Research on Operational Characteristics of Imported Rails under Conditions of East Siberian Railway

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Abstract. In world's manufacturing of railroad rails there are several thermal bonding methods: differentiated waterflow quenching, air-blast or spray quenching, rail head's hardening in polymer solution and bulk oil hardening; rails' service durability is strongly dependent on thermo-hardening methods. Until recently, all of rails, produced at Nizhniy Tagil and Kuznetsk Metallurgical Works, were subjected to bulk oil hardening. Only in 2010-2011, in the Russian Federation, differentiated air quenching of rails was started at the JSC "EVRAZ ZSMK"; and rail heads' hardening in polymer solution - at the JSC "Mechel". At the same time, exploitation of imported rails with differentiated hardening has been performed on Russian railways since 1995. Service durability of these rails in Siberia and the Far North is of considerable interest. In this paper we investigated the quality of P65-type rails, made in Japan, removed after use from curved track section of the East-Siberian railway.

Introduction

A general view of the rail with significant lateral wear up to 15 mm is shown in Figure 1.

Figure 1. Rail macrotemplate

The rails were tracked in the curve section of 297 m radius [1]. Total weight load for usable life was 136 million ton gross. The rail was removed in April, 2013, because of lateral wear.

Results of a control chemical analysis of metal test sample, compared with the specifications of the Russian Federation, are shown in Table 1.

Table 1. Chemical composition

Material	Content of chemical elements, %													ppm
	C	Mn	Si	P	S	Cr	Ni	Cu	Al	V	Ti	Mo	N	O_2
Sample	0.78	0.80	0.64	0.016	0.005	0.51	0.02	0,02	0.002	0.003	0.002	0.006	0.0022	4.6
TU 0921-239-01124323-2007 for rail steel 350LDT	0.72-0.82	0.70-1.20	0.35-1.00	not more		0.30-0.70	not more		not more than 0.005	not more than 0.01	not more than 0.025	not more than 0.02	not more than 0.015	not more than 20

According to the content of chemical elements, the metal sample meets Specification 0921-239-01124323-2007, set for the steel used for manufacturing of 350LDT-category rails.

Results of a fractional gas analysis showed that the highest oxygen mass fraction is in aluminates and aluminosilicates, calcium silicate and magnesium spinel (2.6 and 2.2 ppm respectively) and the lowest oxygen fraction of 1.3 ppm is in silicates [2].

The rail cross-section macrostructure was identified by deep etching in 50% hydrochloric acid solution and evaluated in accordance with the guideline document 14-2R-5-2004 "Qualifier of macrostructure defects of rails, rolled from continuously cast arc-furnace steel blanks". The metal microstructure is satisfactory in terms of centerline segregation (I), points' inhomogeneity (II) and segregation streamers (III). The makrotemplate revealed subtle serpentinous oblique cracks on the head fillet face that form a pattern up to 1 mm deep.

Measuring of tensile properties, impact toughness at +20°C, hardness in the head roll face and in the cross section were carried out on coupons, cut off from the sample, in accordance with State Standard P 51685-2000 and Specification 0921-239-01124323-2007. Two additional coupons were tested for toughness at -60°C. Results of mechanical and hardness tests are shown in Tables 2 and 3.

Table 2. Tensile properties and toughness

Coupon №	Tensile properties				Toughness KCU, at a t°C,	
	σ_{Re}	σ_{Rm}	δ_5	ψ	+20	-60
	H/mm^2		%		J/cm^2	
1- Coupon cut from the non-working head fillet	870	1270	12.0	44.0	20 21	4.8
2 - Coupon cut from the working head fillet (crumple zone)	840	1260	13.0	45.0	12 8.6	4.8
Specifications 0921-239-01124323-2007 for rails 350 LDT	-	Not less 1240	Not less 9.0	-	Not less then 15 (1,5)	-

Tensile properties, hardness of the head roll face and of the cross section and impact toughness at +20°C in coupons, cut from the non-working head fillet, meet Specifications 0921-239-01124323-2007 for 350 LDT -category rails.

Table 3. Hardness

Material	Hardness HB							
	Head					rail web	rail foot	
	FCL	10 мм	Fillet		22 мм			
Coupon	404	380	378	-	347	325	339	329
Specifications 0921-239-01124323-2007 for rails 350 LDT	362-400	Not less				Not more		
		341				341	363	

Enhanced hardness at the rail head roll face (HB 404) and diminished impact toughness, determined at + 20°C (8.6-12 J/cm^2) on samples cut from the working head fillet, are caused by strain aging of the rail surface layers during use. Toughness is diminished to 4.8 J/cm^2 at -60°C. This proves that rails, manufactured with differentiated hardening, are unreliable at low temperatures [3-5].

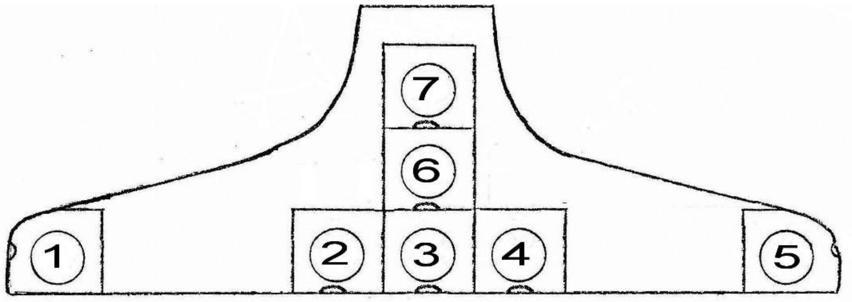

Figure 2. Scheme of coupone's cutoffs

Coupons were cut off according to the scheme shown in Figure 2, to determine tensile properties and impact toughness of the metal at the rail bottom. The coupons were marked with serial numbers (see the scheme). Test results are shown in Table 4.

Table 4. Mechanical properties of the rail cross-section

Coupon №	Tensile properties				Impact toughness KCU, J/cm^2 at t°C	
	σ_{Re}	σ_{Rm}	δ_5	ψ		
	H/mm^2		%		+20	-60
1 (rail foot blade)	630	1020	12.0	58.0	23. 23	9.7
2	780	1200	9.9	28.0	23 19	3.6
3	860	1260	9.5	36.0	15 18	3.6
4	780	1220	11.0	40.0	12 9.8	4.8
5 (rail foot blade)	730	1200	12.0	34.0	23 18	17
6	750	1160	9.5	23.0	9.6 20	7.2
7	670	1090	10.5	25.0	12 15	6.0

The highest values of strength characteristics (σ_{Re} =860, σ_{Rm} =1260 H/мм^2) were obtained on the coupon, cut off at the rail foot, along the vertical axis of the rail sample; they are comparable with the strength properties of the rail head (σ_{Re} = 840-870; σ_{Rm} =1260-1270 H/мм^2). Plastic properties are slightly diminished, in comparison with the head, and are (δ_5= 9.5; ψ=36 %) and (δ_5= 12-13; ψ= 44-45 %) respectively.

Strength properties of the metal are diminished (σ_{Re} = 780; σ_{Rm} =1200-1220 H/mm^2) at some distance from the vertical axis in the direction of the rail foot blades; wherein percent reduction of the area is 28% and 40%, respectively. Percent elongation is diminished to 9.9% and 11% respectively.

In one foot blade the rail foot blade has diminished strength properties (σ_{Re} = 630, σ_{Rm} =1020 H/мм^2), and a percent reduction of area is 58%; while in the opposite foot blade strength properties are somewhat enhanced (σ_{Re} =730; σ_{Rm} =1200 H/мм^2) and a percent reduction of the area is 34%. Percent elongation 12% is equal in both blades.

The coupons, cut along the axis at some distance from the surface, also have diminished strength (σ_{Re} = 670-750; σ_{Rm} =1090-1160 H/mm^2) and plastic properties (δ_5= 9.5-10.5; ψ=23-25 %).

Toughness of the coupons, cut from the foot, at +20°C, is generally in the range of 15-23 J/cm2; two more coupons have toughness 12 J/cm^2, and still other two – 9.6-9.8 J/cm^2, which is comparable to the rail head’s toughness.

Toughness at -60°C is diminished from 3.6 to 9.7 J/cm^2, except for one sample (17 J/cm^2); relatively low values are obtained on coupons, cut from the foot blades (9.7 and 17 J/cm^2).

Hardness in the sample's head and foot cross sections was measured by a Rockwell hardness tester «AFFRI 251 VRSD».

Head hardness was measured from the roll face along the vertical axis to 40 mm depth and from the surface of fillets at 45° to the horizontal line, drawn through control points of hardness measuring in fillets' zone, at an interval of 5.0 mm, at 10 mm depth (see Fig.3)

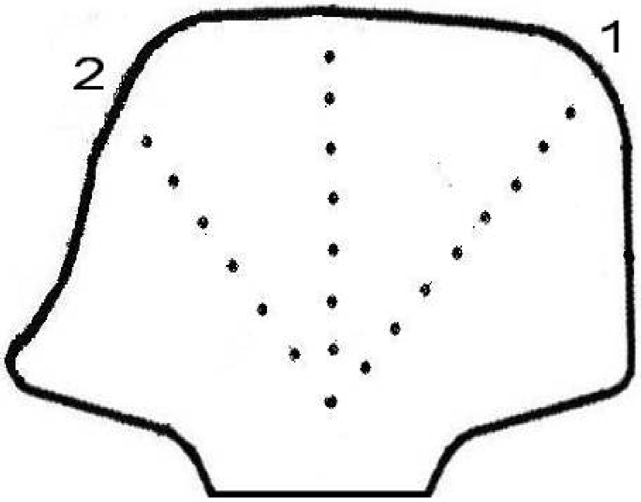

Figure 3. Scheme of hardness measuring in the rail head's cross section

Foot hardness was measured from the foot face along the vertical axis to 35 mm depth and along the horizontal line, drawn through control points of hardness measuring in the rail foot, apart from the vertical axis at an interval of 5.0 mm (see Fig.4)

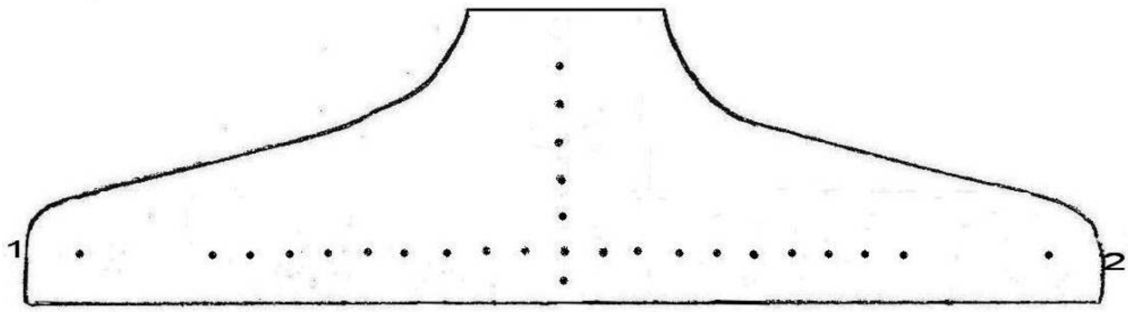

Figure 4. Scheme of hardness measuring in the rail foot's cross section

Table 5. Hardness in the head

Measuring direction	Hardness in the head HRC (HB)								
	at a distance from the surface, mm								
	5	10	15	20	25	30	35	40	45
along the vertical axis	37.3 (361.7)	37.1 (359.9)	36.8 (357.2)	36.3 (352.7)	34.2 (333.8)	33.3 (325.7)	32.7 (321.4)	32.9 (322.1)	-
from fillet 1 (non-working)	38.2 (369.5)	38.1 (368.9)	37.1 (359.9)	36.1 (350.9)	35.2 (342.8)	35.2 (342.8)	34.1 (330.7)	33.3 (325.7)	32.9 (322.1)
from fillet 2 (working)	37.7 (355.3)	37.4 (362.6)	36.4 (353.6)	36.9 (358.1)	35.7 347.3)	35.5 (345.5)	-	-	-

Table 6. Hardness in the foot

M.d.	Hardness in foot HRC (HB)													
	distance from foot surface													
	5	10	15	20	25	30	35	40	45	50	55	60	65	70
1	34,9 (334)	34,5 (337)	33,1 (324)	33,7 (329)	30,6 (303)	33,1 (324)	29,6 (295)	-	-	-	-	-	-	-
7 mm														
2	33,6 (328)	32,9 (322)	31,7 (312)	30,5 (302)	26,9 (275)	25 (263)	24,6 (259)	24,8 (261)	28 (283)	28,1 (284)	28,8 (289)	27 (276)	28,1 (284)	31,4 (309)
3	33,2 (325)	33,3 (327)	32,9 (322)	31,7 (312)	31,2 (308)	25,2 (263)	24,8 (261)	23,5 (253)	28,1 (284)	27,9 (282)	28,4 (286)	28,1 (284)	28,8 (288)	31,7 (312)

Note:
M.d.- measurement direction
1 - along vertical axis
2 - from vertical axis, horizontally towards side 1
3 - from vertical axis, horizontally towards side 2

Hardness in the head cross section diminishes on drawing from the surface. Horizontal hardness towards the blades at a distance of ~ 25 mm from the vertical axis is almost identical: 30.5 (302) - 33.6 (328.4) HRC (HB); at 40 mm distance it diminishes to 23.5 (253) -25 (262.7) HRC (HB); and then enhances to 31.7 (311.6) HRC (HB).

Additionally, hardness was measured in the foot surface spot sample of the template of ~ 330 mm length, after grinding on the depths up to 1 mm. Measurements were performed along rolling direction, by every 10 mm, in five zones: in the axial zone, and at distances of 20 and 40 mm to the left and to the right from the axis. The results are shown in Table 7.

On the sample surface at a distance of ~ 250 mm from the end face, axial zone hardness is almost identical: 35.2 (342.8) - 37.8 (366.2) HRC (HB) to the left and to right up to 40 mm from the axis; farther at a distance of ~ 80 mm hardness diminishes to 23.3 (251.8) – 29.2 (291.6)HRC (HB) in all marked points.

Assessment of nonmetallic contaminations was performed on a microsection, cut off and prepared from the head sample side. Objectionable lines of alumina and titanium nitride, as well as alumina and titanium nitride, cemented by silicates, have not been identified in the sample as well as lines of brittle-fracture complex oxides [6-8].

A single globular inclusion of 10.0 mm diameter is identified. Mainly there are filamentary sulfides scored in 1.5 points on the State Standard 1778-70 scale. Single titanium nitrides occur as light pink crystals of various forms in separate sulfide inclusions. A single plastic silicate of 135 microns length is identified.

Table 7. Hardness on foot base surface

№	Hardness on foot base surface HRC (HB)				
	40mm Left from axis	20mm Left from axis	in axial zone	20mm Right from axis	40mm Right from axis
1	36.6 (355.4)	37.8 (366.2)	36.8 (357.2)	37.3 (361.7)	35.8 (348.2)
2	36.2 (351.8)	37.6 (364.4)	36.7 (356.3)	36.9 (358.1)	35.7 (347.3)
3	36 (350)	37.5 (363.5)	36.2 (351.2)	37.2 (360.8)	35.4 (344.6)
4	36.8 (357.2)	37.3 (361.7)	36 (350)	36.5 (354.5)	35.7 (347.3)
5	36.1 (350.9)	37.3 (361.7)	35.2 (342.8)	37.6 (364.4)	35.9 (349.1)
6	36.4 (353.6)	37 (359)	35.6 (346.4)	36.2 (351.8)	36.1 (350.9)
7	36.2 (351.8)	37.6 (364.4)	35.9 (349.1)	36 (350)	35.7 (347.3)
8	35.8 (348.2)	37.6 (364.4)	36 (350)	36.3 (352.7)	35.6 (346.4)
9	35.7 (347.3)	36.5 (354.5)	35.8 (348.2)	36.3 (352.7)	36.1 (350.9)
10	35.8 (348.2)	36.8 (357.2)	35.8 (357.2)	36.8 (357.2)	35.7 (347.3)
11	36.1 (350.9)	36.9 (358.1)	36.5 (354.5)	36.2 (351.8)	35.7 (347.3)
12	36.2 (351.8)	37 (359)	36.8 (357.2)	37.1 (359.9)	36 (350)
13	36.1 (350.9)	36.8 (357.2)	36.9 (358.1)	37.4 (362.6)	35.7 (347.3)
14	36.9 (358.1)	37.1 (359.9)	36 (350)	37.1 (359.9)	36.1 (350.9)
15	36.3 (352.7)	36.8 (357.2)	37.1 (359.9)	36.9 (358.1)	35.9 (349.1)
16	36.9 (358.1)	36.2 (351.8)	36.4 (353.6)	36.8 (357.2)	35.9 (349.1)
17	36.9 (358.1)	37.3 (361.7)	36.6 (355.4)	37.1 (359.9)	35.6 (346.4)
18	36.5 (354.5)	37.3 (361.7)	37 (359)	36.8 (357.2)	36 (350)
19	36.8 (357.2)	36.8 (357.2)	37 (359)	36.5 (354.5)	36.3 (352.7)
20	36.9 (358.1)	37.1 (359.9)	36.8 (357.2)	36.9 (358.1)	35.3 (343.7)
21	36.3 (352.7)	37 (359)	36.5 (354.5)	37.1 (359.9)	35.3 (343.7)
22	36.3 (352.7)	37 (359)	36.2 (351.8)	37.2 (360.8)	35.2 (342.8)
23	35.2 (342.8)	36.8 (357.2)	36 (350)	36.8 (357.2)	36.3 (352.7)
24	33.2 (324.8)	34.7 (338.3)	36.2 (351.8)	36.2 (351.8)	35.6 (346.4)
25	29.1 (290.8)	33.9 (331.1)	34.7 (338.3)	33.2 (324.8)	33.4 (326.6)
26	26.8 (274.6)	29.1 (290.8)	26.8 (274.6)	23.3 (251.8)	26 (269)
27	27.1 (276.7)	26.4 (271.8)	26.7 (273.9)	25.1 (262.7)	27.3 (278.1)
27	27.8 (281.6)	24.9 (261.4)	23.6 (253.6)	26.1 (269.7)	28.1 (273.7)

№	Hardness on foot base surface HRC (HB)				
	40mm Left from axis	20mm Left from axis	in axial zone	20mm Right from axis	40mm Right from axis
29	28.1 (273.7)	24.4 (258.4)	23.3 (251.8)	26.3 (271.1)	27.3 (278.1)
30	29 (290)	25.6 (266.2)	23.9 (255.4)	26.4 (271.8)	29 (290)
31	29.2 (291.6)	26.5 (272.5)	24.8 (260.8)	27.3 (278.1)	28.9 (289.3)
32	29 (290)	26.6 (273.2)	25.4 (264.8)	26.5 (272.5)	27.3 (278.1)

Metal microstructure was studied it cross-microsections, cut from the head, mid-neck , mid-foot and blades after etching in 4% alcoholic solution of nitric acid. In non-etched microsections of head roll face there are structural integrity failures in the form of serpentinous cracks with depths up to 1.1 mm (Figure 5). Cracks cavities are partially filled with an indiscrete gray mass being a product of corrosion.

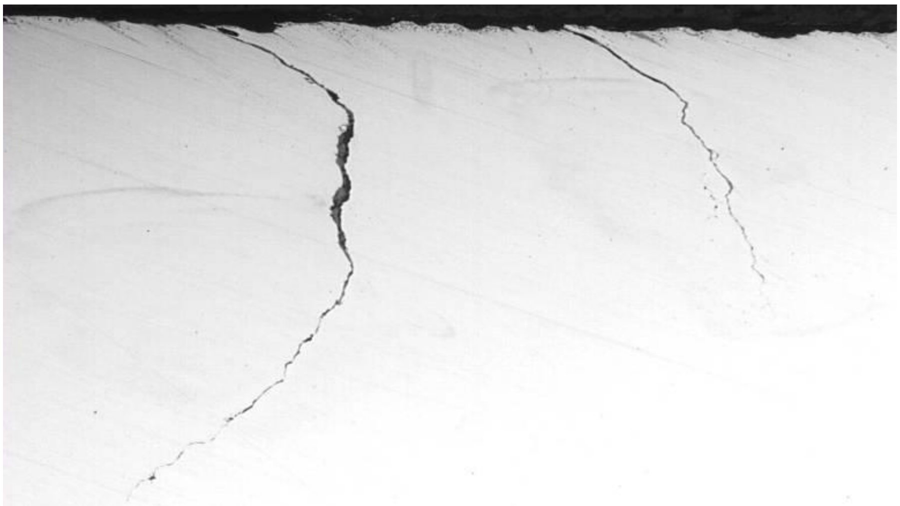

Figure 5. Cracks in the rail head, ×50

After chemical etching of microsections in 4% nitric acid alcoholic solution, structures with deformed grains are observed on cracks' edges; decarbonizing is not observed. On the working surface of the head the structure is deformed; sometimes there are strain aging layers up to 0.065 mm resulting from use.

The rail section metal microstructure is sorbitic and plate-like pearlite, and is typical for differentiated heat-strengthened state, which dispersion diminishes with distance from the head surface. The zone of diminished hardness, identified in the foot, is composed of granular and plate-like pearlite.

Conclusion

Metallographic study of P65-type rail, made in Japan, after use at the East Siberian Railway, has found:

1. According to the content of chemical elements, the metal sample meets Specification 0921-239-01124323-2007, set for the steel used for manufacturing of 350LDT-category rails.
2. The macrostructure of the metal is satisfactory.
3. Tensile properties, hardness of the cross section and impact toughness at +20°C in coupons, cut from the non-working head fillet, meet Specifications 0921-239-01124323-2007 for 350LDT-category rails.

Enhanced hardness at the rail head roll face (HB 404) and diminished impact toughness, determined at + 20°C (8.6-12 J/cm^2) on samples, cut from the working head fillet, are caused by strain aging of the rail surface layers during use.

Foot surface hardness, measured at spot samples along the length is generally 35.2 (342.8) – 37.8(366.2) HRC (HB); also there are zones with hardness diminished to 23.3 (251.8) – 29.2 (291.6) HRC (HB).

4. Contamination of non-metallic inclusions is insignificant. However, there are objectionable inclusions of exogenous origin (globules of 10.0 micron diameter).

5. The rail section metal microstructure is sorbitic and plate-like pearlite, which dispersion diminishes with distance from the head surface.

6. Subtle serpentinous oblique cracks up to 1 mm deep on the head fillet face as well as significant lateral wear up to 15 mm occurred during use.

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