The Solidus Temperatures of Steels

Anna Karner, Robert Pierer and Sebastian Michelic

qoncept dx GmbH, Peter Tunner Str. 19, 8700 Leoben, Austria

How to calculate the non-equilibrium solidus temperature? What is the disadvantage of empirical equations? Why should you be careful when considering the cooling rate?

Based on our developed software tool, a quick and easy generation of quasi-binary Fe-C phase diagrams of steels can be done. Although the Fe-C phase diagram is of enormous importance for the metallurgist, it is important to keep in mind that additional elements and the cooling rate change the areas of the individual phases. This is of highest relevance during continuous casting of steels because some steels are particularly prone to cracking.

1 INTRODUCTION

In a previous article we checked the results of 32 empirical equations for calculating the liquidus temperature of typical low alloyed and stainless steels. The present article deals with the calculation of the non-equilibrium (true) solidus temperature (in the following article referred to as solidus temperature for the sake of simplicity). Like calculating the liquidus temperature, the solidus temperature can be estimated with empirical equations. However, these equations do not consider the cooling conditions, which results in inaccurate values of the solidus temperature. In order to consider cooling conditions and thus the microstructure, the solidus temperature must be determined based on microsegregation models.

For a detailed evaluation of microsegregation models, we recommend the following article:

+ T. Kraft and Y. A. Chang: Predicting microstructure and microsegregation in multicomponent alloys, JOM, Vol. 49 (1997), pp. 20–28. LINK

Regarding microsegregation models in continuous casting, their verification and relevance for process control, we recommend the following two articles:

+ M. Bernhard et al.: On the Relevance of Microsegregation Models for Process Control in Continuous Casting of Steel, 26th International Conference on Metallurgy and Materials, (2018), pp. 38-44. LINK
+ D. You et al.: On the modelling of microsegregation in steels involving thermodynamic databases, IOP Conf. Series: Materials Science and Engineering 119, (2016). LINK

2 BACKGROUND

Microsegregation models consider the effect of the cooling rate ($\dot{T}$) by introducing the so-called back diffusion coefficient (α) which is a function of the solute diffusion coefficient in solid, the local solidification time (t_f) and the secondary dendrite arm spacing (λ_2). In order to introduce the cooling rate, the relation between the local solidification time, the temperature difference (range) between liquidus and solidus temperature must be considered (see **Appendix**). Since the temperature difference between the liquidus and solidus temperature is not known a priori, a local solidification time must first be assumed, and a solution must be determined iteratively. Finally, an equation which describes the relationship between the secondary dendrite arm spacing and the local solidification time must be implemented. Such equations describe the development of the secondary dendrite arm spacing during solidification based on the considerations of coarsening kinetics. However, the relevant literature (see references in [1]) determined mainly empirical equations based on experimental measurements.

Like the model described by D. You et al. (source information see above) qoncept developed a model to calculate the phase transformation temperatures of steel. In addition, the model has been expanded to enable quasi-binary Fe-C phase diagrams to be created quickly and easily, considering the cooling rate and the chemical composition of steels. **Figure 1** shows an example of the result for steel grade A (the chemical composition is illustrated in **Table 1**) and a cooling rate of 1 K/s. The dashed lines show the famous Fe-C phase diagram in equilibrium. Although the Fe-C phase diagram is of enormous importance for the metallurgist, the illustration clearly shows how the additional elements and the cooling rate change the areas of the individual phases. It is important to mention the resulting triangular tube of δ-Fe, γ-Fe and liquid (L).

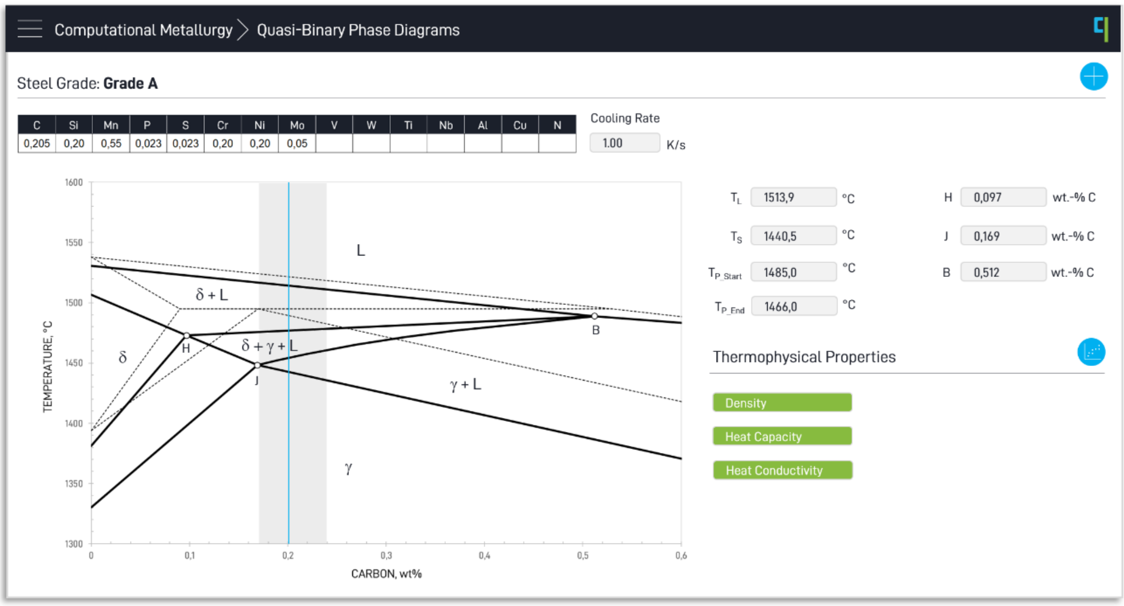

Figure 1: Quasi-binary Fe-C diagram based on the chemical composition of steel grade A

Since steel grade A is defined by a carbon content of 0.17 - 0.24 *wt.-%*, we have drawn this area in gray in the diagram. The blue line represents the situation with 0.205 *wt.-% C*. With the help of the points H, J and B the different solidification paths can be characterized:

Area 1 ($c_C < H$): $L \rightarrow L + \delta \rightarrow \delta \rightarrow \delta + \gamma \rightarrow \gamma$

Area 2 ($H < c_C < J$): $L \rightarrow L + \delta \rightarrow L + \delta + \gamma \rightarrow \delta + \gamma \rightarrow \gamma$

Area 3 ($J < c_C < B$): $L \rightarrow L + \delta \rightarrow L + \delta + \gamma \rightarrow \gamma + L \rightarrow \gamma$

Area 4 ($c_C > B$): $L \rightarrow L + \gamma \rightarrow \gamma$

The knowledge of the solidification path is of highest relevance during continuous casting of steels, because some steels (in particular, these are steels which are in area 2) are particularly prone to cracking. These steels grades are often referred to as peritectic steels. As shown in **Figure 1**, steel grade A follows the solidification path of area 3. However, if the carbon content moves to its lower end (0.17 *wt.-%*), it approaches this critical range more and more.

3 EMPIRICAL EQUATIONS

In order to discuss the results of the empirical equations to calculate the solidus temperature, we used the steels summarized in **Table 1** (the same steel grades applied in our previous article).

	C / %	Si / %	Mn / %	P / %	S / %	Cr / %	Mo / %	Ni / %	Cu / %	Al / %	O / %	
A	0.17 – 0.24	≤ 0.40	0.40 – 0.70	≤ 0.045	≤ 0.045	≤ 0.40	≤ 0.10	≤ 0.40				(Cr + Mo + Ni) ≤ 0.63
B	0.07 – 0.13	≤ 0.40	0.30 – 0.60	≤ 0.035	≤ 0.035	(≤ 0.40)						
C	0.22 – 0.29	≤ 0.40	0.60 - 0.90	≤ 0.035	≤ 0.035	0.90 – 1.20	0.15 – 0.30					
D	0.38 – 0.44	≤ 0.30	0.60 – 0.90	≤ 0.025	≤ 0.025	0.70 – 0.90	0.15 - 0.30	1.65 – 2.00	≤ 0.25			
E	0.17 – 0.23	≤ 0.40	0.65 – 0.95	≤ 0.035	≤ 0.035	0.35 – 0.70	0.15 – 0.25	0.40 – 0.70				
F	0.52 – 0.59	≤ 0.40	0.70 – 1.00	≤ 0.025	≤ 0.025	0.70 – 1.00						
G	0.93 – 1.05	0.15 – 0.35	0.25 – 0.45	≤ 0.025	≤ 0.015	1.35 – 1.60	≤ 0.10		≤ 0.30	≤ 0.05	≤ 0.0015	

Table 1: Chemical composition of the steel grades considered in the present article

Figure 2 shows the result of the empirical solidus temperature equations. The dark bar represents the smallest, the lighter bar the highest calculated solidus temperature. The green area marks the calculated solidus temperature using our developed model, whereas the range (expansion) of this area results from a cooling rate of 0.1 *K/s* and 10 *K/s*. The white numbers indicate how many empirical equations out of 11 are within the range of the microsegregation model. Again, the goal here is not to validate the empirical equation with our results. The results of these considerations are only intended to express how large the scatter band of the empirical equations is and what results a microsegregation model calculates taking the cooling rate into account.

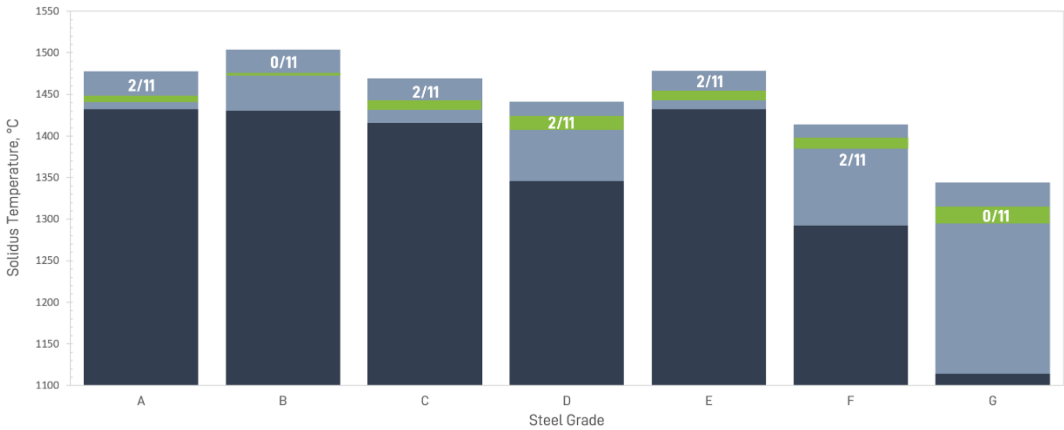

Figure 2: The results of the 11 used equations to calculate the solidus temperatures of the steel grades A to G

4 THE EFFECT OF THE COOLING RATE

As already mentioned, empirical equations do not consider the cooling rate. Microsegregation models consider the cooling rate by integrating the relationship between the secondary dendrite arm spacing and the local solidification time. Both parameters are necessary to calculate the back-diffusion coefficient necessary (a parameter in the equation to calculate the concentrations of solutes in the residual liquid). **Figure 3** shows the results of two different cooling rates on the quasi-binary Fe-C diagram of steel grade A. It can clearly be seen how the cooling rate effects the end temperature of the peritectic transformation, but most importantly the solidus temperature. It can also be seen that with increasing carbon content the difference between the solidus temperature close to equilibrium (i.e. cooling rate = 0.1 *K/s*) and the solidus temperature at 10 *K/s* increases. For steel grade A, the temperature difference is 10 °C.

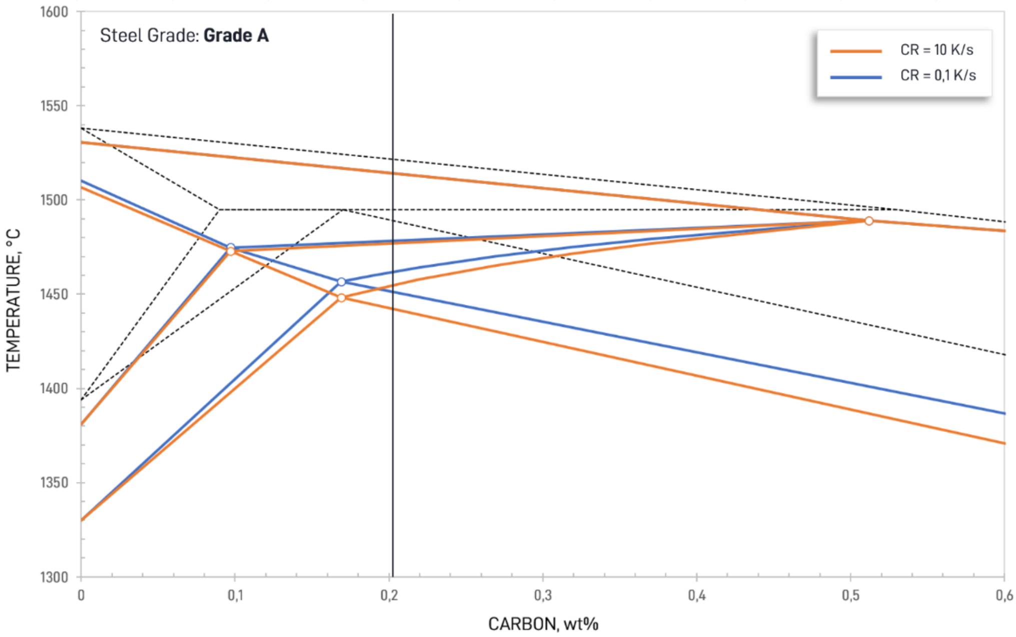

Figure 3: Quasi-binary Fe-C diagram for two different cooling rates.

In order to illustrate the importance of the relationship between the secondary dendrite arm spacing and the local solidification time, we applied additional three empirical equation from the relevant literature [1-3] in our software tool. The left diagram of **Figure 4** shows the results of the secondary dendrite arm spacing as a function of the cooling rate in a double logarithmic scaling. The right diagram shows the resulting solidus temperatures.

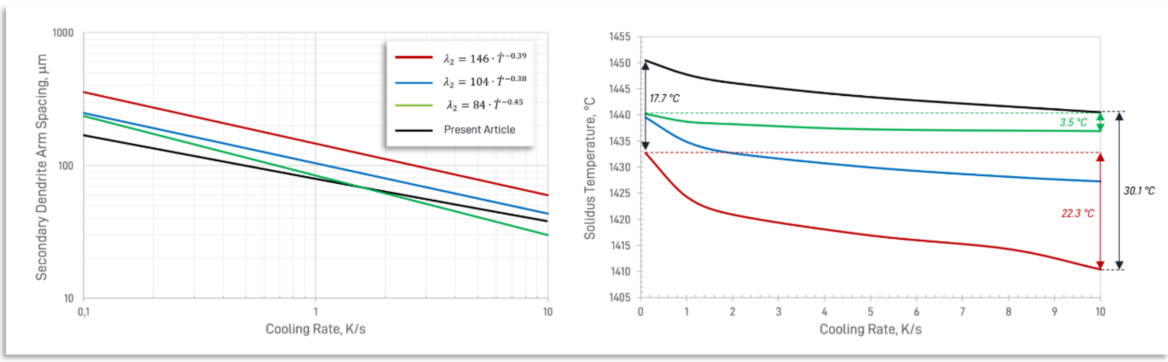

Figure 4: Secondary dendrite arm spacing as a function of cooling rate (left) and the effect on the calculated solidus temperature (right).

Considering the secondary dendrite arm spacing equations, it can be seen that all four models follow a very similar trend. The values vary from 176 - 358 *µm* at a cooling rate of 0.1 *K/s* to 38 - 59 *µm* at a cooling rate of 10 *K/s* which are typical values found in continuously cast steel products. However, the effect of these various equations on the calculated solidus temperature results is really large. The difference between the lowest and highest solidus temperature for the same steel grade vary from 17.7 °C at 0.1 *K/s* to 30 °C at 10 *K/s*. The highest difference of the solidus temperature between 0.1 and 10 *K/s* shows the equation according to Suzuki et al [1] (22.3 °C), the lowest values shows the equation according to B.

Weisgerber et al. [3] (3.5 °C). For a better understanding, these numbers are shown in the diagram on the right in **Figure 4**.

When you perform solidification calculations for the continuous casting process, please keep the following in mind:

Under certain continuous casting conditions and using a solidification model, a difference in solidus temperature of 10 °C leads to a difference in the calculated metallurgical length of 2 m.

5 SUMMARY

Empirical equations to calculate the solidus temperature do not consider the cooling conditions, which results in inaccurate values of the solidus temperature. In order to consider cooling conditions and thus the microstructure, the solidus temperature must be determined based on microsegregation models. The present article showed how large the scatter band of the empirical equations is and illustrated the results of our software tool taking the cooling rate into account. Applying three additional equations describing the relation between the cooling rate and the secondary dendrite arm spacing, we showed how these equations influence the calculation results of the solidus temperature.

Based on our developed software tool, a quick and easy generation of quasi-binary Fe-C phase diagrams of steels can be done. Although the Fe-C phase diagram is of enormous importance for the metallurgist, it is important to keep in mind that additional elements and the cooling rate change the areas of the individual phases. This is of highest relevance during continuous casting of steels because some steels are particularly prone to cracking.

6 APPENDIX

The relations between cooling rate, the local solidification time and the temperature difference between liquidus and solidus temperature are considered in our model as follows:

$\lambda_2 = A \cdot t_f^N$, where $t_f = \frac{T_L - T_S}{\dot{T}}$

$A = 27.3 - 13.1 \cdot c_C^a$, where $N = \frac{1}{3}, a = \frac{1}{3}$

7 REFERENCES

[1] A. Suzuki, T. Suzuki, Y. Nagaoka and Y. Iwata: Nippon Kingaku Gakkai Shuho, Vol. 32 (1968), 1301.

[2] M. M. Wolf: Effect of solidification rate on microstructure, Continuous Casting, Volume Nine, 1997.

[3] B. Weisgerber, M. Hecht and K. Harste: Investigation of the solidification structure of continuously cast slabs, Steel Research, Vol. 70 (1999), No. 10, pp. 403 – 410.