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Microstructural Characteristics of Prematurely Failed Cold-Strip Mill Work-Rolls: Some Observations on Spalling Susceptibility

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A comprehensive metallurgical investigation was carried out on samples of prematurely failed cold-strip mill work-rolls used in an integrated steel plant to study the influence of microstructural characteristics on failure propensity and roll life. The samples pertained to 3 wt.% Cr-base forged steel work-rolls, which exhibited variations in roll life despite operation under similar mill environments. Optical and SEM revealed that while a uniform dispersion of fine globular carbides was conducive to higher roll life, carbides of angular and/or elongated morphologies acted as stress-raisers, induced microcracking of the tempered martensite matrix, and accentuated eventual spalling. From the standpoint of nonmetallic inclusions, higher life rolls were cleaner. Low/poor life rolls showed higher incidences of MnS and angular TiN inclusions, which often provided sites for the precipitation of undesirable elongated carbides. Although microprobe analysis indicated that carbides in these rolls were essentially M_7C_3, quantitative metallography revealed that, apart from morphology, roll performance was profoundly influenced by carbide content and count. Interestingly, while higher life rolls were characterized by carbide contents of >4.5 vol.% and counts of >200,000 number/mm^2, rolls exhibiting low and poor lives showed significantly lower values of these features. X-ray diffractometry of spalled roll specimens indicated that while higher life rolls contained minimal retained austenite, rolls exhibiting lower lives inevitably contained >10% retained austenite. The deleterious effect of excessive retained austenite on the spalling susceptibility of cold-strip mill work-rolls was attributed to its possible transformation to martensite under imposed rolling stresses.

Keywords cold-strip mill, roll failure, spalling, work-rolls

1. Introduction

In integrated steel plants producing high-quality flat products, forged alloy steel work-rolls are commonly used for cold rolling. These rolls are generally supplied to mills in the hardened and tempered condition with a surface hardness of around 90 Shore D. The primary requirements of work-rolls used in cold-strip mills are outstanding resistance to wear and plastic deformation and good rolling-contact-fatigue strength. As insurance against wear and plastic deformation, rolls must, therefore, possess high surface hardness and great depth of hardening (Ref 1). Work-rolls for cold rolling must also possess excellent texturing characteristics, because this has an important bearing on the surface quality of the rolled strip (Ref 2). The complex and severe service conditions imposed by cold rolling generate a variety of stresses on the rolls, and this necessitates the specificity of rolls for appropriate usage. The specificity of rolls is not only dictated by the steel composition and melting methods, but also by the type of heat-treatment imparted to the rolls.

Work-rolls for the cold rolling of steel sheet and strip generally contain 0.7 to 1.0 wt.% C and 1.0 to 5.0 wt.% Cr, with small quantities of other alloying elements (Ref 3). Until approximately 1970, steel containing 2 wt.% Cr was the standard material used for the manufacture of cold-strip mill work-rolls. However, from 1970 onward, 3 wt.% Cr-base steels were developed for achieving improved hardenability, superior wear properties, and increased resistance against rolling accidents. Around 1978, 5 wt.% Cr-base steel was introduced as the work-roll material to secure further improvements in the depth of hardening, wear resistance, and rolling-contact-fatigue strength (Ref 4). Incidentally, work-rolls of both 3 and 5 wt.% Cr-base steels continue to be used in cold-strip mills today.

The performance of work-rolls in cold-strip mills is not only governed by their metallurgical quality, but also by the imposed service conditions. In present-day cold-strip mills, work-rolls are subjected to severe operating conditions in view of the high mill speeds used, and the demanding requirements of mill productivity and product quality. This naturally enhances the chances of premature roll failures by surface degeneration, and subsurface cracking and spalling. Whereas surface degeneration and subsurface cracking can be eliminated by careful grinding of the roll surface, spalling inevitably results in catastrophic failure, which grossly reduces roll life and, in turn, lowers mill productivity.

Spalling is the culmination of a fatigue phenomenon and involves the removal of large, or shallow, metal peelings from the roll body (Ref 5). The genesis of spalling is complex. It may be thermally and/or mechanically induced as a consequence of severe cyclic stresses, cold working, and/or work hardening. A spalled roll is subjected to deep dressing and consequently results in early scrapping. In the case of cold-strip mill work-rolls, the problem is compounded by the fact that

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while high surface hardness and deeper depth of hardening are key property requirements for achieving high resistance to wear and plastic deformation, it is this high hardness and the associated internal stress that render the rolls thermally unstable and crack-sensitive, and, therefore, susceptible to spalling.

In industrial practice, work-rolls are generally procured from different manufacturers on the basis of standard specifications that govern chemistry, surface hardness, roll geometry, and dimensions. Although such rolls are expected to yield guaranteed service lives in terms of material tonnage rolled, their performance may often vary widely despite usage under similar mill-operating environments. The inconsistency in roll performance in a particular mill during a given campaign period is largely attributed to premature failures, notably by spalling, and may be noticeable in rolls supplied by different manufacturers, or alternatively, in different batches supplied by a specific manufacturer. Roll spalling in cold-strip mills is undoubtedly operation-sensitive, but, then, mill abuse is a bit too overemphasized vis-à-vis roll material quality. Microstructural differences with regard to type, proportion, morphology, and the distribution of phases undoubtedly exist in batches of industrially supplied rolls; the specific influence of such individual attributes on roll performance is, however, not clearly known. A systematic study of roll microstructures is worth pursuing because it is critical to understand the influence of microstructural characteristics on spalling susceptibility that affects the performance of cold-strip mill work-rolls under similar mill operating conditions.

It is from this perspective that a comprehensive microstructural investigation was carried out on prematurely spalled samples of 3 wt.% Cr-base forged steel work-rolls used in a multistand, high-speed, cold-strip rolling mill. The study pertains to an integrated steel plant under the Steel Authority of India Limited, where work-rolls exhibited wide variations in roll life despite usage under similar mill-operating conditions and environments. The article discusses the microstructural characteristics of prematurely spalled cold-strip mill work-rolls with regard to failure propensity and roll life.

2. Experimental

Samples for the investigation were collected from the barrel portion of prematurely spalled cold-strip mill work-rolls. The broken samples were ultrasonically cleaned with acetone for the removal of adherent rolling debris prior to visual and microscopic examination.

For optical microscopy, specimens approximately 15 × 10 mm in size were sectioned from the spalled samples. In these specimens, portions pertaining to the working surfaces of rolls were polished by conventional metallographic procedures to a scratch-free finish. Polished and unetched specimens were examined through optical microscopy at a magnification of 500× to observe nonmetallic inclusion characteristics. For the microstructural examination of phases such as martensite, carbide, and retained austenite, the specimens were etched in Vilella's reagent (4 g of picric acid + 5 mL of HCl in 100 mL of ethanol) and were observed at 1000× magnification.

Quantitative metallographic studies were carried out through image analysis to determine the volume fractions of different phases present in the spalled roll samples. The volume percentages of the carbides present in the roll microstructures were determined in each specimen by randomly scanning 20 image fields at 500× magnification and calculating the average of all measured values. Quantitative image analysis of carbides was also carried out to determine their average sizes and counts per unit area. Because the retained austenite in the spalled roll specimens was not optically discernible, its content was not determined through image analysis. Instead, retained austenite measurements were carried out on selected roll specimens using x-ray diffractometry (XRD). During testing, an accelerating voltage of 30 kV and a beam current of 20 mA were used. A 2θ-range of 24 to 61 degrees was scanned at an angular (2θ) speed of 2 degrees per minute.

Scanning electron microscopy (SEM) was carried out on Vilella-etched specimens to study carbide morphology and distribution at high magnifications as well as to observe the nature of the tempered martensite matrix. Concurrently, electron-probe microanalysis (EPMA) was also carried out on Vilella-etched roll specimens to determine elemental enrichment in the carbides. The studies were carried out at 15 kV accelerating voltage using a probe current of 5×10^{-8} A. Quantitative elemental microanalysis was also performed in some selected roll specimens to determine the composition and type of carbides present in the microstructures.

Table 1 Roll life and performance details of cold-strip mill work-rolls

Roll sample	Supplier	Roll life, t	Roll life range, 1000 t	Scrap diameter, mm
C1	X	45,526	>30	561.90
C2	Y	34,136	>30	564.75
C3	X	31,630	>30	563.85
C4	Y	28,800	20-30	573.95
C5	Z	26,794	20-30	565.60
C6	Y	24,832	20-30	569.50
C7	Y	23,555	20-30	572.40
C8	Z	13,148	5-15	569.60
C9	Z	9,999	5-15	578.20
C10	X	6,017	5-15	577.60
C11	X	5,075	5-15	569.10
C12	X	2,608	<5	582.40
C13	X	1,141	<5	582.90
C14	X	746	<5	583.85

3. Results and Discussions

3.1 Material and Roll Life

The cold-strip mill work-rolls investigated had a barrel diameter (nominal) of 585 mm and a barrel length of 1420 mm at the time of commissioning in the mill. The investigated rolls pertained to different manufacturers, and were supplied to the cold-strip mill in a hardened and tempered condition with a surface hardness of around 90 Shore D. The stipulated scrap diameter (i.e., the diameter corresponding to the desired hardness depth) for this class of rolls, which yield desired roll lives without undergoing premature failure is 545 mm. Although the minimum guaranteed service life of such rolls in the particular plant was reported to be around 30,000 tonnes (t), inadequate roll life was often attributed to premature roll failures by spalling. The details pertaining to sample number, supplier, roll life (in terms of material tonnage rolled), and diameter at spalling stage (scrap diameter) are furnished in Table 1, while the chemical compositions (in weight percent) are shown in Table 2.

The service lives of the rolls investigated (Table 1) showed

Table 2 **Chemical composition (in wt.%) of cold-strip mill work-roll samples**

Roll sample	C	Mn	Si	P	S	Ni	Cr	Mo
C1	0.88	0.44	0.65	0.010	0.012	0.30	2.95	0.24
C2	0.90	0.24	0.35	0.011	0.013	0.15	3.10	0.24
C3	0.88	0.46	0.62	0.015	0.012	0.30	3.10	0.22
C4	0.98	0.28	0.35	0.023	0.020	0.12	3.47	0.26
C5	0.79	0.23	0.22	0.014	0.011	0.24	3.12	0.21
C6	0.89	0.25	0.32	0.012	0.013	0.12	3.05	0.22
C7	0.90	0.26	0.35	0.020	0.015	0.14	3.11	0.22
C8	0.82	0.25	0.24	0.012	0.010	0.23	3.10	0.22
C9	0.81	0.24	0.23	0.015	0.016	0.22	3.05	0.21
C10	0.87	0.42	0.60	0.027	0.009	0.30	2.90	0.21
C11	0.87	0.47	0.66	0.016	0.006	0.22	3.01	0.22
C12	0.88	0.47	0.60	0.021	0.004	0.30	3.10	0.23
C13	0.88	0.47	0.56	0.017	0.010	0.27	3.10	0.21
C14	0.89	0.46	0.60	0.023	0.010	0.30	3.06	0.25

wide variations, ranging between 746 and 45,526 t. In steel rolling mills, the work-roll life is conventionally expressed in terms of the total tonnage of material rolled before the rolls fail or are discarded after wearing down to the stipulated scrap diameter through normal usage. It can be clearly observed from Table 1 that of 14 rolls investigated, 3 rolls gave lives of less than 5,000 t, 4 rolls give lives between 5000 and 15,000 t, 4 rolls gave lives between 20,000 and 30,000 t, and 3 rolls gave lives greater than 30,000 t. The data in Table 1 clearly show that work-rolls (C12, C13, and C14) that failed catastrophically and yielded lives of less than 5000 t were virtually discarded at the commissioning diameter (at approximately 585 mm). In contrast, rolls such as C1, C2, and C3, which yielded service lives greater than 30,000 t, were scrapped at significantly lower scrap diameters (561.90–564.75 mm). Broadly speaking, the 14 rolls investigated could be classified into four distinct batches on the basis of the aforementioned roll lives.

The chemical compositions (Table 2) of all failed roll samples showed that these conformed to the 3 wt.% Cr-base steel composition. As can be seen from Table 2, the C content was found to vary between 0.79 and 0.98 wt.%, while Cr was found to vary between 2.90 and 3.47 wt.%. The Mo content in these rolls varied between 0.21 and 0.26 wt.%, while the Ni content was found to range between 0.12 and 0.30 wt.%. As mentioned earlier, increased Cr content in steel rolls is known to impart superior wear resistance, achieve a greater depth of hardening, and promote the formation of a more complex M_7C_3 carbide. As the Cr content of steel increases from 1.75 to 3.25 wt.%, the type of carbide changes from M_3C (hardness 840-1100 Vickers hardness number [VHN]) to M_7C_3 (hardness 1200-1600 VHN), which virtually becomes the predominant carbide when Cr content reaches 5 wt.% (Ref 1). Nickel, despite being a noncarbide former, promotes hardenability. However, because Ni lowers the M_s (martensite start) temperature of steel and promotes the formation of larger amounts of retained austenite, its content in roll steels needs to be judiciously regulated. Molybdenum is known to significantly improve the hardenability, temper resistance, and wear resistance of steels. Its presence at the level of 0.21 to 0.26 wt.% is normal for this class of steel rolls.

3.2 Microstructural Features

3.2.1 Nonmetallic Inclusions. Optical microscopic observations of unetched roll specimens mainly showed the presence of sulfide and oxysulfide inclusions. In some samples, however, angular, orange-colored TiN inclusions were also seen. Typical inclusion fields in spalled roll samples exhibiting low roll lives are shown in Fig. 1(a) to (c) at 500× magnification. It can be clearly seen from Fig. 1(a) that the inclusions observed in roll sample C8 were elongated and elliptical MnS. In some places, however, cubic TiN inclusions were also observed. In roll sample C10, numerous TiN inclusions were observed, as shown in Fig. 1(b). The typical inclusions observed in roll

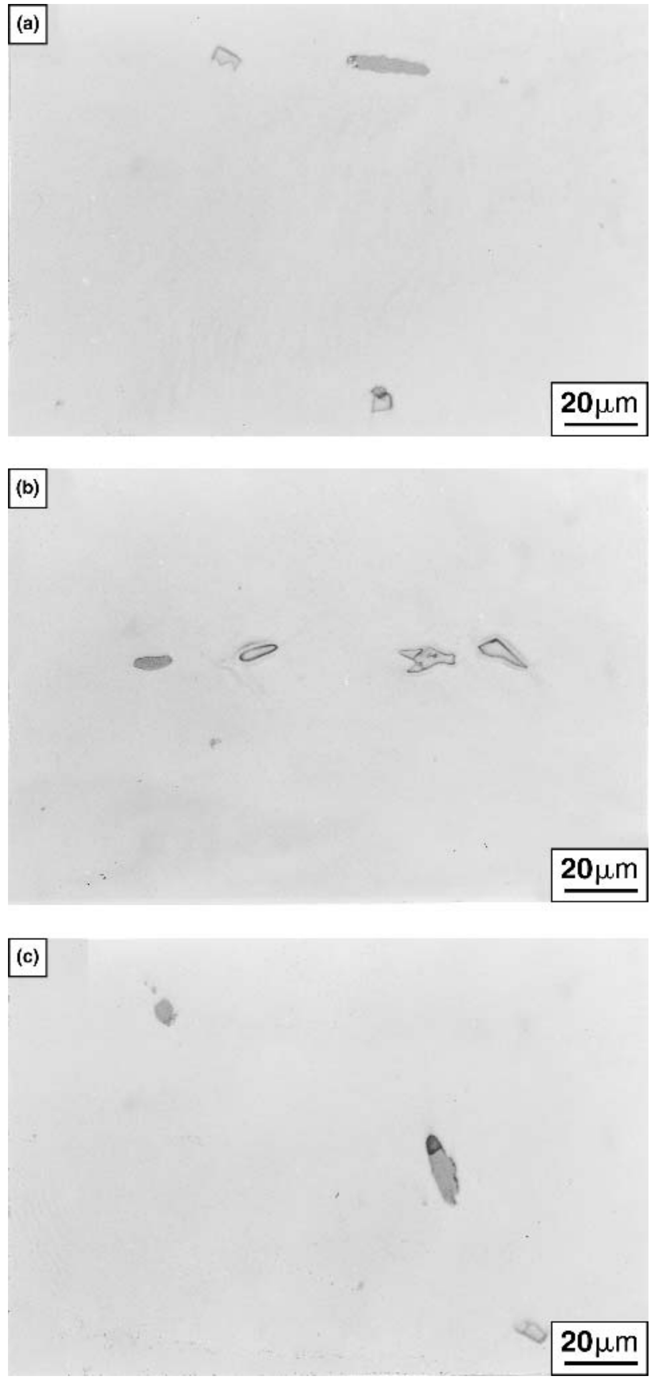

Fig. 1 Typical inclusion fields in spalled, cold-strip mill work-roll samples: (a) sample C8 showing elongated MnS and cubic TiN inclusions; (b) sample C10 showing an array of angular TiN inclusions; and (c) sample C7 showing oxysulfides and a few TiN inclusions. Magnification was 500× for all images.

sample C7 were mostly oxysulfides, as shown in Fig. 1(c). A few angular TiN inclusions were also observed. Microstructural observations of unetched roll specimens C1, C2, and C3, which exhibited higher roll lives (i.e., >30,000 t), showed relatively cleaner fields with lower populations of sulfide and TiN inclusions.

Spalling is a fatigue phenomenon, which, again, is profoundly influenced by the characteristics of the nonmetallic inclusions in the steel (Ref 6) While sulfide and oxysulfide inclusions are considered to be relatively innocuous in terms of the fatigue properties of steel, hard and brittle inclusions such as oxides (e.g., silicates and alumina) and nitrides are considered to be detrimental. The detrimental effect of cubic TiN inclusions on contact fatigue resistance steels is attributed to the fact that such hard and angular inclusions act as stress-raisers and are instrumental in nucleating microcracks (Ref 7). It is also recognized that the harmful effects of brittle inclusions are minimized when they are encapsulated by sulfides (Ref 8). This possibly explains the relatively inferior performance of rolls C8 (roll life 13,148 t) and C10 (roll life 6017 t), which exhibited a higher incidence of TiN inclusions compared with roll C7 (roll life 23,555 t), and mostly contained sulfide and oxysulfide types of inclusions.

3.2.2 Matrix Characteristics. The Vilella-etched microstructures of the spalled roll samples showed carbides of varying morphologies and sizes distributed in a matrix of tempered martensite. In most of the samples, retained austenite was not optically discernible. Typical microphotographs of Vilella-etched spalled cold-strip mill work-roll samples are shown in Fig. 2 at 1000× magnification. The microstructure (Fig. 2a) of cold-strip mill work-roll sample C1, which exhibited the highest roll life (45,526 t), showed a uniform dispersion of numerous fine globular carbides in a matrix of tempered martensite. In contrast, the microstructure (Fig. 2b) of roll sample C11, which exhibited a lower service life (5075 t), showed carbides of comparatively larger size and angular morphology.

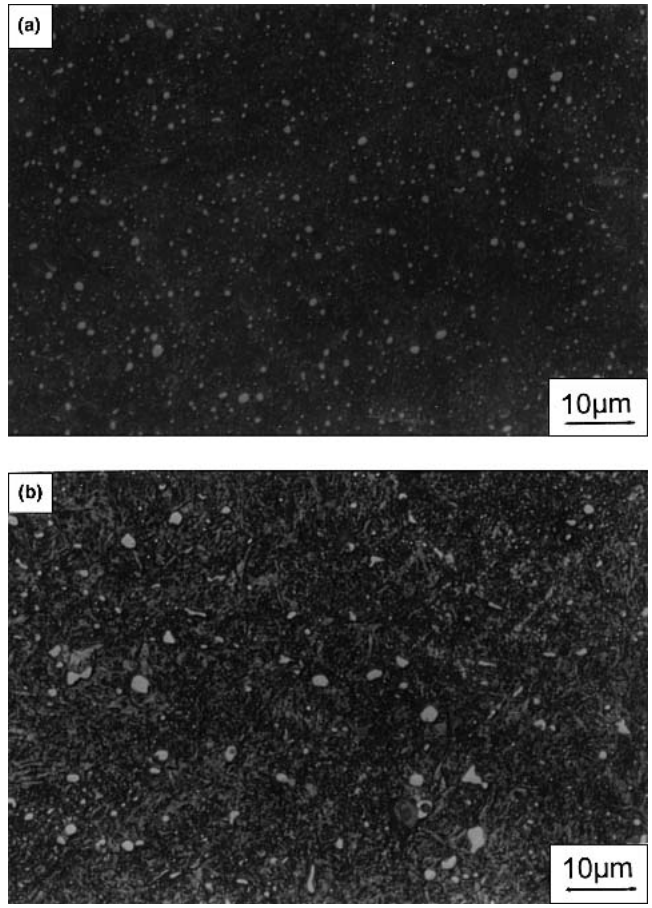

Fig. 2 Optical micrographs of Vilella-etched, spalled, cold-strip mill work-roll samples: (a) high-life sample C1 showing greater density and uniform dispersion of fine globular carbides, in dark-etching tempered martensite; (b) low-life sample C11 showing coarse and angular carbides in tempered martensite. Magnification was 1000× for both images.

Typical microstructures observed in rolls having poor lives C13 (life 1141 t) and C14 (life 746 t) are shown in Fig. 3(a) and (b), respectively, at 1000× magnification. The microstructure in Fig. 3(a) showed a low density of carbides. However, carbides of elongated (rod-like) as well as fine globular morphologies were found dispersed in the matrix of tempered martensite. The arrangement of rod-like carbides in Fig. 3(a) is presumably indicative of their location at prior austenite grain boundaries. A thick, ellipsoidal, gray-colored MnS inclusion observed at the bottom left of the micrograph was found to be associated with the elongated carbides. Interestingly, carbides were invariably found in intimate association with nonmetallic inclusions in other regions as well. This indicates that large MnS inclusions possibly provide sites for the precipitation of elongated carbides, which are otherwise undesirable. It is, therefore, possible that clean steels, with minimal content of nonmetallic inclusions, would be desirable for preventing the precipitation of such unwanted, elongated carbides.

The microstructure in Fig. 3(b) shows a segregated zone of coarse, angular carbides and a massive, cubic TiN inclusion in the matrix of tempered martensite. Carbides of irregular/angular morphologies, which occur as segregated regions, are known to accentuate cracking propensity, to lower wear resistance and toughness, and to impair the grindability of tool steels (Ref 9). A roll microstructure, consisting of a uniform dispersion of fine size globular carbides, is desirable in the sense that fine carbides, owing their thinness and cohesion with the tempered martensite matrix, assist in pinning dislocations and impeding their propagation under rolling stresses (Ref 10). In contrast, coarse and angular carbides have less cohesion with the steel matrix. Such carbides can act as potential stress-raisers, where stresses generated under rolling could exceed the roll material tensile strength, and, consequently, promote the generation and propagation of microcracks, culminating in spalling.

Carbides of angular, elongated, and lamellar morphologies are known to form if higher heating temperatures and faster cooling rates are encountered during the spheroidization heat-treatment of forged steel rolls. Incidentally, forged steel rolls are usually volume-hardened and tempered in the range of 550 to 600 °C to impart the desired level of toughness. The rolls are subsequently induction-hardened and tempered at lower temperatures (100 to 260 °C) to confer high surface hardness (around 90 Shore D) and greater depth of hardening (Ref 11). Carbide morphology needs to be controlled in volume hardening, because, otherwise, higher austenitization temperatures would be necessary during subsequent induction hardening for ensuring the dissolution of undesirable nonglobular carbides. Higher austenitization temperatures in the final induction hardening stage are not desirable, because this would inevitably entail greater dissolution of alloy carbides and, consequently,

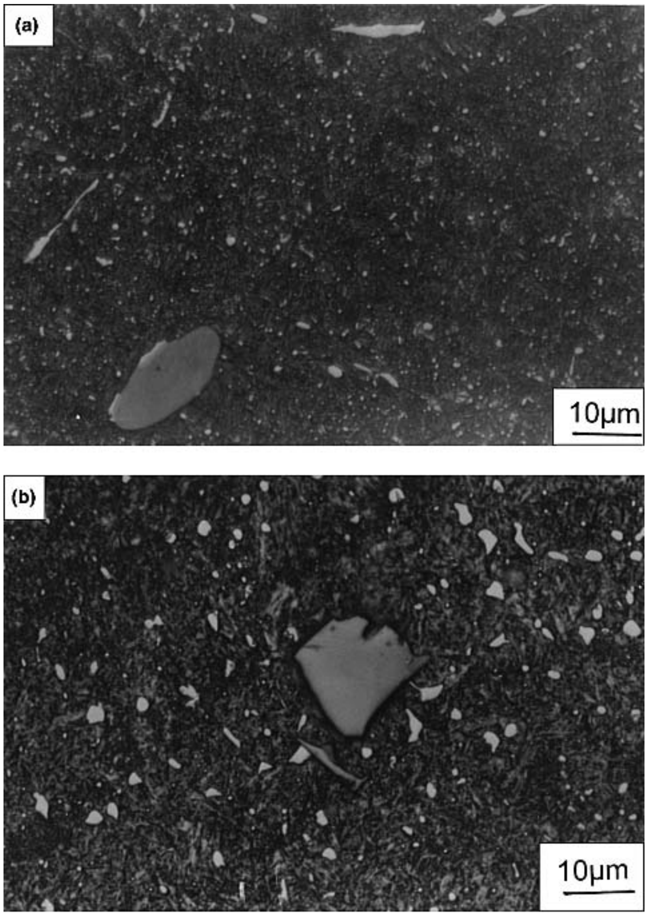

Fig. 3 Optical micrographs of Vilella-etched, spalled, cold-strip mill work-roll samples exhibiting poor roll life: (a) sample C13 showing elongated/rod-like as well as few globular carbides, and an elliptical MnS inclusion associated with carbide precipitates is also seen; (b) sample C14 showing segregated region of coarse angular carbides. Magnification was 1000× for both images.

would result in a lower fraction of carbides being retained in the as-hardened state. This can, undoubtedly, lower the as-quenched hardness of the roll. Moreover, with the greater dissolution of carbides at higher hardening temperatures, the austenite becomes enriched in alloying elements, and consequently, the M_s temperature is lowered. This ultimately results in a greater amount of retained austenite in the matrix of the as-quenched roll and induces other complexities during the rolling operation.

3.3 Quantitative Metallography

3.3.1 Carbide Characteristics. For deconvoluting correlations between carbide characteristics and roll life, quantitative metallographic measurements using image analysis were performed. The quantitative image analysis data pertaining to carbide content (volume percent), carbide count (number per square millimeter), and average carbide size (micrometer) in the spalled samples of cold -strip mill work-rolls are shown in Table 3.

It can be seen from Table 3 that of 14 cold-strip mill work-roll samples, the carbide content was found to vary between approximately 1.5 and 5.0 vol.%. In the three roll samples (C12, C13, and C14) exhibiting poor roll life (i.e., <5000 t), the carbide content varied between 1.5 and 2.8 vol.%, with a batch average value of 2.3 vol.%. In the four roll specimens (C8, C9, C10, and C11) exhibiting roll lives between 5,000 and 15,000 t, the carbide content varied between 2.5 and 3.0 vol.%, with a batch average value of 2.8 vol.%. In the four roll specimens (C4, C5, C6, and C7) exhibiting roll lives between 20,000 and 30,000 t, the carbide content ranged from 3.2 to 4.0 vol.%, with a batch average value of 3.5 vol.%. In the three roll samples C1, C2, and C3, exhibiting roll lives greater than 30,000 t, the carbide content varied between 4.5 and 5.0 vol.%, with a batch average value of 4.7 vol.%. The variation of roll life (batch-wise) with carbide content (batch average value) in each category is shown in Fig. 4. It is clearly evident from Fig. 4 that roll batches exhibiting higher service life were characterized by higher average volume percentages of carbides. This behavior is desirable, because a higher volume percentage of hard alloy carbides in a matrix of tempered martensite contributes to the enhanced wear resistance of cold-strip mill work-rolls and, thereby, provides adequate insurance against surface degeneration.

Regarding the influence of carbide population density, the data pertaining to the carbide count shows a similar trend. In the batch of poor-life rolls (C12, C13, and C14), the carbide counts ranged from 79,905 to 84,580 number/mm^2, with a batch average value of 81,752 number/mm^2. In the class of rolls exhibiting low roll lives (i.e., between 5000 and 15,000 t; roll samples C8, C9, C10, and C11), the carbide counts varied between 62,502 and 148,303 number/mm^2, with a batch average value of 109,281 number/mm^2. In the batch of rolls (sample numbers C4, C5, C6, and C7), exhibiting roll lives between 20,000 and 30,000 t, the carbide counts ranged from 159,262 to 185,683 number/mm^2, with a batch average of 168,806 number/mm^2. In the roll samples C1, C2, and C3, which exhibited roll lives of >30,000 t, the carbide counts varied between 200,044 and 211,647 number/mm^2, with a batch average of 204,719 number/mm^2, which was significantly higher than that observed in samples exhibiting low and poor roll lives. The variation of roll life (batch-wise) with average carbide count is shown in Fig. 5. The carbide population density data (Fig. 5) show an increasing trend in carbide count value with the increase in roll service life. It is of interest to mention that because the hardness of the tempered martensite matrix is much lower than that of the dispersed alloy carbides, the tempered martensite matrix is not very effective in enhancing wear resistance. A high carbide population density coupled with a high volume percentage of carbides is, therefore, desirable, and it is indicative of a greater dispersion of fine-sized carbides, which in turn, confer wear-resistance to the roll microstructure.

The average carbide sizes (Table 3) determined in the spalled cold-strip mill work-rolls were found to vary between 0.76 and 0.95 μm, with an average value of 0.80 μm. In the class of rolls exhibiting lifetimes lower than 5000 t, the average carbide size varied between 0.82 and 0.89 μm, with a batch average value of 0.85 μm. In the roll samples exhibiting lives between 5000 and 15,000 t, carbide size varied between 0.76 and 0.95 μm, with a batch average value of 0.81 μm. In the roll samples exhibiting service lives between 20,000 and 30,000 t, the average carbide sizes varied between 0.77 and 0.83 μm, with a batch average value of 0.79 μm. In the three roll samples (C1, C2, and C3) that exhibited service lives of >30,000 t, the average sizes of carbides varied between 0.80 and 0.83 μm,

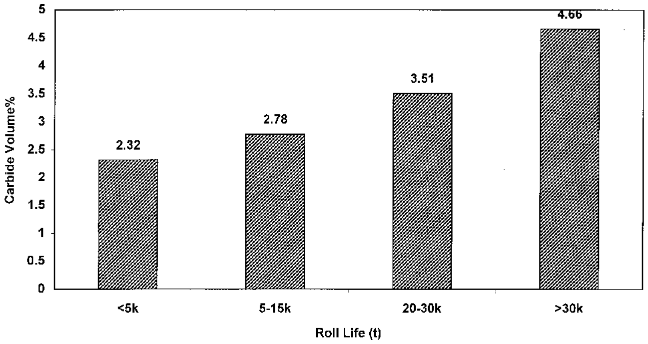

Fig. 4 Variation of roll life (batch-wise) with average volume percentages of carbides. k, thousand

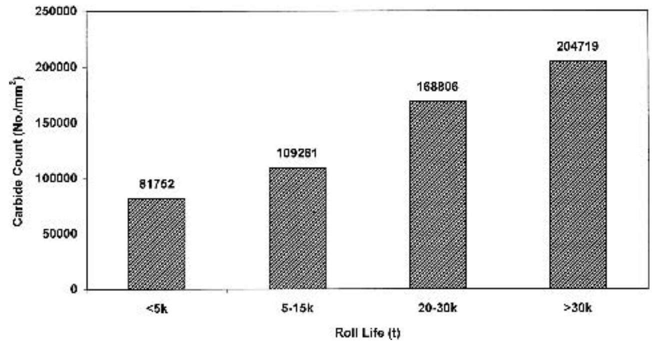

Fig. 5 Variation of roll life (batch-wise) with average carbide count. k, thousand

Table 3 Quantitative metallographic data of carbides in cold-strip mill work-roll samples

Roll sample	Roll life range, 1000 t	Carbide characteristics (individual rolls)			Carbide characteristics (batch averages)		
		Content, vol.%	Count, No./mm^2	Size, μm	Content, vol.%	Count, No./mm^2	Size, μm
C1	>30	4.53	211,647	0.80	4.66	204,719	0.81
C2	>30	4.96	202,468	0.83	4.66	204,719	0.81
C3	>30	4.50	200,044	0.81	4.66	204,719	0.81
C4	20-30	4.02	185,683	0.77	3.51	168,806	0.79
C5	20-30	3.44	159,262	0.83	3.51	168,806	0.79
C6	20-30	3.23	169,324	0.78	3.51	168,806	0.79
C7	20-30	3.35	160,963	0.80	3.51	168,806	0.79
C8	5-15	2.96	148,303	0.76	2.78	109,281	0.81
C9	5-15	2.66	122,681	0.77	2.78	109,281	0.81
C10	5-15	2.46	103,639	0.77	2.78	109,281	0.81
C11	5-15	3.04	62,502	0.95	2.78	109,281	0.81
C12	<5	2.65	84,580	0.89	2.32	81,752	0.85
C13	<5	2.81	80,771	0.84	2.32	81,752	0.85
C14	<5	1.50	79,905	0.82	2.32	81,752	0.85

with a batch average value of 0.81 μm. It can, therefore, be seen that the batch average values of carbide size for the different roll batches (based on roll lives) did not vary significantly. The effect of batch-wise, average carbide size in the range of 0.79 to 0.85 μm on roll life is not very apparent.

3.3.2 Retained Austenite Content. As mentioned earlier, retained austenite was not optically discernible in the spalled cold-strip mill work-roll samples. Thus, retained austenite content was determined by the XRD technique for some typical spalled samples, and these data are furnished in Table 4. It is observed from Table 4 that retained austenite in the cold-strip mill work-roll samples varied between 6.4% and 17.8%. Incidentally, the least retained austenite content (6.4%) was obtained for roll sample C1, which yielded the highest roll life of 45,526 t. In contrast, the highest percentage of retained austenite (17.8%) was found in roll sample C9, which exhibited a significantly lower roll life of 9999 t. Roll samples C5 (life 26,794 t) and C8 (life 13,148 t), which also exhibited inadequate roll lives, showed retained austenite contents of 8.5% and 12.5%, respectively. The retained austenite data of spalled cold-strip mill work-rolls, therefore, indicate that low retained austenite content is beneficial to roll life.

The retained austenite data (Table 4) show an interesting relationship with the carbide volume percent data (Table 3) and are graphically depicted in Fig. 6. The carbide contents in rolls samples C1, C5, C8, and C9 were 4.5, 3.4, 3.0, and 2.7 vol.%, respectively, against corresponding retained austenite contents of 6.4, 8.5, 12.5, and 17.8 vol.%. This shows that the retained

Table 4 Retained austenite content in some typical cold-strip mill work-roll samples

Roll sample	Retained austenite, %	Roll life, t
C1	6.4	45,526
C5	8.5	26,794
C8	12.5	13,148
C9	17.8	9,999

austenite content exhibits an inverse trend with respect to the carbide content. This is metallurgically understandable, because a higher retained austenite content signifies a higher austenitizing temperature during the induction hardening of the roll and, consequently, a greater dissolution of alloy carbides. This obviously results in highly alloyed austenite, a lower M_s temperature, and a greater amount of austenite retention following roll hardening.

Retained austenite is a metastable phase in hardened and tempered steel, and is susceptible to phase changes under applied stresses. Thus, the plastic deformation of the roll working surface during the rolling of a sheet or strip may induce martensitic transformation accompanied by a volume expansion. This naturally would result in an increase in internal stresses in the roll body and would render the roll crack sensitive and prone to spalling. Besides which, the grindability of steel is known to be impaired when retained austenite is greater than 10% to 12%. Because steel tends to become susceptible to

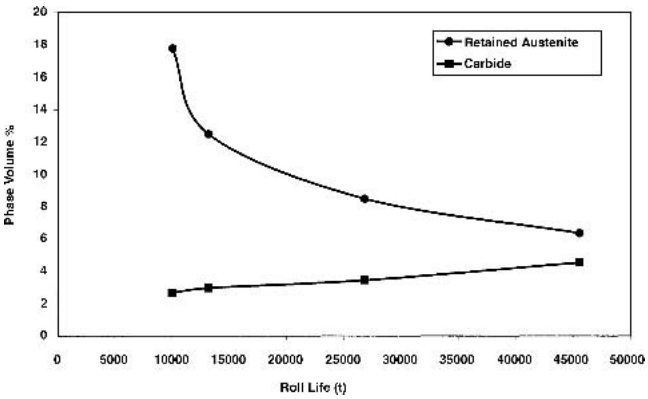

Fig. 6 Variation in roll life with retained austenite content and average volume percentages of carbides.

cracking with slight variations in grinding conditions at higher retained austenite contents (>25 vol.%), the surface finish can grossly deteriorate (Ref 12). Thus, uneven roll surfaces can be produced that impair the surface finish of cold-rolled products. The deleterious effects of surface roughness in lowering fatigue resistance are well known (Ref 13). It is, thus, clear that an improper surface finish of a roll will adversely affect its contact-fatigue resistance during actual usage. The hardness and wear resistance of the roll working surface can also be seriously affected at higher retained austenite contents, particularly when the carbide population in the microstructure is low. A careful examination of the roll life data (Table 1) and retained austenite content (Table 4) reveals that retained austenite content needs to be kept below 8.5% to assure optimum roll performance under normal mill-operating environments.

3.4 Scanning Electron Microscopy

Scanning electron microscopy was carried out on Vilella-etched specimens of spalled cold-strip mill work-rolls to observe the carbide morphology and matrix features at high magnifications. The secondary electron images of some typical spalled cold-strip mill work-roll samples (i.e., C1, C13, and C14) are shown in Fig. 7(a) to (c), respectively, at a magnification of 4000×. It can be clearly seen from Fig. 7 that while roll sample C1, exhibiting the highest roll life (life 45,526 t), showed a uniform dispersion and high density of fine globular carbides, the carbide morphologies in lower life rolls such as C13 (life 1141 t) and C14 (life 746 t) were coarse, angular, and/or elongated. Figure 7(b) shows microcracking associated with the coarse and angular carbides in roll sample C13, while Fig. 7(c) showed microcracking associated with the elongated and angular carbides in roll sample C14. These SEM observations at high magnifications indicated that carbides with angular and/or elongated morphologies are undesirable in heat-treated, cold-strip mill work-rolls, because they increase the propensity for microcracking of the tempered martensite matrix and eventually accentuate roll spalling (Ref 14).

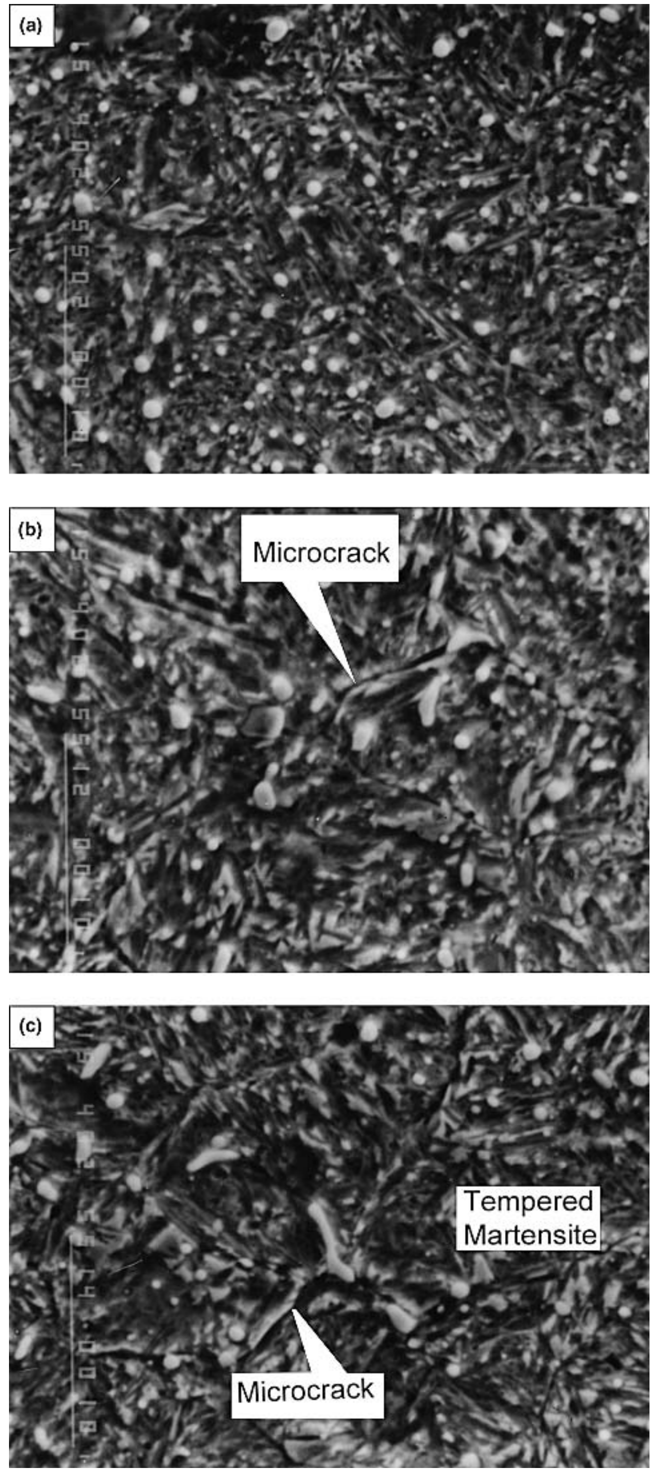

Fig. 7 Scanning electron microscopy images of Vilella-etched, spalled, cold-strip mill work-rolls: (a) high density of fine globular carbides in roll sample C1, which exhibited the highest roll life of 45,526 t; (b) angular carbides associated with microcracking of the matrix in poor life (1141 t) roll sample C13; and (c) elongated, rod-like carbides associated with microcracking of the matrix in poor life (746 t) roll sample C14. Magnification was 4000× for all images.

3.5 Electron-Probe Microanalysis

The EPMA scans of the carbides observed in a typical cold-strip mill work-roll sample (C14) is shown in Fig. 8 at 4000× magnification. The secondary electron image of the Vilella-etched roll sample shows coarse and fine carbides of both angular and globular morphologies. Figure 8(b) shows the Cr x-ray dot-mapping image of the same region and indicates that the carbides are essentially Cr-rich with respect to the matrix. Energy-dispersive spectrometry of carbides pertaining to the

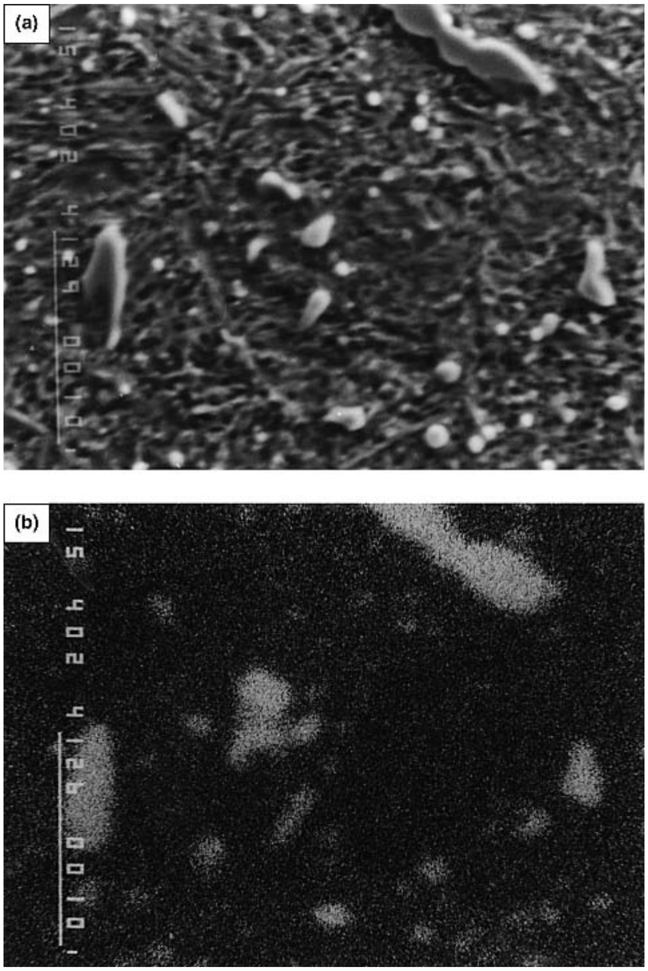

Fig. 8 Electron probe microanalysis scans of typical carbides in spalled cold-strip mill work-roll sample C14: (a) secondary electron image showing low carbide density, and carbides of coarse and angular morphology; and (b) Cr x-ray map. Magnification was 4000× for both images.

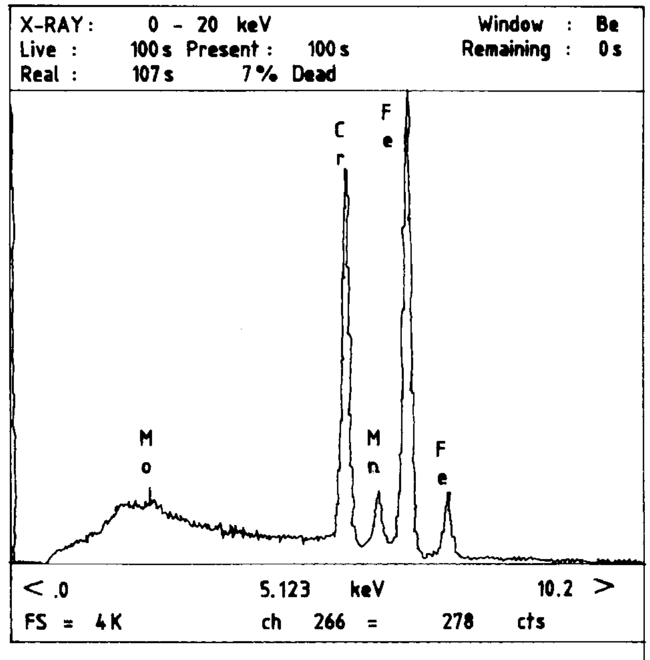

Fig. 9 Energy-dispersive spectrometry spectrum of a typical carbide in a spalled sample of cold-strip mill work roll

Table 5 Quantitative electron-probe microanalysis of a typical carbide in cold-strip mill work-roll

Element	wt.%	atom.%	K, %	ZAF	Z	A	F
C	8.45	30.27	2.98	2.835	0.829	3.417	1.00
Si	0.68	1.04	0.46	1.466	0.909	1.613	1.00
Cr	3.65	3.02	4.39	0.830	1.025	1.004	0.807
Mn	1.07	0.84	1.03	1.044	1.043	1.001	1.00
Fe	84.13	64.83	81.95	1.027	1.024	1.003	1.00
Total	97.98	100.00	90.81	…	…	…	…

Note: Z, atomic number correction factor; A, absorption correction factor; F, fluorescence factor; K, intensity ratio of a particular element in an unknown sample and a pure standard.

same sample also corroborated Cr enrichment in the carbides, as shown in Fig. 9. Quantitative elemental microanalysis of carbide particles was carried out for some typical spalled samples of cold-strip mill work-rolls. The quantitative microprobe analysis of spheroidal carbides in a typical spalled sample of cold-strip mill work-roll is shown in Table 5. It can be clearly observed from the microanalysis data that the C content of the globular carbides is 8.45 wt.%, while that of Cr is 3.65 wt.%. The combined concentrations of C, Si, Cr, Mn, and Fe add up to 97.98 wt.%, which is considered to represent a high index of accuracy and reliability, because the relative accuracy of EPMA has been reported to be ±5% (Ref 15). The atomic percentage data in Table 5 show that while the value for C is 30.27 at.%, the combined value for Si, Cr, Mn, and Fe is 69.73 at.%. The atomic percent ratio of C to (Si + Cr + Mn + Fe) is almost equal to 3 to 7 wt.%, and therefore, the carbide formula is M_7C_3, where M stands for the metallic radicals.

4. Conclusions

- Microstructural studies have revealed that rolls exhibiting higher service life contained uniform dispersion of fine globular carbides in a matrix of fully tempered martensite with minimal retained austenite. In contrast, rolls exhibiting low and poor service lives showed a preponderance of coarse carbides with angular and/or elongated morphologies.
- From the standpoint of nonmetallic inclusions, rolls with higher lives were in general "cleaner," while rolls exhibiting poor and low service lives were "dirtier." The presence of MnS and TiN types of inclusions were found to be detrimental, in the sense that while large MnS inclusions provided sites for the precipitation of elongated carbides, the hard and angular TiN inclusions were potential stress-raisers for impairing the fatigue strength of rolls.
- Although EPMA investigations indicated that carbides in the investigated rolls were essentially of the M_7C_3 type, quantitative metallography revealed that, besides carbide morphology, roll life was profoundly influenced by carbide content and count. Quantitative image analysis revealed that while rolls with higher lives inevitably exhibited carbide contents of >4.5 vol.% and counts of >200,000 number/mm^2, rolls with low and poor lives showed significantly lower values for these features.

- The size distribution of carbides in the spalled roll samples did not show significant variations in the batch-wise, average carbide sizes. The effect of carbide size on roll life is, thus, not critical.
- X-ray diffractometry revealed that while higher life rolls contained minimal retained austenite, rolls exhibiting lower lives inevitably contained >10% retained austenite. The deleterious effect of higher retained austenite content on the spalling susceptibility of cold-strip mill work-rolls was attributed to its possible transformation to martensite under imposed rolling stresses.

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