Technical Report

History of Steel Sleepers and the Latest Developments

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Abstract

The development of steel railway sleepers, which are manufactured and marketed by Nippon Steel & Sumitomo Metal Corporation and Nippon Steel & Sumikin Texeng. Co., Ltd., started in 1982 as export products for foreign mining railways. The shape of present sleepers is basically designed based on the shape and design method of steel sleepers in Europe and America, but it has been improved based on the quantitative research on safety and long service-life performance. Also, development on fastening devices has been given for improved usability and cost efficiency. This report reviews the history of developments in steel sleepers and introduces the recent optimization of heavy-weight heavy-duty steel sleepers applied in steel making plant railways.

1. Introduction

Steel railway sleepers, which have been used in various countries in Europe, Africa, and Asia for many years, are also used in Japan for steelmaking plant railways and for part of the main lines (mainly in freight yards) and Apt system sections of JR (Japan Railways). Steel sleepers have the following characteristics.

- Steel sleepers, which can be completely reused, are environment-friendly materials.
- (2) Steel can be flexibly processed by stamping, making it possible to manufacture products in various dimensions and forms.
- (3) The large lateral ballast resistance exerts a significant inhibiting effect on track misalignment.
- (4) The load is effectively dispersed, which allows for a reduction of the ballast depth.
- (5) The weight equivalent to that of wooden sleepers facilitates the transport and construction work.

Nippon Steel & Sumitomo Metal Corporation and Nippon Steel & Sumikin Texeng. Co., Ltd. have been manufacturing and providing steel sleepers that make the most of these characteristics for not only our steelmaking plant railways, but also those of other steel manufacturers, while distributing to private railway companies as well (**Photo 1**). In this report, we look back on the history of steel sleeper technologies developed by Nippon Steel & Sumitomo Metal starting from the background of the launch of technical development of steel sleepers to the present day. Furthermore, we introduce our



Photo 1 Steel sleeper

latest initiatives toward the improvement of application technologies of steel sleepers.

2. Development of Steel Sleepers

The steel sleeper development of Nippon Steel Corporation (hereinafter referred to as "NSC") was started in 1982 when NSC conducted a project on sleepers for export for use in overseas mining railways. After that, we started manufacture by rolling of steel sleepers for light axle loads (axle load P=18 to 25 t) in January 1984. In July 1985, a railway development team was set up in the development group under the Civil Engineering and Construction Technologies Office of the Equipment Engineering Unit at the time to embark on a project called Long Service Life Track Structure Research, which was a three-year full-scale study of application technologies that finished in 1988.

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Since then, through the improvements of various parts including fastening devices from 1992 made in the pursuit of sales expansion to the JR group and other private companies, we have continued the development of technologies.

2.1 Grounds for determining the cross-sectional shapes of steel sleepers

2.1.1 Start of a committee for turnout structure improvement/development for heavy axle load and its development outcomes

The history of the development of steel sleepers at NSC dates back to the Heavy Axle Load Turnout/Understructure Improvement/ Development Research Committee established in July 1979. To meet the demand for technical support and cooperation regarding construction and renovation of railways in various overseas countries, Japan's steel and turnout manufacturing industries had to acquire expertise. Given this situation, the activities of this committee were promoted with the goal of the application of steel sleepers to turnouts for heavy railcars with heavy axle load and also to general tracks. The committee's head office was set up in the Japan Railway Engineers' Association, the members of which consisted of Japanese National Railways (hereinafter referred to as "JNR"), Nippon Steel Corporation, Nippon Kokan Kabushiki Kaisha, Kawasaki Steel Corporation, and the Japanese Railway Turnout Manufacturers' Association. By the committee, research and development were boosted using data obtained regarding both Japan and overseas, through surveys of steel sleeper usage/installation statuses and analysis of the results of investigations into the actual conditions in railway construction sections. The accomplishment of these activities was reported in the Heavy Axle Load Turnout/Understructure Improvement/Development Research Report in March 1983.1) An outline of the content of the report is described in the following subsections. 2.1.2 Concepts regarding design conditions and allowable stress

The basic concepts used for determining design conditions and allowable stress of steel sleepers are as follows.

(1) Design loads

Two types of steel sleepers were studied: Sleepers for light axle load and those for heavy axle load. JNR's PC sleeper design axle load (P=16t; for Shinkansen lines and regular railway lines) was adopted for sleepers for light axle load and the standard axle load E80 (P=36t; for steel structures) used by the American Railway Engineering Association (AREA) for designing bridges was adopted for sleepers for heavy axle load.

(2) Design methods

The JNR's method for designing PC sleepers and the German Federal Railway's (Deutsche Bundesbahn [hereinafter referred to as "D.B."]) method for designing steel sleepers were employed. The allowable stress of the base material was determined based on the concept of the D.B.

2.1.3 Concepts regarding the shapes, dimensions, and weight

Regarding the cross-sectional shapes and dimensions of steel sleepers, four cross-sectional shapes were designed for sleepers for light axle load and three shapes for sleepers for heavy axle load, with reference to the shapes of existing steel sleepers (in the shape of an upturned bowl) used in various European countries. For the shapes and dimensions of the ends of steel sleepers, lateral ballast resistance tests were conducted and the test results were compared to those of PC and wooden sleepers. Based on the results of the comparison, the drawing height, bending radius, and bending gradient were determined. The weight of sleepers was determined with reference to the weight of the wooden sleepers used by JNR (60 kg per sleeper) in consideration of a corrosion margin of 1 mm.



Fig. 1 Fugure of form measure (light axleload, heavy axleload)

Based on the conditions described above, the thickness of a steel sleeper for light axle load was determined as 8 mm and that for heavy axle load 11 mm. After the consideration of various factors including the results of tests on the steel sleepers as designed, restrictions regarding manufacturing, and packing style when shipped (when stacked up), one shape was selected for each sleeper type. The shapes and dimensions of the steel sleepers for light axle load and heavy axle load are shown in **Fig. 1** along with other performance data. These were the first shapes determined in the history of bowl-shaped steel sleepers currently used in Japan.

2.2 Development of NSC steel sleepers

Alongside the activities in the above-mentioned committee, NSC started developing its own steel sleepers when it was approached in 1982 by two companies handling mining railways, Companhia Vale do Rio Doce (hereinafter referred to as "C.V.R.D.") based in Brazil and also by British Columbia Mining Railways in Canada (hereinafter referred to as "B.C.R"). The development was promoted under a cooperative development structure of the Civil Engineering and Construction Technologies Office of the Equipment Engineering Unit (hereinafter referred to as "PET-B") at that time, Bar Steel Engineering Department in Yawata Works (hereinafter referred to as "Yawata Bar Steel"), and Yawata R&D Lab. (hereinafter referred to as "Yawata Lab.") of the Central Research Laboratories. In the development, based on the design conditions proposed by each company during discussions (Table 1¹), the allowable stress of steel materials to be used was determined while referring to JNR's and D.B.'s past researches and the cross-sectional properties required of sleepers were examined.

2.2.1 Determination of allowable design stress intensity

By referring to JNR's and D.B.'s past research results, NSC determined the allowable stress intensity (bending, tensile, and compressive stress) of steel sleeper materials in conformity to the Design Standard for Steel Structures by the Architectural Institute of Japan and also determined the allowable stress intensity involved in fatigue following D.B.'s concept, which was based on DIN (Deutsches-Industrie-Norm).²⁾ The determined conditions are as follows.

- (1) The stress condition at the lower end of a sleeper satisfies the allowable stress intensity for flexural yielding.
- (2) The allowable tensile stress intensity is a safety factor value that is 1.7 to 1.8 times the yield strength.
- (3) The allowable compressive stress intensity is set to the yield strength level in consideration of the fact that maximum com-

		C.V.R.D	B.C.R
Condition	Rolling stock load	Locomotive: 10.2 t/wheel	Cooper E-80
		Fraightcar: 11.25 t/wheel	$(\approx 36 \text{ t/shaft})$
	Operation speed	Low ground 60 km/h	40 mile/h
		High ground 40 km/h	$(\approx 65 \text{ km/h})$
	Minimum curve speed	143.24 m	12° (R=1746.38/12°
			=145.5 m)
	Track gage	1 000 mm	1 435 mm
	• Rail	136lb	115lb
	Annual transport volume	7000 ten thousand t/year	$1.2-1.5 \times 1000$ ten thousand t/year
Existing	Existing sleeper plane measure layout	Wood: 240×2300 @500	Wood: 9"×8" (≈230×2400)
		PC: @645	@20" (≈51 cm)
Plan	Sleeper plane measure	260×(2000–2300 mm)	280×(2300–2600 mm)
	Sleeper layout space	650mm	650 mm

Table 1 Steel sleeper plan condition¹⁾

pressive stress intensity works on the lower end of the center of a sleeper, but no buckling occurs as long as the compressive stress intensity does not exceed the yield strength.

(4) Allowable fatigue stress intensity conforms to the concept of D.B. based on DIN5018.

2.2.2 Consideration of cross-sectional properties required

Cross-sectional properties required for steel sleepers were calculated in accordance with the flow as shown in **Fig. 2**²). The results were compared to the specifications and properties of the cross sections of existing steel sleepers to determine the optimum cross-sectional shapes.

2.2.3 Grounds for determining the final cross-sectional shapes

The cross-sectional shapes of steel sleepers were determined based on the various allowable stress intensity values determined and the required cross-sectional properties examined. The final basic forms were determined such that the value obtained when the section modulus was divided by weight became maximum, selected from the cross-sectional shapes that satisfied the required section modulus by reference to the cross-sectional shapes that JNR had examined. In addition, the forms of the bends at the ends were checked in various indoor tests conducted jointly by the three sections mentioned above from 1983 to 1984, and the bending height with lateral resistance equivalent to that of the PC-3 sleepers was set to 210 and 170 mm.

We determined the cross-sectional shapes on the grounds of the following matters.

- (1) Web width: The cross section for sleepers for light axle load that JNR had researched was adopted.
- (2) Bulb shape: The shapes for sleepers for light axle load and heavy axle load that JNR had researched were adopted.
- (3) Flange slope: Upper portion: 40/30≈1.33, JNR/≈1.78, ≈1.56 Lower portion: The slope that JNR had researched was adopted.
- (4) Corner R: The cross sections that JNR had researched were adopted.
- (5) Sleeper length: Set to 2000 to 2600 mm in accordance with the conditions proposed by the mining companies.
- (6) Thickness and height of the cross sections: A corrosion margin of 1 mm (both sides) was set in addition to the calculated cross-section factor required. Moreover, the thickness and height were selected such that the value obtained when the cross-section factor was divided by weight became maximum.



Fig. 2 Calculation flow for the section design of steel sleepers²)

The thickness of webs was made thicker than that of the flanges in consideration of corrosion caused by rain, snow, etc. The determined cross sections are shown in **Fig. 3**²⁾.

Since then, the basic cross-sectional shapes of NSC steel sleepers have not changed to date. However, regarding the cross section of steel sleepers for heavy axle load, the thickness and other properties were improved when they were applied to steel making plant railways, developing into the shape currently used. (The improvement includes the changes in the thickness of the flange from 10 mm to 11 mm and in the unit mass from 33.17 kg/m to 35.36 kg/m.) 2.2.4 Cold single-piece stamping

For the stamping process of these steel sleepers, Yawata Bar Steel invited subcontracting companies that were engaged in maintenance operations at NSC steelworks to take part in a contest to develop methods for stamping steel sleepers with the final cross-sectional dimensions (Fig. 3) and the shapes of the ends by putting forward proposals. However, forming these sleepers with complicated shapes that required high finishing accuracy by stamping were difficult at that time. As a result, only one company was able to propose





a forming method.

However, the proposed method was composed of three stamping processes (cant slope: one process; forming of the ends: two processes) due to the complicated forms and high finishing accuracy requirement. Soon after the rolling of materials of steel sleepers began in January 1984, mass production was started with many unsolved issues regarding the quantity of products shipped and cost efficiency due to the three step stamping. In order to solve these issues, NSC started developing a method for cold single-piece stamping of sleepers in July 1985 and completed the development in July 1986. This new method allowed for manufacture in one single stamping process of sleepers, which had been manufactured in three stamping steps.

(1) Development of stamping dies

Steel sleeper shapes are designed to have chokes at both ends to obtain lateral ballast resistance and taper (cant) of 1:40 in the longitudinal direction of a sleeper. NSC worked on the development of upper and lower dies to cold stamp these sleepers in one forming process and filed a patent application for the method of manufacturing steel sleepers with hooks in 1986, for which a patent was granted in 1988 with dies and forming processes included in the scope.

The method was characterized by the supine position that the material of a sleeper assumed during stamping when it was set using a guide metal fitting for positioning and preventing misalignment. In addition, the upper die punch was connected to the rolling cylinder in the upper part of a stamping machine, which allowed the die to freely move up and down.

The stamping operations and situations during the forming process are as follows (**Fig. 4**).

- (i) The upper die punch rolls both ends of the material into flat shapes splaying out. The material starts to yield to the bend punch from the part with which the bend punch is in contact.
- (ii) When rolling down the material until the bend punch of the upper die punch comes into contact with the bend die dice, the bending in the longitudinal direction of the sleeper (cant) and the bending at both ends can be completed simultaneously.
- (iii) As the characteristics of the dies, the upper bend punch is a roller type and the lower bend die dice has a wheel type prom-



Fig. 4 Steel sleeper one piese forming

inence at the center of the roller, which forcibly forms a concave in the bent part at the ends and prevents undesired expansion in the width direction.

(2) Continuous manufacturing

The achievement of the single-piece stamping for steel sleepers realized the establishment of a highly productive and economical manufacturing method that also significantly improved the product quality including the finishing (dimension) accuracy. After that, in addition to this ability of the method, equipment that allowed for continuous drilling for fastening devices and continuous finishing operations by pressing up were gradually added.

3. Development of Fastening Devices for Steel Sleepers

To expand the sales of steel sleepers, not only the base material but also the fastening devices that secure rails to the base material need to be durable and cost competitive.

Steel sleepers, the development of which was started as products for the overseas market, were originally manufactured by rolling two types of sleepers (for light axle load and heavy axle load) from 1984 to 1985. However, the exports were greatly influenced by the Plaza Accord in 1985. By the Plaza Accord, the U.S. adjusted the exchange rate in order to correct the adverse balance of international payments of the U.S. and higher dollar situation against other currencies that occurred in the course of Reaganomics under an agreement between other countries. Whereas the yen had remained around 250 yen against the dollar before the Plaza Accord, it rose by 30% or more in only one year or so, reaching 150 yen against the dollar once. This yen's sharp rise directly hit the export industry in Japan, which forced the Japanese economy into a serious recession caused by the strong yen. The steel sleepers of NSC also lost their competitiveness like other products and the decrease in the number of orders for export became conspicuous. Given this situation, NSC that needed to change the direction of business and to expand the sales in the Japanese market started developing fastening devices with the aim of cost reduction of products, in parallel with the development of new products including short steel sleepers and steel railroad crossings. The history of the development of various fastening devices is shown in Fig. 5. Some of such initiatives are described as follows.

3.1 Bolt fastening

The bolt fastening method for steel sleepers was adopted in 1984. The utility was evaluated in actual steel making plant railway tracks. This rail fastening method was widely used in Japan and took into account heavy loads that characterize steelwork railways.



Fig. 5 History of fastener development details

3.1.1 NSC rail fasteners: Rigid fastening

Direct fastening devices manufactured in 1984

These fasteners were designed by the PET-B and were manufactured by a fastener manufacturer. Fixed seats for placing bolts for securing sleepers to rails were welded to sleepers. Fastening T-bolts were placed on the fixed seats, and sleepers were secured to rails by tightening rail clips. Gauge adjustment plates installed on the back were able to be used to adjust the railway gauges. These fasteners required rail clips for chocks to prevent rails from inclining at curves. We have been providing two types of fasteners, fasteners for sleepers with light axle load and for sleepers with heavy axle load. The use in actual rail tracks was started in 1984.

3.1.2 NSC rail fasteners: Elastic fastening

Elastic fastening devices manufactured in 1987

The Long Service Life Track Structure Research started in July 1985 selected the development of NSC elastic fastening devices as a research theme to solve a remaining issue regarding the reliability of fasteners that were used to secure steel sleepers to rails. The need to develop plate spring fastening devices that were prevalently used for utility railways in Japan, which were high-speed and light-load railways, was recognized in order to expand the use of NSC steel sleepers to utility railways in addition to railways in steel making plants. NSC designed and prototyped plate spring fastening devices to carry out usability evaluation tests for them under the guidance of the Railway Technical Research Institute in Japan. The development of these plate spring fastening devices was completed in 1987.³ After that, they were tested on actual railways during promotion activities. Despite that, the high production costs forced the relinquishment of these fastening devices.

The fastening method of these fastening devices remains today as the TH-type bolt fastening for insulated sections and as the TWtype in non-insulated sections. Since these methods involve welding for joining fixed seats, checking for fatigue cracks on the welds and fastening torque and looseness of the bolts are required in the maintenance work.

3.2 Line spring fastening

Line spring fastening, a fastening method developed in the U.K., is a standard method currently used in Japan. Fastening devices used for this method can be installed and removed using special tools. Only fastening line springs in predetermined positions achieve the fastening power required. In addition to this, large resistance to railcreepage can be obtained. As no bolts are used for this method, torque management and other similar maintenance work are not required, optimally contributing to labor saving. When NSC steel sleepers were launched for steel making plant railway use and railway company use, these line spring fastening devices were selected to be used as fastening devices for NSC steel sleepers that were capable of reducing the costs and also of contributing to the efficiency of maintenance work.

3.2.1 Forged fixed seat

Forged fixed seat manufactured in 1986

NSC manufactured a fixed seat exclusively used for Pandrol clips (line springs) in order to adopt the line spring fastening method for the steel sleeper fastening devices. The dimensions (shape) of a fixed seat made by Pandrol were followed. The SM material (a rolled steel material for welded structures) was selected in consideration of the weldability to the base material of steel sleepers. Plate bending type plates were manufactured by forging.

The use of this fixed seat involved a high level of product inspection required by Pandrol in terms of warranty of Pandrol clips' (line springs') performance (securing of fastening power). Therefore, the manufacture of this fixed seat required particularly close attention. In addition, when welding the fixed seat, the penetration bead welding was performed at grooves to perform full penetration welding for the entire thickness, thereby resisting the shear force from the rail bottoms. As a result, the following issues regarding workability arose.

- (1) Penetration bead welding, which requires a high level of skills, caused the processing efficiency to decrease.
- (2) As the manufacture involved downward groove welding, each welding orientation of a steel sleeper required a different inclination, which significantly reduced the processing efficiency.
- (3) Use of a grinder was required to finish weld beads on the rail side of a fixed seat, requiring much labor and time (due to friction between rails and beads).
- These issues significantly increased the welding costs.
- 3.2.2 Hot-extruded fixed seat

Hot-extruded fixed seat manufactured in 1987

In order to avoid the issues entailed in the welding of the plate bending type fixed seat (forged fixed seat), an inexpensive form of fixed seats with high functionality that made it easy to secure high quality was examined, and a hot-extruded fixed seat using a rolled product made by Hikari Works was adopted.

The specifications of welding in the following two cases were examined.

- (i) Fillet welding on three sides from which the rail side was excluded
- (ii) Welding on all sides (four sides): Groove welding for one side on the rail side and fillet welding on the other three sides

Whereas the fillet welding on the three sides allowed for significant reduction of the welding cost, there was concern over the possibility of detachment of fixed seats when the steel would be rusted due to rainwater that might enter the bottom of the seats from the non-welded side on the rail side. Therefore, corrosion at the bottom of this fixed seat welded on three sides was studied, resulting in no detachment observed. In addition to this study, a static load test and dynamic fatigue test were conducted, which showed the safety against loads of trains. In view of these results, fillet welding on three sides was adopted.⁴)

3.2.3 Hook-in fixed seat

Hook-in fixed seat manufactured in 1997

In pursuit of the expansion of the sales of NSC steel sleepers by reducing prices, a new mechanism was developed: A hole (18×44 mm) for securing a fixed seat was made in the base material of a steel sleeper to support loads of trains (lateral pressure) with the hole surface.⁵⁾ A static angle load test and dynamic angle fatigue test were conducted in-house to check deformation and fatigue resistance. Along with that, a fixed seat with the new mechanism was tested on the tracks of private railway companies. In this manner, examination toward adoption was promoted. However, as this fixed seat was not sufficiently appreciated in terms of stability when installed, adoption was not realized.

3.2.4 Single-piece fixed seat

Single-piece fixed seat manufactured in 2001

The development of a single-piece fixed seat for a revised line spring fastened steel sleeper with reduced price was launched. In this development, the fixed seat was formed from the base material of a steel sleeper by hot-pressing up the base material in pursuit of the reduction of the material costs and installation costs of the fasteners. Existing researches show that the strength and durability of the base material are equivalent to or greater than those of PC sleepers. This fixed seat also needs to have the same level of durability as that of the base material in order to make this fixed seat formed by pressing capable of enduring the pressure of rails and lateral pressure work on it.

(1) Hot stamping of fixed seats

In the initial stage of the development, the single-piece fixed seat had a hole, into which a line spring was inserted, with openings on both sides, following the form of existing fixed seats for line springs. The following items were examined (verified) as elements required for the development of this fixed seat.

- (i) The position, shape, dimensions, and processing methods of the slit
- (ii) Heating temperature, range to be heated, and heating methods
- (iii) Shapes of the upper and lower dies
- (iv) Number of pressings
- (v) Cooling methods

As a result of the study on these subjects required for the development, the final form of the hole for inserting a line spring was determined such that it had one opening only on one side, which allowed for development of the single-piece fixed seat within the specified dimensions and thickness (≥ 7.5 mm). (2) Strength (durability)

The durability of the single-piece fixed seat was checked in a

static angle test and dynamic angle fatigue test. In order to check that the single-piece fixed seat had the durability equivalent to that of the base material of sleepers, live load A (wheel load: 9.75 t; lateral pressure: 6.0 t) with the maximum modulus of premium $(m+3\sigma)$ as prescribed in Japan's technical standards was selected as the load used in the tests from among the design loads of rail fastening devices. A model of a beam on continuous elastic foundation was used to calculate the rail pressure and lateral rail pressure. The angle between the resultant force (8.96 t) and the vertical axis was set to 47° to conduct an angle test.

In the static test, the strain value measured on the fixed seat was $350 \ \mu$, which became 72.5 MPa when converted into stress, constituting around 22% of the allowable value (323 MPa). This confirmed that the strength is sufficiently high to be practically used. The fatigue test was conducted using the same test load as that used in the static test, and repeated loading (2 million times at repeating rate 1 Hz) to observe if any crack was formed. As a result, the durability was also confirmed to be sufficiently strong.⁶

(3) Residual stress test

The residual stress distribution during hot pressing of the fixed seat was measured by the intercept method using a strain gauge. The result showed that the residual stress in the fixed seat was a compressive residual stress, working favorably on fatigue resistance.

(4) Production of a special installation tool

In time for the manufacture and shipment of the product, a new special tool for installing line springs exclusively used for this single-piece fixed seat was produced. This tool was a revision of the existing tool that had the disadvantage of the fulcrum (hook) that was to be fit at the edge of the hole of a fixed seat (with holes on both sides), whereas the single-piece fixed seat had an opening only on one side. Due to this difference in the structure between them, the fulcrum of the existing tool only contacted the surface of the single-piece fixed seat, and the hook did not catch hold. The fulcrum of the improved special tool has no hook but has a metal plate in order to prevent the single-piece fixed seat from being damaged when installing a line spring (**Photo 2**).

In 2002, a prototype of a steel sleeper with the single-piece fixed seat was made adopting a thicker fixed seat as a steel sleeper for heavy axle load for use in steel making plant railways. The prototype was tested on actual railways, but a crack from the notch of the



Photo 2 Install tool

base material due to train loads was found. For this reason, the product is currently sold for use only in steel sleepers that are in exclusive use for light axle load.

4. Development of Optimum Specifications of a Steel Sleeper for Heavy Axle Load Used in Steel Making Plants

In steel making plants, rail cars with heavy axle load (with approximately 36 to 50 t per axle), as typified by torpedo cars (hereinafter referred to as "TPC"), are used. Under such conditions, repeated loading by heavy axle load often causes the welds on the fixed seats of fastening devices to develop cracks due to fatigue, which determines the service life of steel sleepers. This means that if the life of fastening devices can be extended by preventing fatigue cracks, the cycle for replacing sleepers can be extended and maintenance costs can be reduced as well. Given this, examination on the service life extension of steel sleepers for heavy axle load was started in 2006.

As described above, various types of fastening devices are used for steel sleepers. For rail cars with heavy axle load in steel making plants, fastening devices using hot-extruded fixed seats (line spring fastening) have been most preferred in terms of the durability, simplicity of inspection and construction, and costs, except for locations under special conditions such as buried sections of railroad crossings. Thus, here we describe the examination on the extension of service life of hot-extruded fixed seats.

4.1 Fatigue test on the initial fastening device specifications and FEM analysis results

A fatigue test and FEM analysis were carried out to check the resistance to fatigue of hot-extruded fixed seats (width of the fixed seat: 70 mm) of the initial fastening device specifications.

The test was a dynamic angle fatigue test shown in Photo 3 in which the effects of wheel loads and lateral pressure were reproduced. In order to reproduce steel sleeper conditions on actual TPC railways, the imposed load was determined adopting a static loading condition under which the strain measured by a strain gauge placed at the toe of the weld on the rail side became 2200 μ (maximum value in the road test). For fatigue load, the test load was $P_{min} = P_{max}/10$ and the loading rate was 3 Hz. The progress of cracks was examined by conducting a magnetic particle inspection according to the progress from the time point when the strain amplitude was decreased by 5%. As a result, cracks were observed to start from the toe of welds on the fastening device (Fig. 6). The number of cracks found was approximately 540000, and the number of cracks that became B Cracks (cracks formed across half of the width of the fixed seat) was approximately 1.11 million; and the number of AB Cracks (cracks formed across the entire width of the fixed seat) was approximately 1.49 million.

Furthermore, the test loads imposed on the rails were separated into the horizontal and vertical components, and for each compo-



Photo 3 Fatigue test



Fig. 6 Crack progress mode

nent, the load to be analyzed was calculated based on the balance between the forces of the rail and sleeper to conduct FEM analysis. Contour diagrams showing the stress that occurred in the vicinity of the toe of the weld in the short-side, long-side, and vertical directions of the sleeper are shown in **Fig. 7**. The analysis results show that tensile stress occurred at the toe of the weld in the long-side and vertical directions of the sleeper. Cracks are considered to have occurred due to the tensile stress in these directions.

4.2 Measures for extending the service life

Based on the initial fastening device specifications (Case 1), a similar fatigue test and FEM analysis were conducted to examine the measures as follows that were expected to make a contribution to the service life extension.

- Case 1: Basic case (width of a fixed seat: 70 mm)
- Case 2: Processing using a grinder
- Case 3: Disposing of residual stress
- Case 4: Processing using a grinder plus disposing of residual stress
- Case 5: Shortening of beads
- Case 6: Shortening of beads plus processing using a grinder
- Case 7: Widening of the fixed seat (70 mm \rightarrow 120 mm)
- Case 8: Welding on four sides The characteristics of each measure are as follows.

A rotary burr grinder was used for the processing in Cases 2, 4, and 6 to remove undercuts and smooth the curvature at the toes of the welds. In addition, the base materials were slit in the depth direction by approximately 0.5 mm in order to reduce residual tensile stress caused by welding. The processing and management methods conformed to the coin test as specified in the Steel Structure Fatigue Design and Practical Guide.

In the disposing of residual stress in Cases 3 and 4, an excess load was applied from the back side of steel sleepers and then re-



Fig. 7 Result of finite element method

moved in order to generate springback, thereby giving residual compressive stress to the toes of welds. The average welding residual tensile stress was approximately 143 MPa at the toes of the welds in a prior test conducted for checking. After the excess load was applied, the average stress was approximately -178 MPa.

The shortening of beads in Cases 5 and 6 was designed to keep the toes of welds away from the portions with large stress in order to reduce the stress at the toes of welds that was mostly caused by wheel loads and lateral pressure.

In the widening of the fixed seat in Case 7, the width of the fixed seat was increased, taking note of the fact observed in the basic case that as the location was closer to the shoulder of the sleeper from the toe of the weld, the strain decreased. In addition, the width was set to 120 mm, which was the limit over which the hook of the beater would not come into contact with the line spring clip during machine tamping.

In Case 8, as the welding on three sides in the basic case caused tensile stress inevitably at the toes of welds due to plate bending deformation, welding on four sides was tested expecting a decrease of the tensile stress caused.

The fatigue test results of the cases above are shown in **Fig. 8**. The results of Case 6 (shortening of beads plus processing using a grinder) and Case 7 (with a width of the fixed seat of 120 mm) were favorable together with FEM analysis results.

In Case 4, given the existence of undercuts, which was considered to exert adverse impact when the excess load was removed in Case 3 with processing of residual stress only, the processing using a grinder was added. However, the effect obtained was not as expected. It is thought that the improved residual compressive stress was re-distributed for each magnitude of the working load and then eliminated.

In Case 8 (welding on four sides), as considered from the FEM analysis results that the finished form of the toe of each weld intensified the concentration of stress, initial cracks were actually formed at an early stage in the fatigue test.

In addition, although the measure involving shortening of beads can extend the service life, the weld length of the areas in which beads are shortened bears the force imposed by the fastening of a line spring, entailing an issue regarding the static strength at the welds.

Based on the results described above, an inexpensive and reliable measure that involves "processing using a grinder plus 120 mm width of the fixed seat" was adopted as basic specifications for NSC steel sleepers for heavy axle load for use in steel making plant railways, in view of the service life extension effect.





Photo 4 Koa Iron Crosstie

4.3 Development of new hybrid sleepers

At Kashima Works, the Koa-type steel sleepers (Koa Iron Crossties) shown in **Photo 4** have been used since 1999. This type of sleeper with a structure in which the back of a steel sheet pile is filled with concrete can reduce the stress imposed on the welds on a fastening device, the portion with the weakest fatigue strength. Therefore, this structure was considered to be effective in improving the fatigue resistance.

As a result of fatigue tests conducted for both Koa Iron Crossties and steel sleepers that used hot-extruded fixed seats with the back of the sleepers filled with concrete as with Koa iron crossties, no cracks were found in both types of sleepers after loads were applied repeatedly (10 million times). The FEM analysis also showed that the maximum main stress working on the toe of the weld was reduced to approximately 60 MPa, which means both types were



Photo 5 Construction tests

highly effective in extending the service life.

Next, sleepers were tested by being installed in a steel making plant railway (track gauge: 1067 mm) to investigate the construction time that would differ depending on the weight. The sleepers tested were Koa Iron Crossties (277 kg) and steel sleepers with hot-extruded fixed seats (93 kg; without concrete filling). The constructed track in the test is shown in **Photo 5** and the time that each type of sleeper required for the operations involved in the construction is shown in **Fig. 9**. When making comparisons per sleeper, the construction time of a Koa Iron Crosstie was longer due to the weight heavier than a steel sleeper with a hot-extruded fixed seat. However, Koa Iron crossties have an advantage of the interval between sleepers that can be made longer thanks to the high cross-sectional stiffness of steel sheet piles. Therefore, the construction times converted into the track length are almost equal.

Based on the results described above, an appropriate type of sleeper is selected that is superior in terms of the life cycle cost in accordance with the service environment, operation frequency, and axle loads in individual steel making plant railways when a new railway is constructed and when repair specifications are determined.

5. Conclusion

Since the launch of rolling the materials of steel sleepers in 1984, followed by the start of shipment of steel sleepers to Nippon Steel & Sumitomo Metal and other private companies (for use in yards for storing materials, etc.) in 1986, the study and improvement on various aspects of steel sleepers have been continuing up to the present day. The cumulative shipments for about 30 years by 2015



Fig. 9 Comparison of construction time for two sleeper types

amounted to 800000 sleepers with a steady increase in the use of steel sleepers. In view of the fields of railways where technologies and needs constantly evolve, we must continue developing technologies for improving workability and cost efficiency, in pursuit of the provision of more reasonable and cost-efficient steel sleepers.

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