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Influence of Microalloying on Mechanical and Metallurgical Properties of Wear Resistant Coach and Wagon Wheel Steel

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Micro alloy steels are emerging as a potential new material to replace conventional carbon steels to achieve longer coach and wagon wheel life. Two commercial heats of micro alloy steels were made and processed into 910 mm outer diameter (O.D.) coach and wagon wheels. The properties of normalized wheels were evaluated and compared with those for R-19/93 conventional carbon grade wheel. It was found that normalized wheels properties such as fracture toughness, Charpy impact energy, endurance limits, and wear resistance were superior to that of R-19/93 grade wheel.

Keywords fatigue strength, fracture behavior, mechanical property, metallurgical properties, micro alloy, wear resistance, wheel steel

1. Introduction

The increasing demand of introducing higher operating speeds and higher axle loads in Indian Railways needs to maintain the highest integrity and reliability of railroad wheels. This requires the use of a superior quality steel made through modern and economic process route.

The performance of wheels in a service has been related to wheel defects such as abrasion of wheel tread, shelling, thermal crack, wheel plate fatigue, and fracture.[1] Higher abrasion resistance usually achieved at a higher hardness of a steel can produce a lower fracture toughness and a higher fatigue crack growth rate. Therefore, the development of a wheel steel with a higher abrasion resistance, a higher fracture toughness, and a lower fatigue crack growth rate is an important challenge.

A superior quality wheel steel must satisfy the requirements to counteract the problem of wear, thermal crack, fatigue, and fracture leading to a sudden catastrophic failure.

Detailed study on the selection of a proper wheel material had been carried out worldwide.[1-17] It is well known that in a plain carbon wheel steel, the fracture resistance increases with a decrease in carbon content. Likewise, grain refinement and reduction in non-metallic inclusions increase the fracture resistance.[10]

Conventionally, wear resistance coach and wagon wheels produced at Durgapur Steel Plant (DSP) of Steel Authority of India Ltd. (SAIL) consisted of a ferrite-pearlite microstructure with carbon in the range of 0.57-0.67%. These wheels were given normalizing heat treatment after forging and rolling operations. The fracture toughness never exceeded 50 MPa√m. Premature failures of wheels in service due to fatigue and fracture were frequently noticed. Carbon content of these wheels is now restricted to 0.52% max to improve the fracture resistance. Now, the wheels are rim quenched and tempered. In industrial operations, rim-quenching carries with it the danger of water droplets falling on the hub and thereby giving rise to localized stresses in the hub. In addition, a variation of hardness through the rim depth results in uneven wear. Also, rejection is substantial due to variation in mechanical properties caused by process deviations.

This investigation studies the possibilities of achieving at least comparable mechanical properties, wear resistance, and fracture toughness to plain carbon R-19/93 grade coach and wagon wheel steel by suitable micro alloying and heat treatment. Normalizing heat treatment will eliminate localized stresses in the hub and minimize the variation of hardness through rim depth and uniform wear. Keeping these requirements in view, this investigation was carried out on normalized wheels made from micro alloyed wheel steels with addition of vanadium, niobium, and molybdenum.

2. Literature Review

2.1 Wheel Materials

All over the world, the most prevalent wheel material grades fall under class B or class C (AAR) specifications. A detailed comparison of mechanical properties and other characteristics between wrought and cast AAR class C wheels with the same rim face hardness found no significant differences in strength, hardness distribution through cross section, fatigue crack growth characteristics, and wear behavior.[7]

It has been suggested that for these grades keeping the carbon contents in the upper half of the specified range (0.73-0.77%) and minor additions of chromium and molybdenum (up to 0.20% and 0.05%, respectively) would be beneficial to achieve the minimum (specified) hardness of 321 BHN at the condemning diameter.[1]

Several studies have investigated in detail[5,6,8-17] how to improve wheel hardness levels, in terms of both the rim face hardness distribution and the hardness profile through micro

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Table 1 Chemical Composition and Room Temperature Mechanical Properties of Coach and Wagon Wheels as Per Indian Railways Specification (IRS R-19/93)

Chemical Composition, wt.%										Mechanical Properties, Charpy U Notch Energy (CUN), and Hardness (BHN)				
C	Mn	Si	S	P	Cr	Ni	Mo	Cu	V	YS, MPa	UTS, MPa	El, %	CUN, J/cm^2	BHN
0.52 max	0.60/0.80	0.15/0.40	0.03 max	0.03 max	0.25 max	0.25 max	0.06 max	0.28 max	0.05 max	50% of UTS	820-940	14 min	15 min	277-241

alloying, while retaining a pearlitic microstructure. However, there was not much improvement in fracture toughness of wheels, as the carbon level was not reduced.

The propensity of martensite formation and/or thermal cracking under conditions of thermal abuse is an additional factor in a selection of wheel materials. Transformation studies on standard and micro alloy compositions have shown that the critical cooling rate required to develop martensite in the latter wheel composition is somewhat higher than in the former, for the same carbon equivalent level.[5,6] The micro alloy compositions should therefore be less sensitive to martensite formation during conditions of thermal abuse.

Higher strength levels and improved hardness profiles, in a micro alloy wheel have also resulted in a considerable decrease in the incidence of rolling contact fatigue (RCF) defects (shells). Given the probability of catastrophic wheel failures from such defects, the lower susceptibility of RCF initiation has proven to be the major advantage of a micro alloy wheel under high axle load conditions.[1]

2.2 Alloy Design

Wear, fatigue, and thermal damage are the main deterioration processes upon which wheel life is dependent. However, in recent years, the development and introduction of modified wheel profiles have altered the relative contribution of the above deteriorating processes while considering the overall performance of wheels.[3] In particular, the incidence of sudden wheel failures due to fatigue crack propagation has become of increasing concern, as this type of failure mode is catastrophic. Therefore, while designing a suitable alloy for coach and wagon wheel, one will have to consider above-mentioned deteriorating processes.[13]

The development work conducted at the Commonwealth Steel Company[1] on wheel steels was aimed at improving the overall mechanical properties of a wide range of wheel grades. This was obtained by additions of vanadium ($\leq$0.1%) to the steel and modifying the heat treatment process, which follows the rolling of the wheel blank.

The additions of vanadium, which result in a refinement of grain size, together with a modification of heat treatment procedure have led to a general improvement of all tensile and Charpy impact properties.

Most important improvements associated with new micro alloy wheels are summarized as: (1) a considerably flatter rim hardness profile, and (2) a marked improvement in fracture toughness.

Recently, attention is given not only to the heat treatment of carbon pearlitic steels for improving the properties but also to the methodology of getting fine-grained steels by deoxidation with aluminium and lately by micro alloying with vanadium.

Micro alloying with vanadium is intended for further refinement of the grain size and thus improving the plastic properties. With a 0.12% vanadium addition, the grain has been refined by 1-2° as to ASTM, compared with carbon steels. An appreciable increase in yield and tensile strength has also been achieved in addition to toughness properties.[1]

Micro alloying with vanadium alone does not provide sufficient grain growth control, although the pinning action of vanadium carbonitride increases as the nitrogen content increases.[20] The niobium carbide was found to possess a better capability to hinder austenite grain growth in medium-carbon steels than vanadium carbonitride.[17] The niobium-vanadium combination can potentially provide even higher strength properties of medium-carbon and eutectoid steels.[18,19,21,22] The strength level of vanadium micro alloy steels increases with an increase in vanadium and nitrogen content as well as an increase in cooling rate. However, yield strength increment in niobium treated steels was assumed to be cooling rate independently.

In micro alloy ferrite-pearlite steel, increasing pearlite content above the equilibrium proportion produces a dilute pearlite with cementite plates thinner than in the equilibrium pearlite. Therefore, one of the methods for improving the toughness of this grade of steel is to lower carbon content and to keep or even increase the proportion of pearlite by producing diluted pearlite. In steels with a higher proportion of pearlite, the ferrite phase tends to be distributed at prior austenite grain boundaries. The most effective remedy for this is to refine the prior austenite grain.[17]

The most critical requirements for a wheel according to specification R-19-93 (Table 1) are adequate strength, adequate wear resistance, higher fracture toughness, and low fatigue crack growth rate. This can be achieved by keeping carbon level at 0.52% max. and with suitable micro alloying with vanadium and niobium.[19]

3. Experimental Procedure

3.1 Chemistry Optimization in Laboratory

In the first stage, laboratory heats were made at Research and Development Center for Iron and Steel (RDCIS) of SAIL to optimize a suitable chemistry of micro alloy coach and wagon wheel within the overall range of the chemistry specified in the R-19/93 specification of Indian Railways. Laboratory heats of 50 kg weight each were made in air induction furnace and ingots were cast in 25 kg cast iron molds with 100 mm square cross-section. Ingots were reheated to 1250 ± 10 °C and hot rolled into plates of 20 mm thickness. Finish rolling temperature was maintained at 950 ± 10 °C. All hot rolled plates were air cooled to ambient temperature. For normalizing treatment, plates of all heats were kept at 980 ± 5 °C for 1.5 h in the reheating furnace and air-cooled after taken out from the furnace. Test specimens were fabricated from the test coupons cut from the normalized plates. The chemical composition, mechanical properties, and Charpy V notch energy at room temperature and BHN hardness of 7 laboratory heats are shown in Table 2. Chemistry of heat L6 was selected for further industrial trial heat.[19] Selection of micro alloy elements was based on the fact that vanadium is required to achieve the desired grain size as well as the required properties in normalized condition. The molybdenum addition facilitates to achieve the desired hardenability for obtaining uniform hardness. The combined effect of niobium and vanadium is beneficial for achieving finer grain size and higher tensile strength and fracture toughness.

In the second stage, pilot scale trial wheel steels with addition of chromium, molybdenum, vanadium, and niobium were made through electric arc furnace in DSP of SAIL. The chemistry, mechanical properties, grain size, Charpy V notch energy. and BHN hardness of normalized wheels processed in Wheel and Axle Plant of DSP of SAIL are shown in Table 3. It is obvious from the results of F2 heat that the requirements of R-19/93 specification of Indian Railways could be met by this chemistry with a little adjustment of alloying elements.

3.2 Industrial Scale Wheel Production at Steel Plant

Two heats of 120 ton wt. were made through BOF-VAD route in the steel making shop at DSP. The chemistries of two experimental wheel steels and R-19/93 grade plain carbon wheel steel are shown in Table 4. The normal steel making procedure was followed as practiced for low alloy grade steels. The heat processing procedures, VAD treatment, and teeming of ingots were similar to that followed for conventional R-19/93 grade wheel heats. 54 numbers of ingots of 3 t weight were cast from each heat using bottom teeming practice. The ingots were cut into cheese blocks after proper inspection. Normal forging and rolling schedules were followed as applicable in case of R-19/93 wheels. Cheese blocks of micro alloy steel were forged and rolled into BG coach wheels of 915 mm O.D. in the Wheel and Axle Plant. The soaking zone of the gas-fired rotary reheating furnace was maintained at 1270-1290 °C and the duration of

Table 2 Chemical Composition and Room Temperature Mechanical Properties of Coach and Wagon Wheel Steels Made in Laboratory for Optimisation of Chemistry

Heat	Chemical Composition, wt.%										Mechanical Properties, Charpy V Notch Energy (CVN) and Hardness (BHN)				
No.	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	V	YS, MPa	UTS, MPa	El, %	CVN, J/cm^2	BHN
L1	0.47	0.85	0.34	0.023	0.027	…	…	…	…	0.057	450	750	19.2	19.9	235
L2	0.47	0.88	0.39	0.032	0.023	…	…	…	…	0.086	500	825	15	23.3	244
L3	0.56	1.09	0.13	0.024	0.027	0.24	…	…	…	…	608	1027	15	4.4	270
L4	0.56	1.09	0.13	0.024	0.027	0.24	…	…	…	0.048	587	1035	14	4.9	278
L5	0.58	1.99	0.23	0.039	0.040	0.15	…	…	…	…	576	965	9	12.5	269
L6	0.53	1.16	0.22	0.042	0.037	0.14	…	…	…	0.11	544	886	18.4	15	255
L7	0.49	0.85	0.23	0.045	0.035	0.29	…	0.06	…	0.12	513	841	14	16.3	236

Table 3 Chemical Composition and Room Temperature Mechanical Properties of Coach and Wagon Wheels Made Through Electric Arc Furnace Route

Heat	Chemical Composition, wt.%										Reheat Temp.	Mechanical Properties, Charpy V Notch Energy (CVN), and Hardness (BHN)					Grain Size
No.	C	Mn	Si	S	P	Cr	Nb	Mo	Al	V	°C	YS, MPa	UTS, MPa	El, %	CVN, J/cm^2	BHN	ASTN no
F1	0.44	0.75	0.33	0.030	0.036	0.34	…	0.074	0.005	0.16	905	487	749	20.2	41.3	241-245	6-8
											950	544	800	23	26.3	225-229	7-8
											970	518	783	21	33.8	217-235	6-8
F2	0.55	0.80	0.39	0.021	0.045	0.29	0.019	0.13	0.030	0.16	870	571	876	17	23.4	248-255	6-8
											930	590	970	17	22.5	285-277	6-8
											950	586	960	17	12.5	302-279	6-8

Table 4 Chemical Composition of Steels Investigated, wt.%

Steel	C	Mn	Si	S	P	Mo	Nb	V	Al	N	Fe
A	0.51	0.67	0.35	0.026	0.028	0.15	0.057	0.11	0.014	0.0082	bal.
B	0.49	0.68	0.22	0.030	0.021	0.20	0.072	0.13	0.021	0.0089	bal.
R-19/93	0.47	0.66	0.25	0.024	0.026	…	…	…	0.008	0.0073	bal.

soaking was 2 h. The finishing temperature of wheel rolling was recorded in the range of 980 ± 20 °C. Forging pressure for micro alloy wheels was recorded in the range of 140-180 bars in comparison to 140-150 bars for normal R-19/93 wheels. The hot rolled wheels were stacked in pair on the mill floor and cooled to room temperature.

During heat treatment, wheels were reheated to 1000 ± 10 °C temperature in gas fired rotary reheating furnace and time of soaking was maintained for 2 h. Wheels were removed from furnace one by one and kept separately in air for cooling. Detailed property evaluation was performed at the RDCIS laboratory.

4. Discussion of Results

4.1 Drop Weight Testing

Two heat-treated wheels (one wheel from each heat) were selected for drop weight testing and the tests were performed according to the conventional procedure followed for R-19/93 grade rim quenched and tempered wheels. In conventional drop weight test, the height of drop is kept 10 ft and the weight of tup is 1 t. The normalized wheels of both the heats sustained three blows without crack formation and met the acceptance criterion for R-19/93 grade wheels.

4.2 Hardness Testing

The Brinell hardness numbers (BHN) were measured on a full rim section of heat-treated wheel (Fig. 1). The hardness values measured at the specified locations as per Indian Railways specification are in the range of 250-277 BHN. Flatter hardness profiles of micro alloy wheels compared with that of R-19/93 grade wheel are likely to give longer wheel life.

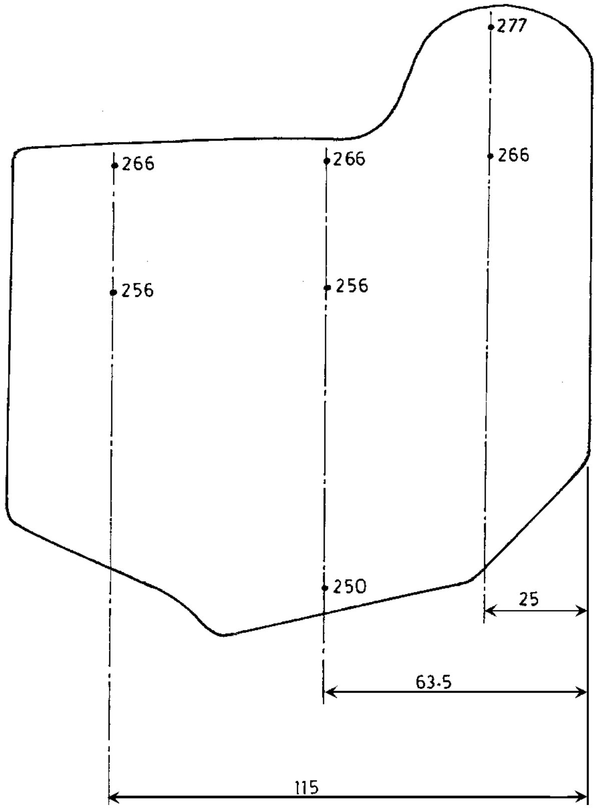

Fig. 1 Hardness profile in BHN of a normalized wheel section of micro alloyed steel A, showing all dimensions in millimeters (Heat No. 973/9220, Wheel No. 5162)

4.3 Mechanical Testing

Tensile test pieces of drop weight-tested wheels were gas cut from the rim of wheel and the specimens were fabricated from the specified locations as per R-19/93 grade wheel specification. Tensile and Charpy U notch impact tests were conducted at room temperature to evaluate the mechanical properties and impact energy. It is evident that YS values of micro alloy steels are in the range of 583-611 MPa, appreciably higher than that of R-19/93 grade steel (Table 5). Also the UTS values in the range of 864-896 fall well within the specified range of IRS R-19/93 specification (Table 1). The Charpy U-notch impact energy at room temperature of micro alloy wheels is higher than that of the R-19/93 grade wheel indicating better toughness property (Table 5).

4.4 Fracture Toughness Testing

The fracture toughness was measured at room temperature using a 10 ton capacity servo hydraulic controlled MTS machine and 50 mm (2 in.) W compact tension specimens obtained from the rim region of heat-treated wheels. The fracture toughness was evaluated using the ASTM E399 procedure for fracture toughness testing.[23] The results are 63-66, 59-64, and 56-61 MPa$\sqrt{m}$ for micro alloy steel A, microalloy steel B, and R-19/93 grade steel, respectively. Experience shows that fracture toughness of standard carbon wheel decreases with increasing tensile strength (UTS). Even with the higher tensile strength, micro alloy steel wheel showed no less values of fracture toughness compared with R-19/93 grade standard carbon wheel. Adequate improvement in fracture toughness was also observed in case of medium carbon rail steel by micro alloying with vanadium/niobium.[24] Higher fracture toughness was also confirmed by drop weight testing. Micro alloy wheel sustained the specified drops without showing any cracks.

4.5 High Cycle Fatigue Testing

Specimens of 5 mm round gauge diameter were fabricated from rim location of wheel. The high cycle fatigue test was carried out using Roell Amsler rotating bending fatigue testing machine UBM 200 (Gottmadingen, Germany) at different stresses. The endurance limits ($>10^7$ cycles) were determined to be 350, 390, and 300 MPa for micro alloy A, micro alloy B and R19/93 grade wheel steels respectively. It is obvious that micro alloy wheel showed higher endurance limits 350-390 MPa in comparison of 300 MPa for R19/93 grade wheel.

The development of most wheel defects is associated with the occurrence of plastic deformation in the wheel rim causing early crack formation. Therefore, higher yield stress is desirable for restriction of plastic deformation. Micro alloy wheel yield strength is significantly higher than that of R-19/93 wheel. The generation of defects caused by plastic deformation will be expected to be minimized in the case of micro alloy wheel. This fact needs to be verified quantitatively by conducting rolling contact fatigue tests on the wheels under investigation.

4.6 Microstructural Analysis

Samples for metallographic studies were cut from the tensile tested pieces from wheel rims. The samples were polished for inclusion analysis and microstructural investigation. The quantitative evaluation of inclusion content was done on a TAS (Q-600, Leica, Germany) Image Analyser. The average volume fraction of inclusion obtained on A and B micro alloy wheel samples were 0.22 and 0.27% respectively. The optical microphotographs are shown in Fig. 2. Fine grained ferrite-pearlite microstructures are evident in both A and B micro alloy wheel steels. The grain size measurement was done on TAS (Q-600) Image Analyzer. The grain size measurement was conducted at 20 locations of polished and nital etched specimen and the mean values were reported 6.6 and 6.84 ASTM Nos. in the case of A and B steels, respectively. Polished and nital etched samples were observed in a JSM-840A (JEOL, Ltd., Tokyo,

Table 5 Room Temperature Tensile Properties (YS, UTS, Elongation El), Room Temperature Charpy U-Notch (CUN) Impact Energy and Brinell Hardness Values for Steels Studied

Location	YS, MPa	UTS, MPa	El, %	CUN, J/cm^2	Hardness, BHN
Micro alloy steel A Rim	583	864	18.4	37.6	277-250
Micro alloy steel B Rim	611	896	17	35.2	255-248
R-19/93 Rim	505	844	14	28.3	272-229

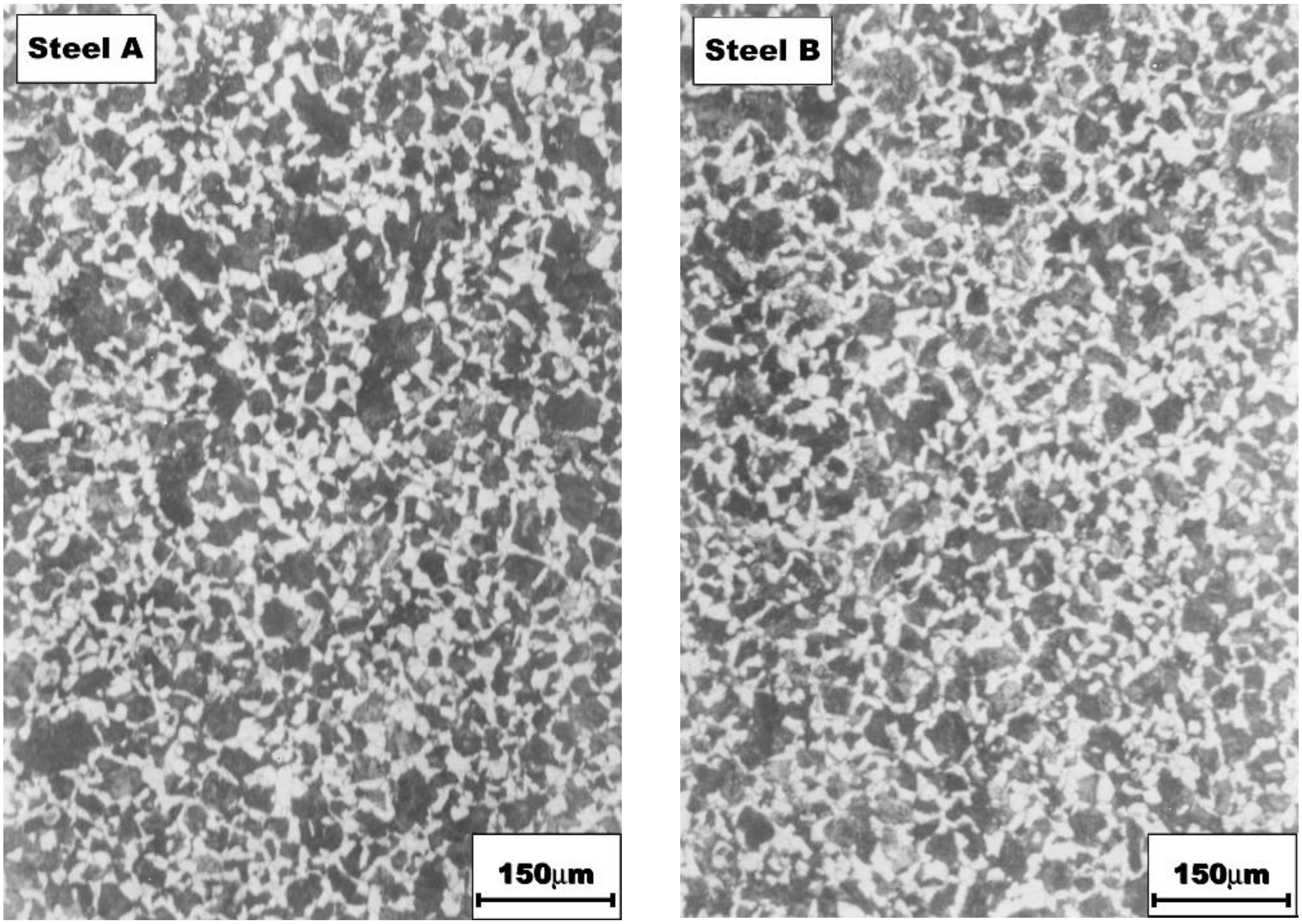

Fig. 2 Photomicrographs of microalloyed wheel steels A and B reheated to 990 °C (grain size, ASTM no. 6-7), (black phase: pearlite, white phase: ferrite) ×100

Japan) model scanning electron microscope (SEM) to study the microstructural features. The SEM photomicrograph of wheel steel A (Fig. 3) exhibits fine ferrito-pearlitic microstructure at higher magnification, 2000X. The photo also shows the presence of Nb, V (CN) in ferrite (dark phase), which was confirmed by taking the x-ray images of the precipitate. Figure 4 shows SEM fractographs of tensile-fractured surfaces of wheel steel B in as forged-rolled and as normalized conditions. The fractographs indicate that as normalized micro alloy, steel B (Fig. 4b) shows ductile fracture (dimpled appearance) primarily due to the formation of uniform smaller grains of ferrite and pearlite after normalizing treatment. The fracture features observed in Fig. 4(a) are brittle (cleavage) and are marked by intergranular cracking and cleavage steps.

4.7 Wear Testing: Rolling-Sliding Mode

The wear tests were conducted in Amsler wear testing machine at room temperature under a dry regimen with a slip of 10% maintained between rail and wheel specimens. Disc type test specimens of 40 mm diameter and 10 mm thickness, with bore of 16 mm fabricated from rim location of micro alloy and R-19/93 forged wheels were used for the determination of rolling–sliding wear rate. All samples used were of the same dimension. The mating discs of 880 MPa grade pearlitic rail of the same dimensions as used for wheel samples were used. The average surface roughness was kept at around 1 µm by ground finishing the specimens with emery papers. The specimens under test were continuously cleaned with woollen cloth to avoid the entrapment of wear debris and to achieve uniformity in experimental procedure. Calculation of the maximum contact pressure at two applied loads, 1741 N and 1861 N, was done on the basis of the hertzian contact theory according to the formula:

$$p = 0.59[\mathrm{LE/R}]^{1/2}$$

where P, maximum contact pressure (MPa); L, load per unit contact width in (N); E, Young modulus, 2.042×10^5 MPa; and R, radius of the disc (mm). The contact pressures worked out in this way were 786.6 MPa and 813.3 MPa and were recommended by Indian Railways as the requirement of their track conditions. Wear tests were conducted at speeds of 300 rpm. The contact shear stress, Ss in MPa, was worked out with the relationship:

$$\mathrm{Ss} = 0.3\ \mathrm{P}$$

The calculated contact shear stresses were 236 MPa and 244 MPa for contact pressures 786.6 MPa and 813.3 MPa, respectively. Wear rate was calculated by dividing the loss in weight of disc by total running time of 8 h. The dimensions of all the specimens tested were the same after machining and grinding operations. The average wear rates for three tests for A, B, and R-19/93 wheel steels were reported in mg/h (Fig. 5).

The weight loss of A, B, and R-19/93 grade wheel steels at contact shear stresses 236 and 244 MPa are shown in Fig. 4. In R-19/93 wheel steel, the weight loss was about 58% and 72% more at contact shear stresses 236 MPa in comparison of A and

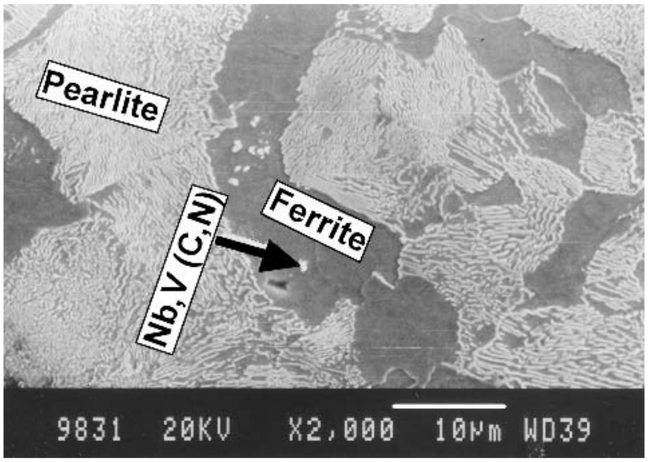

Fig. 3 SEM photomicrograph of micro alloyed wheel steel A exhibiting the presence of Nb, V (CN) precipitate in ferrite phase (arrow shows the position of Nb, V (CN) precipitate analyzed)

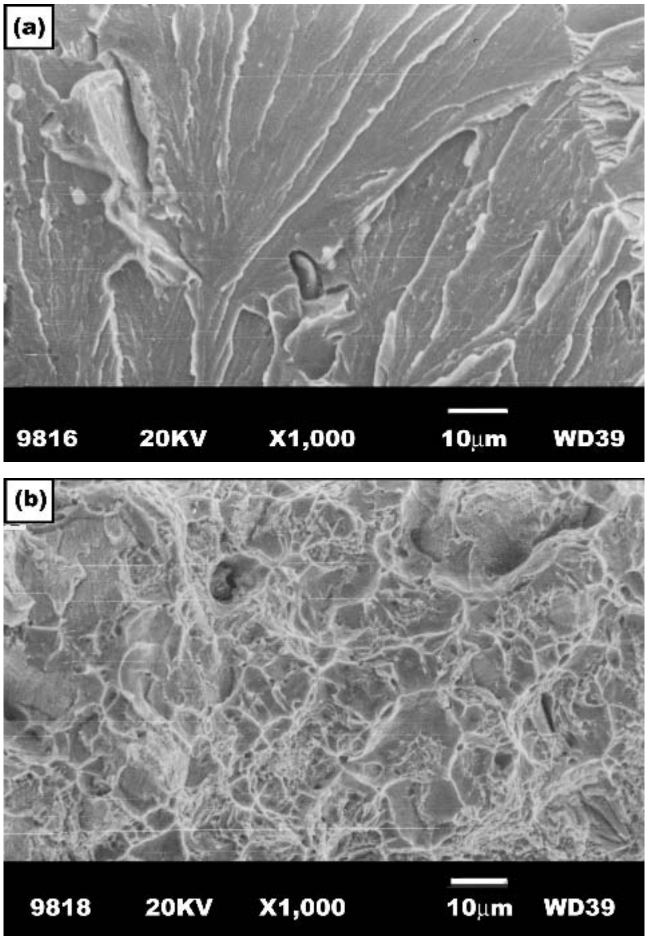

Fig. 4 SEM fractographs of tensile fractured surfaces of **(a)** as forged-rolled and **(b)** as normalized micro alloyed wheel steel B revealing brittle fracture in case of forged-rolled wheel where normalized wheel shows a ductile fracture

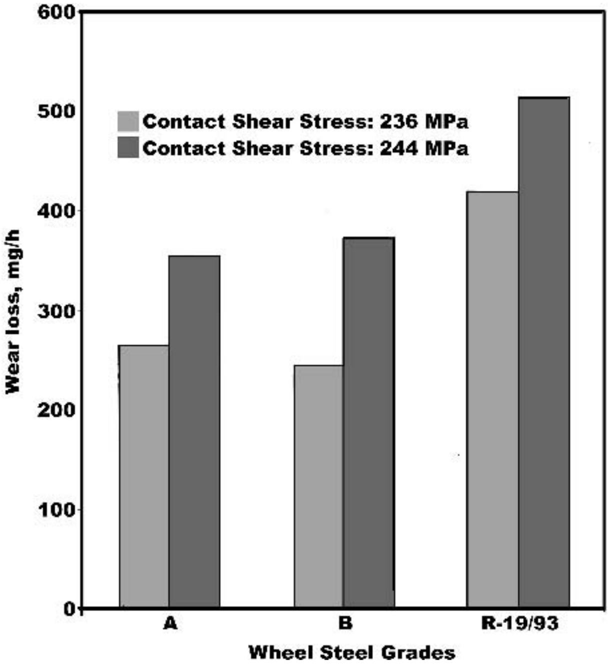

Fig. 5 Wear loss of wheel steels investigated under rolling-sliding mode (samples of same dimension used)

B micro alloy wheel steels, respectively, whereas in case of higher contact shear stress 244 MPa the weight loss of R-19/93 wheel steel was 38% and 45% more in comparison of A and B micro alloy wheel steels respectively. Wear resistance of micro alloy wheel steel is superior to that of R-19/93 grade wheel, but the difference of weight loss in case of micro alloy and standard R-19/93 grade wheel steels becomes smaller with an increase in contact shear stress (Fig. 5). Further tests at higher contact shear stresses could not be conducted as the maximum load carrying capacity of the machine used was limited to 2000 N.

4.8 Service Performance Evaluation

BG coach wheels of 915mm O.D. made from wheel steel A were supplied to Indian Railways for field performance test. Twenty-four wheels were fitted in 3 coaches of Black Diamond Express. Service performance was checked for 8 months at 3 month intervals. No failure was observed during 100 days of service in any of 24 micro alloyed wheels. In normal wheels a few failures were reported. No failures were reported in 8 months. About 10-20 mm wear in diameters of different wheels was noticed after running of nearly 200 000 km track distance. Since the hardness profile of micro alloy wheel was uniform, unlike that for R-19/93 wheels, it may be predicted on the basis of laboratory wear test as well as field trials that the life of micro alloy wheels may be about 30% more on account of wear. The important economic factors are: (1) 30% less wear rate of micro alloy wheel due to finer pearlitic-ferritic microstructure; (2) elimination of heat treatment process: rim quenching and tempering; and (3) flatter hardness profile enhancing wheel life.

5. Conclusions

1) The investigation of trial commercial micro alloyed wheels showed superior properties compared with the properties stipulated in IRS-R19/93 specifications.
2) Normalized micro alloy wheel steel showed a fine grain ferrite-pearlite microstructure of ASTM grain size no. 6-7.
3) The wear resistance properties of micro alloy wheel steel is superior to that of R-19/93 wheel steel (~40% lower wt. loss).
4) Micro alloy wheel steel has a higher endurance limit and can delay the initiation of fatigue crack. This will lead to the improvement of wheel life in service.
5) Service performance test of micro alloy wheel has revealed that its life may be about 30% more on account of wear.

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