4th International Ingot Casting Rolling Forging (ICRF) Conference
21–23 June 2022, Pittsburgh, Pa., USA
DOI 10.33313/530/017

Process Design for Induction Hardening of a Steel Work Roll Using Simulation

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INTRODUCTION

Work rolls used in the rolling of steel billets are generally made of high-hardenability chromium alloy steel and must be heat treated prior to entering service to ensure a sufficiently hard working surface. In combination with a hard surface, the roll should also possess superior resistance to wear and thermal shock. [1] Compared to other surface hardening methods, induction hardening (IH) has become a popular process for hardening steel work rolls. However, designing the critical IH process parameters can be challenging, given the large temperature gradients induced in the roll.

The large temperature gradients encountered during induction heating, and the subsequent liquid quench, can present themselves radially and axially during the scanning induction hardening process of a large work roll. Consequently, small variations in processing parameters can have significant effects on the microstructure obtained and the in-process and residual stresses. Many IH processing parameters can have a significant effect on the product's in-service performance and include, but are not limited to, the preheat temperature, frequency and power supplied to the inductor, cooling power of the quenchant, relative inductor scanning rate, inductor or quench head dwells, and the environmental temperature. [1]

Surface treatments, in combination with increasing surface hardness, aim to induce residual surface compressive stresses. Residual stress has long been known to significantly influence the fatigue and wear performance of steel work rolls. High levels of surface compressive stresses are desirable to arrest crack formation and offset any tensile loads experienced by the roll in service. However, the surface compression must be balanced by tensile stresses, which in an induction hardened work roll, generally occur just below the hardened layer. [2 - 5] Given the location of the tensile stress peak subsurface, and the Hertzian stress distribution induced from rolling contact, a properly designed case depth and residual stress profile is critical in ensuring the work roll is able to withstand the harsh conditions during operation.

Given the breadth of possible process parameter combinations available for any given induction hardening process, and the significant time and cost associated with physical, experiment-driven trial-and-error approaches, computer simulation is well suited for the task of process parameter evaluation and determination. The following examples utilize the commercially available heat treatment simulation software DANTE to examine how heat treatment simulation can be used to evaluate and determine appropriate process parameters for the induction hardening of a steel work roll to meet case depth and hardness requirements, while ensuring a low probability of developing quench cracks. Distortion and residual stresses are also predicted by DANTE, which are critical for evaluating product performance in-service. [5 – 6]

With computer hardware and software becoming available to a wider group of industry analysts and experts, in-service performance and fatigue modeling of components prior to physical testing are being utilized across many industries to discover design problems prior to any physical part being manufactured. The importance of residual stress on in-service and fatigue performance has been previously mentioned, but if the post-heat treatment models are to accurately represent reality, then the residual stress state from heat treatment must be considered as the initial condition for these subsequent simulations. [7 – 8] Residual stress is also an important consideration when performing any post-heat treatment or mid-life rework grinding operations, as the removal of material will cause a rebalancing of the residual stresses. If the tensile field is too close to the surface after the initial surface hardening, grinding may bring the tensile field within the Hertzian contact stress field and can cause premature failure of the roll in-service. [4]

DISCUSSION

1. Model Description

To explore the benefits of process design using heat treatment simulation to determine appropriate induction hardening process parameters, a generic work roll geometry was created using Abaqus CAE. The model assumes cyclic symmetry, which is an appropriate assumption given that the part exhibits circumferential symmetry about its axis and is subjected to circumferentially uniform thermal loads (i.e., heat transfer coefficients and ambient temperatures). The latter assumption is also reasonable when little is known about the uniformity of the thermal cycles being simulated and an initial evaluation needs to be conducted. Figure 1(A) shows the CAD model, with dimensions, of the work roll used for this study. The roll barrel has a diameter of 458 mm, a length of 1000 mm, and is the only section of the roll that is hardened in this example. This example also assumes that the prior heat treatment to obtain the appropriate microstructure has been completed and that the roll has been properly stress relieved and is dimensionally accurate. However, DANTE can also be utilized to model the initial heat treatment and stress relief cycle, with the results then used as the initial conditions for the IH process simulation. In this way, the microstructure, residual stress, and dimensional changes induced by the bulk heat treatment can be carried forward, resulting in an overall more accurate prediction.

Figure 1(B) shows a schematic of the assumed induction hardening process. DANTE does not model the electromagnetic (EM) phenomenon directly, but can take the Joule heating history from an EM simulation to be used as the thermal load for the DANTE heat treatment model. If EM modeling is unavailable, or is undesirable, the Joule heating profile can be determined and defined through a trial-and-error approach when the desired case depth and surface temperature are defined. All of the examples shown in this paper had Joule heating profiles defined manually, with the help of several custom DANTE algorithms. For the examples described here, the inductor has an axial size of 100 mm, which remained constant for all cases examined. Several parameters were varied to evaluate the effects on the final product, including the inductor scanning velocity, preheat temperature, and the quench delay, which is the time delay between the end of heating and the start of quenching.

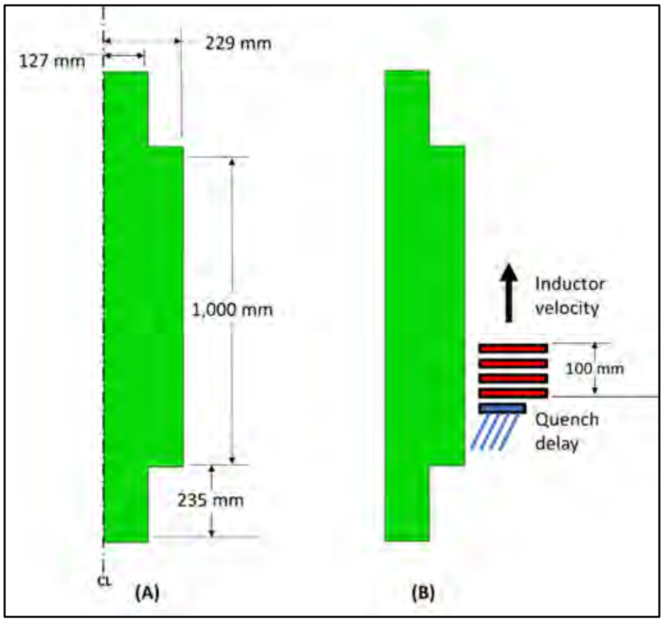

Figure 1. A) CAD model of generic work roll, with dimensions; B) schematic of the induction hardening process.

2. Results

When manually defining the Joule heating profile, it is necessary to define the target case depth and surface temperature prior to executing any models. The examples described here target a 70 mm case depth and an in-process surface temperature of 1100° C. Given these constraints, the inductor velocity was set to 5 mm/s and the quench delay was set to 5 seconds. The results from these conditions were used to compare further process parameter changes.

2.1 Baseline Model

The initial model, referenced as the Baseline model, starts with the roll at room temperature (20° C). The residual stress is shown in Fig. 2 for the Baseline model and reveals potential issues with the residual stress magnitude in the axial and hoop directions. While the magnitude of the surface compression is high, approximately 600 MPa, the tension needed to balance the thick layer of near-surface compression is substantial; 1000 MPa and 700 MPa in the axial and hoop directions, respectively. While the high surface compression will certainly improve the wear characteristics and fatigue performance, the high magnitude of triaxial stress at mid-radius is concerning, as any defect acting as a stress concentrator has a good chance of initiating a crack.

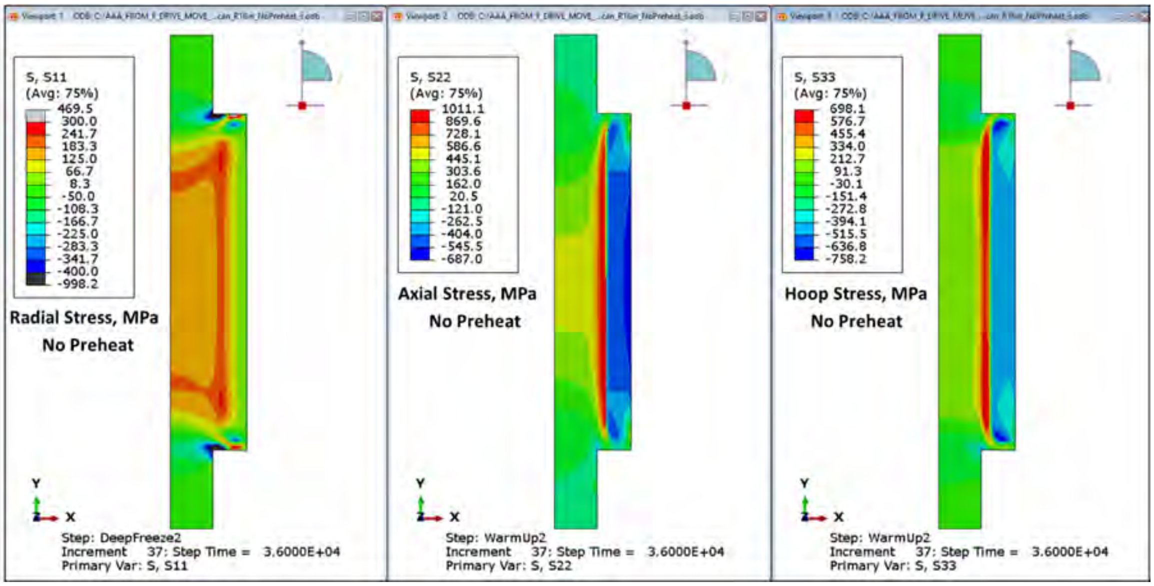

Figure 2. Residual stress distribution with no preheat, 5 mm/s scan rate, and 50% power.

A few notes on the results in Fig. 2:

1) Given the starting location of the inductor relative to the roll neck-barrel junction, the starting end behavior generally requires a dwell of the inductor to harden that location to the proper depth. This behavior was not accounted for in the models shown, though it can, and should, be accounted for.

2) The finishing end behavior can be just as problematic as the starting end behavior, though the finishing end tends to overheat if power is not shutoff prior to the inductor making it past the end. The models shown turn the power off as soon as the top of the inductor reaches the top of the roll barrel to avoid needless complications.

3) The near-surface of the roll barrel is in a state of triaxial compression and the volume of material just below the hardened case is in a state of triaxial tension. Contact and bending loads should not penetrate this deep into the roll, by design, but any defect located in this area could cause issues, as many different types of defects act as stress concentrators in a significantly stressed region.

4) The radial stress in the roll neck-barrel connection should not be trusted, as no filet was added due to the roll barrel being the point of interest. Sharp corners in FEA simulations act as stress concentrators much like the defects described previously. Actual rolls will have fillets or knocked-down edges to prevent these concentrators.

5) Several model iterations were required to describe the Joule heating versus depth required to hit the case depth and surface temperature targets. Manual Joule heating definitions can be useful in learning how a component behaves to power and frequency changes, with the power controlling the magnitude of Joule heating and the frequency controlling the depth of heating.

2.2 Inductor Scan Rate Comparison

There is an obvious desire to perform heat treatments as quickly as possible in industry, so the inductor scanning rate is the first parameter to be evaluated in this study. From Fig. 3, if the inductor scan rate is doubled (whether the rate of the inductor is relative or actual is inconsequential), from 5 mm/s to 10 mm/s, and the power is not adjusted, the temperature does not reach a sufficient magnitude. In this case, the temperature did not even reach the austenitizing temperature. To account for the increase in inductor velocity, the power must be increased. For this case, the adjustment appears linear and doubling the scanning rate required a doubling of the power input to the inductor. Generally, the power will need to increase if the inductor scanning rate is increased, though it may not always be a linear type of relationship as many other parameters influence power requirements. The temperature profiles of the left and right contour plots in Fig. 3 appear different, but the Baseline (left contour) has been cooling for twice as long as the faster scanning rate case, so more thermal energy has had time to be removed from the core.

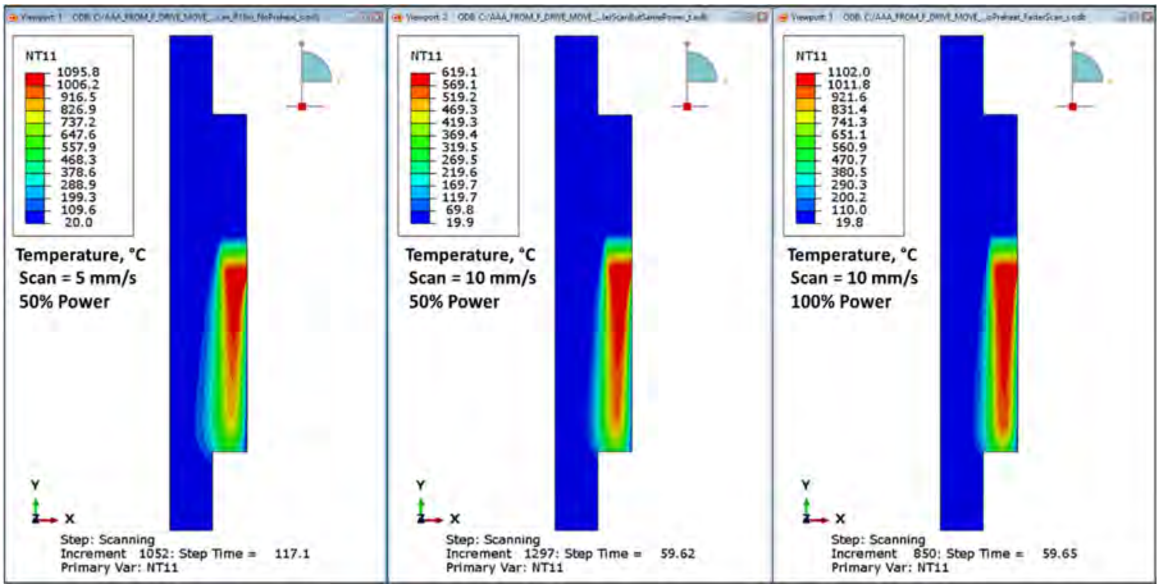

Figure 3. In-process temperature distribution comparing scan rates and power supplied to the inductor.

Generally, the scan rate is going to be limited by the inductor, particularly its power capabilities. Figure 4 shows that the two scan rates produce approximately equivalent residual stress profiles after the power is adjusted to account for the increased scan rate. The maximum scan rate will vary between inductors and systems and simulation can be a useful tool in helping to determine the optimum scanning rate for a given system and component.

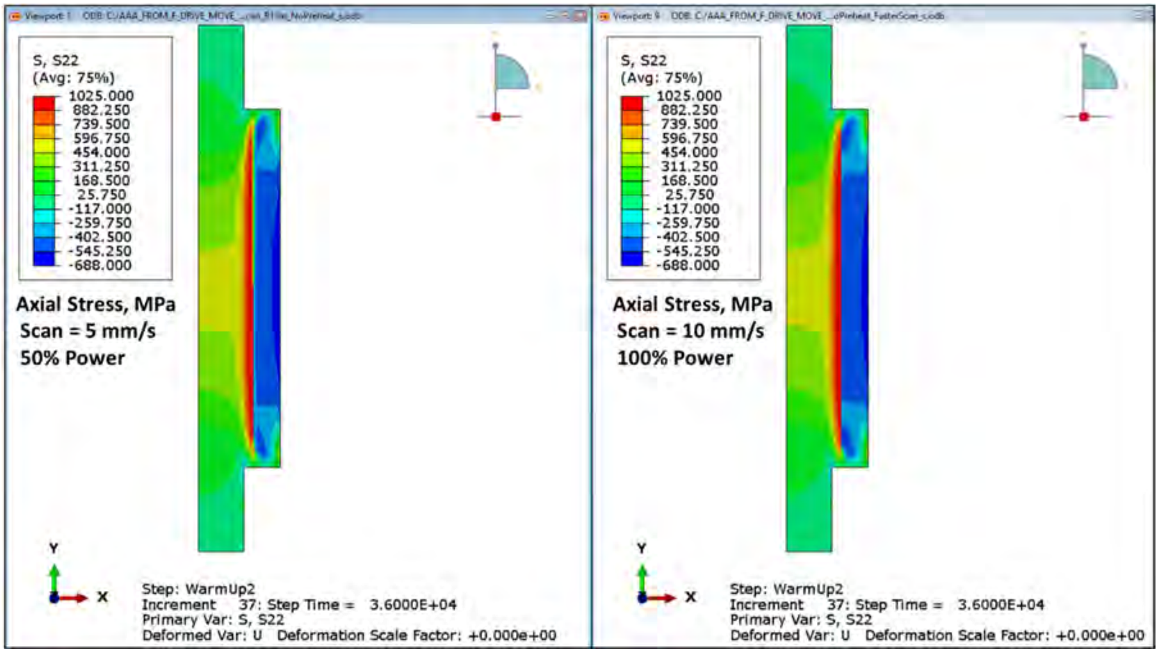

Figure 4. In-process temperature distribution comparing scan rates and power supplied to the inductor.

2.3 Preheat Temperature Comparison

Another parameter that has been shown to have a significant effect on the in-process and residual stress is the preheat temperature applied prior to induction hardening. [9 – 10] Figure 5 compares the residual hoop stress in the Baseline model, having no preheat, with two preheating temperatures, 300° C and 500° C. The model assumes that the roll is preheated in a furnace, such that the entire roll is through heated, though induction preheating is another viable option. The residual stress states look very similar in the hoop direction, though there is a slight decrease in the tensile stress at the case-core transition and a slight increase in the core tensile stress as the preheat temperature is increased. However, Figure 6 shows the residual stress in the axial direction, which shows a modest increase in surface compression as the preheating temperature is increased, with a pronounced increase in the core tensile residual stress, particularly for the 500° C preheat temperature.

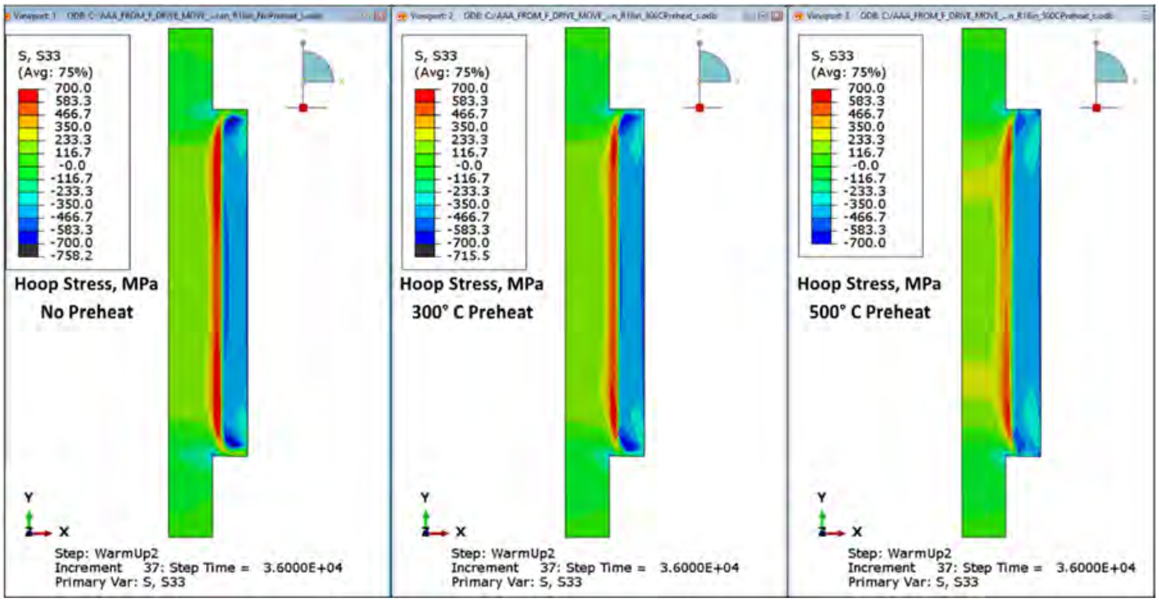

Figure 5. Residual stress distribution in the hoop direction comparing preheat temperatures, with modified power.

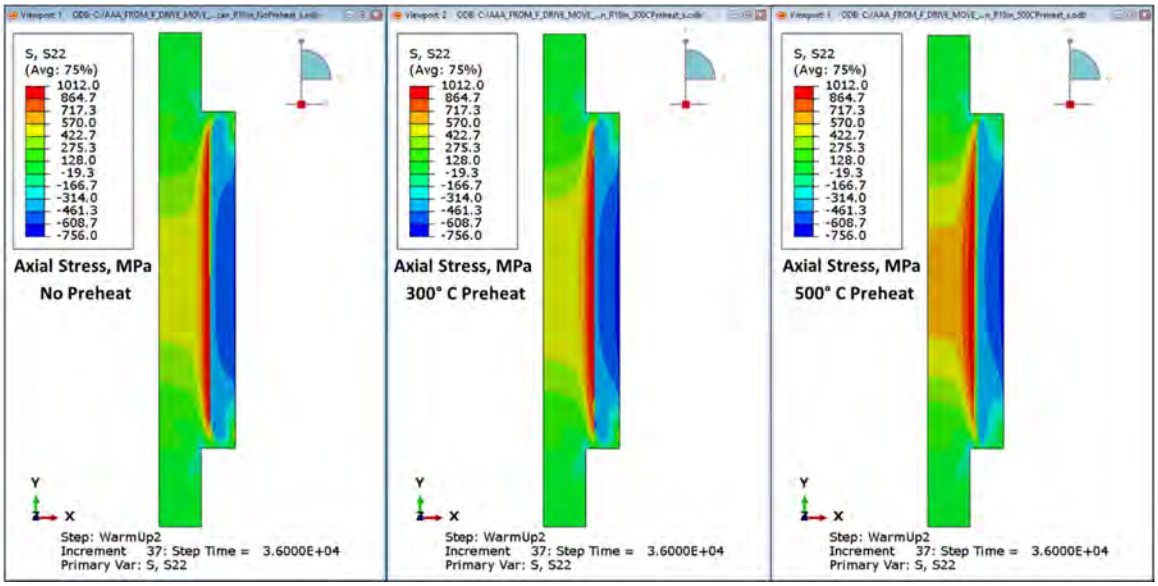

Figure 6. Residual stress distribution in the axial direction comparing preheat temperatures, with modified power.

Although preheating the roll did not significantly alter the residual stress in the hoop direction for this case, preheating did reduce the in-process hoop stress by 100 MPa, when starting with a roll at 500° C instead of 20° C, as shown in Fig. 7. The stress evolution can be evaluated for all cases to ensure that, in addition to a favorable residual stress profile, the in-process stress state does not exceed the material's strength limits at the processing temperatures. Depending on the roll manufacturing process, consideration may need to be given to inclusions at a given depth and their influence on the stress state.

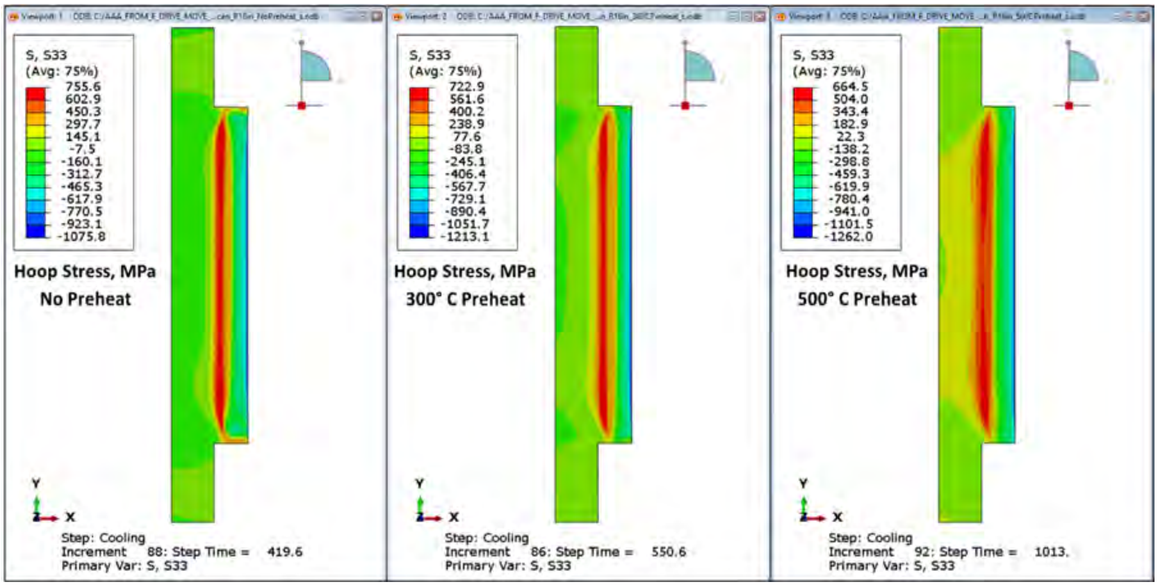

Figure 7. In-process stress distribution at time of maximum tension, comparing preheat temperatures with modified power.

The final parameter explored in this study was the quench dwell time. Generally, delaying the start of quenching after some volume of material is no longer being Joule heated can significantly influence the case depth and the stress at the case-core transition. Figure 8 compares the final martensite phase fraction (top) and axial stress (bottom) for the 5 second quench dwell of the Baseline model (left) and a 20 second dwell (right). All other processing parameters were held constant between the two models. Given the 70 mm deep case, the quench delay has a less significant effect on the roll than on induction hardened components with shallower case depths and steeper thermal gradients. For components with case depths in millimeters, instead of 10s of millimeters, quench delays separated by a few seconds can have significant effects and often determine whether a component is acceptable for service.

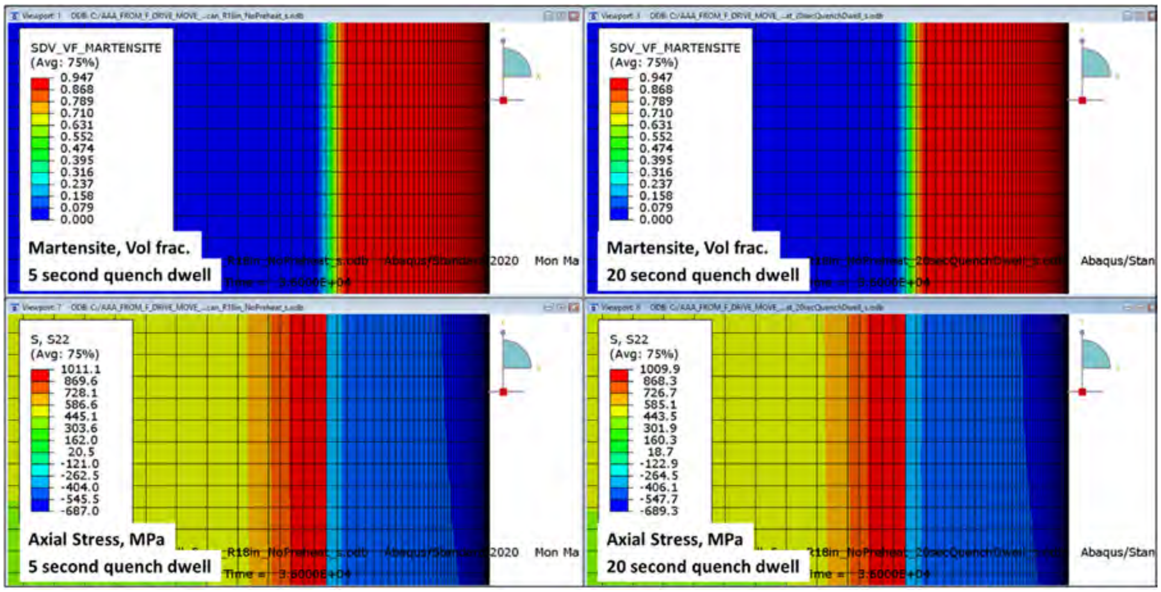

Figure 8. Final martensite phase volume fraction and axial stress distribution at mid-length of the roll barrel, comparing quench dwell times.

Figure 9 is a snapshot in time at the location shown in Fig. 8, showing the temperature profile several seconds after the inductor has passed by the location. It is clear that there is a slight increase in temperature in the mid-case region, but the thermal energy is unable to diffuse further towards the core before the quenchant pulls it out as heat. The shallow thermal gradients induced by the lower frequency required to induce eddy currents at greater depths is mainly responsible for the behavior witnessed.

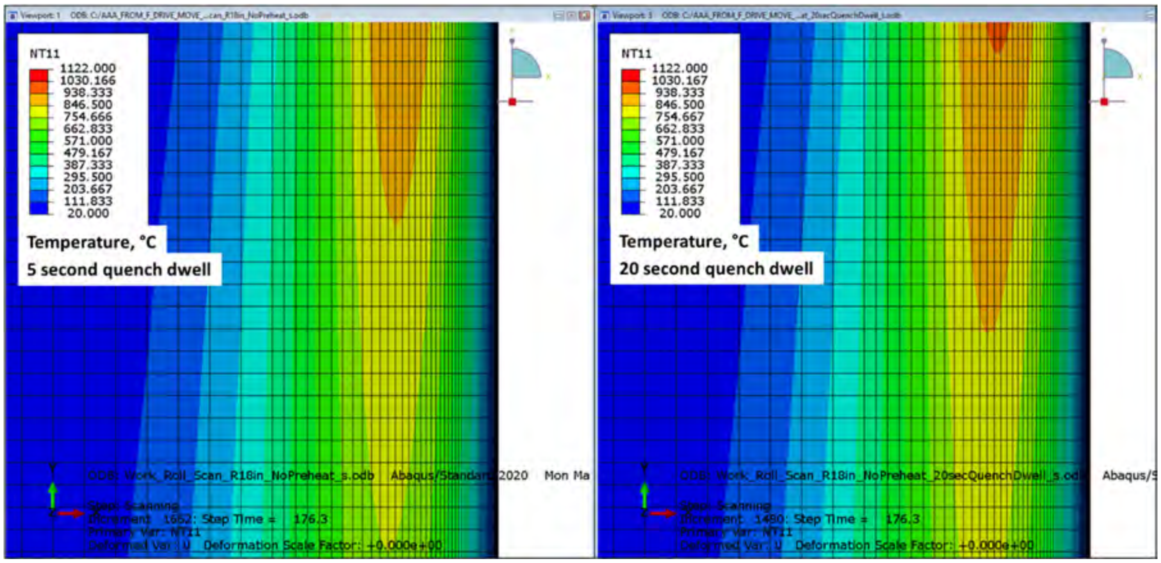

Figure 9. In-process temperature distribution at mid-length of the roll barrel, comparing quench dwell times.

CONCLUSIONS

As processing demands continue to place tremendous loads, both mechanical and thermal, on steel work rolls, simulation will become an integral part of the design phase. The integration of heat treatment simulation will be necessary to quickly determine optimum processing conditions for a range of critical material characteristics, including, but not limited to, hardness, in-process and residual stress, distortion, and microstructural phase distribution. Not included in this list are the material properties that must also be at optimum values relative to other property requirements, which include yield strength, tensile strength, impact strength, ductility, and many more. Achieving these conditions can be challenging for any designer, especially given the number of possible processing parameter combinations involved in induction hardening of such a large component.

In the preceding study, the commercially available heat treatment simulation software, DANTE, was used to evaluate several different processing parameters related to induction hardening of large steel work rolls. It was shown that, for the specified case depth and in-process surface temperature, preheating the roll barrel prior to induction harden can help reduce the in-process and residual tensile stresses by reducing the sharp thermal gradient between the case and core. Preheating can also help improve the surface residual compressive stresses by pulling the surface into deeper compression as the entire body cools and contracts. However, this phenomenon can also increase the subsurface tensile stress. The simulations also revealed that the scanning rate showed very little effect on the residual and in-process stresses when the power was adjusted to reach austenitization temperatures. Furthermore, increasing the quench dwell showed no significant effect due to the very large, required case depth typical to these work rolls. From past experience, shallower cases show more of an effect from a quench dwell due to the thermal energy bleeding deeper into the part. Regardless, a few DANTE simulations showed that variations in a few parameters could be significant to the in-process and residual stresses of large work rolls, saving untold time and money on actual experiments on physical rolls.

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