

## Investigation and Analysis of the Occurrence of Rail Head Checks

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### Abstract

Wear and rolling contact fatigue (RCF) defects are most important causes of rail damage, and often interaction competitive at present railway track. Head check is one of rolling contact fatigue (RCF) defects, and generally occurs in mild circular curves and transition curves that are set at both ends of sharp circular curves. Wear tends to limit the crack growth of head checks by removing the material from the RCF surface. In order to clarify the conditions of the occurrence and growth of head checks, the authors measured the interacting forces between wheels and rails and the angle of attack of wheelset, and carried out contact analyses using the actual profile data of wheels and rails. The effects of the lateral force, the contact geometry, and the wear rate at rail gauge corner on the formation of head checks were also analyzed by using the worn profiles of actual wheels and rails and the data obtained by a track inspection car. Some specific range of wear rate at the gauge corner was identified as having close relation with occurrence of head checks.

**Keywords :** *Rolling contact fatigue (RCF) defects, Head check, Rail gauge face wear, Wheel flange wear, Lateral force, Contact analysis, FEM stress analysis*

### 1. Introduction

Head check is one of rolling contact fatigue (RCF) defects and consists of many small cracks located at the gauge corner of high rails of curved track. Those cracks occur continuously along the longitudinal direction of rails and grow against the running direction of rails. The head checks generally occur in mild circular curves and transition curves that are set at both ends of sharp circular curves. In Japanese railway, some cracks of head checks often grow up to the generation of rail spall as shown in Fig. 1, which may cause rolling noise and lead to rail break though only on rare occasions [1]. A number of serious accidents caused by RCF damage have happened abroad [2], accompanied with serious human and economic loss. Recently, the damage of head checks is remarkable according as railway vehicle runs with a higher velocity and its body trends to become lighter, then a lot of maintenance such as grinding and renewals of rails have been executed to refrain rolling noise and to avoid rail break [3-5]. It is well known that the cracks of RCF

and the wear interact mutually and raise an important maintenance problem of railway track. A high wear rate shortens the life of rails and results in the frequent rail replacement. In contrast, a low wear rate means that the cracks of head checks have time to develop in the plastic deformation and these cracks may propagate deeper into the inner part of the rails with potentially disastrous consequences. In order to clarify the formation conditions of head checks, the authors measured the interacting forces between wheels and rails and the angle of attack, and carried out contact analysis of wheels and rails. The effects of



Fig. 1 Rail Head Checks on Outer Rail

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**Table 1.** Main Features on Measured Vehicles

Form	Old type-A	Old type-B	New type-A	New type-B
Static wheel load	53 kN	51 kN	36 kN	46 kN
Profile	Modified arc tread			
Running velocity	80 km/h	100 km/h	80 km/h	100 km/h

lateral force, contact geometry, and wear rate on the formation of head checks were analyzed using the measured data of dynamic applied load, actual worn profiles of wheels and rails, and data obtained by track inspection car.

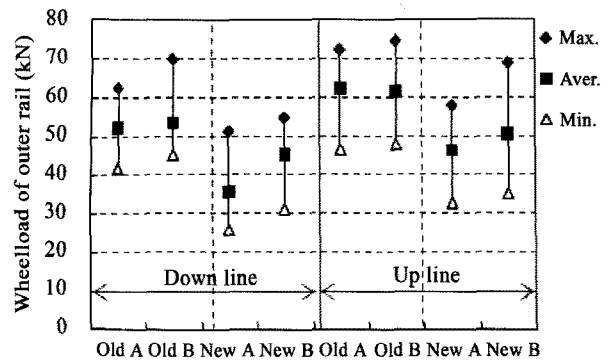
## 2. Field investigation of the track with rail head checks

### 2.1 Measurement of dynamic vehicle-track interaction in track test sections

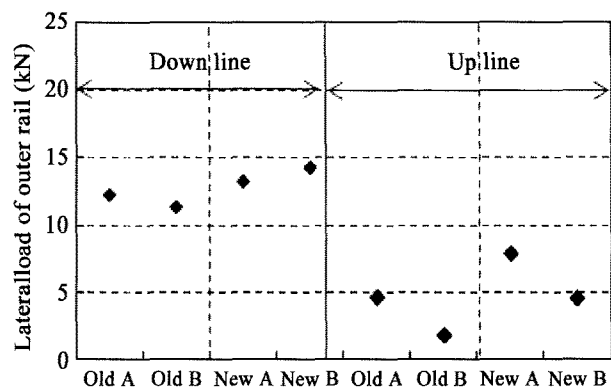
Two test sections were selected on tracks of same curve section with radius of 800 m and cant of 69 mm in the double track line, the one on the outer rails of the up line and the other on the outer rails of the down line. The test section each on up line or down line has the same length and is located at the position of the same mileage. The cracks of head checks were largely different between on the outer rails of the up line and on those of down line of test sections. The outer rails of the down line test section already had obvious head checks, and the outer rails of the up line test section had none. The wear amount measured at rail gauge corner in the direction of 45 degree (hereafter called rail gauge face wear) were about 1.5 mm with head checks and 2.8 mm without head checks. In addition, the outer rail of the test section is heat treated one with the hardness of Hv340, and the inner rail is as-rolled one with the hardness of Hv250. They are both equivalent to the standard rail of JIS50 kg. Table 1 shows main features of running vehicles, and all wheels of measured vehicles have modified arc tread profiles used in Japanese narrow gauge system.

At a selected test site in the track of test section (hereafter referred to as dynamic test point), the dynamic interacting forces between vehicle and track were measured. The strain gauge was used to measure wheel loads and lateral forces while various types of trains were passing. At the same time, the angle of attack was also obtained by the wheel strain measurement while various types of trains were passing. The measured results of the first wheel set of each bogie of vehicles including the motor coach and trailer were collected, and their details are described in the followings.

Fig. 2 shows the results of wheel loads measured at the dynamic test point. The maximum and minimum values of



**Fig. 2** Measured Results of Wheel Load



**Fig. 3** Measured Results of Maximum Lateral Force

the wheel load were in the ranges of 50~75 kN and 25~50 kN respectively. Compared with the static wheel load shown in Table 1, it is apparent that the dynamic wheel loads are significantly larger than the static ones on the track. The results also exhibit that the dynamic load on the track of the up line is higher than that of the down line for the same type vehicle, and that the old type vehicles have larger dynamic wheel loads than the new type vehicles.

Fig. 3 shows the measured results of maximum lateral forces. The maximum lateral forces were in the range of 10~15 kN on the track of the down line, and 2~7 kN on the track of the up line. These results represent that the track having head checks has larger lateral forces than the track without head checks. It is noticeable that the lateral forces caused by new type cars are larger than that caused by old type cars, although the new type cars tend to cause lighter dynamic wheel load in comparison with the old type cars.

Fig. 4 indicates the maximum values of the angle of attack. The angles of attack at outer rail of up line having no head checks were in the range of 0.08~0.2 degree, while they were in the range of 0.2~0.25 at the outer rail of down line having head checks. This result means that the angle of attack is larger at the site of occurrence of head checks than at the site without occurrence of head

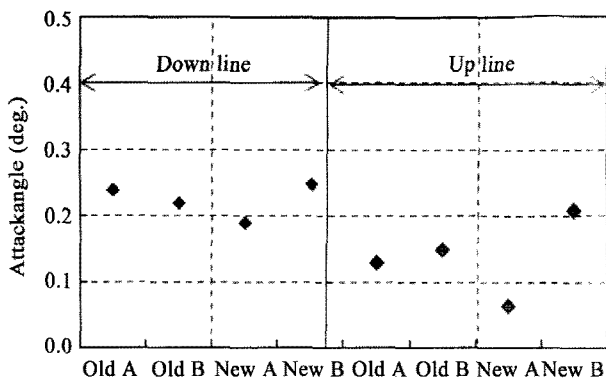


Fig. 4 Measured Results of Maximum Angle of Attack

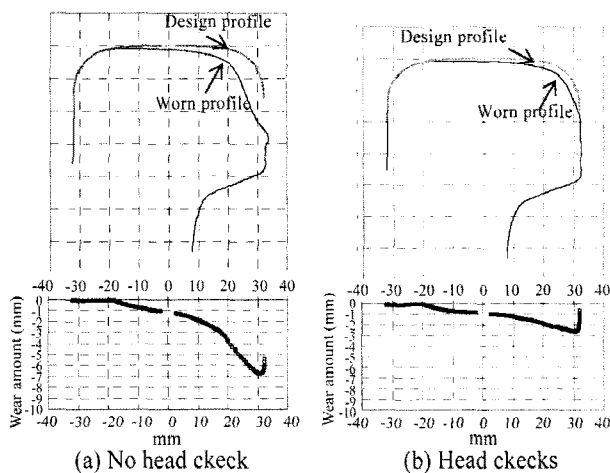


Fig. 5 Relationship of Head Checks and Wear Amount

check. The effect of different car types on the angle of attack is not clear from the measured results.

It is well known that the lateral force and the angle of attack dominate the gauge face wear. Therefore, there were obtained the reasonable results that a higher wear rate of 1.4 mm/100 MGT corresponding to a higher lateral force and a larger angle of attack at the site of occurrence of head checks, and reversely a low wear rate of 0.8 mm/100 MGT was observed at the site without head checks.

## 2.2 Worn profiles of rails and wheels in track test sections

The visual inspection was carried out in the track test sections, and it indicated that the damage of head checks is largely different depending on the propagation of wear. In order to study the effects of rail worn profiles on head checks, the rail worn profiles were investigated at the equal distance of 10 meter for 100-meter length.

Fig. 5 shows examples of worn profiles and wear amounts on the outer rail. The rail with a severe wear shown in Fig. 5(a) had no head check observed. However, Fig. 5(b) shows a moderated worn profile, where the cracks of head checks were observed.

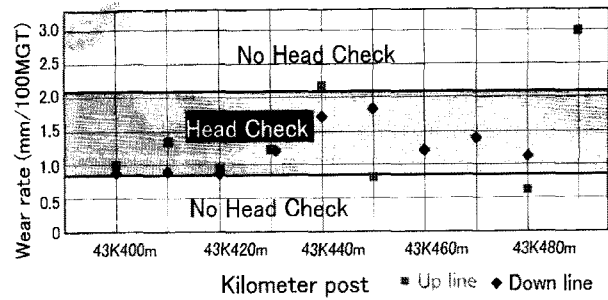


Fig. 6 Relationships of Head Checks and Wear Rate

Since the cracks of head checks generally exist at rail gauge side, the gauge face wears were calculated by measuring the worn profiles in the test sections of outer rails. At the test sections of the up line, the gauge face wear was in the range of 1.3~6.3 mm, including two cases of head checks and without head check. A detail analysis indicated that there occurred no head checks when the wear amount was over 4.2 mm or below 1.8 mm. On the other hand, the gauge face wear was in the range of 1.6~3.7 mm in the test section of the down line, where the cracks of head checks occurred and tended to cause rail spall at some places.

Fig. 6 shows the relationship between rail gauge face wear rate (the ratio of wear amount and accumulated passing tonnage) and occurrence of head checks in the test sections of 100 meters. As shown in Fig. 6, a severe wear rate can restrain the formation of head checks, and an extremely low wear rate restrains the occurrence of head checks. It is evident that the

cracks of head checks occur easily in the range of wear rate of 0.9~1.8 mm/100 MGT, but there occur no cracks of head checks when the wear rate is lower or higher than the value aforementioned. This result suggests that the head checks only occur in some specific range of wear rate due to the interacting competition phenomena of wear progress and crack growth caused by wheel-rail interacting forces. Although the volume of measured data is not so much, a quantitative relationship between wear rate and growth of head check has been given for the heat-treated outer rail of the curved track with the radius of 800 m. Certainly, more surveys should be performed in other railway lines or for other rail materials

The worn profiles of wheels were measured for various vehicles passing the test sections. Fig. 7 shows two typical profiles of the worn wheels of new type-A car and old type-A car, after the running mileages of 0.18 million kilometres and 0.12 million kilometres respectively. In Fig. 7, the worn wheel of new type-A car indicates the flange wear of 2 mm after the running mileages of 0.18 million kilometres, but the worn wheel of old type-A car shows

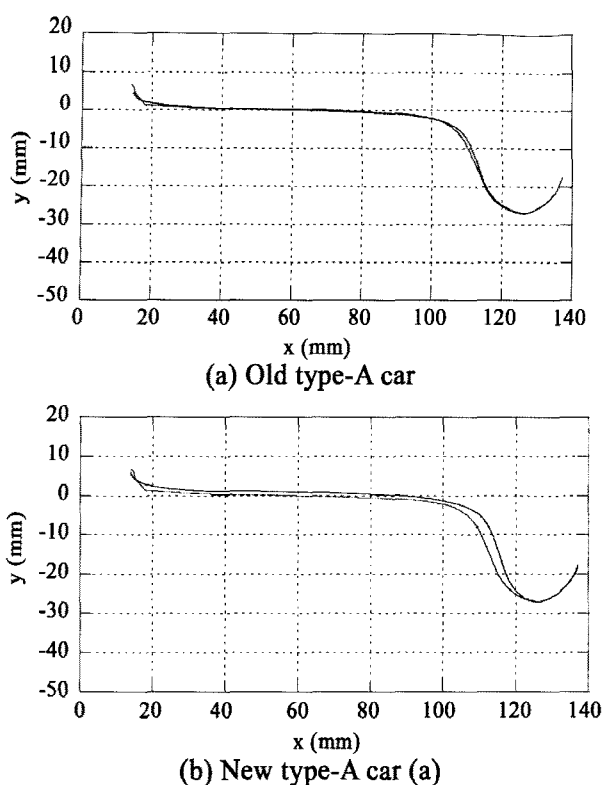


Fig. 7 Wheel Worn Profiles of Various Vehicles

almost no obvious shape change compared to the design profile of the wheel. This may be because new type cars have larger lateral force than old type cars according to the measured results of dynamic testing. In addition, the worn profiles of eight wheels of new type-A cars of a given train were measured and compared with those of eight wheels the old type-A cars of another train to confirm the above. As the result, there is a common trend that the worn profiles of wheels of new type cars have much larger shape change than those of old type cars.

### 2.3 Actual wheel-rail contact geometry

To study the effect of worn wheel profile on head checks of rails, the contact geometries of actual wheel and rail were analyzed. Fig. 8 shows two typical contacts between each of two different worn wheels and a worn rail. The profiles of two worn wheels are after the running mileages of 0.12 million kilometres and 0.18 million kilometres respectively, and the worn rail represents the profile measured at dynamic test point of the down line, where the head checks already exist. Fig. 8(a) shows a two-point contact of wheel-rail at the rail head and the rail gauge corner because of a gap between the worn rail and the worn wheel of old type car. However the worn wheel of new type car shown in Fig. 8(b) has a fitting contact (hereafter called conformal contact) with the worn rail. The profile of worn wheel of the new type car is fully in

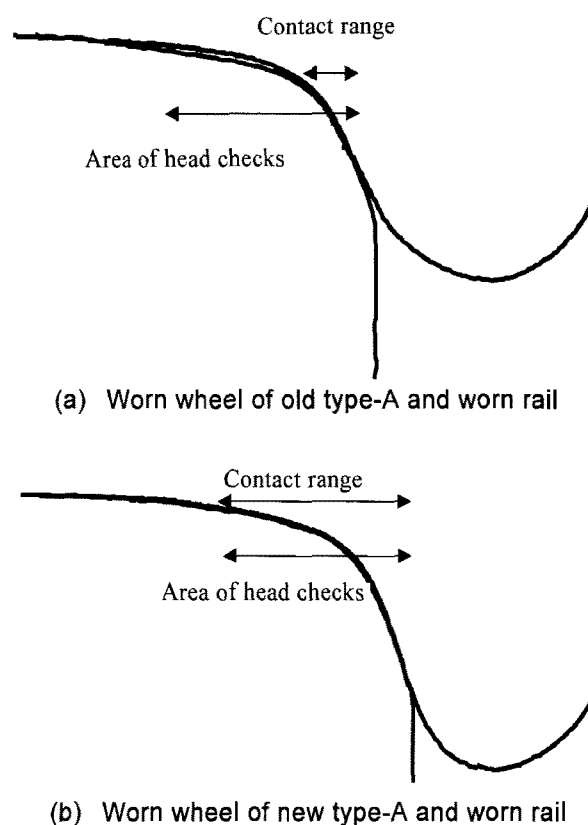


Fig. 8 Contact Geometry Between Worn Wheel and Worn Rail (Worn Rail: Gauge Face Wear of 2.8 mm)

conformity to the profile of worn rail and head checks occur at the wheel-rail contact area, thus it is apparent that the wheel flange wear of new type-A car is thought to contribute to the formation and the growth of head checks, more than that of old type-A car.

### 2.4 Lateral force from data of track inspection car

Fig. 9 shows the measured results of the lateral force by track inspection car, in the test section of 100-meter from 43 km 400 m to 43 km 500 m near the dynamic test site. It should be noticed that at the location of the mileage of 43 km 500 m a crossing is installed, where the track alignment is poor. In Fig. 9, the results of wear rate and occurrence of head checks were also indicated, corresponding to the related lateral force. The maximum values of lateral force were 10~25 kN, and their average values were 5~15 kN at the locations of head check occurrence in both the up line and the down line. It is seen that the lateral force on the track of the down line is larger than that of the up line at the locations of head checks occurrence. On the track of the up line, the significant variations of the maximum lateral force of 7~28 kN were observed accompanied with the wear rate of the wide range of 0.7~3.2 mm/100 MGT, at the locations with head checks and without

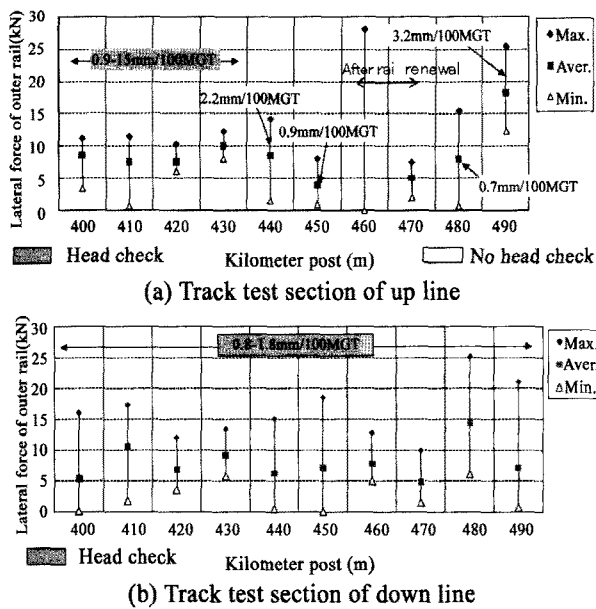


Fig. 9 Varied Lateral Forces from the Track Inspection Car, Corresponding to Head Check and Wear Rate

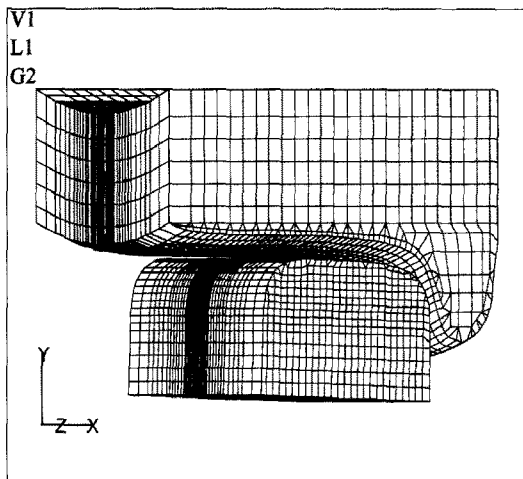


Fig. 10 A Wheel-rail Contact Model of Three-dimensional FEM

Table 2. Stress Analyses Cases

No	Wheel worn profile	Rail worn	Wheel load kN	Lateral force kN
1	Old type-A car	1.5mm*	62	5
2		2.8mm*	53	12.5
3	New type-A car	1.5mm*	46	8
4		2.8mm*	38	13

\*: Gauge face wear amount

head checks. The maximum lateral force at the site of 43 km 490 m was 25 kN, leading to a severe wear of 3.0 mm/100 MGT and no occurrence of head check. In addition, on the track of the down line, the maximum lat-

eral forces were in the range of 10~25 kN, their variations were slightly small compared to those on the track of the up line. As a result, the wear rates on the track of the down line were in 0.8~1.8 mm/100 MGT, and the head checks occurred at all locations. The results verify that the head checks easily occur on the tracks with the moderate lateral force and no severe rail wear.

### 3. Contact stress analysis

A three-dimensional wheel-rail contact model shown in Fig. 10 was used to simulate the contact between the wheel and the rail. The contact stress analysis for various profile combinations of wheels and rails was carried out elasto-plastic finite element method (FEM). To realize the contact geometry of actual wheel and rail, the wheel load, the lateral force and the angle of attack measured at dynamic test points, and the worn profiles of actual wheel and rail were used in stress analyses. Table 2 describes conditions for contact stress analysis including various load conditions. Here, the averages of wheel load and the maximum of lateral force for each type car are given, and the static and dynamic friction coefficients are assumed as 0.5 and 0.3 respectively.

Fig. 11 shows typical stress distributions caused by the applied wheel load and lateral force, in which the contact geometry is formed by a combination of worn rail and worn wheel. In Figs. 11 (a) and (b), the contacts between the worn rail and the worn wheel of old type car are obvious by at two points, and the maximum contact stresses tend to be generated at contact points on the rail crown. However, the contacts between the worn rail and the worn wheel of new type car shown in Figs. 11 (c) and (d) greatly differ from those in case of old type car, because of the conformal contact between worn wheels and worn rails. The conformal contact area is positioned near the gauge corner, 15~18 mm apart from the rail crown. The conformal contact area almost coincides with the cracked area of railhead. It is evident that the wheel flange wear of new type-A car strongly affects on the occurrence and growth of head checks.

### 4. Discussions

Wear and RCF are the most important causes of rail damage at present and often mutual competitive. Wear and RCF of rails have interrelated damage mechanisms, affecting the maintenance cost of track and the safe running of trains. Head check is one kind of RCF defects and develops at gauge corner of outer rail of the curved track due to the tangential forces and microscopic slip at the wheel-rail

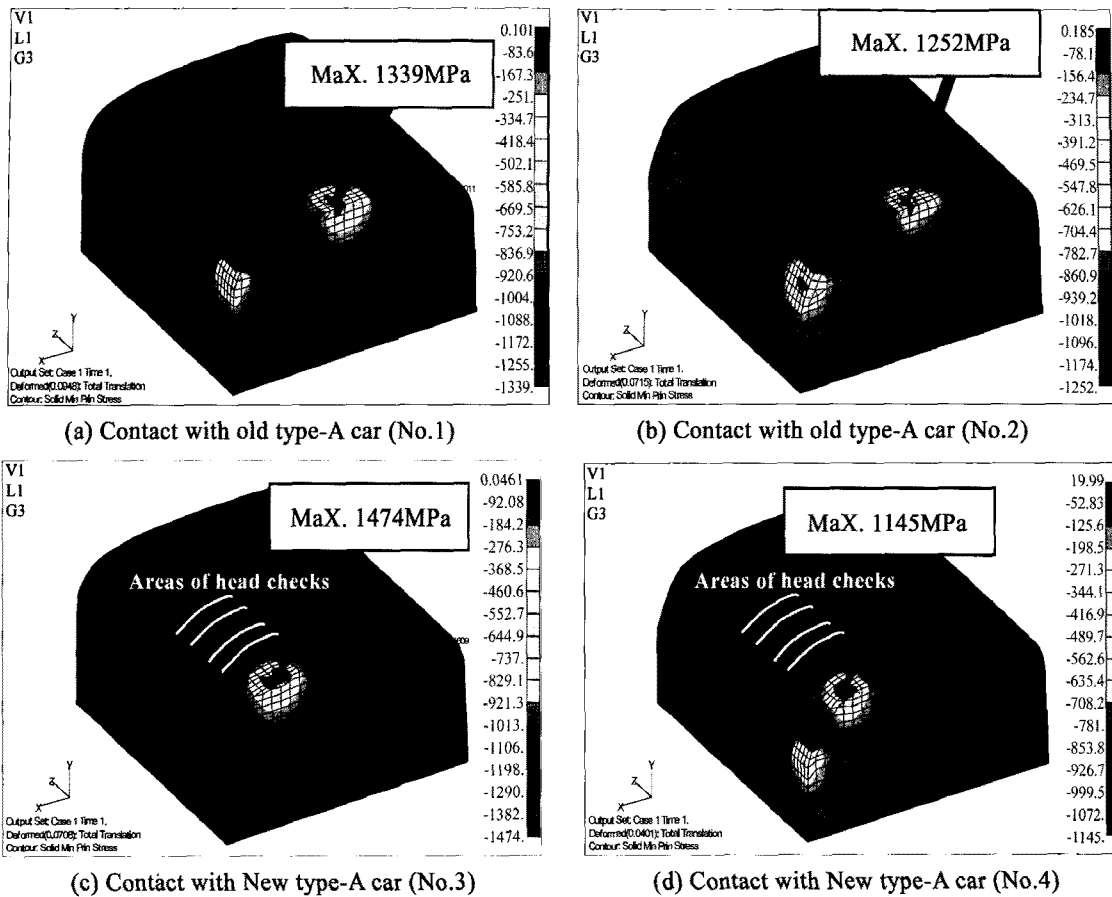


Fig. 11 Maximum Principal Stress on the Worn Rail of Head Check

interface. Some wear progress should be beneficial, since the length of cracks of head checks may be shortened by wear progress, or very short cracks may be removed completely by wear; thus the risk of cracks growing to the dangerous lengths and causing rail breaks is significantly reduced. In order to restrain the occurrence and growth of head checks, some value of wear rate should be suggested, which responds to the wear rate over 2.1 mm/100 MGT for the heat treated outer rail in curved track of radius of 800 m. From the viewpoints of reducing the cracks of head checks, railhead needs to be re-profiled periodically by grinding. Rail grinding is effective for getting rid of the fatigue layer of material surface and for eliminating the close conformity of the wheel-rail profiles, leading to great reduction the risk of head checks [6]. Consequently, it will be necessary to repeat the grinding at regular intervals to prevent the worn rail profiles from forming a conformal contact with worn flange profiles. In addition, the wheel turning is generally performed when the running mileages of vehicle reach 0.20 million kilometres, which is the practice of Japanese railway. However, it would be necessary to shorten the period of wheel turning for the worn wheel of new type car, in order to avoid the

conformal contact between worn wheel flange and worn rail.

In our study, it has been made clear that the occurrence of head checks is closely related with wheel-rail contact geometry. In fact, the problem is very complex, especially depending on the profiles of wheels and rails, track conditions (poor alignment, radius of curve and rail material etc.), and vehicle operation characteristics (vehicle type and vehicle load etc.). The combined influences of these factors are decisive factors for mutual interaction between wear progress and crack formation.

## 5. Conclusions

Wear and RCF crack of rails are problems of great significance to the railway industry. In order to clarify the track conditions at the sites of occurrence of head check, the authors analyzed the data of dynamic track point and the data obtained by the track inspection car. It is evident that maximum lateral forces are about 10~25 kN at the site of occurrence of head checks. These studies have shown that wear and head checks are competitive phenomena, in that the former can partially or entirely remove any cracks formed in the surface, consequently the critical

value of wear rate is suggested to be over 2.1 mm/100 MGT in which range there will be no head checks. It is made clear that head checks easily appear in a wear rate of 0.9~1.8 mm/100 MGT for the head treated outer rail. The analyses of contact geometry and contact stress between actual wheels and rails verify that the new type car is responsible for conformal contact between worn flange and worn rail having head checks. The flange wear of worn wheel profile has a large influence on the formation and the growth of head checks since the maximum contact stress generates in conformity with the area of occurrence of head checks.

Rail grinding is suggested for removing head checks. Depending on the wear rate, however, not all head checks grow into long cracks, and unnecessary grinding ultimately increases the maintenance costs. Anyway, the other benefit of rail grinding is to change the contact geometry between the worn wheel and worn rail. Thus, finding the optimum combination of wear and grinding to maintain railhead profile and prevent cracks of head checks from growing is a key to the running safety and cost efficiency of railway system.

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