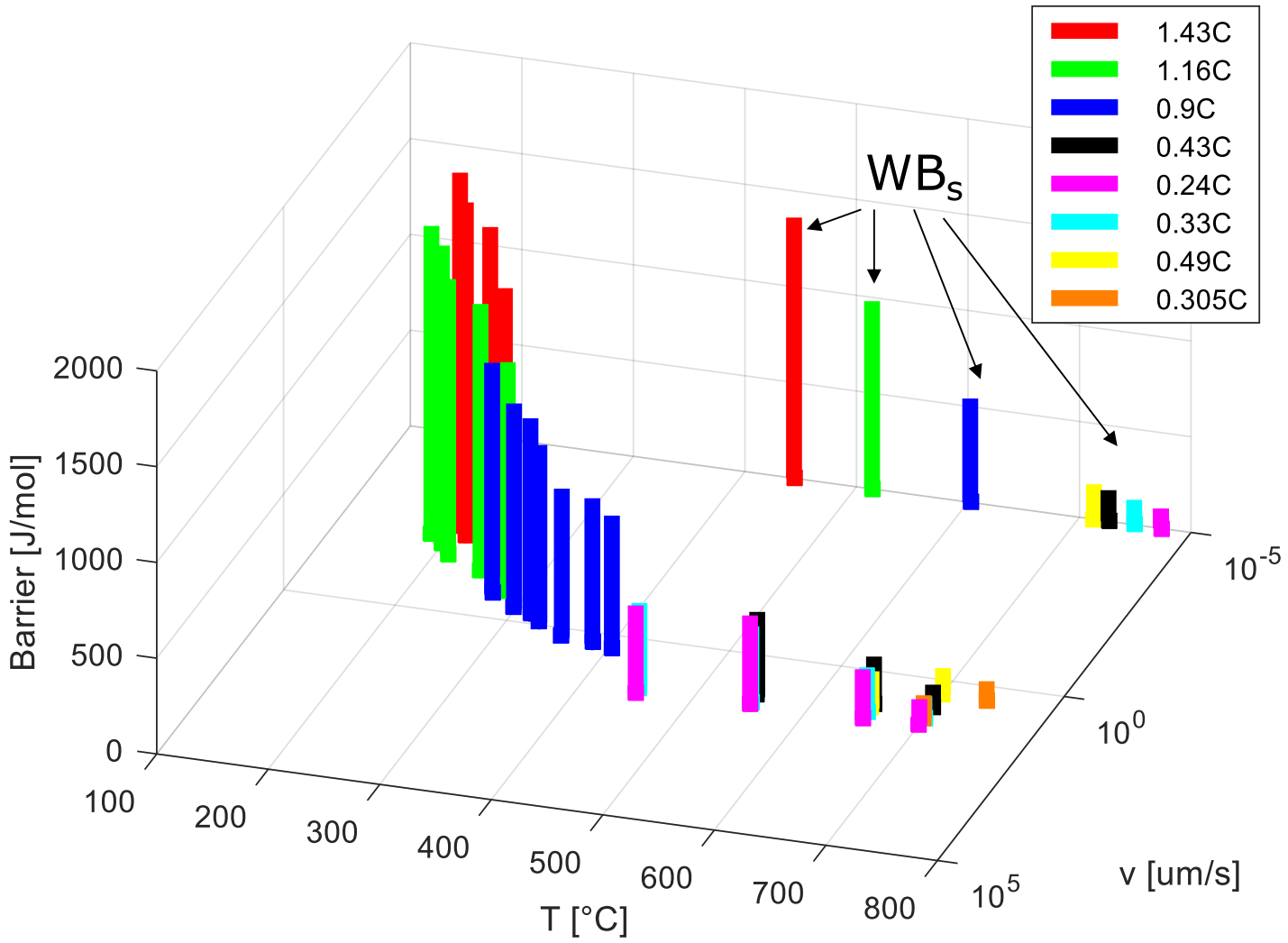
F.G. Caballero et al, Acta Mater. 59 (2011) 6117 - 6123

Evaluation of the barrier from experiments on Fe-C

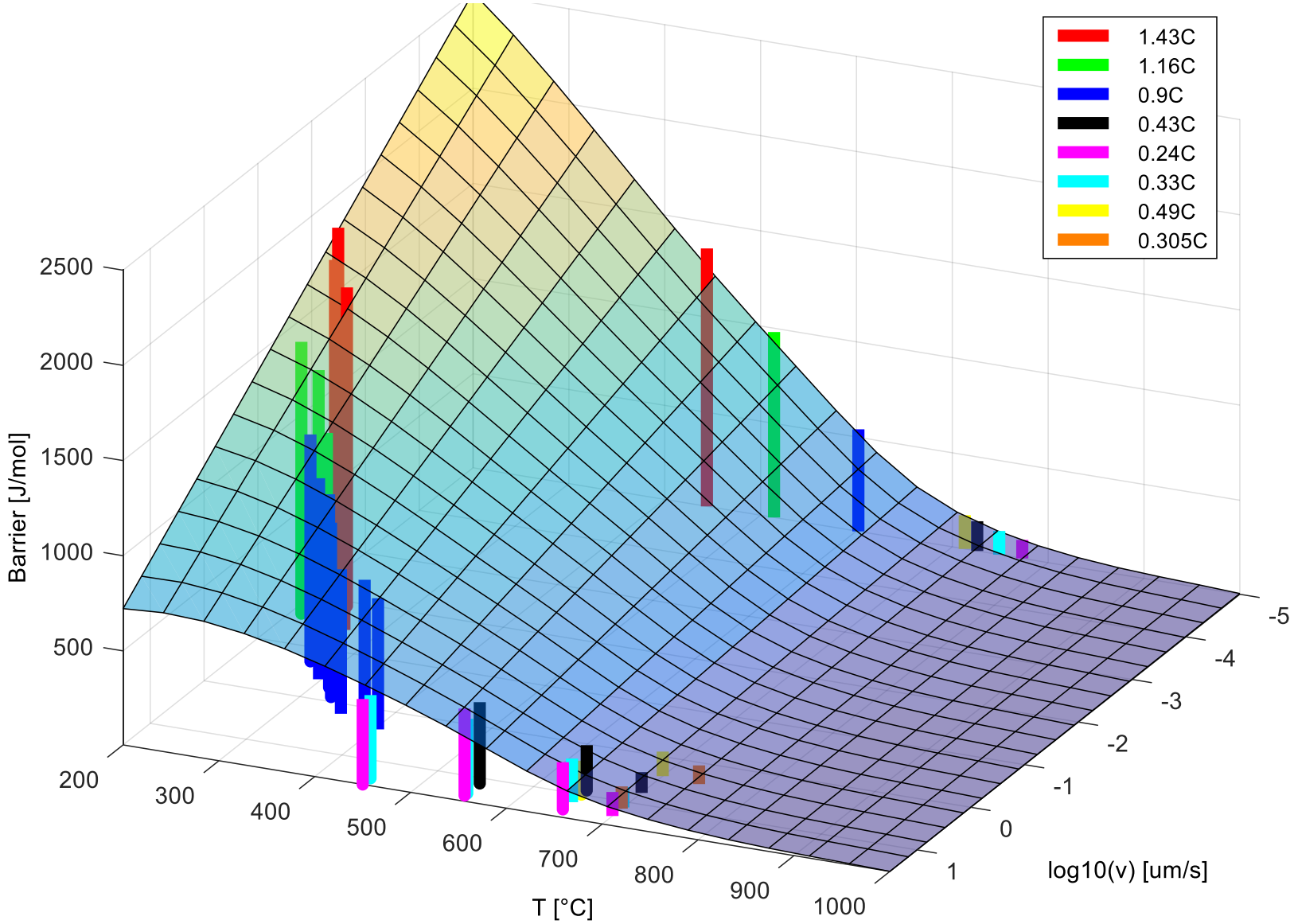




The function : $B_m(v,T)$



Try to fit a function : $B_m(v,T)$



4. Conclusions

- It is possible to represent the data on WS and bainitic ferrite with Zener-Hillert type of model including a thermodynamic barrier.
- We need to express the barrier as a function of growth rate, temperature and alloy content.
- Interfacial energy needs to be assessed!