Development of the “A-train”: towards a new generation

Takeshi KAWASAKI

R&D Centre
Kasado administrative division
Hitachi, Ltd.,
Higashitoyoi 794, Kudamatsu-city, Yamaguchi-Pref. 744-8601 JAPAN
Tel: +81 833 41 8728
Fax: +81 833 41 8694

Co-authors: Toshiaki MAKINO, Seijiro TODORI, Kentarou MASAI, Hideshi OHBA, Masakuni EZUMI

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Introduction

Railways, which can transport a large number of passengers safely, rapidly, and comfortably, are being reconsidered because of their superior environmental friendliness. But their environmental impact is nevertheless being scrutinized and designs of future railway cars will need to consider the environment. One requirement is to reduce the running energy, which accounts for more than 90% of the life cycle energy [1]. This necessitates a lightweight design. Moreover, the structure of the interior should be easy to change because a commonplace interior will bore passengers. Another social problem that should be considered is population demographics. The size of the work force is rapidly decreasing because of a declining birth-rate and fewer skilled workers. To respond to this situation, railway cars, which are typical labour-intensive products, need new structures to enable easy handling at every stage of fabrication, maintenance, and disposal. Furthermore, in order to fascinate passengers who are using other transportation system, it is also important to create delightful artistic designs.

Although conventional railway cars have become lightweight, they still have very complicated structures. This increases the number of parts used in fabrication, increases the manpower needed for maintenance and disposal, and makes it difficult to classify materials during disposal. Moreover, there are physical limits to possible new designs imposed by the capacity of bending machines and the workability of materials.

As a result of a fundamental study and reliability test on the ideal method of producing aluminium railway cars, we have developed the “A-train” railway car concept, which features an innovative structure and innovative manufacturing techniques. The “A-train” satisfies not only the requirement for reduced running energy, but also those for environmental friendliness, suitability for the changing labour structure, and exciting design. We have made more than 200 of these railway cars under this concept and they have been favourably received.

This report describes the concept of the “A-train” and the world’s first application of friction stir welding (FSW) to a double-skinned car body.

A-train

In addition to the demands of passengers, such as comfort, reliability and speed, railway cars must be able to adapt to future social issues, such as the decrease in the birth-rate and preservation of the environment. In order to meet all of these requirements, as shown in Fig. 1, future railway cars must use labour saving manufacturing techniques whilst at the same time satisfy the requirements for higher performance. Thus, after numerous investigations and reliability tests, we developed a new railway car system and named it the "A-train" [2].
The “A” of “A-train” embodies many meanings, such as Amenity, Advanced, Ability, and Aluminium. The “A-train” development results from three main achievements. The three key development stages of the "A-train" consisted of interior, fittings and fixtures and the car body, as indicated in Fig. 2. The car body is a simple and homogeneous structure using only aluminium hollow extrusions joined by FSW. The interior is designed to be assembled from several modules. The fastenings are designed for easy tightening and loosening using nuts and bolts. The details of each development are shown below.

**Interior**

In order to make the initial fittings and subsequent refurbishments easier, our “A-train” uses modular interiors. We decreased number of module parts as a result of the development of multifunctional materials. For an example, integration of the interior panel and thermal insulation as shown in Fig. 3. The multifunctional component which unified external beauty and the heat insulation function was developed. In order to meet customer's interior design, a process that can manufacture a freely curved surface and a right angle edge was developed. The size of the module panel is also standardized. For this reason, all interior work is completed by installation of just one module panel.
Fixings
In order to attain easy tightening and loosening with high reliability, a sleeve clinching method was applied to attach interiors with hollow extrusion [3].

By using the usual torque method it was difficult to keep high axial force of tightening bolt. Because, torque, especially near the yield point, is greatly affected by friction under the bolt head and in the threads. But the sleeve clinching method does not control torque to stretch the bolt, but directly stretches the bolt. The procedure of the sleeve clinching method is shown in Fig. 4. The steel bolt is axially loaded in tension and the aluminium nut is then plastically deformed from sleeve onto the threads of the bolt. Although a handgun tool is required for sleeve clinching, handling of the tool is easy and each tightening (clinching) needs only about 2 to 3 seconds. Furthermore, the direction of tightening is not affected by gravity and this method releases us from the time consuming work of turning nuts. A nut can be freely loosened and re-tightened by a conventional tool after sleeve clinching. Compared with the conventional method, we can keep axial force higher and can attain a reduction in variation of axial force. Adoption of the sleeve clinching method has already started in some automakers besides the railroad vehicle.
In order to solve the two contradicting subjects, such as ease of manufacture and the improvement in reliability, we adopted aluminium hollow extrusions for car body [4].

The section of rolling stock is shown in Fig. 5. The improvement of manufacturing technology in hollow extrusions, and development of an A6N01 aluminium alloy which has good extrusion characteristics and high strength, made it possible to apply extrusions to the body full length of 25m. The thickness of its surface sheet is between 2.0 and 3.0 mm. By using hollow extrusions for all the sections of rolling stock, flexibility of the design are improved, reduction of number of parts, the flexible determination of the thickness of surface sheet according to the stress level, and the simplification of a welding line are attained. Furthermore, the welding line was minimized by making in agreement the direction of extrusion, and the length direction of the body. By efficient design and the minimization of variation in manufacture, the uniformed structure can attain improvement in labour saving, strength reliability and lightweight. Moreover, we can attain the improvements on comfort such as characteristics of vibration and noise, because hollow extrusions consist of two surface sheets. Furthermore, by adopting FSW, which we mention details in the next chapter, to join hollow extrusions, we keep high strength and reliability and good appearance of welding line.

Fig. 4. Principle of sleeve clinching method.
Application of FSW

FSW, which can attain high quality, was used for joining the hollow extrusions that constitute a rolling stock for the first time in the world [5]. Then, we explain the outline of the development to apply FSW to a rolling stock.

**Friction stir welding**

A conceptual figure of FSW is shown in fig.6. FSW is the solid phase joining process developed by The Welding Institute (TWI) in UK in 1991 [6]. The principle of FSW is that it does not melt materials like conventional MIG welding, but softens materials by frictional heat and mixes the material in solid phase by rotation of cylindrical tool. Specifically, using the cylindrical component called "tool" which has a projection called "pin" at a tip, we insert it into materials with rotation. Since it does not melt materials but softens, FSW inputs less heat into material compared with conventional arc welding. As a result, welding distortion is small and strength characteristics remain high. The benefits obtained when FSW is applied are shown in Table 1. This joining method has already applied to railway vehicles, the airplane, the vessel, and the car.
Applying FSW

Generally, the induced load during welding and control of a gap are important consideration when using FSW. The load applied during welding is generated by friction between a tool and the welding material. The load depends on the joining conditions and materials. For this reason, it is required for equipment to have high rigidity and firm clamping. Since FSW does not require any filler, it cannot fill any metal into gaps. Thus, it is required to precisely control gaps.

The method of applying FSW to join hollow extrusions is illustrated in Fig. 7. The method consists of main three parts, joining equipment, joining conditions, and geometry of joint. The high stability and easy but stable clamping of joining equipment enables 25 m sections to be joined continuously. The rigidity of the equipment was sufficient to resist significant deformation of the welding equipment. Research and numerous experiments have optimised the joining conditions, such as the rotation speed, welding speed, and tool geometry. Furthermore, we examined the joining conditions which can be stabilized in joining, even when a gap existed. A joint needs to satisfy the strength against load during

### Table 1. Benefit of applying FSW to railway car body.

<table>
<thead>
<tr>
<th>Item</th>
<th>Benefit</th>
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<tbody>
<tr>
<td>Welding deformation</td>
<td>1/13 of distortion compared with MIG</td>
</tr>
<tr>
<td>Strength</td>
<td>Static and fatigue strength is higher than MIG</td>
</tr>
<tr>
<td>Impact</td>
<td>Absorb higher energy than MIG</td>
</tr>
<tr>
<td>Work force</td>
<td>No need skilled person. Easy automation</td>
</tr>
<tr>
<td>Size accuracy</td>
<td>Transverse shrinkage is 1/3 of MIG</td>
</tr>
<tr>
<td>Defects</td>
<td>No boid will be occur</td>
</tr>
<tr>
<td>Appearance</td>
<td>Tone of welding line is same as parent material</td>
</tr>
<tr>
<td>Workability</td>
<td>No need filler, shield gas</td>
</tr>
<tr>
<td>Work environment</td>
<td>No gas, lights</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Consumption energy is lower than MIG</td>
</tr>
</tbody>
</table>

Fig.6. The principle of Friction Stir Welding (FSW).
Examination of FSW

(a) Methodology
The stress distribution of an FSW joint for hollow extrusions during joining was analysed using FE calculations. The friction of the welding between the tool and work piece causes simultaneous heating and loading of the sample. Three-dimensional FE thermal stress analysis with an elastic-plastic element was used. Two-dimensional FE structural analysis with a plane strain element was carried out in order to determine the stress distribution of the FSW joint as a structural element of railway car body. Static and fatigue tests were carried out in order to determine strength and fracture modes.

(b) Results
Figure 8 (a) shows the optimised FSW joint for hollow extrusions and (b) shows the MIG joint for hollow extrusions [7] [8]. The FSW joint has a rib just under the joint in order to prevent plastic deformation caused by joining load and heat. The thickness of the surface sheet near the joint has increased. And it has tapered compared with that of an ordinary surface sheet, because a bending moment occurs at the surface sheet near the joint.
Figure 9 shows the three-dimensional FE thermal stress analysis on the FSW joint under heating and loading caused by friction between tool and material. This figure shows that high compressive stress, especially right under the tool and at the rear of the tool, was produced at the rib perpendicular to the surface sheet.

Figure 10 shows the result of FE analysis when a tensile load, which is at right angles to the welding line, acts on the joint. It shows one of example of the stress distribution in the joint from among several loads, which work at the time of operation (such as shearing load and bending moment). The figure

Compressive stress occurs right under the tool because of the vertical load during joining, and compressive stress occurs at the rear of the tool because of heat input from the tool. This means that examination of the compressive stress distribution at vertical rib should take into account vertical welding force and heat input. Even though heating and loading of the rib occurs during FSW joining, but the maximum stress of the rib never exceeds proof stress.

Figure 10 shows the result of FE analysis when a tensile load, which is at right angles to the welding line, acts on the joint. It shows one of example of the stress distribution in the joint from among several loads, which work at the time of operation (such as shearing load and bending moment). The figure
shows that the maximum stress occurs at the surface of the sheet. Part of the joint is under compressive stress. Here, stress at the surface of the joint is distributed uniformly and is the same as the nominal stress. The crack propagation from the contacted slant surface, shown as part A in Figure 10, was evaluated. The result shows that the stress at part A was about 1/10 of the nominal stress of hollow extrusion. Kendall’s analysis model predicts that the stress intensity factor range \( K \) never exceeds the threshold value of stress intensity factor range \( K_{th} \) even if the nominal stress amplitude of the surface sheet is 130 MPa, which is nearly equal to proof stress \([9]\). This means crack propagation will never occur from a contacted slant surface. This kind of evaluation was also carried out for shear loads and bending moments. The load test described in the next paragraph also indicates that there was no fracture from contacted slant surface.

![Stress distribution diagram](image)

**Fig. 10.** Stress distribution.

Static and fatigue tensile tests were performed. The static tensile test shows that fracture occurs in the HAZ. The nominal tensile strength was 271 MPa, which is approximately same as that of the parent material. This tensile strength is high because of the increased thickness of the HAZ in the FSW joint that makes up for the loss of strength due to the heat input.

The fatigue strength of the FSW joint is the same as that of the MIG joint. Fracture of all specimens occurred in the HAZ. Although the thickness of the HAZ increased, the stress concentration caused by the complicated shape of the joint and local bending deformation decides the strength of the FSW joint. The static and fatigue test results under our welding and testing conditions show that the tensile strength of the FSW joint for hollow extrusions is equivalent to that of the flat ground MIG joint.

**Conclusion**

We developed a new railway car system, the “A-train” which can meet the requirements of society and train operators based on the demands of passengers. Now, many of the vehicles produced by our company adopted this system, and we have applied it to 200 or more cars to date. By introducing such a railway car system, society, passengers, and a train operating company can receive many benefits in all aspects of the life cycle. For this reason, we think that the vehicles which adopted this system will increase in number from now on. Moreover, we are going to continue to try hard in the future to produce better vehicles.
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Bibliography