Development of High Strength Pearlitic Steel Rail (SP Rail) with Excellent Wear and Damage Resistance

Hiroyasu Yokoyama*, Shinji Mitao** and Mineyasu Takemasa***

* Senior Research Engineer, Heavy-Steel Products Research Dept., Materials & Processing Research Center
** Team Manager, Heavy-Steel Products Research Dept., Materials & Processing Research Center
*** Team Manager, Product Design and Quality Control, Bar and Structure Sec. Fukuyama Works

NKK has developed a high-strength pearlitic rail named the SP (Super Pearlite) rail, which has superior wear and damage resistance and is most suitable for heavy haul railroads. Comprehensive research on the relation between microstructural factors and wear and RCF (Rolling Contact Fatigue) behaviors revealed that refining the pearlite colonies greatly improves wear and damage resistance. In the SP rail, the pearlite colonies are refined through microalloying design and TMCP (Thermo-Mechanical Controlled Processing). This paper introduces the basic properties of the SP rail including its wear and RCF behaviors as well as the concept of microstructural control.

1. Introduction

In North America, the railroads are mainly used for transporting cargoes such as grain and ore. Transportation efficiency has been improved mainly by mass transportation through increasing the load capacity of freight cars. Long trains hauling more than 100 freight cars full of cargoes, called mile trains, run across the North American continent. A fully loaded freight car weighs close to 160 tons, nearly 2.5 times as heavy as Japan's passenger coaches. The requirements for rails used for such heavy haul railroads are very strict, because the performance of rails is one of the most important factors for improving the efficiency of railroad cargo transportation.

The establishment of technologies for producing clean steel and the development of on-line heat treatment technologies of rails in Japan since the 1970s have greatly improved the ability of rails to withstand wear and RCF (Rolling Contact Fatigue) damage[1-4). **Fig.1** shows recent changes of railroad car weight in North America. Increasing car weight, which has been made possible by improving the wear and damage resistance of rails, has greatly improved transportation efficiency, but this has encouraged the use of even heavier cars, making the requirements for rails even more stringent. The wear resistance and RCF damage resistance of rails need to be improved even further.

NKK has developed a high-strength SP (Super Pearlite) rail, which has significantly higher wear resistance and RCF damage resistance over the conventional heat-treated rail, through microstructural control by means of microalloying design and TMCP (Thermo-Mechanical Controlled Processing). This paper outlines the basic concept of the microstructural control for developing the SP rail and its basic properties.

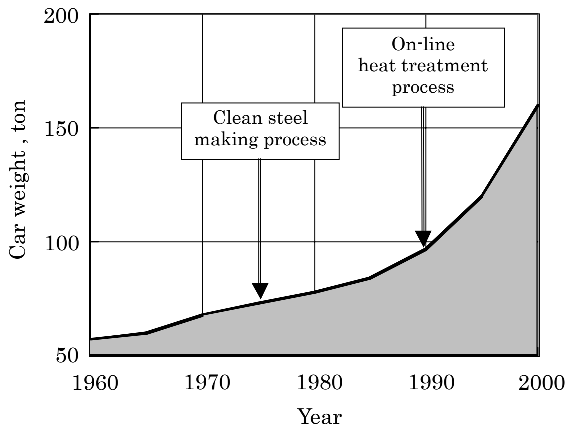


Fig.1 Change of car weight in North America

2. Concept of microstructural control

As **Fig.2** schematically shows, the basic factors that define the microstructure of pearlitic steel are colony size (D_{PC}), lamellar spacing (λ), and volume fraction of cementite (V_θ). To produce the heat-treated rail, the rail is subjected to slack quenching from the austenite state (γ) at an appropriate cooling rate after completion of hot rolling. During the cooling process, the lamellar spacing (λ)

is refined, and the hardness and wear resistance are improved. The lamellar spacing in the state-of-the-art heat-treated rail is as fine as about 0.1 μ m, which is nearly the limit that is industrially achievable[5].

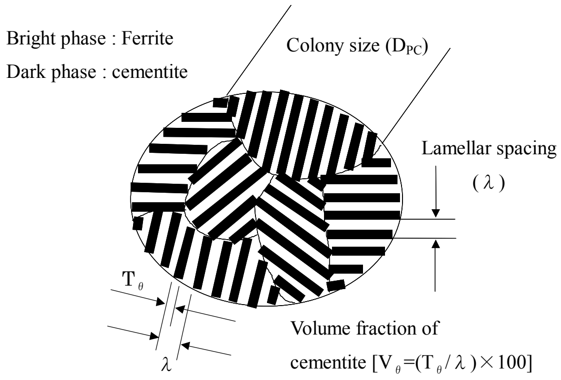


Fig.2 Schematic drawing of pearlitic structure

Recently, a new highly wear resistant rail was developed, in which the carbon content is increased from the eutectoid composition (0.8%) to the hyper-eutectoid level (0.9%)[6]. The increase in the volume fraction of cementite (V_θ), stemming from the increased carbon content, affects the structural changes at the micro to nano level when plastic deformation occurs under rolling contact with the wheel. As a result, the surface hardness of the rail increases the longer it is used, thus helping to improve the wear resistance of this type of rail[7].

As noted above, it is known that the wear resistance is improved by controlling the lamellar spacing (λ) and the volume fraction of cementite (V_θ). However, the effects of changes in the microstructure of pearlitic steel on its wear resistance and RCF damage resistance have not been systematically identified.

We therefore prepared a large number of pearlitic steel specimens having a wide variety of microstructures, in order to clarify what type of microstructural control can improve wear resistance and RCF damage resistance. Firstly, microstructural features of each specimen were quantified, then the characteristics of each specimen were evaluated by the newly developed RCF test machine (**Photo 1**)[8]. Thus, the correlation between the microstructure and wear and damage resistance was systematically clarified.

In the newly developed RCF test machine, a wheel sample and rail sample, both in the form of a disc 130 mm diameter and 30 mm thick, are contacted and rotated. The wheel sample is made of pearlitic steel with Vickers hardness (HV) of about 370. The contact angle between the wheel sample and rail sample (angle of attack) can be varied to more accurately simulate wear and RCF behaviors on curved railroad sections with various curvatures. The details of the change in wear and RCF behaviors with varying angle of attack are given elsewhere[8,9].

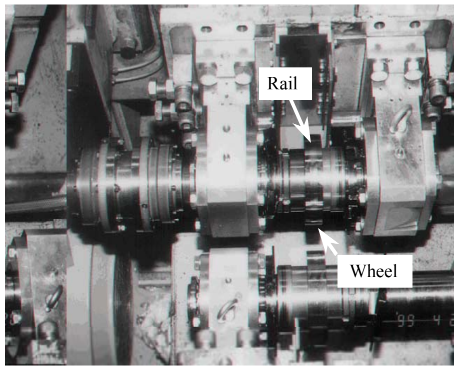


Photo 1 Appearance of the RCF test machine

Photo 2 shows some of the microstructures of the steel specimens used for this test. **Table 1** shows the results of quantitative microstructural analysis and hardness measurement for each specimen. Note that the hardness varies in the range of HV 270 to 395 with varying values of D_{PC}, λ, and V_θ.

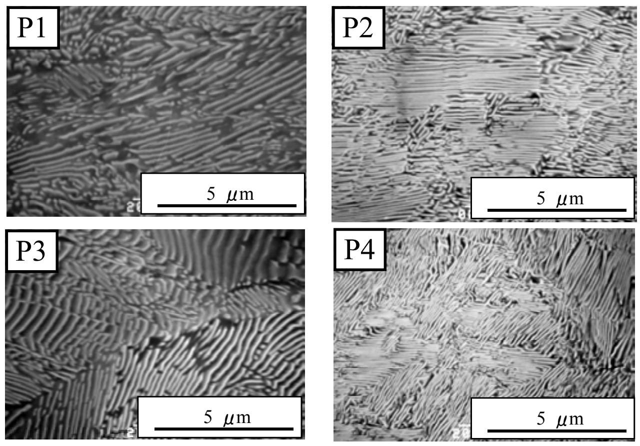


Photo 2 Microstructure of the steel specimens

Table 1 Quantitative microstructural analysis results

Code	Colony size, D_{pc}(μ m)	Lamellar spacing, λ (μ m)	Volume fraction of cementite, V_θ(%)	HV
P1	150	0.35	41	270
P2	80	0.15	47	390
P3	80	0.33	47	295
P4	55	0.11	49	395

The wear resistance and RCF damage resistance of pearlitic steel specimens of various microstructures were evaluated including those specimens shown in **Photo 2** and

Table 1. The wear resistance was evaluated in terms of weight loss per hour in five hours' continuous rolling contact test under dry conditions with the contact pressure between the wheel and the specimen of 2.2 GPa, rotating speed of 1200 rpm, and angle of attack of 3°. The RCF damage resistance was evaluated in terms of the length of time it took for the RCF damages to become visible when the specimens were subjected to the RCF test under lubricated conditions. **Photo 3** shows typical damages caused by the RCF test.

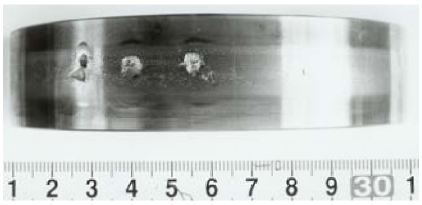


Photo 3 Appearance of the sample after RCF test

Considering the effect of microstructural change on the hardness, an analysis was carried out on the correlation between the microstructure, and the RCF damage resistance and wear resistance[9]. **Figs.3** (a) and (b) compare the values calculated from the microstructural factors and those observed in the experiment with regard to the time to damage occurrence and the weight loss respectively. The observed and calculated values agree quite well in both cases.

Fig.4 illustrates the effects of microstructural control on the RCF damage resistance and wear resistance. The basic microstructure for evaluating the effect of microstructural control on wear resistance is set to be the typical microstructure of ordinary rails, namely, D_{PC} =150 μ m, λ =0.35 μ m, and V_θ =41%. In this case, increasing the volume fraction of cementite to 50% improves the wear resistance by 4.3%, whereas reducing the lamellar spacing to 0.10 μ m improves the wear resistance by 30%. However, as explained previously, the lamellar spacing of 0.10 μ m obtainable by heat treating is nearly the theoretical limit, and even finer spacing is difficult to obtain. Further, the wear resistance is improved by 16% by refining the colony size down to 50 μ m. Although the effect of refining the colony size has attracted little attention in the past, it has become evident that such refinement effectively improves the wear resistance as well as RCF damage resistance. Therefore, we studied the microalloying design and manufacturing process, with particular attention to the colony size refinement.

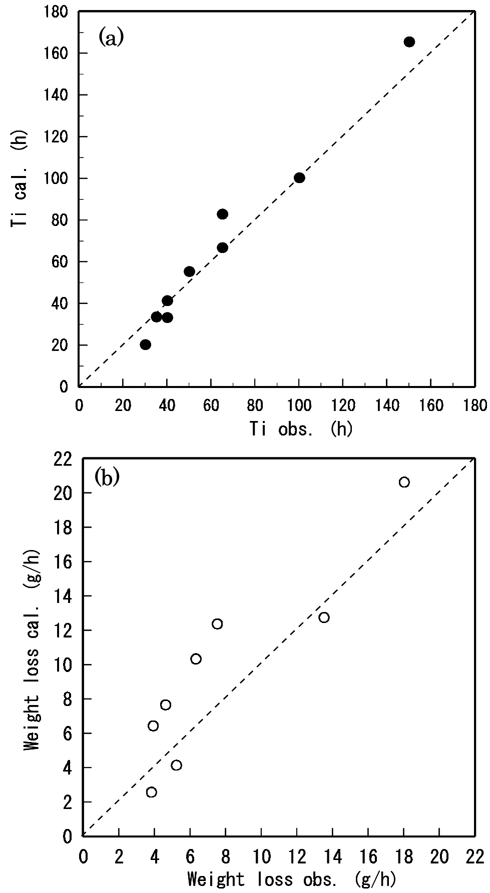
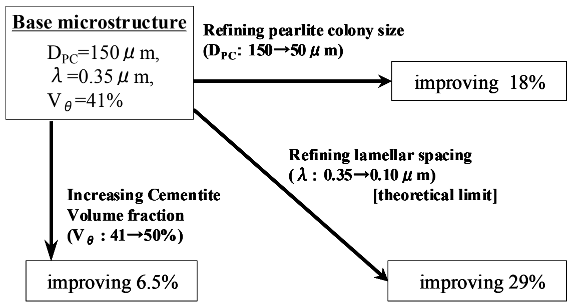
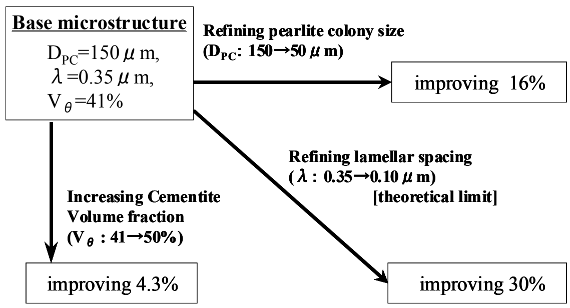


Fig.3 Observed and calculated values in RCF and wear tests: (a) RCF test, (b) Wear test



(a) Damage resistance



(b) Wear resistance

Fig.4 Improvement of RCF damage and wear resistance through microstructural control

3. Basic performance of the SP rail

3.1 Microstructure and mechanical properties

The SP rail is a steel rail of 0.82% carbon in which the colony size is refined by microalloy addition and TMCP. **Photo 4** shows a typical microstructure at 5 mm below the head surface. The results of quantitative microstructural analysis are D_{PC}=50 μm, λ=0.11 μm, and V_θ=48%. This microstructure is similar to that of specimen P4 shown in **Photo 2**.

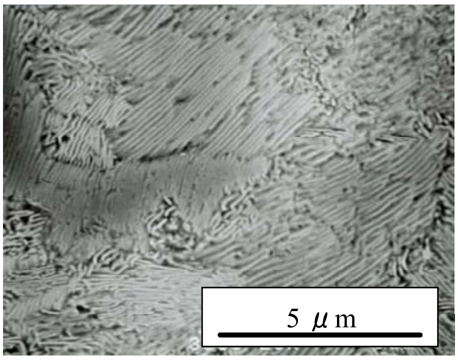


Photo 4 Microstructure of the SP rail

Table 2 compares representative tensile properties of the SP rail with those of the conventional heat-treated rail, both measured following the standard of AREMA (American Railway Engineering and Maintenance Association). The strength of the SP rail is almost the same as that of the conventional heat-treated rail, but its elongation is superior.

Table 2 Tensile properties of the SP rail

	YS (MPa)	TS (MPa)	El (%)	R.A. (%)
SP	876	1312	16.0	38.4
THH370N	900	1303	13.5	26.1

Sampling and dimensions of tensile test specimens.

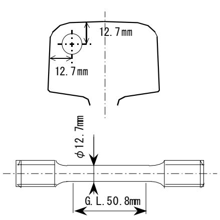


Fig.5 shows the performance (tensile strength and elongation) of the SP rail actually produced. It is clear that the strength and elongation performance of the rail are excellent and stable.

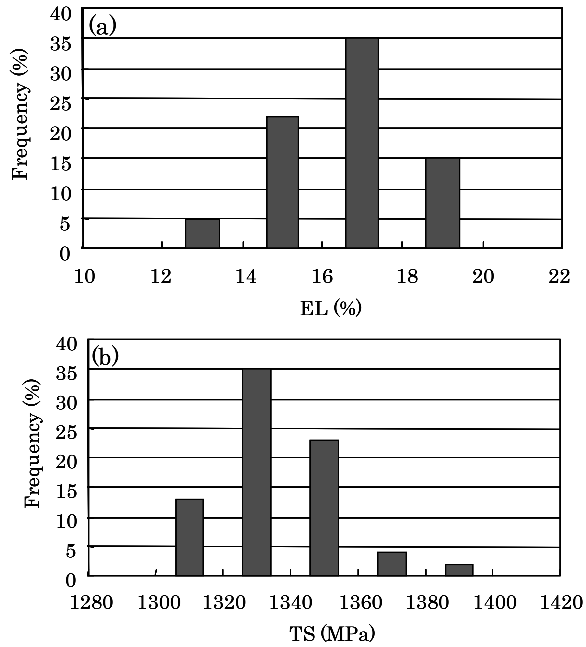


Fig.5 Production results of the SP rail: (a) EL, (b) TS

Fig.6 compares the hardness distribution in the SP rail with that in the conventional heat-treated rail along the depth from the head surface. The surface hardness of the SP rail is almost the same as, or slightly higher than, that of the conventional heat-treated rail; however, the SP rail maintains the hardness deeper into the rail body.

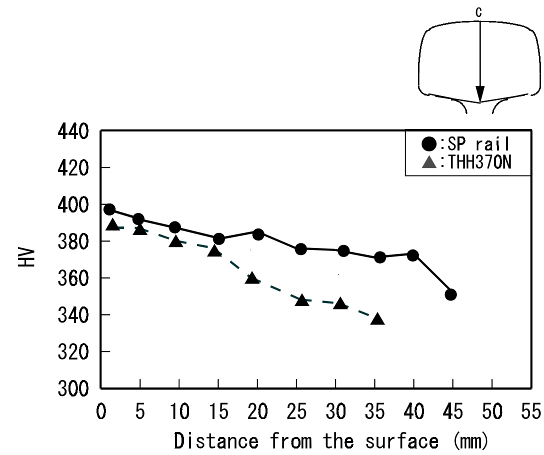


Fig.6 Hardness distribution from the rail surface

3.2 Wear resistance

Disc-shaped specimens of 30 mm diameter and 8 mm thick were taken from 3 mm below the head surface of the rails, and were subjected to wear tests by the Nishihara-type wear test machine. These specimens were rotated in contact with wheel specimens (pearlitic steel of HV 370) under dry conditions with contact pressure of 1.5 GPa, rotating speed of 800 rpm, and slip ratio of –10%.

Fig.7 shows the relationship between weight loss (abrasion loss) and the number of rotations. If the weight loss of the conventional heat-treated rail (THH370N) is given an index value of 100, the weight loss of the SP rail falls in a band of 75 to 80 at all numbers of rotations. Thus, the wear resistance of the SP rail is improved by 20 to 25% over that of the conventional heat-treated rail. The usable life of a rail limited by wear can be represented by the number of rotations required to cause a certain amount of weight loss; i.e., 1.25g. The SP rail requires about two times as many rotations as the conventional heat-treated rail for causing this amount of weight loss, indicating that the life of rails could significantly be extended.

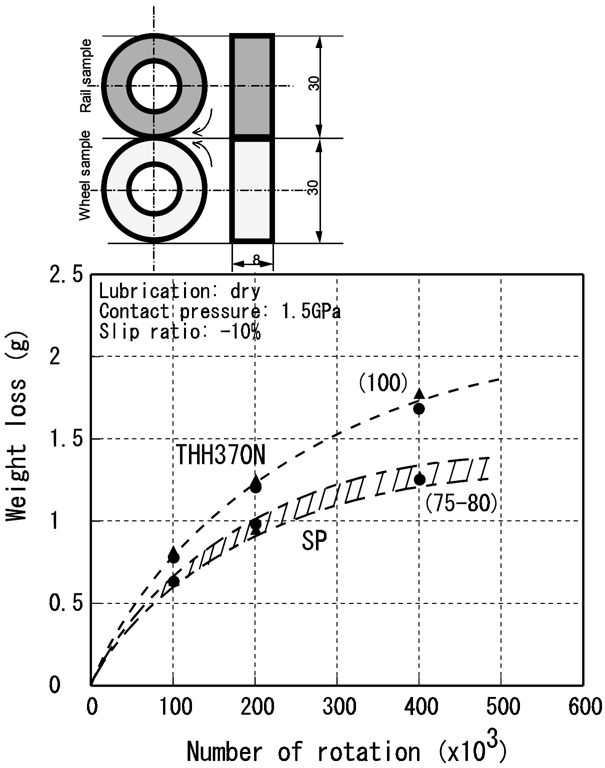


Fig.7 Relationship between weight loss and number of rotations

Photo 5 shows cross-sectional microstructures of the conventional heat-treated rail and SP rail specimens taken near the contact surface, both after 100000 rotations. The conventional heat-treated rail shows a number of small cracks near the surface, while the SP rail shows almost no cracks.

Photo 6 shows the same specimens but at a higher magnification. Both specimens show noticeable plastic deformations caused by the rolling contact but still retain traces of lamellar structures. The specimen of the conventional heat-treated rail exhibits a tendency that cracks are generated and develop along the boundaries between colonies as indicated by the arrow. The specimen of the SP rail also shows cracks, but they are significantly smaller and do not develop to connect with each other.

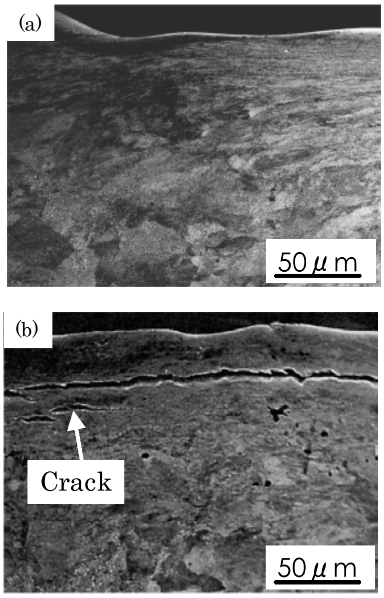


Photo 5 Microstructure near the surface after wear test: (a) SP, (b) THH370N

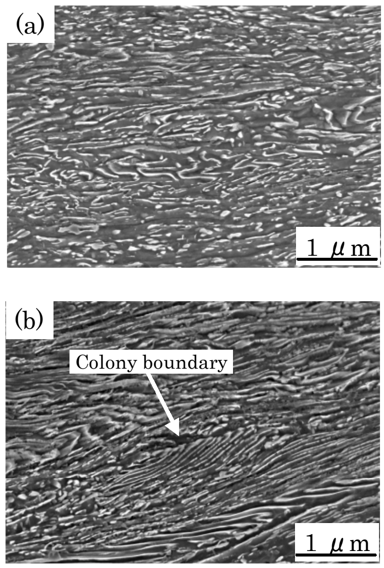


Photo 6 Microstructure near the surface after wear test: (a) SP, (b) THH370N

Fig.8 schematically shows the process of wear resistance improvement that occurs in association with refining the colony size by microstructural control. The lamellar structures exhibit significant anisotropy governed by the lamellar direction when subjected to plastic deformation. Accordingly, high stress concentrations occur along the colony boundaries, making them crack-generating sites.

Presumably, refining the colony size disperses these stress concentrations, suppressing crack generation and propagation, and also suppressing separation as abrasion dust, thereby improving wear resistance.

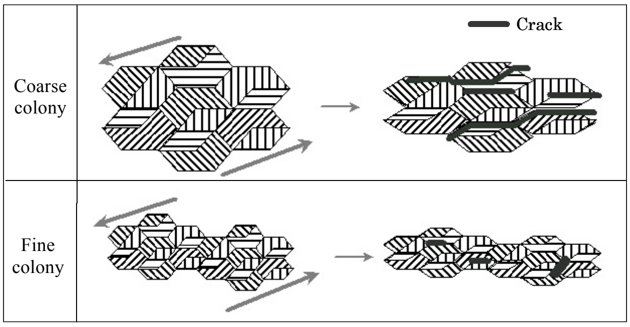


Fig.8 Improvement of wear resistance through microstructural control (schematic diagram)

3.3 RCF damage resistance

Likewise, disc-shaped specimens of 30 mm diameter and 8 mm thick with curved contact faces were taken from 3 mm below the head surface. These specimens were rotated in contact with wheel specimens under oil lubricated conditions with contact pressure of 2.2 GPa, rotating speed of 800 rpm, and slip ratio of –20%. **Fig.9** compares the time to RCF damage (flaking) in the conventional heat-treated rail with that in the SP rail, indicating that the RCF damage resistance of the SP rail is improved by about 40% over the conventional heat-treated rail.

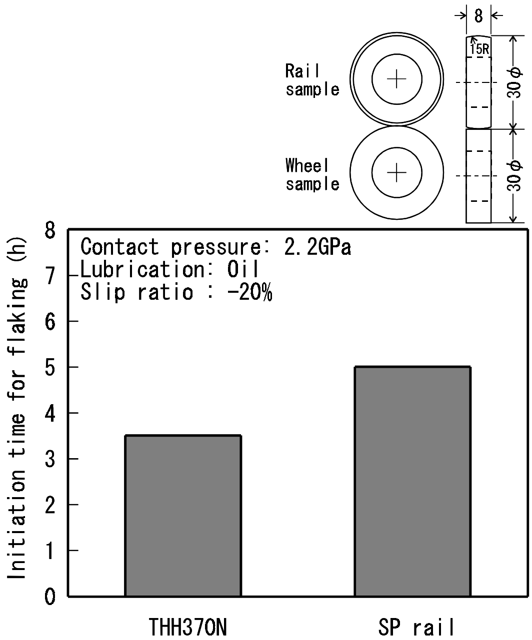


Fig.9 Initiation time for flaking

3.4 Welded joint performance

Fig.10 shows a longitudinal hardness distribution at 5 mm below the head surface of a flush-butt welded joint of the SP rail, welded under the same conditions as those for welding the conventional heat-treated rails. An excellent hardness distribution was obtained. Further, the static bending performance was evaluated by the 4-point bend test following the standard of AREMA (**Fig.11**). As **Table 4** indicates, the bend test confirmed that both the modulus of rupture and the deflection conform to the specifications.

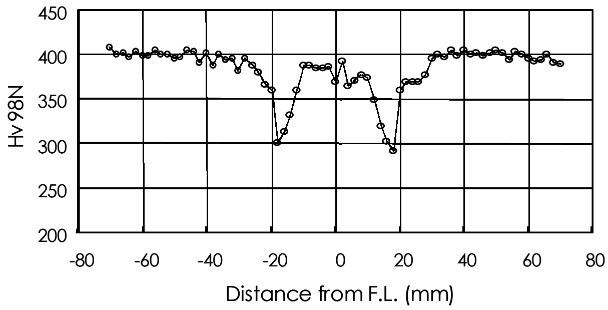


Fig.10 Hardness distribution near the weld joint

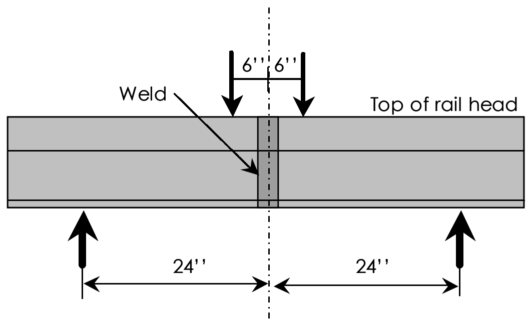


Fig.11 Test method (4-point bend test)

Table 4 Results of the bend test

Weld joint	Modulus of rupture (ksi)	Deflection (inch)
SP-SP	176.2 188.2	1.032 1.459
AREMA spec.	Min. 125	Min. 0.75

4. Conclusion

A systematic study on microstructural control of pearlitic steel was carried out for the purpose of developing a high-quality rail that has excellent wear and damage resistance and that comfortably satisfies the requirements of heavy haul railroads, notably those in North America. The results indicate that, contrary to the generally-accepted view, refining the colony size effectively improves the wear and damage resistance. On the basis of such findings, NKK developed the SP rail that has small colony sizes realized by applying microalloying design that includes microalloy addition, and TMCP. The evaluated properties of the SP rail closely reproduced the laboratory study results. It was confirmed that the welded joints of the SP rail, welded under the same conditions as those for welding conventional heat-treated rails, exhibit an excellent hardness distribution and static bending properties.

The superb performances of the SP rail are now being verified by field tests in North America. The outstanding wear and damage resistance of the SP rail will no doubt contribute to a significant reduction in the cost of railroad maintenance.

References

1) Y. Kataoka et al. 1992 RAIL STEEL SYMPOSIUM PROCEEDINGS, (1992), 11.
2) H. Schmedders et al. ibid. 35.
3) K. Fukuda et al. The Fourth International Heavy Haul Railway Conference, Brisbane, (1989), 51.
4) K. Sugino et al. ibid., 41.
5) Yamamoto, S., The 161st and 162nd Nishiyama Memorial Technical Symposiums, Iron and Steel Institute of Japan, (1996), 215.
6) M. Ueda et al. 6th International Heavy Haul Conference, Cape Town, (1997), 355.
7) Ueda, M. et al., Tetsu-To-Hagane (Iron and Steel), 87, (2001), 190.
8) H. Yokoyama et al. Proc. of CM2000 (Tokyo), (2000), 154.
9) H. Yokoyama et al. 7th International Heavy Haul Conference, Brisbane, (2001), 551.

<Please refer to>
Hiroyasu Yokoyama
Steel Product Research Dept. Material and Processing Research Center
Tel : (81) 84-945-3629
E-mail : hiroyoko@lab.fukuyama.nkk.co.jp