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Production by FSW of Free-Shape Hollow Profile in AA5754 for Automotive Application

Topi Taavitsainen*  Pedro Vilaça†  Tommi Mutanen‡

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Abstract

In automotive industry there are several high potential applications of closed hollow profiles in aluminum alloys, but the extrusion process is not technically easy to apply to several aluminum alloys, namely the AA5754, one common alloy in automotive industry. Thus, the development of a feasible and reliable solution to produce closed hollow profiles in low thickness of AA5754 represents an important innovation opportunity.

In this paper an innovative clamping is presented enabling the application of the Friction Stir Welding (FSW) in the production of these components. The conditions developed for the application of the FSW enables the production of box shape profiles with low thickness in a wide range of aspect ratio and lengths. The innovative approach was tested in a wall thickness of 3 mm. The innovation is based on a new clamping system enabling the use of conventional tool architecture with dedicated geometric features. The main challenge was to produce sound welds between thin plates in a corner joint design, when the activation of the FSW joining mechanisms demands the application of a significant mechanical energy.

Metallographic analysis including EBSD was conducted to evaluate the weld zone. The mechanical properties of the joint and resultant profiles were addressed via micro-hardness, dedicated corner opening test (COT) and quasi-static crashworthiness test. The results demonstrate the feasibility of the concept, by presenting a sound weld zone overmatching the base material in hardness, and matching the base material in COT. The FSW components clearly overcome the COT and crashworthiness resistance of similar structures welded by TIG.

Keywords: FSW, Clamping system, AA5754, Free-shape box hollow profile, Automotive

*Department of Engineering Design and Production, School of Engineering Aalto University. Email topi.taavitsainen@aalto.fi
†Department of Engineering Design and Production, School of Engineering Aalto University. Email pedro.vilaca@aalto.fi
‡Autom consulting, Finland
Introduction

Automotive industry’s interest in using aluminum alloys in car chassis structures is increasing due to the perceived need to produce more energy efficient vehicles with lower environmental impact [1]. The production of chassis and other automotive structural components based on the typical high strength-to-weight ratio of the aluminum alloys, enables to lower the vehicles weight complying with increasing structural safety demands [2]. Another advantage is the high recyclability of the aluminum, associated with the fact that secondary aluminum uses about 7% of the energy required to produce primary aluminum and reduces emissions of CO and CO$_2$ [3]. This allows structural design solutions with cost savings and low ecological footprint [4]. The good corrosion resistance of the Al-Mg alloys, such as the AA5754 tested in this work, is also a relevant advantage, mainly when compared with the magnesium alloys that are one other common alternative of lightweight metallic materials for automotive applications [5].

One of the disadvantages of the structural aluminum alloys is the low weldability both by resistance welding, e.g., due to the low electrical resistivity and high thermal conductivity and fusion welding, e.g., due to the softening of the HAZ and high susceptibility for formation of porosity and hot cracking. The Friction Stir Welding (FSW) [6] of aluminum alloys, has proven to deliver defect-free joints, with good mechanical properties and low distortion. Moreover, the thermo-mechanically affected zone (TMAZ), including the dynamically recrystallized zone (nugget), presents good toughness and formability. Due the lower heat input, the HAZ does not undergo as severe aging phenomena as in fusion welding processes [7].

One of the challenges of applying the aluminum alloys in automotive industry is that the production of closed-hollow profiles, a typical solution to attain the design specifications, is rather difficult except by extrusion for Al-Mg-Si alloys [8]. In this work, a joint design, tool features, and clamping system were developed to allow the production of closed-hollow profiles in AA5754-H22 with a wall thickness of 3 mm. The new concept enables the application of conventional FSW, i.e. with no need of complex bobbin tools or using extrusions [9][10], in the production of any aspect ratio hollow profiles with closed-box shape. One major potential application of the long hollow profiles with closed-box shape is in chassis for buses and coaches. [11]

The main technological and metallurgical features of the joints are assessed by optical microscopy and EBSD. The mechanical properties of the joints are presented in terms of hardness field, Corner Opening Test (a dedicated solution similar to bending test) and quasi-static crashworthiness test, especially relevant for automotive applications.
Methods

Materials

The material selected for this study is AA5754-H22 (EN AW-Al-Mg3) representing one important material for automotive industry e.g. bus chassis construction. This aluminum grade, as most of the 5000-series aluminums, has good mechanical properties and excellent corrosion resistance.

Table 1: Chemical composition (wt-%) of AA5754. [12]

| Composition | Si | Fe | Cu | Mn | Mg  | Cr | Ti | Al  |
|------------|----|----|----|----|-----|----|----|-----|
| AA5754     | 0.40 | 0.40 | 0.10 | 0.50 | 2.6-3.6 | 0.30 | 0.15 | remainder |

The temper for the selected material was H22, that is cold-rolled and annealed to 1/4 hardness. Tensile tests of base material were conducted addressing the yield strength and ultimate tensile strength for material batch. Yield strength and ultimate tensile strength longitudinal to rolling direction were 170.3 MPa and 286.1 MPa respectively. Yield strength and ultimate tensile strength transversal to rolling direction were 179.8 MPa and 288 MPa respectively. Hardness measured for base material was: top section 79HV05, longitudinal section 78HV05 and transversal section 73HV05. Since there is remarkable difference in mechanical properties depending on the rolling direction, it should be considered.

Plate thickness of 3 mm was decided to be investigated since it is a common thickness in automotive manufacturing.

Development of clamping system

The FSW process applies mechanical energy in the joint zone. Within the processed materials, part of this energy is then transformed into heat and activation of the solid state joining mechanisms. The mechanical energy nature of the FSW demands strong and precise clamping of the components in order to achieve sound welds. One major challenge is to fully close the visco-plastic flow domain within the processed zone, preventing loss of material by production into flash and maintaining high internal forging pressure, e.g. to avoid internal voids [13]. This challenge is particularly difficult to respect in the FSW of low thickness components in “L” shape joints with conventional architecture tools. Other specifications for the clamping system were set to fulfill the following objectives:

- No deflection by force applied during welding cycle
- Uniform distribution of clamping forces
- To enable the clamping of different plate thicknesses in similar and dissimilar joints
- To be modular enabling the clamping of workpieces with wide range of dimensions
- Repeatability, precision and fast clamping operation
- To enable full penetration welds easy to extract from clamping system, e.g., preventing the adhesion of the aluminum to the anvil
The inner anvil does not need to be removed during the execution of all the welds.

In Fig. 1, the concept of the clamping system and the real clamping system implemented to perform the weld tests, is depicted.

Figure 1: Dedicated clamping system implemented for production closed box-shape hollow profiles

The nomenclature in Fig. 1a is the following: A. is the outer anvil, which is attached to the welding machine table, B. is the inner anvil, which is inside the hollow profile during processing, C. is the top clamp which applies clamping force to top plate, D. is the copper insert(s) whose main objective is to act as a heat sink. Arrows marked with letter F illustrates the clamping forces applied to the workpiece. Clamping forces are applied as close as possible to the zone being processed while the rest of the workpieces remain free. In practice, this means that the clamping system enables free plate dimensions. Also, the admissible thickness of the workpiece can vary within rather large scale. With low plate thicknesses, e.g., 5 mm or less, the peripherical zone of the shoulder of the tool will rotates outside the aluminum plates and over the copper insert. The vertical position of the copper insert D in the outer anvil A, can be continuously modified. A gap between the shoulder and the copper insert should exist to avoid any direct contact (Fig. 1c E) but the gap is minimized to assure full side constrain for the vertical aluminum plate. In Fig. 1c the offset (G) between joint line (H) and tool axis (I) is illustrated.
Numbers in Fig. 1a illustrates a possible weld sequence. Corner marked with number 1, represents the first to be welded. After welding one corner, the “L” shape workpiece the component is removed, rotated and inserted back in the clamping system for the subsequent weld producing a “U” shape. The welds 3 and 4 are done to close the hollow box profile, and the small inner anvil B, is then removed from the interior of the profile. Clamping system is modular and other alternative welding sequences are possible, namely by adding other components, e.g., additional outer anvil, or even for very large closed sections, a second inner anvil may be used. After some iterations in the development of the original design concept, the final clamping system produced fulfilled all the requirements. Further development for the clamping system will include hydraulic actuators to produce uniform clamping forces and reduce the set-up time, and a cooling system for optimal thermal management.

The clamping system also enables welding plates with different thicknesses which makes production of tailored box-section possible. Other authors show good results with structures like tailor-welded blanks (TWB). Tailor-welded blanks are studied mainly as a method to optimize the resistance-to-weight ratio of the structures [14][15].

**FSW equipment and parameters**

Welding was performed with an Esab Legio 5UT FSW welding machine with maximum forging force of 100 kN enabling alternative control of the vertical forging axis by force, position and speed. The welds were made according to ISO 25239:2011.

To overcome the need for an internal anvil, the FSW of closed hollow profiles typically are implemented based on bobbin-tool architectures with constant gap or self-reacting [9]. Nevertheless bobbin tools are expensive and the life of the probes are compromised by the complex and highly demanding thermal and mechanical loading [16]. Thus in this work it was decided to use a conventional tool architecture supported by a smart design of the clamping system presented before.

The FSW welding tool used is based on modular design enabling the combination of different shoulders and probes features and fine tuning of probe length with 0.1 mm increments [17]. This modular tool design is dedicated for R&D on FSW of aluminum alloys. Considering that the tool geometry and features have the most important role in the quality of the FSW joints in aluminum alloys, this tool enables optimal processing conditions and full penetration. The tool material was AISI-H13 quenched and tempered to hardness over 50HRC. The final tool dimensions and features were selected as the best ones from a comprehensive and systematic experimental analysis. As depicted in Fig. 2a, the main features for the selected tool are:

- The probe is conical with round-bottom scrolls with 1.5 pitch
- The shoulder is a planar shoulder with 2 CCW scrolls with pitch 2 (half rotation between inner and outer shoulder diameter) requiring no tilt angle to perform the weld and thus enabling welding in any direction with CW rotation.

The AA5754-H22 plates were milled to the right dimension and to ensure good fitting between abutting surfaces. Workpiece was cleaned with ethanol before welding. The remaining welding parameters were:

- Shoulder diameter 15 mm
The position of the tool in relation to the joint line, and rotation direction of the tool in relation to the joint design were key issues supporting the success of the clamping system solution. To enable full containing of the visco-plastic flow of material, and avoid generation of excessive flash, the following conditions should be attained: i) the advancing (shear) side of the welds have to be positioned in the outer anvil side; and ii) a small tool axis off-set to weld joint line should exist bias to inner anvil, i.e., retreating (flow) side of the welds. The best off-set value found was 1.1 mm.

**Testing plan**

Welded samples were tested with different microstructural and mechanical testing methods. The microstructural methods are optical microscopy (OM) and EBSD. From the conventional mechanical testing methods only the measurement of the hardness field in the vicinity of the weld zone was applied, because others, such as uniaxial tensile and bending testing, do not apply directly to the joint configuration. To complement the characterization of the mechanical performance under quasi-static loading, two other tests were implemented, namely: the Corner Opening Test (COT) and the quasi-static crashworthiness tests.

For comparison of FSW with other alternative conventional fusion welding technique, based on COT and crashworthiness tests, the same corner joints were welded by a qualified welder with manual TIG and joint preparation according to ISO 9692-3:2013 to produce the same size of the box shape hollow profiles. The parameters for the TIG weld joints were:

- I = 90 A, V = 13.8 V, Heat Input = 2.2 kJ/cm
- Shielding gas: 100 % Ar
- Filler wire: OK Tigrod 5356 (ISO 18273:2004), Ø= 2.4 mm

The Corner Opening Test (COT), was implemented in a purpose-built rig as depicted in Fig. 3. This test promotes the bending of the weld joint with the root of the welds under tensile which corresponds to the most demanding loading situation. The results are mostly sensitive to root defects such as Lack of Penetration (LOP) and internal voids. The FSW joints were compared with similar structural design produced by TIG welding process and direct bending of the base material with a radius of 5 mm.

![Schematic presentation of COT](image1)

(a) Schematic presentation of COT

![Photograph of testing setup](image2)

(b) Photograph of testing setup

Figure 3: Test setup for Corner Opening Tests (COT)

All the FS welds tested were extracted from one of the 4 corners of the final box shape hollow profiles. Thus all the welds have a length of 200 mm. For the tests based on cross-sectional analysis, i.e., optical microscopy, EBSD and hardness, the cross-section was extracted 100 mm from the starting point (about the middle). Because there are no standards for the COT it was decided to extract specimens with dimension of 40 mm in each leg and 40 mm in width (see Fig. 3a). Considering the 200 mm length welds, 3 specimens for the COT were extracted, namely: 1) about 45 mm from the starting point of the weld; 2) from the middle; and 3) about 45 mm from the end.

Crashworthiness tests, as depicted in Fig. 4, were performed to assess the buckling behaviour (modes and stability), structural integrity and energy absorption capacity. These tests are typical in the analysis of the structural performance of key automotive components. The crashworthiness tests were applied to box shape hollow profiles with cross-section of 100x50 mm and length of 160 mm after extracting 20 mm from both ends. The box shape hollow profiles produced by FSW were compared with the same geometry produced by TIG welding process.

**Equipment and parameters**

Concerning the laboratory testing conditions, the samples were prepared for optical microscopy by cutting perpendicular to processing direction and grinding with Tegramin automated station. Polishing was done by hand with 1200-2000-4000 grit papers and fine polishing with 3 and 1 micron diamond paste.

The optical macrographs were taken from specimens using Nikon Epiphot 200 inverted metallurgical microscope. The microscope was equipped with Nikon DS-U1 digital sight.
The EBSD studies were performed with Zeiss Merlin FE-SEM, and the sample preparation also included polishing with 1/4 micron diamond and finishing in colloidal silica suspension for 5 hours.

The microhardness testing was performed with CSM instrumented platform with micro-combi testing head equipped with Vickers indentator. Equipment uses indentation depth and Oliver & Pharr method to calculate hardness value. The platform includes an optical video microscope, X, Y and Z automated tables and antivibration table. Testing load was set to 50 g and pause 10 sec.

The COT was done with MTS 810 servo-hydraulic universal testing machine equipped with purpose-built testing rig including linear rolling guides and cars. During the COT the built-in data acquisition system was used to record force and displacement data. The force-displacement data was treated with MATLAB software for plotting force-displacement curves and calculate absorbed energy during test.

Quasi-static crashworthiness test were performed with servo-hydraulic testing rig with external extensometers and force data acquisition system. Cross-head downwards velocity was set to 5 mm/min [18]. Test setup is presented in Fig. 4. Boundary conditions in more detail are presented in Fig. 4b. A 5 mm deep grooves was manufactured to upper and lower anvil (Fig. 4a A and C) to prevent sliding. Lower anvil is fixed to the ground and upper anvil is free to translate and rotate in all directions. Test sample has 150 mm of free length in the start of testing In Fig. 4b and 4c the actual testing equipment is shown.
Results

Optical macrographs

Fig. 5 presents the most representative macrographs from the optical microscopic analysis. Fig. 5a and Fig. 5b present the 2 different patterns, concerning the comparison of the 3 cross-sections extracted from the start, middle and end of the welds. The only relevant difference between the Fig. 5a and Fig. 5b exists in the macro from the start of the welds. In fact, although most of the welds were fully sound (Fig. 5a), some of the welds joints presented a void in the advancing side at the starting region (Fig. 5b). Because most of the welds are sound, the problem is not related with the clamping system. Thus, the transient condition at the start region should be further developed to achieve correct viscosity in the material being processed and reduce the susceptibility to produce internal voids. This will be implemented via tuning the axial force, dwell time and/or ramp-on of the welding speed.

(a) Cross-sections of sound weld extracted from start, middle and the end
(b) Cross-sections of defective weld extracted from start, middle and the end

(c) Cross-section from the middle of the weld

Figure 5: Optical microscopy analysis

Fig. 5c represents the typical macrographs of all the sound welds (e.g. no internal voids) inspected at the middle and at the end of the weld. The Fig. 5c depicts a fully developed nugget region over all the thickness (full penetration), with evidence of the lateral offset in relation to the original joint line. An alignment of particles exists at the advancing side of the root of the weld, but with an offset from the sensitive original joint line. This fact is relevant because the original joint line is fully processed. There is an evident tail of the nugget near of the top face of the joint.
The EBSD (Electron Backscatter Diffraction) studies depicted in Fig. 6, were performed to analyze the microstructure of base material (Fig. 6a and Fig. 6b) and dynamically recrystallized zone (DRX) of the TMAZ, i.e., weld nugget (Fig. 6c and Fig. 6d).

Microstructure of the base material is in accordance with the H22 temper condition. Namely, the elongated grains along rolling direction are evidences of the residual deformation introduced within the microstructure during cold forming stages. The colourful noise within some of the grains of Fig. 6b is caused by dislocations in material. The partial annealing has relaxed deformation in the others grain via static recrystallization (SRX) [19].

![EBSD images](image_url)

Figure 6: EBSD images of base material and weld nugget

From the analysis of the EBSD images, it is not evident any texture effect both at the nugget and base material. But, when comparing the nugget with the base material, it is noticeable the significant reduction of grain size and equiaxed grain orientation in
the nugget. The grain size refinement is a known phenomenon in FSW [20][21][22]. The 2nd phase particles are evident within base material grains, mainly in Fig. 6a. These particles, trap dislocations and exert a significant pinning effect on grain boundaries, are fully disseminated within the nugget.

**Microhardness**

Fig. 7 presents the distribution of the microhardness in the vicinity of the weld joint. The results show significant increase in hardness of the material directly processed by the probe of the tool when compared with the original base material hardness which was about 73HV (in the transversal section). In the nugget zone, the average hardness was about 110HV with a maximum hardness of about 130HV. The remaining zone of the TMAZ in contact with the shoulder exhibits values of about 100HV. Other authors also published similar results in FSW of Al-Mg aluminum alloys, mainly associated with the grain refinement and dynamic recrystallization (DRX), typically found in the TMAZ of FS welds.

![Microhardness map (HV 0.05)](image)

Furukawa, Horita, Nemoto, Valiev, and Langdon [23], measured the Vickers microhardness in Al-3% Mg solid solution alloy subjected to intense plastic deformation and demonstrate conclusively that the Hall-Petch relationship is an appropriate description of the hardness of the material down to the finest grain size examined experimentally (90 µm). Based on the Hall-Petch relationship proposed by this work: $HV = 43.6 + 48.2/\sqrt{d}$. To the average hardness measured in the nugget region (110HV) should corresponds a grain size of about 0.5 µm, this fact was in agreement with the measurements in the EBSD tests.

Considering that the hardness correlates with direct proportionality with yield strength of the material, e.g. $HV \cong 3 \cdot \sigma_y$ [24], it should be expected that increased hardness in the weld provides better mechanical properties.
Corner Opening Tests (COT)

Standard mechanical testing methods for this joint type do not exist, thus COT was used to compare FSW samples to TIG welded and mechanically bended structures with a similar geometry.

The total energy absorbed by the COT specimen before failure is depicted in Fig. 8. This figure presents the results for 3 different welds by FSW, 3 different welds by TIG and 3 different mechanically bended specimens. For each of the 3 FS welds, COT results were also evaluated at 3 different regions of the weld joint, namely, start, middle and end region. From these results it is possible to conclude that the best of the FS welded samples, with about 27 J, are almost as good as bended samples (about 30 J), even with sharp corner geometry that is substantially more susceptible for stress concentration. Bended samples have some radius in the corner and FS welded samples have sharp corners. The samples with the lowest amount of energy absorbed in this test are the TIG welded samples with about 10 J.

Among the specimens from FSW, some of the samples extracted from the start of the weld joint have a very small mechanical resistance (e.g. FSW1). This is due to the fact that some welds have an internal void in the start, as addressed before in the optical microscopic analysis.

Fig. 9 presents the typical behavior of the force versus displacement for the good (Fig. 9b) and bad (Fig. 9a) FS welds. For the good FS welds after an elastic response period, there is a progressive damage accumulation under constant force (about 1.3 kN), i.e. in a quasi-perfect plastic behavior. In the bad FS welds, the initial elastic period is similar to the good welds in all the regions and the maximum force attained is also the same (about 1.3 kN), but the life of the joints is significantly affected by the detrimental effect of the internal void, mainly at the start region of the weld. The TIG welds have a smaller maximum force (about 0.8 kN) and do not present the quasi-perfect plastic regime of the FSW, i.e., after achieving maximum value, the force undergoes a negative gradient until failure. If the mechanical bending of the base material represents the optimal behavior,
then this behavior is very similar to the one obtained for the good FS welds, but with a maximum load of about 1.5 kN.

![Force-displacement plots from Corner Opening Tests](image)

**Figure 9: Force-displacement plots from Corner Opening Tests**

**Quasi-static crashworthiness tests**

The quasi-static crashworthiness tests were performed for FS welded and TIG welded box shape hollow profiles samples. Samples after testing are shown in Fig. 10. Different buckling modes produced in FS welded samples are shown in Fig. 10a and failure in the base material of sample FSW3 is shown in Fig. 10b. FS welded samples withstand more displacement without failures. TIG welded samples lost their stability around 13 mm of displacement and test was aborted.

In table 2 energies absorbed by structures up to 10 mm of displacement are shown. There is a significant difference in the energies between FS welded samples and TIG welded ones. This is due to imperfections introduced to the structure by TIG welding.

**Table 2: Energy absorbed with displacement $\Delta y = 10$ mm**

| Sample ID  | Energy (J) | Sample ID  | Energy (J) |
|------------|------------|------------|------------|
| FSW1 crash | 977        | TIG1       | 791        |
| FSW2 crash | 888        | TIG2       | 773        |
| FSW3 crash | 955        | TIG3       | 837        |
(a) Order from left to right: FSW1 crash, FSW2 crash, FSW3 crash and TIG2

(b) Failure in base material. Location marked in (a) with red rectangle

Figure 10: Samples after quasi-static crashworthiness tests

Force-displacement plots derived from crashworthiness tests are shown in Fig. 11. FS welded starts buckling at significantly higher loading than TIG welded counterparts. This behavior is due the fact that FS welded samples have a better dimensional accuracy and less imperfections. Force needed to start buckling in FS welded samples is near 150 kN and tensile yielding strength of the material times the area of cross-section results force of 155 kN.

(a) FSW welded samples
(b) TIG welded samples

Figure 11: Force-displacement plots from quasi-static crashworthiness tests
Conclusions

The most significant observations from the present study are the following:

- The new clamping system enable the production with conventional FSW tools of free-shape box closed hollow profiles in AA5754-H22 with 3 mm. This fact represent a good opportunity for innovation in automotive structural design mainly focusing the application in buses and coaches.

- The best technological conditions and parameters resulted in FS welds with full penetration and no alignment of particles at the root along the original joint line. Nevertheless a void in the advancing side at the starting region existed in some of the FS welds.

- The EBSD analysis emphasized the small equiaxed grain size with some texture not evident originally at the base material.

- The hardness in the TMAZ increased from the 73HV of base material into an average value of 110HV with a maximum of 130HV.

- A non-standard Corner Opening Tests was developed and implemented. The results show that the FS welds present an elastic-perfect plastic behaviour similar as bended base material (even considering the sharp corner geometry) and significantly overcoming alternative application of TIG welding.

- The critical buckling load of the FSW box profiles during the quasi-static crashworthiness tests is close to the yield limit and the factures are localized away from the TMAZ of the FSW joints. The buckling of all the FSW box profiles during the quasi-static crashworthiness tests retain the axial symmetry. These facts complies with the high demanding requirements of automotive structural design.
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