



FRICITION STIR WELDING OF ALUMINIUM ROOF PANELS FOR METRO VEHICLES

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Abstract – This paper presents the development and industrial implementation of Friction Stir Welding (FSW) for aluminium roof panel assemblies of metro vehicles within the Stadler SBB project. The base material is EN AW 6005A T6 extruded aluminium alloy (group 23.1, EN 15608), with a wall thickness of 3.5 mm and panel dimensions of 2,214 × 2,348 mm. FSW (ISO 4063, process No. 43) was selected for its advantages over fusion welding: reduced heat input, no filler material or shielding gas, minimal distortion, and superior surface finish. Welding was performed on a CNC milling machine at 170 cm/min using a tool with a 15 mm concave shoulder and 6 mm threaded probe. Process qualification per ISO 25239-4 included tensile, bend, and macrographic testing, with all results meeting quality level C (ISO 25239-5). The symmetrical welding sequence covered 12 joints per assembly (27.7 m total), with a maximum pre-weld gap of 0.3 mm, under a three-phase quality control plan. The results confirm FSW as a reliable, efficient, and environmentally sound solution for serial production of aluminium railway components.

Keywords – Friction Stir Welding, aluminium alloy EN AW 6005A, metro vehicles, ISO 25239, railway manufacturing.

1. INTRODUCTION

The railway vehicle manufacturing industry is undergoing a structural transformation driven by growing demands for weight reduction and environmental sustainability. Modern metro vehicles are increasingly designed as aluminium structures, primarily due to their favourable strength-to-weight ratio, inherent corrosion resistance, and high recyclability at end of service life [1]. However, the application of conventional fusion welding processes - MIG and TIG - to aluminium alloys introduces a range of technological limitations: a pronounced heat-affected zone (HAZ), residual stresses and distortions, and thermal softening of the material. In the EN AW 6005A-T6 alloy, which is widely used in the manufacture of extruded profiles for railway vehicles, these effects can locally reduce mechanical properties by 30–40% [2].

Friction Stir Welding (FSW *Friction Stir Welding*), developed at TWI in 1991 [3], represents a fundamentally different approach to joining metallic

materials. The process is based on generating heat through friction between a rotating tool and the workpiece, causing material plasticisation without reaching the melting point - typically at temperatures of approximately 80% of the solidus temperature [4]. FSW joints exhibit superior mechanical properties compared to fusion welding: a narrower heat-affected zone, lower residual stress levels, and negligible distortions [5]. Industrial application of FSW in the railway sector was pioneered by Japanese manufacturers in the late 1990s, soon followed by leading European players - Bombardier, Alstom and Stadler - establishing FSW as the dominant joining technology for aluminium extruded components in this industry [6, 7].

Existing research on FSW joints of EN AW 6005A-T6 alloy confirms tensile strengths in the range of 74.4–80.8% of the base material value [2], noting that the dominant factors influencing joint quality are shoulder diameter, rotational speed, and travel speed [8]. It has been shown that a concave

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shoulder geometry yields superior mechanical results compared to a flat geometry [9], while compressive residual stresses in the weld nugget zone contribute to improved fatigue characteristics relative to fusion welding [10, 11]. The environmental sustainability aspect further supports FSW technology: the process consumes 40–60% less energy, eliminates toxic fume emissions [4], and on average requires approximately 42% less energy per unit weld length compared to the GMAW process [12], resulting in a substantially higher sustainability rating in systematic comparative analyses [13].

This paper presents the complete industrial development of FSW technology for extruded aluminium panels of metro vehicle roof assemblies within the Stadler SBB project. The work encompasses base material characterisation, tool geometry design, process parameter optimisation,

welding sequence definition, qualification according to ISO 25239-4, and the three-phase quality control programme applied in serial production.

2. MATERIAL, EQUIPMENT AND FSW WELDING PARAMETERS

2.1 Base Material

All components were manufactured from extruded aluminium in accordance with EN 755-2: EN AW 6005A T6. This alloy belongs to the 6xxx series (Al-Mg-Si), with minor additions of manganese and chromium that improve corrosion resistance and toughness. According to EN 15608, the material is classified in group 23.1. Chemical composition and mechanical properties are presented in Table 1 and Table 2.

Tab. 1. Chemical composition of EN AW 6005A T6 (EN 573-3)

Si [%]	Fe [%]	Cu [%]	Mn [%]	Mg [%]	Cr [%]	Zn [%]	Ti [%]	Al [%]
0.5-0.9	0.35	0.3	0.5	0.4-0.7	0.3	0.2	0.1	balance

Tab. 2. Mechanical properties EN AW 6005A T6 (EN 755-2)

Yield Strength R_e [MPa]	Tensile Strength R_m [MPa]	Elongation [%]	Hardness [HBW]
215	255	6	85

2.2 Welding Machine

Welding was performed on a CNC milling machine manufactured by Fooke, equipped with an integrated FSW module (Fig. 1). The machine is designed for single-pass welding of 6xxx series aluminium alloys at material thicknesses up to 27 mm, and its main technical specifications are shown in Fig. 4.



Fig. 1. FSW welding machine

2.3 Tool Geometry

For this project, an FSW tool (Fig. 2) was selected with a concave shoulder of 15 mm diameter and a tapered probe with a nominal diameter of 6 mm and right-hand thread. The concave shoulder geometry was designed to form a local "reservoir" of plasticised material, ensuring continuous mixing in the joint zone, stable heat input, and proper weld face

formation. The geometry of both the shoulder and probe is critical for weld quality: the shoulder generates approximately 70% of the total frictional heat input through friction with the workpiece surface, while the probe contributes the remaining 30% by stirring the material at weld depth [8].



Fig. 2. FSW tool geometry

2.4 Clamping Fixture and Assembly

The high thermal expansion coefficient and pronounced thermal conductivity of aluminium result in rapid heat redistribution during the welding process. As the tool approaches the end of the joint, the accumulated heat may cause a tendency for the profiles to spread apart due to thermally induced forces, which negatively affects the dimensional accuracy of the assembly and the weld quality. These effects were successfully mitigated through the use of an appropriate clamping system.

Horizontal clamping was achieved using a specialised pneumatic system with diaphragm cushions, thereby eliminating surface damage to the profiles during clamping. For vertical restraint, manual clamps were used, positioned individually for each profile. Due to the characteristic FSW profile geometry defined by the customer, the use of a hydraulic clamping system was not required. The procedure for assembling the profiles into a sub-assembly prior to welding is shown in Fig. 3.

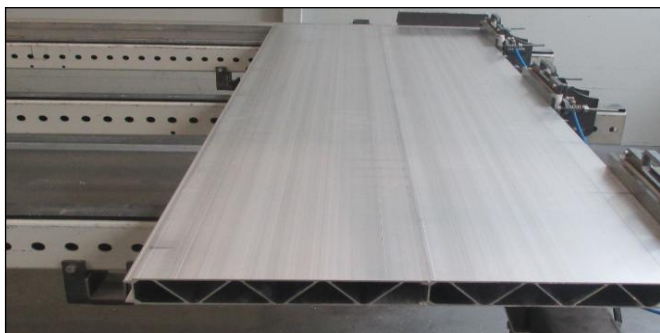


Fig. 3. Assembly of profiles into the FSW sub-assembly

After completing the sub-assembly installation in the clamping fixture (Fig. 4) and activating the mechanical and pneumatic clamping systems, a visual inspection of the gaps at all joints between profiles was carried out. The maximum permissible gap was 0.3 mm - a value above which characteristic FSW defects such as voids and tunnel defects in the weld root zone may occur.

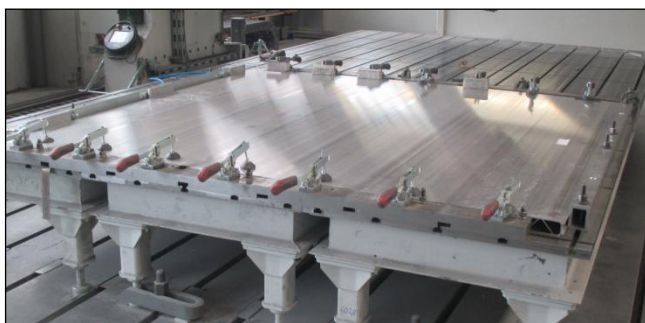


Fig. 4. Clamping fixture for FSW welding of the sub-assembly

2.5 Surface Preparation Prior to Welding

Prior to welding, a standard inspection and preparation procedure was carried out, encompassing: visual inspection of the FSW tool condition, mechanical-chemical cleaning of the clamping fixture working surfaces, verification of ambient conditions in the workshop, and checking of all fluid levels in accordance with the machine preventive maintenance procedure.

Preparation of the profile contact surfaces at the joint locations was carried out in three steps:

mechanical cleaning with stainless steel brushes to remove the oxide layer, degreasing with technical alcohol, and final wiping with clean white cloths. Following surface preparation, the profiles were assembled, the sub-assembly was formed, and placed into the clamping fixture.

2.6 Welding Parameters

Welding parameters were determined through the production of test welds and preliminary welding procedure qualification (pWPS), in accordance with the requirements of EN ISO 25239. According to this standard, the first and last 50 mm of each welded joint are treated as technological run-off and excluded from weld quality assessment. The adopted welding parameters are presented in Table 3.

Tab. 3. Key FSW Welding Parameters

Parametar	Vrednost
Welding speed	170 cm/min
Tool rotational speed	3200 min ⁻¹
Tool tilt angle	2 °
Axial force	7000 N

2.7 Welding Sequence

Welding was performed according to a predefined symmetrical sequence (Fig. 5), with the aim of achieving uniform heat input distribution and minimising thermally induced panel distortion during the process.

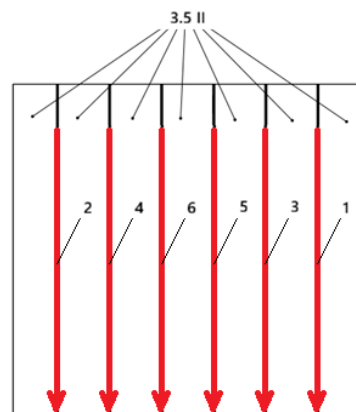


Fig. 5. Welding sequence

The sequence began with weld 1 at the far right of the panel, then continued symmetrically with weld 2 at the far left, following an alternating pattern through to the final weld pair - of the assembly — yielding a total of 12 welds per panel. The defined sequence was entered and stored in the machine control programme, fully automating the process. The operator's role was limited to defining the axis zero positions and initiating the welding cycle. Upon completion of welding on the first side of the panel, the identical

sequence was applied to the second side of the assembly.

3. QUALITY CONTROL PLAN

Primenjen je program kontrole kvaliteta u tri faze u skladu sa ISO 25239-5 (nivo kvaliteta C):

3.1 Pre-Weld Inspection

Verification of base material certificates (EN 10204: 3.1), dimensional inspection of extruded profiles, fit-up and joint gap inspection (≤ 0.3 mm), FSW tool geometry inspection, laser calibration of the CNC machine, and verification of operator qualification (ISO 25239-3).

3.2 In-Process Inspection

Continuous monitoring of welding parameters (rotational speed, axial force, travel speed) by the machine control system; verification of the welding sequence; real-time visual inspection of the weld face via a camera system.

3.3 Post-Weld Inspection

Visual Testing (VT) of 100% of welds following each panel assembly. Macrographic examination is periodically performed on 50 mm specimens cut from the start and end of each assembly, as agreed with the customer. All joints demonstrated full compliance with ISO 25239-5, quality level C.

4. CONCLUSION

1. FSW process No. 43 (ISO 4063) has been confirmed as the optimal joining technology for serial production of extruded aluminium metro vehicle roof panels, satisfying both customer requirements and ISO 25239 standards.
2. EN AW 6005A T6 alloy demonstrates excellent weldability by the FSW process. Neither preheating nor post-weld heat treatment is required for the wall thickness range of 3.5 mm.
3. The symmetrical welding sequence with 12 joints effectively minimises panel distortion through balanced heat distribution.
4. All mechanical test results (tensile, bend, macro) comply with the requirements of ISO 25239-5 for quality level C.
5. As a solid-state process with zero emissions, requiring no consumables other than the FSW tool, FSW represents a fully green manufacturing technology aligned with current sustainability objectives in the railway industry.

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