NIPPON STEEL TECHNICAL REPORT No. 85 JANUARY 2002

UDC 625 . 143

Development of HE Rails with High Wear and Damage Resistance for Heavy Haul Railways


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Abstract

Many types of head-hardened rails have been developed and popularly used on heavy haul railways. In order to meet the demand for rails with higher wear and damage resistance, the authors studied the method of increasing the cementite volume fraction in pearlite structure in addition of the conventional method of increasing hardness of pearlite steel. As a result of this study, Nippon Steel developed the new rail named HE rail of 0.9 mass% carbon steel. In this report the authors introduce the characteristics of wear and damage resistance and the performance in the actual site as compared with the current heat-treated DHH370 rail of 0.8 mass% carbon steel.

1. Introduction

Railway transportation is attracting attention once again as an effective means of the modal shift in transportation, as this is being promoted with a view to higher transportation efficiency and conservation of global environment. The railway transportation is divided into freight trains and passenger trains, and while heavy loading is eagerly pursued in the former, higher speed is the main subject of development in the latter. In this situation, rails tend to be used in more and more demanding conditions. Pearlite steels containing eutectoid carbon (0.8 mass % C or so) have been used conventionally for the rails because of their excellent wear resistance. During the 1980s to 1990s, NHH rail[1)] was developed based on a technology to form fine pearlitic structure by off-line heat treatment, and then DHH rail[2)] based on another by in-line heat treatment, and they have since been widely used in heavy haul railways of the world as wear resistant, high strength rails.

The trend of the heavy hauling, however, has advanced in ever-increasing paces: an increase of the loaded weight of a freight car, for instance, from 100 to 125 t is being studied in railways in North America. This will inevitably make the service life of rails shorter and the costs of track maintenance higher, and in this situation, development of a new rail capable of solving these problems has been awaited.

This paper lists the problems occurring to the rails of heavy haul railways, on which heavy wheel loads are imposed, introduces a new hyper-eutectoid rail (hereinafter called HE rail) developed on the basis of new concepts for solving the problems[3)]. The paper also describes findings obtained through use of the new rail in actually operated railway tracks and the prospects of its improved performance to be confirmed through further use.

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2. Main Problems Occurring to Rails in Real Tracks

The problems occurring to the high rail of a curved track include: (1) wear, which is a fundamental feature of a rail (an example is shown in **Photo 1**); (2) internal fatigue damage of a rail head (see **Photo 2**); (3) head check and peeling of a gauge corner caused by the limit of metal flow (see **Photo 3**); and (4) flaking occurring at portions a little to the rail center from the gauge corner (see **Photo 4**).

In the case of the low rail of a curved track, the problems are such as: (5) spalling caused by the false flange resulting from wear of the running surface of a wheel and the limit of metal flow resulting from repeated widening of the gauge length or excessive lubrication (see **Photo 5**); and (6) corrugation resulting from non-adhesive (slipping) contacts of wheels peculiar to curved tracks (see **Photo 6**).

On the other hand, the problems characteristic to the rails in tangent tracks include: (7) surface metal flow and spalling caused thereby; and (8) rolling contact fatigue, which is sometimes called rail head shelling or dark spots, seen especially in high speed passenger railways (see **Photo 7**).

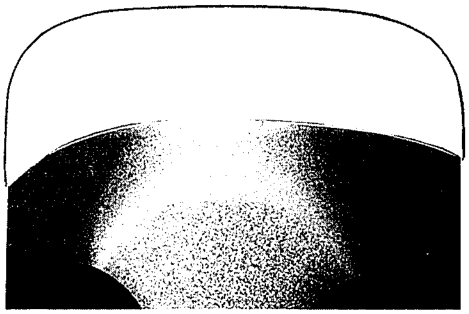


Photo 1 Wear

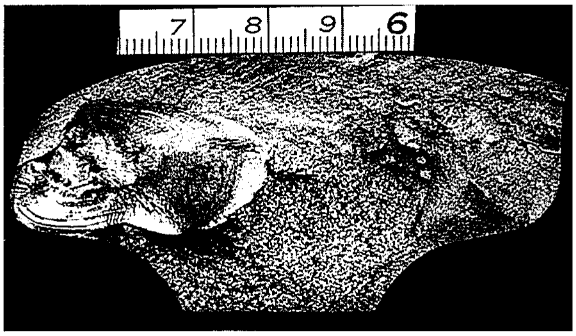


Photo 2 Internal fatigue damage

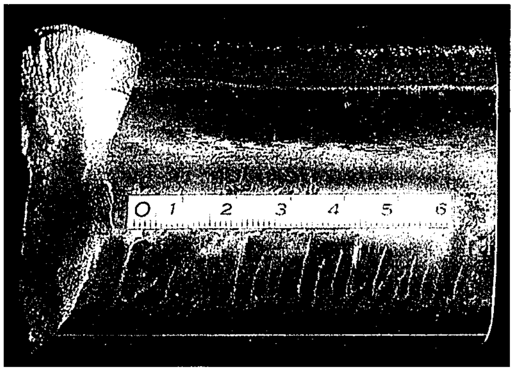


Photo 3 Head check

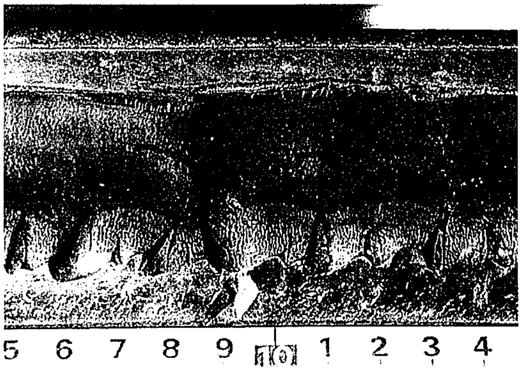


Photo 4 Flaking

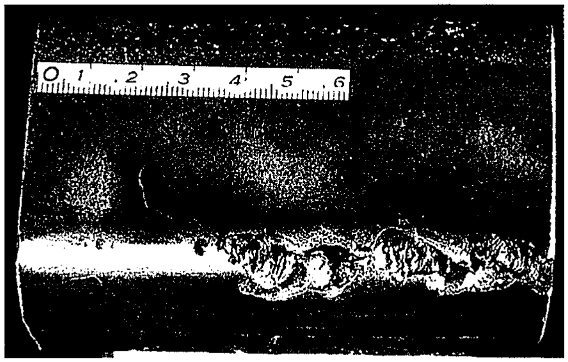


Photo 5 Spalling

Photo 6 Corrugation

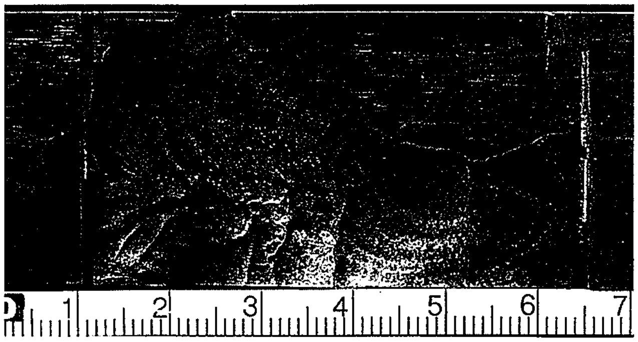


Photo 7 Rolling contact fatigue (dark spots)

Besides these, there are problems such as local wear and weld defects of rail joints as a consequence to the recent increase in welded rail joints to form long rails, in place of fish plate joints.

In view of these problems, the NHH rail and the DHH rail were developed to improve resistance against (1) wear and (2) internal fatigue damage. Then, with respect to prevention of the rolling contact fatigue occurring in tangent tracks of high speed railways, it was made clear that bainite steel having a comparatively low carbon content had excellent resistance against the rolling contact fatigue and, on this basis, developed a bainite steel rail[4)] as a substitute for the pearlite steel rail conventionally used for its good wear resistance. Expansion of use of the new bainite steel rail in operating railways is being promoted.

With regard to the welded rail joints, Nippon Steel's newly developed technologies include an enclosed arc welding method[5)] using a weld metal containing a higher amount of carbon than conventional ones and automatic welding technologies[6)].

The HE rail developed for further improving the properties required of the rails for heavy haul railways in view of the problems listed before is explained hereafter.

3. Concept of New Rail Material in Consideration of Structural Change under Rolling Contact

As a result of a search for a new seed technology to enhance wear resistance to replace the conventional hardening method by formation of fine pearlite lamellae, it was discovered by us that wear resistance was governed by the increase in hardness resulting from a structural change of rolling contact surface layer and that the increase in hardness was accelerated when the volume fraction of cementite in the pearlite lamellae increased. Based on the findings, it was confirmed that use of hypereutectoid steel for the rail was effective for solving many of the above problems occurring to the rail.

Fig. 1 shows the influences of the repetition of rolling contacts and the carbon content of steel (in this case, the cementite volume fraction in a homogeneous pearlitic structure without pro-eutectoid cementite) over the amount of wear and the change of surface layer hardness under rolling contact conditions. From the result shown in the figure, it became clear that, the higher the cementite volume fraction, the larger became the amount of work hardening of the rolling contact surface layer after a certain number of repetition of the rolling contacts and, accordingly, the smaller the rolling wear. This means that, the higher the cementite volume fraction in the pearlite lamellae, the better the wear resistance tends to be. In order to clarify the reason for the increase in the work hardening of the rolling contact surface layer, the authors observed the change of its nano-structure using a transmission electron microscope and differential thermal analysis.

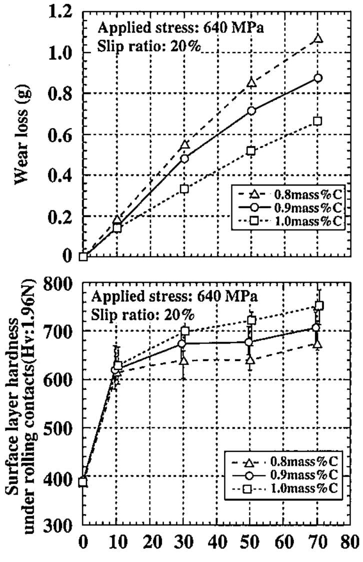


Fig. 1 Influences of repeated rolling contacts and carbon content over wear loss and surface hardness change

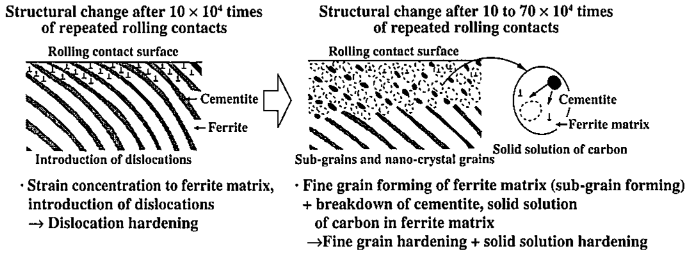


Fig. 2 Nano-structure change of rolling contact surface layer as hardness increases

It was discovered, as a result: that what happened in the rolling contact surface layer as a consequence of large plastic deformation by the rolling contacts with the wheels were dislocation hardening of the ferrite in the pearlite lamellae and a mechanical milling hardening effect such as hardening of ferrite through formation of ultra fine grain (nano-crystallization) and through solid solution of carbon by decomposition of cementite; and that, the larger the cementite volume fraction, the larger these hardening effects became and so did the amount of work hardening[7,8)]. The changes of the nano-structure are schematically illustrated in **Fig. 2**. The results shown in Figs. 1 and 2 can be summarized as follows: the larger the carbon content in the pearlite, the harder the rolling contact surface layer becomes through contacts with the wheels, even when the initial hardness is the same, and consequently, the more enhanced the wear resistance becomes. It follows that the wear resistance of a rail is further enhanced when the conventional rail hardening measures are combined with the hypereutectoid rail steel.

4. Effects of Hypereutectoid Pearlitic Steel to Improve Rail Performance

It was made clear in the previous section that, by use of the hypereutectoid steel having a high cementite volume fraction , the hardness of the rolling contact surface layer of the rail was increased through the rolling contacts with the wheels and thus the resistance against the (1) wear was improved. But, application of the hypereutectoid pearlitic steel to the rail is considered effective also for solving other problems of rails.

4.1 Enhancement of Hardness of Rail Surface Layer through Rolling Contacts

The increase in the hardness of the rolling contact surface layer is effective for reducing the occurrence of the (5) spalling, (6) corrugation and (7) surface metal flow in tangent tracks among the problems of the rail listed in section 2, besides the improvement of wear resistance.

4.2 Enhancement of Hardness as a Result of Transformation Behavior of Hypereutectoid Steel

Fig. 3 compares the continuous cooling transformation (CCT) diagrams of the hypereutectoid steel and conventional eutectoid steel.

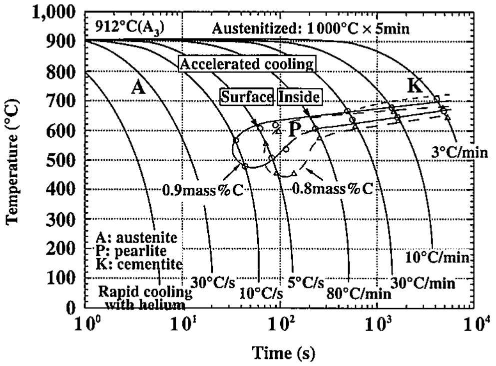


Fig. 3 Continuous Cooling Transformation diagrams of 0.8 mass % C steel and 0.9 mass % C steel

From a comparison of the pearlite transformation noses of the two, it is understood that the nose of the hypereutectoid steel shifts toward the high cooling rate and high temperature sides and that of the hypereutectoid steel is somewhat flatter and the cooling rate-sensitivity of its transformation commencement temperature becomes smaller than that of the eutectoid steel. This is expected to be effective for controlling the deterioration of internal hardness caused by difference in cooling rate between the surface layer and inside the rail during the heat treatment of a rail head by accelerated cooling. This makes it possible, by maintaining the hardenability of the steel, to produce a rail in which the rail head internal hardness is lowered only slightly.

Fig. 4 shows hardness distribution of rail heads from the surface to the inside. The internal hardness of the hypereutectoid steel rail is higher than that of the conventional heat-treated eutectoid steel rail by about 10 points. In consideration of a report[9] to the effect that higher hardness is advantageous for suppressing the problem of the (2) internal fatigue damage of a rail head occurring to the high rail of a curved track described in section 3, the high internal hardness contributes also to further improvement of the (1) wear life and suppression of the (2) internal fatigue damage of a rail head.

In addition, since the pearlite transformation nose of the hypereutectoid steel shifts to the high cooling rate side as seen in Fig. 3, its pearlite transformation becomes stable and, for this reason, with the increase of the cementite volume fraction of the hypereutectoid steel, it is possible to obtain a pearlitic structure having a hardness of HB 400 to 430, a level far higher than HB 370 to 390 stably achievable in the commercial rail production with the eutectoid steel. This means that the minimization of the pearlite lamella space, which is a synonym of strengthening, is effective for suppressing the (3) head check and peeling and (4) flaking seen in the high rail of a curved track, in addition to the above-said wear and other problems.

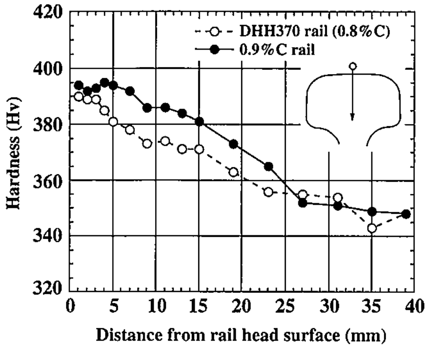


Fig. 4 Hardness distribution in rail heads of 0.8 mass % C steel and 0.9 mass % C steel

Table 1 Material properties of hypereutectoid rail and expected advantages of its use

Material properties of hypereutectoid rail	Expected advantages in use
Large work hardening of surface layer by rolling contacts	(1) Enhanced wear resistance (5) Suppression of spalling (6) Corrugation resistance (7) Plastic flow resistance
Enhancement of hardness of inside and whole rail by heat treatment	(1) Enhanced wear resistance (2) Internal fatigue damage resistance, (3) Suppression of head check and peeling, (4) Suppression of flaking

As described above, many of the problems of railway tracks can be solved through the use of the hypereutectoid steel for the rail together with the increase of the cementite volume fraction in pearlite lamellae and the minimization of the pearlite lamella space, and thus, the application of the hypereutectoid steel to the rail realizes conventionally unachievable effects. **Table 1** summarizes material properties of the hypereutectoid rail and expected advantages of its use in railway tracks.

5. Development of Hypereutectoid Steel Rails (HE Rails)

When the carbon content of steel is increased, what is important is how to secure its ductility. This is, more specifically, a problem as to how to obtain good elongation at a tensile test. Formation of fine crystal grains is effective as a measure to enhance local elongation in the total elongation. **Fig. 5** shows the relation between austenite (γ) grain size and the total elongation. It is clear from the figure that, when the γ grain size of a 0.9 mass % C steel is controlled to 60 μm or less, an elongation figure of 10% required in relevant standards is secured. Further, through studies of control of rolled γ structure of high carbon steels, the authors discovered (a) that high carbon steels recrystallized very quickly after working and the static recrystallization was completed immediately after rolling, forming fine γ grains, but (b) that grain growth between rolling passes was so quick that the fine γ grains grew into large grains, and (c) that a continuous rolling with a short inter-pass time was effective for suppressing the grain growth, thus, fine γ grains could be obtained through accumulation of rolling recrystallization.

Based on the above, a new process to obtain highly ductile fine pearlitic structure was developed, wherein two universal mill stands were used for tandem finish rolling and an in-line accelerated cooling was applied after the finish rolling. As a result, the mechanical

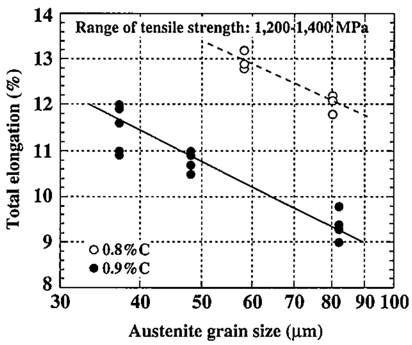


Fig. 5 Influence of austenite grain size on total elongation

properties shown in **Fig. 6** were obtained with the chemical composition of the HE rail shown in **Table 2**. High strength and good ductility were obtained both with a hypereutectoid rail (HE370) having a Brinell hardness of 370 and another (HE400) having a Brinell hardness of 400. **Fig. 7** shows rail head hardness distribution of HE370 and HE400. In the case of HE400, an unprecedented hardness of HB 370 was obtained at 15 mm from the surface. **Table 3** shows the results of the HE rails (N = 3) at the drop weight test used for evaluating the impact resistance of commercially marketed rails. It is seen in the table that the HE rails also have as good ductility as conventional heat-treated rails.

Fig. 8 shows hardness distributions of flash butt welded joints and **Table 4** the results (N = 3) of a slow bending test of the welded joints. The hardness distribution of the welded joint of the HE rails is the same as that of the conventional heat-treated rails, and no anomalies such as welding defects were seen at the bend fracture of the HE rails at the slow bending test, demonstrating sufficiently high performance figures to satisfy the standards of the American Welding So-

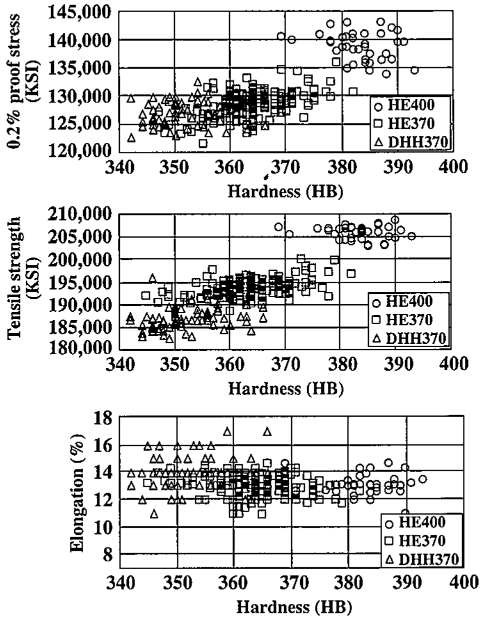


Fig. 6 Mechanical properties of HE rail

Table 2 Example of chemical composition of HE rai
(mass %)

C	Si	Mn	P	S	Cr
0.89	0.48	0.61	0.014	0.009	0.25

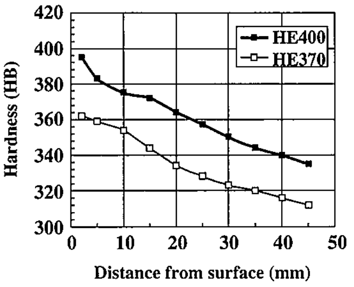
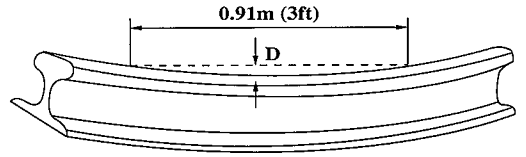


Fig. 7 Hardness distribution in rail heads of HE rails

Table 3 Drop weight test results of rail base metal

Test condition	
Weight	8.9kN (2,000lb)
Height	10.6m
Span	0.91m (3.0ft)
Test temperature	+20°C
Posture	Rail head up

Results		
Specimen No.	Deflection: D (mm)	
	0.9mass%C rail	0.8mass%C rail
1	20.0 (No failure)	21.0 (No failure)
2	20.0 (No failure)	22.0 (No failure)
3	19.0 (No failure)	20.0 (No failure)



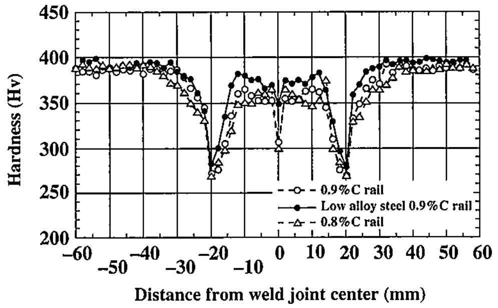
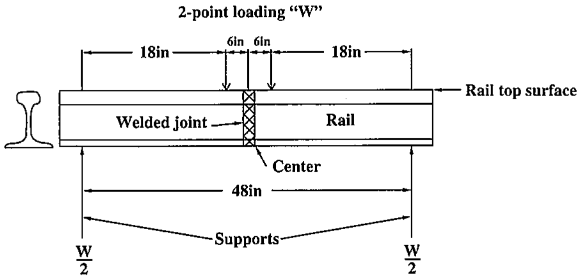


Fig. 8 Hardness distribution of flash butt welded joints

Table 4 Slow bending test of flash butt welded joints

Test No.	Fracture load [kN(tonf)]	Deflection [mm(in)]
1	2,313(236)	27.0(1.06)
2	2,391(244)	30.0(1.18)
3	2,567(262)	36.0(1.42)
AWS standard equivalent	1,911(195)	19.1(0.75)



AWS: The American Welding Society

ciety (AWS) for heat-treated rails. From the above, weldability of the HE rail was confirmed to be as good as that of the conventional heat-treated rails.

6. Expected Improvements of Rail Service Life and Track Maintenance (Performance in Real Tracks)

HE rail was installed in North American heavy haul railways for test and evaluation, and enhanced wear life, which is the main object of its development, and improved performance regarding many of the problems described in section 4 have been/are being confirmed. Some examples are explained below.

Fig. 9 compares the wear life of the HE rails used for the high rail of a curved track with the same of the conventional heat-treated rails. The service life of the HE rail is better by about 20% in a 440-m radius curve (a 4 deg. curve) and by about 40% in a 290-m radius curve (a 6 deg. curve). The service life improvement effect of the HE rail tends to be larger in tighter curves where applied stress and the slip ratio are higher. This reflects the fact explained referring to Fig. 1 that, the more the rolling contacts are repeated, the more the rolling contact surface layer is work-hardened as the carbon content increases and, as a consequence, the more the wear resistance is improved.

Fig. 10 shows rail head metal flow of the low rail in a curved track. Whereas formation of a lip, which leads to occurrence of a surface crack or peeling, is seen at the boundary of metal flow in the conventional heat-treated rail, the HE rail little showed the lip formation.

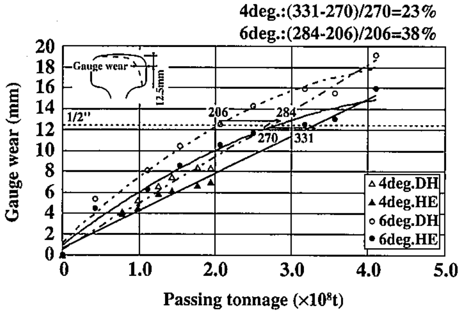


Fig. 9 Wear life of high rail of curved track

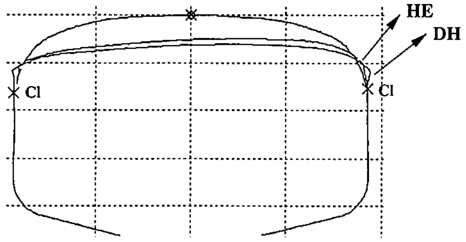


Fig. 10 Metal flow of low rail of curved track

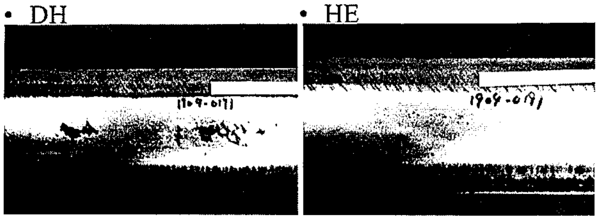

• DH • HE

Photo 8 Rolling contact surface conditions of rails actually used in railway tracks

Examples of the rolling contact surface are shown in **Photo 8**. While a surface defect looking like the spalling is seen in the conventional heat-treated rail, no such defect is seen in the HE rail. In the usual practice, head top surface defects of this kind are removed by grinding at an early stage to prevent them from developing into serious ones. From the results shown in Fig. 10 and Photo 8, it is expected that the grinding work of the rails can be reduced by the use of the HE rail and thus track maintenance costs are cut down.

Further, when the internal hardness of the rail head is increased, the resistance against the internal fatigue damage is expected to improve as described in Table 1 in section 4 and, thus, the HE rail is expected to reduce profile grinding of the rails as a measure to optimize the rail/wheel contact to prevent the internal fatigue from accumulating.

7. Summary

Nippon Steel has developed varieties of new rails responding to the requirements for enhancing transportation efficiency and rationalizing the track maintenance of heavy haul railways. This paper focused on nano-structural change of the rail surface layer under rolling contacts with wheels, and described a possibility of improving wear and damage resistance of the rail based on a new philosophy to enhance hardness of the rail under the rolling contact conditions by raising the cementite volume fraction in pearlite lamellae, in addition to the conventional measures to raise hardness to improve wear resistance. For bringing the possibility into reality, hypereutectoid steel was applied to the rail, and the problem of low ductility of a high carbon rail was solved by application of a TMCP technology. Through trial use in actually operated tracks for evaluation, the new rail proved effective for reducing track maintenance costs thanks to its improved wear life and capability of suppressing surface defects.

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