Hardenability Analysis of a 4340 Steel Disk

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Introduction

The processing of steel alloys has as much of an impact on their final properties as the compositions of the alloys themselves. Specifically, the heat treatment of steel alloys influences their microstructure, which has a profound effect on their mechanical properties such as stiffness, hardness, toughness, and overall strength. When steels are cooled from their austenitizing temperature, the microstructure that forms is directly related to the cooling rate[1]. Slow cooling results in ductile equilibrium microstructures like pearlite, whereas fast cooling results in very hard microstructures like martensite. The ability of a steel to be cooled into a martensite phase across its entire cross-section is its hardenability[1]. It is often desirable to maximally harden a steel component by quenching it, but there is a limit to the depth of the hardenability of a steel component as its thickness increases due to induced temperature gradient in the component. For a large enough part, it is possible that a single quenching step can result in a different microstructure at its surface than at its core. This can be a desirable outcome for specific engineering applications due to the balance in hardness and ductility provided by a composite microstructure, but if a 100% martensite (or tempered martensite) structure is required, then limited hardenability depth can be a detriment to the resulting steel part due to a low uniformity of mechanical properties in the steel microstructure[5].

In the context of modern computer-driven engineering design, the end microstructure of the process and therefore the hardenability depth of the component can be computed before any physical testing/manufacturing is done. To that end, we designed a two-step simulation process to determine the microstructure of a simplified part based on its cooling rate. The main simulation used was finite element analysis (FEA), which simulated the cooling rate of a steel disk being quenched in a water bath. The determined cooling rate was then used in conjunction with a calculated time-temperature transformation (TTT) diagram for the steel alloy which the part was made from to determine the end microstructure achieved in both the core and on the surface of the disk. This simulation process was made to approximate a simple heat treating process in which a part is designed to be rapidly cooled for maximum hardness (100% martensite) in preparation for tempering heat treatment.

Simulation Methodology

The TTT diagram of 4340 steel was simulated using ThermoCalc. 4340 is a high strength steel with a carbon content up to 0.43%, and with small amounts of other alloying elements such as chromium, manganese, molybdenum, and silicon[2]. The composition of the 4340 was taken directly from Matweb[2] and input into the built-in steel property model calculator in ThermoCalc. The property models used were the start, half, and finish times and temperatures for pearlite, bainite, and martensite.

The simulated component was in the shape of a disk, representing a simple engineering component that needs to be quenched and tempered to gain high strength. The metal sample was defined to be at 1000 K, surrounded by water at 298 K. The disk had a diameter of 0.2 m and thickness of 0.01 m. It was modeled as a 2D cross section surrounded by a $1m^2$ of water that was rotated about the center to make a 3D shape. This approach was based on a Comsol simulation example of a glass of water cooling at room temperature[3], as our Comsol software does not contain the Metals Processing Module required to run quenching simulations[4]. Heat flow in the metal and into surrounding water was simulated, including the convection heat transfer effects of the motion of the water as due to temperature differentials and the creation of turbulent flow. The material properties for 4340 steel as included in Comsol were used to simulate a sample of 4340 steel being quenched in the water using the model described above. The calculated cooling rate from the Comsol simulation was then compared with the simulated TTT diagram to infer the final microstructure within the sample at its surface and core.

However, the initially described FEA method (Figure 1) was computationally intractable, as all simulations failed to calculate beyond a few thousandths of a second. To simplify the simulation to a practical level, the next iteration of the FEA simulation did not model the quenching water at all, assuming perfect mixing would cause the water temperature to be constant. This would mean that the convection heat flux can be simplified as a constant cooling rate that changes as a step function at specific temperatures.

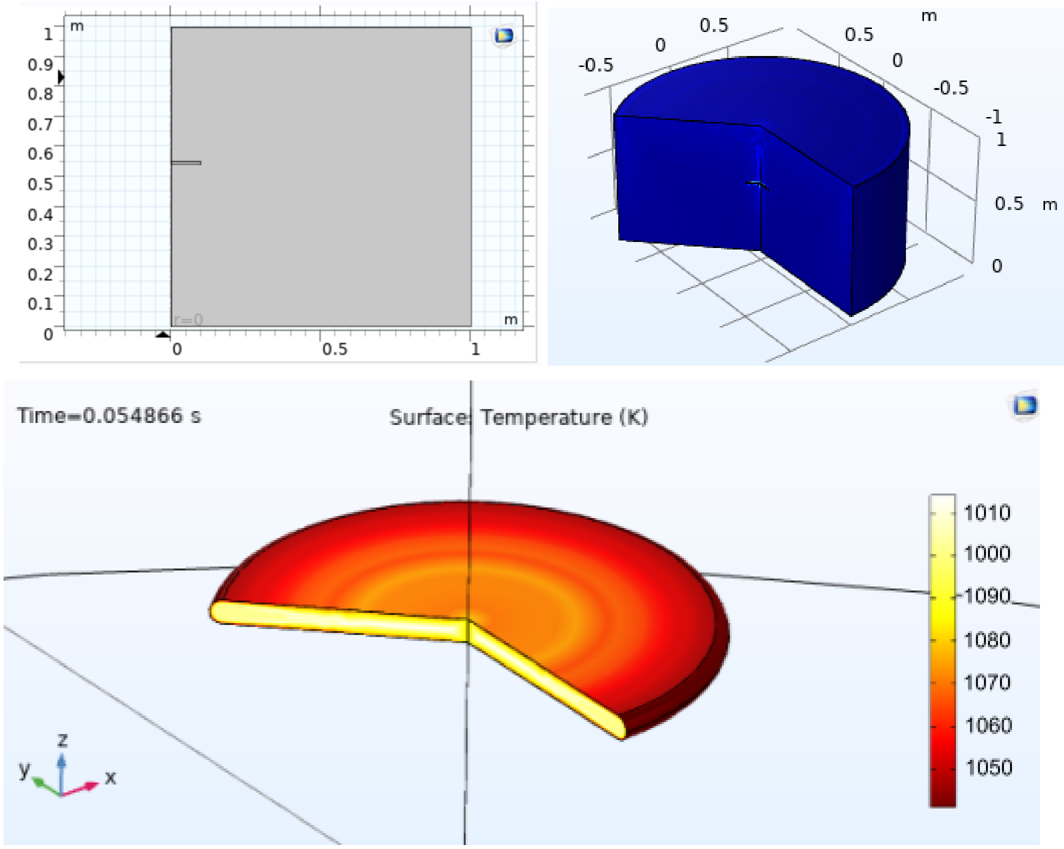

Figure 1a, 1b, 1c (starting at top left): 1a. Disk geometry, 1b. Visualization of the disk in a large water bath, 1c. Simulated cooling of the disk under turbulent model

A data table of these reference heat transfer rates as a function of temperature was taken from the quenching example video on Comsol's website[3] and is shown below in figure 2.

t	f(t)
0	200
300	200
500	2800
650	750
1300	750

Figure 2: Heat transfer step function for the steel quenching simulation

This version of the FEA simulation ran much faster and was able to simulate the first 1000 seconds with time steps of 0.01 seconds, making simulation feasible given the limitations of the software version used.

Results/Discussion

3D heat maps of the metal sample after varying cooling times are included below in Figure 3. The sample cooled faster on the outside edges than in the center, with the very center of the disk cooling the slowest . This resulted in a temperature gradient within the solid material in which the core is hotter than the surface.

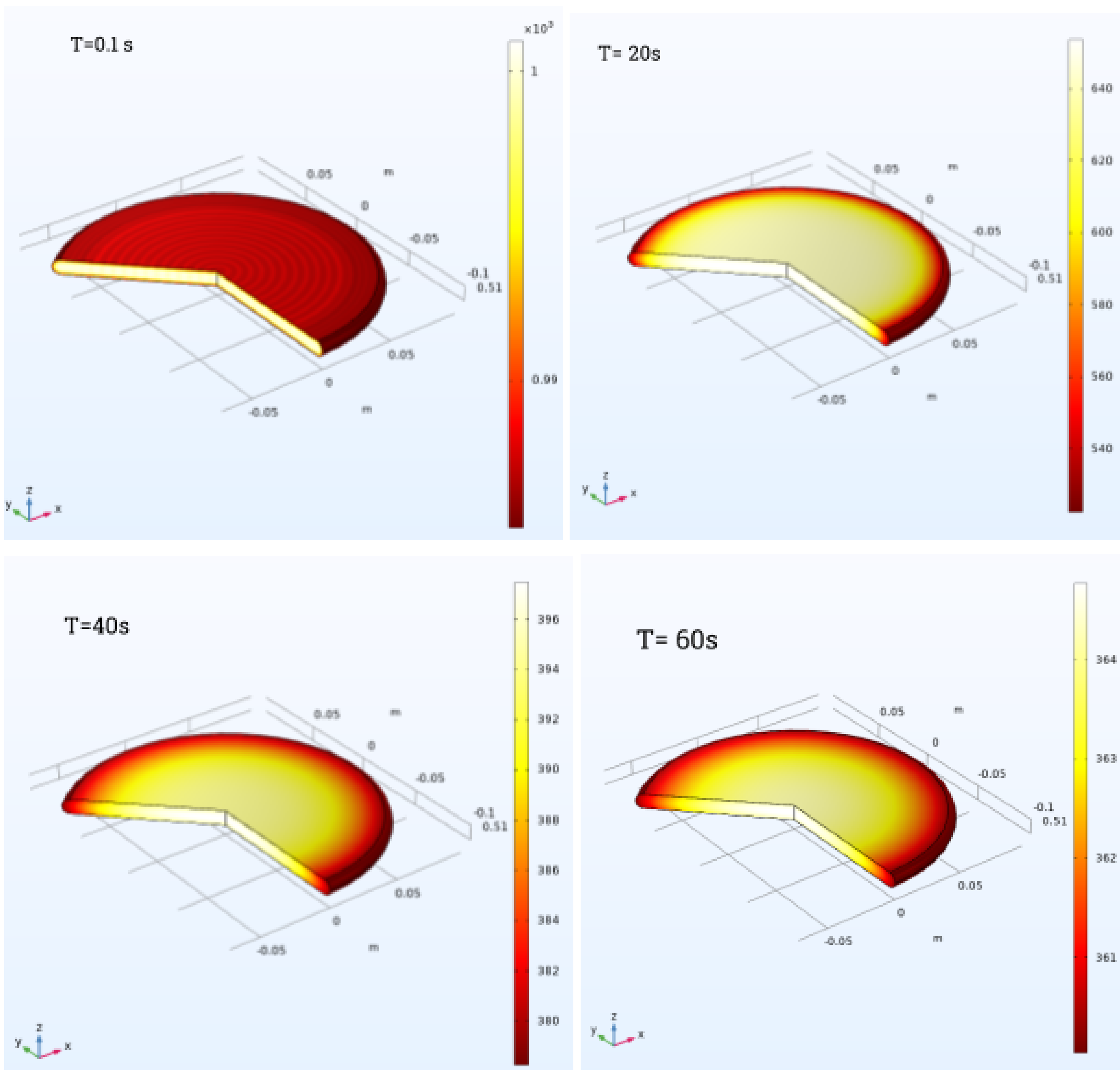

Figure 3: Temperature in the disk at different simulation times

A point at the center of the metal sample and a point on the outer edge were chosen to compare the cooling rates across this temperature gradient. From the changing temperature at these points, Comsol automatically produced a temperature vs time graph which is included as Figure 4.

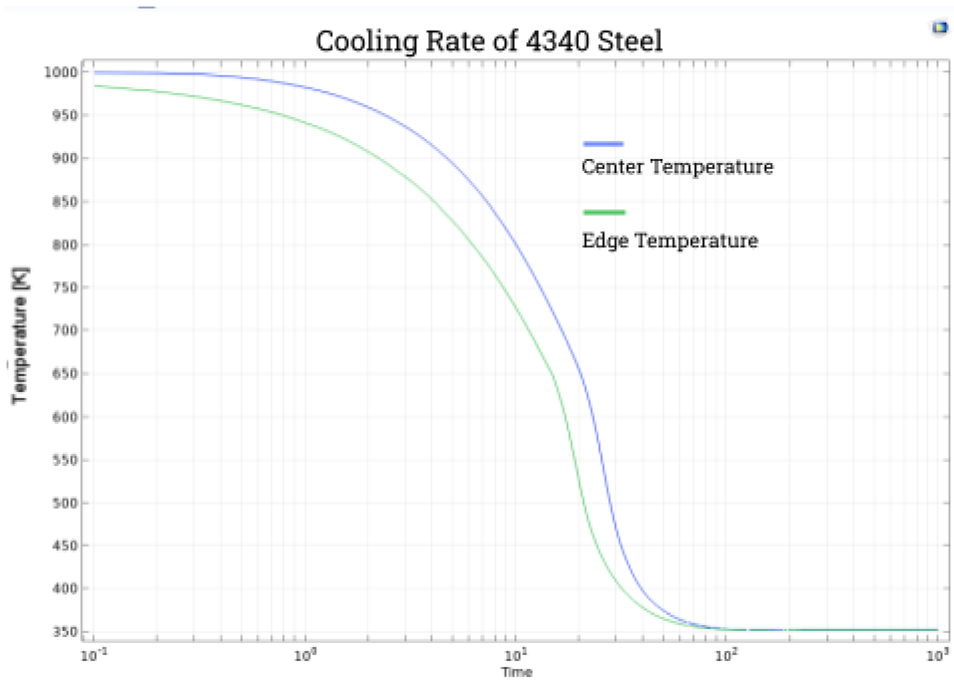

Figure 4: Cooling curves for the disk at the center and edge

Both the center and edge of the disk follow the same cooling path, with the center cooling slightly slower than the edge as expected. Figure 4 shows that there is no significant difference in cooling rate between the core and surface of the disk.

The second part of the designed simulation process was to infer the end microstructure of the part at the edge and core of the disk. First, the TTT diagram for the 4340 steel was simulated using the described methodology. The simulation results are seen below in Figure 5.

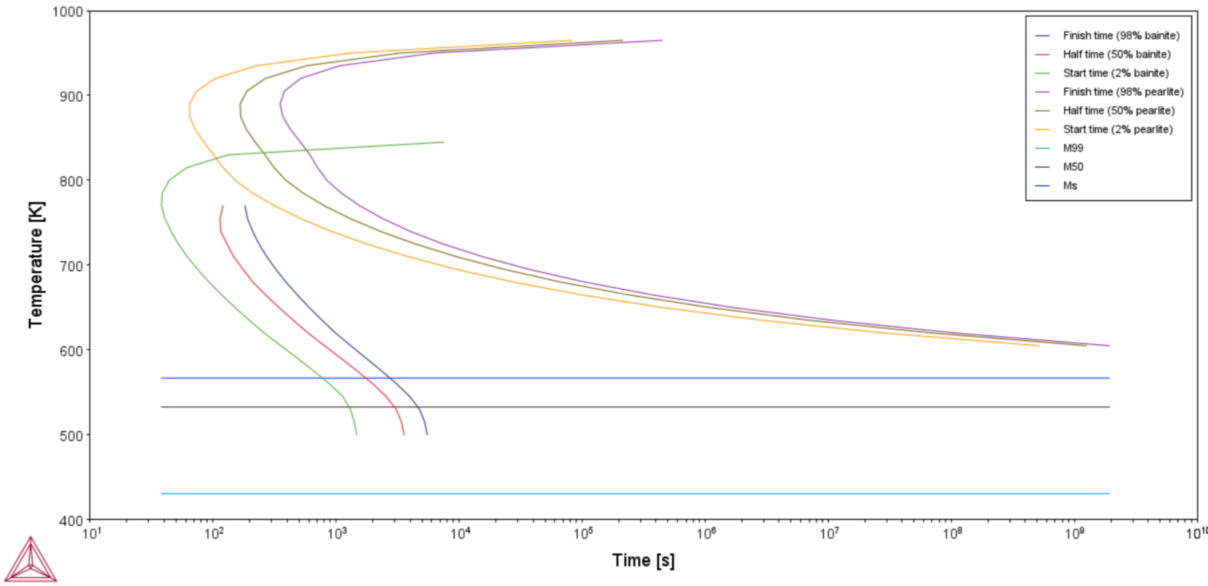

Figure 5: ThermoCalc simulated TTT diagram of 4340 steel

The calculated TTT diagram is a good approximation of the transformation behavior of the 4340 steel, despite some conceptual inaccuracy regarding the pearlite curves. Specifically, 4340 is a hypoeutectoid steel, meaning its equilibrium-cooled microstructure should show a proeutectoid α phase that solidifies before the pearlite (which would show as a separate start time, temperature). This was a limitation of the property model calculator used, but should not affect the simulation results here since we only consider a high cooling rate via water quenching (i.e. no pearlite). To compare the FEA cooling data against the TTT diagram generated by ThermoCalc, the Comsol graph was scaled so its time scale matched the logarithmic TTT diagram time scale, and then it was overlaid onto the TTT diagram (Figure 6).

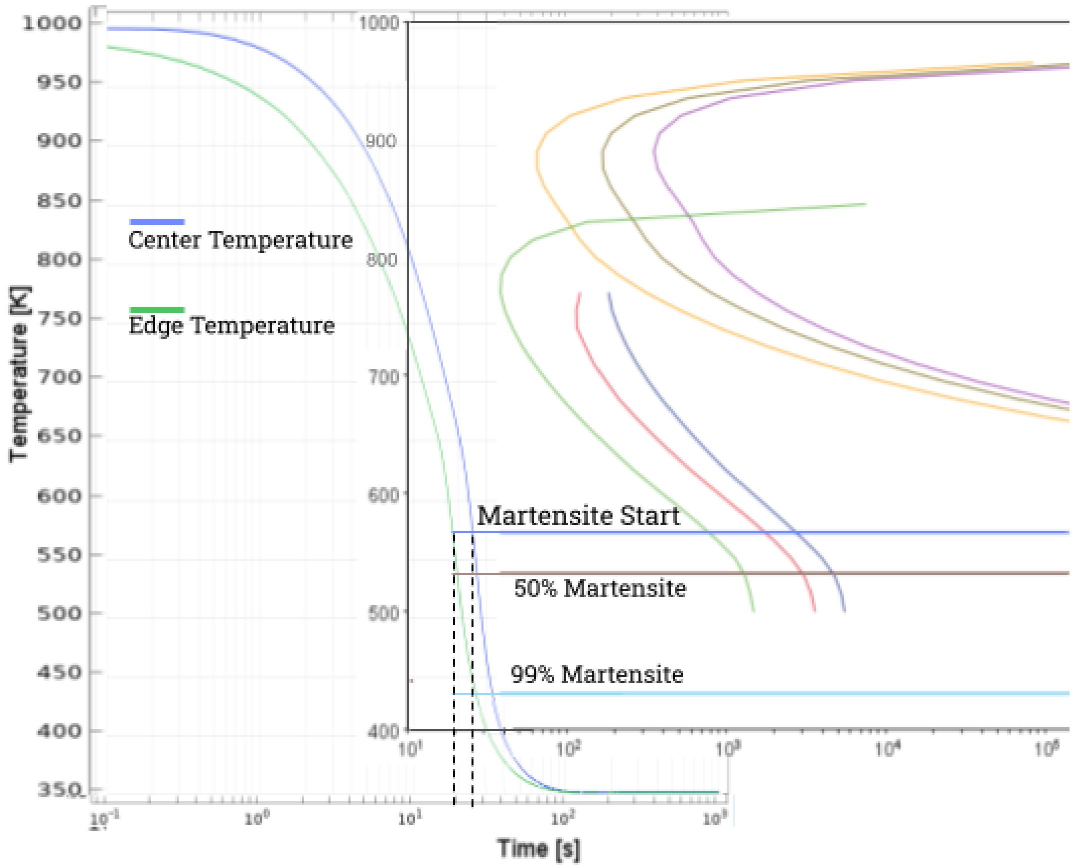

Figure 6: Combined TTT/cooling rate diagram

The results of these simulations indicate that the steel sample reached the martensite start temperature within 20 seconds, and 99% had transformed within 40 seconds. After 60 seconds, the disk is well below the temperature corresponding to the martensite transition. The high cooling rate from water quenching results in a 100% martensitic microstructure in the disk.

Conclusion

The simulation performed on the 4340 steel disk indicated that with this geometry, there is no limit to the depth martensite will form via quenching. Given that the presumed goal of the heat treatment processing is to make a high-strength tempered martensite part, the simulation of the processing methods described above proves that this microstructure is easily attainable. Additionally, the same simulation methodology can easily be modified to be applied to different processing routes, notably with hot oil quenching, air cooling, or any combination of cooling methods.

References

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