Manufacture and Properties of Deep Head Hardened Rail

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Slack-quenched rails made by Nippon Steel have made an important contribution to reducing the maintenance cost of railroads. Recently, the number of companies that use heavy lubrication and grinding of rail heads to improve rail life has been increasing. Thus, depending on the conditions under which the track will be used, rails with various types of hardness and a much deeper hardened layer are in great demand. To satisfy this demand, Nippon Steel has developed a new heat-treated rail called the deep head hardened (DHH) rail, which can be produced by in-line direct heat treatment with a special cooling system designed by Nippon Steel. Features of DHH rail are as follows: (a) various grade types of hardness, (b) a deep and uniformly hardened layer in the rail head, and (c) high weldability. The construction of these rails has been completed and tested. The new rail will be available late in 1987.

Because of increases in train speed and freight car capacity aimed at improved efficiency, rails are subject to severer conditions than ever. The tonnage of trains has increased markedly, and the axle load and tangential force or impact force applied to the rails by the wheels have become exceedingly great.

Recognizing the increasingly severe service conditions for rails, in 1976 Nippon Steel developed a new head hardened (NHH) rail that is continuously slack-quenched by air after being subjected to induction heating (*1*, *2*). In 1979 the company developed NS-II rail (Super rail), the purpose of which was to prevent the welded joints from softening (*3*).

In a test conducted at the Facility for Accelerated Service Testing (FAST) (*4*, *5*), these rails proved to have excellent wear resistance. As a result, they have been widely used in the United States, Canada, Australia, Brazil, and other countries, in which their use has contributed to a saving in track maintenance costs.

In recent years railways have been making the following technical changes:

1. Development and practical use of lubrication technology aimed at improved fuel efficiency in train operation and prolonged rail service life (*6*),
2. Implementation of rail head grinding to secure the optimum rail top profile while eliminating rail surface damage and matching between rails and wheels (*7*), and
3. Use of 125-ton or heavier freight cars rather than the 100-ton cars introduced in the 1970s.

These changes made necessary the development of rails based on an entirely new concept. The manufacture and properties of deep head hardened (DHH) rail, developed by Nippon Steel in response to the foregoing technical changes, are described in this paper.

OBJECTIVES OF DEVELOPING NEW RAILS

In developing new rails, Nippon Steel gave the recent changes in rail applications careful consideration and set the following objectives.

1. To develop rails of different strengths (hardnesses) for different uses: The use of lubrication reduces rail wear and causes fatigue layers to accumulate on the rail surface, which can cause damage to the rail surface. For this reason, it is necessary to use a rail that is slightly less hard than conventional high-strength rails. On the other hand, with the increase in freight car tonnage, medium-strength (H_B 285–320) rails have come to be used in tangent and gently curved tracks. Thus, rails of different hardnesses are necessary to meet diverse service conditions.
2. To increase hardened layer thickness: Rail head grinding requires that the rail interior have the same wear resistance as the rail surface. This means that the hardened layer should be made as thick as possible.
3. To improve weldability: Improving rail weldability is an important point to facilitate welding work and cut welding cost.
4. To secure homogeneous rails: In order to ensure a high level of rail safety under increasingly severe conditions, it is important to produce rails that are homogeneous throughout.

The off-line heat treatment process based on high-frequency induction heating currently employed at Nippon Steel cannot be applied to the manufacture of rails that meet the above-mentioned requirements without significant slowdown of hardening speed and marked deterioration in production efficiency. In addition, with this process, it is extremely difficult to obtain hardened layers of the desired thickness. In view of this, a direct heat-treatment process was developed to produce such rails.

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DIRECT HEAT-TREATMENT TECHNOLOGY

Selection of Coolant

Various cooling media were studied and subjected to laboratory tests. The test results are shown in Table 1. It was found that salt, air, and mist might be feasible as cooling media for the direct heat treatment. These three media were thus subjected to detailed laboratory tests. In addition, the media were used in a heat-treatment test on rails immediately after rolling.

Test Results

Salt

A salt bath capable of accommodating 4-m rails was fabricated, and a heat-treatment test was conducted on rails immediately after rolling. The test results obtained with standard carbon steel rails are shown in Figure 1.

By maintaining the salt bath temperature at 400°C, it is possible to produce rails whose strength is comparable with that of NHH rails. In order to produce medium-strength (H_B 285–320) rails, it is necessary to raise the salt bath temperature to 500°C or higher, which poses the problem of salt evaporation. In addition, immersion of the rails causes the salt bath temperature to rise. Therefore, a large-scale heat removal system is needed if a salt bath is to be employed on an industrial scale.

Mist

A testing facility capable of treating 39-ft rails was built, and a heat-treatment test was conducted on rails immediately after rolling. The test results obtained with standard carbon steel rails are shown in Figure 2.

The test results indicate that it is possible to produce medium-strength and high-strength rails comparable with NHH rails. However, the influence of surface properties, especially scale, was found to be so great that the cooling rate varied throughout the length of the rail. In addition, local bainitic or martensitic structure makes it extremely difficult to secure uniform quality.

Because one of the primary objectives was to produce rails that were homogeneous throughout, mist, which causes

TABLE 1 SELECTION OF COOLANT FOR STANDARD CARBON STEEL RAIL

Grade / Cooling media	High strength rail (H_B ≒ 370)	Medium strength rail (H_B ≒ 300)	Estimation
Boiling water (98℃)	· Insufficient cooling capacity · Martensitic or banitic structure	· Martensitic or banitic structure	No good
Hot water (60~70℃)	· Martensitic or banitic structure	· Martensitic or banitic structure	No good
Quenching oil (100~180℃)	· Martensitic or banitic structure	· Martensitic or banitic structure	No good
Salt.	(Good)	· Salt evaporation · High cost	Adoptable
Air	· Insufficient cooling capacity	(Good)	Adoptable
Mist	· Local banitic structure	· Local banitic structure	Adoptable

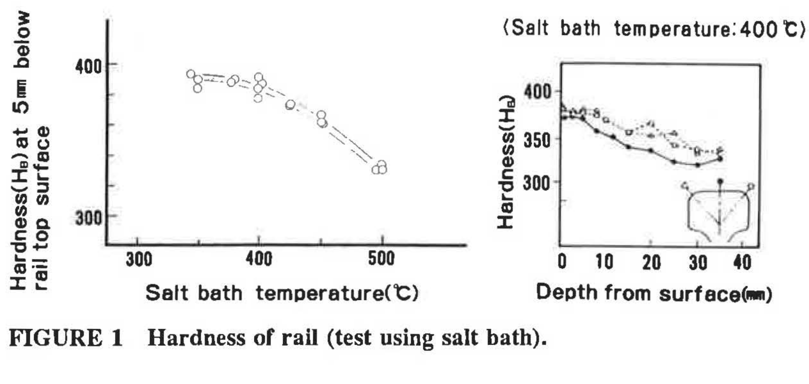


FIGURE 1 Hardness of rail (test using salt bath).

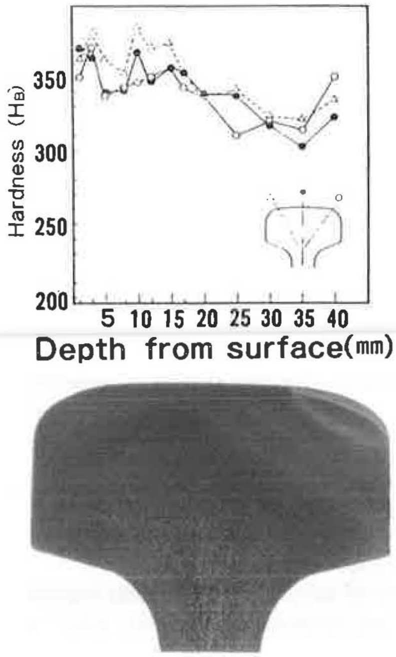


FIGURE 2 Hardness (*top*) and macrostructure (*bottom*) of rail (test using mist).

substantial variation in rail quality, was judged extremely difficult to use as a cooling medium.

An example of the variation in cooling with mist is shown in Figure 3.

Air

The test using air was conducted on rails immediately after rolling at a testing facility capable of treating 39-ft rails. The test results, obtained with standard carbon steel rails (Figure 4), indicate that rail quality is homogeneous throughout and that rails of different hardnesses can be produced by varying the air pressure. However, it is difficult to produce rails comparable in strength with NHH rails.

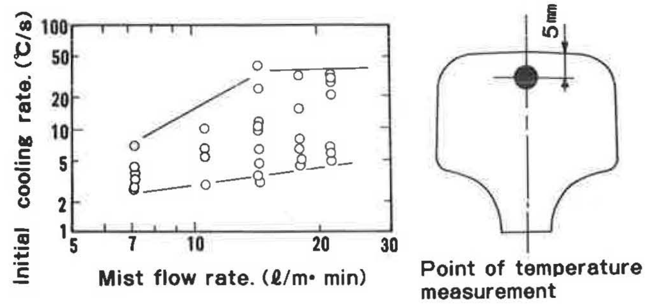


FIGURE 3 Variation of cooling rate in mist cooling.

Test results obtained with alloy steel rails (which have the same composition as Super rails) are shown in Figure 5. By adding elements such as chromium and silicon, it is possible to manufacture high-strength rails comparable with NHH rails.

Use of Air for Direct Heat Treatment

On the basis of the test results, it was decided to employ air quenching for the direct heat treatment. As the test results indicate, direct heat treatment with air quenching produces rails that are homogeneous throughout, and facilitates heat treatment of alloy steel. The drawback with this process is that, because air cannot cool the rails at the required rate, it is extremely difficult to manufacture high-strength ($H_B \doteqdot 370$) rails of standard carbon steel on an industrial scale. Though this problem may be solved by raising the air pressure, it is difficult to apply this method in industrial production.

Eventually it was decided to manufacture high-strength rails by adding very small amounts of alloying elements. Figure 6 shows initial cooling rate versus rail head surface hardness for three types of steel. The cooling rate can be controlled by regulating the air pressure with nozzles designed on the basis of the test results.

PROPERTIES OF DHH RAIL

The principal properties of rails manufactured by direct heat treatment using air quenching are described below.

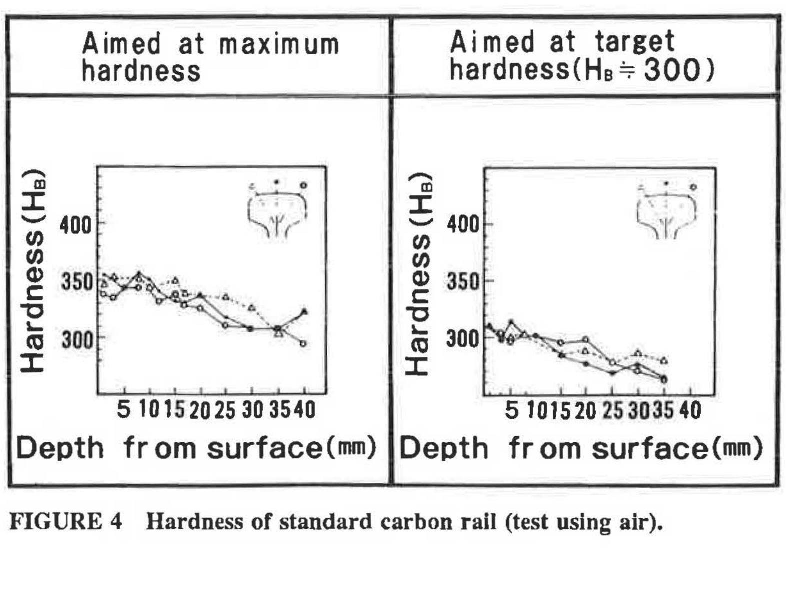


FIGURE 4 Hardness of standard carbon rail (test using air).

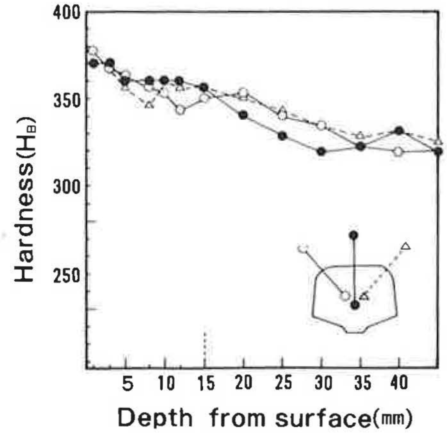


FIGURE 5 Hardness of alloy steel rail (test using air).

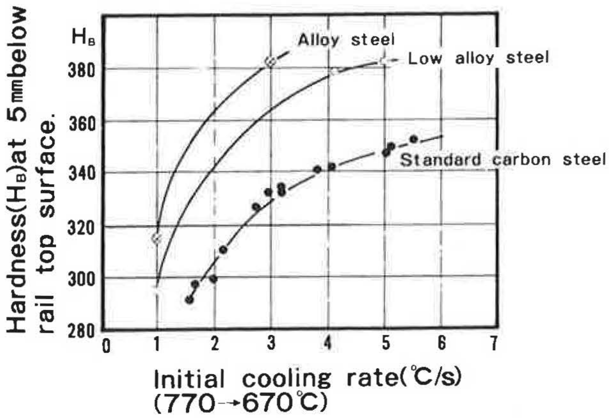


FIGURE 6 Relation between hardness and initial cooling rate.

Rails manufactured by this process are called deep head hardened rails.

Mechanical Properties

The mechanical properties of DHH rail in comparison with those of NHH rail are shown in Table 2. The strength of DHH rail measured at a point near the surface is almost the same as that of conventional NHH rail, but at a point further inside, it is higher than that of NHH rail.

Hardness and Structure

Figure 7 shows the section hardness distribution and macrostructure of direct heat-treated rails manufactured with an aimed hardness of H_B 370 compared with conventional NHH rail. It can be seen that the two types of rail have nearly the same surface hardness, but that the DHH rail has hardened deeper than the NHH rail. The DHH rail shows a uniform macrostructure pattern, whereas the NHH rail shows a softened layer caused by reheating.

Figure 8 shows the microstructure of both types of rail. Like NHH rail, DHH rail has a fine pearlitic structure.

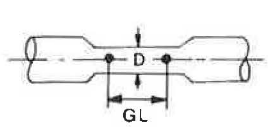
Figure 9 shows the hardness distribution over the entire section of DHH rail. The rail head shows a good hardness distribution.

Wear Resistance

Figure 10 shows the results of a wear test using test pieces taken from the head surface layers of various types of rail. In the case of rails that have a pearlitic structure, harder rails generally show better wear resistance. This suggests that DHH rail can retain the wear resistance of its surface layer even

TABLE 2 MECHANICAL PROPERTIES OF DHH 370 RAIL COMPARED WITH NHH RAIL

	DHH 370 rail				NHH rail			
Item / Sampling position	0.2% proof stress (Mpa)	Tensile strength (Mpa)	Elongation (%)	Reduction of area (%)	0.2% Proof stress (Mpa)	Tensile strength (Mpa)	Elongation (%)	Reduction of area (%)
5 mm, D=6 mm, GL=21 mm (3.5D)	863	1,294	15	34	843	1,304	15	35
15mm, 15mm, D=12.7 mm(1/2") GL=50.4 mm(2")	834	1,275	12	29	745	1,157	10	25



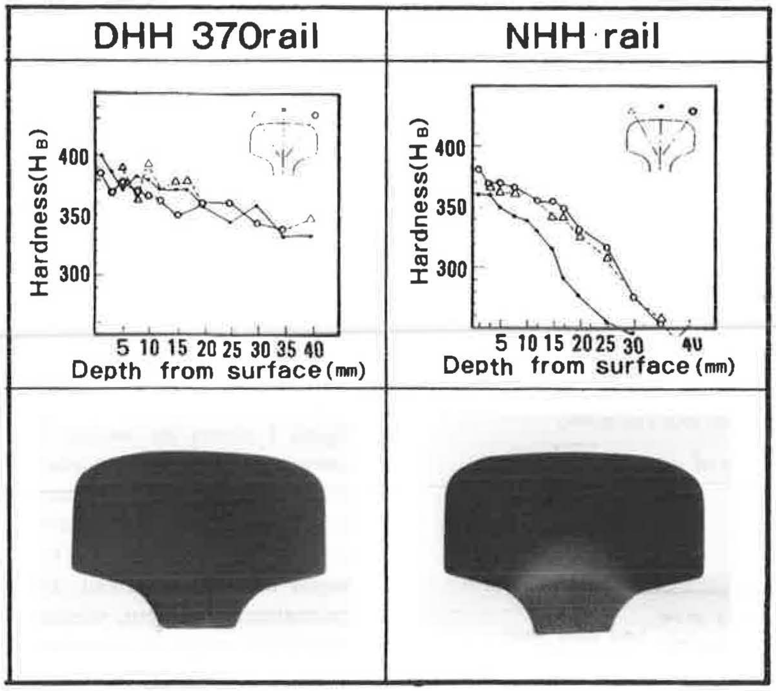


FIGURE 7 Hardness (*top*) and macrostructure (*bottom*) of DHH 370 rail compared with NHH rail.

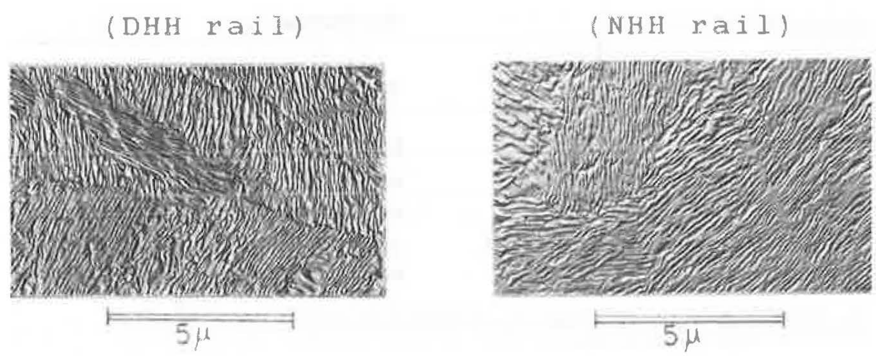


FIGURE 8 Microstructure of DHH rail compared with NHH rail.

when the head surface is ground; the wear resistance of its surface layer is almost the same as that of NHH rail.

Rolling Contact Fatigue Characteristics

Figure 11 shows the results of a rolling contact fatigue test conducted on DHH and NHH rail. The test was conducted on rail that was oil lubricated to prevent wear. The DHH 370 rail showed excellent resistance to damage compared with that of conventional NHH rail. DHH 340 rail also showed good resistance to damage.

Residual Stress

Figure 12 shows the residual stress in DHH and NHH rails. In the direct heat-treatment process, the amount of rail bending can be minimized by controlling the air blow. Hence the reduction through roller straightening can also be minimized. This makes it possible to reduce the surface residual stress in the rail top to near zero.

Weldability

Figure 13 shows the hardness distribution of DHH rails subjected to flash-butt welding. Compared with conventional NHH rail, in DHH rail the hardness of welded sections is subject to less deterioration, which suggests that no heat treatment is needed after welding.

DHH rail that is manufactured by adding a small amount of alloying elements and by controlling the rate of air quenching offers excellent weldability, as shown in Figure 13, thanks to the favorable effect of the alloying elements.

MANUFACTURE OF DHH RAIL

On the basis of the results found during development, Nippon Steel started construction of production equipment at the beginning of 1986. The equipment was completed at the end of May.

Each rail is rolled to 150 m, cut to specified lengths, and immediately subjected to direct heat treatment. It has become

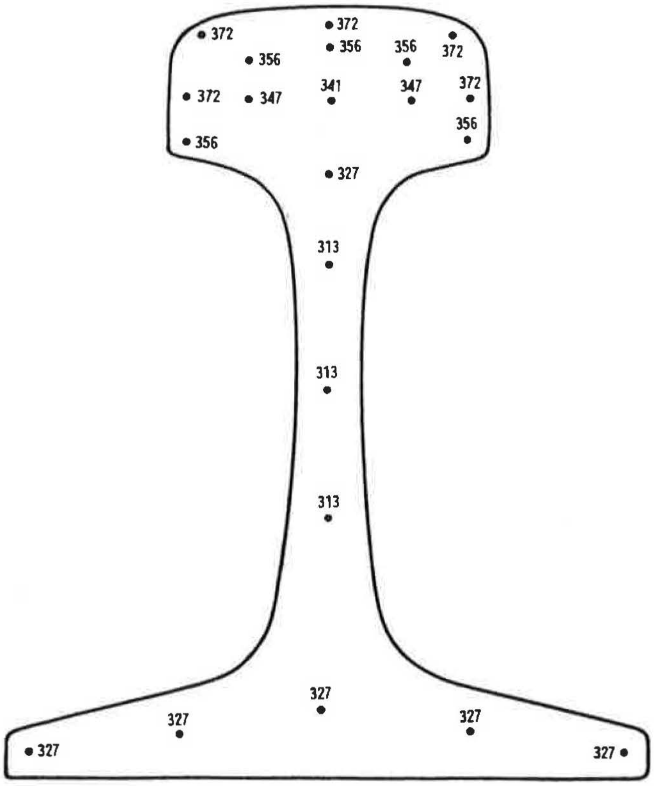


FIGURE 9 Hardness distribution on transverse section of DHH 370.

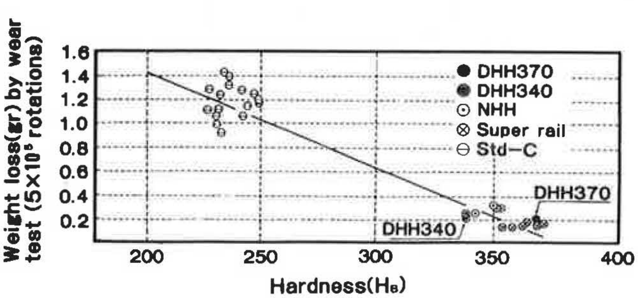


FIGURE 10 Relation between weight loss by wear test and rail hardness.

possible to produce large volumes of high-strength rails; formerly, production was limited by the capacity for off-line heat treatment.

The production equipment features a fully automatic rail conveyor system and an automatically controlled cooling system; hence it can stably produce high-strength rails.

Testing of the equipment and an in-depth quality examination of rails produced by the equipment was completed in 1987, and Nippon Steel has started shipment of high-strength rails manufactured by this equipment. Nippon Steel plans to market three types of rails—DHH 340 ($H_B \doteqdot 340$), DHH 370 ($H_B \doteqdot 370$), and DHH 370S ($H_B \doteqdot 370$)—to be produced by this equipment. All three types can be applied, depending on track conditions and the use of suitable lubrication. Continued research and development for further improvement of rail quality is expected.

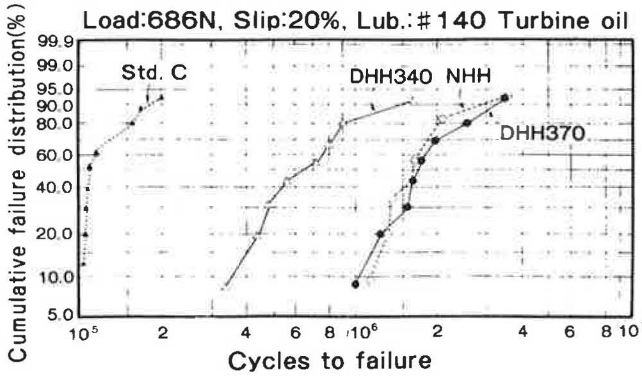


FIGURE 11 Rolling contact fatigue characteristics of various rails.

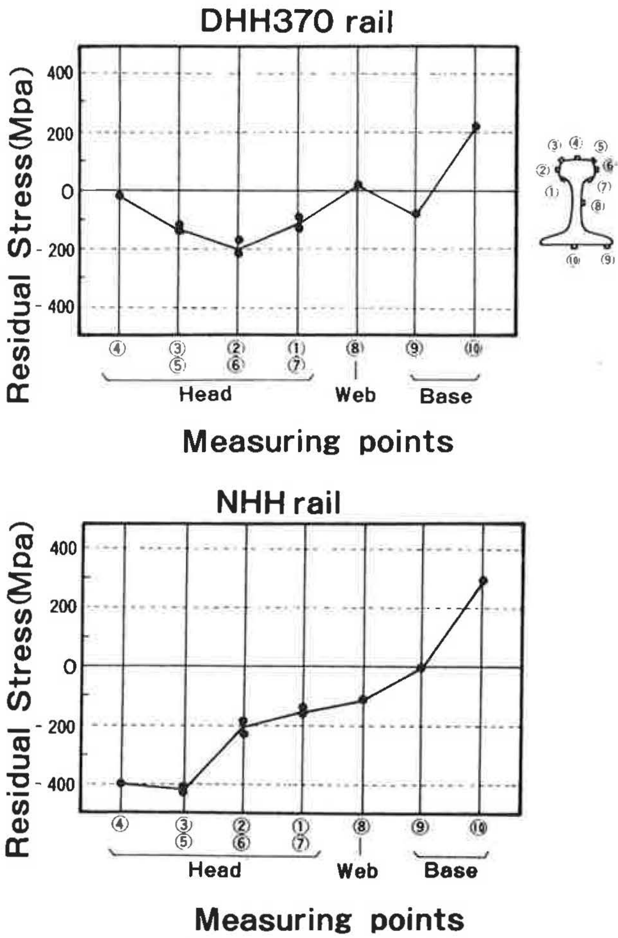


FIGURE 12 Typical residual stress on rail surface.

CONCLUSION

Nippon Steel has developed new heat-treated rails called DHH rail, the features of which are as follows:

1. Various grade types of strength and hardness,
2. A deep and uniformly hardened layer in the rail head,
3. High weldability, and
4. Uniform quality throughout the entire length.

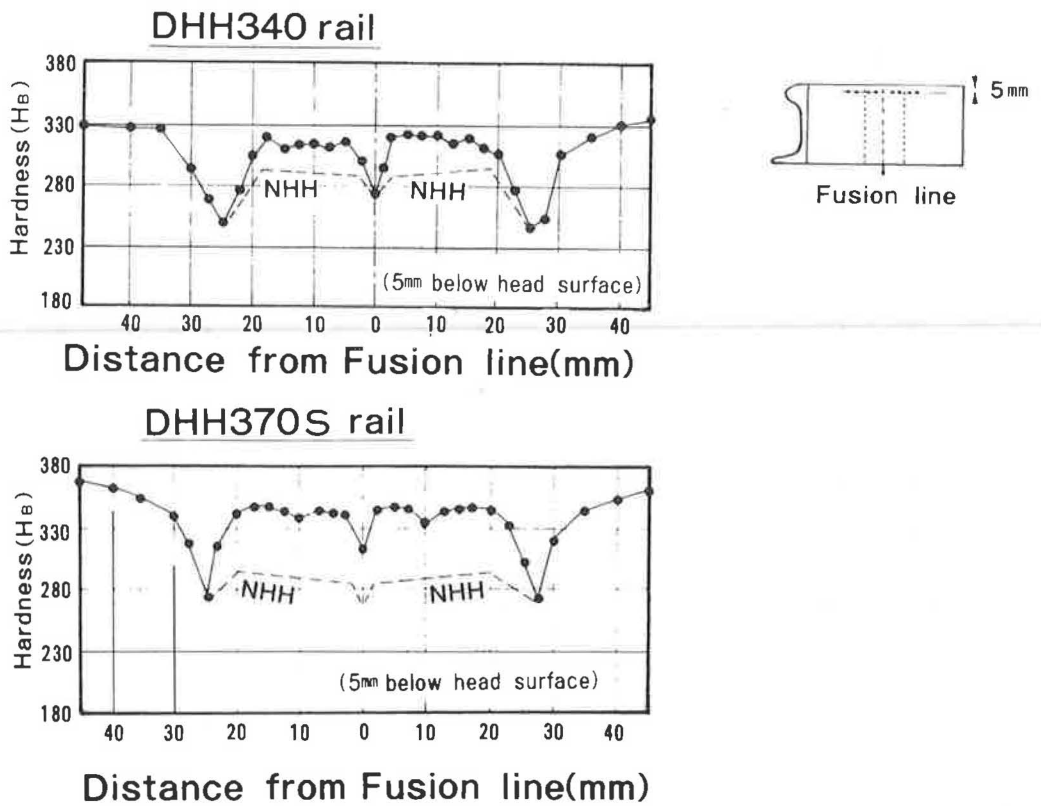


FIGURE 13 Weldability—flash-butt welding (welder k355).

Nippon Steel has completed the production equipment and started commercial shipment of DHH rail.

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