Technical Report / Research

Development of Technologies to Improve the Reliability of Rail Flash Butt Welds

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Abstract

In overseas heavy haul railways, wear and damage of rail heads increase as freight car loads increase for the purpose of transportation efficiency. Rail welds are the weakest part of rails, therefore, these issues are likely to become apparent. Flash butt (FB) welds, which are widely used in overseas heavy haul railways, are facing problems of wear and rolling contact fatigue at the rail head due to softening in the heat-affected zone (HAZ), and horizontal split web (HSW) due to residual stress, so countermeasures are desired. Nippon Steel Corporation has developed technologies to reduce HAZ width by controlling the FB welding conditions and to reduce residual stress by post weld heat treatment (PWHT). In this report, examples of their development and practical application are presented.

1. Introduction

The mission of heavy haul railways is to transport large quantities of goods at a time. In recent years, overseas heavy haul railways transporting natural resources such as iron ore and coal have increased the freight car loads to improve transportation efficiency. In line with the trend, the load exerted on rails from wheels has increased, and the wear and the rolling contact fatigue damage on rail heads have become apparent. To address this issue, Nippon Steel Corporation has developed and put into practical use high hardness rails containing high carbon content, which are excellent in wear resistance and rolling contact fatigue damage resistance.[1]

Further, rails are welded, but the welds are inferior in quality to the base metal, therefore wear and/or damage occur more frequently. **Photo 1** and **Photo 2** show examples of the wear and the damage at the welds of Flash Butt (FB) welding used widely in overseas heavy haul railways. Photo 1 shows an example of the wear and the rolling contact fatigue damage that occurred in the heat-affected zone (HAZ) of FB welds.[2] Photo 2 shows an example of the damage termed as horizontal split web (HSW).[2] A crack originating at welds occurred at the rail web, propagated in the horizontal direction, and then lead to breakage. The residual stress at the welds is considered to be exerting a great influence on the occurrence and progress of the crack.[3, 4]

To deal with these issues, Nippon Steel has supplied long rails that can reduce welding points. In 2014, production and shipping structures of 150 m rails (General use rail length is 25 m.) were established, and supply to domestic and overseas markets was started.[5]

Furthermore, Nippon Steel has also made efforts in the development of the technology to improve the reliability of the FB welds for the purpose of improving the weld quality. As such examples, this report introduces the HAZ width reduction technology by controlling FB welding conditions, and the residual stress reduction technology by Post Weld Heat Treatment (PWHT).[6]

2. HAZ Width Reduction Technology by Controlling FB Welding Conditions

2.1 Factors and countermeasures for wear and rolling contact fatigue damage at FB welds

Figure 1 shows examples of wear and rolling contact fatigue damage, the schematic image of hardness distribution, and the wear profile at FB welds. As shown in the figure, wear and the rolling contact fatigue damage at FB welds occur mainly in the HAZ softened area.[2, 7] Since hardness of the softened area is lower than that of the rail base metal, wear is likely to progress and the rolling contact fatigue damage due to plastic flow is also more likely to occur. Therefore, reduction of the HAZ width including the softened area

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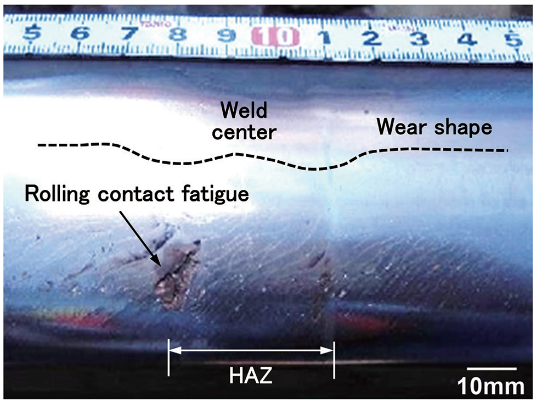


Photo 1 Example of wear and rolling contact fatigue that occurred at FB welds²⁾

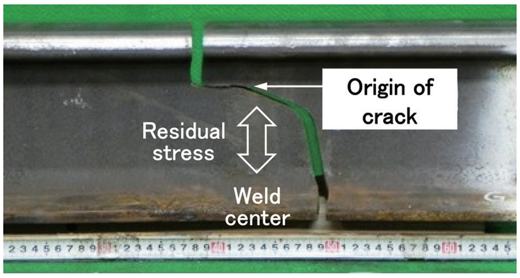


Photo 2 Example of horizontal split web that occurred at FB welds²⁾

can reduce wear and rolling contact fatigue damage.

Here, the FB welding process is shown in **Fig. 2**. The FB process consists of (a) pre-heating process, (b) flashing process, and (c) upsetting process. In the pre-heating process (Fig. 2(a)), the rail end faces are energized while they are in contact with each other to raise their temperature and facilitate the generation of arc discharge. In the next flashing process (Fig. 2(b)), a voltage is applied across both ends of the rails set at a certain distance apart to repeatedly generate arc discharge. The arc discharge causes part of the molten metal layer to scatter outward from the weld. When the rail end faces wear out due to this molten metal loss, the distance between the rail end faces increases and the arc discharge becomes unstable. Therefore, the rails are brought closer together to keep the distance between the rail end faces constant. The temperature distribution of the weld in the flashing process affects the HAZ width and the size of the softened area. In the subsequent upsetting process (Fig. 2(c)), the rails are joined by applying pressure to the butt surfaces. In this process, a part of the weld is pushed outward.

Next, the mechanism of the formation of the softened area in the HAZ is described. **Figure 3** shows the temperature distribution in the flashing process and the hardness distribution after cooling at the FB welds. In the flashing process, the temperature at the weld center rises up to near melting point, and the microstructure of a portion of the HAZ changes, resulting in a softened area. Specifically, in the temperature range from the A_1 transformation point up to the austenite single-phase region (hereinafter referred to as the softening temperature range), the hardness decreases as the laminar cementite in pearlite, the microstructure of the rail, changes to spherical cementite. In other words, by controlling the temperature distribution in the weld in the flashing process, the softening temperature range can be reduced, so the HAZ width can be reduced.

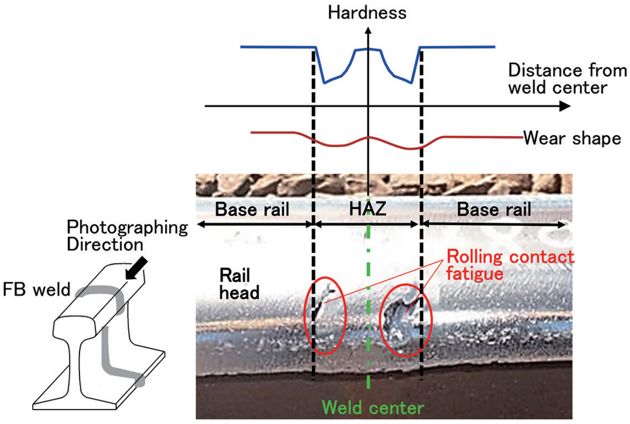


Fig. 1 Example of wear and rolling contact fatigue, and schematic image of hardness distribution and wear profile at FB welds

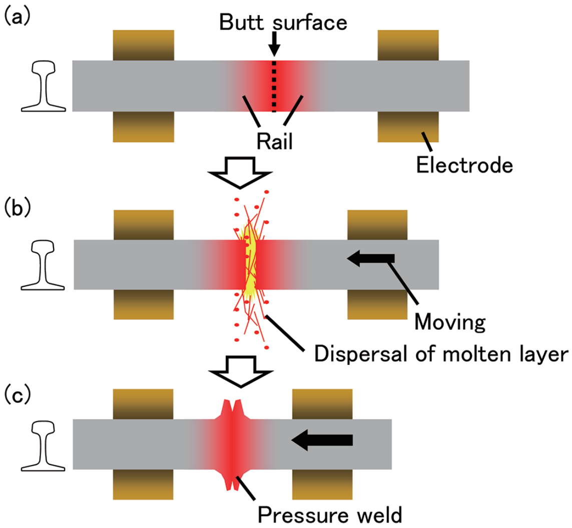


Fig. 2 FB welding process
(a) Pre-heating process, (b) Flashing process, (c) Upsetting process

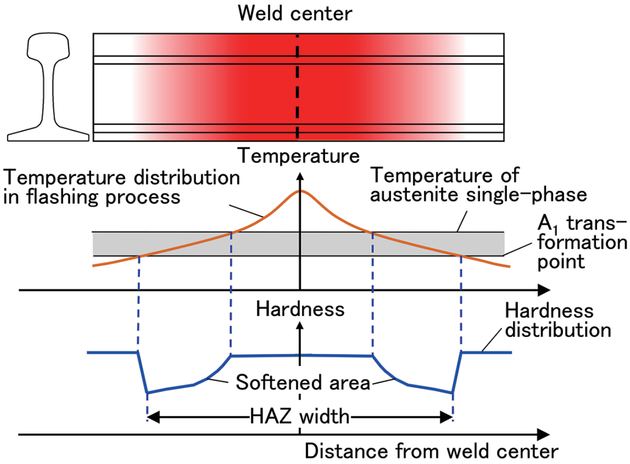


Fig. 3 Schematic image of temperature distribution in flashing process and hardness distribution after cooling at FB welds

2.2 Study on reduction of HAZ width at FB welds

2.2.1 Concept of reduction of HAZ width at FB welds

The relationships among the temperature distribution in the flashing process, hardness distribution after cooling, and the HAZ width at the FB welds are shown in **Fig. 4**. As Fig. 4 shows, the softened area and the HAZ width vary depending on the temperature gradient in the softened area. In order to reduce the HAZ width, it's effective to steepen the temperature gradient in the softened area. As the method to achieve this, we studied the increase of the molten metal loss in the flashing process. In the flashing process, part of the weld heat is diffused outward with the molten metal loss, and the remaining heat is transferred to the base material, resulting in temperature gradient. Therefore, it's possible to steepen the temperature gradient of the welds by increasing the molten metal loss, and by reducing the amount of the heat remaining in the welds. As a means to increase the molten metal loss in the flashing process, it is effective to increase the travel velocity of the rail (hereinafter referred to as flashing velocity) which is the amount of the molten metal loss per unit time, or to increase the rail travel distance (hereinafter referred to as the flashing distance) in the flashing process which is the entire amount of the molten metal loss. Then, the influence of the changes in these two factors in the FB welding conditions upon the HAZ width was studied.

2.2.2 Experimental method

The compositions of the test sample rail steel were C content: 0.6 to 1.0 mass%, Si content: 0.05 to 1.00 mass%, and Mn content: 0.3 to 2.0 mass%. The rail head hardness was 280 to 465 HB, and the microstructure was of perlite. The rail size was 136 RE which is widely used in overseas heavy haul railways.

FB welding conditions are shown in **Table 1**. For FB welding, a fixed type FB welding machine manufactured by the Progress Rail Services Corporation was used. The flashing velocity was varied within a range of 0.2 to 2.8 mm/sec, the flashing distance was varied within a range of 3 to 32 mm, and the relationship with the HAZ width was studied. The HAZ width was defined as the distance in the longitudinal direction between the white areas which appear on either side of the weld on the observed sectional microstructure. Furthermore, as for the welds having different HAZ widths, hardness distribution and wear resistance were evaluated. The weld hardness distribution was evaluated with the hardness measured at a depth of 5 mm from the rail head surface. Wear resistance was evaluated by a rolling fatigue testing machine using a real size wheel and a rail. Test conditions were the same as those of heavy haul railways, and the vertical direction load exerted from the wheel to the rail was set at 15 to 20 tons, and the cumulative passing tonnage was set at 100 million gross tons. After the test, wear resistance was evaluated with the longitudinal profile of the rolling contact surface of the welds.

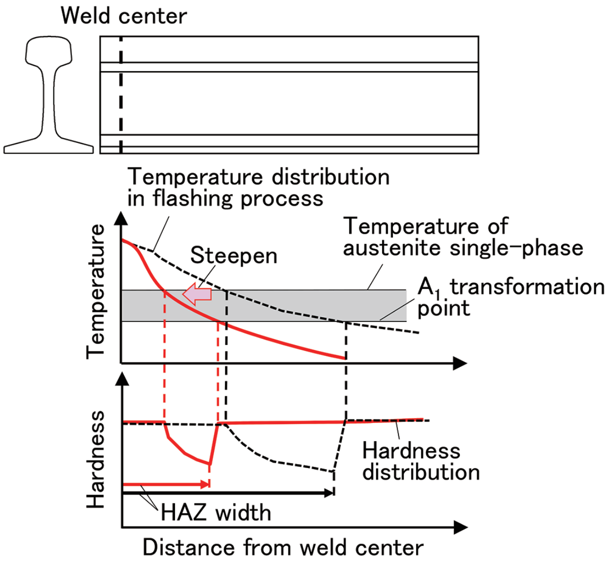


Fig. 4 Relationship among temperature distribution in flashing process, hardness distribution after cooling and HAZ width at FB welds

Table 1 FB welding conditions

Parameter	Value
Flashing velocity (mm/sec)	0.2 – 2.8
Flashing distance (mm)	3 – 32

2.2.3 Experimental result

In **Fig. 5**, relationships between FB conditions and the HAZ width are shown. As shown in Fig. 5 (a), the HAZ width reduces as flashing velocity increases, and becomes almost constant above the flashing velocity of 2.1 mm/sec. Further, as Fig. 5 (b) shows, as the flashing distance increases, the HAZ width decreases, and becomes almost constant above the flashing distance of 20 mm. In **Photo 3**, the cross-sectional microstructures of FB welds each having different HAZ widths are shown.[6] The HAZ width of 33 mm is the general FB welds HAZ (hereinafter referred to as conventional HAZ), and the HAZ width of 23 mm is the width reduced by controlling the FB welding conditions (hereinafter referred to as narrowed HAZ). The hardness distribution and wear resistance of these FB welds were evaluated. **Figure 6** shows the result of comparing the hardness distribution of the FB welds.[6] The softened area was 8 mm in the narrow HAZ compared to 14 mm in the conventional HAZ, indicating that the softened area was reduced along with the reduction of the HAZ width. **Figure 7** shows the evaluation result of wear resistance on the surface of the rail head of the FB welds.[6] By

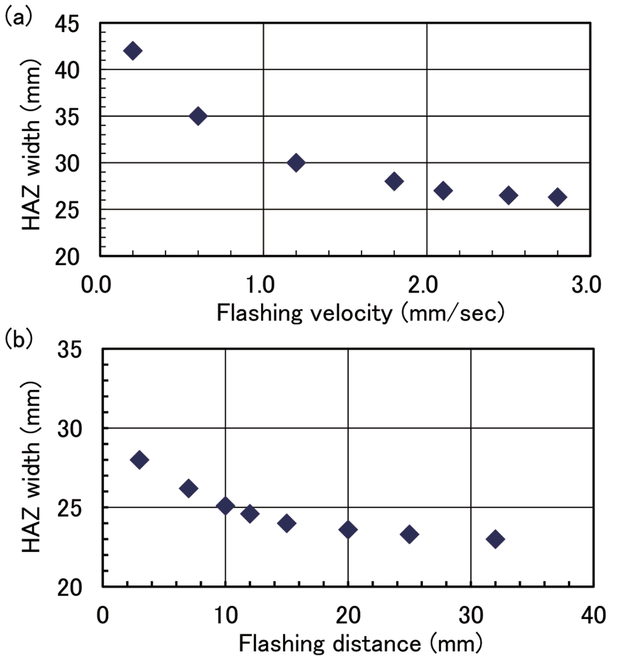


Fig. 5 Relationship between FB welding conditions and HAZ width (a) Flashing velocity, (b) Flashing distance

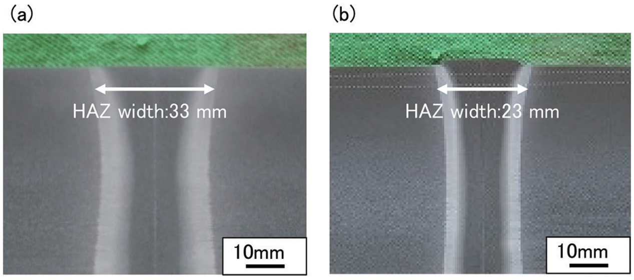


Photo 3 Cross-sectional macrostructure of FB welds
(a) Conventional HAZ, (b) Narrowed HAZ

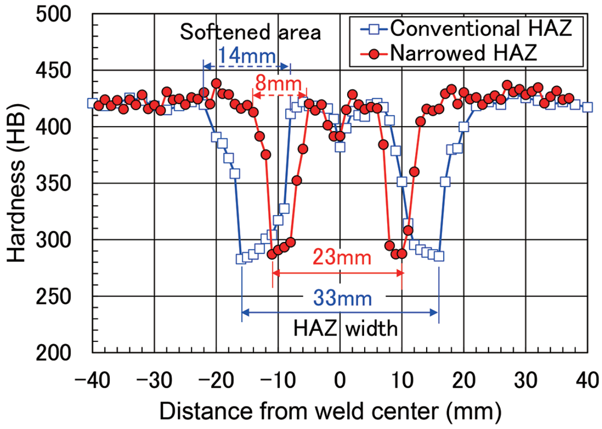


Fig. 6 Hardness distribution at FB welds

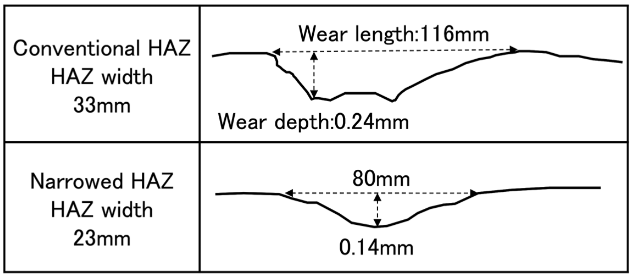


Fig. 7 Longitudinal wear profiles at rail head surface of FB welds after 100 million gross tons

reducing the HAZ width, the length of wear that progressed from the softened area was reduced from 116 mm to 80 mm, and the maximum depth of wear was reduced from 0.24 mm to 0.14 mm. Thus, it is confirmed that reducing the HAZ width by controlling the FB welding conditions improved the wear resistance.

3. Residual Stress Reduction Technology by PWHT

3.1 Factors of HSW at FB welds and countermeasures

The vertical tensile residual stress which occurs in the vertical direction at the FB weld influences HSW.[3, 4] Therefore, generation of HSW is suppressed by reducing the residual tensile stress at the FB welds. Firstly, the generation mechanism of the residual stress at the FB welds is described below. At the FB welds, residual stress is generated by the contraction that tends to be developed during the cooling process after welding and the constraint of the circumferential base metal. The temperature distribution of the FB welds in the longitudinal direction right after welding, contraction which tends to be developed during the cooling process, and the residual stress distribution after cooling are shown schematically in **Fig. 8**.[6] In the weld center where temperature is higher than its circumference, contraction which tends to be generated during the cooling process becomes large; however, in reality, since the contraction is restrained by the circumferential base metal, a high tensile residual stress is generated in the vertical direction. In the meantime, compressive residual stress occurs in the circumferential base metal to constrain the contraction in the weld center. For the weld as a whole, as shown in Fig. 8(c), the residual stress after FB weld changes from tensile to compressive as one moves away from the weld center and the residual stress gradually approaches zero at further distance from the weld center. Then, we studied changing the residual stress distribution after FB welding by providing a temperature distribution different from the one of welding by PWHT which reheats the FB welds.

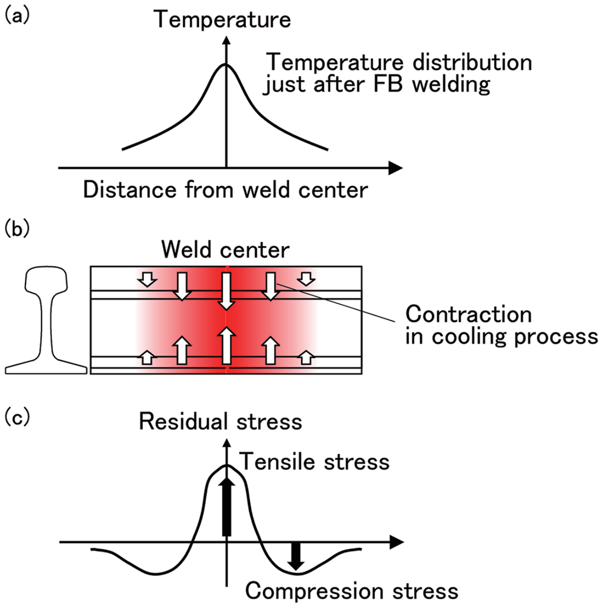


Fig. 8 Various distributions in the longitudinal direction of FB welds
(a) Temperature just after FB welding, (b) Contraction in cooling process, (c) Residual stress after cooling

3.2 Study on residual stress reduction at FB welds

3.2.1 Concept of residual stress reduction method at FB welds

The appearance of the PWHT equipment used for FB welds is shown in **Photo 4**.[6] This equipment heats the two areas away from the weld center by induction-heating (IH) after welding. **Figure 9** shows the temperature distribution at the FB welds after heating by PWHT, and the relationship between the contraction and the compressive stress that attempt to occur during the cooling process of PWHT.[6] Tensile residual stress is considered to be generated at the high temperature areas heated by PWHT, and compressive residual stress is considered to be generated in the area away from the heated areas. Based on the mechanism of residual stress generation associated with the temperature distribution in PWHT, we considered that heating the location away from the weld center would provide compressive stress at the weld center and reduce the tensile residual stress generated at the weld center in FB welding. Residual stress in the FB welds is considered to vary also due to the change in the temperature distribution which varies depending on the heating distance between the weld center in the FB welding and the heating center in PWHT, heating temperature, and the heating width in PWHT. Then, these PWHT conditions were varied, and the influence of the variations on the residual stress at the weld was studied.

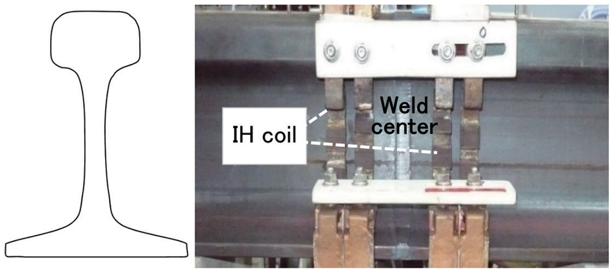


Photo 4 Appearance of the PWHT equipment (IH)

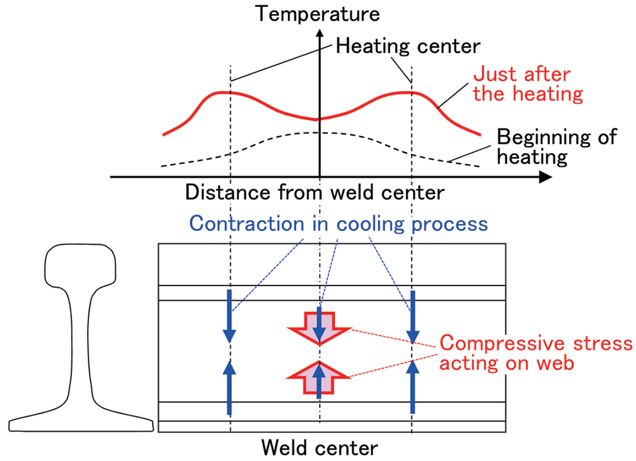
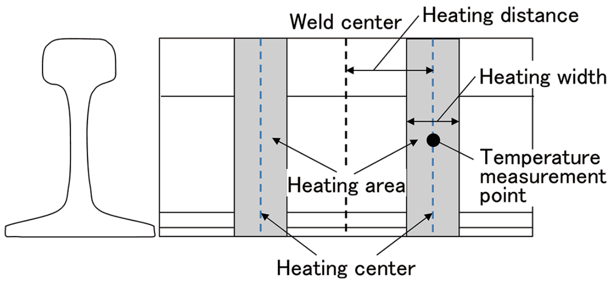


Fig. 9 Relationship among distribution of temperature, contraction in cooling process and compressive stress at FB welds by PWHT

Table 2 PWHT conditions

Parameter	Value
Heating distance (mm)	12 – 160
Heating temperature at web (˚C)	400 – 750
Heating width (mm)	12 – 170



3.2.2 Experimental method

PWHT was applied to the conventional HAZ of the FB welding joint in chapter 2. PWHT conditions are shown in **Table 2**. Heating distance was changed in a range from 12 to 160 mm; likewise, heating temperature, 400 to 750°C, and heating width, 12 to 170 mm, and the relationships among these factors with the residual stress at the weld were studied. The residual stress at the welds was obtained by attaching a strain gage to the center of the weld center line, cutting a sample 15 mm long × 15 mm wide × 10 mm thick from the rail centered on the strain gage, and measuring the amount of strain change before and after the sample was taken.

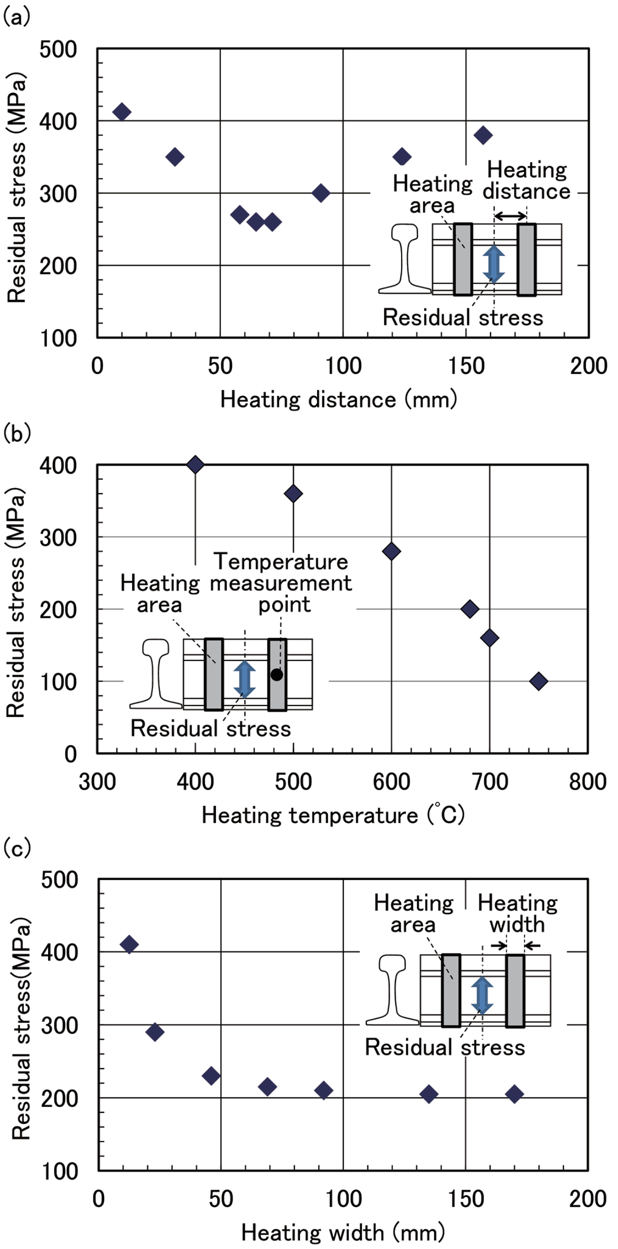


Fig. 10 Relationship between PWHT conditions and residual stress at FB welds
(a) Heating distance, (b) Heating temperature, (c) Heating width

3.2.3 Experimental result

In **Fig. 10**, the relationship between the PWHT conditions and the residual stress at the FB weld is shown.[6] As shown in Fig. 10 (a), up to about 65 mm of heating distance, residual stress reduced by increasing the heating distance, while above this heating distance, the residual stress increased. This suggests that, in the change of residual stress by PWHT, the compressive residual stress becomes highest at 65 mm in heating distance. As shown in Fig. 10 (b), the residual stress reduced by increasing the heating temperature. However, it is important to determine the upper limit of the heating temperature because if the heating temperature become too high, the base metal in and around the heated area become softened, resulting in the deterioration of wear resistance and rolling contact fatigue damage resistance. As shown in Fig. 10 (c), the residual stress reduced by increasing the heating width, and above 50 mm in heating distance, the residual stress became almost constant. Based on these experimental results, the PWHT conditions, which give the highest reduction effect of the residual stress reduction at the center weld were selected.

4. Development and Evolution in Future of Technology to Improve FB Welds Reliability

4.1 Development of technology to improve reliability of FB welds

In order to verify the combined effect of the HAZ width reduction technology by controlling the FB welding conditions and the residual stress reduction technology by PWHT, PWHT was applied to the FB welds having varied HAZ widths, and the relationship between the HAZ width and the residual stress was studied. Specifically, HAZ widths are 33 mm for the conventional HAZ and 23 mm for the narrowed HAZ. **Figure 11** shows the relationship between the HAZ width and the residual stress in FB welds and the change in the residual stress by PWHT.[6] When the HAZ width was reduced, the residual stress as welded increased from 450 MPa to 570 MPa. However, the residual stress was reduced to 200 to 220 MPa by applying PWHT, regardless of HAZ width. Reducing the HAZ width improves wear resistance but increases the residual stress as welded, which may lead to the occurrence of HSW. However, by applying PWHT properly, the increase of the residual stress with HAZ width reduction could be effectively suppressed. Namely, by applying this technology, it is considered that wear, rolling contact fatigue damage, and the occurrence of HSW at FB welds are reduced.

4.2 Application example of developed technology

These developed technologies were applied for the international patents.[8–10] These technologies are provided as a welding solution technology for customers who apply FB welding to improve the reliability of FB welds. As an example, the case of the Union Pacific Railroad of the Union Pacific Corporation is introduced.[6] In 2015, the HAZ width reduction technology and the residual stress reduction technology were transferred to the rail welding workshop of the company in Stockton. As a result, the HAZ width was reduced from 33 mm to 27 mm and the residual stress was reduced from 570 MPa to 290 MPa.

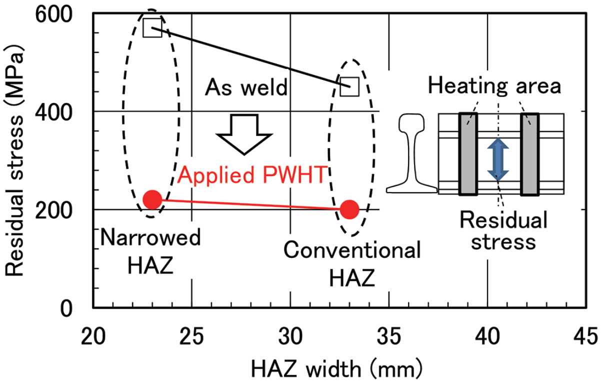


Fig. 11 Relationship between HAZ width and residual stress at FB welds, and reduction of residual stress by PWHT

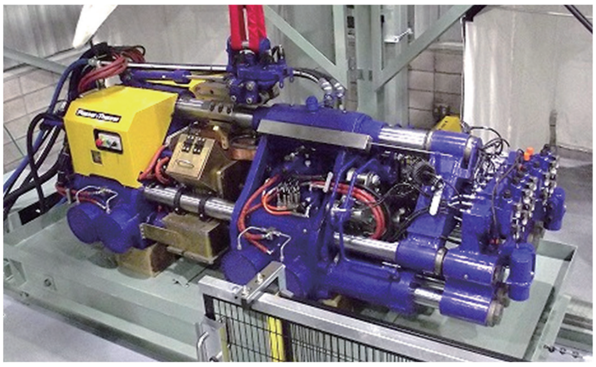


Photo 5 Appearance of mobile FB welding equipment

4.3 Evolution in future

In domestic and foreign railway companies, in addition to the fixed type FB welding machine used in rail welding workshops, the use of mobile type FB welding machines is widespread on-site at railway construction sites. To cope with such customer trends, Nippon Steel introduced a mobile type FB welding machine manufactured by Plasser & Theurer (**Photo 5**). Hereafter, we will utilize the mobile type FB welding machine in combination with the fixed type FB welding machine, and tackle how to solve customer issues, and challenge further improvement of the reliability of the FB welds.

5. Conclusion

As examples of the development of technologies to improve the reliability of FB welds in rails, technologies to reduce HAZ width by controlling FB welding conditions and to reduce residual stress by PWHT were introduced. The operating environment of rails is expected to become more severe in future, and further quality improvement of rail welds will be required. We will continue to develop welding technologies that address the issues of rail welds and contribute to the development of safe and secure railway transport.

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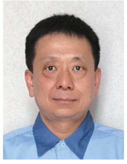

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