MAXIMIZING DEPTH OF HARDNESS OF CONVENTIONALLY HARDENED 3%CR FORGED STEEL WORK ROLLS THROUGH OPTIMIZATION OF CHEMISTRY, AUSTENITIZATION, AND QUENCHING

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Abstracts

Depth of hardness of conventionally hardened forged steel work rolls can be increased through judicious selection of both alloy composition and heat treatment parameters. The use of extended austenitization and quench cycles on rolls with typical 3.25% Cr, 0.50% Mo analysis was found to produce depths of hardness similar to those created by standard heat treatment cycles applied to rolls with significantly higher alloy content. This is advantageous when the cost of raw materials and elevated processing risks for high alloy grades are taken into consideration.

Key words: Forgings; Work rolls; Hardenability.

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1 INTRODUCTION

This paper describes different methods that may be used to provide a cold mill work roll with a working zone hardness of sufficient depth so as to preclude the need for a rehardening operation during usage. Proper alloy additions, austenitizing temperatures, and quench rates can all be used to enhance the depth of the working zone hardness.

2 BACKGROUND

There are a number of roll surface characteristics that are necessary to guarantee optimum performance in a cold rolling operation. Certainly resistance to rolling contact fatigue spalling and possession of sufficient toughness to avoid spalling during momentary mill overloads are of paramount importance. Equally as important, cold mill work rolls must possess the proper depth of hardness for the specific mill application to assure the required wear performance. Insufficient depth of hardness results in more frequent roll rehardening and roll changes in the mill and increased cost to the roll user.

The work roll grades, forging techniques, and methods of heat treatment utilized by Lehigh Heavy Forge on our work rolls have delivered rolls meeting the demands of the respective mills. However, the next generation of cold mill work rolls demands even greater roll wear characteristics. Therefore, through selective alloy additions, Lehigh Heavy Forge successfully developed a modified 3 to 4%Cr work roll which is capable of delivering a significantly greater depth of hardness, with attendant wear resistance, than other rolls in this chromium range. However, with the market price of alloys increasing at alarming rates, Lehigh Heavy Forge also concentrated on improving the depth of hardness by controlling key final heat treatment variables. This report will describe all aspects of the program along with pertinent roll data developed.

3 ALLOY SELECTION

The relative effectiveness of the individual alloying elements in shifting the isothermal transformation curves, and thereby increasing hardenability, is difficult to evaluate in the highly alloyed roll grades. The interaction of alloying elements and complex carbides is responsible for this situation. However, we did review the level of principal alloying elements in our current work roll grades to decide whether an increase would be beneficial to hardenability.

Increasing the **carbon** content of a low alloy grade is the most inexpensive and effective method for increasing the hardenability. However, in the more highly alloyed grades, modest increases in carbon content have a negligible effect on hardenability. A review of isothermal transformation diagrams for 3 to 4%Cr steels with a carbon range from 0.70% to 1.00% showed very little shift in the position of the bainitic curve[1] as the carbon content increased. Although an increase in austenite carbon level shifts the bainitic curve to longer times, a decrease in the austenite chromium content caused by an increase in the bulk carbon content leads to the formation of more undissolved carbides. The net result is that there is little change in hardenability.[2]

In addition, unnecessarily increasing the carbon content may have a negative effect on the performance of the roll. During quenching, a compressive stress state develops in the rim of the roll body due to a combination of thermal and transformational stresses. This compressive stress state can be largely retained after quenching and tempering to provide a beneficial hoop stress while the roll is in service, and these high compressive stresses will resist the propagation of mill-induced cracks in the working zone of the roll. However, elevated tempering temperatures, required with the higher carbon content material, will reduce the level of residual stresses.(3)

The effect of **chromium** on hardenability was evaluated for two chromium analyses: 3.25% and 5.00%. For each grade, the optimum austenitizing temperature was determined, and using these data, a continuous cooling diagram was developed for each grade[3]. The two diagrams are superimposed on a single continuous cooling diagram presented in Figure 1 below.

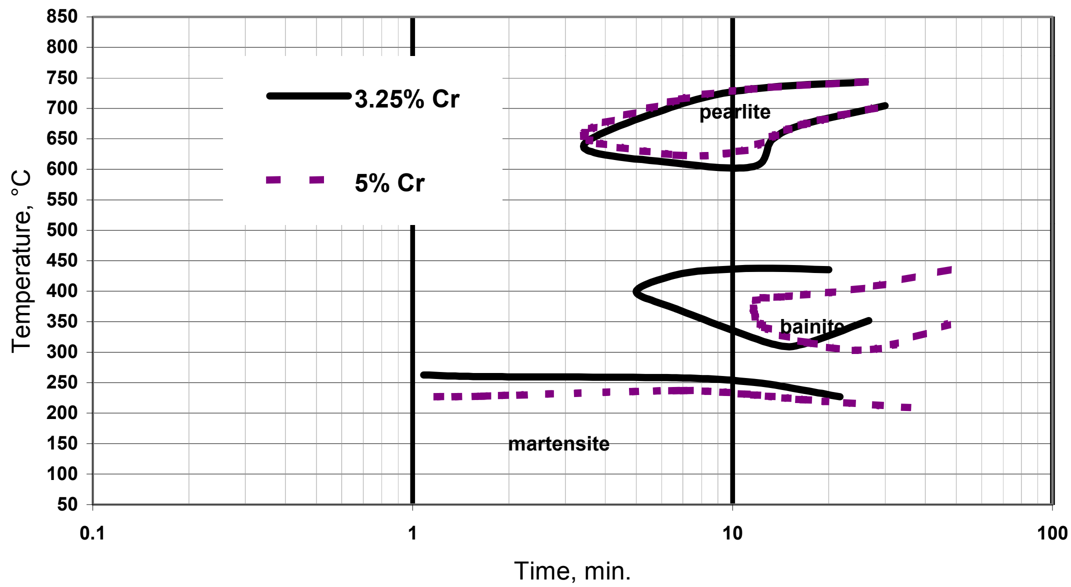

Figure 1. Effect of Chromium on Phase Transformations

There can be significant benefit to hardenability by increasing the chromium content of the steel provided that other changes are also made, such as increasing the carbon content. Undissolved carbides in these steels are chromium-rich. Hence, as the chromium content of the steel increases, more carbon reacts with chromium to form chromium-rich carbides. Therefore, at a given austenitizing temperature, an increase in the base metal chromium content results in a decrease in the dissolved carbon content of the austenite. The CCT diagram in Figure 1 shows the maximum benefit to hardenability by increasing the chromium content from 3.25% to 5.00% (at a constant carbon content), provided that complete carbide dissolution is achieved during heat treatment. Since final heat treatment of work roll grades are not designed to provide complete carbide dissolution, increasing the chromium content from 3.25% to 5.00% may offer little or no additional benefit to hardenability. In addition, the austenite grain size decreases with increasing chromium content due to the increase in undissolved carbides. Both the reduction in austenite carbon content and the refined austenite grain size have negative effects on hardenability that also offset any positive effect of an increase in the austenite chromium content.(3)

However, wear performance does benefit by increasing the chromium content. The predominant carbide type changes from M_3C to the significantly harder M_7C_3 as the chromium content increases from 1.75% to 3.25%. The carbide type is virtually all M_7C_3 when the chromium content reaches 5.00%.(3)

Nickel, a non-carbide former, promotes hardenability, although it was uncertain as to the amount required for the subject application. Using derived equations predicting the critical cooling rate necessary to achieve a 90% martensitic microstructure, it was determined that a 1% addition of nickel should reduce this critical cooling rate by almost 250%.[(4)] A comparison of continuous cooling diagrams for 3.25% Cr material with and without a 1% nickel addition is presented in Figure 2 below.[(5)]

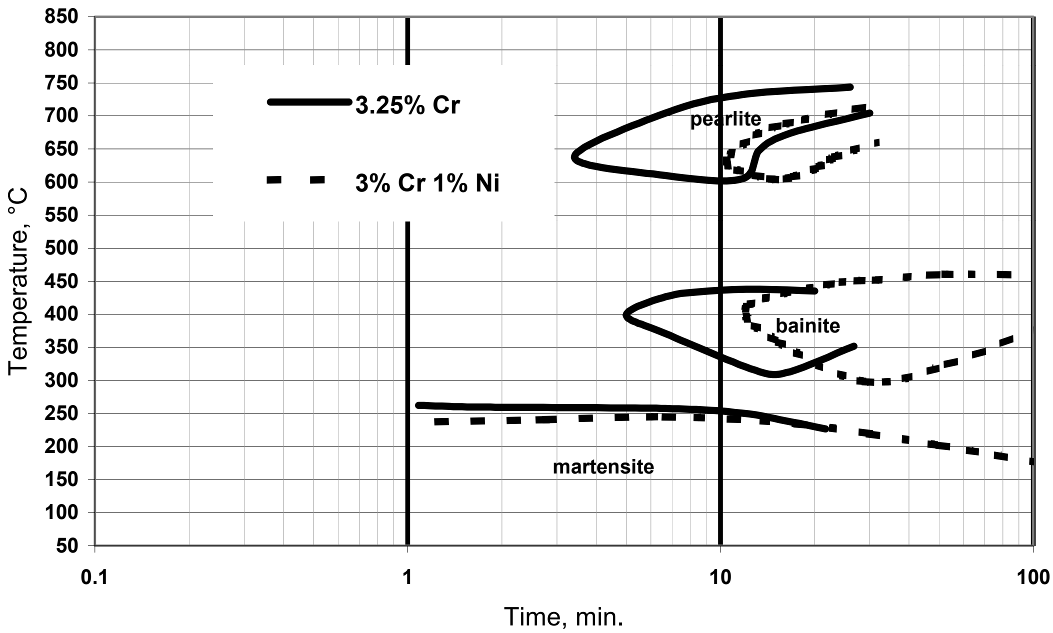

Figure 2. Effect of Nickel on Phase Transformations

Although the nickel addition should have a positive effect on hardenability, it should also promote more retained austenite since it will lower the M_s temperature of the steel. It was calculated that the M_s temperature would decrease by approximately 28°C with a 1% nickel addition.[(6)]

Molybdenum has a significant influence on the response of a steel to thermal treatment. Most importantly, molybdenum significantly improves hardenability, temper resistance, and wear resistance. Using derived equations predicting the critical cooling rate necessary to achieve a 90% martensitic microstructure, it was determined that a 1% addition of molybdenum would reduce this critical cooling rate by over 300%.[(4)]

Although **vanadium** is not added as an alloy to enhance hardenability, the level of vanadium in a cold mill work roll is very important. The presence of vanadium will promote a fine austenitic grain size and allow formation of vanadium-rich MC carbides, which are harder particles than the M_7C_3 carbides. However, an excessive vanadium addition would reduce the carbon content of the austenite and consequently detract from the hardenability.

After consideration of the contributions of the individual alloying elements, Lehigh Heavy Forge decided on the following chemical analysis range for a deep hardening roll. All values are expressed in weight percent.

Table 1. Chemical Analysis, CRYO II

C	Mn	Si	Ni	Cr	Mo	V
.70/.90	.30/.75	.30/.60	.25/1.00	3.00/4.00	.50/1.50	.05/.20

Using test material of the composition shown in Table 1 above, the optimum austenitizing temperature was developed. This temperature provided a maximum hardness without coarsening the grain size. Work rolls of varying diameter were heat treated using the proposed parameters and a typical hardness profile for this grade, named Cryo Deep Case II (CRYO II), was developed. The hardness profile expected in CRYO II work rolls is shown below along with the typical hardness profile in standard 3.00/4.00%Cr (STD) work rolls with no significant additions of nickel or molybdenum.

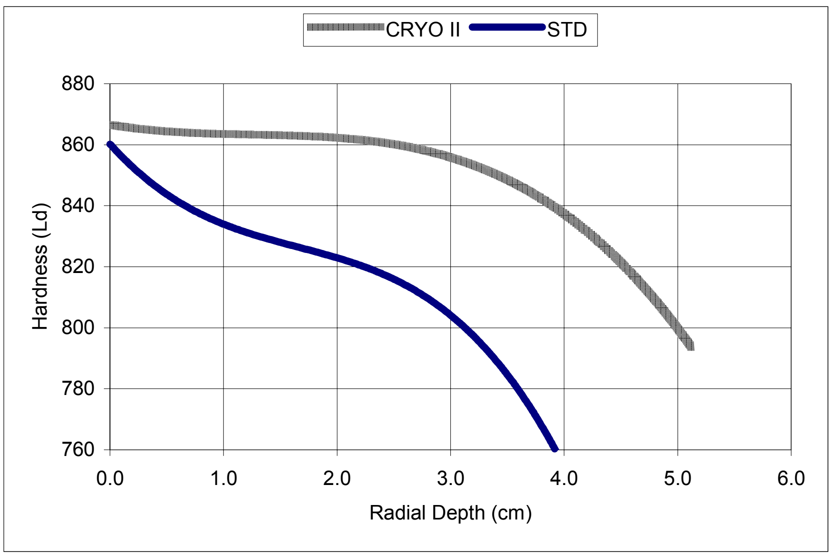

Figure 3. Comparative Hardness Profiles

Obviously the addition of nickel and molybdenum has had a significant beneficial effect to the hardness profile. However, not all customers require this extensive depth of hardening. Therefore, Lehigh Heavy Forge has developed two intermediate grades, of a nominal 3.25%Cr-0.50%Mo analysis (RMS and Mod RMS), which offer intermediate depth of hardness with the same heat treatment times and temperatures used for the CRYO II rolls. There is no quantitative method for assigning a hardenability factor to roll grades due to their high alloy composition. Martensitic hardenability factors, termed DI (ideal diameter) which are based on the original work of M.A.Grossman, can be calculated for carbon and low alloy steels in accordance with ASTM A 255 (“Determining Hardenability of Steel”). However, it is possible to calculate the relative hardenability of the roll grades using ASTM A 255 if the multiplying factor from chromium is ignored since the chromium content is similar in the four cold mill work roll grades under discussion. The calculated DI values of the four work roll grades are shown in Table II. In addition, based on hardness profile data from these rolls which were all identically heat treated, the expected loss in hardness at a radial depth of 2.5 cm is included. A graph of Mod DI versus loss in hardness is shown in Figure 4.

Table 2. Modified DI Values

Grade Name	Nominal Composition	Mod DI (cm)	Loss in Hardness (Ld) at 2.5 cm
STD	3.25%Cr	3.73	50
RMS	0.7%C-3.25%Cr-0.5%Mo	7.52	30
Mod RMS	0.8%C-3.25%Cr-0.5%Mo	8.08	20
CRYO II	0.8%C-4%Cr-0.5%Mo-0.8%Ni	9.58	10

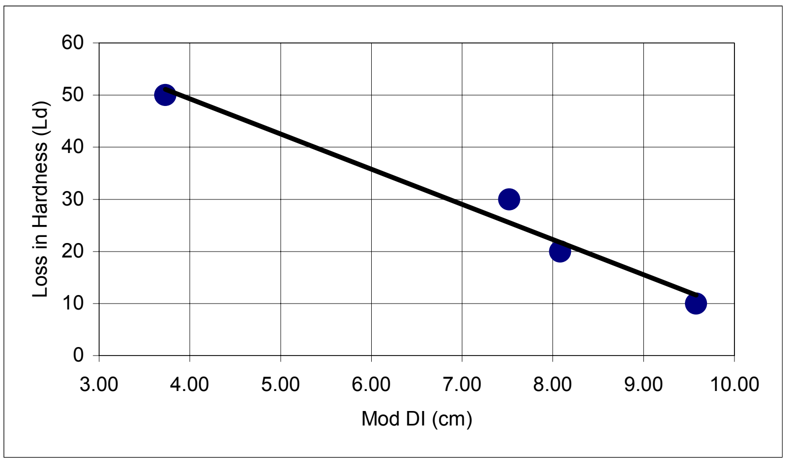

Figure 4. Loss in Hardness Related to DI

4 FINAL HEAT TREATMENT – QUENCH RATE

Even though the work roll composition can be optimized to provide the greatest depth of hardness, the value of the alloying elements can be lost without maximizing the quench rate after austenitization. By varying the amount of agitation in our vertical water quench tank, Lehigh Heavy Forge measured the resultant effect on the hardness profile in the Mod RMS work roll. These data are shown in the graph below.

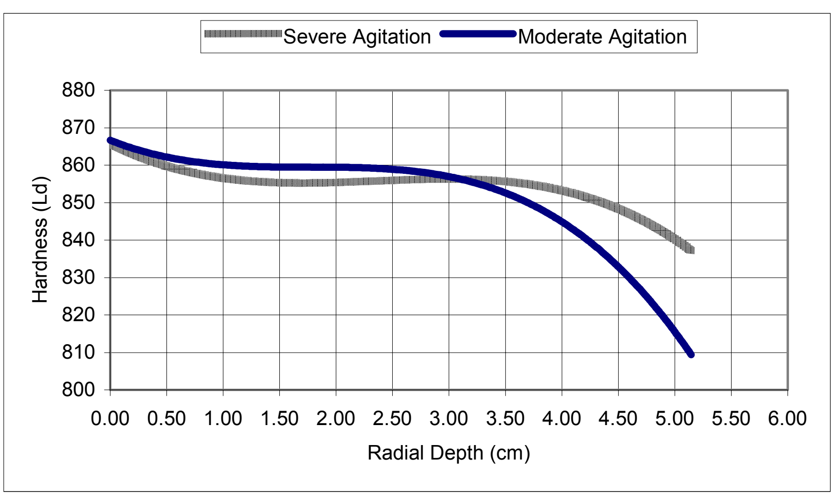

Figure 5. Effect of Quench Rate on Hardness Profile

As evidenced in Figure 5, agitation has extremely important influence on the heat transfer characteristics of the quenching medium. It causes a mechanical disruption of the vapor blanket in the first stage of quenching and produces smaller, more frequently detached vapor bubbles during the next stage. In addition, agitation also circulates cool liquid to replace the heated liquid surrounding the roll.

Equally important is the temperature of the quenching medium which affects the ability of the quenchant to extract heat from the roll. In general, maintaining the water quench temperature to below 25°C maximizes the cooling power of the quenchant. As shown by the graph in Figure 6, the cooling power dramatically decreases with higher quenchant temperatures[7].

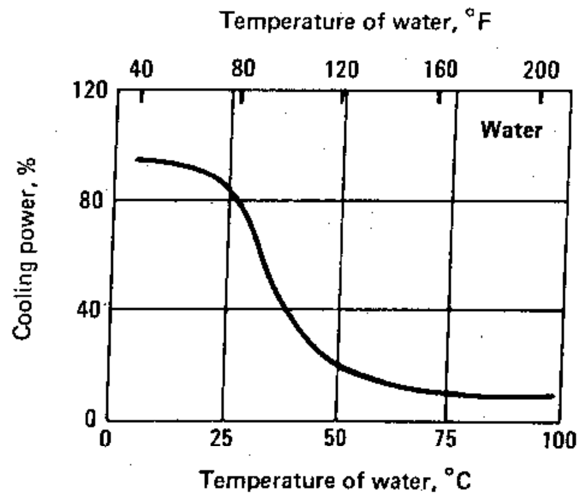

Figure 6. Effect of Quench Temperature on Cooling Power

5 FINAL HEAT TREATMENT – AUSTENITIZING TEMPERATURE

Cold mill work rolls produced by Lehigh Heavy Forge are final heat treated in conventional, gas-fired vertical furnaces. Our experience shows that this method of heat treatment, as opposed to induction hardening, results in a hardened working zone with an underlying bainitic zone of moderate strength and hardness which resists the propensity to deep spalling behavior. In addition, residual stress testing of the roll surface shows extremely high levels of compressive residual stresses that inhibit the formation of fatigue cracks which may be initiated by mill incidents.

As stated previously, our selection of an austenitizing temperature is based on the temperature at which the martensitic hardness is maximized without coarsening the grain structure. Generally, as the austenitizing temperature is increased, the austenite carbon content increases and eventually reaches the bulk carbon content at the A_{cm} temperature (about 945°C for 3.25%Cr-type grades). In addition, the martensitic hardness level increases with increasing carbon content and approaches a plateau at a carbon level of approximately 0.70%. Therefore, in order to maximize hardness at greater depths below the roll surface, the roll temperature at the required depth needs to be sufficiently high to increase the austenite carbon content by dissolution of alloy carbides. Therefore, using computer modeling, heat treatment practices have been revised to develop higher roll temperatures at the minimum useable roll diameter. For example, a 58.5 cm diameter work roll of the Mod RMS composition was heat treated using two different austenitizing times in order to develop a 20°C difference in roll temperature at a 2.5 cm radial depth.

Subsequent incremental hardness testing of this roll showed that the hardness at the 2.5 cm radial depth increased by slightly more than 10 Ld. However, the effect on hardness at depths beyond 2.5 cm was even greater as shown in Figure 7 below.

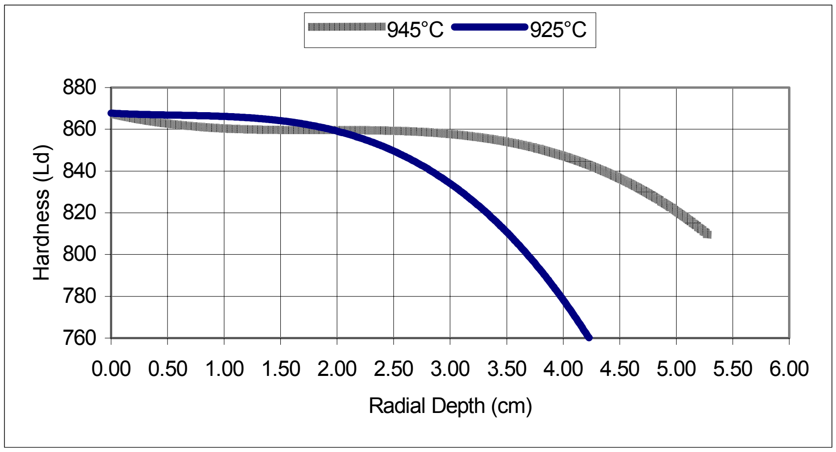

Figure 7. Effect of Roll Temperature on Hardness

There are two inherent dangers with increasing the austenitizing temperature. First, if the austenitizing time is excessive, the roll temperature on the bore surface may be increased to the level at which a martensitic zone of extreme depth is created. Although a slightly harder bore surface is beneficial to preventing fatigue cracks from developing on the bore surface, excessive depth will result in insufficient ductile core material and render the roll less susceptible to impact loading. Lehigh Heavy Forge therefore models the final heat treatment of every roll so that (1) the proper roll temperature is achieved at the required useable roll diameter and (2) the roll temperature is minimized at the central or bore region.

A second risk associated with higher austenitizing temperatures is the formation of more retained austenite. Due to the high alloy content of cold mill work rolls, the expected level of retained austenite is between 5 and 10%. Significant increases in austenitizing temperature, as well as alloy content, can double the amount of retained austenite present. Therefore, work rolls which receive enhanced austenitizing temperatures and/or times in order to increase the depth of hardness will be cryogenically treated at –75°C followed by additional tempering. Experimental data shows that this treatment successfully reduces retained austenite levels to below 10%.

For comparative purposes, a graph was prepared to exhibit the hardness profiles of a 65 cm diameter Mod RMS work roll heat treated with optimized austenitization and quench cycles vs. a 65 cm diameter CRYO II work roll given standard heat treatment cycles. The graph is presented in Figure 8 below. This graph implies that the Mod RMS work roll composition is capable of achieving a hardness profile equal to or better than the CRYO II composition. The Mod RMS work roll hardness profile has been enhanced due to higher internal roll temperatures and the probable dissolution of more alloy carbides.

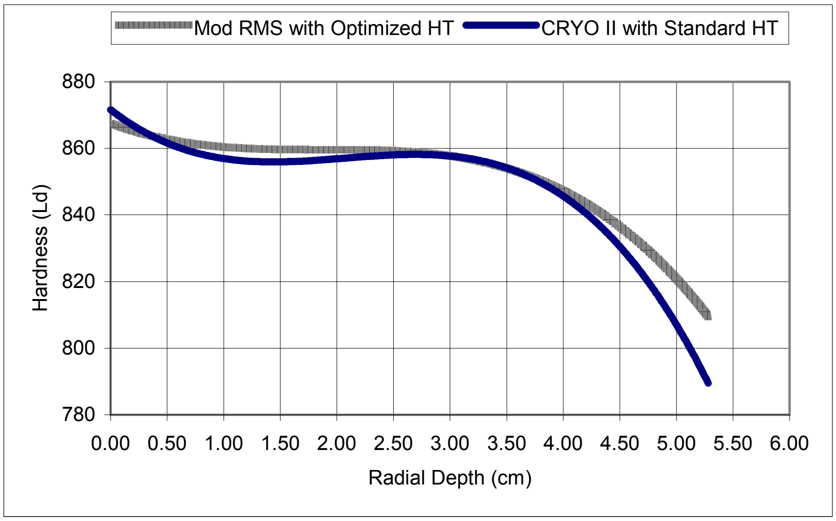

Figure 8. Similarity of Hardness Profiles

6 SUMMARY

The depth of hardness of conventionally hardened forged steel work rolls can be increased through judicious selection of both alloy composition and heat treatment parameters. The use of extended austenitization and quench cycles on rolls with typical 3.25% Cr, 0.50% Mo analysis was found to produce depths of hardness similar to those created by standard heat treatment cycles applied to rolls with significantly higher alloy content. This is advantageous when the cost of raw materials and elevated processing risks for high alloy grades are taken into consideration.

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