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Development of Field Fusion Welding Technology for Railroad Rails

Makoto Okumura*1 Kenichi Karimine*1
Kouichi Uchino*1 Nobutaka Yurioka*1

Abstract:

In recent years passenger train speed and freight train load have been increased to enhance the efficiency of railroad transportation. These trends have increased the severity of the rail service environment as to wear resistance and fatigue damage resistance. Nippon Steel has met these challenges by developing high-performance and high-strength rails. Continuous welded rails (CWRs) have been increasingly laid to simplify track maintenance and inspection, control noise and vibration, and to ensure travel safety. Rail welding techniques are of the utmost importance for the laying of CWRs. The development and commercialization of new fusion welding techniques involving the novel idea of increasing the carbon content of the weld metal, a breakthrough in conventional welding technology, are described for in-track welding of high-performance and high-strength rails. The present status of automatic rail fusion welding technology expected to evolve further is introduced, and the future trends of rail welding are considered.

1. Introduction

Railroads have an important role to play in creating an efficient transportation system premised on safety. Specifically, passenger train speed and freight train load (axle load) have been increased to carry more passengers and freight at higher speeds. These trends impose more complex load and impact force on rails and constitute an extremely punishing service environment for rails. In particular, a large wheel load and horizontal pressure or tangential force act on the rail head running surface that contacts the wheels, and form a more complicated stress field right below the rail surface. The rail base is repeatedly exposed to large bending stress. As a result, rails must be improved in terms of wear resistance, resistance to fatigue damage that occurs in various forms, and bending fatigue strength to overcome these severe service conditions.

To meet this market demand, Nippon Steel developed the new head hardened (NHH) rail and NS II super rail, the head of which is reheated and slack quenched after rolling to produce a fine pearlite microstructure[1]. The company also developed high-strength rails, including the deep head hardened (DHH) rail with its head hardened to an unprecedentedly great case depth by in-line heat treatment after rolling[1]. At present, we are working to develop new rails to reduce the rolling fatigue damage (such as dark spots, shelling, and flaking) on top of the rail head that becomes a problem during high-speed train travel[2].

Continuous welded rails (CWRs) are increasingly being used as railway rails to simplify track maintenance and inspection, control noise and vibration, improve riding comfort, and to stabilize high-speed running. Standard-length rails (25 or 50 meters)

*1 Technical Development Bureau

shipped from a mill are welded into a length of 100 to 200 meters (or 400 meters) at a rail welding factory or a temporary base at trackside (primary welding). The joined rails are transported to the track site and welded into a greater length (secondary welding). Then, expansion joints and crossings are welded to the ends of the CWR to make an integrated rail length of several hundred to one thousand-plus meters (tertiary welding). Four welding processes are selectively used in Japan: flash butt welding (FBW), a pressure welding process, mainly for primary welding; gas pressure welding (GPW) for primary and secondary welding; enclosed arc welding (EAW), a fusion welding process, for secondary and tertiary welding; and thermite welding (TW), another fusion welding process, for secondary and tertiary welding[3].

The performance of fusion welds compared with pressure welds depends on the welding material and the rail steel chemistry. Unless appropriate welding materials are used, new rails now on the market cannot perform as well as initially designed. For the main purpose of establishing fusion welding techniques adapted to these newly developed rails, the authors conceived the idea of utilizing a weld metal with as high a carbon content as the rail steel and proposed new fusion welding processes for improving the reliability of rail weld joints by controlling the distribution of residual stresses in these joints[4-10]. The development history of the new fusion welding processes was reported with the pressure welding processes in Ref. 9). This report gives another overview of these rail welding techniques, including new findings obtained thereafter, describes the practical applications of the new rail welding process, and considers the future trends of rail welding technology.

2. New Enclosed Arc Welding (EAW) Process[4,5]

2.1 Problems with conventional EAW process

Enclosed arc welding (EAW) is a butt welding process for rails. First, the rail base is welded in multiple layers in the flat position in a square groove of about 17mm, using a coated electrode. Then, the rail web and head are enclosed with water-cooled copper shoes and continuously welded while molten slag is removed. Finally, the rail head is welded in multiple layers to a depth of about 15mm. In Japan, this EAW process is used especially on the track rails of the Shinkansen[11]. One of the track rail problems was the wear resistance of the weld metal that is lower than that of the base metal becouse of the low-carbon low-alloy composition of the weld metal, which depends on the electrode used, and the tempered bainite microstructure formed in the welded metal. The resultant localized wear causes vibration and noise[12]. Another problem was the tendency for high-temperature liquation cracking to occur in the heat-affected zone (HAZ), causing rolling contact fatigue and transverse fissure[13].

2.2 Solution of problems by use of high-carbon weld metal

A cylindrical disk specimen containing part of a rail weld was prepared and tested in air against a wheel material of the same geometry by the Nishihara wear test method at the load of 490 N and slip ratio of 9%. **Fig. 1** shows precise specimen surface profiles after 400,000 revolutions. When a conventional low-carbon low-alloy electrode was used, clearly concave portions were formed in the weld. When a high-carbon prototype electrode was used, no such concave portions were observed in the weld. The specimen weld exhibited a pearlite microstructure with slight grain-boundary ferrite for the high-carbon prototype electrode and

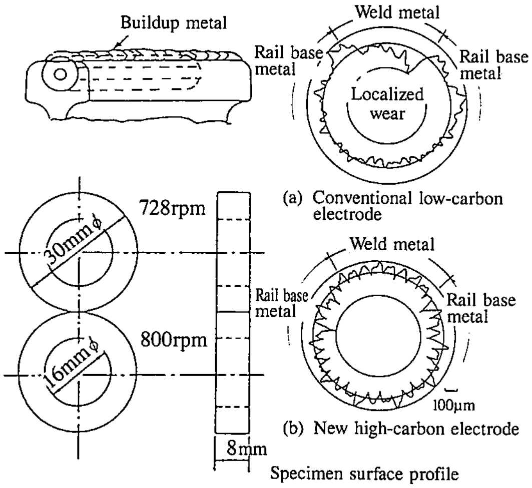

Fig. 1 Results of Nishihara wear test

a bainite microstructure for the conventional low-carbon low-alloy electrode. The weld metal deposited by the prototype electrode was approximately as hard as that deposited by the conventional electrode. The surface profile differences shown in **Fig. 1** were believed to have resulted primarily from the difference in the microstructure of the weld metal. The increased carbon content of the weld in the top of the rail head was thus confirmed to be extremely effective in preventing the localized wear of the enclosed arc weld.

Table 1 list typical chemical compositions of currently used rail steels. Electrodes were made on a trial basis by holding silicon, manganese, phosphorus and other elements within the rail steel composition ranges given in **Table 1** and changing only the carbon content in stages. Rails were EAW from the web to the head, and rail welds were inspected for HAZ liquation cracking along the fusion boundary. Each microscopic specimen was observed by optical microscopy at a magnification of 100×, the projected length onto the fusion boundary of defects judged as liquation cracks was measured, and the ratio of the total length of liquation cracks to the total length of the fusion boundary was defined as the crack incidence. The test results are shown in **Fig. 2**. It was confirmed that the HAZ liquation cracking tendency is closely correlated with the difference in the carbon content between the weld metal and rail steel, and that the crack incidence increases with increasing carbon content difference or decreasing weld metal carbon content when the former difference is 0.3% or more[14]. It was also clear that the cracking tendency increases with increasing electrode diameter and weld current or heat input.

2.3 Quality design of high-carbon electrodes and selection of optimum welding conditions with high-carbon electrodes

When developing new high-carbon electrodes, a low-hydrogen coating composition (mainly CaO-CaF_2) was adopted by taking cold cracking resistance into account. When the carbon con-

Table 1 Chemical compositions of rail steels (wt%)

	C	Si	Mn	P	S	Cr
Standard carbon rail steel	0.68	0.20	0.88	0.020	0.007	—
High-strength rail steel	0.79	0.23	0.97	0.025	0.009	0.16

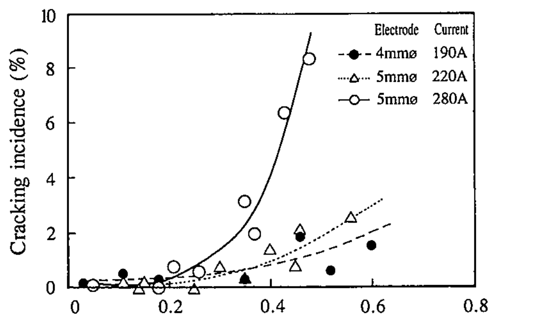

Fig. 2 Effect of difference in carbon content between base metal and weld metal on HAZ liquation cracking incidence

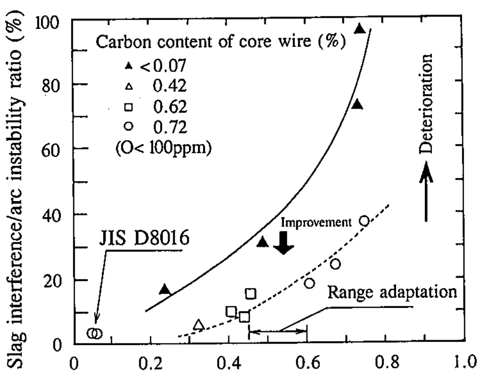

Fig. 3 Electrode core wire carbon content and arc stability

tent of the weld metal was increased by using a low-carbon core wire with the conventional coating composition and by adding graphite to the coating material, the phenomenon of the arc being destabilized by its interference with molten slag was recognized. **Fig. 3** shows the results of a study conducted by the laser schlieren method to quantitatively determine this arc destabilization phenomenon. This phenomenon was improved by minimizing the graphite added to the coating material and using a high-carbon core wire as suggested by the study results. The coating composition was also improved by reducing slag formation and optimizing the CaO/CaF_2 ratio and TiO_2 content to facilitate the remelting of solidified slag and to improve slag flowability. The net outcome was the development of an unprecedented high-carbon electrode.

A high-carbon weld metal ($C \geq 0.5\%$) solidifies into a microstructure composed of only austenite, thus the impurity elements phosphorus and sulfur are low in their solubility limit. The interdendritic microsegregation of phosphorus and sulfur is promoted because the temperature region of the mushy zone is large. As a result, solidification cracking (hot cracking) susceptibility increases. This disadvantage calls for measures to reduce or render harmless the interdendritic microsegregation. **Fig. 4** shows the results of a study conducted to achieve this. A molybdenum content of 0.1% to 0.2% in the weld metal was found to approximately halve the solidification cracking susceptibility. The molybdenum effect may be explained as follows. In the weld metal solidification process, the molybdenum segregated with the phosphorus in the vicinity of the interdendritic region captures the phosphorus, suppresses its grain-boundary segregation[15], and prevents the deterioration of high-temperature ductility.

Adding a small amount of molybdenum is as effective as reducing the contents of the impurity elements phosphorus and sulfur to prevent the solidification cracking of the high-carbon weld metal. This solidification cracking is difficult to completely prevent by material considerations alone. **Fig. 5** shows the results of a study conducted on the prevention of solidification cracking in terms of the welding procedure. As indicated by the open circle at "2/3" on the horizontal axis, solidification cracking was found to be completely preventable using direct current, electrode positive (DCEP) over the available current range, making the electrode electrically positive, weaving the electrode, and adopting such a welding speed (equivalent to electrode consumption of two-thirds per pass) that the weld pool can be controlled in elliptical form. The enclosed arc manipulation of the conventional EAW process produces an elongated teardrop-shaped weld pool and increases the solidification cracking tendency. Weaving the electrode to avoid interference with weld slag and to distribute the heat input to both walls of the groove increases the solidification rate at the solidification tip of the weld pool and forms a fine-grained solidification microstructure where cellular dendrites or columnar crystals are mixed. Under the direct current elec-

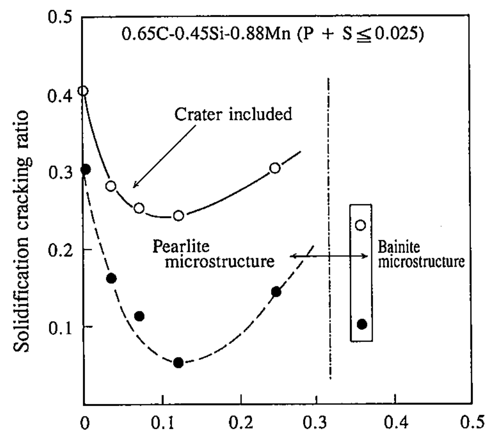

Fig. 4 Effect of molybdenum on hot cracking

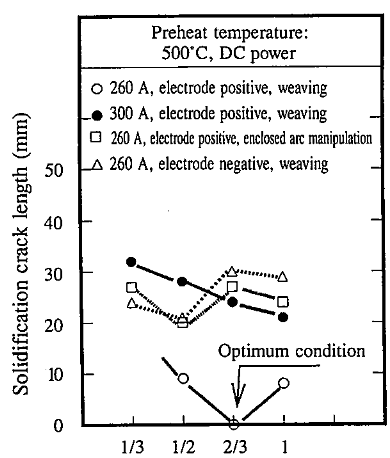

Fig. 5 Solidification cracking and welding conditions

trode negative (DCEN) condition, weaving the electrode forms straight coarse columnar crystals because the amount of heat at the center of the weld pool is so large that the pool's effect of distributing the heat input is diminished. As a result, the solidification cracking susceptibility is increased. Direct current electrode positive (DCEP) is thus recommended for the new EAW process.

2.4 Establishment and performance evaluation of new EAW process

2.4.1 Application to high-strength rails

Like the rail base metal, the rail weld metal varies in required properties from portion to portion: the head must have good wear resistance, the base must have high strength and ductility, and the web must have strong weldability rather than high mechanical strength. The carbon content of the weld metal was optimized to meet these property requirements by focusing on the optimum carbon content of the weld metal, and necessary electrodes were designed for the specific rail portions. In addition, a buildup sequence was established, based on the optimum welding conditions for the high-carbon electrode discussed in the preceding section. The results are summarized in **Fig. 6**. To prevent liquation cracking, the conventional EAW process butters the groove faces and deposits multiple layers with low current in the rail head, furnace cools and anneals the rail web and base after welding, and takes a total time of about 2 hours to complete one rail weld joint[11]. The new EAW process with the high-carbon electrode adopts the buildup sequence of one layer per pass without appreciably lowering the weld current for multilayer welding. The post-weld heat treatment (PWHT) of the rail weld consists of rapidly heating the entire section, reheating and slack quenching (RSQ) the head, and normalizing and air cooling the web and base. A very short total welding time of about 75 minutes is thus achieved.

Engineers from the Iwamizawa and Chiba rail centers conducted rail welding and laying tests using the new EAW process at the Shiraishi Station of Hokkaido Railway Co. and between Ueno and Ohmiya on the Tohoku Shinkansen of East Japan

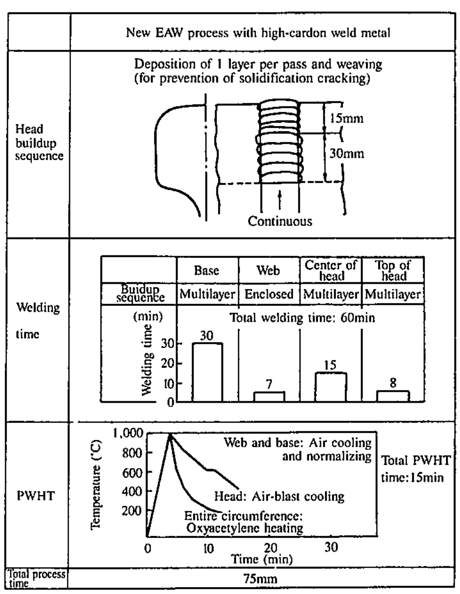

Fig. 6 Conditions of new EAW process

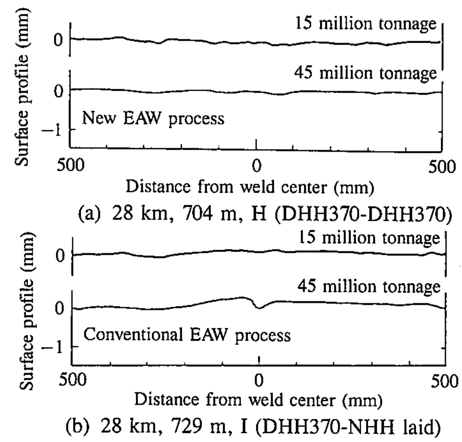

Fig. 7 Change in surface profile of head top in rail weld

Railway Co.[16]. **Fig. 7** shows some results of the weld follow-up survey on the Tohoku Shinkansen. The head top surface profiles of a rail weld made by the new EAW process differed little between 15 million tonnage and 45 million tonnage. The head top of a rail weld made by the conventional EAW process wore badly after 15 million tonnage and developed a local drop of 0.25mm to 0.30mm at 45 million tonnage. These results show the new EAW process makes rail welds with much higher local wear resistance than those made by the conventional EAW process.

2.4.2 Application to standard carbon rails

Based on the results of the application of the new EAW process to high-strength rails, as described in the preceding section, a technical study was conducted to meet demand for expanding the applicable scope of the new EAW process to include standard carbon rail welding and repair welding. High-strength rails are post-weld heat treated to homogenize the microstructure of the head, to improve the wear resistance of the head, and to ensure the desired ductility of the web and base. Shortening the total welding time of standard carbon rails requires that the wear resistance and joint performance of standard carbon rail welds be ensured in the as-welded condition without subsequent PWHT.

A rail head top welding electrode developed for high-strength rails is based on reheat and slack quench after welding is completed. Because the hardness level in the as-welded condition would be too high for practical application, a special electrode was developed to achieve a weld metal carbon content in the neighborhood of 0.5%. The formation of grain-boundary ferrite in the weld metal is slightly greater than in the base metal under the influence of the hypoeutectoid carbon content, but the pearlite interlamellar spacing is relatively small and the hardness level is somewhat high. The wear resistance of the weld metal is thus comparable to that of the base metal.

Fig. 8 compares the shape of residual stress distribution in as-welded joints with different weld metal compositions. Characteristic differences in the form of weld residual stress distribution are observed between the high-carbon weld metal and the low-carbon low-alloy weld metal. By making the most of the characteristics of the two types of residual stress distributions, a new weld buildup sequence was developed that leaves the rail head and base in compressive residual stresses and strengthens

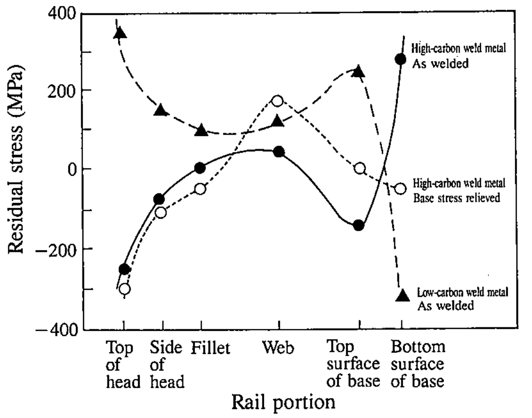

Fig. 8 Residual stress distribution at enclosed arc weld center

Table 2 Joint performance of JIS 60kg rails welded by new EAW process

Type of steel	Three-point slow bending (head up)		Bending fatigue (base in tension)
	Fracture load	Deflection	Not fractured after 2 × 10^6 cycles, stress amplitude
Standard carbon rail*1	1.63MN	52mm	275MPa
	1.44MN	33mm	
	1.60MN	47mm	
High-strength steel rail*2	1.75MN	32mm	≧ 304MPa
	1.70MN	37mm	
	1.72MN	31mm	

*1 As-welded *2 Reheated and slack quenched (DHH370 rail)

the head top against rolling contact fatigue and the base against bending fatigue[17]. A low-carbon low-alloy electrode is used for the rail base to stabilize its bending fatigue strength and deposit decorative beads on the top surface of the base. A high-carbon electrode is used for the rail web and head to protect them from HAZ liquation cracking and localized wear.

Standard carbon rails welded by the new EAW process were test laid in four positions at the Zeze Station of the Tokaido Main Line of West Japan Railway Co. for comparison with the conventional EAW process. The standard carbon rail welds are now undergoing a follow-up survey, with the results of evaluation on their wear resistance change with time scheduled to become available in the first half of 1995.

A new high-performance, high-efficiency EAW process that uses an unprecedented high-carbon weld metal was developed and commercialized, as discussed above, and is finding increasing use. **Table 2** summarizes the performance results of JIS 60kg rail weld joints made by the new EAW process. This new process provides joint performance results comparable to those obtainable with the conventional EAW process.

3. High-Performance Thermite Welding (TW) Process[6]

3.1 Problems with conventional TW process

The thermite welding (TW) process welds rails by melting steel at a high temperature of 2,000°C or more by the oxidation-reduction reaction of aluminum and iron oxide and by pouring the molten steel into a square-groove weld enclosed by a refractory mold[18]. TW is extremely efficient: the aluminothermic reaction and casting operation are completed in a few minutes, and the total welding process is completed in about 40 - 60 minutes. Because of this high efficiency, almost all railroad rails around the world are now field welded by the TW process. In Japan, following a recent review the proportion of thermite welds was increased to more than twice that of enclosed arc welds among field rail welds[3].

The TW process, however, produces thick and wide reinforcement at a rail weld. When railroad car wheels pass over the thermite weld joint with the reinforcement, a high stress concentration acts on the toe of the reinforcement and, coupled with the tensile residual stress superposed on the rail base top surface, reduces the bending fatigue strength of the rail weld joint compared with that of rail joints welded by other processes. Since the concept of welding condition control is difficult to introduce into the TW process, thermite welds easily vary in internal soundness, and their service performance is increasingly variable.

3.2 Study on improvement in reliability of TW process

The optimization of the reinforcement shape that affects the bending fatigue strength of thermite welds was discussed in detail in Ref. 9). Results of a basic study conducted on the effects of thermite reaction process factors on the internal soundness of thermite welds are described below.

The weld metal composition of rails should be as high in carbon as in the base metal, as already stated. **Table 3** outlines the test thermite mixtures. The high-carbon mixture had ferroalloy added to adjust the weld metal to the same chemical composition as the JIS 60kg standard carbon rail. The low-carbon mixture had the carbon content reduced to the carbon level of conventional structural steel.

The stoichiometric proportions of aluminum and iron oxide in a thermite mixture are based on the thermite reaction formulas. The theoretical proportion of aluminum is calculated from the chemical analysis of iron oxide (mill scale). The chemical composition of iron oxide was calculated from the analyses of total iron and ferrous oxide (FeO) by assuming that iron oxides other than FeO are all ferric oxide (Fe_2O_3). The deviation of the actual aluminum proportion from the theoretical aluminum proportion was defined as the aluminum excess ratio α (%). The temperature at which the molten steel is poured into the mold after completion of the aluminothermic reaction in the crucible is important because the temperature affects the amount of the rail base metal melted, the cooling rate of the weld, and the internal soundness of the joint. **Fig. 9** shows the relationship between the aluminum excess ratio α and the molten steel pouring temperature (measured with a radiation pyrometer) when the former was changed. The aluminum excess ratio α at which the pouring temperature is maximum (optimum) is not zero but negative, probably due to the chemical analysis error of mill scale. This experimental finding suggests the risk of the molten steel pouring temperature lowering when the aluminum proportion is insufficient or excessive. The molten steel pouring temperature is slightly lower with the high-carbon mixture than with the low-carbon mixture, probably because the proportion of ferroalloy added as carbon source to

Table 3 Outline of test mixtures

Type	Chemical composition (wt%)						Weight (kg)
	C	Si	Mn	Al	T.Fe	O	
High-carbon mixture	0.57	0.04	2.39	19.08	58.51	17.7	13.5
Low-carbon mixture	0.14	0.01	1.35	19.13	61.92	15.4	11.3

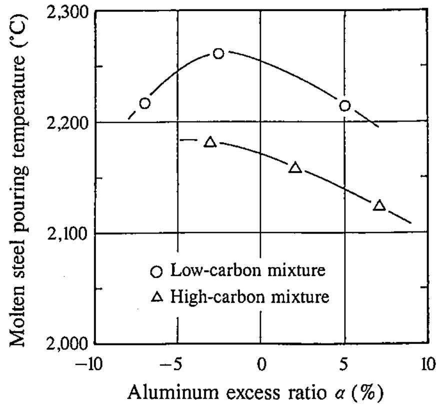

Fig. 9 Effect of aluminum excess ratio α on molten steel pouring temperature

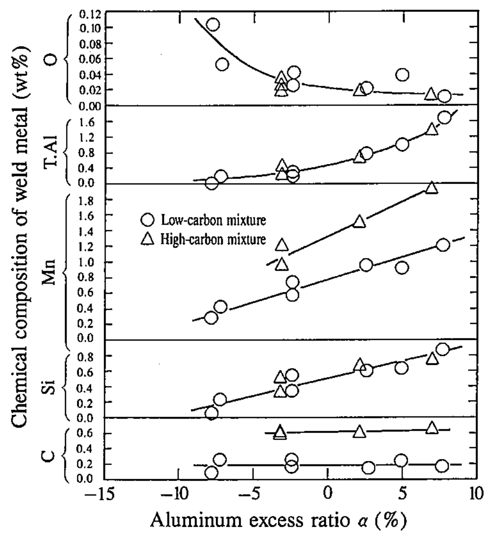

Fig. 10 Effect of aluminum excess ratio α of mixture on chemical composition of weld metal

the high-carbon mixture is high enough to cool the molten steel. The amount and type of additive material are important factors.

The affinity of major rail steel alloying elements for oxygen decreases in the order of aluminum, silicon, manganese, and iron. The aluminum content changes the yield of other alloying elements in the thermite molten steel. **Fig. 10** shows the effect of the aluminum excess ratio α on the change in the yield of thermite molten steel alloying elements. As the aluminum excess ratio α increases, the weld metal increases in total aluminum, decreases in oxygen, and increases in silicon and manganese. When the aluminum excess ratio α is 2.5% or more, the oxygen content is almost constant, suggesting the saturation of the deoxidation reaction of the molten steel. The decrease in the molten steel temperature with the increase in aluminum excess ratio α is presumed to affect the further increase in silicon and manganese. Carbon did not change as significantly as the other alloying elements, and its yield remained constant, irrespective of the aluminum excess ratio α. These results indicate that as far as optimizing the molten steel temperature, the aluminum content of the steel can be utilized as an effective index for controlling the aluminum excess ratio α close to zero as the optimum condition.

The molten steel obtained as a product of the thermite reaction is poured into the rail weld through a self-tapping thimble installed as a plug in the bottom of the crucible; this thimble is a refractory cylinder filled with silicate. When the thermite reaction proceeds through the crucible, with the result that the silicate in the thimble comes into contact with the molten steel and is completely melted, the thimble loses its function as the plug, becomes hollow, and allows the molten steel to flow into the mold. The timing of pouring the molten steel into the mold is important in ensuring the stable quality of the joint. There exists an optimum "tap time" or an interval from ignition of the thermite reaction until the crucible is tapped. **Fig. 11** shows the measured values of the crucible tap time from the start of the thermite reaction to the pouring of the molten steel in the conventional TW process. That time varies from 10 to 30 seconds, and the molten steel pouring temperature decreases with the longer tap time. The amount of silicate is adjusted by allowing a settling time of 5 to 10 seconds for the slag to separate from the molten steel after the end of the thermite reaction. This is related to the variation in tap time and is an important issue requiring improvement.

Photo 1 shows an experimental apparatus constructed of heat-resistant glass for directly observing the thermite reaction taking place in the crucible and typical observation results. The thermite mixture is piled mountain-shaped (convex) in the container simulating the crucible. This follows the standard procedure of the conventional TW process. When an extremely small

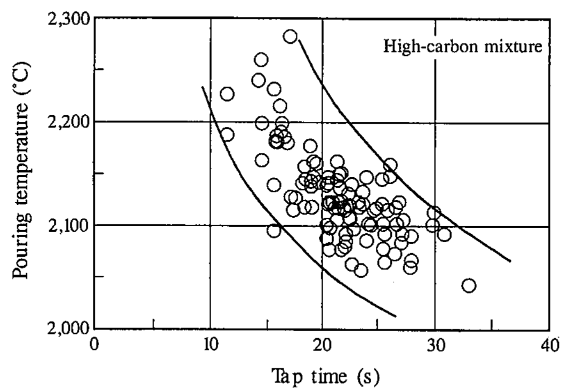

Fig. 11 Effect of tap time in crucible on pouring temperature of molten steel

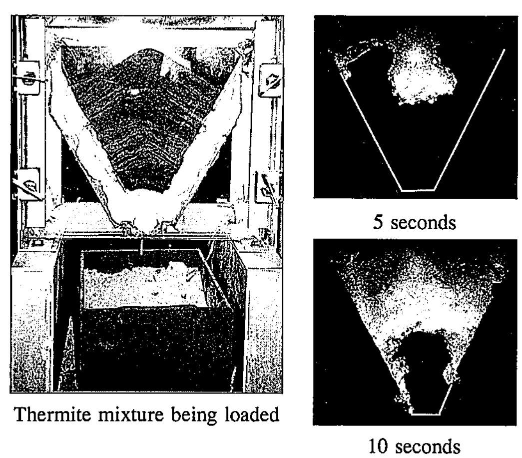

Photo 1 Observation of thermite reaction in crucible by simulative experimental apparatus

part of the thermite mixture is ignited at the reaction start temperature (measured at 1,310°C by the authors), the thermite reaction is initially caused locally and then induced in a chain-like manner, spreading throughout the mixture. This progress of the reaction can be visually observed. Observation of the propagation of the reaction interface showed that the reaction propagation form is not concentric but that the reaction branches into two parts: one propagates from the ignition point directly downward into the crucible and the other propagates along the slope of the mixture and down the wall of the crucible. In terms of propagation speed, the molten steel following the latter reaction path tended to reach the bottom of the crucible faster. A risk was recognized in pouring of the molten steel being started while some of the mixture was still unreacted, depending on the performance of the self-tapping thimble.

Utilizing the direct observation technique discussed above, the grain size, composition, deposit pattern, ignition method, and other details of the thermite mixture are being studied to ensure a uniform thermite reaction in the crucible, and the findings are helpful in optimizing the TW process. The thermite mold structure is also being studied to improve the microstructural shape of the toe of the weld reinforcement that is important for improvement in the bending fatigue strength of the thermite weld joint. The results of these studies will be utilized to improve the thermite mixture and mold and to establish a new higher-performance TW process.

4. Next-Generation Automatic Rail Fusion Welding Process[7,8)]

4.1 General description

The above-mentioned EAW and TW processes have been improved since their introduction; they have long been used making the most of their characteristics and will not soon be replaced by other welding processes. Completion of rail welds using the EAW process takes a long time and necessitates the education and retention of skilled welders. The TW process is likely to vary in joint quality and lacks stability. Since developing automated fusion welding as a next-generation rail welding process that overcomes the problems in the EAW and TW processes, produces highly reliable weld joints and does not require welders with advanced technical skills, Nippon Steel has been working on an automatic continuous fusion welding process. This is based on the narrow-gap electroslag welding (ESW) process and designed to use the gas metal arc welding (GMAW) process for the rail base.

Photo 2 shows a general view of the automatic rail fusion welding machine. The new process is based on controlling the movement of a nonconsumable electrode nozzle to feed the filler wire in unison with horizontal and vertical position detection mechanisms. The vertical movement of the electrode nozzle is automatically controlled to hold the welding current below a specified threshold making use of the characteristic that this current increases with decreasing distance between the nozzle contact tip and the molten metal surface (wire electrode extension). **Fig. 12** schematically illustrates the path of the electrode nozzle on the rail transverse section. The path is divided into 13 regions, and an optimum combination of welding conditions can be selected for each region. These conditions include the current threshold, voltage, nozzle traverse speed, wire feed speed, flux feed rate, and wire rotational speed. Optimum welding conditions can be predetermined and preset. These operating positions and times, including the switching of the shielding gas, the hydraulic operation of the moving copper shoe during a switch from the GMAW process for the base to the ESW process for the web, and special treatment like crater treatment, are all incorporated as variables into sequence control programs and controlled accordingly. The rails are welded fully automatically from start to end. The electrode nozzle is positioned at midwidth in the groove before welding begins and automatically follows the groove geometry during welding without any detecting technique. Since the filler wire rotates the arc at a speed of about 50rpm in the GMAW process at narrow gap of 17mm, there is no need for the electrode to follow the groove profile.

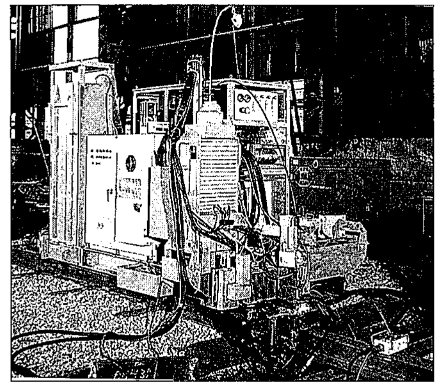

Photo 2 Automatic fusion welding machine for rails

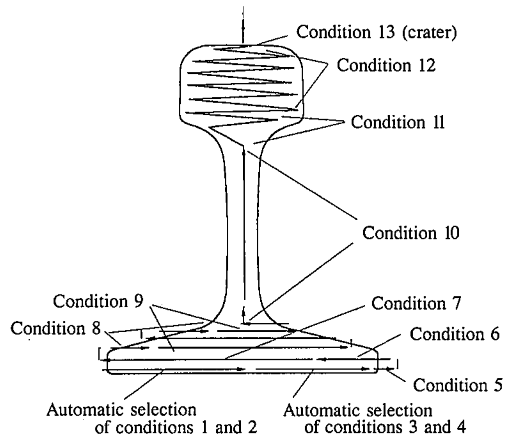

Fig. 12 Electrode nozzle path and welding condition change regions

The new automatic fusion welding process is also based on the idea that the carbon content of the weld metal should be high or close to that of the rail steel. This process is characteristic in that the newly developed welding wire and the auxiliary filler metal are both high in carbon, as shown in **Table 4**. The welding flux used in the ESW process is a newly developed low-melting

Table 4 Chemical compositions of welding materials (wt%)

Welding material	C	Si	Mn	P	S
Wire	0.75/0.81	0.3/0.4	1.1/1.6	<0.005	<0.005
Plate	0.70/0.80	0.1/0.3	0.7/1.0	<0.015	<0.010
Flux	CaO-SiO_2-TiO_2: Low-melting point melt flux				

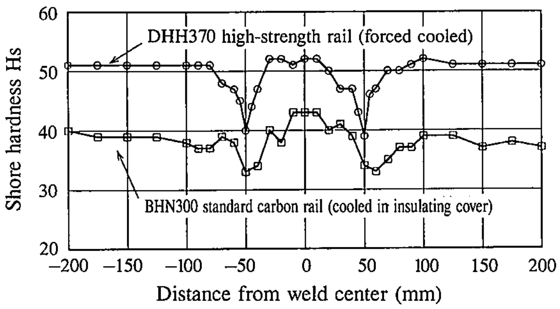

Fig. 13 Head top hardness distributions of automatic fusion weld joints in rails

point flux adapted to this high-carbon weld metal.

4.2 Study of commercialization with prototype machine

To commercialize the above-mentioned automatic fusion welding process, a post-treatment technique was developed that reheats the weld to about 1,000°C with an oxygen-propane flame after welding and removes the reinforcement around the weld by hot trimming. Also established were the RSQ method that imparts an optimum hardness distribution to the head of the rail using the reheating operation in this post-treatment technique, and a heat treatment method that improves the bending fatigue strength of the base weld by inducing compressive residual stress in the weld surface. The latter method quickly cools, after reheating and reinforcement trimming, the base of the rail from the temperature region where the rail steel retains thermoplasticity to the temperature region where the nail steel loses thermoplasticity. The latter method also utilizes the cooling shrinkage time lag between the steel surface and core[8].

A prototype machine was fabricated by the combination of the above automatic fusion welding and post-treatment techniques, and was tested for commercialization on the test track of a railroad company in the United States. The head top hardness distributions of automatic fusion welds in rails are shown in **Fig. 13**, and the static bending test results of these welds are given in **Table 5**. The automatic fusion weld joints were confirmed to be higher in quality than conventional thermite weld joints. **Table 6**

Table 5 Results of four-point slow bending test (AREA standard 132lb rail, head up)

Type of rail steel	Fracture load tons (kip)	Deflection mm (inches)	Fracture surface inspection
BHN300	181 (400)	30.5 (1.20)	Good
SC rail	181 (400)	29.0 (1.14)	Good
DHH370	203 (449)	20.0 (0.79)	Good
High-strength rail	201 (445)	20.0 (0.79)	Good

Table 6 Results of welding time study (AREA standard 132lb rail)

Pretreatment		Welding (automatic)	Post-treatment		Finish grinding, etc.
Groove setup	Welding preparation		Post-treatment preparation	Heating-trimming-cooling	
33minutes	12minutes	20minutes	6minutes	20minutes	14minutes

shows the results of a welding procedure time study conducted on the prototype machine. Up to 100 minutes are required to complete one automatic fusion weld joint. To shorten this to the conventional TW time of 40 - 60 minutes as well as to reduce the size and weight of the equipment, it was judged essential to eliminate or sharply reduce the pre- and post-treatment tasks. The authors are now working to meet these challenges and improve the automatic fusion welding process by developing techniques to automate pre-treatment and simplify post-treatment.

For the automation of pre-treatment, there are established an alignment unit that can be used with an existing puller to set the weld groove (aligning rails to be welded and setting the groove gap) and a copper shoe drive unit and electrode nozzle control unit to make welding preparations (such setting the copper shoes, backing cake and auxiliary filler metal, and adjusting the electrode position in the groove). The development of these elementary techniques is expected to allow one rail weld joint to be completed in 50 - 60 minutes by the new process when applied to JIS 60kg rails used by Japanese railroad companies. Methods are under study to reduce time every further. **Fig. 14** schematically shows the concept of an automatic fusion welding machine incorporating all necessary elements for pre-treatment, welding, and

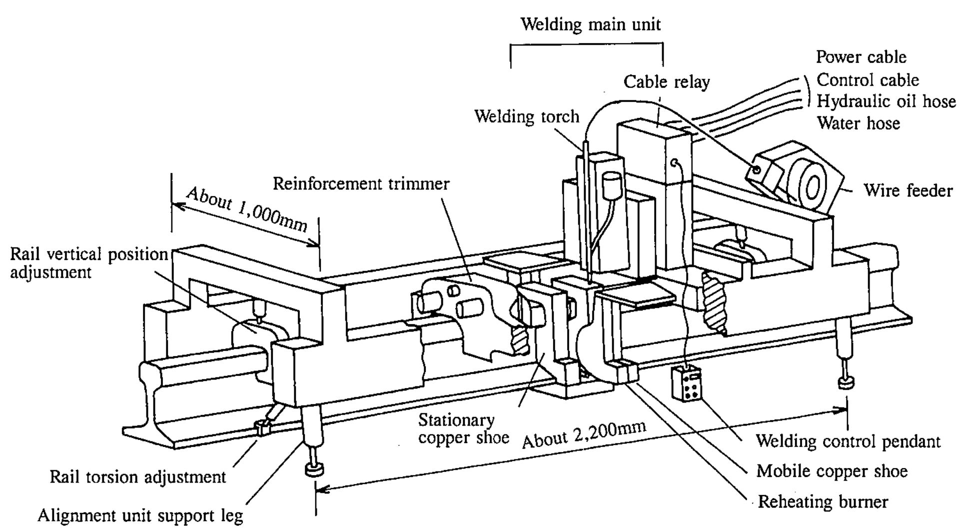

Fig. 14 Concept of automatic fusion welding machine for rails

post-treatment operations. A system that uses a high-rail truck to carry a power supply and other necessary materials and devices is also conceptualized. Nippon Steel is working with Japan's railroad companies toward the commercialization of the new automatic fusion welding process.

5. Future Trends in Rail Welding

The greater speed and axle load of railroad trains are increasing the severity of rail service environments in Japan and abroad. We must meet the demand for rails with higher performance, strength, and stiffness. Use of longer continuous welded rails (CWRs) is one major trend of the times. The importance of welding technology in rail application and fabrication will not change. Welding processes used for CWRs will be improved and modified in their equipment, materials, and procedures in response to environmental changes. Apart from the demand for such improvements and modifications, automatic fusion welding will be increasingly called for as an in-track rail welding method to replace the EAW and TW processes.

Nippon Steel must meet this demand by completing its automatic fusion welding process as soon as possible. Automatic welding technology with flash butt welding (FBW), which is not a fusion welding process and cannot ever be a complete substitute for the EAW and TW processes, is already employed for welding rails on tracks in North America, with some applications showing good results as a replacement for the TW process[19]. Railroad technology is in the midst of rapid progress, and the development of original rail welding techniques is expected to contribute toward further advances in railroad engineering.

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