Study on Contact Rolling Fatigue of Rails*
(2nd Report, Analysis by High Speed Rail Testing Machine)

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This is a report on the result obtained by using a high speed rail testing machine, which is described in the first report. The contact rolling defects of the actual rail were observed in the laboratory. Especially, the running surface layer of the rail was investigated in detail and the possibility of surface crack propagation was analyzed by fracture mechanics.

The main results obtained are as follows: (1) Defects on the running surface; cracks are initiated at the surface and propagate much in the wheel running direction and a little in the opposite direction. In this test, however, white phase is observed in the running surface layer and cracks run out through the white phase. (2) Head checks at the gauge corner; many cracks occur at the gauge corner with the same pitch and with the same inclination to the wheel direction. (3) The above tendency is very similar to that the Shinkansen. (4) The possibility of crack propagation was calculated by fracture mechanics and would be very small for shorter cracks of 0.5 mm in depth due to the friction effect of cracked surfaces themselves.

Key Words: Fatigue, Contact Rolling Fatigue, Rail Steels, White Phase, Fatigue Crack Propagation.

1. Introduction

It is very difficult to analyze perfectly the contact problems because there are many factors which complicatedly relate to each other and the contact surface condition changes during contact rolling. Therefore, there has been no experimental report about the defect between actual rail and actual wheel under high speed in the laboratory.

This report concerns an analysis of the defects of rails performed by using the high speed rail testing machine, which was described in the previous report⁽¹⁾, to clarify the contact rolling problems on the Shinkansen. The contact rolling defects of the tested rail were observed in the laboratory. Especially, the running surface layer of the rail was investigated in detail, and the possibility of surface crack propagation was analyzed by fracture mechanics.

2. Experimental Procedures

The material used is an actual plain carbon rail (588 N/m). Table 1 lists the chemical compositions and mechanical properties of the tested rail. The rail is

Table 1 Chemical compositions and mechanical properties of rail

C	Si	Mn	P	S	Al	σ_{B2} MPa	σ_B MPa	E/ %	R.A. %	H _B
0.63	0.23	0.96	0.016	0.016	0.013	—	892	15	—	269

(wt %, $\phi 14$ mm, GL=50 mm)

bent into a semi-circular shape of inside diameter $\phi 6000$ mm by a three-roll bender using a special roll of which surface profile just matches the rail head to prevent the deformation of the rail head shape as much as possible.

The wheel running speed was 170 to 210 km/h and almost 170 km/h. Radial load was 132 kN which was 1.6 times the nominal load on the Shinkansen. The defects were detected at 235×10^{10} Gross N and the defective rail was removed at 314×10^{10} Gross N. Gross N means two times the total passing tonnage (load) per one rail in this case.

Testing items in this experiment are as follows. Appearance; visual inspection. Fundamental properties; chemical compositions, tensile test, macro-etching of cross section, S-print, hardness distribution of running surface and surface layer. Detected failure; surface depression, micro-structures of running surface and surface layer of cross section, metal flow of surface layer, chemical analysis of white phase, etc.

3. Testing Results and Discussion

Figure 1 shows an appearance of dark spot (shelling defect). The location of the dark spot is about 50 mm far from edge

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Fig. 1 Dark spot by high speed rail testing machine
(Total passing tonnage; 235×10^{10} Gross N)

Fig. 2 Dark spot by high speed rail testing machine
(Magnified Fig. 1)

Fig. 3 The vertical section of dark spot (Magnified Fig. 2)

Fig. 4 Surface structure and cracks

point of sleeper to the wheel running direction. Putting the distance from the center axis of rail head surface to gauge corner (GC) as d , the center of the dark spot is expressed by $d=12$ mm.

Figure 2 shows a part of the magnified Fig. 1 and its vertical section. From this figure, the cracks seem to initiate from the tread surface or its subsurface (for instance, about $250\mu\text{m}$ in thickness).

Figure 3 also shows a part of the magnified Fig. 2. White phase, which has not been etched with nital etchant, is observed on the running surface of the rail and is $250\mu\text{m}$ in thickness. Several cracks run out through the white phase and propagate towards the wheel running direction. The reason why there are cracks and not white phase in D and E in Fig. 3 is that the white phase has been removed by the successive repetition of loading. In fact, the surface at these locations is remarkably uneven.

Figure 4 shows a micro-structure and cracks at arbitrarily chosen surface. The white phase is also observed like a narrow band and a few cracks run in the transverse direction. There can exist an uncountable number of cracks in the running surface of the rail.

Figure 5 illustrates a micro Vickers hardness distribution at rail head surface and subsurface. The hardness number shows $H_V=270$ to 280 in virgin mother material and $H_V=350$ to 400 at workhardened gauge corner. There exists a part of extraordinarily high hardness number $H_V=650$, where white phase is observed. The white phase consists of about 90% martensite and 10% retained austenite.

Figure 6 shows head checks which are generally observed at gauge corner. As the thrust load was not applied in this test, the flange of wheel would occasionally contact the gauge corner of tested rail as it rolls. There are a countless number of cracks whose pitch is 2 to 3 mm and whose inclination to the wheel running direction

Fig. 5 Vickers hardness distribution

Fig. 6 Head checks by high speed rail testing machine

is 120 to 130 degrees. These phenomena are very similar to those of the Shinkansen²⁾

4. Analysis by Fracture Mechanics

The possibility of crack propagation is investigated about the dark spots, which are discussed in chapter 3, under the successive repetition of loading. The depth of the crack is assumed to have a maximum value of 0.46 mm. Analysis is conducted about the vertical crack and the inclined crack. The authors apply the calculated results by Murakami Y. et al.⁽³⁾⁻⁽⁵⁾ to the above dark spots. That is, there is a semi-circular crack in a semi-infinite elastic body. External forces are the

tween the speed (150 to 200 km/h) and adhesive coefficient μ is represented by the following formula⁽¹¹⁾;

$$\mu = 13.6 / (V+85) \text{ ----- (8)}$$

Putting $V=170$ km/h, and $\mu=f$, $f=0.043$ is obtained from eq.(8). This value can be approximately assumed as $f \approx 0.1$. In the case of the rail with driven wheel and inclined crack, f takes the minus sign ($f=-0.1$). From Fig. 8 and eq.(4), F_{II} can be given. Then, K_{II} is calculated by substituting the values of F_{II} , P_0 and a into eq.(4). Table 2 lists the above values ($K_{I\max} \approx K_{II}$).

According to Otsuka A. and co-worker's study⁽¹²⁾, the threshold of fatigue crack propagation, K_{IIth} , takes a value of $1.5 \text{ MPa}\sqrt{\text{m}}$. When friction co-efficient of crack surface itself f_c is 0.2, the crack will propagate, but it does not propagate in the case of $f_c = 0.5$. In fact, the defect, described in chapter 3, was observed at 235×10^{10} Gross N (two times the actual passing tonnage) and the rail was removed at 314×10^{10} Gross N. The defect did not propagate at all as far as its outer appearance was concerned.

Table 2 Values of F_I and K_I
($f=-0.1$)

α	$f_c = 0.2$				$f_c = 0.5$			
	e/c	θ_0°	F_I	K_I	e/c	θ_0°	F_I	K_I
0°	1	0	0.058	2.45	1	0	0.030	0.67
	-1	0	-0.052		-	-	0	
45°	1.2	0	-0.066	2.13	1.2	0	-0.033	0.83
	-0.9	0	0.030		-1.5	18	0.017	

The authors can set a guide line that the friction coefficient f_c is 0.2 to 0.5 and that the cracks whose depth are less than 0.5 mm do not propagate at all. However, the cracks will propagate even under the above condition if the following conditions are added; tensile stress produced by rail shrinkage, the crack opened by rust, larger dynamic stress due to the deterioration with the passage of time etc. These problems will be investigated in near future.

5. Conclusions

The main results obtained in this test are as follows:

- (1) The contact rolling defects are observed in the tested rail under actual wheel which runs at high speeds 170 to 210 km/h in the laboratory.
- (2) Dark spots; the cracks initiate from the rail running surface and propagate not only in wheel running direction but also in the opposite direction. The white phase, whose thickness was about $250\mu\text{m}$, was observed in the running surface and it consisted of about 90% martensite and 10% retained austenite. The chemical compositions of white phase are just the same as those of the matrix.
- (3) Head check; many cracks occur in the gauge corner. Their pitch is 2 to 3 mm and their angle to wheel running direction is almost 120 to 130°.
- (4) The above results are just the same as in the case of the Shinkansen.

- (5) The possibility of crack propagation was analyzed by fracture mechanics and it is confirmed that vertical crack ($\alpha = 0^\circ$) and inclined crack ($\alpha = 45^\circ$) are mainly affected by shear stress field and the crack surface itself develops a stress due to the friction effect. The cracks whose depth is less than 0.5 mm usually do not propagate at all.

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