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Using Heat Treat Simulation to Characterize Sensitivity of Quench Hardening Response in Hot Mill Steel Work Rolls

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Abstract

Quench hardening of work rolls for steel rolling is used to impart both residual compression and hardness to the roll surface to promote durability, wear resistance and life. Minimizing required roll re-dressing and mill down time are important cost drivers for improved work roll surface life. Developing the necessary metallurgical and mechanical response of these rolls in heat treatment is complex, often involving a heating and quenching sequence in which thermal gradients are controlled at both the outer surface and by application of internal cooling through the roll's hollow center. Depth of hardness, along with surface and internal residual stresses, are challenging to control. Typically, methods for developing such heat treating practices are based heavily on in-plant experimental trials, as well as "experience."

The advent of accurate heat treatment simulation allows for analytically based process engineering to be used to examine roll heat treatments to improve depth of hardening and overall metallurgical response. In this paper, virtual experiments are conducted to characterize practical heating, cooling and quenching regimes to study how varied practices may be used to control residual stress, hardness and metallurgical structure. Because of heat treatment's highly non-linear nature, simulation is a valuable tool for examining part response sensitivities. The heat treatment response of a typical steel mill work roll is examined under a variety of heating and quenching conditions. The relationship between residual stress and hardness is not straightforward, as will be shown. Therefore, the use of heat treatment modeling, which allows examination of the in-process thermal and transformation stresses in conjunction with microstructural changes, is an important tool for understanding the heat treatment of these rolls.

Introduction

Control of surface residual compressive stresses has long been established as a key factor in promoting increased wear resistance and operating life in steel work rolls for hot mills. [1 - 3] Typically produced from high alloy steels (e.g. Cr > 3.0%), the rolls are designed to take advantage of both Cr carbide and surface compressive stresses to resist wear, thermal fatigue, and cracking from load excursions typically encountered in normal production. [4] Surface compressive stresses are important because they act to both reduce the effective stress at the roll surface by countering surface tension from loading, and thus better resist crack initiation and wear. The benefits of surface compression for reducing both wear and crack initiation propensity are well documented.

For hot mill work rolls, residual surface compression is most typically introduced by heat treatment.[5] The usual heat treating practice for these rolls includes controlled heating to a predetermined austenitizing depth on the roll body, controlled quenching, and subsequent tempering operations, sometimes including cryogenic treatment. Greater control of the austenitizing and hardening response, as well as reduction in core tensile stresses is often achieved by removing the roll core by center boring prior to heat treatment. Through a combination of controlled heating/center cooling, followed by quenching, the heat treater thus has great flexibility in adjusting the depth of heating, hardening depth, and the roll internal thermal gradients during the heat treatment process. Consequently, the resulting surface and internal residual stress profiles possible from such heat treatments can have significant variation.

Quantifying and predicting these thermal, metallurgical and residual stress responses remain a substantial challenge to the manufacturing engineer. Recent advancements in quantitative process simulation (modeling) have made it possible to study in-situ the combined effects of heat treatment thermal and transformation strains on resulting part residual stresses. DANTE® is a finite element based software tool that calculates the residual stress, dimensional change, hardness and metallurgical phase volume fractions of steel parts as a result of heat treatment.[6] The DANTE database includes mechanical and thermal property data for steel microstructural phases as functions of temperature and rate, as well as the necessary phase transformation kinetics parameters to address both heating and cooling transformations.[7] In this study, the DANTE software was used to examine the residual stress response sensitivity of a typical alloy steel, hollow, hot mill work roll. Baseline hardening response using a nominal 203mm depth of austenitizing was first compared with industry reported stress, hardness and retained austenite values for establishing the validity of the model. Subsequently, the depth of austenitizing was adjusted to three (3) additional shallower depths to predict how the depth of heating, surface hardness, surface residual stress, and core residual stress vary with changing austenitizing depth.

Approach

The hot mill work roll chosen for this study was of design typical for rolling hot strip products. The roll chemistry was 3.25%Cr, 0.50%Mo, 0.73%C, with balance of iron. A continuous cooling transformation (CCT) diagram for the steel is shown in Figure 1.

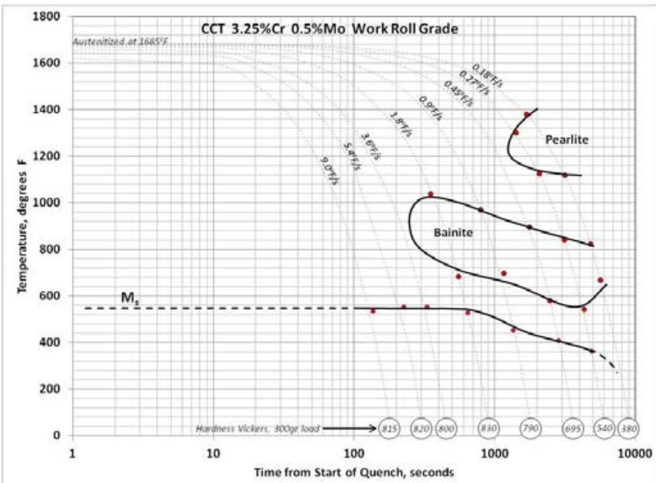


Figure 1: Experimentally determined continuous cooling transformation diagram for the 3.25% Cr alloy roll steel.

The roll chemistry is designed such that a specific austenitized depth on the roll body can be hardened to martensite. The roll core is not austenitized during heat treating, and remains pearlitic throughout the heat treatment.

The roll shape is shown schematically in Figure 2. The overall length is 4400mm, with the roll body itself being 2080mm in length. The diameter of the roll body is 612mm, and there is an 88mm diameter bore extending the length of the roll.

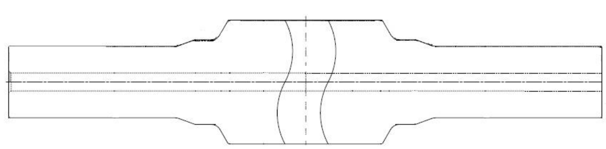


Figure 2: Schematic of the work roll shape.

During heat treatment, the entire roll is preheated to 480°C, and subsequently the roll body alone is flash heated at 965°C to achieve the desired austenitizing depth. Internal cooling is often applied through the roll bore to control the depth of austenitizing to the designed amount.

Upon austenitization of the roll body, the roll is then typically quenched in a high velocity water quench tank. Water quenching is applied to the entire roll surface, including the bore which typically sees somewhat reduced cooling power relative to the roll outer diameter.

For the study presented in this paper, the roll body austenitizing depth was varied between 127 – 203 mm. Subsequently, a high velocity water quench was applied to the roll outer surface, with a reduced water quench in the roll bore. The models were simplified to a 2-D axisymmetric slice though the roll body, as shown in Figure 3.

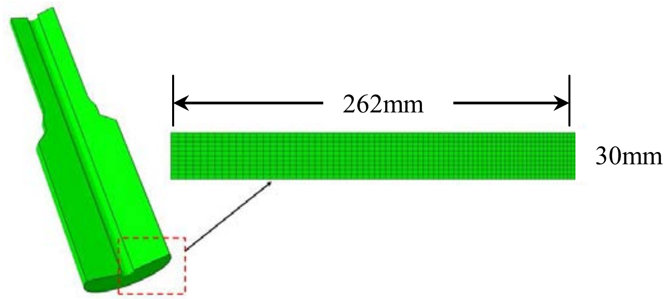


Figure 3: 2-D mesh slice through the roll body for the DANTE models.

Table 1 summarizes the general heat treating practice for the roll.

Table 1: Summary of General Heat Treatment Process Sequence for the Work Roll.

STEP	PROCESS
1	Preheat 480°C
2	Flash Heat Roll Body at 965°C to Achieve Desired Austenitizing Depths of 203mm, 178mm, 152mm and 127mm
3	Water Quench

For this study, four (4) austenitizing depths for Step 2 were examined as indicated in Table 1. Using DANTE, the austenitizing depths were modeled by applying varied internal convection in the roll bore, as per industry practice. The water quench practice was consistent for all cases. Tables 2 and 3 describe the convection heat transfer boundary conditions applied for the bore cooling during heating (to control austenitizing depth), and the convection cooling applied to the roll outer body and bore during the water quench. As industry practice typically holds the rolls for a set austenitizing time, and use internal cooling to control depth, this was the approach taken for the models in this paper.

Table 2: Internal Convection Cooling Heat Transfer Coefficients Applied to Roll Bore to Achieve Desired Austenitizing Depth during Flash Heating.

Austenitizing Depth	Roll Bore HTC
203mm	64 W/m^2 K
178 mm	120 W/m^2 K
152 mm	220 W/m^2 K
127 mm	480 W/m^2 K

Table 3: Water Quench Convection Cooling Heat Transfer Coefficients Applied to the Roll Body during Quenching.

Location	Water Quench HTC
Outer Surface	14,000 W/m^2 K
Inner Bore Surface	4,000 W/m^2 K

The heat treatment model for the 203mm austenitizing depth was executed first, and compared with industry data provided to DANTE Solutions for validation purposes.[8] The favorable agreement, described in the Results section of this paper, prompted the additional model runs for 178mm, 152mm, and 127mm austenitizing depths. The model results were then examined for comparative metallurgical (martensite and hardness profiles), as well as residual stress response.

Results

The predicted roll surface residual stress, hardness and retained austenite values for the 203mm austenitizing depth are shown in Table 4, and compared with industrial reported results for this same roll material and heat treatment. [8]

Table 4: Comparison of DANTE Roll Model with 203mm Austenitizing Depth with Comparable Result Reported to DANTE Solutions from Industry for the Same Roll Material and Heat Treatment.

Attribute	DANTE Model	Reported Industrial Result
Surface Residual Stress	-960 MPa	-890 – -1000 MPa
Surface Retained Austenite	26%	22% - 26%
Surface Hardness	HRC 60	HRC 57 - 61

The favorable results comparison in Table 4 prompted the additional model runs for the 178mm, 152mm and 127mm austenitizing depths. Surface residual stress, surface retained austenite and surface hardness comparisons are presented in Table 5.

Table 5: Summary Results for DANTE Roll Models with Four Different Austenitizing Depths.

ROLL AUST. DEPTH	ATTRIBUTE			
	Outer Surface Residual Stress	Bore Surface Residual Stress	Outer Surface Retained Austenite	Surface Hardness
203mm	-960 MPa	-319 MPa	26%	HRC 60
178mm	-1014 MPa	-412 MPa	26%	HRC 60
152mm	-1065 MPa	-470 MPa	26%	HRC 60
127mm	-1096 MPa	-500 MPa	26%	HRC 60

While the results shown in Table 5 indicate definite variation in surface and roll bore residual stress with varying the austenitizing depth, little variation is seen in surface hardness and surface retained austenite. Therefore, the utility of using surface hardness data and even estimates of surface retained austenite as a means of assessing residual stress response and sensitivity in actual industrial practice is of little use. Furthermore, reaction tensile stresses are present within the roll. For large parts such as this 612mm diameter roll, these stresses can be quite significant. At first glance, using the 127 mm austenitizing depth may seem desirable for achieving greater surface compression. However, internal metallurgical response and the internal stresses must also be assessed. Heat treatment modeling readily allows for this assessment.

Figure 4 shows comparative axial stress profiles for the roll section from the outer surface to the inner bore surface. The profiles reveal that while decreasing the depth of hardness increases the surface compressive stresses on the roll body, the internal reaction tensile stresses also increase dramatically. In fact, the internal stresses in excess of ~900 MPa may have a propensity to produce internal cracking or possible roll failure. It should also be noted that decreasing the austenitizing depth not only increases the internal tensile stresses, but also shifts these higher tensile stresses closer toward the roll mid-radius.

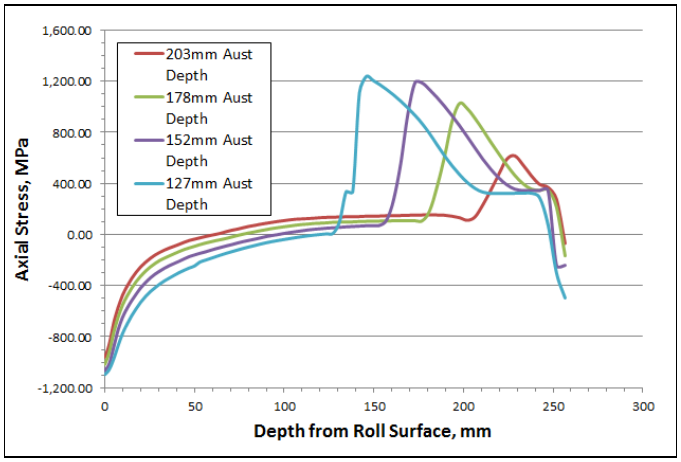


Figure 4: Comparative axial stress profiles for the roll body, showing the effect of austenitizing depth.

The model reveals that the internal tensile stresses occur just below the martensite transformation transition location. Compare Figure 5, which shows the predicted martensite profiles for each model, with Figure 4. The spikes in the internal tensile reaction stresses occur within 15 mm of the martensite transformation boundary.

Examination of the model contours provides graphic illustration of the relationship. Figures 6 – 9 show composite contour plots of the flash heating austenitizing depth, post quench axial stress, and post quench martensite phase fraction. The relationship between shallower austenitizing depth, greater surface compression, and higher internal tension moving toward the roll mid-radius is clearly evident.

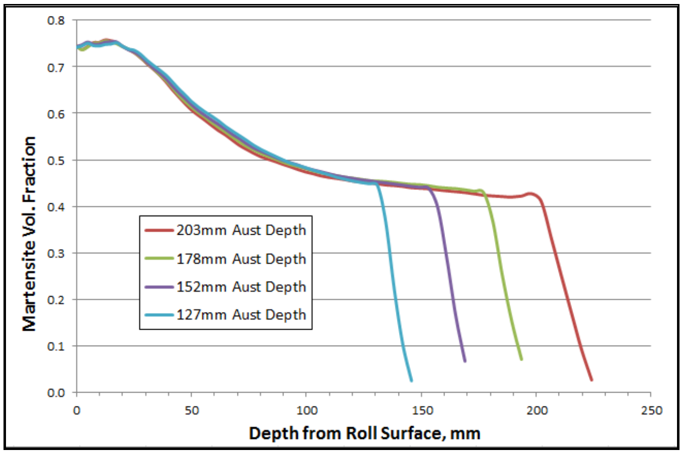


Figure 5: Comparative martensite volume fraction profiles for the roll body, showing the effect of austenitizing depth. Compare with the stress plot in Figure 4.

Figure 6 shows composite contour plots of the austenitized layer after heating, and the axial stress and martensite after quenching.

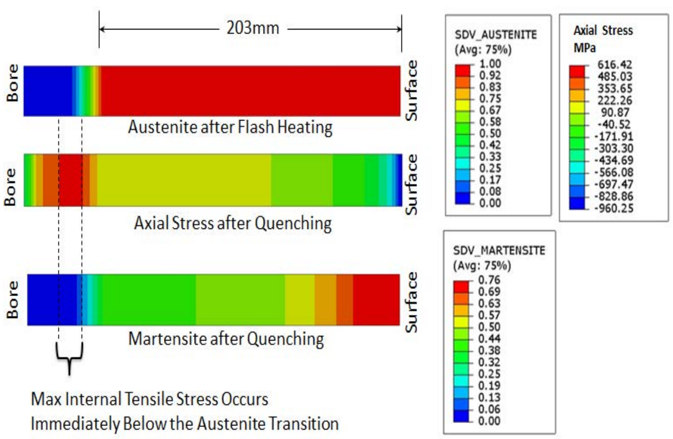


Figure 6: Composite contour plot showing flash heated austenitizing depth relative to the post quenching axial stress and martensite phase fraction profiles for the roll austenitized to 203mm depth.

The contour map composites are valuable in providing a visual cue to the relationship between the location of the reaction tensile stress and the depth of austenitizing. As seen also in Figure 4, and shown further in Figures 7 – 9, as the austenitizing depth decreases, the increased surface compression is accompanied by an increased internal tensile reaction stress which shifts inward towards the roll mid-radius.

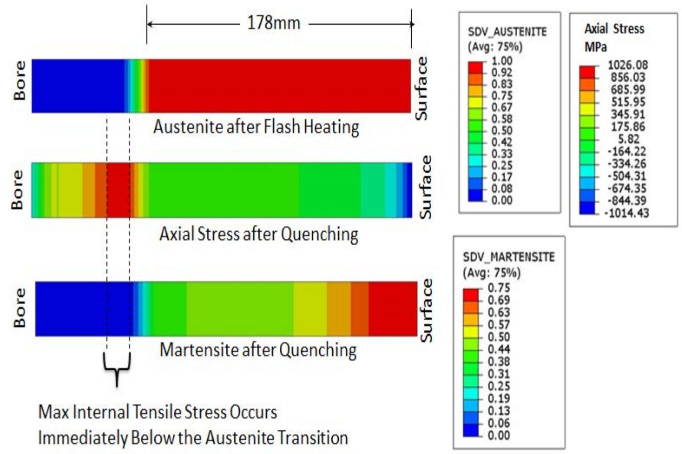


Figure 7: Composite contour plot showing flash heated austenitizing depth relative to the post quenching axial stress and martensite phase fraction profiles for the roll austenitized to 178mm depth.

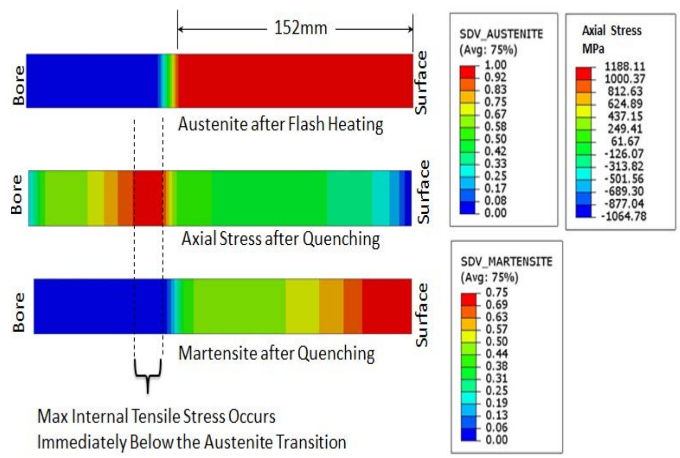


Figure 8: Composite contour plot showing flash heated austenitizing depth relative to the post quenching axial stress and martensite phase fraction profiles for the roll austenitized to 152mm depth.

Examining the residual stress results both numerically and qualitatively through the comparative contour maps shows key correlations between surface compressive stress magnitude, magnitude and depth of the internal reaction tensile stress, and the applied austenitizing depth. The heat treatment models allow both for virtual process design to assess these responses, as well as a tool for understanding the material physics behind the responses. For the subject roll and heat treatment in this paper, these will be described further in the next section.

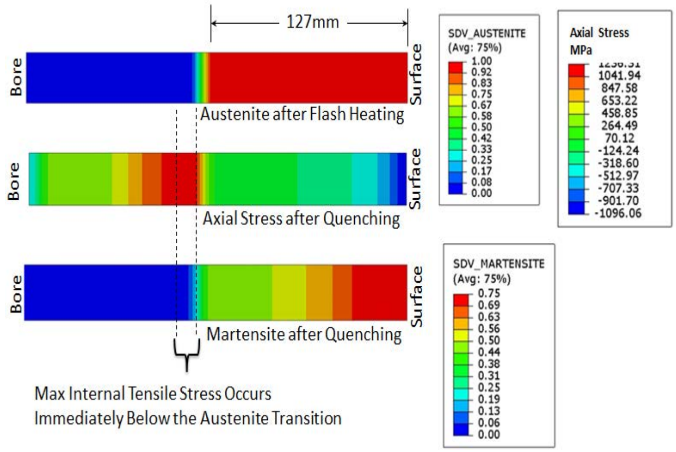


Figure 9: Composite contour plot showing flash heated austenitizing depth relative to the post quenching axial stress and martensite phase fraction profiles for the roll austenitized to 127mm depth.

Discussion

The model results showed a correlation between the applied austenitizing depth, the magnitudes of both the resulting surface compression and internal tensile residual stresses, and the depth at which the maximum internal tensile stress occurs. This data is tabulated from the models in Table 6, and graphically summarized in the plot in Figure 10.

Table 6: Tabulated Stress Results for DANTE Roll Models with Four Different Austenitizing Depths.

	Austenitizing Depth			
	207mm	178mm	152mm	127mm
Surface Compression, Axial	-960MPa	-1014 MPa	-1065 MPa	-1096 MPa
Max Internal Tensile Stress, Axial	616 MPa	1026 MPa	1188 MPa	1236 MPa
Depth from Surface of Max. Internal Tensile Stress	228mm	198mm	173mm	150mm

From both Table 6 and the Figure 10 graphic, the model shows the following:

- Surface residual compression increases (becomes more compressive) with decreasing austenitizing depth
- The internal reaction tensile stress increases (becomes more tensile) with decreasing austenitizing depth
- The location of the internal maximum tensile stress shifts closer to the roll surface with decreasing austenitizing depth

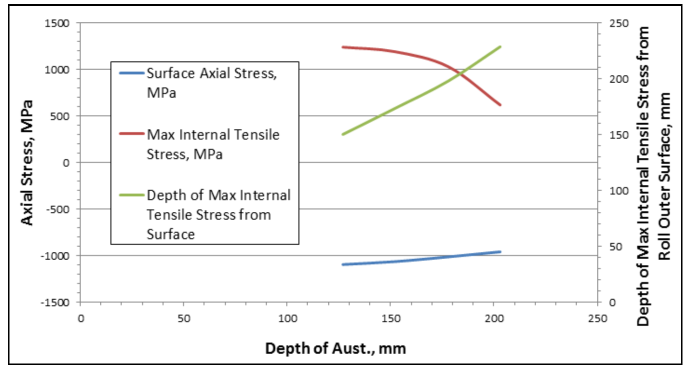
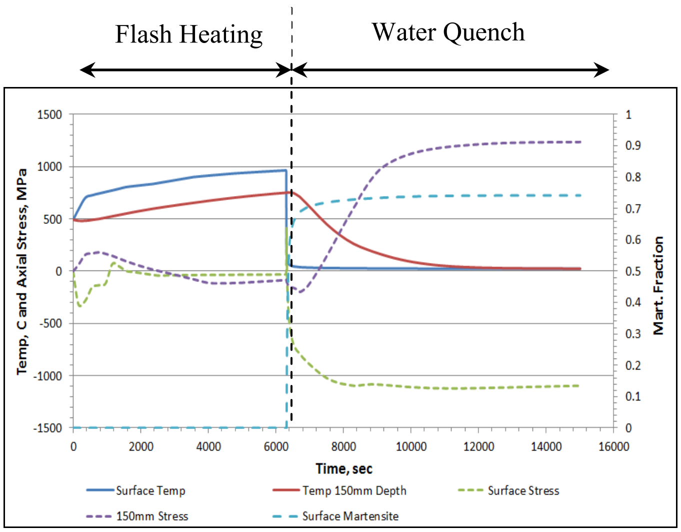


Figure 10: Composite contour plot showing flash heated austenitizing depth relative to the post quenching axial stress and martensite phase fraction profiles for the roll austenitized to 127mm depth.

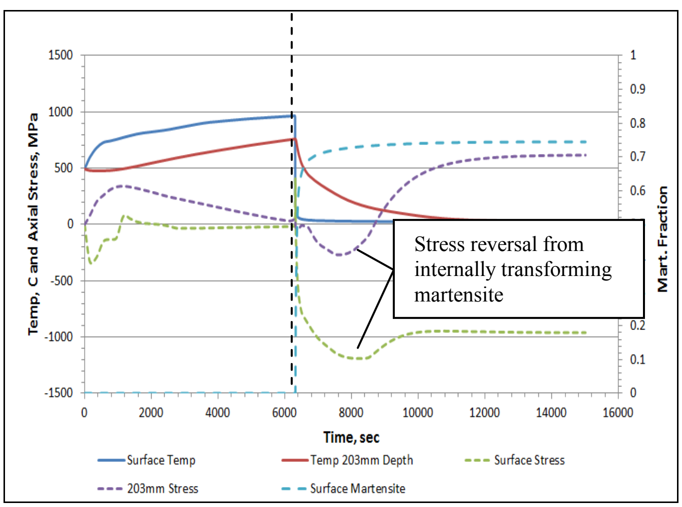
The driving force behind the residual stresses is a combination of both thermal and transformation strains. As the roll cools, both the austenitized shell and heated pearlitic core will shrink. Transformation of the austenitic shell will produce a combination of martensite, bainite and pearlite. The 3.25% Cr steel hardenability is such that the 50% martensite depth remains a constant 90 mm for all of the austenitizing depths examined in this study (see Figures 5 – 9). Hardness to this depth can be expected to be uniform between all of the austenitized conditions.

The martensite transformation causes a volumetric expansion of the transforming steel. This will place the roll surface region in compression. Simultaneously the roll pearlitic core will shrink under thermal contraction. However, the volume of this contracting core will vary more directly with the austenitizing depth (see again Figures 5 – 9). The shrinking core will act to pull the outer shell inward and also act to increase surface compression. As deeper layers of the shell partially transform to martensite (depth range 127mm – 203mm for this study), the surface compression will be become more dispersed and drop. A more shallow overall martensitic shell means a greater volume of the internal shrinking pearlitic core acting to place the surface in compression. The higher local surface compression will created higher subsurface reaction tensile stress near the transformation boundary, as seen in the stress profile predictions in Figure 4. Conversely, a deeper overall martensitic shell will have less pearlitic core shrinkage, and the deeper martensitic transformation will act to reverse the surface compression response.

Examining the local temperature, axial stress and martensite evolution during the process at key locations in the roll can add additional insight into the mechanism controlling the residual stress magnitudes. In Figure 11, the temperature, and stress evolution is compared at the surface and at the austenitizing depth for the 127mm and 203mm heated rolls. Also plotted is the surface martensite formation. What can be clearly seen in the plots is the effect that greater austenitizing depth has in reducing the surface compression in the 203mm austenitized roll. The expanding martensite transforming at the greater depths acts to reverse the initially induced surface compression. For the 127mm depth austenitized roll, the internally transforming martensite volume is insufficient to produce the stress reversal, and higher surface compression is maintained. Consequently in the 127mm austenitized roll, the subsurface reaction tensile stresses are also higher.



a) Roll austenitized to 127mm depth



b) Roll austenitized to 203mm depth

Figure 11: Temperature, stress and martensite evolution comparison between the 127mm and 203mm depth austenitized rolls. Deeper martensite transformation in the 203mm austenitized roll produces a stress reversal at the surface.

Conclusions

A DANTE heat treatment process model was validated against provided industrial data for a quench hardened 3.25% Cr hot mill work roll. The model was subsequently utilized to characterize the differing residual stress responses arising from varying the austenitizing depth in the roll prior to quench hardening. The results showed important relationships between the austenitizing depth, surface compressive stress magnitudes, and the depth and magnitude of the internal reaction tensile stresses. The heat treatment simulations showed that increasing the austenitizing depth resulted in a decrease in the surface compressive residual stresses, and also reduced the internal tensile stress. The stresses are controlled by a combination of thermal and transformation strains acting simultaneously. For a given part geometry and heat treating schedule, process modeling incorporating the thermal and transformation strain metallurgical and mechanical effects is necessary to understand key process sensitivities.

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