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On-site investigation and analysis of flaking damage leading to rail break

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ABSTRACT

In order to know the relationship between the occurrence of flaking leading to the rail breakage and wear of the rail, on-site investigations and analysis of the broken rail were carried out. As a result, it was found out that the occurrence rate of the flaking damage was high at gauge corner side of high rail in moderate curves with radius from 800 m to 1800 m. It was also found that the rail wear in the section where lubrication was applied was about a half of that in the section without lubrication. Moreover, it was found that flaking damage was generated on the running surface or in the close vicinity of the surface of rail head under the condition of repeated loading of shear and tangential forces caused by the rolling contact with wheels. It could be assumed that the balance between the wear and the accumulation of micro-strain or fatigue was a key to occur the flaking damage.

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1. Introduction

In recent years, the rolling contact fatigue damage at the gauge corner (hereinafter referred to as GC) side of high rail in moderate curves is considered as one of the issues that have to be avoided in Japan Railway. The types of damage that are mainly observed at GC of high rail are headcheck, GC cracking and flaking. They are shown in Figs. 1–3. A number of cracks generate side by side with a relatively narrow spacing in headcheck damage. Sometimes, removal of debris occurs if the cracks of headcheck bind to each other. GC cracking is generated mainly on the head hardened rail (HH340) laid in a curve with radius of 800 m or less. The crack frequently shows a lambda shape on the running surface occurring side by side with headcheck cracks. Meanwhile, flaking normally gives a pit with a size of several mm on the damaged surface and typically occurs under the condition of oil lubrication. These damages can be the origin of rolling noise and be a possible cause of rail break when they grow. Detection of these damages is not easy even by means of an ultrasonic rail flaw inspection car because they occur at GC side of rail where the observation by the incident ultrasonic wave from the running surface of rail is difficult. After an accident of derailment happened at a subway line in 2000 in Japan, rail grinding at GC has been restricted in order to restrain the climbing of wheel flange onto GC of rail. As an alternative action, rail replacement has been conducted spending a large amount of financial and laborious cost. So that, development of the effective countermeasures is very strongly anticipated.

On the contrary, investigations on headcheck damage have been preferentially and powerfully carried out in European countries after the Hatfield derailment accident in England in 2000 with lots of reports on headcheck damage and their countermeasures. As for headcheck, a series of studies have been made also in Japan by Takikawa and Iriya [1] on the countermeasures for headcheck from the rail material point of view using a rail/wheel rolling contact fatigue test machine. Meanwhile, about GC cracking, the authors are developing new rail material that is expected to have a high damage resistance as well as an improved wear resistance taking the balance between wear and fatigue of rail material into consideration.

On flaking damage, many occurrences have been reported [2] in recent years in the conventional lines in the metropolitan area where oil lubrication has been operated to high rail of curves as a countermeasure against the wear of both of rail and wheel. There had been no report on the rail break caused by the flaking damage in the light axle load railway with a very high density traffic within the area of Japan Railway Company. Unfortunately, a case of rail break was found recently that might be the first case caused by rolling contact fatigue associated with a surface delamination under oil lubrication. The phenomena of flaking damages have been observed and investigated for long period in the engineering field of gear and bearing [3] and also reported its occurrence in heavy haul railway rail [4]. There have not been the studies on the flaking under lubrication so far in Japan where the tribological contact conditions of rail and wheel, such as rail material, contact geometry and lubrication, are different from those employed in European and American railway companies. However, it is very important to know the influence of oil lubrication on the wear and fatigue of high rail in curves since the oil lubrication is becom-

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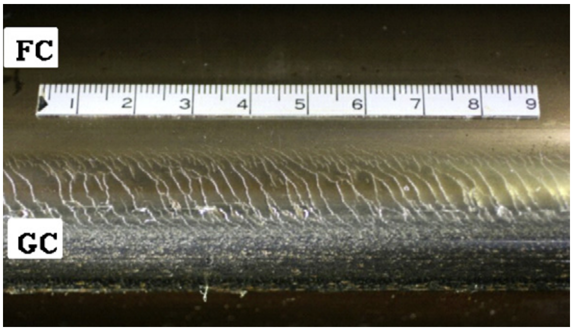

Fig. 1. Headcheck.

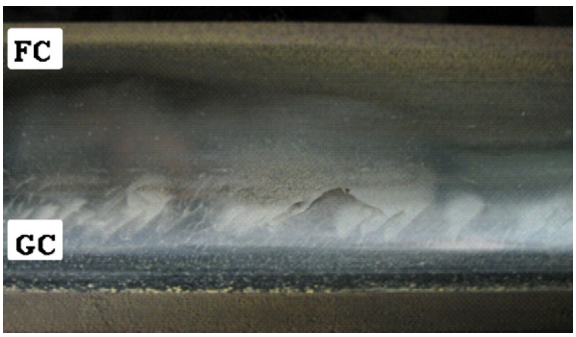

Fig. 2. Gauge corner cracking.

ing one of the normal maintenance operations in the metropolitan area.

The purpose of this study is to propose the effective countermeasure against the flaking damage under the condition of oil lubrication. As the first stage of the study, this report presents the results of some on-site investigations and analysis of the broken rail aiming at knowing the relationship between the occurrence of flaking and wear of the rail that is suffering from the damage.

2. On-site investigation

On-site investigations were carried out for the conventional line operated with oil lubrication in order to understand the condition of occurrence of flaking damage. At the sites for investigation, JIS 60 kg rail was laid. Especially in the curve with radius of less than 800 m, head hardened rail (HH340) was used for high rail. The vehicle with the modified arc tread profile wheel was passing through the site. The other specifications were; axle load of 6.5 ton, annual passing tonnage of 44 million gross tonnage (hereinafter given by MGT) and maximum velocity of 90 km/h. For the lubrication, mineral oil was used. It was fed to GC side of high rail of the curve in question by an on-board oil supplier.

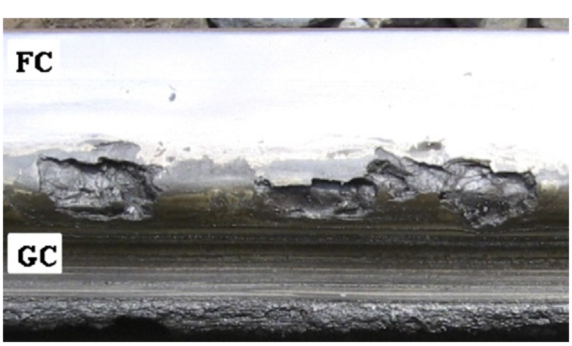

Fig. 3. Flaking.

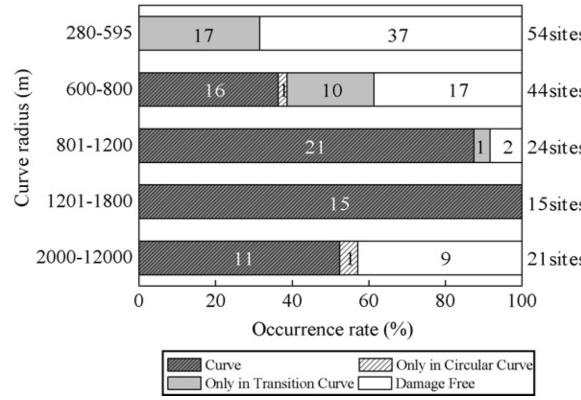

Fig. 4. Relationship between curve radius and flaking occurrence rate.

Fig. 4 shows the relationship between curve radius and flaking occurrence rate. A site was counted into the flaking occurrence site even if only a part of the curve in question was suffered from the damage. Of the 158 investigation sites, the flaking damages were found at 93 sites that were about 60% of the sites. It was recognized that the occurrence rate was higher at GC side of high rail in moderate curves with radius from 800 m to 1800 m. There was a site where the flaking was found only after 8 months (28.8 MGT) from the latest rail replacement. On the contrary, no flaking damage was observed in a line where no lubrication had been operated even though the line was parallel to the line for investigation.

Considering the fact in mind, the rail wear was measured at two sites. The two sites were similar to each other in the track and vehicle conditions except for the lubrication. That is, oil lubrication was performed on one site and not performed on the other site. The relationship between curve radius and rail wear per 100 MGT is shown in Fig. 5. It was confirmed that the rail wear at the site with lubrication was about a half of that at the site without lubrication.

These field observations showed that the wear of rail was significantly suppressed by the oil lubrication. As a result, it could be considered that the rolling contact fatigue accumulated especially at the moderate curves with radius from 800 m to 1800 m where the pressing load from the passing wheel was relatively low. Such accumulation of fatigue could be thought of as a possible cause of flaking damage.

3. Material analysis of broken rail

Analysis of a sample rail used in service and broken because of flaking was carried out from the metallographic point of view. The

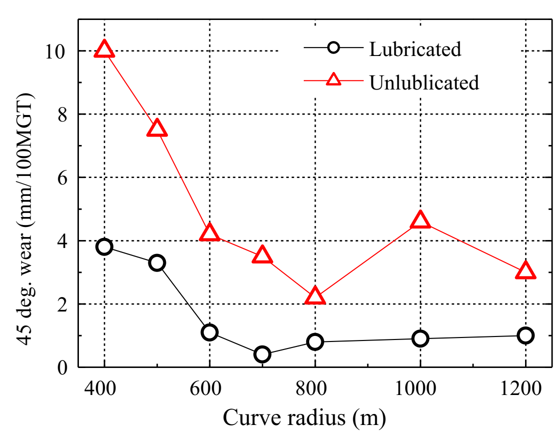

Fig. 5. Relationship between curve radius and rail wear per 100 MGT.

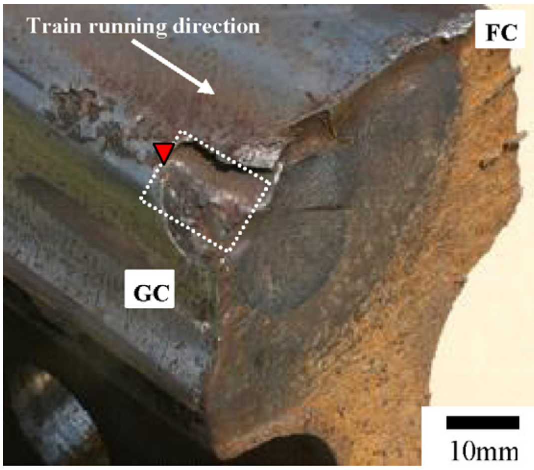

Fig. 6. Appearance of the flaking damage.

Fig. 8. Fracture surface of branched transverse crack.

specimen was a 60 kg normal rail (as rolled standard carbon rail) laid as high rail in a curve with radius of 1000 m. The rail had been used in service for 9 years and 8 months with 410 MGT until the brake.

3.1. Fracture surface

Fig. 6 shows the appearance of the rail in question. Delaminations were observed on GC side at the position with the smallest radius of curvature of rail head. Headcheck occurred on the running surface between the delamination and the rail center. Lubrication oil adhered uniformly on the surface of side wear and the rolling contact band on the running surface.

The fracture surface around the origin of the crack is shown in Fig. 7. This was the area surrounded with a rectangle box in Fig. 6 observed from an upper point obliquely downward. Though details of the fractographic pattern on the fracture surface were lost by repeated contacts between surfaces of the crack, it was possible to estimate the fracture type and the propagation path by visual observation of the remaining macroscopic fractographic characteristics. The propagation path of the crack was estimated through the visual observation. A point on GC side of rail shown with red arrow in Fig. 7 could be regarded as the origin of the crack. At the point, the radius of curvature was smallest in the geometrical shape of 60 kg rail. In the initial stage, cracks occurred and propagated toward the train running direction keeping their fracture surfaces almost parallel to the running surface and the side surface of rail. The cracks branched in the succeeding stage. The crack parallel to the side surface propagated continuously in the subsurface of GC and resulted in the delaminations. On the other hand, the crack parallel to the running surface propagated and branched downwardly to the bottom forming the transverse crack that was the cause of the rail break.

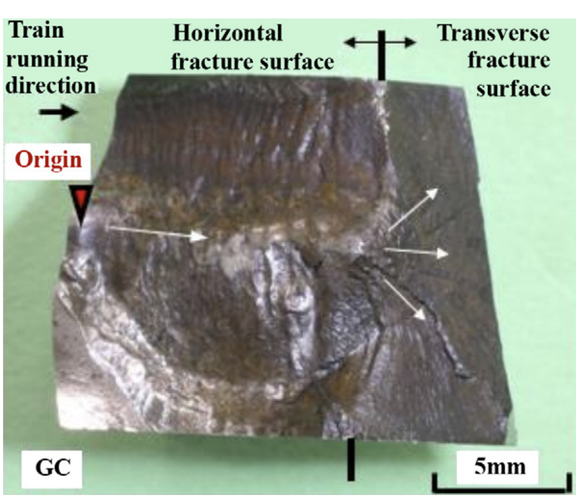

Fig. 7. Fracture surface around the origin of crack.

Fig. 8 shows the transverse fracture surface. The brown–black area was regarded as a fatigue fracture surface. On the oval area with relatively smooth surface near GC, beach-mark that was a typical pattern of the fatigue fracture surface could be identified. Based on the evidence, it was considered that the fatigue crack propagated moderately in this area. The area that was surrounding the oval fatigue fracture surface seemed less smooth than the inner oval area. It meant that the propagation rate gradually increased with the growth of the fatigue crack. The crack propagated rapidly through the brown area that was surrounding the brown–black area giving a very rough fracture surface. Taking the surface patterns described above into consideration, after the branching from the horizontal crack, the transverse crack propagated very slowly as a fatigue crack at the first stage, then it extended continuously increasing the propagation rate gradually, finally the crack propagated rapidly to the bottom as a brittle crack breaking the rail.

3.2. Wear and hardness of rolling contact surface

It was estimated based on the observation of the fracture surface that the origin of the flaking crack was at the surface or in the close vicinity of the surface of the running surface of the rail. Here, in order to characterize the surface of the broken rail, the measurement of wear and hardness of the rail head were carried out.

Fig. 9 shows the wear profile of the rail head of the broken rail measured at the train approaching side. The wear amount was defined as the distance between the two points. One was the point on the measured wear profile and the other was the point on the standard profile of a new rail. The distance was measured along the normal line to the worn surface of the broken rail after superposing the profiles of the worn rail and new rail making the side and neck of the rail head of both rails overlap to each other. Observing the result, it was possible to confirm that the wear amount was high on GC side while it gradually decreased when approaching to FC side. The area where the flaking damage occurred was located at the boundary between the area showing relatively uniform wear amount (running surface) and the area showing high wear amount

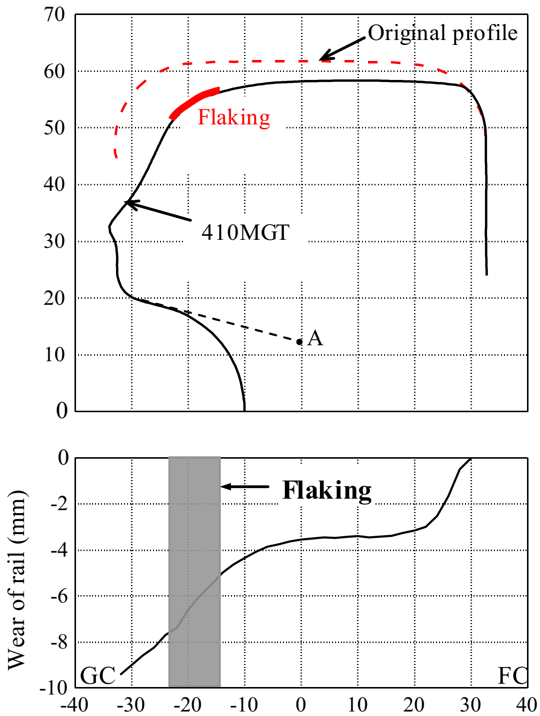

Fig. 9. Wear of rail.

(side surface), 14–23 mm from the center toward GC side. The wear amount was 5.0–7.5 mm at the boundary area where the flaking occurred.

The measurement of the Vickers hardness of the running surface of the rail was performed. The specimen was taken from the approaching side of the broken rail. The surface of the specimen for the measurement was finished with chrome oxide abrasive treatment, then provided for the measurement by means of Vickers hardness tester. The hardness was measured at every 1 mm from the center to both FC side and GC side. The hardness distribution is shown in Fig. 10. The hardness of the flaking rail was higher than that of the new rail (HV about 270) at each point of measurement. The hardness was almost same at the area from FC side to the center of the rail. When the point of measurement approached to GC side, the hardness became higher. The highest hardness appeared at around 10–20 mm to GC side from the center. It was considered that the area where the flaking occurred was suffered from very hard work given by the rolling wheel of the trains.

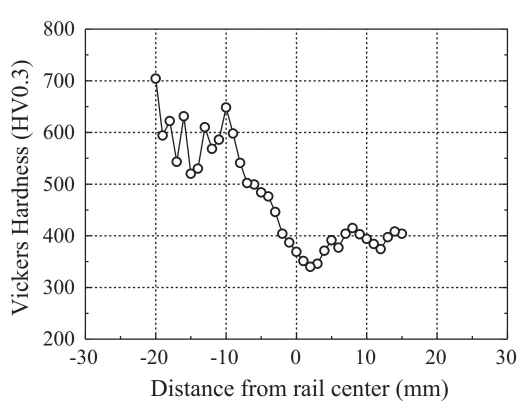

Fig. 10. Hardness distribution along the traverse direction on rail running surface.

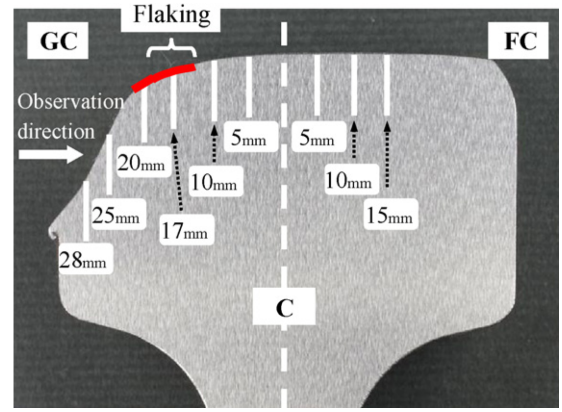

Fig. 11. Metallographic observation point.

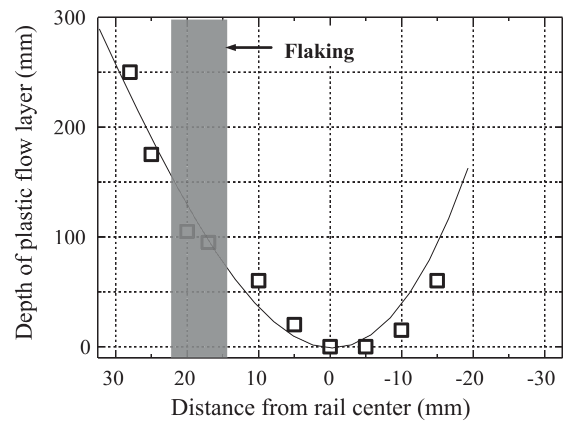

Fig. 12. Distribution of depth of plastic flow layer.

3.3. Metallographic observation of running surface layer

Metallographic observation of the running surface layer was performed in order to evaluate the state of plastic flow caused by the repeated rolling contact with wheel. As shown in Fig. 11, the metallographic structure was observed at every 5 mm from the center to both of FC and GC sides. The observation of the running surface layer was made on sections. The sections were taken from the head of the rail keeping the observation surface parallel to the rail longitudinal direction. The observation was carried out from GC side. The sections for metallographic observation were finished with a standard process such as etching of a mirror polished surface with Nital (3% nitric acid with 97% alcohol). The magnification of 200-folds and 500-folds were employed for the observation.

Fig. 12 shows the depth of the plastic flow layer at each observation point. The depth of the plastic flow layer was evaluated on the photographs of metallographic structure of each observation point. Although the existence of the plastic flow layer was verified at all observation point except the center, the layer reached deeper with the increase of the distance of the observation point from the center. The layer was deeper at GC side than FC side.

The direction of the plastic flow was opposite from the train direction at the observation points on GC side. On the other hand, the direction of the flow was same to the train direction at the points on FC side. In Fig. 13, examples of the observation of the plastic flow in the metallographic structure of the rail center, the position of the origin of the flaking (17 mm to GC side from the rail center), and a position near FC side (15 mm to FC side from the rail center) were given.

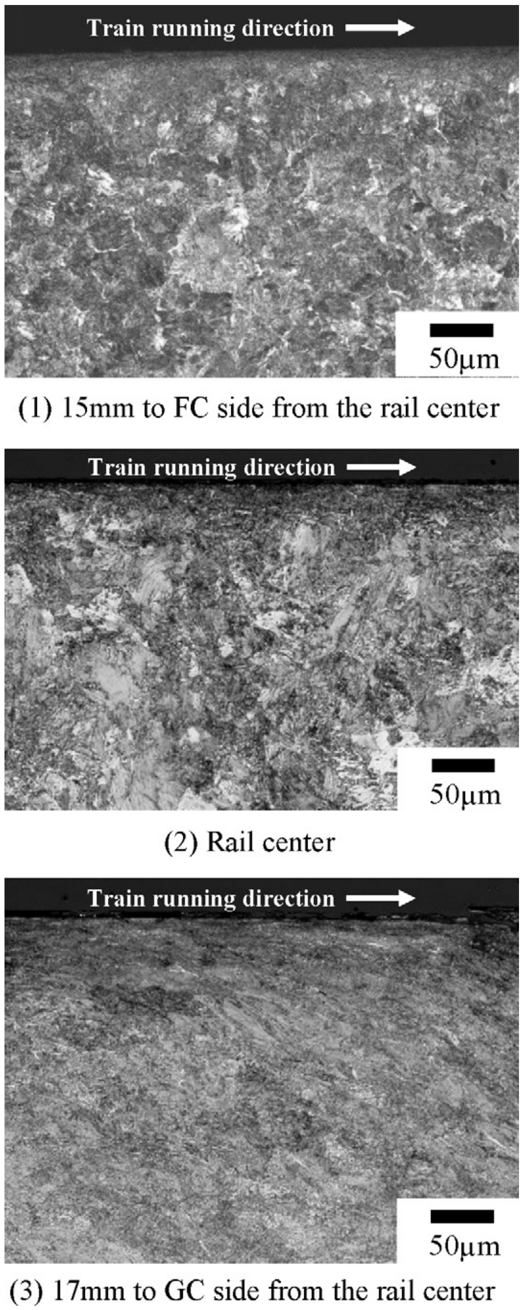

Fig. 13. Metallographic structure of plastic flow.

Comparison of the plastic flow directions at the observation points from GC side to FC side showed the inversion of the flow direction that was generally observed in the rail used at tangent track. As mentioned above, the depth of the plastic flow layer increased gradually from the rail center toward both of FC and GC sides. Large value of the depth of the flow layer meant that the tangential force acting on the point in question was large. Taking the depth of the flow layer into account, it was possible to think that the condition for the generation of the flaking damage crack could be prepared by the repeated rolling contact of wheel at GC side.

3.4. Hardness distribution with depth

Metallographic observation of the plastic flow layer showed that a strong tangential force acted at the origin of the flaking near GC side (17 mm to GC side from the rail center). In order to estimate the strain accumulated at the point by the repeated rolling contact of wheel, the hardness distribution measurement was carried out along the depth direction into the rail head on the section. A similar measurement was carried out at the same time at the rail center position. A Vickers hardness tester was used for the hardness measurement.

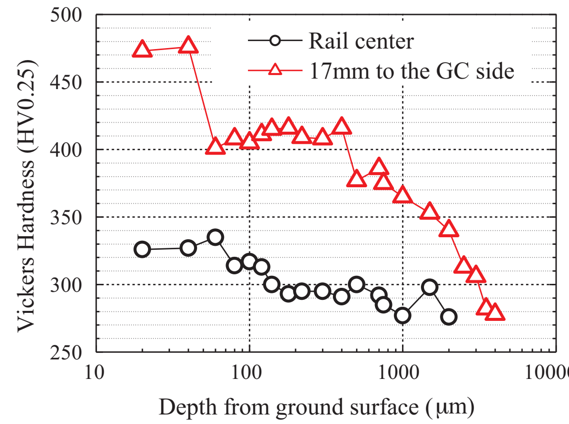

Fig. 14. Hardness distribution on section.

Fig. 14 shows the result of the measurement. At the position of the occurrence of the flaking, Vickers hardness was as high as 470 HV from the surface to a depth of 60 μm. Very strong plastic flow structure was detected in the metallographic observation at this point. The Vickers hardness decreased gradually from 470 HV at the depth of around 60 μm to 400 HV at 400 μm in the rail head. Then, the Vickers hardness decreased moderately to the normal value of the new rail material of 270 HV. The distribution of the micro-strain was presumably generated by the rolling contact with the wheel and accumulated in the subsurface layer of rail head material. Based on the measurement of Vickers hardness, the area where the hardness was higher than the normal value of the new rail material reached to the depth of 3000 μm. It could be considered that very strong tangential force acted on the area.

Flaking damage was observed at the area that was characterized by the very high hardness and the formation of the plastic flow layer. Taking these results into consideration, it was thought that the initial cracks were generated on the running surface or in the close vicinity of the surface under the condition of repeated shear and tangential forces caused by the rolling contact with wheels. Since the flaking damage appeared at the boundary between the areas characterized with and without remarkable wear amount, it could be assumed that the balance between the wear and the accumulation of micro-strain or fatigue was a key to occur the flaking damage. If the accumulation of fatigue was superior to the wear, the flaking might occur.

4. Conclusions

In this study, occurrence of the flaking damage and its relationship with the wear of rail under oil lubrication operation was investigated with the following results.

1. Higher rate of occurrence of the flaking damage was confirmed at GC side of high rail in moderate curves with radius from 800 m to 1800 m. The shortest period from the latest rail replacement to the generation of flaking in the field was only 8 months (28.8 MGT). It was also confirmed that the rail wear at the site

with lubrication was about a half of that at the site without lubrication.

2. Flaking damage occurred on the running surface or in the close vicinity of the surface under the condition of repeated loading of shear and tangential forces caused by the rolling contact with wheels. It could be assumed that the balance between the wear and the accumulation of micro-strain or fatigue was a key to occur the flaking damage.

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