OPTIMIZATION OF MICROSTRUCTURE FOR IMPROVED DAMAGE TOLERANCE AND WEAR CHARACTERISTICS OF BACK-UP ROLLS[1]

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Abstracts

This investigation characterized the microstructure of back-up roll alloys as a function of thermal history and then identified structure/property relationships for these materials. Commercially produced cast and forged steel back-up rolls made in both 3%Cr and 5%Cr compositions were evaluated by optical and high resolution electron microscopy. Mechanical testing including axial fatigue and fracture toughness (K_{IC}) was performed on selected samples. The microstructure developed during final heat treatment established comparable mechanical properties in both cast and forged rolls. The carbide morphology exhibited some correlation to the observed behavior of these materials, but the processing history of each roll also affected test results. From the results of this study, it is expected that back-up rolls, cast or forged, 3% Cr or 5% Cr, will exhibit similar performance in service. Any differences observed can be attributed to deficiency in casting and/or heat treatment.

Key words: Backup rolls; Microstructure; Performance.

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1 INTRODUCTION

The back-up roll heat treatment operation develops the key microstructural characteristics that govern roll performance attributes, such as wear resistance, damage tolerance and contact fatigue resistance. Isothermal transformation studies conducted more than 60 years ago identified 0.40C – 3.0Cr alloy steel compositions that exhibited a rapid bainite transformation critical to deep hardening of heavy sections.(1) Adaptation of the early research to industrial roll heating and quenching technology suggests two objectives;

a) Maintain a cooling rate that avoids primary pearlitic reaction through the working layer of the roll barrel, and
b) Ensure sufficient undercooling to suppress a reconstructive bainitic transformation, preventing delayed development of a degenerate grain boundary phase during the lengthy industrial tempering sequence

The present work elucidates the influences of prior processing history in the development of the ultimate roll microstructure by decremental and differential heat treatment. Mechanical testing was performed on ring samples removed from selected production rolls after hardening.

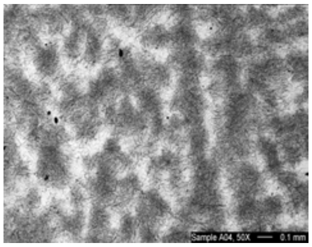
2 ROLL PRODUCTION

2.1 Melting, Ingot Making and Forging

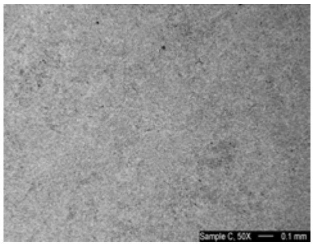
The selection of roll chemistry optimizes solidification behavior and hardening response. For instance, the 5% Cr grade exhibits about 20% more hardenablity, but solute enrichment of the interdendritic liquid increases by about 40% compared with the 3% Cr grade. Constitutional supercooling of the remaining enriched liquid phase delays local volumetric contraction between the dendrite arms, producing vacuum pressure conditions within the resulting microshrinkage voids. Stronger affinity for dissolved gases in the 5% Cr grade mandates additional precautions in the refining of forging ingots, because hot deformation seals the microcavities that would otherwise act as collection sites for diffusing hydrogen.

The ingot mold design must discourage formation of centerline shrinkage or macro-segregation defects that represent dangerous internal stress risers. More pronounced segregation in the 5% Cr rolls requires special precautions to avoid internal solidification defects because greater inherent hardenability exaggerates the magnitude of residual tension imposed on the roll by quenching. In these cases, additional forging reduction can be specified to consolidate a poor ingot center, provided that the forge press is sufficiently powerful (2).

C	CR	MO	V	HRC	AUST °C	TEMPER °C	UTS MPa	FATIGUE MPa	K_{IC} MPa-$m^{1/2}$
ROLL 1 - NUCOR - 1350 mm - CAST HOT MILL ROLL - 745 HLd									
.42	3.23	.74	.13	51.4	970 SELAS	525	1730	448	25
ROLL 2 - COMMONWEALTH - 1372 mm - CAST HOT MILL ROLL - 675 HLd									
.43	3.11	.75	.11	42.7	954 SELAS	565	1320	310	46
ROLL 3 - LIA WU - 1350 mm - CAST HOT MILL ROLL - 725 HLd									
.44	3.56	.73	.27	48.5	970 SELAS	550	1720	379	31
ROLL 4 - WCI - 1350 mm - FORGED HOT MILL ROLL - 707 HLd									
.42	3.06	.74	.27	45.2	970 CAR	545	1570	482	47
ROLL 5 - AHMSA - 1254 mm - FORGED HOT MILL ROLL - 725 HLd									
.35	5.26	1.02	.36	46.9	970 SELAS	550	1585	517	29.5
ROLL 6 – ALGOMA - 1450 mm - CAST HOT MILL ROLL - 735 HLd									
.54	4.55	.84	.30	48.0	985 SELAS	555	1380	414	27.5
ROLL 7 - NORTH STAR - 1450 mm - FORGED HOT MILL ROLL - 735 HLd									
.48	5.15	1.00	.40	51	? ----	? ----	1725	517	33



ALGOMA 1450 mm – 48 Rc



AHMSA 1254 mm – 47 Rc

Figure 1. Both cast and forged rolls have similar chemical specifications, but constitutional supercooling may induce microshrinkage and broadened the temperature range for displacive transformation to occur during heat treatment of the 5%Cr grade. Hot working chemically homogenizes the inherent solidification structure.

50 X - Optical comparison of structural features at low magnification highlights the remnant dendritic pattern in the cast steel roll (top). Isolated inclusions are also discernable in both roll samples. The forged roll micrograph depicts a contrasting homogenous transformation product which has been fully tempered to a lower hardness level (bottom).

Forged rolls undergo a more uniform lower bainite reaction at any given radial location, whereas cast roll structures tend to exhibit a broader transformation range due to dendritic alloy partitioning. The same bulk hardness and penetration depth can be achieved in both types of rolls when aggressive quenching techniques are employed to minimize carbon diffusion, causing predominantly displacive transformation to occur at significant undercooling despite dendritic coring.

Wide die forging reduction (>1100MPa) effectively consolidates secondary shrink cavities at the axial center of ingots exceeding 3 meters in diameter, but it still may not eradicate the shallow alloy rich channel segregate streaks (5-10mm size) associated with the thermal mass of the original ingot. Hot working of the roll barrel surface in "V" shaped dies does chemically homogenize the much finer scale dendritic network (< 200μm) to improve heat treatment response.

The comparatively slender net-shaped ingots used to make cast rolls require that carbon and alloy concentration be controlled to avoid excessive solute partitioning. In modern up-hill teemed ingots, accentuated columnar solidification with fine secondary dendrite arm spacing (average < 150μm) drives channel segregates deep below the surface. Subsequent dilution of the internal mushy center zone through a submerged entry nozzle mitigates the natural macro-segregation problems. Consequently, rolls made from chilled, net-shaped ingots often exhibit better nondestructive examination signatures than those produced from conventional forging ingots, which require 2-3 times the final roll cross section to make a given roll design configuration. Engineered solidification technology allows net-shaped cast back-ups to receive the same aggressive heat treatment previously reserved for internally sound forged rolls.

2.2 Heat Treatment

Commercial roll hardening involves steps that precondition the microstructure and establish deep core properties, followed by controlled re-austenitizing of the roll barrel and continuous cooling transformation. Repeated normalizing operations refine the prior grain size, accelerating bainite nucleation. Preliminary austenitizing treatments also establish a stable carbide phase that moderates carbon dissolution kinetics during the final hardening step.

The extreme delay in the pearlite reaction exhibited by these alloys, facilitates differential heating of only the outer layer of the back-up roll barrel. Hardening temperatures (925^{o} -1025^{o} C), determine the carbon concentration of the austenite as well as its grain size. Declining austenite temperatures are encountered along the affected radius from the surface inward due to conductive heat transfer limitations. Radiant burner technology minimizes slope of the thermal gradient, but develops a distinct transformation boundary with the underlying core material. Conventional car bottom furnaces overheat the surface to achieve adequate hardening temperature at discard size, producing more gradual transformation with a different residual stress profile.

Commercial quenching operations typically employ forced air and/or water sprays directed at the rotating hot roll. Marginal cooling rates can encourage interfacial carbon diffusion, however, enabling enriched austenite transformation to a fine secondary pearlite constituent during the long industrial temper cycle. The resulting mixed microstructure lacks hardness needed to resist cumulative fatigue because the carbon has been depleted from the dominant coarse upper bainite phase. The presence of a second brittle pearlite phase outlining the prior austenite grains impairs toughness, contributing to surface spalling.

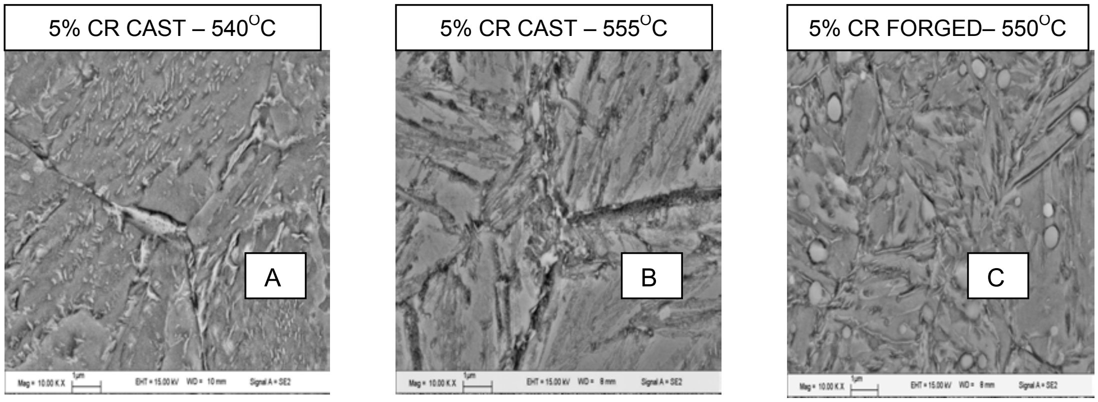


Figure 2. High-resolution electron microscopy identifies characteristic features of a primarily displacive bainitic transformation. (Magnification = 10,000 X)

A) Supersaturated bainitic ferrite precipitates Fe_3C carbides at preferred crystallographic orientations within the ferrite plates. An alliotriomorphic ferrite colony is visible at the triple point of the prior austenite grain boundary, austenitized at 985^{o}C.

B) Second stage – Tempering effects have eliminated the preferred orientation of the metastable carbides, voring a dispersion of tiny alloy carbides within the bainite plates.

C) Both inter-lath carbide films and large (3μm) undissolved carbides remain following austenitization at 70^{O}C, theoretically providing wear resistance within a tempered matrix.

Preferred quenching practices involve aggressive cooling that enables displacive transformation reactions to prevail at a depth exceeding the discard diameter of the roll. The thermal gradient developed in the differentially heated zone actuates a range of martensite start temperatures that roughly parallels the radial temperature profile produced by quenching. Hydrostatic compression caused by rapid cooling further discourages diffusion of carbon. Attendant dislocation density within the supersaturated austenite promotes a martensite/lower bainite microstructure at isothermal holding temperatures near the M_s (3).

Commercial tempering at slow heating rates with extended hold time sustains a dynamic process in which favored transitional equilibrium carbide composition changes depending on local alloy diffusivity and temperature. Small Mo_2C carbides do precipitate independently as Cr rich M_7C_3 evolves from the original Fe_3C. Larger undissolved alloy carbides established by preliminary thermal treatments remain unaffected. Mild secondary hardening reactions retard softening at temperatures (475^{o}-575^{o}C) that can also induce temper embrittlement.

3 EXPERIMENTAL PROCEDURE

Seven back-up rolls manufactured for various hot-mill applications shown in the Table were evaluated. Four of the rolls (**1**, **2**, **3** and **6**) were made from net-shaped ingots cast by metal-to-metal solidification practice. The other three rolls were forged. Four rolls (**1**, **2**, **3**, and **4**) had nominally 3% Cr chemistry, the other three (**5**, **6** and **7**) were 5% Cr with slightly higher Mo and V content.

All rolls, with the exception of rolls **4** and **7**, were differentially hardened by employing rotary flash heating in a Selas furnace and controlled high pressure water spray quench to produce a finely tempered martensite/lower bainite structure. The forged roll **4** was flash heated in the stationary position and water spray quenched, and roll **7** was made by a foreign producer of forged back-ups. All rolls were tempered to meet hardness requirements.

Test material for evaluation was obtained from ring sections machined from one end of each roll barrel. Rockwell 3 hardness (HRC) penetration traverses were made to a depth of approximately 120mm. The average hardness values over a distance of 13mm below the roll surface are reported in the Table. The corresponding microstructures were also determined for each roll using optical and high resolution electron microscopy.

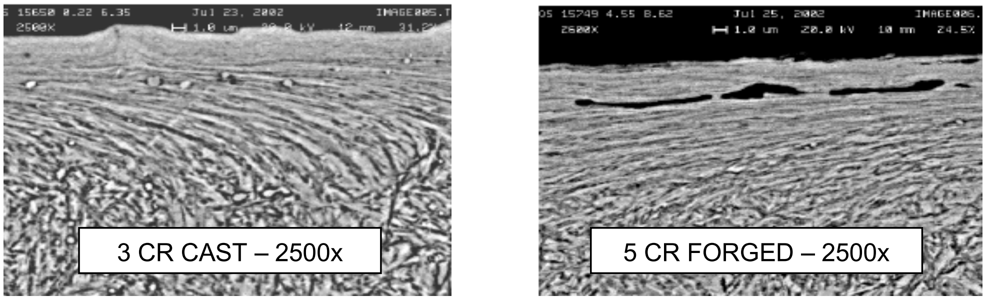
Specimens were subjected to various mechanical tests including tension, axial fatigue, and fracture toughness (K_{IC}). Triplicate (or duplicate) tension tests were performed on 12.8mm diameter specimens obtained from each roll in the circumferential orientation close to the roll surface. The tensile strength values are reported in the Table. Reversed axial fatigue tests were likewise performed on twelve 6.4mm diameter specimens obtained from the same location and orientation as the tension tests. These tests were performed at frequencies of 30 to 40Hz and discontinued after 10 million cycles of stress reversals (“runout”), the corresponding stress amplitude was shown as the fatigue limit in the Table.

Duplicate K_{IC} tests were performed on each roll at room temperature on 1T compact-tension (CT) specimens having 25.4mm thickness in accordance with ASTM E399. The crack tip location was approximately 13mm below the roll surface with crack propagation in the radial direction towards the surface. The K_{IC} test results are also reported in the Table.

4 DISCUSSION

Wear resistance is the paramount attribute desired in back-up rolls. Non-uniform wear adversely affects product shape during longer rolling campaigns. Extended service exposure to potential rolling accidents has superceded fatigue endurance as an important consideration in material design for back-up rolls.

Recently published work from Oak Ridge National Laboratories HTML comparing high hardness, 70 HSc, roll specimens documented relatively minor differences among forged and cast steel back-up rolls made by various manufacturers (4). No definitive effect of increased carbide phase volume in the 5% Cr grade could be shown, even in the absence of self-generated wear debris. These results failed to support previously reported data obtained from selected mills and in laboratory simulations contrasting softer 3% Cr roll samples with harder 5% Cr materials (5,6,). The discrepancy infers critical importance of comparably heat treated microstructure in the assessment of wear resistance, confirming that hardness level is the most important factor when abrasion and plastic deformation wear conditions coexist (7).



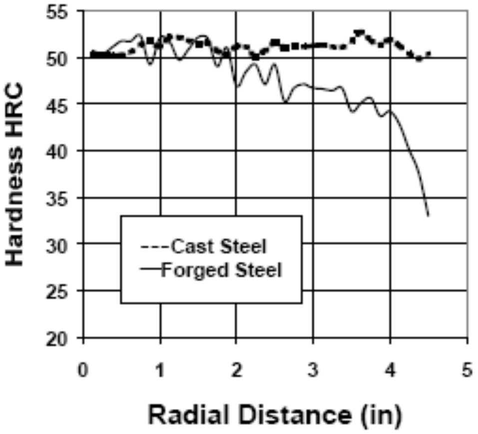


Figure 3 - Comparison of hardening response in a 3.23 Cr net-shaped cast roll (USA) and a 5.15 Cr forged roll (Japan)

Top - Micrographs of block-on-ring wear test specimens confirm a similar cold work response and microstructure.

Left - Hardness penetration in the 5% alloy forged roll is inferior, because an inadequate subsurface austenitizing temperature failed to dissolve enough carbon from the stabile alloy carbide, impairing hardenability.

Damage tolerance Bethlehem Steel's Homer Research Laboratory identified some mechanistic effects of carbide morphology on fracture behavior of 3%Cr and 5%Cr vacuum melted roll grade specimens. The work also examined the synergy between composition the dependent austenitizing conditions (8). The research demonstrated that the prior austenitic grain size influenced notch impact properties differently than fracture toughness. While higher hardening temperature favored crack propagation behavior, the impact resistance was associated with grain refinement, suggesting that heat treatment could produce an optimal microstructure to match roll service conditions. The work attributed an observed toughness deficit in the 5%Cr grade to an increased presence of interlath carbide and temper embrittlement susceptibility associated with higher Cr content. Subsequent publications contradict this particular conclusion, citing the use of modified heat treatment procedures to manipulate carbide dissolution kinetics 5% Cr grade (9,10).

The size of the bainite platelet, determined by the quenching practice, also influences resistance to cleavage fracture. Likewise, the residual compression pattern imparted by the quenching transformation strains governs progressive tunnel crack propagation that precedes catastrophic spall detachment (11). These technical attributes that define damage tolerance in service both derive from the heat treatment. The present work established comparable toughness in a Selas differentially hardened 3%Cr cast roll sample and a 3% Cr forging hardened in a car furnace by simply re-tempering the cast roll to a matching hardness level, despite noticeable differences in the macroscopic appearance of specimen fractures.

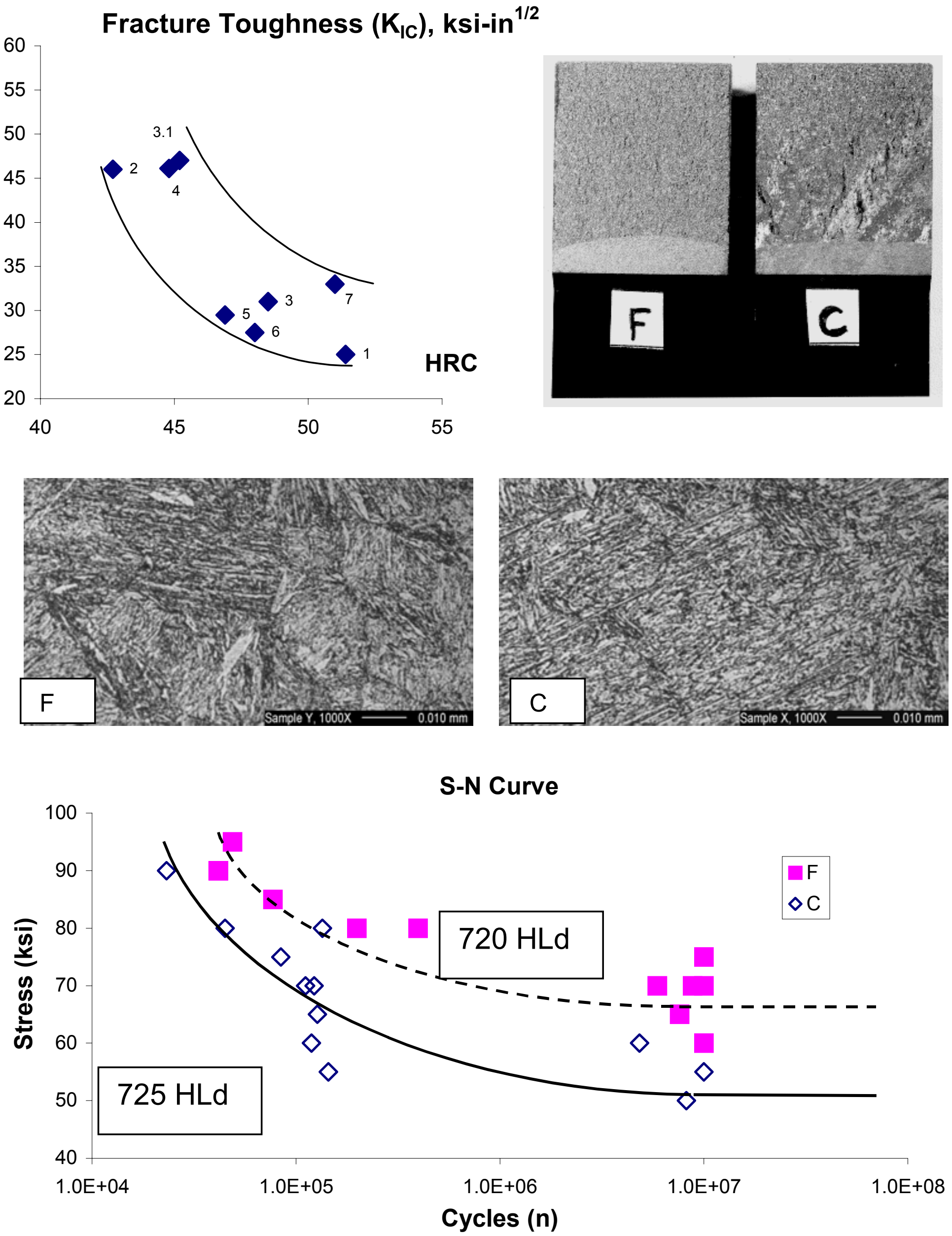


Figure 4. Comparison of the averaged (2 tests) K_{IC} data confirms as inverse relationship with hardness. The 3%Cr forged roll exhibited exceptional toughness at 45 Rc. Re-tempering the corresponding cast roll sample to match that same hardness level restored the fracture toughness properties, despite the coarse macrographic appearance of the specimen fracture. Note that both cast and forged steel specimens exhibit high endurance limits. The SN curve illustrates the advantage imparted by hot work consolidation of interdendritic microshrinkage. The microstructural appearance of the two rolls is remarkably similar.

Fatigue Endurance determined by axial testing highlights the important role of microshrinkage porosity as a crack initiation site. Consequently, the SN life expectation curve reflects a statistical advantage for forged roll specimens. Both types of rolls exhibit a significant safety factor for designed mill operating loads when hardened to the 65-75 HSc hardness level, however. At 70 HSc, the cyclic endurance ranges between 410-480 MPa (12). Slack quenching that produces a soft (55-60 HSc limit) reconstructive upper bainite surface micro-structure tends to devolve a secondary, harder pearlitic boundary phase within the working layer of the roll due to mass effects of the large component. In this regard, the relatively diffusionless transformation to martensite and lower bainite associated with accelerated quenching rates, attainable in both cast and forged steel roll of either 3% Cr or 5% Cr analysis, assures that the preferred hardness and corresponding fatigue resistance can be achieved without degradation of roll performance from new to discard size.

5 CONCLUSIONS

1. Microstructural differences observed between 3% Cr and 5% Cr back-up rolls are principally attributable to the efficacy of the final heat treatment, and not necessarily to the chromium content.
2. There is no discernable difference in fracture toughness or wear behavior between 3% Cr and 5% Cr back-up rolls tested at equivalent hardness levels.
3. Although the microstructures of cast rolls exhibit dendritic segregation, both cast and forged rolls display similar fracture toughness when heat treated to the same hardness level and microstructure.
4. Based on this study, it is expected that properly heat-treated back-up rolls, whether cast or forged, 3% Cr or 5% Cr, will perform equally well under comparable service conditions.

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