Technical Report

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Development of Long-Life Rails for Overseas Freight Railways

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Abstract

To improve wear resistance and surface damage resistance of overseas freight railways, the authors studied and performed an increase of volume fraction of the cementite phase (carbon content) in the pearlite structure as an alternative to a conventional method of increasing the hardness thereof. As a result, the work-hardening rate of rolling contact surface was increased, leading to increased hardness to thereby significantly improve wear resistance and surface damage resistance. By using these effects, Nippon Steel & Sumitomo Metal Corporation have developed hyper-eutectoid steel rails. These rails have excellent properties in actual tracks and have contributed to the improvement of the service life of freight railways.

1. Introduction

Railways play an important role in both Japan and other countries as facilities for mass transportation with high punctuality and safety. Recently, in light of environmental issues such as global warming and air pollution, railways are being reevaluated as a means of intercity passenger transportation that emits less CO_2 and exhaust gas. Furthermore, due to its excellent transportation efficiency, developing countries and countries favored with natural resources are promoting the construction of new railways as a means for transportation of both passengers and natural resources. Thus, railways continue to play an important role as a pillar of transportation even today.

Railways can be divided into two kinds: overseas freight railways, handling mainly ore and the like, and railways for passengers, like bullet trains. Along with the development of natural resources and the development of economy, heavy hauling in freight railways (**Photo 1**), reduced train car weight, and increased speed in passenger railways are being promoted in order to improve transportation efficiency. In railway transportation in such countries as North America and Australia in particular, the wheel load (weight loaded on a wheel) has doubled to 20 tons in just the past 25 years,[1] as shown in **Fig. 1**. In conjunction with changes in environment surrounding railroad tracks, the environment surrounding rails, which constitute a part of railroad system, is growing harsh. To cope with increasing wear and damage to rails caused by higher loads and higher speeds, the development of rails with excellent durability and reliability is desired, in order to improve economic efficiency.

Photo 1 Example of increase of superimposed load on an overseas freight railway

Given these changes in usage, the Nippon Steel & Sumitomo Metal Corporation has developed[2-6] and put into practical use hyper-eutectoid steel rails (HE RAIL®) in order to improve wear resistance and surface damage resistance. These rails are characterized by the application of effect of increased hardness of a rolling contact surface caused by the promotion of work-hardening of contact with train wheel increasing of carbon content of their steel.

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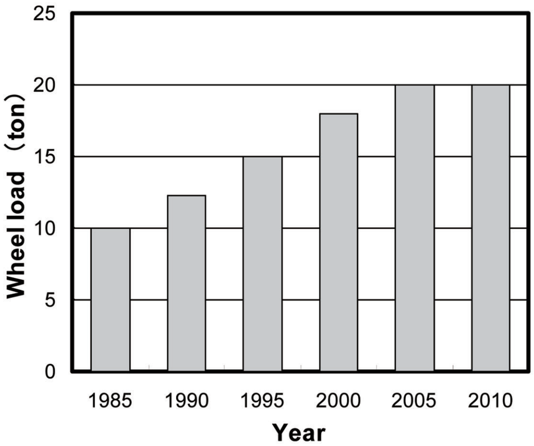

Fig. 1 Change of wheel load in an overseas freight railway

This article introduces the results of a laboratory-based study on hyper-eutectoid pearlite steel, and describes the characteristics of the hyper-eutectoid steel rails so developed.

2. Technical Issues in Overseas Freight Railways

The major characteristics demanded for railway rails in order to support railroad cars as a structural member are rigidity, strength and weldability. Furthermore, as a member for supporting travelling cars, suppression and/or prevention of wear and surface damage at the rail head surface (which the wheel contacts) is considered necessary.

Particularly in overseas freight railways, which handle natural resources such as iron ore, coal, and grains, wheel loads are large, as stated previously, and the contact pressure at the rail head (the rolling contact surface) is high. Increased wear and the occurrence of plastic-deformation-caused surface damage such as flaking becomes evident, as shown in **Photo 2**,[6] due to these large loads. Wear and damage of these kinds are the major factors that determine the service life of rails, and therefore, improvement of wear resistance and surface damage resistance is the most important technical issue in prolonging rail life.

3. Development of Hyper-eutectoid Steel Rails

3.1 Improvement of wear resistance

Conventionally, increasing the hardness of the steels used has been considered an effective means for improving the wear resistance of rails.[7-9] In this study, in order to improve wear resistance further, the authors have studied the control of the microstructure and the amount of carbide in the steels in addition to control of the hardness.

3.1.1 Control of the microstructure

The influence of the microstructure and the amount of carbide on wear resistance in high carbon steel was studied. A two-cylinder rolling contact wear test was carried out for two steels; one with 0.8 mass% carbon and another with 1.2 mass% carbon. In order to produce test pieces of different microstructures, the test pieces were heat-treated in prescribed processes.[10] **Photo 3** shows the microstructure and hardness of the respective test pieces. The microstructures of the test pieces created were pearlite steel (0.8 mass% C) consisting of a lamellar structure of hard carbide (cementite: Fe_3C) and soft ferrite (Fe); tempered martensite steel with a structure of carbide dispersed in ferrite (0.8 mass% C); and spheroidal carbide steel with a high volume fraction of carbide (1.2 mass% C). By controlling the heat-treatment condition, the hardness of the respective steels was controlled to be within HV 284-306.

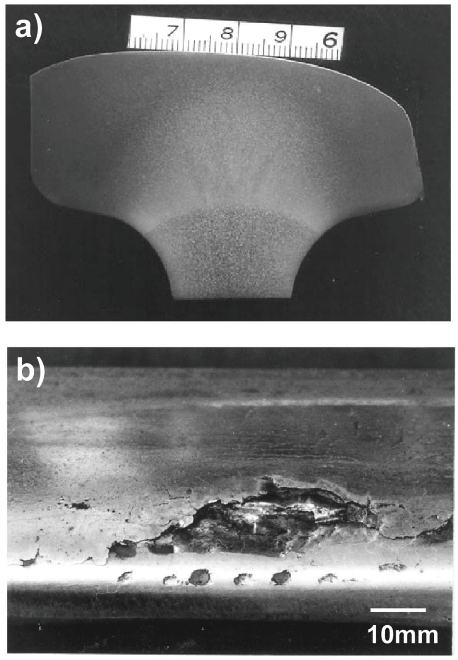

Photo 2 Examples of wear and damage in overseas freight railways
a) Wear, b) Flaking (surface damage)

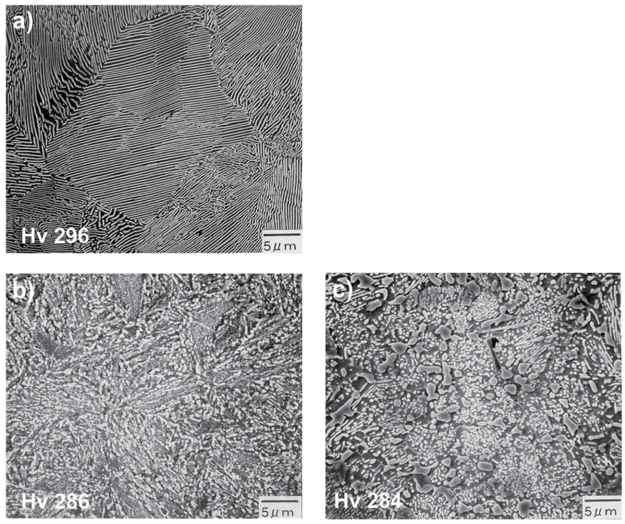

Photo 3 Microstructures of high-carbon steels
a) Pearlite steel, b) Tempered martensite steel, c) Spheroidal carbide steel

Figure 2 shows the relationship between number of rolling cycles and the amount of wear in the high-carbon steels. Comparison of the amount of wear of pearlite steel with the tempered martensite steel shows that the pearlite steel is remarkably less worn than the tempered martensite steel. On the other hand, the spheroidal carbide steel with the increased volume fraction of hard carbide is more worn than either the pearlite steel or the tempered martensite steel, both of which have a lower carbon (carbide) content.

Figure 3 shows the relationship between the number of rolling contact cycles and the post-test rolling contact surface hardness of

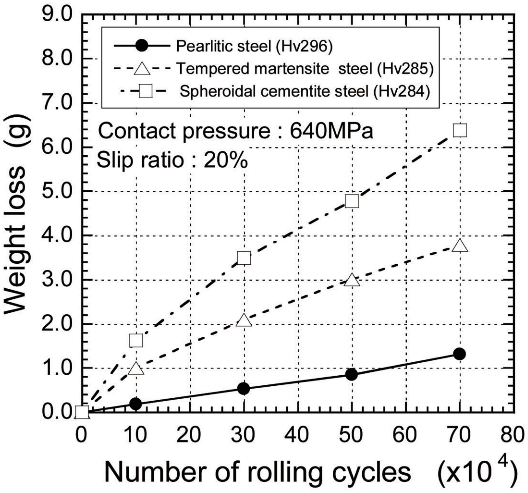

Fig. 2 Relationship between the number of rolling cycles and weight loss in the high-carbon steels

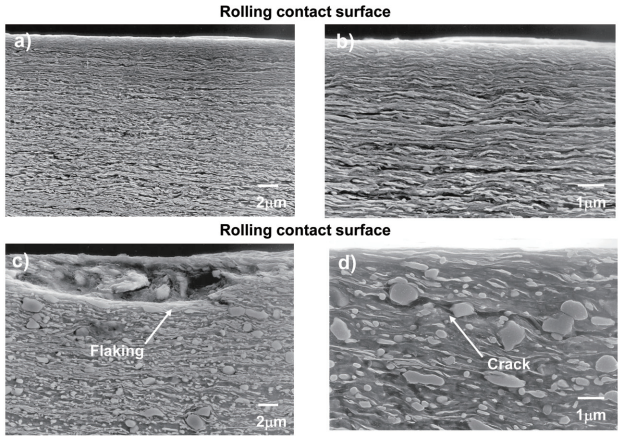

Photo 4 Cross-sectional SEM images of test specimens directly under the rolling contact surface after 700,000 cycles
a) Pearlite steel, b) Pearlite steel at high magnification, c) Spheroidal carbide steel, d) Spheroidal carbide steel at high magnification

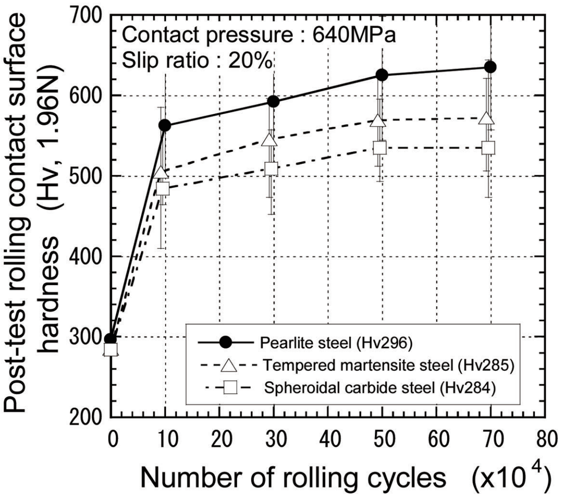

Fig. 3 Relationship between the number of rolling contact cycle and post-test hardness in the high-carbon steels

high-carbon steels. Beyond a certain number of cycles, the hardness of a rolling contact surface of pearlite steel becomes higher than that of spheroidal carbide steel and tempered martensite steel. Similarly to the case of wear, the hardness of a rolling contact surface shows good correlation with the microstructure. From these results, it was confirmed that wear characteristics are greatly influenced by the microstructure. Pearlite steel having a lamellar structure consisting of cementite and ferrite has a higher hardness of the rolling contact surface and has the highest wear resistance.

Photo 4 shows cross-sectional SEM images of pearlite steel and spheroidal carbide steel directly under the rolling contact surface after 700,000 cycles. In the pearlite steel having a lamellar structure consisting of hard cementite and soft ferrite, the lamellar structure is refined and laminated in the direction of plastic flow. In the spheroidal steel where carbide is dispersed in ferrite, a trace of exfoliation with a maximum depth about 10 μm is observed on the rolling contact surface. Furthermore, directly under the rolling contact surface, the formation of a crack is observed, which is considered to have propagated along a boundary between matrix ferrite and cementite.

From the above observations, it is considered that the increase in wear resistance of pearlite steel is realized by the lamellar structure, which is maintained and then refined on the rolling contact surface, thereby increasing the hardness of the rolling contact surface and suppressing the occurrence of the microscopic exfoliation that is caused by plastic deformation.[10)]

3.1.2 Utilization of carbide in pearlite structure

In order to improve the wear resistance of pearlite steel, an increase in the volume fraction of cementite in a lamellar structure, or in other words, an increase in the carbon content, was studied. A two-cylinder type rolling contact wear test was conducted using test pieces of pearlite steel with carbon content varied in the range of 0.8-1.0 mass% (Hardness: HV 385-395, lamellar spacing: 80-90 nm).

Figure 4 shows the relationship between the number of rolling contact cycles and the amount of wear, and **Fig. 5** shows the relationship between the number of rolling contact cycles and the post-test rolling contact surface hardness. When the number of rolling cycles exceeds a certain threshold, the amount of wear decreases as the carbon content in the steel increases. At the same time, the hardness of a rolling contact surface increases along with the increases in carbon content. This means, in pearlite steel in particular, that when the volume fraction of cementite is increased, the hardness of the rolling contact surface increases, and as a result, the development of wear of the rolling contact surface is suppressed, and wear resistance is improved.

In order to clarify the effect of the increase of carbon content on the increase of hardness of a rolling contact surface, attention was paid to the difference between the pre-test rolling contact surface hardness and the post-test rolling contact surface hardness of the test piece. The ratio of the increase of the hardness after the rolling contact wear test to the pre-test hardness is called the work hardening ratio (%) of a rolling contact surface, and is defined by expression (1). The work hardening ratio of the rolling contact surface of the test piece was figured respect to the carbon content to find the relationship between the two.

The work hardening ratio of a rolling contact surface (%) = {(Post-test rolling contact surface hardness − pre-test hardness)/pre-

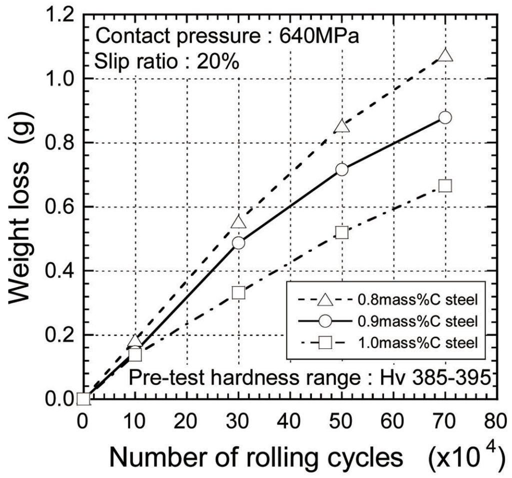

Fig. 4 Relationship between the number of rolling contact cycle and weight loss of the pearlite steels

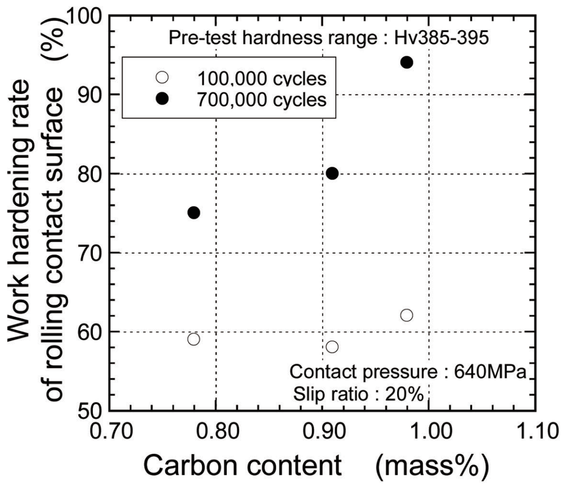

Fig. 6 Relationship between the carbon content and work-hardening rate of a rolling contact surface with respect to the pearlite steels

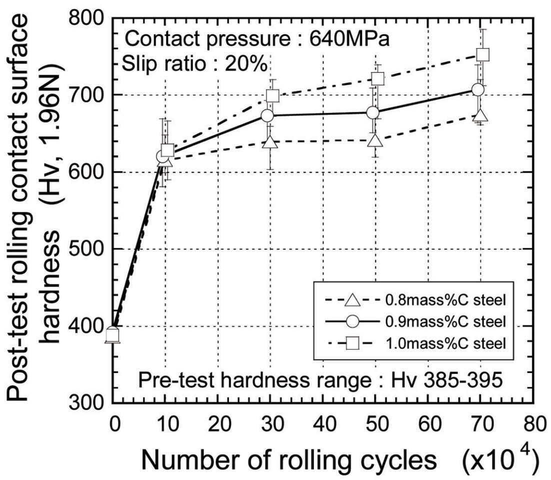

Fig. 5 Relationship between the number of rolling contact cycle and post-test hardness of the pearlite steels

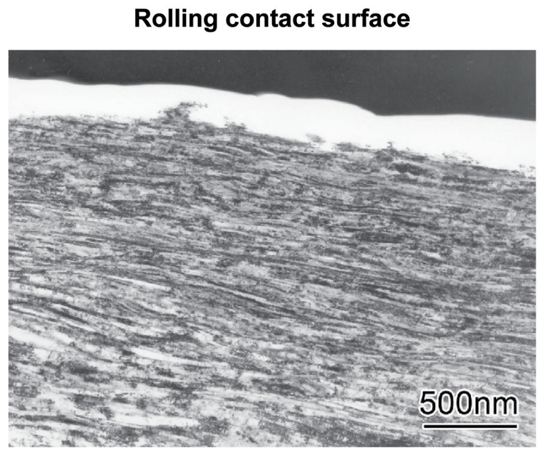

Photo 5 TEM image of the cross-sectional bright field directly under a rolling contact surface after 700,000 cycles

test hardness} × 100, where all values of hardness are given in Vickers hardness (HV).

Figure 6 shows the relationship between the carbon content of the steel and the work-hardening ratio of the rolling contact surface at 100,000 cycles and at 700,000 cycles. At 100,000 cycles, no noticeable relation is observed between the carbon content and the work-hardening ratio. However, at 700,000 cycles, an increase in the work-hardening ratio is noticed as the carbon content increases.

For the purpose of clarifying the mechanism of the increasing work-hardening ratio, the structural change directly under the rolling contact surface was investigated.

Photo 5 shows the TEM image at 700,000 cycles of the cross-sectional thin film structure directly under a rolling contact surface of a test piece containing 1.0 mass% of carbon. It is observed that, directly under the rolling contact surface, the pearlite lamellar structure is refined in the direction of plastic flow, and macroscopically, the cementite phase still exists.[11,12)]

Figure 7 shows the result of an analysis of the test piece directly under the rolling contact surface with a three-dimensional atom

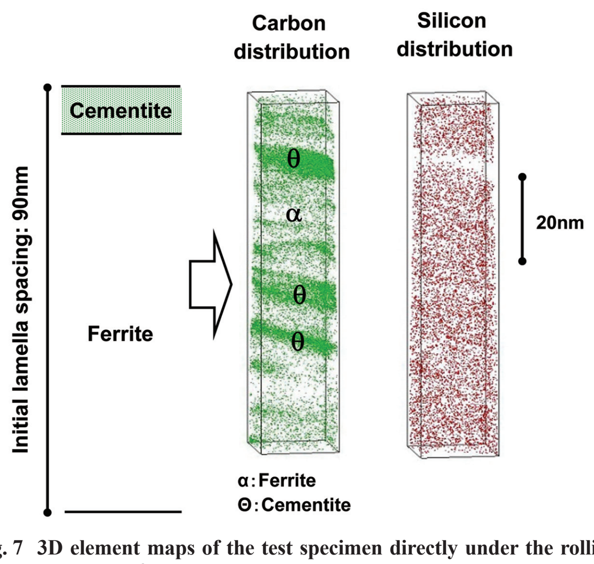

Fig. 7 3D element maps of the test specimen directly under the rolling contact surface probe (3D-AP) at 700,000 cycles. Judging from the presumed existence of a cementite phase, based on the concentration distribution of carbon and silicon, it is noticed that the lamellar spacing directly under the rolling contact surface is reduced from 90 nm in the initial state to about 10-30 nm, and the cementite layer is also becoming very thin-film-like.[11,12]

Figure 8 shows the distribution of concentrations of carbon atoms in the section where the 3D-AP analysis was conducted. Observation of the carbon distribution in detail indicates that carbon is not only concentrated in the thin-film-like cementite phase, but also, although partially, distributed broadly in the ferrite phase.[11]

As the result of further investigation of the structure, the tendency for matrix ferrite to be refined and further refined to fine grain sizes of nanometer-order, along with an increase of carbon content,[13,14] is confirmed directly under the rolling contact surface.

Figure 9 shows schematically the structural change of pearlite steel directly under the rolling contact surface. It is noted that shear deformation caused by a strong force in tangential direction, has mainly taken place on directly under the rolling contact surface of the test piece. As a result, several things have taken place, including the refining of the lamellar structure, the refining of the matrix ferrite phase, and the partial dissolution of the lamellar cementite phase and solid solution of carbon into ferrite matrix. These are confirmed by the results from test pieces exposed to severe plastic deformation, such as in a mechanical milling experiment.[15] Among these, the phenomena of hardness of the rolling contact surface increasing along with the increase of carbon content of steel is attributed to the increase of the volume fraction of the hard cementite phase. This increase promotes the refining of matrix ferrite and the solid solution of carbon into matrix ferrite, thereby promoting work-hardening of the rolling contact surface.[13]

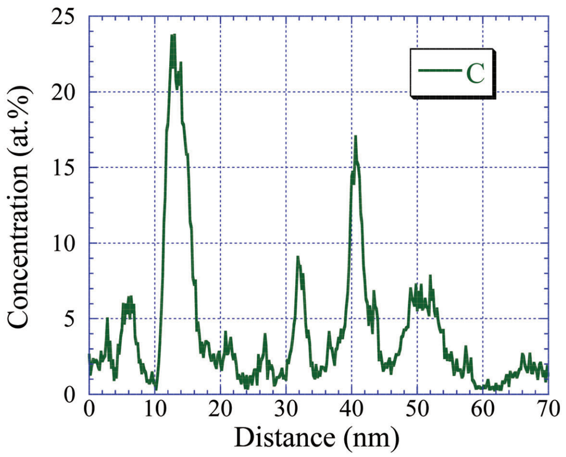

Fig. 8 Concentration profile of a carbon atom in the test specimen directly under the rolling contact surface

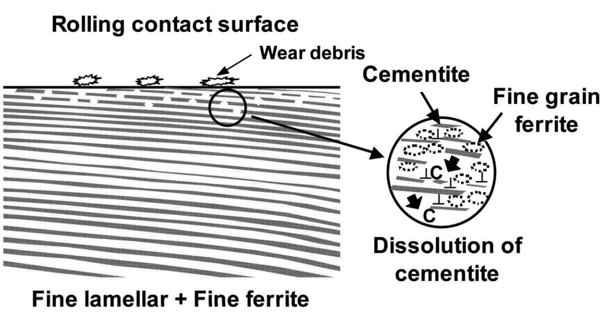

Fig. 9 Structural change of pearlite steel directly under the rolling contact surface

3.2 Improvement of surface damage resistance

Increasing hardness of steels was considered as an effective means for improving rail surface damage resistance, just as it is for improving wear resistance.[7,8] In this study, in order to further improve surface damage resistance, the promotion of work-hardening in pearlite steel by increasing carbon content was studied. The surface damage resistance was evaluated for two pearlite steels (Hardness: HV400), one with a carbon content of 0.8 mass%, and another of 1.0 mass%, using a two-cylinder rolling contact surface damage test machine (200 mm diameter), simulating the actual rail/wheel dimension in a 1/4-scale model.

Photo 6 shows the rolling contact surface appearance after a test (after liquid dye penetrant inspection). Cracks start at the corner of the rail (G.C.: Gauge Corner) which the wheel flange contacts. The quantity of cracks so generated is smaller in steel with higher carbon content. **Photo 7** shows crack propagation behavior directly under the rolling contact surface after the test. Crack damage induced by plastic deformation takes place around the G.C. When the relationship between the carbon content and crack damage is observed, it is found that region of crack propagation becomes smaller as the carbon content increases, and therefore, improvement of surface damage resistance is confirmed.[11]

In order to clarify the mechanism of improvement of surface damage resistance, the change of hardness directly under the rolling contact surface was investigated.

Figure 10 shows the distribution of hardness of a cracked portion. Though hardness values vary depending upon the formation of cracks, a trend of increase of hardness along with increase of carbon content is confirmed in the cracked region.[11]

From above result, improvement in surface damage resistance of a higher carbon content steel is, similarly to the case of wear, considered to be owing mainly to work-hardening of the rolling contact surface promoted by the increase of carbon content. Hereafter, the mechanism will be studied in more detail from the viewpoint of oc-

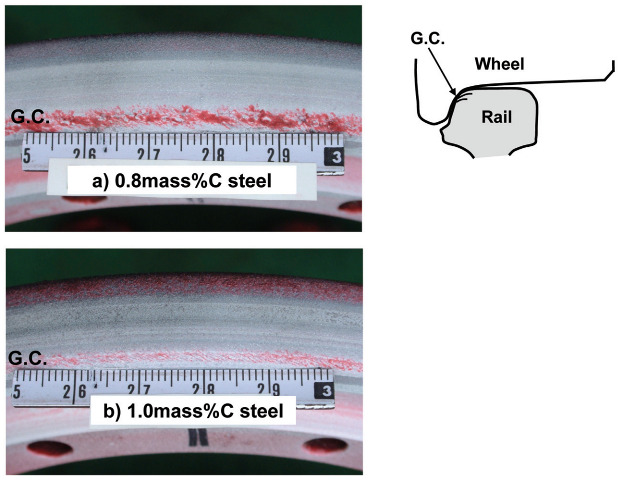

Photo 6 Rolling contact surface appearance of the pearlite steel (subjected to the liquid dye penetrant inspection)

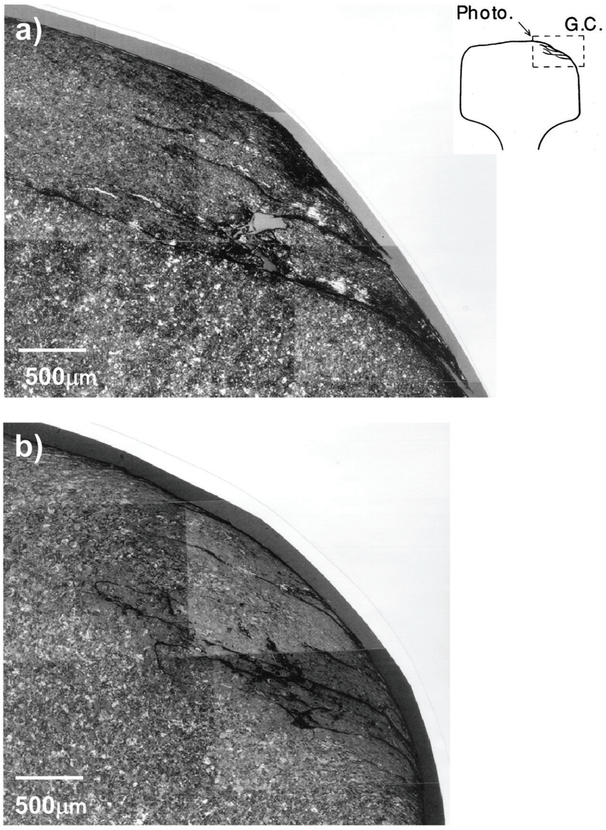

Photo 7 Crack propagation directly under the rolling contact surface a) 0.8mass%C steel, b) 1.0mass%C steel

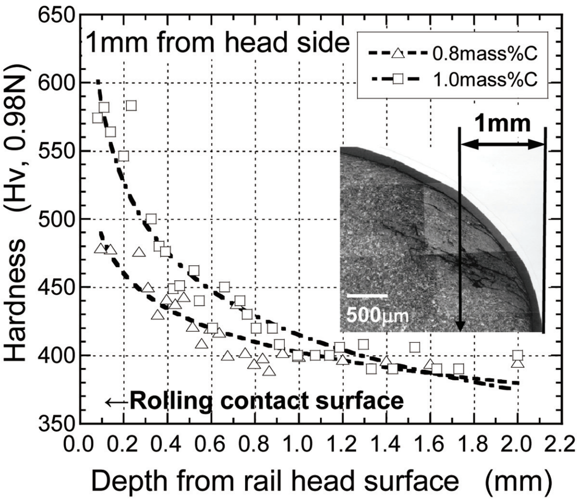

Fig. 10 Cross-sectional hardness distributions of the cracked portion

currence and propagation of fatigue cracks.

3.3 Production technologies for improving ductility and controlling microstructure

When the carbon content is increased in steel to improve wear resistance and surface damage resistance, the ductility of pearlite steel is deteriorated and a pro-eutectoid cementite structure, an embrittling structure, tends to form more easily. In the North American railway standard (American Railway Engineering and Maintenance-of-way Association: AREMA) and the like, it is specified that total elongation shall be 10% or more in the head portion, and pearlite structure shall be secured as microstructure. Accordingly, improving ductility and preventing the formation of pro-eutectoid cementite structures become technical issues to be solved in actual production. Production technologies for improving and controlling these characteristics have been developed.

Refining pearlite blocks is effective at improving the total elongation (ductility) of pearlite steel.[16] Refining of pearlite blocks is achieved mainly by refining austenite (γ) grains before transformation. Further, controlling the cooling rate is important for preventing formation of pro-eutectoid cementite structures.[17]

In the production of pearlite steel rails having higher carbon contents, refining of γ grains is achieved by optimizing the hot rolling temperature, the number of rolling passes, and the amount of reduction. Furthermore, by optimizing the heat treatment conditions, formation of pro-eutectoid cementite can be prevented. It has thus become possible to satisfy such standards for pearlite steel with high carbon contents.

Based on the results of the above study, a method for replacing the conventional methods of improving the hardness of steels has been developed. It is possible to control the microstructure of the steel and promote work-hardening of the rolling contact surface, thereby improving wear resistance and surface damage resistance, by increasing the carbon content in pearlite steel. Further, it is possible to improve the ductility of pearlite structure and control the microstructure using production techniques such as optimizing the hot rolling condition and the heat-treatment condition. In the following chapter, the various characteristics of the high-carbon pearlite steel rails actually produced (hereinafter referred to as "Hyper-eutectoid Steel Rail") are described.

4. Characteristics of Hyper-eutectoid Steel Rail (HE RAIL®)

Hyper-eutectoid steel rails (carbon content: 0.9-1.0 mass%, head surface hardness: HB 370-420) were developed wherein the carbon content and hardness were controlled to secure versatile performance to meet various service environments. In this chapter, the mechanical properties, the characteristics of welded joints, and the performance obtained on actual railroads using hyper-eutectoid steel rails are described.

4.1 Mechanical properties

Table 1 shows a comparison of carbon content and mechanical properties of the head of a representative hyper-eutectoid steel rail with the one of a conventional high strength rail (0.8 mass%). The carbon content of the developed rails was made to be within 0.9–1.0 mass%, and alloys such as Mn, Cr and so on were controlled. Tensile strengths of 1,350-1,440 MPa and total elongations of 10% or more were achieved, and thereby, the high strength and ductility re-

Table 1 Carbon content and head tensile strength properties of the hyper-eutectoid steel rails

Rail	Carbon content (mass%)	Mechanical properties	
		Tensile strength (MPa)	Total elongation (%)
0.8 mass%C	0.80	1,290	14.1
0.9 mass%C	0.90	1,350 - 1,420	13.2 - 13.6
1.0 mass%C	1.00	1,440	10.7

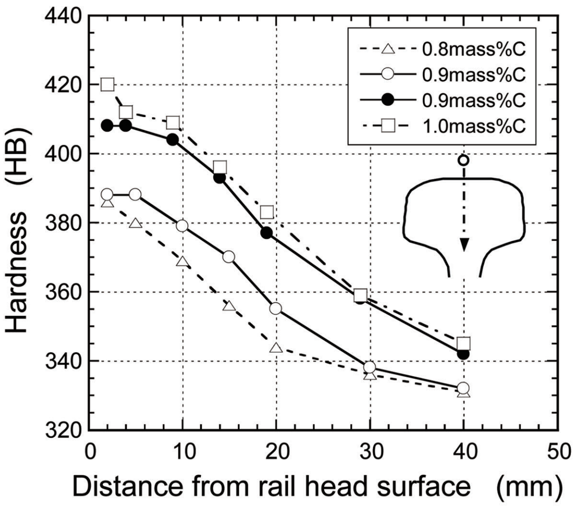

Fig. 11 Cross-sectional hardness distributions of the hyper-eutectoid steel rail head portions

quired for freight railway rails was attained.

Figure 11 shows cross-sectional hardness distributions of the head portions of the hyper-eutectoid steel rails as compared to those of conventional high strength steel rails (0.8 mass%). The hyper-eutectoid steel rails show high hardness distribution from the top of the surface to the inner part. Furthermore, by controlling the carbon content and addition of alloys, and by optimizing heat-treatment conditions, a hardness distribution of HB 420 at the top surface of the head and of HB 370 or more at a point 20 mm below the top surface (the highest level in the world) is realized.[11,18-21] This increase of inner hardness of the rail head contributes to the improvements in wear resistance and fatigue damage resistance of the inner part of the rail head.

4.2 Characteristics of welded joints

On many railways, rails are welded together to form a long rail for the purposes of damage suppression, simplification of inspection work, abatement of noise and vibration, and prevention of track deterioration at rail joints. On freight railroads, flash-butt welding (FB: Flash Butt) in a plant and on-site thermite welding are the main methods used. An evaluation of the characteristics of an FB welded joint is described below.[21]

FB is a welding method in which a voltage is applied across both ends, then both ends are short-circuited temporarily, producing arc discharges between them and preheating both ends. Then flash is repeatedly applied, developing a sufficient molten layer on both ends, and at the end, the rails are pressed against each other and jointed. In **Photo 8** and **Fig. 12**, the macrostructure of a flash butt-welded joint and the hardness distributions of hyper-eutectoid steel rails are shown. In the center region of the hyper-eutectoid steel rail (0.9 mass% C), there exists a softened zone, where the rail was reheated up to the austenite region. Since this softened zone allows local wear and surface damage, railway companies apply heat-treatment right after welding, and thereby suppress softening.

In order to eliminate the heat treatment, as shown in Fig. 12, an alloy-controlling type hyper-eutectoid rail (0.9 mass% C alloy) that suppresses softening due to welding was developed. These rails are used commercially in Canada at the present, and improve welding efficiency.

There are several means of assessing welded joint performance,

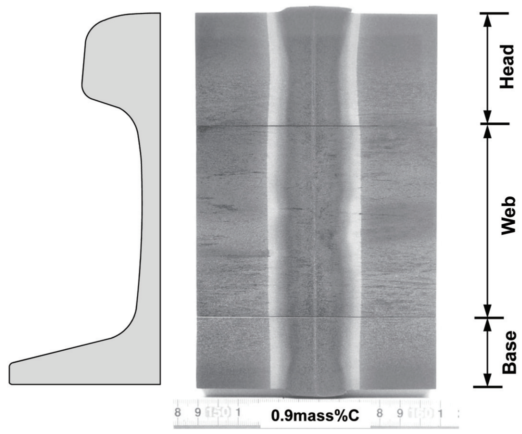

Photo 8 Macrostructure of the flash butt-welded joint of a hyper-eutectoid steel rail

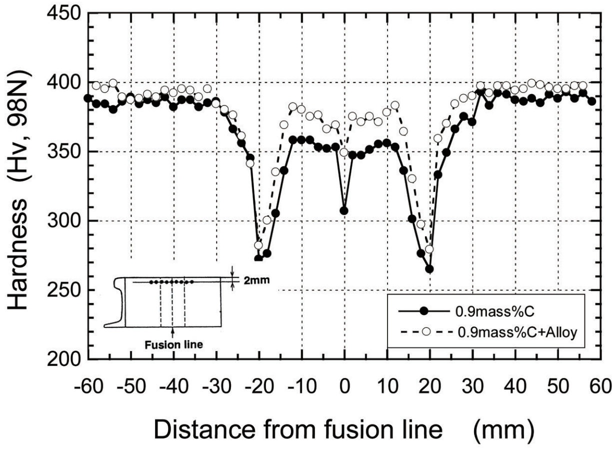

Fig. 12 Flash butt-welded joint hardness distributions of the hyper-eutectoid steel rail

such as a static bending test, a fatigue bending test, and so on. The mechanical properties are greatly influenced by defects that develop mainly at the welded joint. When the carbon content is increased, the ductility and toughness of the steel itself deteriorates, increasing its susceptibility to defects. For this reason, a study on welding conditions becomes necessary to reduce defects in order to maintain the performance of the welded joint. In flash-butt welding of hyper-eutectoid rails, the welding condition was controlled. Weld defects were thus reduced, and welded joint performance that meets the heat treated rail standard advocated by the AWS (American Welding Society) could be attained.

4.3 Performance obtained on actual railroads

Figure 13 shows the relationship between accumulated passing tonnage (accumulated weight of freight that passed over the left and right-side rails) and the amount of wear of a hyper-eutectoid steel rail (0.9 mass% C) installed on an overseas freight railroad, as compared to that of a conventional high strength rail (0.8 mass% C).[6] When the life of the hyper-eutectoid rail and the life of the conventional high strength rail are compared, based on presumed accumulated passing tonnages corresponding to head side wear of about 1/2 inch (12.7 mm), the hyper-eutectoid steel rail has a longer life than the conventional rail. The improvement is about 23% on a railroad track with a radius of curvature of 440 m (4 deg.), and about 38% on a railroad track with a radius of curvature of 290 m (6 deg.).

This result suggests that, on a railroad track with a smaller radius of curvature (i.e., where the rail head contacting force is higher due to increase in centrifugal force), the hardness of the rolling contact surface is increased by work-hardening, promoted by the increase of carbon, and wear resistance is thereby improved. An improvement in service life by using hyper-eutectoid steel rails at sections with sharp curvatures is expected.

Photo 9 shows the appearance of the rolling contact surface of a hyper-eutectoid steel rail (0.9 mass% C) at the accumulated passing tonnage of 170 MGT on a track with a curvature of 400 m, as compared to that of a conventional high strength rail (0.8 mass% C).[6)]

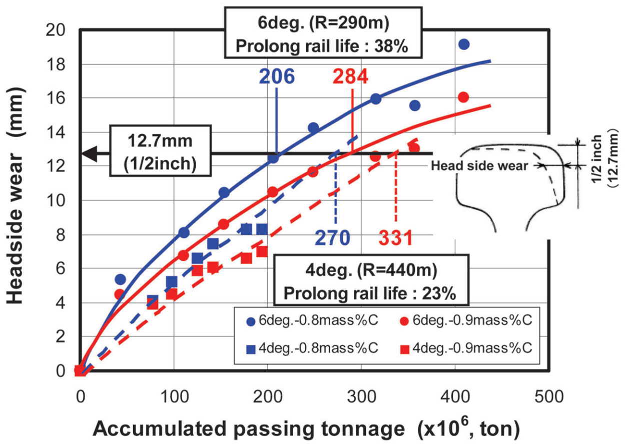

Fig. 13 Relationship between accumulated passing tonnage and head-side wear with respect to the hyper-eutectoid steel

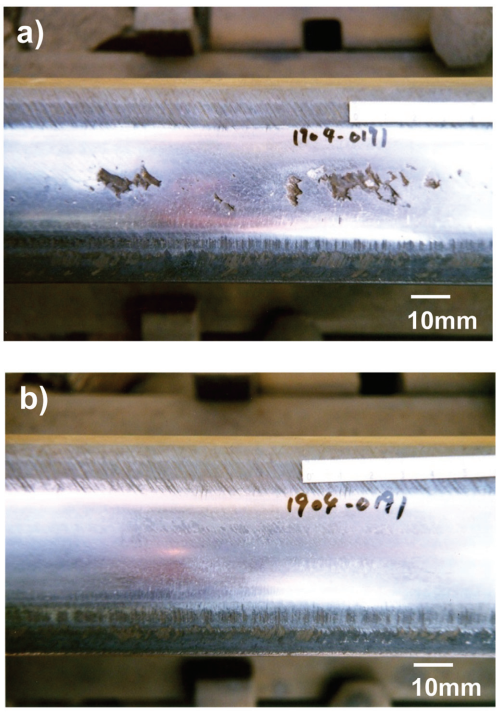

Photo 9 Rolling contact surface appearance of a hyper-eutectoid steel rail
a) 0.8mass%C steel, b) 0.9mass%C steel

On the conventional rail, the occurrence of flaking damage accompanied by cracks is observed. However, there is no such occurrence of damage on the hyper-eutectoid steel rail, a suppressing effect of surface damage is confirmed.

On actual railroad tracks, the occurrence of surface damage like flaking damage is suppressed by carrying out periodical work like grinding to remove such damage. Since the occurrence of surface defects is suppressed on hyper-eutectoid steel rails, a reduction of maintenance work like reprofiling, in other word, a reduction of maintenance and control costs became possible.

5. Present State of Application of Hyper-eutectoid Steel Rail (HE RAIL®) in Practical Use

As mentioned above, hyper-eutectoid steel rails have excellent wear resistance as well as excellent surface damage resistance. The application of all kinds of welding methods currently employed, represented by the flash-butt welding method, is possible, and sufficient joint performance has been attained. Based on these actual achievements, more than two million tons of this type of rail have been shipped to railway companies in North America, South America and Australia, and owing to its excellent durability, they are contributing to prolonging the service life of the rails of freight railways greatly.

6. Conclusion

The results of laboratory tests on hyper-eutectoid pearlite steel has been introduced, and the characteristics of the hyper-eutectoid steel rail (HE RAIL®) so developed have been presented. These rails are aimed at improving wear resistance and surface damage resistance in order to prolong the life of rails for freight railways.

In view of development of natural resources, economic growth and globally worsening environmental issues, it is considered that utilization of environmentally friendly railways will further expand. In line with this, it is anticipated that, for improving transportation efficiency, heavier freight hauling and increasing train speeds will be further advanced, and as a result, circumstances for rail usage will become far harsher. Under such circumstances, it is anticipated that, in addition to the drastic improvement of rail performance, the supply of new rails that incorporated interrelation between rails and wheels will be necessary. In order to respond to such needs accurately and to support highly reliable railway transportation, we consider that research and development of rails which provide high reliability and long life with low maintenance costs are essential.

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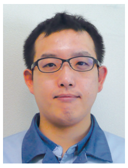

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