ISSN 1983-4764

THE PHYSICAL METALLURGY OF 4% CHROMIUM MOLYBDENUM FORGED STEEL COLD MILL WORK ROLLS[1]

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Abstract

Typically forged steel cold mill work rolls are manufactured with a nominal chromium content of 2%, 3% or 5% based on the roll specifications for a given mill application. The metallurgy of these alloys has been well documented through extensive research. The purpose of this work is to study the physical metallurgy of 4% Chromium Molybdenum forged steel rolls. The influences of melting, forging and final heat treatment (Full Coil Static Induction Hardening Process) on the structure and properties of this alloy are discussed. Mill experience is included in the analysis.
Key Words: Forged steel rolls; Cold mill; Roll technology.

[1] *Technical contribution to the 49th Rolling Seminar – Processes, Rolled and Coated Products, October, 22nd-25th, 2012, Vila Velha, ES, Brazil.*
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ISSN 1983-4764

INTRODUCTION

The development of forged hardened steel roll technology has recently focused even more emphasis on the physical metallurgy of the roll material selected for a given mill application. Key roll properties have been targeted to meet increasing requirements for critical surface finish and texture of flat rolled products, mill productivity, roll shop efficiency and "value in use."

A chronological review of the evolution of alloy design for these materials is summarized in Table 1. The entire range of compositions given are still utilized in the industry. The chromium content has demonstrated the greatest change due to its influence on the wear characteristics of the roll body. Typically forged steel cold mill work rolls are manufactured with a nominal chromium content of 2%, 3% or 5% based on the roll specifications for a given mill application. The metallurgy of these alloys has been well documented through extensive research.(1-4) Specifically, the increasing chromium content has resulted in improved depth of hardness and the development of a more complex, higher hardness carbide (M_7C_3) in material containing greater than 3% Chromium. The equilibrium phase diagram for the FE-CR-C alloy system at 870^o C is shown in Figure 1 and illustrates the relative positions for the nominal alloy compositions listed in Table I and their respective carbide types.(5) The hardness of the M_3C carbide is approximately 65 Rc (840/1100 Vickers) which is similar to the hardness of the martensitic matrix. Due to this similarity, the M_3C type carbide does not contribute significantly to the wear resistance of the roll material. The chromium carbide M_7C_3, depending on the actual chromium content, can range in hardness from 1200 to 1600 Vickers.(6)

Table 1 Typical forged steel cold mill work roll alloys (wt. %)

	Time period of development			
Element	1940's-1950's	1960's	1970's	1980's
C	.70 / 1.00	.70 / 1.00	.70 / 1.00	.70 / 1.00
Mn	.25 / .50	.25 / .50	.25 / .50	.25 / .50
Si	.25 / .50	.25 / .50	.25 / .75	.25 / 1.00
Cr	1.50 / 2.00	2.00 / 2.50	2.75 / 3.25	4.75 / 5.25
Mo	.10 / .20	.10 / .20	.10 / .50	.10 / 1.00
V	.05 / .20	.05 / .20	.05 / .20	.05 / .20

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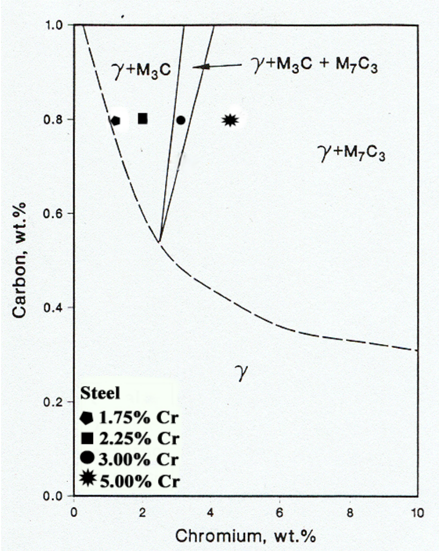

Figure 1: Equilibrium phase diagram for the FE-CR-C system at 870° C (1600° F).

The methodology used for the final heat treatment of the roll body underwent significant development in the 1990's; the result being the successful application of high hardness, ultra deep hardened forged steel work rolls to further enhance the wear characteristics of the roll body.(7) During that time period, the specification for 5% Chromium, high hardness (> 65 Rc, 880 HLd), ultra deep hardened work rolls was recognized as the optimum combination of alloy design and heat treatment to maximize roll performance. It was also determined that certain products of this type required a secondary melting operation, electroslag remelting (ESR). The ESR process was necessary to achieve the metallurgical properties in the roll blank to reduce risk in both the final heat treatment operation and in mill service. Precise control of the melt rate, solidification rate, depth and shape of the molten pool profile during ESR permitted the minimization of eutectic carbide cells and level of segregation in high alloy (5% Chromium) ingots.(8)

Recent roll technology has been focused on the development of a hybrid alloy between the 3% and 5% Chromium grades. The purpose of this paper, therefore, is to discuss the relevant physical metallurgy of 4% Chromium forged steel work rolls. The following topics will be discussed:

Melting and Forging
Final Heat Treatment
Mill Experience/Roll Performance

MELTING AND FORGING

The initial stage of the manufacturing process involves two operations, electric arc furnace (EAF) melting and vacuum stream degassing. All grades are then bottom poured according to guidelines developed for each type alloy (1.8 to 5% Chromium). Subsequent routing of the ingot is dependent on the type of alloy and the roll specification. After stripping, ingots are either immediately given a preheat for forging or are assigned the ESR process. After complete solidification, the ESR ingots are also assigned a preheat for forging. The forging procedures vary according to the increasing alloy content and the respective resistance to deformation. Controlled deformation of high alloy ingots must occur within the proper temperature range to optimize the grain structure and properties and to avoid internal bursts.(9) The post-

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forge heat treatment (Figure 2) establishes the microstructure and physical properties of the roll blank in preparation for the final heat treatment.(10) This section will address the following research as it relates to this stage of the manufacturing process in the development of the 4% Chromium alloy.

- Roll Blank Assessment
- 4% Chromium Alloy ESR Roll Blank (Phase I)
- 4% Chromium Alloy EAF Roll Blank (Phase II)

Roll Blank Assessment

Nondestructive testing (NDT) is performed subsequent to rough machining of the roll blank to verify that both the surface and the interior of the roll body are acceptable prior to final heat treatment. NDT methods include:

- Visual Inspection, Hardness Testing and Ultrasonic Inspection

The transverse mechanical properties of forged roll blanks have previously been determined to provide a quantitative assessment of the degree of both micro and macro segregation throughout the cross-section of the forged roll body.[11] Forged products are evaluated in three directions using the standard tensile specimen:

- Longitudinal, Radial and Transverse

Longitudinal specimens with flow lines parallel to the forging axis exhibit the highest ductility (% reduction of area, % elongation), while transverse specimens exhibit reduced values. Since the transverse direction is perpendicular to both the forging axis and the solidification direction in conventional EAF ingots, it is the specimen used to assess the quality of the blank. Wells and Mehl illustrated this effect by showing the relationship between the reduction of area values and the angle between the direction of the test and the longitudinal axis (Figure 3).(11) An isothermal spheroidize anneal post-forge heat treatment maximizes this effect in the roll blank.

The development of the 5% Chromium alloy in the 1980's included an assessment of the transverse mechanical properties. The sampling procedure was made for a 610 mm (24.0 inches) diameter, rough machined roll body. The transverse mechanical properties for both EAF and ESR roll material are compared in the following figures:

Figure 4 Tensile Strength/Yield Strength
Figure 5 % Elongation
Figure 6 % Reduction of Area

The actual chemical analyses of these forgings are given in Table 2. Both rolls were forged from a 1016 mm (40 inches) diameter ingot with a forge reduction of 2.4 (cross-sectional area ingot/cross-sectional area forging). The post-forge heat treatment (isothermal anneal) of the 5% Chromium alloy produced a spheroidized carbide microstructure.

Table 2 Transverse mechanical testing composition (wt%)

Alloy Type	Type Melt	C	Mn	P	S	Si	Cr	Mo	V	Cu	Ni
5% Cr	EAF	0.88	0.25	0.015	0.008	0.22	4.77	0.18	0.061	0.098	0.181
5% Cr	ESR	0.88	0.29	0.016	0.007	0.35	5.13	0.19	0.080	0.124	0.229
4% Cr	EAF (1)	0.83	0.38	0.013	0.006	0.28	4.05	0.56	0.069	0.119	0.236
4% Cr	ESR	0.81	0.38	0.014	0.007	0.31	4.03	0.58	0.071	0.122	0.188
4% Cr	EAF (2)	0.82	0.39	0.012	0.007	0.32	4.12	0.57	0.076	0.106	0.273

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(1) Phase I; (2) Phase II

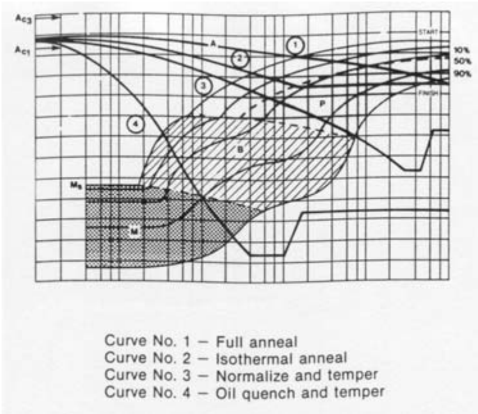

Figura 2: Post-forge heat treatment.

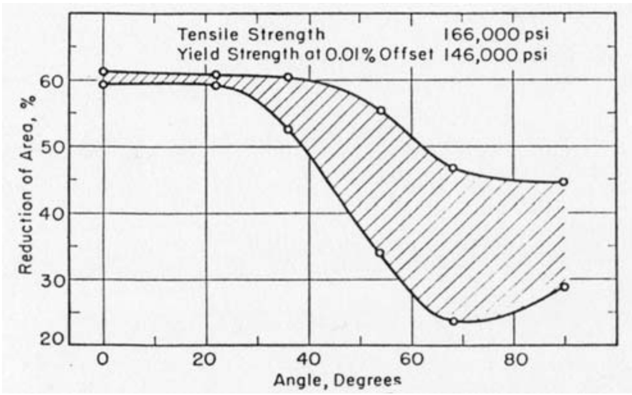

Figure 3: Angle between longitudinal axis and flow direction in specimen to % reduction in area (Wells and Mehl).

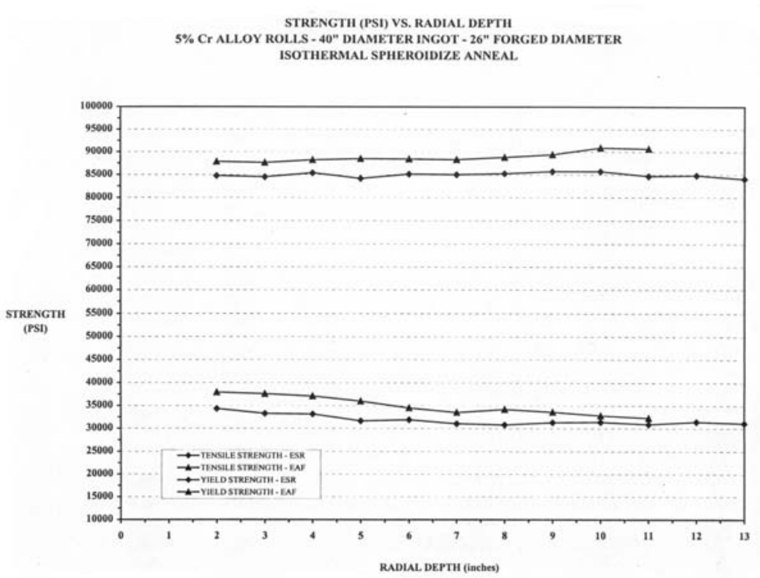

Figure 4. 5% Chromium alloy (EAF/ESR) Transverse mechanical prop. – UTS /yield strength.

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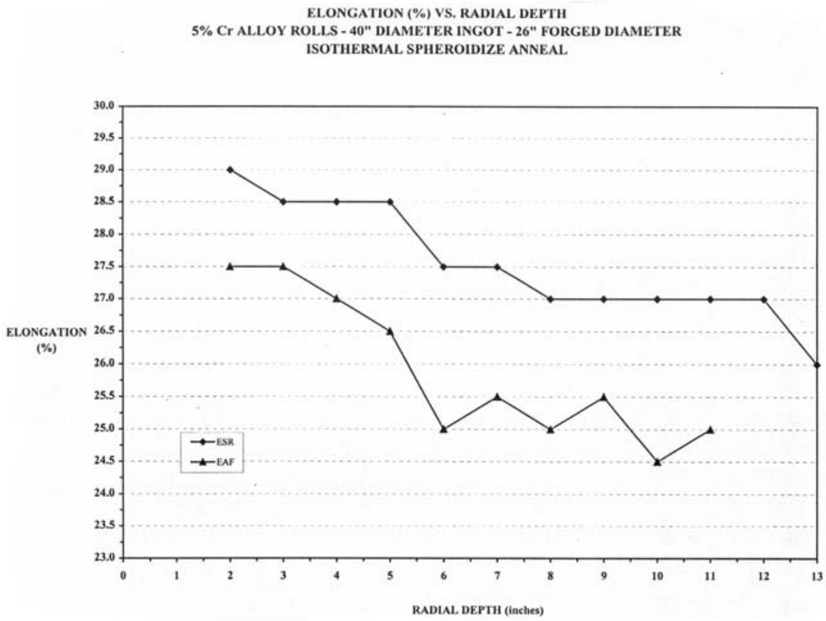

Figure 5: 5% Chromium alloy (EAF/ESR) - Transverse mechanical prop. - % Elongation.

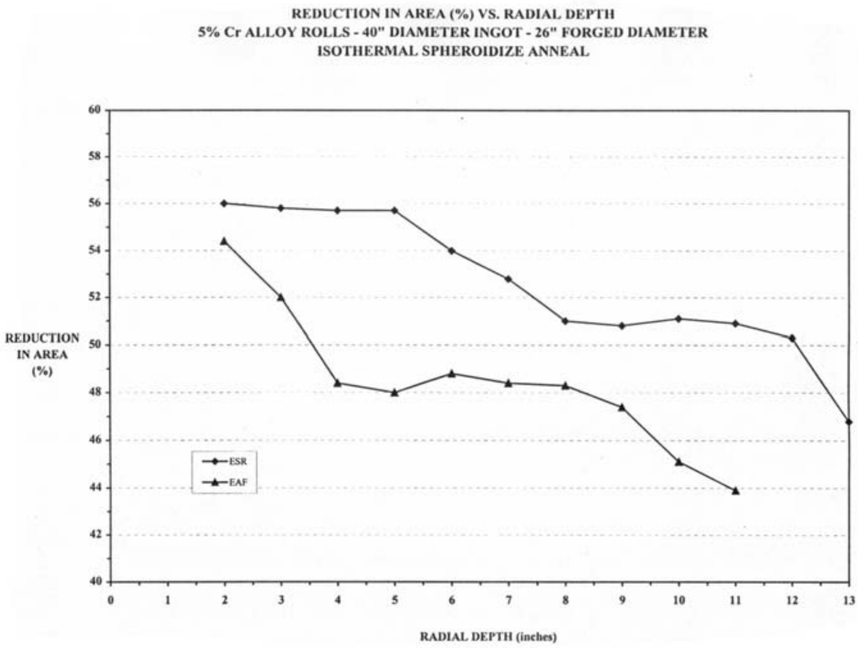

Figure 6: 5% Chromium Alloy (EAF/ESR) Transverse mechanical properties % Reduction of area

The results from the transverse tensile tests show that the ductility of the 5% Chromium ESR material is greater than the EAF material at the interior of the forging. The % reduction of area exhibits the greatest change and can also be observed by examination of the fractured specimens. A “cup/cone” fracture is typical of the specimens obtained near the perimeter of the forging body, while an angular or perpendicular fracture exists in the area of low ductility. The % elongation also displays a change but to a lesser degree than the reduction of area. However, both the tensile strength and yield strength remain relatively constant throughout the cross-section of the forging. A loss of ductility without an associated change in strength is atypical behavior and has been associated with alloy segregation.(11)

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The micro cleanliness of all specimens was evaluated and no relationship to loss of ductility was found. A summary of the cleanliness ratings is included in Table III (ASTM: E45-81, Method A).

Previous investigations have shown an empirical relationship between low ductility of the forged blank interior (% reduction of area < 40%) and the incident rate for both failures in final heat treatment and in-service problems. The correlation of this relationship increases with the more aggressive types of final heat treatment used to manufacture high hardness ultra deep hardened rolls. This is the basis for specifying ESR material for 5% Chromium rolls of this type.

4% Chromium Alloy ESR Roll Blank (Phase I)

In 1993 our roll technology development focused on the manufacturing of a 4% Chromium base work roll material. The following aim composition was selected:

Element:	C	Mn	Si	Cr	Mo	V
Wt. %:	.81	.37	.40	4.00	.53	.06

The initial heats included both EAF and ESR ingots to assess the transverse mechanical properties as described in the previous section of this paper. The results of this work are given in the following figures for a 610 mm (24.0 inches) diameter rough machined roll body:

Figure 7 Tensile Strength/Yield Strength
Figure 8 % Elongation
Figure 9 % Reduction of Area

The actual chemical analyses of these forgings are given in Table II. Both rolls were forged from a 1016 mm (40 inches) diameter ingot with a forge reduction of 2.4. The post-forge heat treatment (isothermal anneal) of the 4% Chromium alloy produced a spheroidized carbide microstructure (Figure 10). A summary of the cleanliness ratings is included in Table 3.

The tensile properties of the EAF 4% Chromium alloy were improved when compared with the 5% Chromium EAF material; however, the EAF 4% Chromium alloy material did not meet our acceptance criteria (% reduction of area > 40%). The decision was made to exclusively manufacture 4% Chromium production rolls using ESR material. Research was to continue on test rolls to improve the ductility of the EAF forging interior.

Table 3 Micro cleanliness evaluation

Alloy Type	Type Melt	A Sulphide	B Aluminate	C Silicate	D Oxide
5% Cr	ESR	0	0	0	1.0
5% Cr	EAF	0	0	0	2.0
4% Cr	ESR	0	0	0	1.5
4% Cr	EAF	0	0	0	2.5

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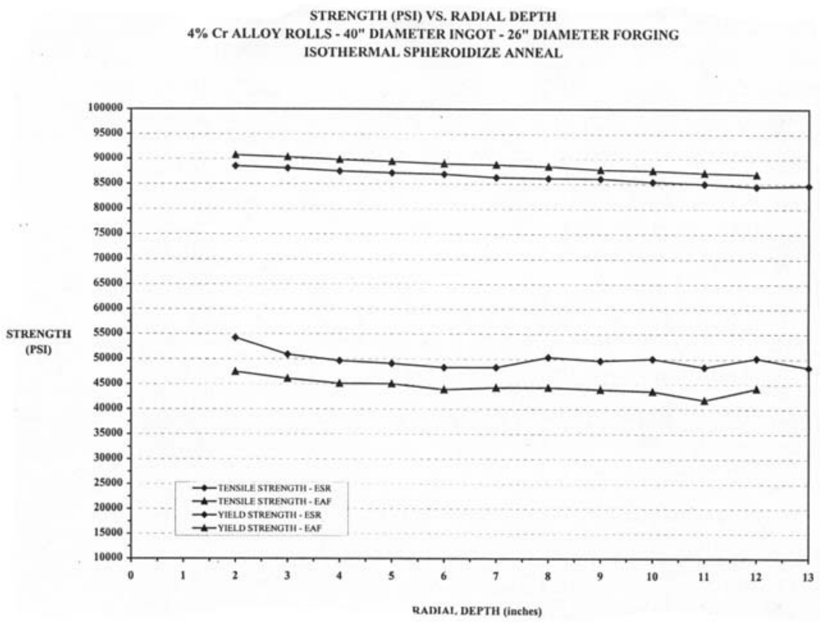

Figure 7: 4% Chromium alloy (EAF/ESR) - Transverse mechanical prop.-UTE /yield strength.

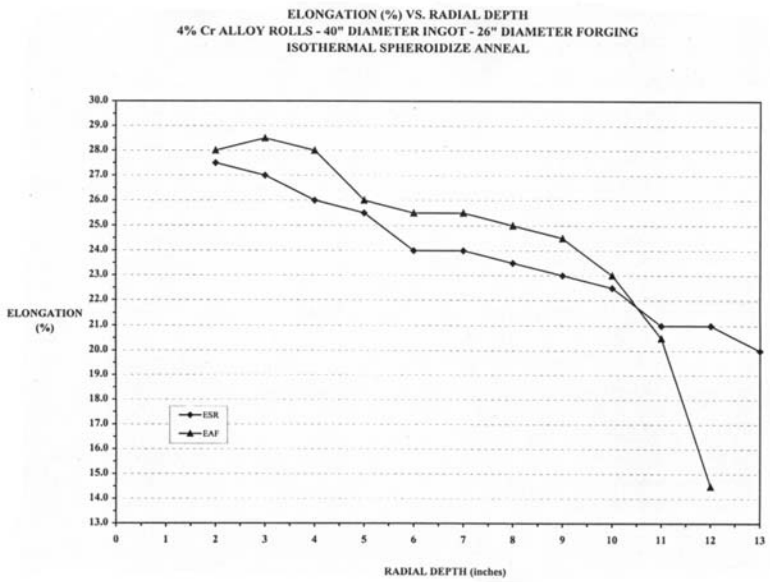

Figure 8: 4% Chromium alloy (EAF/ESR) - Transverse mechanical prop. - % Elongation.

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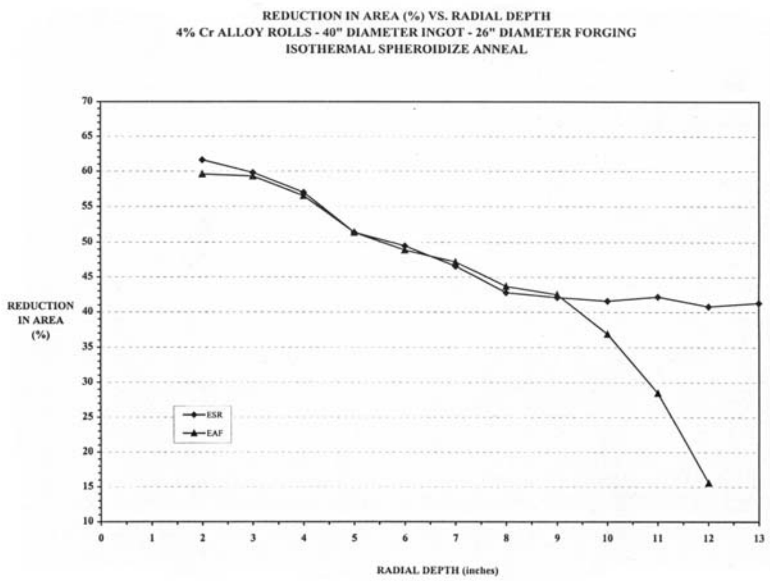

Figure 9: 4% Chromium alloy (EAF/ESR) - Transverse mechanical prop. -% reduction of area.

Figure 10: 4% Chromium alloy - Isothermal anneal – 1500 X - Picral

4%Chromium Alloy EAF Roll Blank (Phase II)

Between 1993 and 1999 extensive research was performed to develop a melting and forging practice capable of meeting our minimum requirements for ductility within the centerline zone of EAF melted material. The following parameters were included in this project:

- Ingot Design
- Ingot Size
- Bottom Pour Variables
- Forge Reduction
- Forging Practice
- Post-Forge Heat Treatment

Test rolls were manufactured in 1999 using EAF 4% Chromium alloy material that met our criteria for mechanical properties. The results of this work are given in the following figures for a 610 mm (24.0 inches) diameter rough machined roll body:

Figure 11 Tensile Strength/Yield Strength

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Figure 12 % Elongation
Figure 13 % Reduction of Area
The ESR results obtained from the previous work are included in these figures for comparison. The decision was then made to introduce controlled mill trials for validation of the EAF 4% Chromium alloy material.

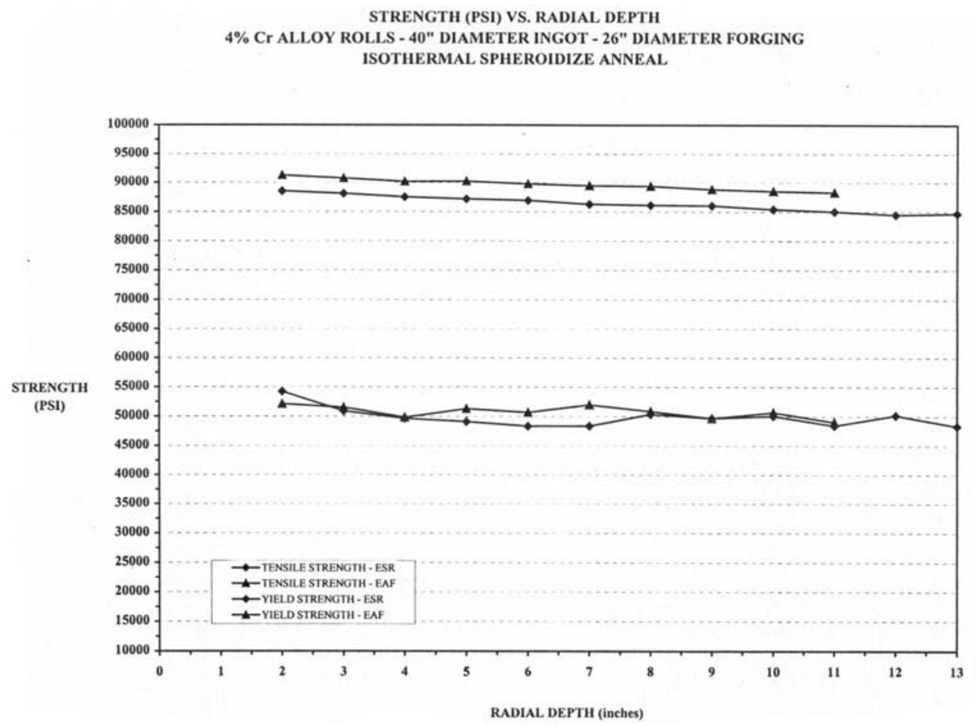

Figure 11: 4% Chromium alloy (EAF*/ESR) Transverse mechanical properties Tensile strength/yield strength *Revised practice

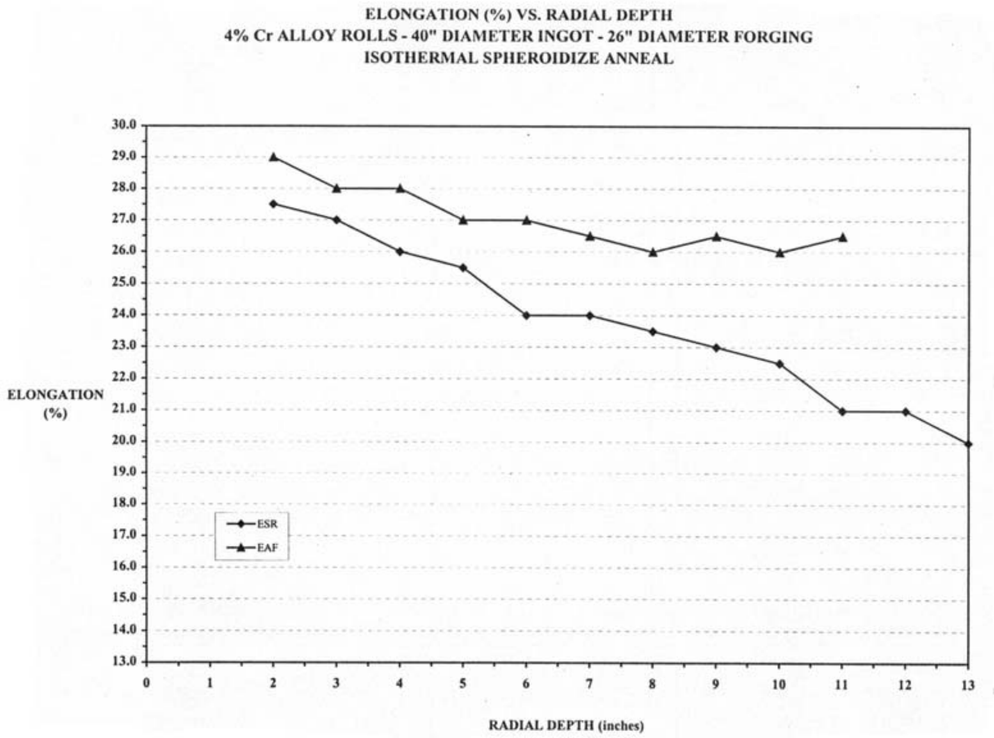

Figure 12: 4% Chromium alloy (EAF*/ESR). Transverse mechanical properties % Elongation
*Revised practice

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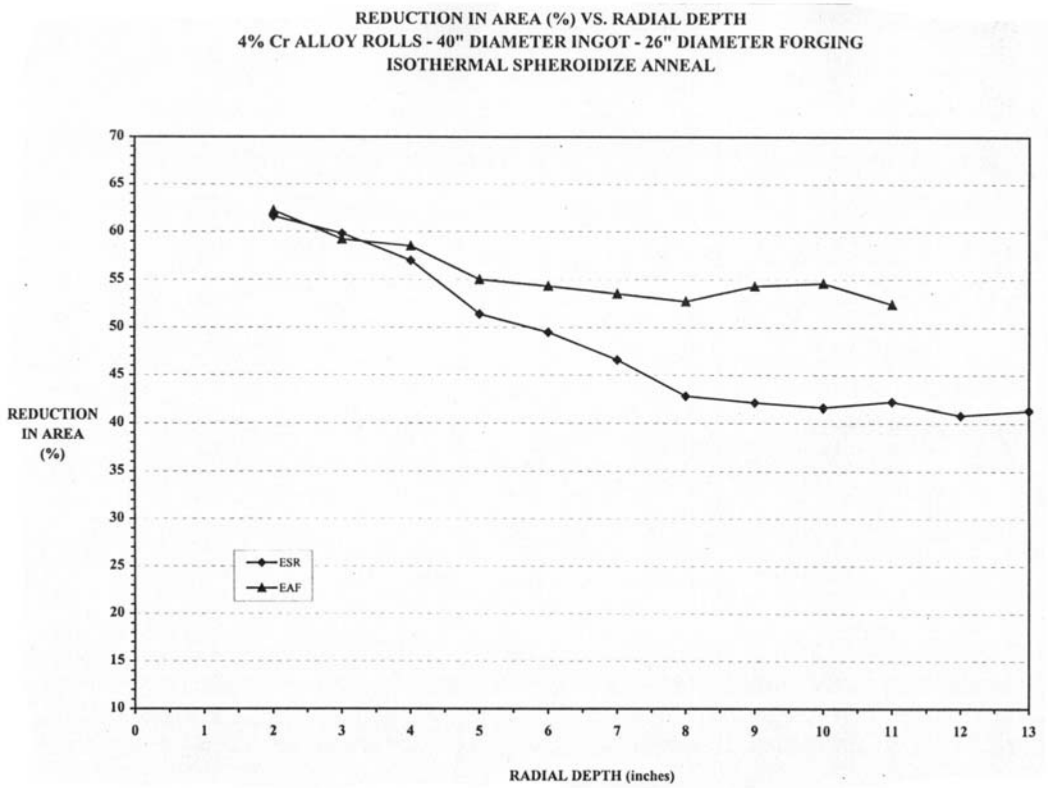

Figure 13: 4% Chromium alloy (EAF*/ESR) Transverse mechanical properties. % Reduction of area *Revised practice

FINAL HEAT TREATMENT

The final heat treatment of the roll body is critical to the performance of forged steel work rolls. Mill productivity, roll shop efficiency and acceptance of flat rolled product quality by the end user are all affected by the metallurgy of the roll.

The physical metallurgy of 4% Chromium work rolls has been evaluated to determine the effects of final heat treatment on key roll attributes:

- Transformation Behavior
- Hardenability (Depth of Hardness)
- Microstructure
- Tempering Response

Transformation Behavior

The transformation behavior was determined with a dilatometer.

Continuous cooling transformation (CCT) diagrams for the 4% Chromium alloy were developed over a wide range of austenitizing conditions (time/temperature) to determine the effective range of conditions that would optimize the resultant microstructures. The CCT diagrams were also used to establish the hardenability profile to meet the specified depth of hardness requirement for a given mill application.

A summary of the key features of the CCT diagrams is given in Table IV where CCT curves for different Chromium contents were also made. The following observations can be made:

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- As chromium increases from 1.8% to 3%, both Ac_1 and α_T first decrease, and then increase in the 4% and 5% Chromium alloys. α_T (alpha transus) is the temperature at which, on heating, the BCC to FCC transformation of the steel matrix is completed. Undissolved carbides are still present in the matrix.
- The bainite start time, B_S, for the 10% contour is especially critical to hardenability since this volume percent coincides with a significant change in hardness of the matrix. The 4% Chromium alloy exhibits the greatest bainite hardenability (5000 seconds).
- The martensite start temperature, M_S, decreases with increasing chromium content, with the 4% Chromium alloy (maximum hardenability) giving the minimum value (150° C, 300° F). The M_S temperature in certain 4% and 5% Chromium alloys appears as a "slope." The rise in M_S temperature with longer cooling times can be explained by the precipitation of carbides upon cooling causing depletion of carbon and chromium in the austenite.

Table 4 Transformation behavior

		Temperature								Time (Seconds) [1]	
Chromium Content	Hardenability	A_{C1} °C	A_{C1} °F	α_T °C	α_T °F	B_S °C	B_S °F	M_S °C	M_S °F	B_S	P_S
4%	Maximum	730	1345	795	1465	400	750	150	300[2]	5000	3500
4%	Minimum	730	1345	805	1480	400	750	280	535	620	500
5%	Maximum	755	1390	810	1490	375	705	165	325[2]	3000	1100
5%	Minimum	755	1390	820	1510	375	705	205	400[2]	900	420
3%	Typical	675	1245	740	1365	430	805	220	430	420	420
2%	Typical	725	1335	770	1420	440	825	230	445	300	225
1.8%	Typical	740	1365	790	1455	475	890	240	465	150	200

(1) 10% Volume Fraction Contour; (2) "Slope" Contour

Hardenability (Depth of Hardness)/Microstructure

The design verification phase of the development of the 4% Chromium alloy included the following procedure on full sized, hardened rolls:

- The body diameter is machined in increments to simulate roll shop conditions. Hardness measurements, using both indentation and rebound devices, are made after each plunge.

The full coil static induction hardening method is utilized for the final heat treatment of the 4% and 5% Chromium alloys.[12] This method involves heating the entire cross-section of the roll body followed by a severe water quench of both the outside diameter and a center hole (bore). Cryogenic treatment is used immediately after the water quench depending on the roll specifications. The transformation behavior of the static induction heating method has two important advantages:

- A constant austenitizing temperature profile is obtained for a pre-determined depth. A single CCT diagram can then be used to predict the transformation behavior.
- Quenching (water/cryogenic) of the entire body length at one time insures continuous cooling of the roll body with no interruption.

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The hardenability results for a 635 mm (25.0 inches) diameter finish machined roll body (120 mm hardening process) are given in Figure 14 (Rc scale) for the 4% and 5% Chromium alloys. The effective range of hardening processes established for the 4% Chromium alloy were applied to four of the same size roll [635 mm (25.0 inches) diameter].

The carbide phase is further analyzed for the 4% and 5% Chromium alloy rolls. A summary of these results, including the lower chromium alloys, is given in Table V. The carbide composition was determined by SEM techniques. Elemental maps and EDAX analysis confirm the undissolved carbides to be M_7C_3. The 5% Chromium alloy carbide shows a higher chromium concentration than the 4% Chromium alloy carbide.

Tempering Response

Forged steel cold mill work rolls are normally tempered in the range of 100° C (212° F) to 260° C (500° F) to meet the specified matrix hardness. The carbide hardness remains constant. A statistical analysis of the tempering response over this range of temperature was made for the 4% and 5% Chromium alloy rolls. A significant correlation exists for these alloys. An increase in tempering temperature of approximately 17° C (30° F) for the 4% Cr alloy reduces hardness in one HRc.

MILL EXPERIENCE/ROLL PERFORMANCE

During Phase I (1993-1999) of the development of the 4% Chromium alloy cold mill work roll analysis, production rolls were exclusively manufactured using ESR material. Approximately 1,220 rolls of this type were shipped during this time period. Since 1999 (Phase II), a total of 25,000 4% Chromium alloy rolls have been manufactured using EAF material.

The roll performance of the 4% Chromium alloy material has validated both the assessment of the EAF roll blank material and the transformation behavior outlined in this paper.

CONCLUSION

The physical metallurgy of the roll material is critical to roll performance. Proper assessment of the forged roll blank is especially important considering the aggressive methods of final heat treatment designed by the roll manufacturer and the stringent roll specifications dictated by high speed continuous mill operations.

Table 5 Carbide analysis

Chromium Content	Carbide Type	Carbide [6] Hardness (HV)	Surface Area (%)	Average Diameter	Carbide Density
2%	M_3C	850/1100	6-7	.6	3.0 x 10^5
3%	M_3C	850/1100	6-7	.8	1.4 x 10^5
4%*	M_3C/M_7	850/1600	7-8	.7	2.4 x 10^5
5%*	M_7C_3	1200/1600	10-11	.6	4.3 x 10^5

*Special induction hardening process

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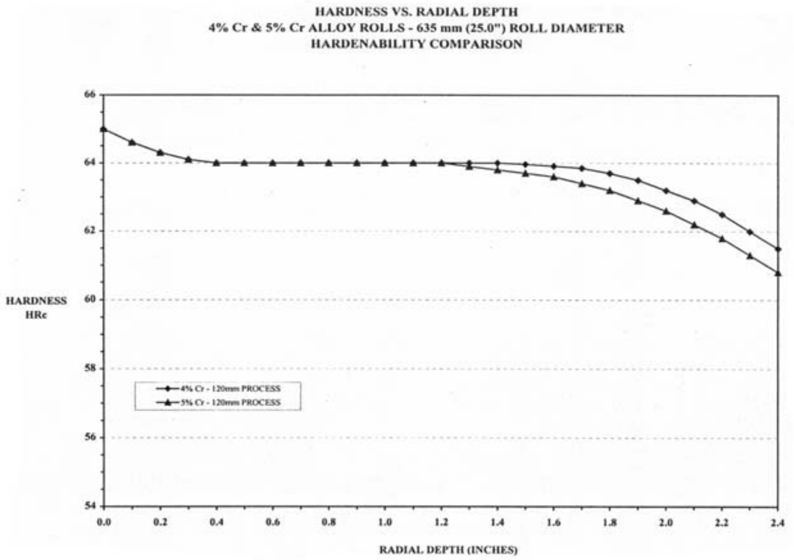

Figure 14: Depth of hardness profiles - 635 mm (25.0 inches) diameter roll (HRc).

Acknowledgements

I would like to acknowledge the input to this paper by the metallurgical staff of Union Electric Steel Corporation. Special recognition goes to Mr. Jason Sychterz, Senior Research Metallurgist, and Mr. Mark Schaupp, Project Metallurgist.

REFERENCES

1 R.L. BODNAR, MINFA LIN, S.S. HANSEN, "The Physical Metallurgy of Forged Cold-Mill Work-Roll Steels," 3rd Mechanical Working and Steel Processing, 1991, Pages 171-185.
2 P. COSSE, C. GASPARD, A. MAGNEE, "Contribution of ESR and Progressive Induction Hardening to the Manufacture of Deep Hardened Work Rolls," 26th Mechanical Working and Steel Processing, 1984, Pages 75-87.
3 S. IZUMIKAWA, S. KAWASHIMA, M. YOSHIKAWA, "New Trend of Forged Hardened Work Rolls and Backup Rolls for Rolling Mills in Japan," 29th Mechanical Working and Steel Processing, 1987, Pages 49-57.
4 P. CARLESS, H.T. GISBORNE, R. PRICE, "Choice of Hardening Method for Forged Steel Work Rolls," 35th Mechanical Working and Steel Processing, 1993, Pages 41-97.
5 L.R. WOODYATT, G. KRAUSS, "Iron-Chromium-Carbon System at 870° C," Metallurgical Transactions A, Vol. 7A, July, 1976, Pages 983-989.
6 T.S. EYRE, Source Book on Wear Control Technology, ASM, 1978, Page 4.
7 G.A. OTT, "The Application, Metallurgy and Maintenance of High Hardness Ultra Deep Hardened Forged Steel Work Rolls," 38th Mechanical Working and Steel Processing, 1996, Pages 91-105.
8 G. HOYLE, Electroslag Processes, Applied Science Publishers, 1983, Pages 2-70.
9 S.A. HEIM, J.E. FIELDING, R.L. BODNAR, "Avoiding Overheating and Burning in Forged Roll Steels," Iron and Steelmaker, Vol. 17, No. 9, September, 1990, Pages 26-34.
10 G. A. OTT, "Manufacture of Forged Steel Rolls," Rolls for the Metalworking Industries, ISS, 1990, Pages 113-120.
11 CYRIL WELLS, ROBERT F. MEHL, "Transverse Mechanical Properties in Heat Treated Wrought Steel Products," Transactions of the ASM, Volume 41, 1949, Pages 715-818.
12 G.A. OTT, "The Development of Forged Hardened Steel Roll Metallurgy to Meet Special Rolling Mill Requirements," 33rd Mechanical Working and Steel Processing, 1991, Pages 159-170.