JOINING ALUMINIUM ALLOYS DISSIMILAR IN THICKNESS BY FRICTION STIR WELDING AND FUSION PROCESSES

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ABSTRACT

The industrial application field of the Friction Stir Welding process is growing and the initial high potential of this technique is being confirmed. Research centres worldwide along with some major industrial production companies are making progresses in developing this technique up to a know-how level where the transfer to the industrial environment is technologically reliable and economically successful. The present work starts with a comparison of relevant welding features for industrial application when resulting from the FSW and fusion welding processes typically applied to aluminium alloys. FSW has the potential to improve the construction of tailor blanks. The results of welding plates of AA1050; AA2024-T3 and AA5083-H111 with different thickness is presented in terms of surface finishing, residual deformation, metallurgical analysis and static strength efficiency of the joints performed by FSW, GMAW and GTAW.

IIW-Thesaurus keywords: *Friction stir Welding; Friction welding; GMA welding; Arc welding; Gas shielded arc welding; GTA welding; Aluminium alloys; Light metals; Butt joints; Mechanical properties; Tailored blanks; Comparisons; Practical investigations.*

1 INTRODUCTION

The constant industrial need in reducing the weight of components and optimising the structural resistance for the intended application, has been forcing the constant development of tailored blanks [1].

Tailored Welded Blank (TWB) is a concept of sheet metal construction where panels of different materials and/or thicknesses are welded together resulting in a single panel with improved characteristics, e.g. mechanical and/or corrosion resistance, such that both base material and weld joint allow the intended plastic deformation, typically stamping [1, 2]. Most applications of TWB are in the automotive industry [3, 4]. An important application of TWB is the possibility to create vehicle structures with high resistance zones alternated with low resistance, creating structures that deform in an intended and controlled way in collision or impact situations [1].

Moreover, industry is increasing the use of aluminium [5, 6]. Worldwide, the aluminium alloys market is expanding into various sectors, most significantly in transport industry where the use of tailor blanks in aluminium is developing [6]. The unique characteristics of aluminium, such as, light weight, high strength, high toughness, versatility of extruding in diverse forms, excellent corrosion resistance and recycling capabilities make it an obvious choice for a variety of welding fabrication applications.

Gas Metal Arc Welding (GMAW) is a flexible and productive method and is therefore widely used for aluminium welding [7]. Three disadvantages are clear in GMAW welding:

- the residual deformation of the welded parts,
- formation of pores in the Weld Metal (WM), and
- strength decrease in the Heat-Affected Zone (HAZ).

Gas Tungsten Arc Welding (GTAW) has the same disadvantages and is limited to low thickness applications [7]. The solid state Friction Stir Welding (FSW) process resulted in a significant increase of quality when joining aluminium alloys [8, 9]. The typical low distortion of the welded parts, along with the no need of consumables, the important reduction of gases and radiation emissions, are some of the much appreciated characteristics resulting from the application of FSW [10]. Moreover, FSW has the potential to improve the construction of tailor blanks [11, 12, 13].

The aim of the present paper is to present a first group of results from a the set of trials, established to investigate the feasibility of using FSW compared to the conventional fusion welding processes GMAW and GTAW, welding plates of dissimilar thickness of the following aluminium alloys: AA1050; AA2024-T3 and AA5083-H111.

The characterisation of the weld quality will be addressed in terms of the surface finishing, distortion

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resulting from the weld bead, x-rays, macrographs and mechanical efficiency of the joints relatively to the base material.

The results obtained show that FSW produces higher resistant TWB for all the aluminium alloys tested.

2 EXPERIMENTAL SET-UP

2.1 Welding and materials

The group of aluminium alloys selected for the present analysis is representative of a relevant application field. For instance AA5083-H111 is the most used aluminium in automotive industry and shipbuilding mainly because of its excellent corrosion resistance. AA2024-T3 is largely used for panels in aeronautical and aerospace construction and AA1050, pure (99.5 %) aluminium is used in food industry, chassis structural components (tube hydroforming) and as electrical conductor.

The present study only focuses on TWB dissimilar in thickness. Along with the 3 different materials selected, the 3 different welding processes investigated: FSW, GMAW and GTAW results in a set of 9 trials, which are established in Table 1.

All the welds are produced in a butt joint arrangement. Because the TWB have different thicknesses, the criteria is to align the bottom surface of the plates before the weld.

FSW is performed on a conventional milling machine with manual control of the position. The tool geometry is a plan shoulder with a threaded pin. The rotation speed of the tool is 1 120 rpm in all trials.

GMAW is performed with a synergic equipment using pulse arc on an automated installation. The GTAW is performed manually by a certified welder. Both GMAW and GTAW use argon as shielding gas with a flow of 15 and 10 l/min, respectively. The filler wire for both processes is AA5356 for welding the AA5083-H111 and AA4043 for welding the AA2024-T3 and AA1050.

The remaining welding parameters used in all the trials are present in Table 2.

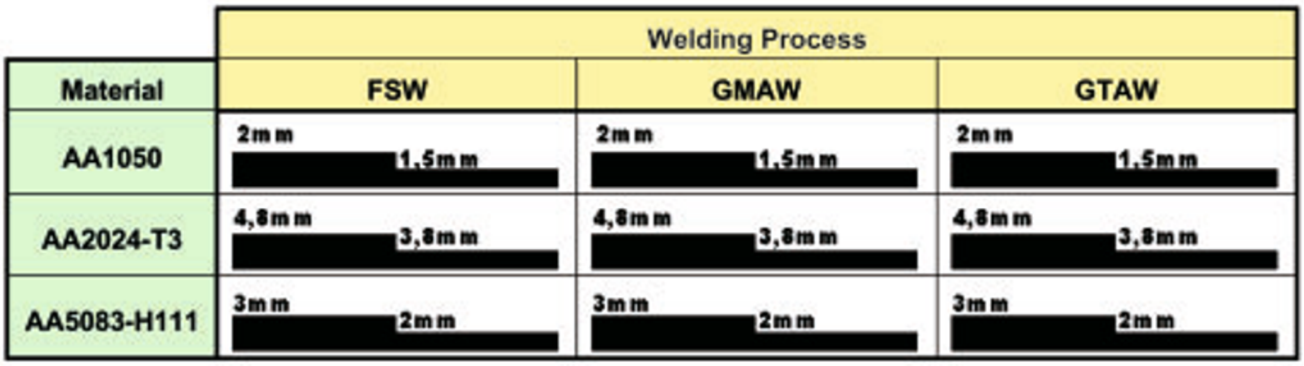
All welds are performed perpendicularly to the rolling direction. For each of the 9 different welding conditions, 3 welds are performed, joining plates of about 200 mm × 150 mm, with the exception of the AA5083-H111, for which the available plates have the dimension of 120 mm × 100 mm for FSW and GTAW, and 240 mm × 100 mm for GMAW.

The finishing of the top surface after welding can be analysed in Figure 1.

2.2 Experimental conditions

For the x-ray inspection of the structural integrity of the welds an ANDREX model CP552 is used with a “source/film” distance of 700 mm, current of 5 mA and tension of about 60 kV. The exposure varied from 15 s for the thinner plates of the AA1050 to 180 s for the

Table 1 – Set of trials implemented to investigate the quality of the TWB dissimilar in thickness



	Welding Process		
Material	FSW	GMAW	GTAW
AA1050	2mm 1,5mm	2mm 1,5mm	2mm 1,5mm
AA2024-T3	4,8mm 3,8mm	4,8mm 3,8mm	4,8mm 3,8mm
AA5083-H111	3mm 2mm	3mm 2mm	3mm 2mm

Table 2 – Welding parameters

	Welding Process		
Material	FSW	GMAW	GTAW
AA1050	Travel speed: 320 mm/min Tilt angle: 4° Dissimilar thick angle: 3° Shoulder/Pin ∅: 10 mm/M3	Welding speed: 400 mm/min Wire feed speed: 2,5 m/min Tension/Current: 16,1 V/52 A Pulsed current	Welding speed (manual): <100 mm/min Current: 105 A Polarity: AC
AA2024-T3	Travel speed: 160 mm/min Tilt angle: 4° Dissimilar thick angle: 5° Shoulder/Pin ∅: 15 mm/M5	Welding speed: 450 mm/min Wire feed speed: 5.5 m/min Tension/Current: 19,9 V/53 A Pulsed current	Welding speed (manual): <100 mm/min Current: 150 A Polarity: AC
AA5083-H111	Travel speed: 160 mm/min Tilt angle: 3.5° Dissimilar thick angle: 6° Shoulder/Pin ∅: 15 mm/M5	Welding speed: 450 mm/min Wire feed speed: 4.6 m/min Tension/Current: 17,7 V/76 A Pulsed current	Welding speed (manual): <100 mm/min Current: 115 A Polarity: AC

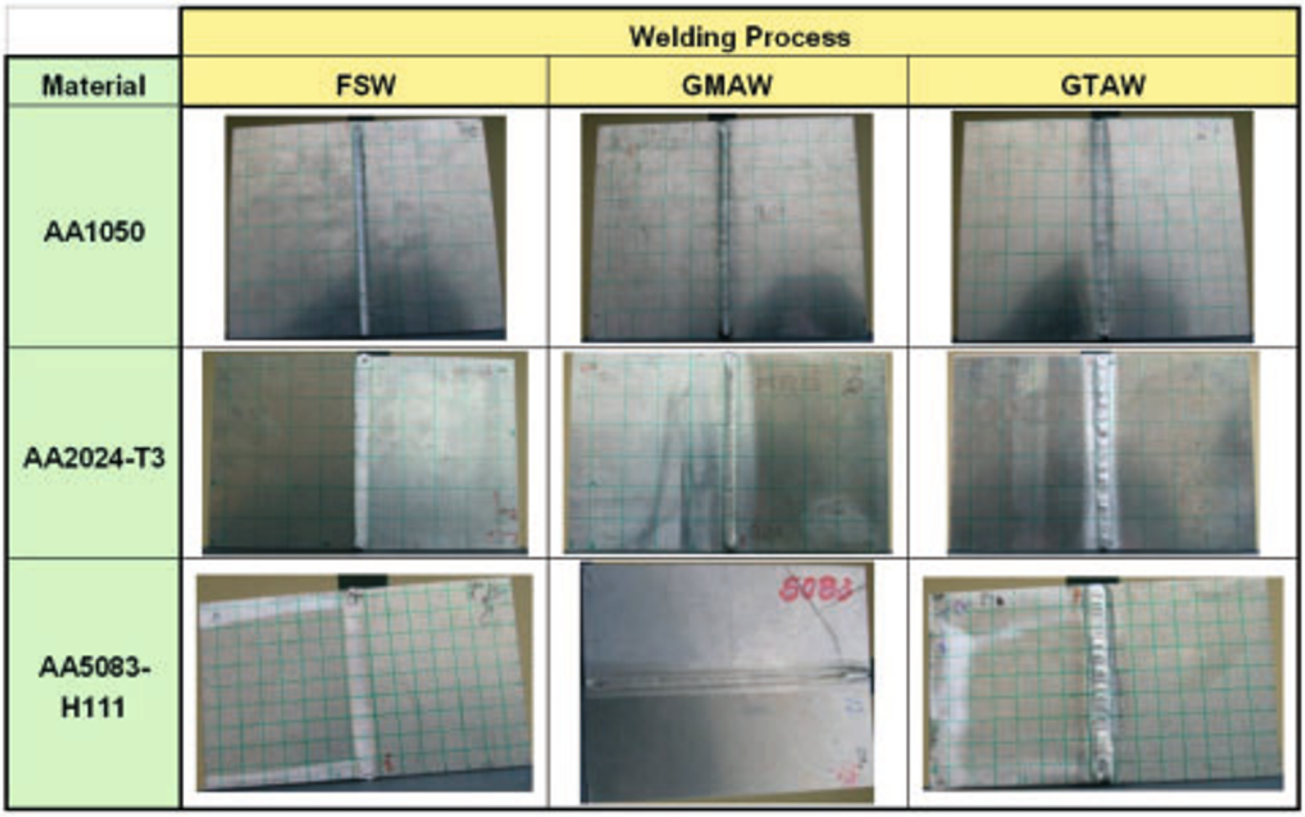


Figure 1 – Samples of the top surface finishing of the welded plates

thicker plates of the AA2024-T3. The film is an AGFA D4. Figure 2, presents the results obtained from this non-destructive technique.

For the macrographs the samples are mounted, polished up to 1 μm, and etched with Keller reagent. Then the different metallurgical zones are identified and measured. The macrographs of the welded plates can be observed in Figure 3. They also allow the measurement of the joint misalignment after the weld.

The bottom surface of all TWB is digitalized by means of a Faro Gold Arm model G06-05. The results are then processed in order to allow the graphical contour level representation of the residual deformation. The residual deformation in the perpendicular direction of the weld plane, can be found in Figure 4.

The uniaxial tensile tests are performed in an Instron 4507, with a load cell of 200 kN and high resolution biaxial extensometer. From each welded plate 3 specimens for tensile tests are taken, with geometry in accordance with EN 895:1995. The results are then treated and the mechanical efficiency ηMP is established for some of the most relevant mechanical properties (yield stress,

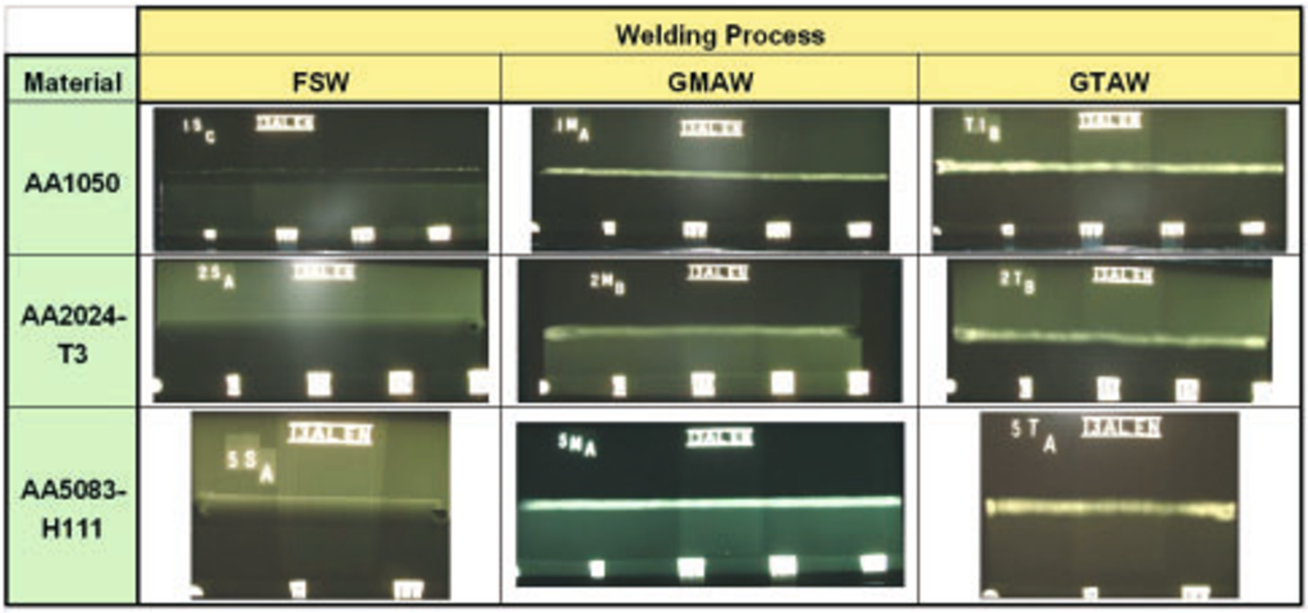


Figure 2 – X-rays of the welded plates

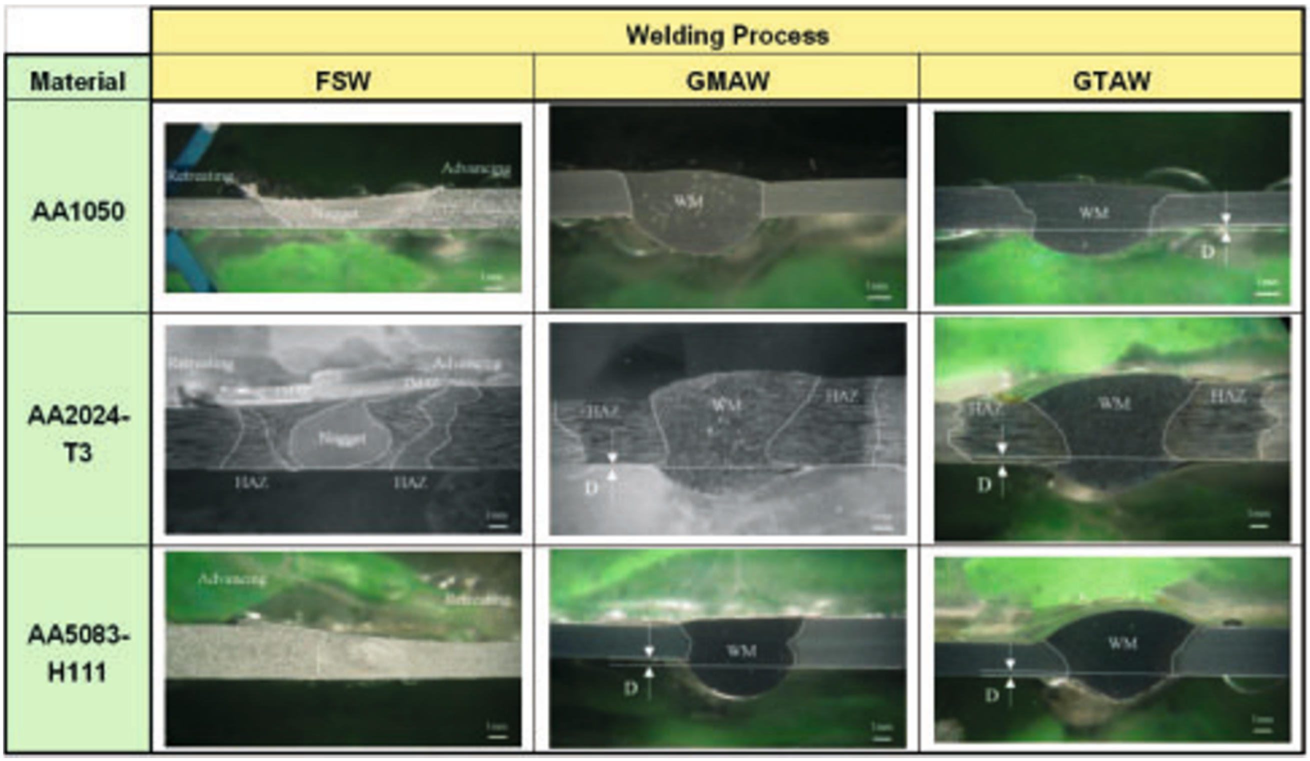


Figure 3 – Macrographs of the welded plates, including the indication of the most significant metallurgical structures resulting from the welds, and the residual misalignment, D

tensile strength, toughness, and elongation) according to expression (1). The results are presented in Figure 5.

$$\eta MP_i = \frac{MP_i \text{ of the TWB}}{MP_i \text{ of the BM of the plate with less thickness in the TWB}} \quad (1)$$

where

MP_i - Mechanical Property i = {yield stress, tensile strength, toughness, elongation}

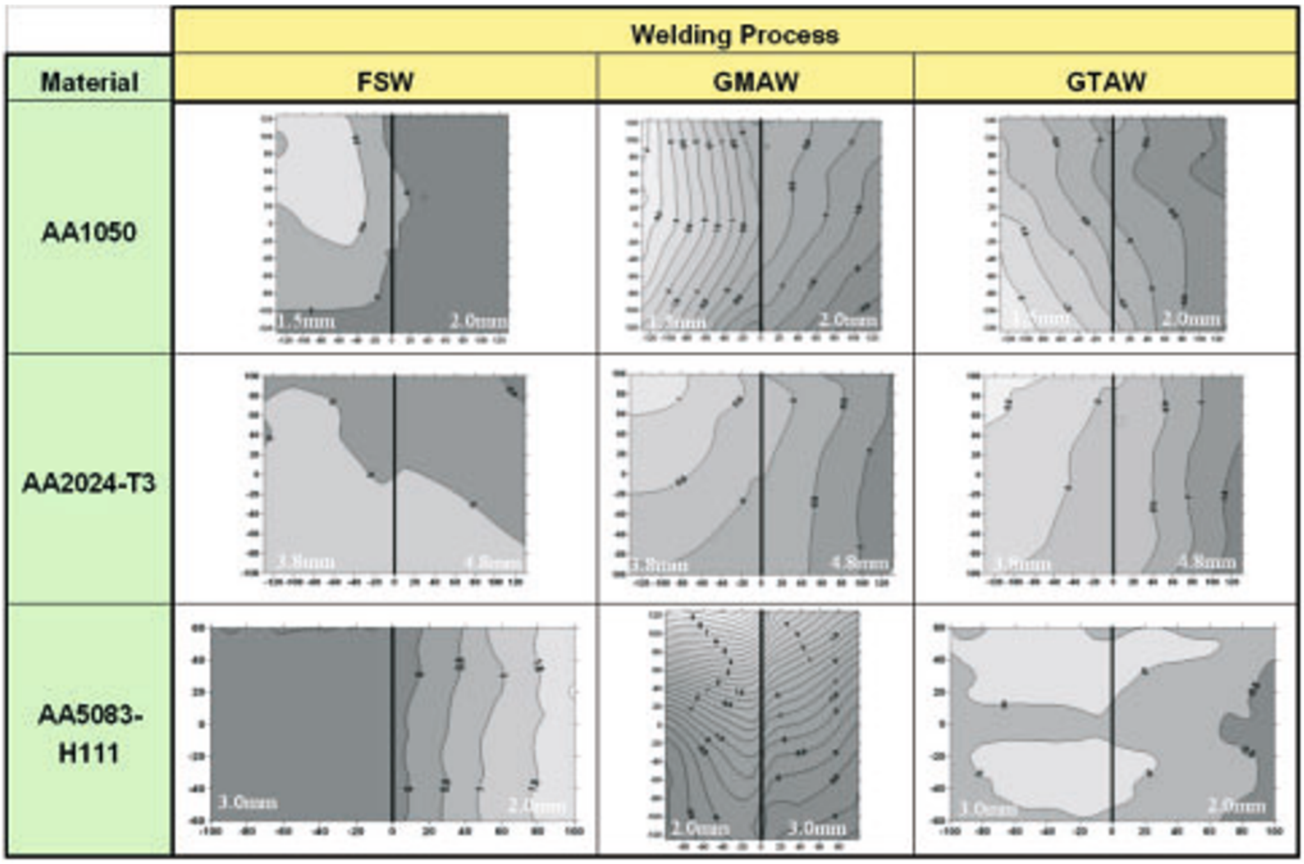


Figure 4 – Contour (0.5 mm between lines) of the residual deformation of the welded plates

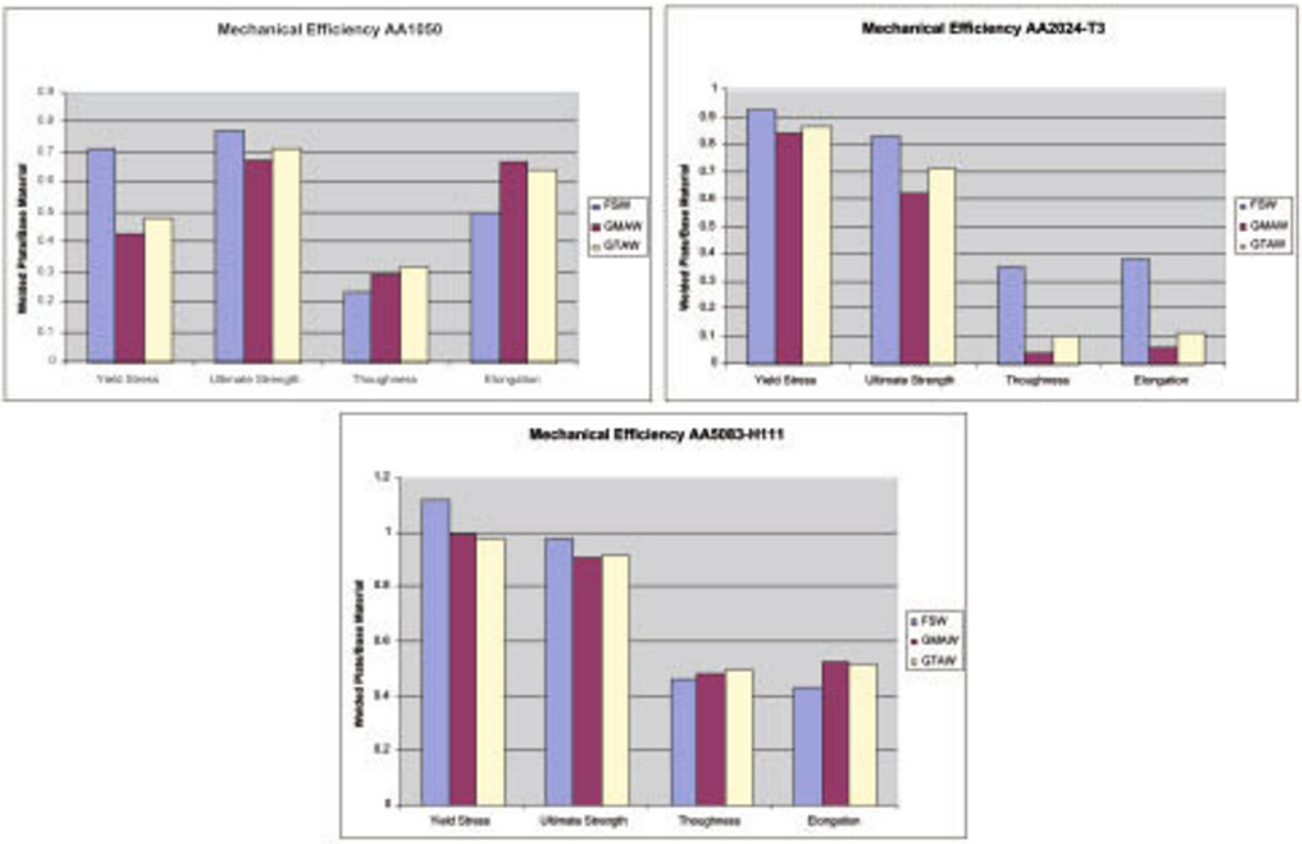


Figure 5 – Efficiency of some of the most relevant mechanical properties of the TWB versus BM of the plate with less thickness in each joint

3 ANALYSIS OF THE RESULTS

3.1 Tailor Welded Blanks of AA1050

The results obtained for the AA1050 indicate a lower welding velocity for the GTAW, and a similar productivity for the GMAW and FSW.

Concerning the weld surface finishing (see Figure 1), FSW resulted in to much flash at the retreating side and the irregular aspect of the root revealed the “stick effect” (to the anvil and tool) of this alloy. GMAW resulted in few spatter and no spatter at all was obtained during the GTAW. Both GMAW and GTAW generated a big root reinforcement of the size of the lower thickness plate (1.5 mm).

The x-ray results (see Figure 2) indicate the intense flash at the retreating side of the FSW weld bead, but no other defects for this process. For the GMAW a regular weld bead was revealed with porosity along the seam near the fusion line. In the case of the GTAW, a porosity is formed along the seam in the middle of the bead.

The metallurgical analysis (see Figure 3) presents the recrystallised zone of FSW, with an arrangement different from the typical onion rings of the nugget. In all the cases, the material does not present an evident HAZ. In GMAW the macrograph shows lots of porosity all over the bead but mostly in the vicinity of the fusion line. Some porosity can also be seen in the toe of GTAW bead. The big root reinforcement is also very clear in this analysis.

Concerning the residual deformation (see Figure 4), FSW presents much better results than any other process. In fact, GMAW resulted in a big angular distortion, around the weld bead. GTAW, presents an intermediate deformation of about 1 mm.

The mechanical resistance of the joints obtained (see Figure 5) show the highest resistance for FSW joints, which results in relatively lower toughness and ductility than the obtained ones in GMAW and GTAW, which show very similar mechanical behaviour.

3.2 Tailor Welded Blanks of AA2024-T3

For the AA2024-T3 the results still indicate the lower welding velocity for GTAW, but in this case, GMAW presents a welding speed 3 times higher than FSW.

The surface finishing (see Figure 1), of FSW seam shows a very regular weld seam with little flash in the advancing side. The GMAW resulted in a regular weld seam with few spatter. No spatter at all was obtained during the GTAW but the joint shows an irregular development. Both GMAW and GTAW generated a face and root reinforcement of about 1.0 mm, as can be confirmed in Figure 3.

The x-ray results (see Figure 2) indicate a homogeneous FSW weld bead, with no defects. In opposition, lots of porosity was revealed for the GMAW more intense at the beginning of the weld seam where there is a lack of penetration. The irregular seam resulting from GTAW is once again identified.

The metallurgical analysis (see Figure 3) of the AA2024-T3, shows very distinct zones affected by the heat dissipated during the performance of the welds. The typical onion rings of the nugget are present in FSW bead preceded by the Thermo Mechanically Affected Zone (TMAZ), HAZ and base material showing the typical grains resulting from the rolling process. In the case of GMAW the macrograph shows lots of porosity all over the bead. GTAW generates only low porosity and the bead shows a dilution and an extension of the HAZ very similar to GMAW.

Relating to residual deformation (see Figure 4), FSW presents better results than any other process. The maximum deformation was obtained for GMAW of about 1 mm.

The mechanical resistance of the AA2024-T3 joints (see Figure 5) shows that the resistance of the FSW joints is higher than any of the others, including the joint toughness and ductility.

3.3 Tailor Welded Blanks of AA5083-H111

For the AA5083-H111 the results still indicate the lower travel speed for GTAW, and GMAW with about 3 times more speed than FSW.

The surface finishing (see Figure 1), of FSW seam shows a very regular weld seam with no flash. GMAW resulted in a regular weld seam with few spatter generating a big root reinforcement of the same size of the lower thickness (2.0 mm) and no face reinforcement is seen. No spatter at all was obtained during GTAW but the joint shows an irregular development. GTAW generated a root reinforcement of about 1.5 mm and a face reinforcement of about 1 mm as can be confirmed in Figure 3.

The x-ray results (see Figure 2) indicate a homogeneous FSW weld bead, with a slight void in the last 50 mm of the seam at the advancing side. GMAW produced a very regular seam having low porosity. An irregular seam resulting from GTAW is once again identified. A lack of penetration because of the seam enlargement near the end is observed.

The metallurgical analysis (see Figure 3) of the AA5083-H111, shows no evident HAZ for any of the processes. GMAW macrograph shows few pores mostly in the vicinity of the fusion line of the thicker plate. No porosity at all is seen in the GTAW bead. The big root reinforcement is also very clear in this analysis. The typical onion rings of the nugget are present in the FSW bead preceded by a mechanically deformed zone. An evident indentation produced by the tool shoulder is seen at the lower thickness plate, reducing the thickness locally in about 0.2 mm.

Concerning the residual deformation (see Figure 4), the FSW shows a small angular rotation of the lower thickness plate. The GMAW has very severe longitudinal residual deformation mainly at the second half of the weld seam. The GTAW presents no deformation, most probably due to the small dimension of the welded plates available for this trial.

The mechanical resistance of the obtained joints (see Figure 5) show the highest resistance for FSW joints and a relatively lower toughness and ductility than the obtained with GMAW and GTAW, which show very similar mechanical behaviour.

3.4 Final remark about the mechanical results

From the analysis of Table 3 that identifies the fracture location in the specimens from the different trials, and Table 4 with the absolute values obtained for all the mechanical properties previously addressed, it is possible to conclude that the highest heat input resulting from the fusion welding processes plays an important role in the reduction of the mechanical strength of the base material near the weld bead both for the non-heat treatable wrought aluminium alloys, such as, the AA1050 and the 5083-H111, and the heat treatable wrought aluminium alloy AA2024-T3.

4 CONCLUSIONS

– The measured mechanical properties for all the trials performed, revealed the highest yield and ultimate tensile strength in the weld beads resulting from FSW and in the case of AA5083-H111. The values obtained are of the same level as those of the base material.
– FSW reached the highest toughness and ductility for the AA2024-T3, but GMAW and GTAW, achieved the better toughness and ductility for the AA1050 and AA5083-H111.
– GMAW always resulted in a fast and regular seam with a high reinforcement on the face and/or the root, high longitudinal and rotational distortion and in the formation of lots of porosity, most significant in the case of AA2024-T3.
– The resulting surface finishing of FSW is much better for AA2024-T3 and AA5083-H111 than for GMAW and GTAW.

Table 3 – Fracture location of the specimens submitted to the uniaxial tensile tests

	Welding Process		
Material	**FSW**	**GMAW**	**GTAW**
AA1050	HAZ on the retreating side	Softened HAZ	Softened HAZ
AA2024-T3	Middle of the weld bead, around the nugget	Fusion line	Fusion line
AA5083-H111	HAZ on the retreating side	Base material	Base material

Table 4 – Absolute values of the mechanical properties obtained from the uniaxial tensile tests

	Welding Process		
Material	**FSW**	**GMAW**	**GTAW**
AA1050	Yield stress: 84 MPa Ultimate strength: 101 MPa Toughness: 2.27 J/mm^3 Elongation: 0.053	Yield stress: 51 MPa Ultimate strength: 88 MPa Toughness: 2.78 J/mm^3 Elongation: 0.071	Yield stress: 57 MPa Ultimate strength: 93 MPa Toughness: 3.04 J/mm^3 Elongation: 0.068
AA2024-T3	Yield stress: 345 MPa Ultimate strength: 457 MPa Toughness: 23.43 J/mm^3 Elongation: 0.060	Yield stress: 313 MPa Ultimate strength:341 MPa Toughness: 2.59 J/mm^3 Elongation: 0.009	Yield stress: 320 MPa Ultimate strength: 391 MPa Toughness: 6.86 J/mm^3 Elongation: 0.021
AA5083-H111	Yield stress: 137 MPa Ultimate strength: 278 MPa Toughness: 19.79 J/mm^3 Elongation: 0.100	Yield stress: 122 MPa Ultimate strength: 259 MPa Toughness: 20.81 J/mm^3 Elongation: 0.122	Yield stress: 120 MPa Ultimate strength: 262 MPa Toughness: 21.36 J/mm^3 Elongation: 0.119

– The “sticky effect” of the AA1050 at the FSW processing temperature, leads to difficulties in pulling out the TWB from the anvil, when the weld is finished, and results in too much flash and the retreating side.
– The x-ray indicates an irregular density of weld bead including few pores in the middle of the bead resulting from GTAW when welding the higher thicknesses.
– The higher welding speed is used for the GMAW followed by the FSW and GTAW. But considering the set-up efforts needed to control the residual deformation, and the resulting intense porosity in the GMAW bead, the results suggests the FSW as the most productive and reliable welding process for the massive construction of WTB, typical in the transport industry.

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