Application of Friction Stir Welding to Construction of Railway Vehicles*

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This paper describes an application of friction stir welding (FSW), solid phase welding, to fabricate railway car body made of aluminium hollow extrusions (double-skinned car body). The construction of double-skinned car body using FSW can reduce deformation and release process from skilled workers compared with the conventional method. In this paper, from the viewpoint of strength, we show our approach from a design of the joint’s sectional shape to the final evaluation test using actual double-skinned car body fabricated by FSW. For design, reaction force in the workpiece coincident with heat input was considered. At load test, we evaluated stress levels at the joint, accuracy of the simulation of the car body and double-skinned car body’s characteristics. As a result, railway car body joined by FSW can meet all the requirements for actual application. These benefits have been applied to 319 vehicles as of June 2002.

Key Words: Railway, Friction Stir Welding, Double-Skinned Structure, Structural Analysis, Welding Joint, Aluminium Alloy, Hollow Extrusion

1. Introduction

The railway vehicle bodies made of aluminium alloy are now getting popular to reduce their weight and improve their environmental impact1). The use of lightweight aluminium alloy reduces the vehicle’s weight, resulting in reduced fuel consumption, which accounts for more than 99% of a railway vehicle’s Life Cycle Energy (LCE)2). A monocoque structure, consisting of beams and plates, has been generally used for railway vehicles. But, this “single-skinned structure” has many components that require welding.

Metal inert gas arc (MIG) welding, a type of fusion welding, is commonly used to join the aluminium alloy components of the bodies. However, the high temperatures generated by MIG welding create large deformations during welding. Moreover, obtaining good joints with MIG welding requires skilled workers because MIG welding strongly depends on a work environment. Overcoming these problems requires the use of a simplified and shortened welding line and a welding method that generates less heat.

One way to simplify and shorten the welding line is to integrate the functions of the beams and plates into aluminium hollow extrusions. A comparison of this “double-skinned structure”3 with the single-skinned one is shown in Fig. 1. The aluminium hollow extrusions can include the functions of the beams and plates because of its high rigidity. Use of the double-skinned structure shortens the length of the welding line and simplifies the welding because the extrusions are all aligned longitudinally. Moreover, the number of components is reduced significantly.

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Fig. 1 Comparison of vehicle body structures
due to the integration of the beam and plate functions. The number of components that need to be fastened to the inner panel can be reduced by integrating the washers into the hollow extrusions as an attachment rail.

On the other hand, from the viewpoint of welding method, the use of friction stir welding (FSW) releases joining process from skilled workers and reduces the heat generated by welding. The basic principle of the process is illustrated in Fig. 2. In FSW, a cylindrical stir rod with a profiled pin is rotated and plunged into the joint. Frictional heat is generated between the stir rod and the workpiece. This heat softens workpiece without reaching the melting point and allows traversing of the stir rod along the welding line. The plasticised material is transferred from the leading edge of the stir rod to the trailing edge and is forged by the intimate contact of the shoulder and the pin profile. This differs from the melting of components with conventional fusion welding, like MIG welding. Since FSW is solid-state welding, i.e., the components are not melted, significantly less heat is generated. This means that there is less shrinkage and deformation during welding, which results in more beautiful outer surface and more accurately assembled vehicle bodies. Additionally, since the components are not melted, the working environment has little effect on the joining process and finish quality, meaning that fewer skilled workers are required. In sum, by using a double-skinned structure and FSW, we can simplify and shorten the welding line and reduce the heat generated by welding.

There have been only a few studies on application of FSW to transportation since its invention in 1991, so a number of technical issues remain in the application of FSW to double-skinned railway vehicles. To apply FSW to construction of railway car body, in this paper, three issues are discussed: design and strength characteristics of the joint, the numerical simulation of the car body connected by FSW and the characteristics of the car body connected by FSW.

First, We design a joint that enables FSW to be used for joining aluminium hollow extrusions. For that joint, strength characteristics during welding are investigated by three-dimensional FE analysis. And strength as a component is investigated by two-dimensional FE analysis and experiments. And finally load test using actual car body is carried out and stress distribution near the joint was measured and its safety for actual application is evaluated.

Second, accuracy of numerical simulation for railway car body joined by FSW is evaluated. To evaluate, we perform three-dimensional numerical structural analysis that simulates the actual load test and deformation and stress distribution are compared. Third, since this is the first time a double-skinned railway vehicle had been constructed using FSW, we assessed its validity as an actual car body. That is, its deformation when a perpendicular load was applied and its equivalent bending comparable to those of a conventionally constructed vehicle.

2. Method

2.1 Joint for friction stir welding

2.1.1 Design of the joint As shown in Fig. 1, each hollow extrusion consists of two parallel surface sheets, truss-shaped ribs that connect the sheets, and joints at either end to connect it to the adjacent extrusions. To design stable joints for friction stir welding which connect hollow extrusions, three factors have to be in consideration: material, the joining conditions, and the strength requirements. Figure 3 shows these requirements. From material’s viewpoint, by selecting suitable aluminium alloy and its heat treatment, the variation in geometries must be minimized to achieve narrower gaps. Because FSW doesn’t use any filler materials which can cover gaps, it is difficult to join materials with gaps. From welding condition’s viewpoint, stable conditions must be optimised to minimize defects even if a gap does form. From strength’s...
viewpoint, both the strength of each joint during welding and the strength of the completed structure must meet certain requirements. Furthermore, to minimize weight, the strength requirements should be satisfied with the smallest cross-sectional area.

We designed the cross-sectional shape of our joint for friction stir welding by considering material and joining process. Figure 4 shows comparison of sectional shape of joints. An MIG joint shown in Fig. 4(a) has been mainly designed to prevent welding shrinkage. Because MIG welding doesn’t generate any load. In contrast, to design the joint for FSW, we must consider several factors in addition to above MIG joint’s conditions: the load and heat generated during welding, the stricter gap allowance than with MIG welding, the reduced thickness of the welding line due to the inclination of the stir rod.

Figure 4(b) shows the cross-sectional shape of the joint for friction stir welding and it embodies above mentioned factors as follows. First, a rib was placed directly under the joining line to support the load during welding. Since the gap allowance is strict, the joint is designed as an I-shape which has no gaps if they have no variety. Second, since the thickness of the stirred zone is reduced after joining, a projection was placed on the surface of the joining line to maintain the thickness and strength of the surface sheet. Third, to diffuse the heat from the stir rod uniformly, a bulge was placed directly under the joining line. Fourth, to reduce the variation in geometry during extrusion, we intend to get good metal flow during extrusion. Namely, the difference in thickness between the joining line and the surface sheet was harmonized.

To ensure stability of the joint designed under material and joining requirements, joining tests were carried out. As a result, it was confirmed that FSW can reduce deformation and shrinkage and can connect hollow extrusions without defects. Thus, from the viewpoints of the joining process and material conditions, this joint is suitable for connecting aluminium hollow extrusions.

2.1.2 Strength of the joint We examined the strength of the joint designed as mentioned above. To confirm the strength of the joint, we considered two load conditions: during welding and as a component of a railway car body. The reason why we consider the strength during welding is the force generated by friction. The friction generated during FSW creates a reaction force in the workpiece coincident with heat input. From above reason, the joint must not only be strong enough as a component of a railway vehicle but also strong enough to withstand the heat and load during welding.

During welding, if local stress is generated in the rib under the welding line, a slight change in the joining conditions and variation of geometry would increase singularity, which could lead to large plastic deformation or a joint fracture. We thus need to ensure that local singular stress is not generated at the rib immediately under the welding line during welding.

As a component of a railway vehicle, the joint must support several kinds of static and fatigue loads in operation.

a. Strength during welding To simulate the distribution of stress generated near the joint by the heat and load during welding, we carried out three-dimensional thermal-stress analysis. We did not consider the micro phenomena, such as softening and stirring of the metal, because their effects are limited. The analysis conditions were defined macroscopically: heat input and load from stir rod. The object area for analysis was set to 250 mm across the welding line and 400 mm along the welding line, as shown by the model in Table 1. This is a part of area set for the preliminary experiment conducted to ensure stability of the joint. The welding line on the upper surface was the evaluation object. The nodes of each component were connected along the welding line. We thus did not simulate estrangement and contact behaviour in the boundary area, but these behaviours do not affect the stress distribution at the rib immediately under the welding line. The four holes at each corner of the model simulate the bolt holes in the sample used in the experiment.

The boundary conditions were set to reflect those in the experiment. A boundary condition against deformation was applied to the four holes at the corners and also to the lower side of the welding line, reflecting contact with the jig. A boundary condition against temperature was applied to the lower side of the welding line, reflecting contact with steel.

The material properties are shown in Table 1. To achieve high accuracy, the material properties must be accurate. It is difficult, however, to measure the temperature at the contact edge of the stir rod with workpiece and to estimate the mechanical properties of aluminium alloys at high temperature. These properties were thus estimated in consideration of various kinds of knowledge. For example, heat from the stir rod was assumed to be transmitted only through the shoulder of the stir rod. Actually, heat is transmitted through the shoulder and pin, which is at the tip of the rod. However, it is difficult to simulate the heat transfer from the pin, and this assumption does not af-
fect the stress distribution in the rib immediately under the welding line. The temperature at the edge of the stir rod was assumed to be 600°C because the A6N01-T5 material melts at temperatures between 615 and 652°C(11).

An eight-node solid element was used to make the analysis model. The LS-DYNA(12) explicit structural analysis program was used for the analysis cord.

b. Strength as a component To evaluate the strength of the joint as a component of a railway vehicle body, the stress distribution in the joint section was estimated using numerical analysis and static and fatigue tests were carried out using a test specimen. Load condition was set to the axial load (tensile load) in the right angle of the joint, which is considered to be one of the primary loads and seems to be the severest for the joint.

For the numerical analysis, we used the sectional model shown at the top of Fig. 5 and the expanded view of the joint model shown at the bottom. Elastic finite element (FE) analysis was employed under two-dimensional plane-strain conditions. We made the model about 600 mm wide to avoid effects from the boundary conditions at either edge. One edge was fixed in all directions, and traction was applied at the other edge. To maximize accuracy, fine elements were provided near the joints.

For the static and fatigue tests, we used element specimens that conformed to the JIS No. 5 test specimen specifications. The convex surface at the welding line was well ground to be flat, because of the prevention from the effect of stress concentration of the burr. Before making the specimen, we checked for defects after welding by non-destructive testing (visual inspection, liquid penetrant testing, and ultrasonic testing).

We used a hydraulic servo-type fatigue tester with a ±98-kN capacity. The fatigue testing conditions were 10 Hz and stress ration $R = 0.1$.

c. Actual application To evaluate the validity of the joint for actual application from strength’s viewpoint, load test using actual car body fabricated by FSW was performed. Six FSW joints were used on each side of the body. Strain gauges were attached around the joints where the FE analysis predicted high stress would occur. The load conditions conformed to JIS E7105 and consisted of a 473-kN perpendicular load applied to the underframe with a tournament jig.

2.2 Numerical analysis
To evaluate the accuracy of the numerical analysis for a railway car body fabricated by FSW, we performed three-dimensional numerical structural analysis that simulated the actual load test. The model for the full analysis and the sub model for the detailed analysis are shown in Fig. 6.

The model for the full analysis covers only one-half of the car body structure due to symmetry. The hollow extrusions were modelled as an equivalent orthogonal anisotropic plate in a manner equivalent to that reported earlier(13). The boundary conditions for symmetry with respect to the cross-section were input and restricted in the up and down direction at the bogie. The analysis code

| Table 1 Conditions for numerical analysis |

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<th>Material properties</th>
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was the CNDYN program for general-purpose structural vibration analysis using the finite element method\(^{(14)}\).

For the detailed analysis, fine elements were used for the areas near window corners and joints, where complex stress fields form. The area of the analysis was set wider than area of window corner because we thought the boundary conditions at the edge of the model would affect stress distribution. It was set to 1 393 mm longitudinally and to 1 368 mm vertically.

![Numerical analysis model of railway car body](image)

**Fig. 6** Numerical analysis model of railway car body

2.3 Characteristics of the car body

Since this was the first time a double-skinned railway vehicle had been constructed using FSW, we assessed its validity. That is, its deformation when a perpendicular load was applied and its equivalent bending rigidity which governs riding comfort was compared with those of a conventionally constructed vehicle made of aluminium alloys.

3. Results and Discussion

3.1 Joint for friction stir welding

3.1.1 Strength during welding

First, we evaluate the accuracy of the thermal-stress analysis. To check the accuracy of simulation, agreement of temperature transition near the joint during welding between the thermal conductivity analysis and experiment was assessed. Figure 7 shows the simulated and experimentally measured temperature generated during welding. The experimental data was obtained during welding test for material and welding condition mentioned before. The section for evaluation in the longitudinal direction was set at the lengthwise centre of the welding line in order to avoid the effects of the edges of the test specimen. In this section, three points were selected for comparison. As shown

![Temperature generated during welding](image)

**Fig. 7** Temperature generated during welding
in Fig. 7, Point A was on the surface sheet, 10 mm from the centre of the welding line, Point B was on the surface sheet, 20 mm from the centre of the welding line, and Point C was at the centre of the rib immediately under the welding line in the vertical direction. The simulation results agreed with the experiment results within about 10%. The tendencies of the temperature curves agreed well. From above results, numerical analysis predicts heat conductivity and temperature distribution with sufficient accuracy.

Using the temperature distribution obtained by simulation, we calculated the stress generated by heat from the stir rod. We then carried out thermal-stress analysis using the material’s non-linear characteristics and clarified the stress distribution near the joint. The results of the FE analysis of the joint are shown in Fig. 8.

In Fig. 8 (a), to make it easier to understand the stress distribution in the rib directly under the joint, only a part of the analysis model is shown. The welding was carried out toward the left from the right along the upper side of the welding line. In the rib directly under the joint, high stress spread out behind the stir rod, where the welding had already been carried out. This figure shows that local stress was not generated near the welding line.

To display the detailed stress distribution in the rib immediately under the welding line, the distribution of the stress along the A-A cross-section is shown in Fig. 8 (b) and (c) for each direction. This figure shows that stress in the vertical direction spread out immediately behind the stir rod from the bottom to the top of the rib. It also shows that stress in the longitudinal direction spread out widely behind the stir rod. That is, local stress was not generated in both directions, and the stress was lower further away from the stir rod. Based on these characteristics, we consider the compressive stress directly below the stir rod to be caused by the vertical force of the stir rod and the stress behind the stir rod to be caused by heat.

Here, based on the above reason, stress in vertical direction must spread just under the stir rod, but Fig. 8 (c) shows vertical stress spreads a bit behind the stir rod. The reason is deformation. In Fig. 8 (d), deformation is shown. Because the welding line behind the stir rod rose up, stress behind the stir rod is higher than the stress just under the stir rod.

In sum, these results demonstrate that the developed joint can be joined with sufficient stability using FSW.

3.1.2 Strength as a structural component

a. Analytical results To clarify the complicated stress distribution near the welding line, we plotted the relative-stress distribution, which is shown in Fig. 9. The benchmark is the nominal stress of the surface sheet, which is indicated by \( \sigma \). This figure reveals no local particular stress, even in the curved and step components. The maximum generated stress was on the outside surface; the stress decreased toward the inside of the joint. In some parts, a compressive stress field also formed. The stress on the outer surface of the joint had a more or less uniform distribution with a value equal to the nominal stress at the surface sheet. These results indicate that the nominal stress of the face sheet or the stress on the outer surface of the welding line can be taken as the generated stress for the purpose of evaluating the strength of the joint.

The joint has a contact surface between two hollow extrusions next to the edge of the welding line (marked A in the figure). The stress at the tip of the contact surface is nearly 10% of the nominal stress. To determine whether the contact surface affects crack initiation and propagation, we used Kendall’s analysis model (15) which normally used for a long elastic lap joint’s crack propagation. Because the joint’s sectional configuration around...
bulged backing and surface sheet as shown in Fig. 9 (b) is similar to a Kendall’s model shown in Fig. 9 (a). We found that the stress intensity factor range, $\Delta K$, was smaller than the threshold stress intensity factor range, $\Delta K_{th}$, even if yield stress has worked at the surface sheet which has allowable minimum thickness. This means that, theoretically, crack initiation and propagation do not occur from the contact surface. On the other hand, the grades of actual welding joints vary widely. To confirm the crack propagation of actual welding joint, in the next paragraph we mention about the results of tensile fatigue test.

b. Experimental results In static tensile test, two specimens are examined. One fractured at the heat affected zone (HAZ) and the other fractured in the parent material area. In both specimens, fractures and crack initiations on the contact surface and in the stirred zone were not observed. The tensile strength of the joint fractured at the HAZ was 271 MPa, and that of the joint fractured in the parent material area was 277 MPa. The tensile strength of both specimens was the same as that of the parent flat specimen even though they had been joined by FSW. The reason for this is that heat affected part of the surface sheet had been thickened to increase its strength.

The results of the fatigue test are shown in Fig. 10. The vertical axis shows the nominal stress at the surface sheet. All of the specimens fractured at the root of the rib where heat was not affected; no crack propagation or initiation from the contact surface mentioned above was observed. The stirred zone did not affect the strength of the joint. These results show that the FSW joint developed for hollow extrusions is at least as strong as the conventional MIG joint for hollow extrusions. Thus, from the strength viewpoint, it is suitable for joining hollow extrusions.

3.1.3 Actual application The stress distribution near the FSW joint around the window corners shown in Fig. 11. In brackets, the results of simulation are shown as well.

Our measurements showed that a maximum stress at the joints of 40 MPa was generated on the inner surface of the welding line. Based on the result, stress to evaluate as a component of rolling stock is calculated with 44 MPa conformed to the JIS E7105. On the other hand, allowable stress of the FSW joint is 80 MPa which is ruled as MIG joint in the JIS because the allowable stress of FSW joint is higher than MIG joint based on the above tests. The mechanical characteristics of the FSW joint we have developed for hollow extrusions are thus sufficient for railway vehicles.

3.2 Numerical analysis

a. Full car body The results of the FE analysis and load tests with respect to the vertical deflection of the vehicle at the side sill are shown in Fig. 12 (a), and those with respect to the out-plane deformation are shown in Fig. 12 (b). The vertical deflection from the FE analysis agreed well with that of the load test. The maximum deflection was 9.59 mm in the load tests and 9.68 mm in the FE analysis, a difference is less than 1%. The tendency of the deformation from the FE analysis also agreed well
with that of the load test. Out-plane deformation at the centre of the underframe was 11.5 mm in the load tests and 11.8 mm in the FE analysis. FE analysis clearly can predict deformation of railway vehicles with sufficient accuracy.

**b. Local stress** First, we confirmed that the boundary condition of the detailed analysis model did not affect the stress distribution at the window corner, the target area of our evaluation using analysis model shown in Fig. 6. To confirm the accuracy of the detailed analysis, we compared the tendency of the out-plane deformation in the detailed analysis with the results of the full analysis mentioned above. The result of comparison of the out-plane deformation with the vertical displacement along the vertical and horizontal lines near the window corner is illustrated in Fig. 13. We found that the deformation and displacement from the detailed analysis agreed with those of the full analysis. This means that detailed analysis simulates a part of the full model of rolling stock precisely.

From Fig. 11, in comparison with the results between the load test and detailed analysis, they are generally in good agreement. Stress at a window corner is generally higher, and it decreases with the distance from the window. The inner surface sheet at the window corner had higher stress than the outer one, while in other areas the sheets had approximately equal stress. The maximum stress at the window corner was 99 MPa in the load test and 85 MPa in the detailed analysis. It was 98 MPa on one side of the surface sheet in the load test and 102 MPa in the FE analysis. The detailed FE analysis thus accurately predicted the results of the load test.

In sum, using the method described here, we can predict characteristics of the railway car body fabricated by FSW and the stress distribution near welding joints and window corners.

### 3.3 Characteristics of the car body

We first evaluate the tendency in the deformation of the vehicle body. The maximum deflection at the side sill was within the criteria based on experience and the displacement of the out-plane deformation at the side panel, which affects contact between a door and the car body, was about the same as that for conventionally built railway vehicles. The maximum deflection in the underframe, which affects contact with the infrastructure, was 11.5 mm, about the same as that for conventionally built railway vehicles. Based on these results, the deformation is same as railway car body fabricated by conventional methods.

The equivalent rigidity of railway vehicles is an important characteristic because it affects riding comfort. We compared the equivalent rigidity of the vehicle, calculated using 0.89 GNm², with that of conventional vehicles made...
of aluminium alloys. Table 2 lists the equivalent rigidities of several types of railway vehicles made of aluminium alloys\(^{(16)}\) in Japan. That for the Shinkansen bullet train is the highest, 3.00 GNm\(^2\), while those for metro and commuter trains was lower (0.32 to 0.87 GNm\(^2\)). The equivalent rigidity for the railway vehicle joined by FSW was higher than that for both the metro and commuter trains, so it is sufficient for practical application.

Given these excellent results, we used FSW to construct 319 double-skinned railway vehicles, both commuter and express, as of June 2002. We also used it to construct 136 single-skinned railway vehicles, both metro and Shinkansen. All of these railway vehicles have been used for commercial use and has no troubles since its introduction.

### 4. Conclusion

We have applied friction stir welding to the construction of double-skinned railway vehicles made of aluminium hollow extrusions. At our study three factors have been investigated.

As far as a development of joint, we first designed a joint for FSW of aluminium hollow extrusions from material and welding condition’s viewpoint. After that, from strength’s viewpoint, two conditions were investigated: during welding and as a component. During welding, three-dimensional finite-element thermal stress analysis revealed that compressive stress is generated in the rib of the joint, while directly under the stir rod and behind it and no local stress occurs. The joint is thus strong enough to handle both the thermal stress and load that occur during FSW. As a component, two-dimensional structural analysis showed that the maximum generated stress was on the outside surface and that no particular local stress occurred in a section of the welding line. Static and fatigue load test showed that the FSW joint is at least as strong as conventional flat MIG joints, meaning that it is strong enough for practical application. In load test using actual railway car body, a maximum stress to evaluate at the joint was 44 MPa and allowable stress was 80 MPa, so the joints are sufficiently safe for actual application.

As far as numerical simulation of the railway car body joined by FSW, the difference in the maximum deflection of the section at the centre with respect to the longitudinal direction between the full analysis and the load tests was 1\%, and the difference in the out-plane deformation was 1 mm. This close matching indicates that numerical analysis using a full model can be used to precisely predict the loads. The results of the detailed analysis showed the same trends in deformation as full model analysis and nearly the same trends in generated stresses as load tests. We can thus use numerical analysis to precisely predict generated stress based on general deformation for railway vehicles.

And as far as car body’s characteristics, the deformations at the side sill, side body, and underframe were nearly the same as those of conventional railway vehicles, and the equivalent rigidity was 0.89 GNm\(^2\), which is higher than that of conventional vehicles made of aluminium.

In sum, we have successfully applied friction stir welding to double-skinned car body. Using these results, we can simplify and shorten welding line and reduce heat input during welding, and this leads small deformation. Moreover, due to FSW is not affected from a work environment, welding process doesn’t require skilled workers. These benefits have been applied to 319 actual railway vehicles as of June 2002.

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### References


