Application Example:

Hardenability Design Using the Steel Model Library

Database(s):	**FEDEMO, MFEDEMO**	Module(s):	**Steel Model Library**
Required version:	**Thermo-Calc 2021a or newer**	Calculator(s):	**Martensite temperatures model, martensite fractions model, pearlite model, bainite model**
Material/Application:	**Steel / Materials Selection**		
Example file:	https://www.thermocalc.com/solutions/example-calculations/hardenability-design-of-steel/		

To run the calculation, download the example file and save it to your computer. Open Thermo-Calc in the graphical mode and then drag the example file into the Project pane. The results are saved in the calculation file, so the program will take a moment to process the file and then load the results. Note that results will only show if you have the Thermo-Calc 2021a or newer.

ABOUT THE EXAMPLE - BACKGROUND

This example focuses on the hardenability design of steel using the Steel Model Library in Thermo-Calc. It shows how to find the optimal compositions for Fe-Mn-C steel to achieve high hardenability for the purpose of strength. Hardenability refers to the ability of steel to form martensite on quenching. It is a measure of the capacity of a steel to be hardened in depth when quenched from its austenitizing temperature. Among various factors, composition is one of the most important factors which has great influence on the hardenability of the steel. In this example, we use the Steel Model Library to investigate the possible composition ranges of Fe-C-Mn alloys to reach a fully martensitic microstructure.

To fulfil the requirement, room temperature martensite fraction should be large and the amount of retained austenite should be small. Meanwhile, other products of austenite decomposition should be avoided during continuous cooling. Such transformation products can be suppressed by fast quenching, yet the cooling rate is usually limited by the capacity of facilities or other problems such as cracking. Therefore, for hardenability purposes, it is desirable to achieve a fully martensitic structure with a relatively low cooling rate. This is done by promoting martensite formation while retarding other transformations through adjusting the steel composition.

EXAMPLE CALCULATIONS AND EXPLANATIONS

Time-Temperature-Transformation (TTT) Diagram

High hardenability steel design means that the steel should have a high martensite finish temperature (Mf) or, in other words, high martensite fraction at room temperature, and at the same time, a long starting time of formation of other austenite decomposition products such as ferrite, pearlite, and bainite. As the ferrite model is still under development, in this example we will consider only pearlite and bainite. Figure 1 shows the calculated TTT diagram of a Fe-2Mn-1C (wt.%) steel using the Thermo-Calc Steel Model Library. Because the TTT diagram is calculated by invoking the Pearlite and Bainite Models independently, the region where pearlite and bainite curves overlap should be interpreted as forming a mixture of the two products. Grain size is taken as 100µm throughout this document. The arrows on the TTT diagram indicate the directions we should search towards for high hardenability, i.e., high temperatures for martensite to start (Ms) and form to a certain percentage (M50), as indicated by the yellow arrow, and long pearlite-start and bainite-start times, as indicated by the blue arrows. Using the TTT diagram is a simplified approach for hardenability analysis, since the transformation kinetics is different under continuous cooling conditions.

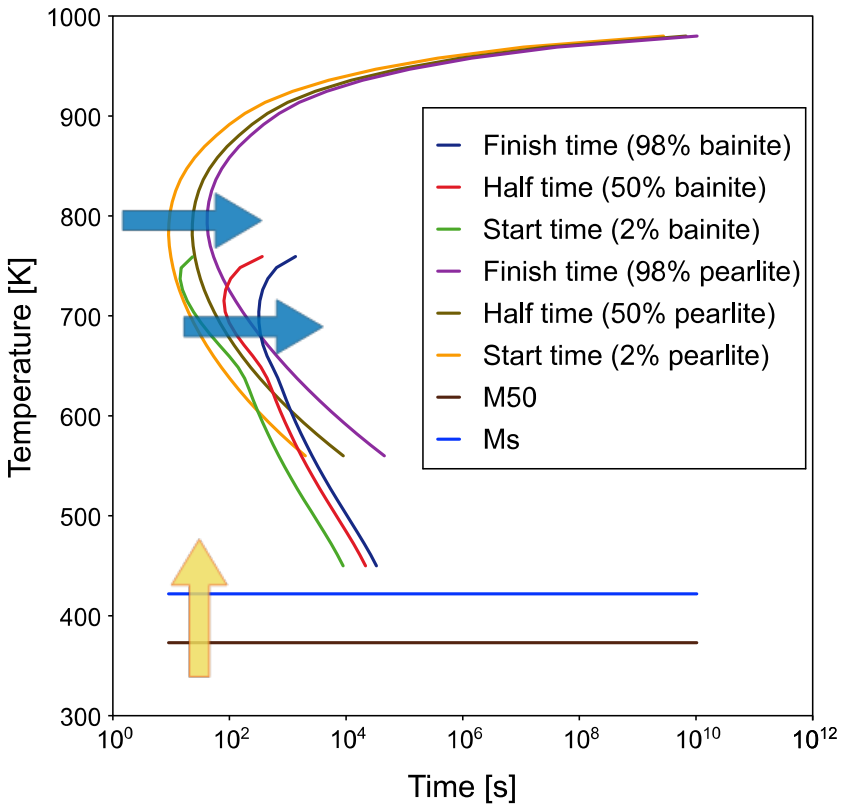

Figure 1. Calculated TTT diagram of Fe-2Mn-1C (wt.%), which shows time-temperature curves for 2%, 50%, and 98% pearlite transformation and bainite transformation, and the Ms and M50 temperatures for athermal martensite. Arrows in the diagram indicate directions towards high hardenability.

Martensite Fractions

In this section we investigate how Mn and C contents influence the amount of martensite at room temperature. Figure 2 shows the calculated Total Martensite Percentage as a function of Mn and C contents for an Fe-Mn-C system using the Martensite fractions model in the Thermo-Calc Steel Model Library. Three contour curves are shown, which correspond to 95%, 90%, and 80% of martensite respectively. According to the calculation results presented in Figure 2, increased concentration of either Mn or C leads to a decrease in martensite fraction. The region of interest for us, where the total martensite percentage is higher than 95%, has a C content lower than 1.2 wt.% and a Mn content lower than 4 wt.%.

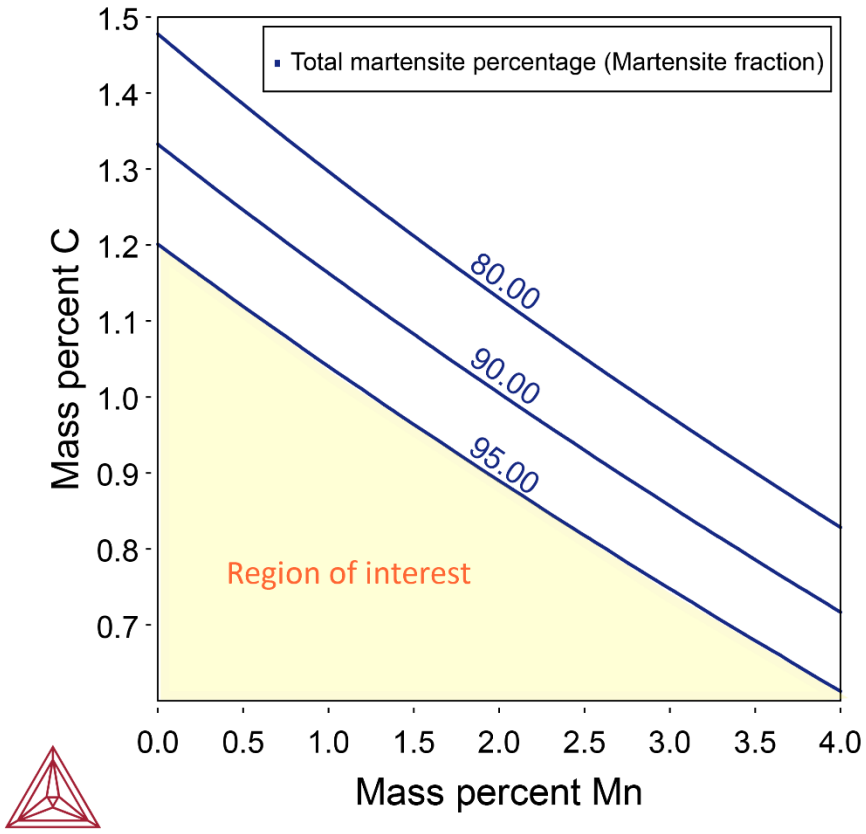

Figure 2. Total Martensite Percentage (80%, 90%, and 95%) as a function of Mn and C contents for Fe-Mn-C.

Pearlite Formation

From the TTT diagram in Figure 1 we can see that the nose of the start time of pearlite (corresponding to 2% of pearlite) of Fe-1 C-2 Mn (wt.%) is at a temperature around 800 K, which means that pearlite is most likely to begin forming within a short time of this temperature. We then calculated the pearlite start time when varying both Mn and C contents at a temperature of 800 K, and the result is presented in Figure 3 as contour curves of pearlite start times equal to 1 s, 10 s, and 100 s respectively, as a function of Mn and C concentrations. As can be seen, increasing Mn content retards the formation of pearlite. On the other hand, the effect of C on the pearlite start time is not monotonic.

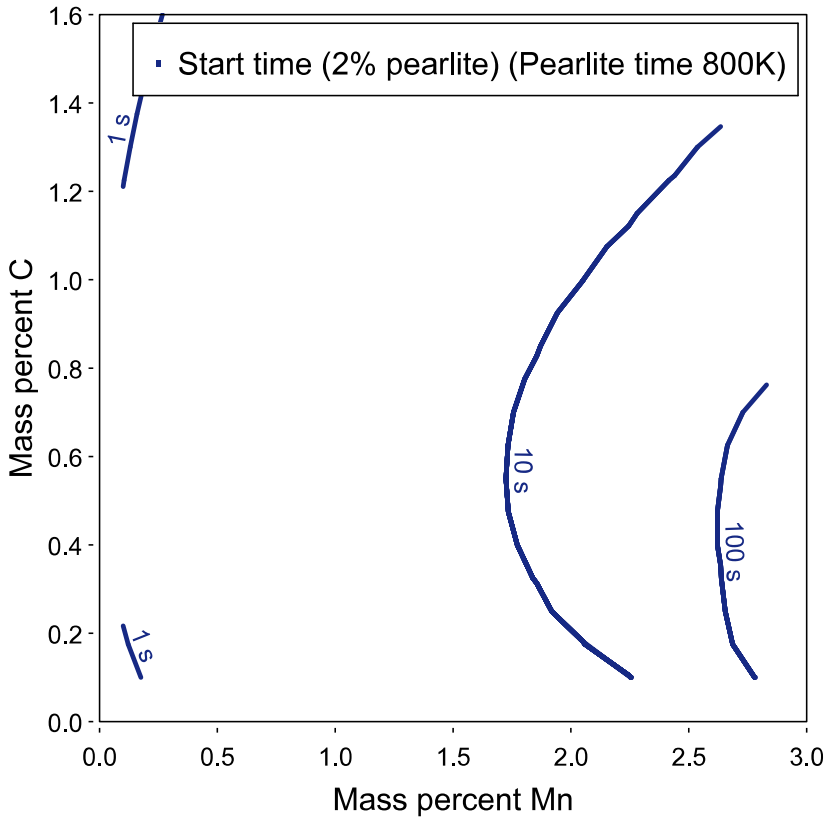

Figure 3. Start time of pearlite formation (2% pearlite, unit: second) as a function of Mn and C contents for Fe-Mn-C at 800 K.

Bainite Formation

From the TTT diagram in Figure 1 we can also see that the shortest start time of bainite (corresponding to 2% of bainite) of Fe-1 C-2 Mn (wt.%) is at a temperature around 700 K. For this composition, bainite is predicted to start shortly after pearlite, so it is not the product that controls hardenability. But in order to keep track of the bainite formation kinetics, we also calculated the bainite start time when varying both Mn and C contents at a temperature of 700 K, and the result is presented in Figure 4 as contour curves of bainite start times equal to 10 s and 100 s respectively, as a function of Mn and C concentrations. As can be seen, increasing Mn and C contents retards the formation of bainite.

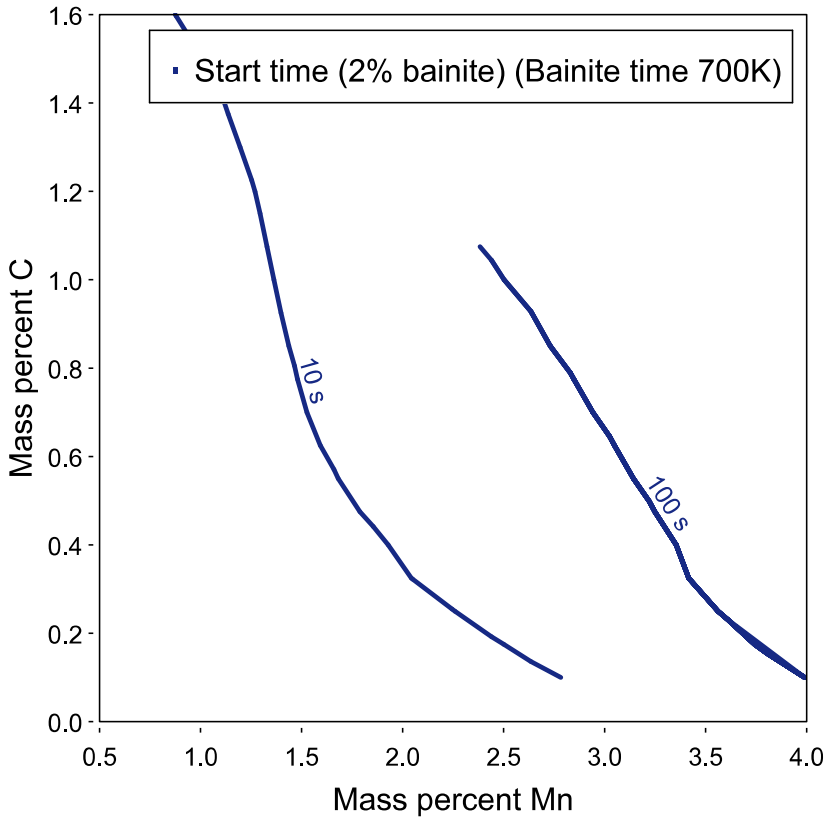

Figure 4. Start time of bainite formation (2% bainite, unit: second) as a function of Mn and C contents for Fe-Mn-C at 700 K.

Composition Selection

As we need to consider both martensite fraction and the formation kinetics of pearlite and bainite, we merge Figures 2–4 into one plot, which is presented as Figure 5. The allowable region of compositions to achieve high hardenability is indicated by the yellow box in Figure 5. Within this composition range, we have more than 95% of martensite at room temperature, the start time of pearlite formation at 800 K is longer than 100 s, and the start time of bainite formation at 700K is also longer than 100 s, which supposedly implies that the pearlite and bainite transformations are sufficiently slow under practical cooling conditions. We can empirically choose Mn content lower than 4% to avoid processing issues.

We can then draw our conclusion that based on the above calculations, the composition that we should consider for achieving high hardenability in Fe-Mn-C steel has been narrowed down to the allowable region indicated in Figure 5, having 0.4–0.8 wt% C and 2.2–4 wt% Mn. The allowable composition that has the lowest Mn content is about Fe–0.7C–3Mn.

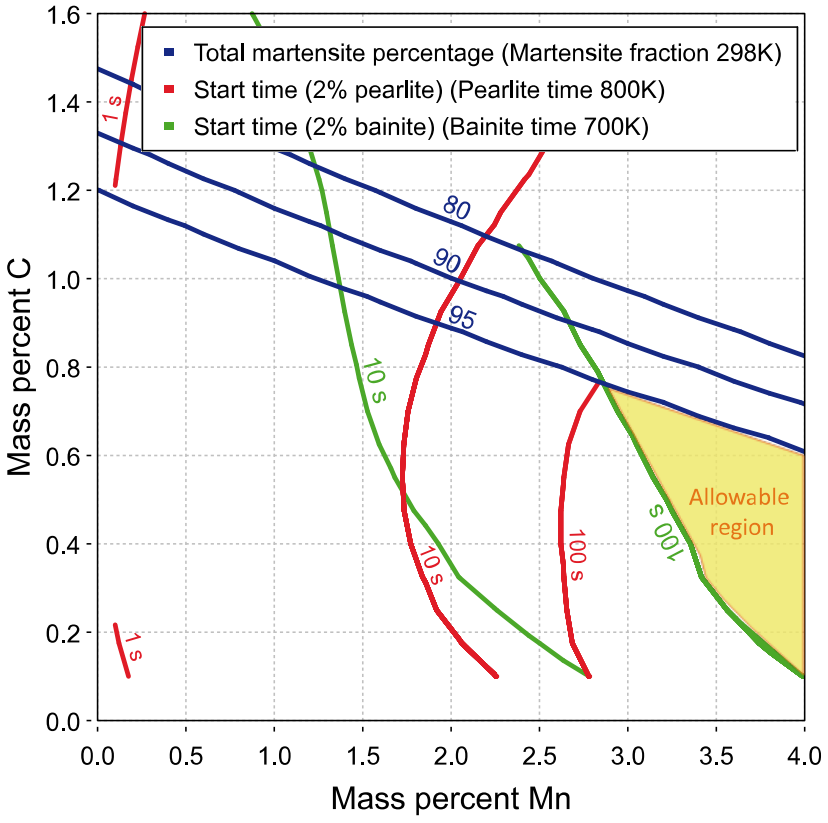

Figure 5. Total martensite percentage, start time of pearlite formation (2% pearlite, unit: second), and start time of bainite formation (2% bainite, unit: second) as a function of Mn and C contents for Fe-Mn-C (merge of Figures 2–4).

Notes about the Example

It should be mentioned that the composition of Fe-1 C-2 Mn (wt.%) in Figure 1 is chosen as an example. A different composition may have a different nose position of the TTT curve of pearlite, which slightly affects the composition range for the allowable region. On the other hand, a TTT diagram can be used as a rough guide and can provide a good starting point for the examination of hardenability. A Continuous Cooling Transformation (CCT) diagram, which records the progress of the transformation of a material as it is cooled over a range of cooling rates, is more practical. Work is currently being done in Thermo-Calc to complete the implementation of a Ferrite model as well as a CCT diagram, which will allow for more advanced designs.