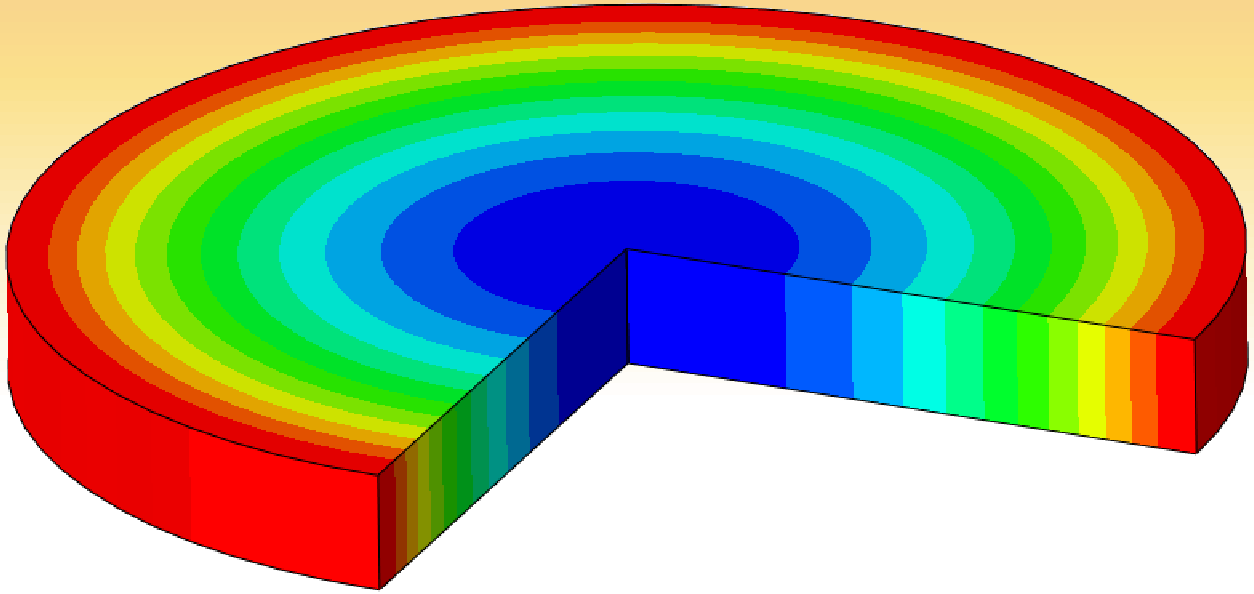
Improving Temperature Uniformity during Induction Tempering using Simultaneous Cooling

Comparison of temperature and hardness uniformity



Introduction

Tempering of steels has traditionally been conducted in furnaces, requiring many hours to complete a cycle due to the relatively slow heating rate. With induction hardening becoming a popular choice in industry, the use of induction for tempering seems like a logical choice to decrease processing time. However, unlike furnace heating, which produces a uniform temperature in the part once thermal equilibrium is achieved, induction heating produces a temperature gradient through the cross-section of a part. This is due to the Joule heating gradient induced by the induction coil. This temperature gradient created by induction heating is acceptable, even preferable, for quenching operations since it helps develop surface compressive stresses by only transforming the near surface to austenite. However, a temperature gradient during tempering means a gradient in hardness, strength, and ductility since the part is effectively tempered at different temperatures.

In an effort to reduce the temperature gradient during induction tempering, DANTE was used to explore the possibility of simultaneously heating with induction and quenching. Since induction heating produces a temperature gradient from the surface of high to low, and quenching produces a temperature gradient from the surface of low to high, it is possible to superimpose these two gradients to improve the overall temperature uniformity through the cross-section of a part.

Model & Process Definition

Part:

- 50 mm diameter cylinder, infinitely long
- AISI 4140 steel alloy

Model:

- A 5 mm axial length section is chosen from the infinitely long cylinder, ignoring end effects
- Axisymmetric cross-section used; assumes thermal boundary conditions are circumferentially uniform

Process 1:

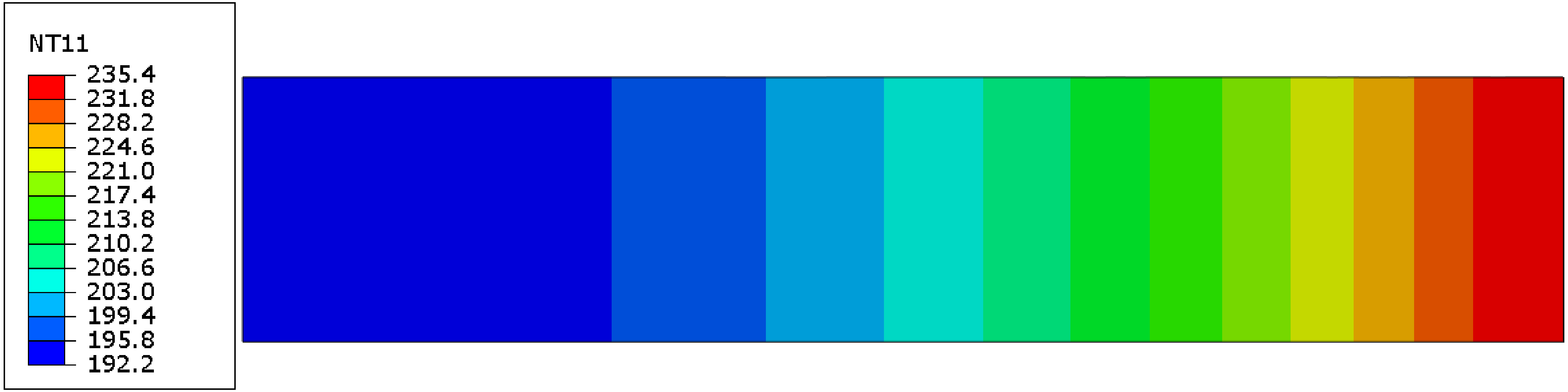
- Assumes initial microstructure is 95% as-quenched martensite and 5% retained austenite
- Use induction heating to achieve a target average temperature of 200° C

Process 2:

- Assumes initial microstructure is 95% as-quenched martensite and 5% retained austenite
- Simultaneously quench the surface while heating with induction to achieve a target average temperature of 200° C
- Same frequency used as Process 1, but with higher power to compensate for the thermal energy removed during quenching

Process 1 Temperature Uniformity

- Joule heating profile created by induction heating reaches a depth of 3.6 mm
- Target average temperature of 200° C
- 40° C temperature difference between surface and core, with the surface being tempered at the **highest** temperature
- Temperature gradient will result in hardness and mechanical property gradient, with the **surface being softer than the core**

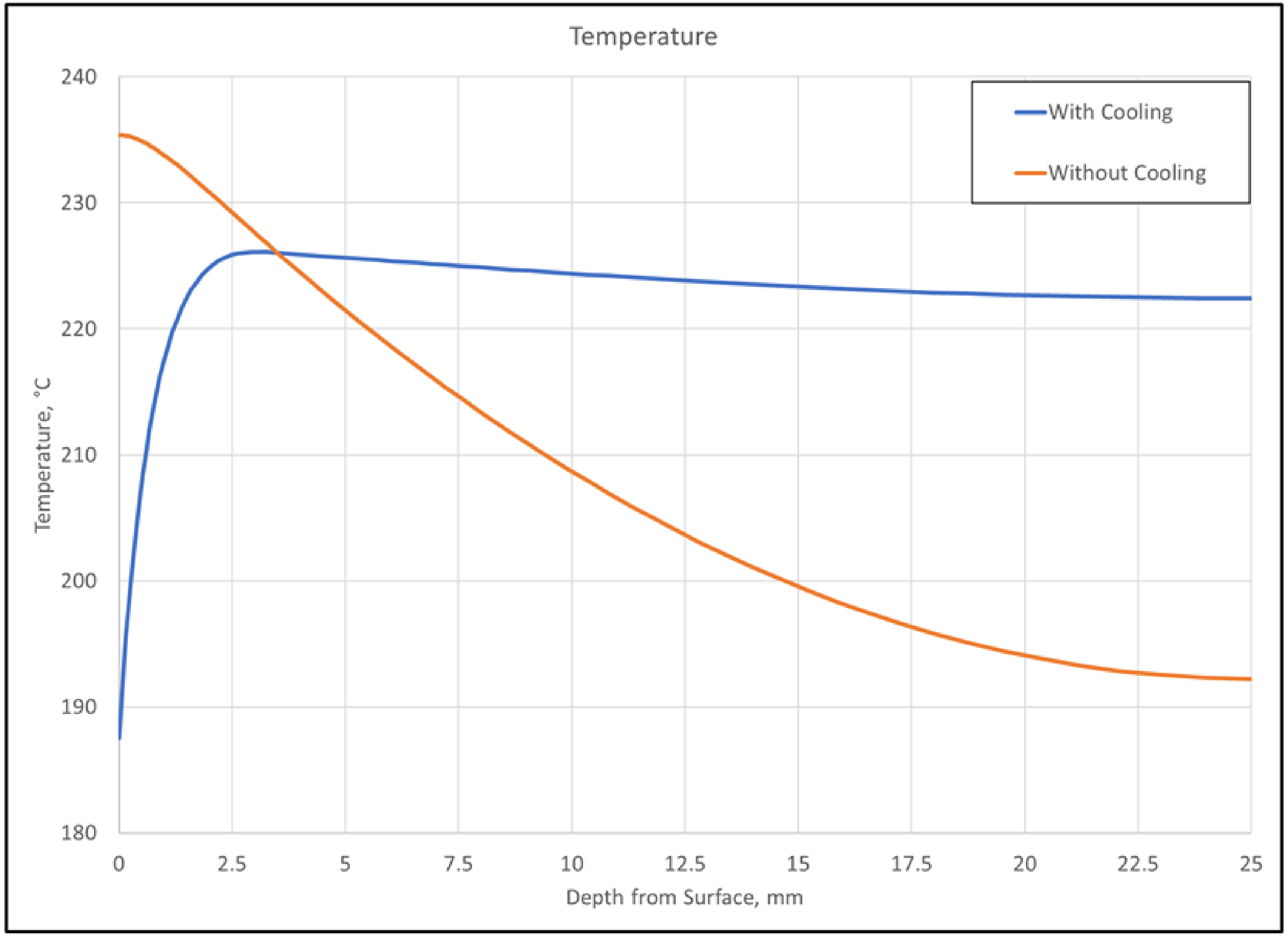


Process 2 Temperature Uniformity

- Joule heating profile created by induction heating reaches a depth of 3.6 mm
- Heat transfer coefficient (8,000 W/m^2K) and ambient temperature (20° C) applied to the surface to simulate quenching
- Target average temperature of 200° C
- 40° C temperature difference between surface and core, with the surface being tempered at the **lowest** temperature
- Temperature gradient will result in hardness and mechanical property gradient, with the **surface being harder than the core**

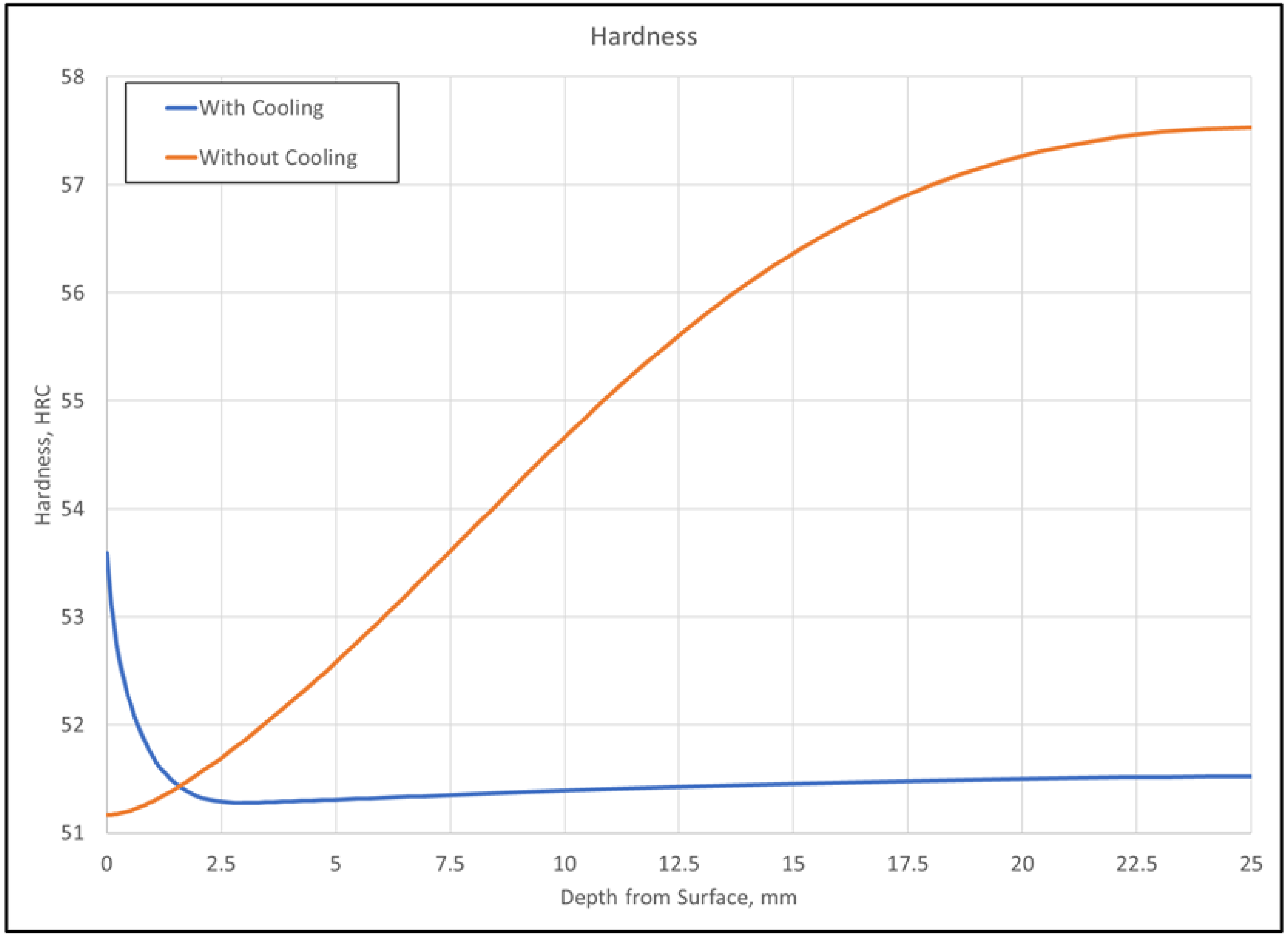
Temperature Uniformity Comparison

- Comparison of temperature profile from the surface to the core after steady-state conditions are reached for Process 1 (without cooling) and Process 2 (with cooling)
- Temperature uniformity never achieved in Process 1 using conventional induction heating to temper
- Temperature uniformity achieved from 2 mm under the surface to the core in Process 2 using induction heating while simultaneously quenching to temper
- Process 2 will result in more uniform hardness, strength, and ductility than Process 1



Hardness Uniformity Comparison

- Comparison of hardness profile from the surface to the core after cooling to room temperature after tempering for Process 1 (without cooling) and Process 2 (with cooling)
- Process 1 never achieves hardness uniformity through the cross-section and has a 6 HRC point difference between the surface and the core
- Process 2 achieves hardness uniformity after 2 mm depth from the surface and has only a 2 HRC point difference between the surface and the core
- Process 2 creates a more favorable material property gradient, with the surface being harder and stronger than the core



Summary

In conclusion, the temperature uniformity of an induction tempered component can be significantly improved if the component is simultaneously cooled while being heated with the induction coil. DANTE modeling was used to show that although the magnitude of the temperature gradient is the same between the two processes, they are inverse to each other.

The cooled and heated condition creates the gradient over a small distance near the surface, whereas the heated only condition spreads the gradient out over the entire cross-sectional thickness. The differences in the two gradients are reflected in the hardness profiles; the cooled and heated condition produces a nearly uniform hardness profile, except for a slight increase near the surface. This is in contrast to the heated only condition, which produces a large hardness difference between the surface and the core, with the core being harder than the surface. A harder core and softer surface can have detrimental effects on fatigue performance.

Heat-treatment simulation software, such as DANTE, can be used to optimize the process with respect to temperature uniformity by determining the appropriate frequency, power, and quench rate. Once optimized using simulation, induction tempering using simultaneous cooling can be an excellent choice to replace time intensive furnace tempering operations, while still maintaining uniform properties after tempering.

Links to Relevant Case Study Material

Additional DANTE Case Studies

https://dante-solutions.com/steel-production