Gas Pressure Welding Method of Rails by Mixed Gas of Hydrogen and Ethylene Gas

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Gas pressure welding (GPW) is a solid phase welding method. This method is commonly used for rail welding in Japan. However, there is concern that the supply of acetylene gas, which is used as the fuel gas in the conventional GPW system, will cease due to the recent tendency of reduction of demand. Moreover, a large volume of CO₂ gas is generated in the GPW process since acetylene gas is a hydrocarbon. Therefore, a new GPW method of welding rails by mixed gas of hydrogen and ethylene gas was developed in order to ensure continued use of GPW in the future. This paper describes this newly developed GPW method.

Keywords: rail, gas pressure welding, mixed gas of hydrogen and ethylene gas, CO₂ emission, mechanical property of welded joint

1. Introduction

In Japan, four welding methods have been generally adopted for production of a continuous welded rail (CWR): flash welding (FW), gas pressure welding (GPW), enclosed arc welding (EAW), and aluminothermic welding (TW). Figure 1 shows the application ratio of each welding method in 2011. Among them, gas pressure welds accounted for approximately 30%. The welded joints produced using the GPW method have the same strength as the base material as the method uses no filler metal. Therefore, GPW is an indispensable welding method for track maintenance.

However, there is concern that the supply of acetylene gas, which is used as the fuel gas in the GPW system, will cease due to the recent tendency of reduction of demand. Moreover, a large volume of CO₂ gas is generated in the GPW process since acetylene gas (C₂H₂) is a hydrocarbon. Given these circumstances, the appropriateness of a mixed gas of hydrogen and ethylene gas (C₂H₄) for the GPW process was examined in order to ensure continued availability of the GPW procedure in the future.

This paper describes the development details of this new GPW method, the mechanical properties of welded joints, and the reduction of CO₂ gas in application of this method.

2. Examination process for GPW method with hydrogen gas

Although the combustion flame of hydrogen gas has high centrality and a high heating capacity due to its high combustion velocity, the combustion flame is difficult to handle. However, a previous study [1] indicated that a hydrogen flame could be stabilized by adding a small amount of hydrocarbon. Therefore, the application of hydrogen gas with a small amount of the hydrocarbon hexane (C₆H₁₄) in the GPW process was examined [2]. This identified appropriate welding conditions in which sound welded joints could be produced. However, there was room for improvement in the workability of this method as it was difficult to mix hydrogen gas and hexane at the welding site.

Under such circumstances, a mixed gas of hydrogen and ethylene gas, which could be contained in a vessel, was developed as an alternative to acetylene gas (mixture ratio of ethylene gas: 40%) in the gas cutting field. If this mix of gas is found to be suitable for the GPW process, it would be possible to maintain the same workability as that of the conventional GPW method.

The welding conditions and heating burner structure were therefore examined in order to apply the mixed gas of hydrogen and ethylene gas to the GPW process.
3. Examination of suitability of mixed gas of hydrogen and ethylene gas for the GPW process

The heating and reducing capacity of a combustion flame are important factors in the GPW process [3]. Consequently, a heating test and welding test using a round steel bar of S45C-Ø25 mm were carried out to investigate the fundamental properties of the combustion flame of the mixed gas.

3.1 Evaluation for the combustion flame of mixed gas of hydrogen and ethylene gas

3.1.1 The influence of combustion condition on heating capacity

The temperature history of the central part of the round steel bars was measured using an R-type thermocouple when the round steel bars were heated with each combustion condition (condition A, B, and C) as shown in Table 1. In addition, the temperature history was also measured when the round steel bars were heated by means of a standard acetylene flame. Figure 2 shows the test results. The time required for the temperature to reach 1250 ℃ is also shown in Fig. 2. From this figure, it is clear that heating capacity of the combustion flame are higher in the order of condition B, C, and A. It also shows that the combustion flame of condition B has almost the same heating capacity as that of a standard acetylene flame.

3.1.2 Reducing capacity of the combustion flame

The GPW test pieces of a round steel bar were produced with each combustion condition (condition A, B, and C) and upset length (20-30 mm) as parameters under an upset force of 20 MPa. In this welding test, a formed bulge was removed by hot shearing immediately after the heating process. In addition, a static bending test in accordance with JIS Z 2248 was carried out for each test piece. At the time of the bulge removal immediately after welding, a crack occurs at the weld interface if the bonding strength of the interface is low. Consequently, such test pieces rupture at a low load. The maximum load of the bending test was set at 250 kN which was equal to that of the base material.

Figure 3 shows the relationship between welding conditions and rupture load. It can be seen that the test pieces produced under combustion conditions B and C have a higher strength than test pieces produced under condition A. Moreover, the test pieces produced under conditions B and C with an upset length of 30 mm have the same static strength as the base material. In contrast, the test pieces produced using a conventional acetylene flame achieve a static strength of 250 kN with an upset length of 20 mm.

On the other hand, the strength of the test pieces produced under condition B is the same as that of the test pieces produced under condition C, even though the amount of mixed gas of hydrogen and ethylene gas increases incrementally in the order: condition A, B, and C. Accordingly, it is considered that condition B is the best combustion condition for GPW execution in this examination range when heating capacity, as mentioned in 3.1.1, is also taken into account. However, an upset length of 30 mm is necessary to achieve a strength of 250 kN in the case of condition B, even though the test pieces produced using a conventional acetylene flame can achieve a strength of 250 kN with an upset length of 20 mm as mentioned above.

According to the above results, it is considered that the reducing capacity of the combustion flame of a mixed gas of hydrogen and ethylene gas is essentially inferior to the reducing capacity of a conventional acetylene flame. Consequently, it is concluded that the examination of combustion condition alone is insufficient to achieve sound welded joints, and it is necessary to expand the shielding area of the combustion flame physically.

### Table 1 Combustion conditions of heating test

<table>
<thead>
<tr>
<th></th>
<th>Quantity of gas flow (ℓ/min)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mixed gas</td>
<td>Oxygen gas</td>
</tr>
<tr>
<td>Condition A</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Condition B</td>
<td>25</td>
<td>&quot;</td>
</tr>
<tr>
<td>Condition C</td>
<td>28</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Combustion flame of acetylene gas: Acetylene:22 ℓ/min, Oxygen:20 ℓ/min
3.2 Examination for structure of heating burner based on GPW test of rails

Section 3.1.2 suggests that the shielding area needs to be expanded. In addition to this, an improved heating burner in which burner nozzles were arranged densely had previously been developed to improve weld quality, and put into practical use [4]. Accordingly, a magnetic particle test and a static bending test were performed for the welded joints of a 60 kg standard carbon rail that were produced using this improved burner, to evaluate the suitability of mixed gas of hydrogen and ethylene gas for the GPW process of rails. Table 2 shows the welding conditions of the test piece. The combustion condition was determined in consideration of combustion condition B as shown in Table 1 and the cross-section area of the rail. However, the set values of upset force and upset length were the same as those of the conventional GPW method. Figure 4 shows the production status of the test piece.

In a magnetic particle test of the test piece, a linear indication of 3 mm in length was detected at the edge of the rail base. In addition, the rupture load and deflection in a static bending test were below the reference values as shown in Table 3, and a hot crack was observed on the fracture. Accordingly, it is considered that this test piece ruptured at low load due to a hot crack which was formed in the edge of the rail base. Figure 5 shows the fracture status of the test piece.

When hot shearing of a bulge is performed immediately after the heating process, a plastic deformation is caused in the area under the edge. Consequently, if bonding work is poor, a hot crack occurs at the weld interface because the bonding strength of the weld interface is not able to resist the stress caused by the plastic deformation [5]. This principle is illustrated in Fig.6. As mentioned above, a hot crack occurred at the edge of the test piece that was produced in this examination. Consequently, it is considered that it is difficult to effectively expand the shielding area of the rail base even when the improved heating burner is applied.

An attempt was therefore made to expand the shielding area of the rail base by increasing the tip diameter. Concretely, adjustment of the tip diameter was achieved
through a GPW test, which was performed to investigate the relationship between the pattern of the tip diameter and the occurrence of defects.

4. Welding conditions of the GPW method by mixed gas of hydrogen and ethylene gas

The above examinations established the welding conditions in which sound welded joints could be achieved for a JIS 60 kg standard carbon rail. Figure 7 shows the standard welding conditions of this new GPW method by mixed gas of hydrogen and ethylene gas. The conditions of upset force and upset length are the same as those in the conventional method. Moreover, the conventional apparatus, such as a compression device and a bulge removal device, can be applied to this new method as they are.

5. Performance evaluation test of welded joints

5.1 Test procedure

5.1.1 Specimens

The specimens of a 1.5 m long JIS 60 kg standard carbon rail were prepared according to the standard welding conditions in Fig.7.

5.1.2 Test items

The following tests were conducted to evaluate the

<table>
<thead>
<tr>
<th>Test items</th>
<th>Magnetic particle test</th>
<th>Hardness test at top surface and longitudinal section</th>
<th>Static bending test</th>
<th>Observation of longitudinal section</th>
<th>Bending fatigue test</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPNo.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>○</td>
<td></td>
<td>○ (HU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>○</td>
<td></td>
<td>○ (HU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>○</td>
<td></td>
<td>○ (HU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>○</td>
<td></td>
<td>○ (HD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>○</td>
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<td></td>
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<tr>
<td>7</td>
<td>○</td>
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<td></td>
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<tr>
<td>8</td>
<td>○</td>
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</tr>
</tbody>
</table>
joint performance of the specimens.

(1) Magnetic particle test
(2) Hardness test at the top surface
(3) Static bending test
(4) Macro- and micro-structure tests in longitudinal section
(5) Hardness test in longitudinal section
(6) Bending fatigue test

Table 4 shows the tests performed for each specimen. In the static bending test column, HU indicates the rail base tension condition and HD indicates the rail head tension condition.

5.2 Test results

5.2.1 Magnetic particle test

In the magnetic particle test in accordance with the instructions for the non-destructive inspection of rail welded parts, all specimens were sound without exhibiting any linear indication.

5.2.2 Hardness test at the top surface

Figure 8 shows the hardness distribution in Brinell at the top surface of the specimen (TPNo.7), measured at pitches of 10 mm. The hardness of the specimen’s weld center is slightly higher than that of base material, and a softened zone of 10 mm in width is observed in the boundary of the heat-affected zone (HAZ). This hardness distribution is almost the same as that of the welded joint obtained using the conventional GPW method.

5.2.3 Static bending test

Figure 9 shows the results of the static bending test for specimens supported at two points that are 1 m apart with the load applied at the center. The rupture load and deflection were higher than in the JR specification with all specimens.

5.2.4 Macro- and micro-structure tests in the longitudinal section

Figure 10 shows the longitudinal macro-section at the center of the specimen (TPNo.7). There are no problematic welding discontinuities on the observation surface. The HAZ width of the rail web region is wider than those of the rail head and rail base region. This form of the HAZ is almost the same as that of a welded joint obtained using the conventional GPW method.

Figure 11 shows the micro-structure in the longitudinal section shown in Fig.10. The micro-structure was observed at the point 5 mm below the top surface at the weld center, at the center of the HAZ, in the fine grain region of the HAZ, on the base material adjacent to the HAZ, and on the base material. At the weld center of the specimen, a pearlite structure with grain sizes slightly larger than those of the base material was observed. A singular structure such as a martensite structure was not observed in any of the parts.

5.2.5 Hardness test in the longitudinal section

Figure 12 shows the distribution of Vickers hardness in the longitudinal section shown in Fig.10, measured at the point 5 mm below the top surface, at the center of the web, and at the point 5 mm above the bottom surface at intervals of 2 mm under a load of 98 N.

The hardness of the weld center at the point 5 mm be-
low the top surface of the specimen is slightly higher than that of the base material. The width of the softened area formed in the heat-affected zone is 10 mm or less, which is almost the same as that of the welded joint obtained using the conventional method. The hardness at the center of the web and at the point 5 mm above the bottom surface is approximately the same as that at the point 5 mm below the top surface.

5.2.6 Bending fatigue test

A four-point bending fatigue test was performed in the HU position to generate tensile stress in the rail base area of a specimen (TPNo.8) supported at a span of 1.3 m (inner span: 0.15 m), by applying a pulsating stress of a minimum of 30 N/mm$^2$ up to two million times. Figure 13 shows the status of the bending fatigue test.

Table 5 shows the test result. It can be seen that the specimen has the same fatigue strength as the fatigue strength of 320 N/mm$^2$ (stress range) of the welded joint executed using the conventional method.
6. The reduction of CO\(_2\) gas in application of the new GPW method

To evaluate the reduction of CO\(_2\) gas in application of the new GPW method, CO\(_2\) emission was estimated when the new method was applied to a JIS 60 kg standard carbon rail, and the emission amount was compared with that of the conventional GPW method. Table 6 shows the estimated results. It can be seen that this new method can reduce CO\(_2\) emission to one third, as compared with the conventional method.

7. Conclusions

An attempt was made to examine a new GPW method of rails by mixed gas of hydrogen and ethylene gas, which can be contained in a vessel, in order to ensure that the use of GPW can be continued in the future. This identified welding conditions in which sound welded joints could be produced. This new GPW method can reduce the CO\(_2\) emissions to one third, as compared with the conventional method, and has the same workability as the conventional method.

Table 5  Result of the bending fatigue test

<table>
<thead>
<tr>
<th>Stress (N/mm(^2))</th>
<th>Number of cycles ((\times 10^6))</th>
<th>Run-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>Max</td>
<td>Range 2(\sigma)</td>
</tr>
<tr>
<td>30</td>
<td>350</td>
<td>320</td>
</tr>
</tbody>
</table>

Table 6  Estimated result of CO\(_2\) emission in welding of a JIS 60 kg standard carbon rail

<table>
<thead>
<tr>
<th>Consumption of fuel gas</th>
<th>New method</th>
<th>Conventional method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mixed gas : 135 ℓ/min</td>
<td>Acetylene gas : 105 ℓ/min</td>
</tr>
<tr>
<td>Welding time</td>
<td>7.5min</td>
<td>7min</td>
</tr>
<tr>
<td>CO(_2) emissions</td>
<td>0.135 m(^3)/min (\times 0.4) (mixture ratio of ethylene gas) (\times 7.5) min</td>
<td>0.105 m(^3)/min (\times 7) min (\times 1.17) kg/m(^3) (density of acetylene gas)</td>
</tr>
<tr>
<td></td>
<td>(\times 2.34) kg/m(^3) (emission factor *)</td>
<td>3.4 kg/kg (emission factor *)</td>
</tr>
<tr>
<td></td>
<td>= 0.95 kg</td>
<td>= 2.92 kg</td>
</tr>
</tbody>
</table>

* Source : Emission factor concerning the use of fuel, Ministry of the Environment

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