

Rolling contact fatigue (RCF) defects of rails in Japanese railways and its mitigation strategies

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ABSTRACT: Rail is the one of the most important materials to support and guide railway vehicles safely and smoothly. Since rail suffers from various interacting forces and environmental atmosphere, wear and fatigue pose large problems with wheel and rail. Hence, wear and fatigue of wheel and rail have been studied so far to keep running safety and some level of riding comfort of vehicle taking into account track maintenance cost. In this review, rolling contact fatigue (RCF) of rail which is one of typical fatigue phenomenon for steel wheel-on-rail system is focused on and the history of RCF defects and the maintenance experience of their mitigation measures in Japanese railways are described. The concept of mitigation strategy is balance between wear and RCF. Controlling wear amount is a key word to mitigate RCF defects based on selecting rail material suitable for vehicle/track interaction together with grinding and lubrication. Furthermore, the purpose of Japanese bainitic steel rail is to obtain the suitable amount of wear to prevent the initiation of RCF crack.

Keywords: Rail, Wear, Rolling Contact Fatigue, 2D Roughness Contact Model, Preventive Grinding

1 INTRODUCTION

Rail is the one of the most important materials for rail way infrastructure to support and guide railway vehicles safely and smoothly. Vertical force and lateral force based on typically vehicle weight and dynamic behaviour such as vehicle negotiating curves interact between wheel and rail. Also, traction force for driving and braking of vehicle interacts between wheel and rail longitudinally. In addition, thermal axial force acts on rail and longitudinal friction force interacts between rail and rail fastening system particularly under continuous welded rail (CWR). Since rail is suffered from such various interacting forces and environmental atmosphere, wear and fatigue pose large problems with wheel and rail. Hence, wear and fatigue of wheel and rail have been studied so far to keep running safety and some level of riding comfort of vehicle taking into account the economical aspect of track maintenance cost. However, the phenomena of wear and fatigue have been understood to obtain better solutions from the practical point of view but not enough from the best practice.

In this review, rolling contact fatigue (RCF) of rail which is one of typical fatigue phenomenon for steel wheel-on-steel rail system is focused on and the his-

tory of RCF defects and the maintenance experience of their mitigation measures in Japanese railways are discussed.

2 HISTORY OF RAIL RCF DEFECTS IN JAPANESE RAILWAYS

(1) Dark cracks generated in gentle curves

The Japanese history of RCF defects in rails is described mainly based on some findings and research achievements obtained so far by Railway Technical Research Institute (RTRI) and Japanese railway operators in Japan. Basically RCF defects must have been initiated just after steel wheel-on-steel rail system was developed. But the first comprehensive report on RCF defects in rails was written by a research project group in RTRI organized by Japanese National Railways (JNR) in 1952¹⁾. At first some defects called “dark cracks” shown in Fig.1 in those days were observed in gentle curves in San-yo line of JNR. Typical cracks were caused together with head checks as shown in Fig.1. The naming of dark cracks is based on superficial feature that some part surrounding cracks look dark presumably due to slightly indented surface. Then such dark cracks posed so serious problem that a research project was

established to study the mechanism of crack initiation following dark cracks. Those cracks were observed not only in curves but also in tangent tracks. Fig.2 shows dark cracks take place in tangent tracks.



Fig.1 Dark cracks in gentle curves

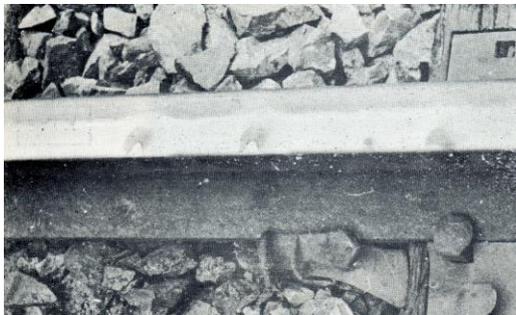


Fig.2 Dark cracks in tangent track

Shortly afterwards they came to be called shelling and/or rail surface shelling which is named to differentiate gauge corner shelling which is called as one of the typical fatigue defects of rail reported in heavy haul railways²⁾. Also, after Hatfield accident³⁾, gauge corner cracks shown in Fig. 3 were focused on to understand their mechanism and establish some appropriate preventing and/or mitigating measures.

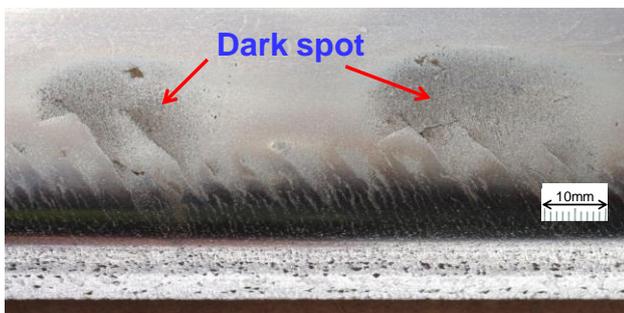


Fig.3 Gauge corner cracks

Considering some features of dark cracks reported in 60 years ago and gauge corner cracks bothering track maintenance engineers nowadays, those

cracks look so similar each other not only superficially but also mechanically and metallurgically. Then the mechanism of initiation and propagation of those two cracks may be the same. In addition, gauge corner cracks are classified to rail surface shellings called in Japan or squats called mainly in UK shown in Fig.4, which is commonly accepted in Japan.

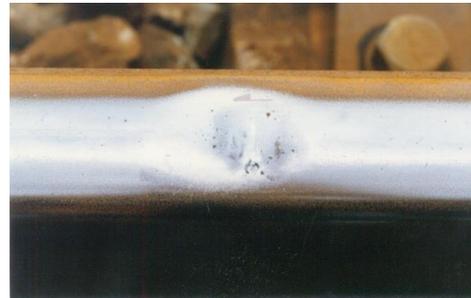


Fig.4 Typical RCF defect "Squat" called in UK and rail surface shelling called in Japan

But of course gauge corner cracks are usually caused under head checks generated at gauge corner. And gauge corner cracks are generated not just at gauge corner but slightly close to the centre of rail crown from the gauge corner. The influence of head checks on the initiation of gauge corners has not been clearly understood yet. Also, gauge corner cracks don't necessarily occur at the location where head checks are observed. Head checks shown in Fig. 5 in the case of as-rolled rails and in Fig.6 in the case of head hardened rails are formed at almost all curves which mean, for example, at transition curves in the case of sharp curves and at circular curves in the case of gentle curves. In these figures, the crack spacing of as-rolled rails is larger than that of head hardened rails, the reason for which is not clearly understood.



Fig.5 Head checks in as-rolled rail

From the different aspects, some curves whose radius is less than, for example, 800m have potentiality of head check formation even if the radius of

curvature is very small, because such sharp curves have their transition curves whose radius of curvature changes from small to large, up to tangent tracks, which means head checks can be generated at some location whose radius of curvature should be most suitable for head check generation.



Fig.6 Head checks in head hardened rail

Somehow, the project group studied a lot including laboratory simulation using a small scale rolling contact machine. In the study report written by the project group, dark cracks were likely to be caused at less wear places as a result and in addition water spray from steam locomotives to reduce wear must have had some impact on dark cracks initiation. After that, steam locomotives were changed to electric locomotives because of modernization of traction power, from steam to electricity. Also, water spray was stopped since the steering performance of electric locomotives should have been improved. Fortunately the number of dark cracks initiation got less than before very much and the problem of dark cracks was settled down as a result.

(2) Rail surface shellings generated in Japanese urban metro railways

In 1970s gauge corner cracks which were called as shellings at that time in Japan as mentioned above posed a large problem in underground railways in Tokyo. Similar to “dark cracks”, an investigation committee was established to understand the mechanism of such RCF defects^{4),5)}. In the investigation report, less wear was newly pointed out similar to dark cracks and also the effect of lubrication on the initiation and propagation was pointed out. So the some appropriate amount of gauge face wear of rail was studied. For the time being, some head hardened rails were changed to as-rolled rails to increase wear to mitigate RCF damage. Fig. 7 shows the correlation between wear rate and RCF defects initiation with the parameter of radius of curvature. This figure shows both of head hardened rail and as-rolled rail may be suffered from RCF defects, squats or gauge corner cracks, in the case of less wear.

(3) First stage of rail surface shelling problem in

Shinkansen

First stage of rail surface shelling problem in Tokaido Shinkansen which is the first Japanese high speed line opened in 1964 was raised. Since then most of the rail failures were related to rail welds. But the number of rail surface shellings had been increasing after about 10 years passed since starting its operation. Fig.8 shows the history of the number of rail failures in Tokaido Shinkansen.

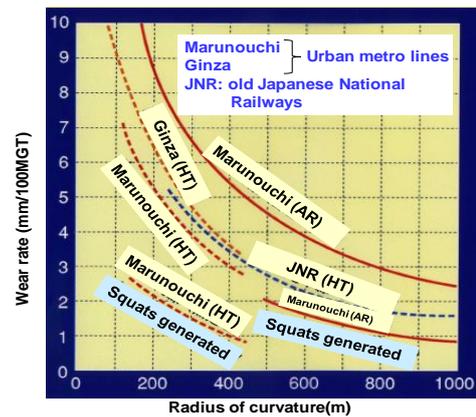


Fig.7 The correlation between wear rate and RCF defects initiation with the parameter of radius of curvature (AR: as-rolled rail, HT: heat treated rail = head hardened rail)

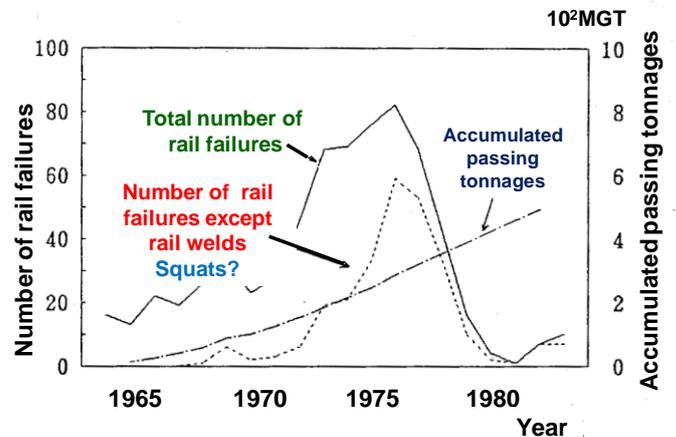


Fig.8 Transition of annual rail failures and accumulated passing tonnages in Tokaido Shinkansen (JIS50T rail)

In this figure, the number of rail failures located not at rail welds was increasing up to 1985. At that time rail surface shellings were not clearly identified by track maintenance people necessarily because the training for the track maintenance people was not enough to check the rail surface shellings, which means obtained data may have included unsuitable ones. But roughly speaking, the trend of changing the main factor of rail failures from rail welds to rail surface shellings can be identified. However fortu-

nately again, the strategy of improving track structure in Shinkansen was implemented since 1977, which was exchanging JIS 50T to JIS 60 rail to reduce the damage of ballast track suffered from impact loads. Hence, the damaged rails of JIS 50T were naturally changed under such a strategy. As a result, the problem of rail surface shellings was superficially settled down again. In a sense this process was very similar to the case of dark cracks, which means the mechanism of crack initiation was not clearly identified so that the effective strategy of mitigation was not obtained, but some strategies to improve other issues changed the situation of damaged rails and the problem of RCF defects was superficially settled down.

(4) Second stage of rail surface shelling problems in Shinkansen

The second Shinkansen line, San-yo Shinkansen, started to operate in 1972. After about 10 years since starting operation, the accumulated passing tonnages reached to 150 to 200MGT, so that the number of rail surface shellings was getting large. Also, the number of rail surface shellings was getting large in Tokaido Shinkansen after JIS 60 rail installation instead of JIS 50T rail similar to San-yo Shinkansen. Then the study group was newly established again in RTRI in 1985⁽⁶⁾. It investigated the history of rail surface shellings and the findings related to RCF defects of rails obtained so far were summarized. So that new research programmes including a large twin disc machine for rolling contact fatigue experiments was started. After 10 to 15 years, preventive grinding method was established under the programme for the time being and basically taking into account Shinkansen wheel rail interface condition.

3 MECHANISM OF CRACK INITIATION, PROPAGATION AND MITIGATION METHOD

(1) Mechanism of crack initiation and propagation

The mechanism of crack initiation and propagation has been studied for a long time around the world. In particular, above-mentioned study has not been carried out enough to understand it even if many findings about some other tribological area are taken into account. Also, some important material behaviour and/or parameters such as crack tip stress condition including residual stress distribution have to be understood to develop this research area. Considering such a status of research front, the author concentrated laboratory simulation using a large twin disc rolling contact machine taking into account the results of roughness contact stress analysis. However, both laboratory experiments and stress analysis for

roughness contact have some limitations. Considering such limitation as limited test arrangements and analytical conditions, some appropriate test arrangements and analytical conditions were selected. Also, some findings were obtained from grinding tests and track site monitoring continued for 5 years from 1980 to 1985 in Tokaido Shinkansen. With regard to grinding frequency, every 100 MGT was not enough at least so that the grinding frequency should be expected to be less than 100 MGT, which was considered to decide experimental arrangements and analytical conditions.

At that time, Shinkansen suffered from many squats caused mainly on the surface of as-rolled (not head hardened) rail installed in tangent tracks so that analytical conditions and experimental arrangements were discussed on the basis of as-rolled rail of JIS 60, tangent track, the running speed of 200km/h and the average slip ratio of 0.01, for the time being.

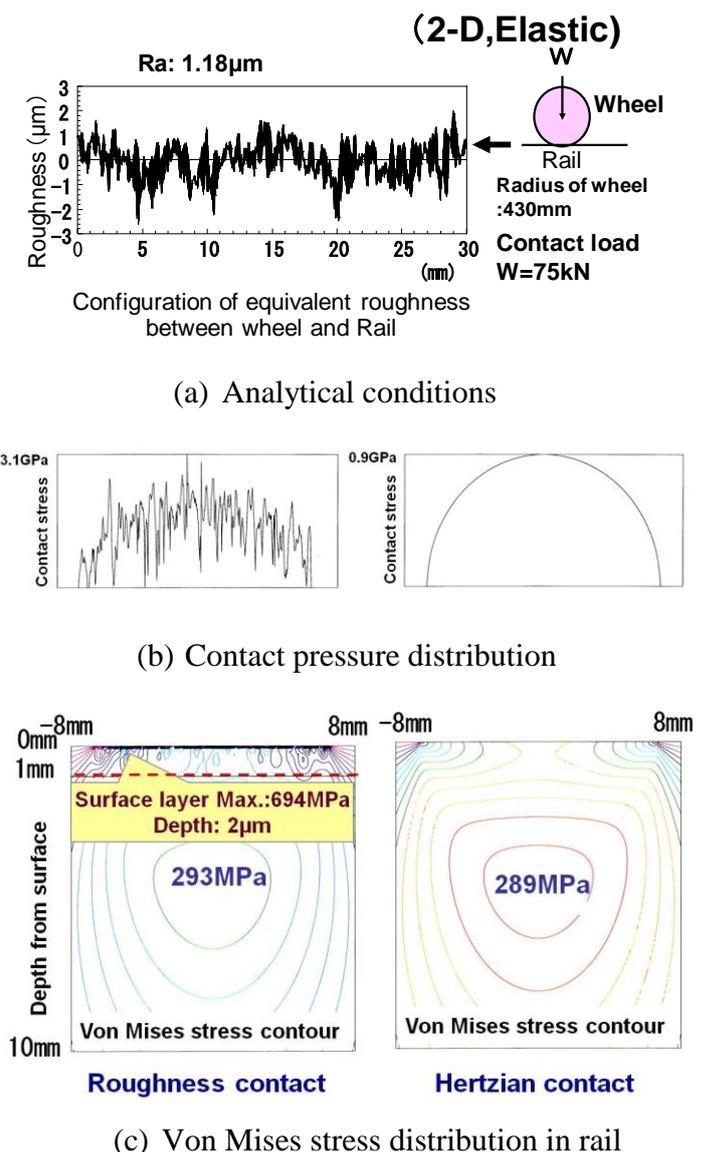


Fig. 9 The effect of roughness at wheel/rail contact interface on stress distribution

Fig. 9 shows the analytical conditions and its results with 2D roughness contact model constructed by Dr. Franklin and Prof. Kapoor under the collaboration between Sheffield Univ. and RTRI^(7),8).

In this figure, with regard to contact pressure between rail disc and wheel disc, roughness contact pressure is much larger than Hertzian contact pressure. Also, with regard to Von Mises stress distribution, the maximum of Von Mises stress is located at the surface or very thin layer of the surface under roughness contact and no such a high stress takes place under Hertzian contact. Since this 2D analytical model is elastic and two dimensional, the analytical results don't have agreement with actual wheel-rail contact stress condition but suggest some important tendency of stress distribution to roughly understand the damage of rail material. From the analytical results, the damage of rail should be very large at very thin surface layer, which can lead to the effect of preventive grinding.

Also, Fig. 10 shows the plastic deformation at the surface of actual rail material. This figure roughly indicates the adequacy of the 2D analytical model and the possibility of RCF crack initiation at the very thin layer.

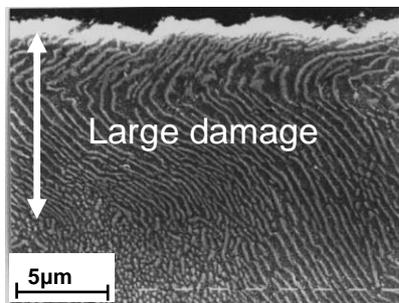


Fig. 10 Plastic deformation at the contact surface layer of actual rail material

Also, it suggests the possibility that effective grinding thickness should be more than 10 microns and less than 0.1mm of rail subsurface combining with analytical results of 2D roughness model. In addition, focusing on the slip plane of metallic crystal, it is identified that the direction of some specific slip planes is deformed to the same direction plastically under repeated loading⁹⁾. Considering above-mentioned analytical and practical information, the grinding thickness was set to be the only variable parameter and other parameters were constant under the grinding frequency of 50MGT in the experiments using a large twin disc machine. Before grinding ex-

periments, rolling fatigue experiments were carried out to investigate a certain suitable test arrangements for the test machine considering the difference of contact conditions between actual wheel/rail contact and wheel disc / rail disc contact for about more than 5 years¹⁰⁾.

(2) Preventive grinding

After the rolling contact fatigue experiments, the experimental arrangements were decided and the grinding experiments with a key parameter of grinding thickness had been continued for more than 5 years.

Fig. 11 shows the results of grinding experiments with the large twin disc machine¹¹⁾. In this figure, some regression curves were obtained to estimate the effect of grinding on RCF. Roughly speaking, 0.1mm of grinding thickness every 50 MGT has an appropriate effect of grinding to extend the service life of rail up to averagely 800MGT.

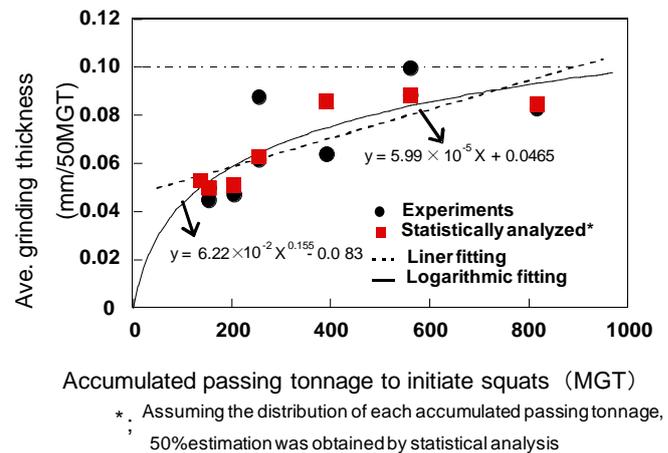


Fig. 11 The effect of preventive grinding on accumulated passing tonnages to initiate squats

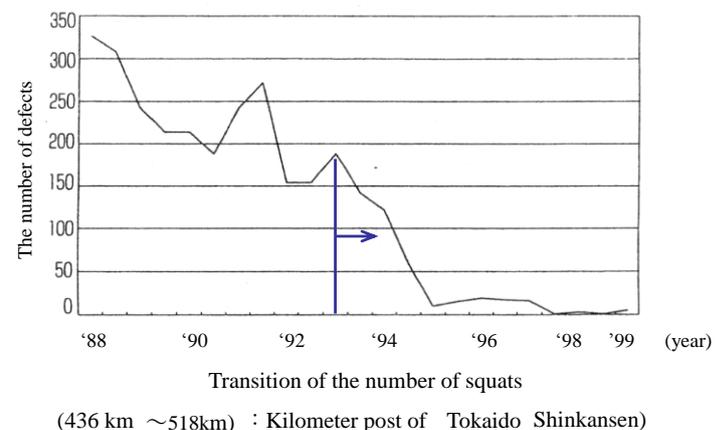


Fig. 12 The effect of preventive grinding on mitigating the initiation of RCF defects (after 1993, whole main line of Tokaido was covered with grinding operation)

The adequacy of this preventive grinding method, 0.1mm/every 50MGT was verified in the operation of Tokaido Shinkansen. Roughly speaking, all rails installed in the main line of Tokaido Shinkansen have been ground once a year, about 40 to 50 MGT of annual passing tonnages since 1993. Fig.12 shows the results of detecting rails in the monitoring section of Tokaido Shinkansen⁷⁾. In this figure, the number of defects dramatically decreased since regular preventive grinding started in 1993.

(3) Balance between wear and RCF

In advance of describing the balance between wear and RCF, some interesting research activity and sophisticated achievements in this research area obtained by European and/or other railways than Japanese ones. Almost all railways must have suffered from wear and RCF and have long history of theoretical and practical approach to get the best solution to mitigate wear and RCF. In particular, just before Hatfield accident, comprehensive and fundamental research project, Integrated study of rolling CONTACT fatigue (ICON)¹²⁾, was implemented as one of EU projects from 1997 to 2000 under the leadership of European Rail Research Institute (ERRI). A lot of very good achievements and findings were obtained, but unfortunately before such good deliverables had not been adopted yet, Hatfield accident took place in October, 2000. After the Hatfield accident, RCF was newly focused on to keep the running safety of vehicle. In addition, another EU project “ INNOvative TRACK system IINNOTRACK)¹³⁾” was organised and coordinated by UIC which involved 36 partners from 11 European countries including international railway organisations as well as rail research specialised universities and representatives from rail operators, infrastructure managers and railway track industry suppliers.

After the Hatfield accident, the whole life rail model and T-gamma model were established^{14),15)}. Fig. 13 shows the concept of T-gamma model. This model is based on friction energy and material strength. According to friction energy, balance between wear and RCF can be evaluated, which is very helpful to select material level and strategy of lubrication and/or grinding. I hope the meaning of damage function should be clearer, for example, RCF function is the rate of crack propagation or plastic deformation and wear function is wear rate and so on. Then the next research subject will be expected to define the damage function.

Also, one of achievements obtained from IINNOTRACK is that heat treated rail, head hardened rail, has great effect on mitigating crack propagation of head checks comparing with as-rolled rail. However, considering mitigating and/or preventing gauge

corner cracks, heat treated rail may not be always effective in mitigating gauge corner cracks.

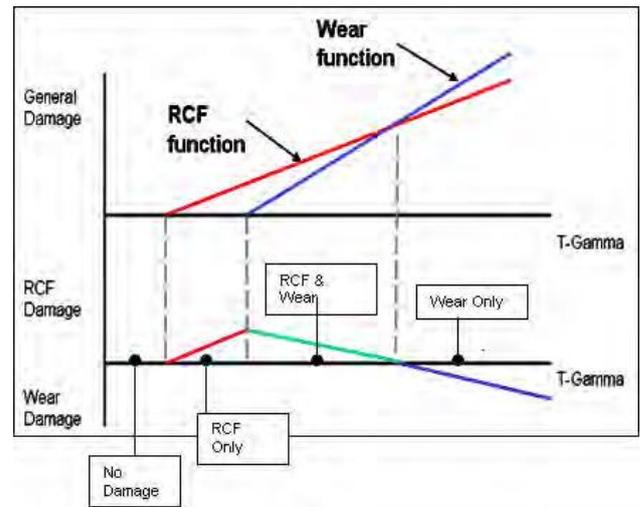


Fig. 13 The concept of T-gamma model describing the balance between wear and RCF

The relation between head checks and gauge corner cracks has not been clearly understood yet. As far as Japanese railways are concerned, gauge corner cracks are basically very close to squats, rail surface shellings called in Japan, so that grinding or wear is a key word to mitigate the initiation of gauge corner cracks¹⁶⁾.

Also, head checks can be generated by the balance between wear and fatigue, which means head checks must be one of RCF defects. Fig. 14 shows the some range of wear rate where head checks are likely to initiate even if the data are very limited.

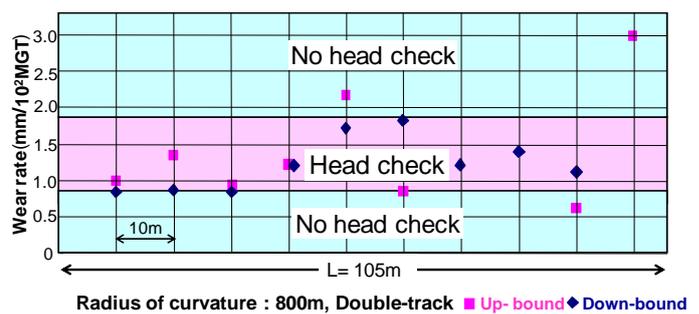


Fig. 14 The relation between wear rate and head checks (heat treated head hardened rails)

In the figure, very small amount of wear rate means damage is very less, too, middle range amount of wear rate means suitable balance between wear and RCF for head check initiation, and large amount of wear rate means fatigue damage is not accumulated and worn out.

Finally squat type RCF defects related to white etching layer must be described because this type of

defects has been posing a large problem in Japanese conventional narrow gauge tracks¹⁷⁾.

Also, some reports have been already published in other railways^{18),19)}. Fig. 15 shows typical squat type RCF defects of white etching layer. Fig. 16 shows microstructure of white etching layer.

The typical cause of forming white etching layer is friction heat generated by wheel sliding on rail. Some other causes, for example, large deformation, should surely have an effect on forming white etching layer.



Fig. 15 Squat type of RCF defects related to white etching layer

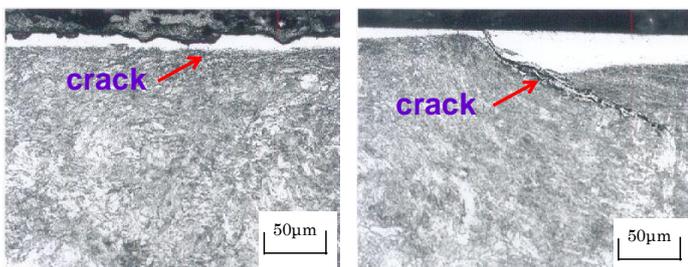


Fig. 16 Micro-structure of white etching layer

From the experience of Japanese railways, driving force and/or braking force interacting between wheel and rail, sliding occurs because of less adhesion coefficient than needed potential of friction and heat is generated to change pearlite to martensite from metallurgical point of view. Since Shinkansen's train operation is well controlled to smooth driving and braking much better than narrow gauge conventional train system, almost no report on white etching layer observed in Shinkansen tracks. Considering the mechanism of white etching layer, martensite, formation, it is not easy to prevent wheel-rail sliding perfectly. Considering the current status of this type of defects, early detection is very important to prevent crack initiation from the martensite layer and to grind off fine cracks if already. Some detec-

tion system may be promising to mitigate this type of defects.

In addition, bainitic steel rail was developed to prevent squats, rail surface shellings, by modifying material structure²⁰⁾. Basically the concept of Japanese bainitic steel rail is to prevent squat initiation based on the appropriate amount of wear, which means the wear resistance of bainitic steel is less than that of pearlitic steel but its hardness is larger than that of pearlitic steel to prevent large plastic deformation and/or to keep the configuration of rail for better running stability and ride comfort.

Finally considering the balance between wear and RCF, rail type and combination with wheel must be focused on because steel material, hardness and chemical composition and the interaction between rail and wheel have great influence on wear and RCF.

4 CONCLUDING REMARKS

This review describes rolling contact fatigue (RCF) defects of rails in Japanese railways and its mitigation strategies. The concept of mitigation strategy is balance between wear and RCF. The effect of grinding is the same as that of wear. Also, the purpose of Japanese bainitic steel rail is to obtain the suitable amount of wear to prevent the initiation of RCF crack. Furthermore, controlling wear amount is a key word to mitigate RCF defects with grinding and lubrication. In addition, it should be better to control vehicle/track interaction. Combination of vehicle/track dynamic interaction and wheel/rail tribology and collaboration of vehicle engineers and track engineers are should be encouraged to improve track maintenance strategy. Further collaboration of the two sectors, vehicle engineers and track engineers, will be expected to improve wheel/rail maintenance level from the aspects of quality and cost.

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