Friction Stir Welding

- the ESAB Way

XA00123720

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1. Introduction

Friction Stir Welding (FSW) was invented by Mr. Wayne Thomas at TWI (The Welding Institute) and the first patent applications was filed in the UK in December 1991. In the very beginning the process was regarded as a ”laboratory” curiosity, but it rather soon became evident that it had a lot to offer in the fabrication of aluminium products.

Friction Stir Welding is a solid-state process, which means that the base materials to be joined do not melt during the joining process. This is a door opener to completely new areas in the field of welding technology. Alloys from 2xxx and 7xxx series, which have traditionally been non-weldable can now be joined with FSW with speed and quality.

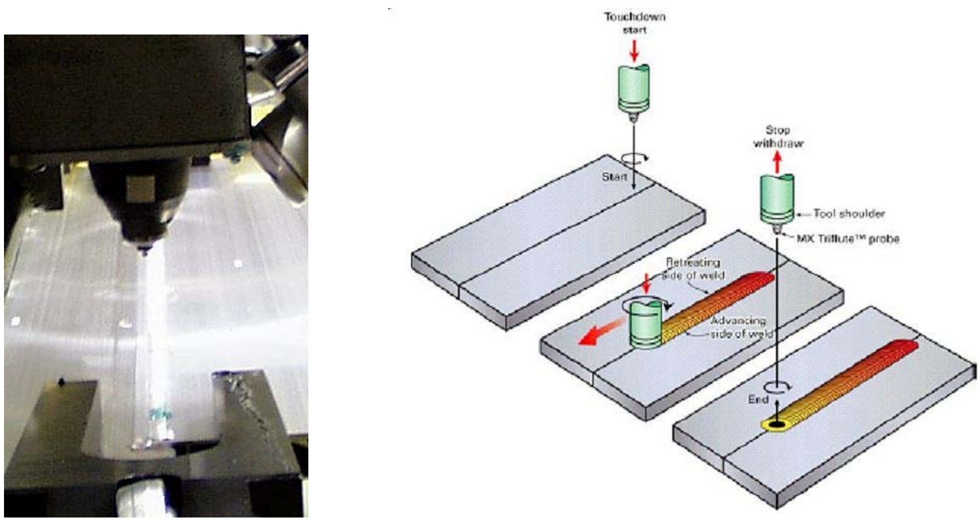


Figure 1. Process principle for friction stir welding. The rotating non-consumable pin-shaped tool will penetrate the material and create friction heat, which will soften the material and make the joining possible. Drawing courtesy of © TWI.

In friction stir welding, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joining area between two pieces of sheet or plate material. The parts have to be securely clamped in a manner that prevents the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the work pieces causes the latter to soften without reaching the melting point and allows traversing of the tool along the weld line. The plasticised material is transferred to the trailing edge of the tool pin and is forged by the intimate contact of the tool shoulder and the pin profile. On cooling down, it leaves a solid phase bond between the two pieces.

Friction stir welding can be used to join aluminium sheets and plates without filler wire or shielding gas. Material thickness from 0,8 to 65 mm can be welded from one side at full penetration and without porosity or internal voids. Materials that have been successfully friction stir welded to date include all aluminium alloys, copper, magnesium, lead and zinc.

2. Process principle

In order to introduce high repeatability and quality in friction stir welding process, certain features are needed from the equipment to be used. Most simple welds can be performed with a conventional CNC machine, but as the material thickness increases and the "arc-time" gets longer purpose built FSW equipment is needed.

2.1. Which materials can be welded?

To keep the answer to the question "which materials can be friction stir welded" short – let's start by saying that all light metals can be industrially friction stir welded. By light metals it is referred to all aluminium alloys, copper alloys, magnesium, zinc and lead. Continuous trials on welding of mild-steels, stainless steels and titanium are being carried out and out of these titanium seems to be most promising at the moment. Also, very comprehensive studies on welding of steels has been done and the most promising results have been gained with tools made of Polycrystalline Boron Nitride (PCBN) – the same material which is used as coating on milling cutter tool tips.

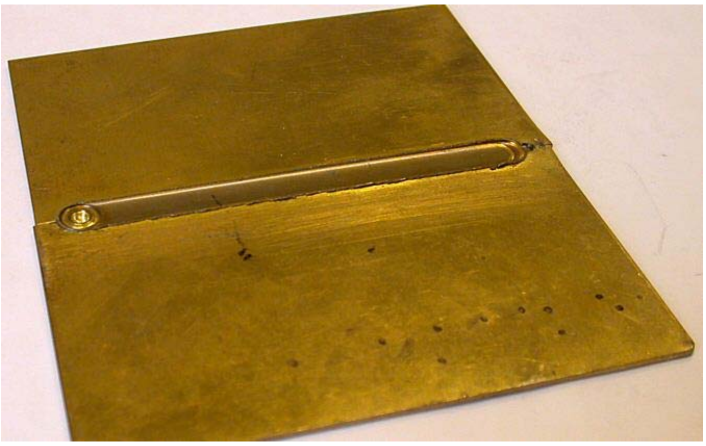



Figure 2. Brass, as well as mixed joints between copper and aluminium can be performed with friction stir welding. © ESAB

2.2. Parameters

The most important control feature is the down force control (Z-axis). It guarantees high quality even if there are tolerances in the materials to be joined. It also enables higher welding speeds, as the down force is main parameter in generating friction to soften the material.

The following parameters are to be controlled in Friction Stir Welding: Down force, welding speed, rotation speed of the welding tool, tilting angle. So with only four main parameters the process is mastered – ideal for mechanised welding.

Table 1 . Main process parameters in friction stir welding.

Parameter	Effects
Rotation speed	Friction heat, "stirring", oxide layer breaking and mixing
Tilting angle	The appearance of the weld, thinning.
Welding speed	Appearance, heat control
Down force	Friction heat

2.3. Tools

The tools are areas of special interest in friction stir welding. By optimising the tool geometry to have more effective "stirring" effect mainly two benefits are gained: Better breaking and mixing of the oxide layer and more effective heat generation which results in higher welding speeds.

The simplest tool can be machined from a M20 bolt with very little effort. With this kind of simple tooling you can weld thin aluminium plates at very slow welding speeds. The tool materials should, however, have a relatively high hardness at elevated temperatures and they should retain this hardness for a long time. Therefore, the combination of tool material and material to be joined is always crucial for the operational lifetime of the tooling to be used. Table 2 shows the forging temperature range of various alloy groups. It is important to notice at this stage that in friction stir welding, the forging tables are very useful tools.

Table 2 . Forgeability temperature range of various alloys.

Alloy group	Temperature range in °C
Aluminium alloys	440…550
Magnesium alloys	250…350
Copper alloys	600…900
Carbon and low-alloy steels	1100…1250
Titanium alloys	700…950

2.3.1. *Tool design*

The simple pin-shaped, non-profiled tool creates friction heat and is very useful if enough down-force can be applied. Unfortunately the oxide-layer breaking characteristics are not very good, and as material thickness is increased, the welding heat at the lower part of the joint might be insufficient. Figure 3 demonstrates a good quality weld with clearly visible, white-etched oxide line. With parameter adjustment and tool geometry optimisation could oxide-layer be more effectively broken.

Figure 3. Oxide layer is clearly seen in the mid-section of the weld line.

To generate more friction heat and break the oxide-layer effectively has been the driving forces in tool development for light-metals. For mild steel and stainless the selection of tool material is added to the list. Figure 4 shows some standard tools trademarked by TWI (The Welding Institute). Triflute MX™ has proven to be a very capable multipurpose tool for welding of all aluminium alloys.

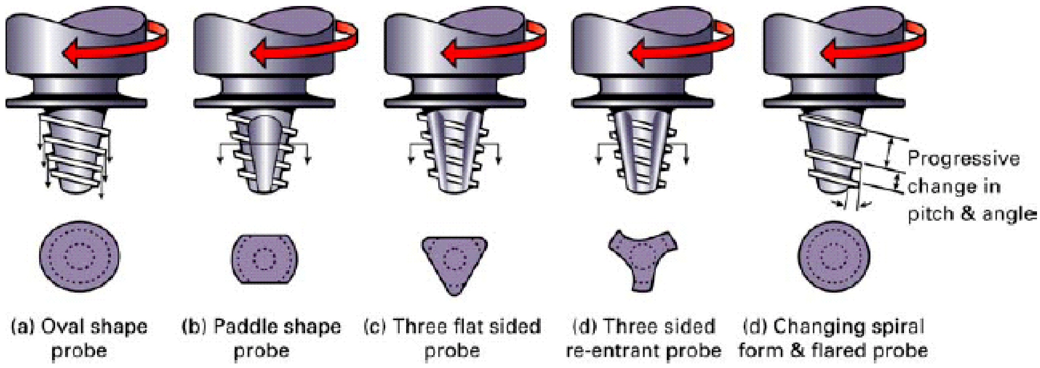


Figure 4. Some of the basic tool shapes for friction stir welding. © TWI.

2.3.2. *Tools for steels*

To weld steels is merely a question of finding a proper tool material, which can withstand the high temperatures (approx. 1200°C) and high pressures (forces) experienced during welding in all axis (Z and X- or Y-axis). Please, these requirements are not related to any specific equipment supplier or type of construction used. The tools are interchangeable, and so far the most promising ones on the market come from an U.S.A. based company called MegaStir[1] (Figure 5) having a polycrystalline cubic boron nitride (PCBN) tip.

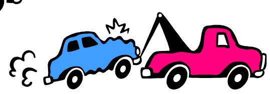
Figure 5. Tools for welding of steels. Tip material is polycrystalline cubic boron nitride (PCBN).

2.4. Equipment

To be successful in welding you must have proper equipment. What is basically needed is an equipment, which is designed for high welding forces without loosing accuracy or repeatability of the process. The welding forces are for the same thickness increasing with increased alloying and with increased welding speed. As an example a 5 mm thick 6082 T6 butt joint can be welded at low speed with a certain downforce but the same welding at 6 m/min needs eight to ten times higher downforce. So the reaction force from the work piece toward the equipment is changing in the same way. The welding forces are trying to separate the work pieces from each other, so the clamping forces are also of a certain magnitude according to Newton’s law. These are very simple rules of thumbs for estimating the capability of equipment and the clamping forces needed.

Increase in down force ⇒ higher welding speed

Increased alloying in aluminum ⇒ lower welding speed



A good surface contact to the work pieces must be maintained constantly. Otherwise the friction will decrease and quality of the weld will be poor. Ways to overcome problems with insufficient contact are welding “too-deep” (shoulder of the tool 0,2…0,3 mm below the

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[1] www.megastir.com

surface level), or to have a large tilting angle on the tool (get more pressure under the backside of the shoulder).

The best welding result is always achieved with equipment having force control. That ensures the full contact with the material all the time. Figure 6 shows a comparison of two plates welded with same welding and rotation speed, but the first one having force control and the latter position control. The quality difference is obvious.

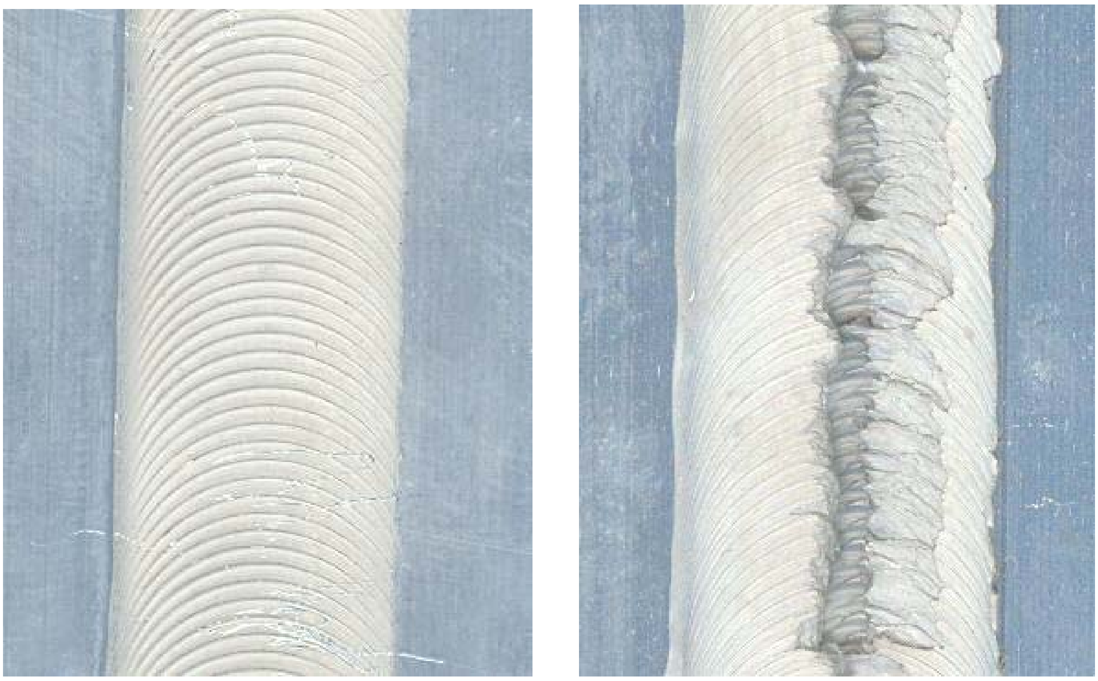


Figure 6. Difference when welding with force control (on the left) and with position control (right). The welding parameters: speed 2 m/min, rotation speed of the tool 1800 rpm, vertical down force on the left hand side 800 kg. Both specimen were welded with the same machine by the same operator. ©ESAB

3. Some words about aluminium

Aluminium as an engineering alloy is – and has been – competing with steel for a number of years. It is approximately three times lighter and three times “weaker” (elastic modulus 70 GPa) and has three times higher thermal co-efficient than steel, “The rule of three 3:s”. Weight savings must often be compensated by improved design in order to avoid unnecessary reduction in strength.

High thermal co-efficient together with the protective oxide-layer of aluminium makes it tricky to arc-weld. The oxide-layer must be broken and removed, and the heat must be inserted rapidly in order to avoid unnecessary thermal expansion in the products. Of course, with friction stir welding these problems typical to aluminium are avoided.

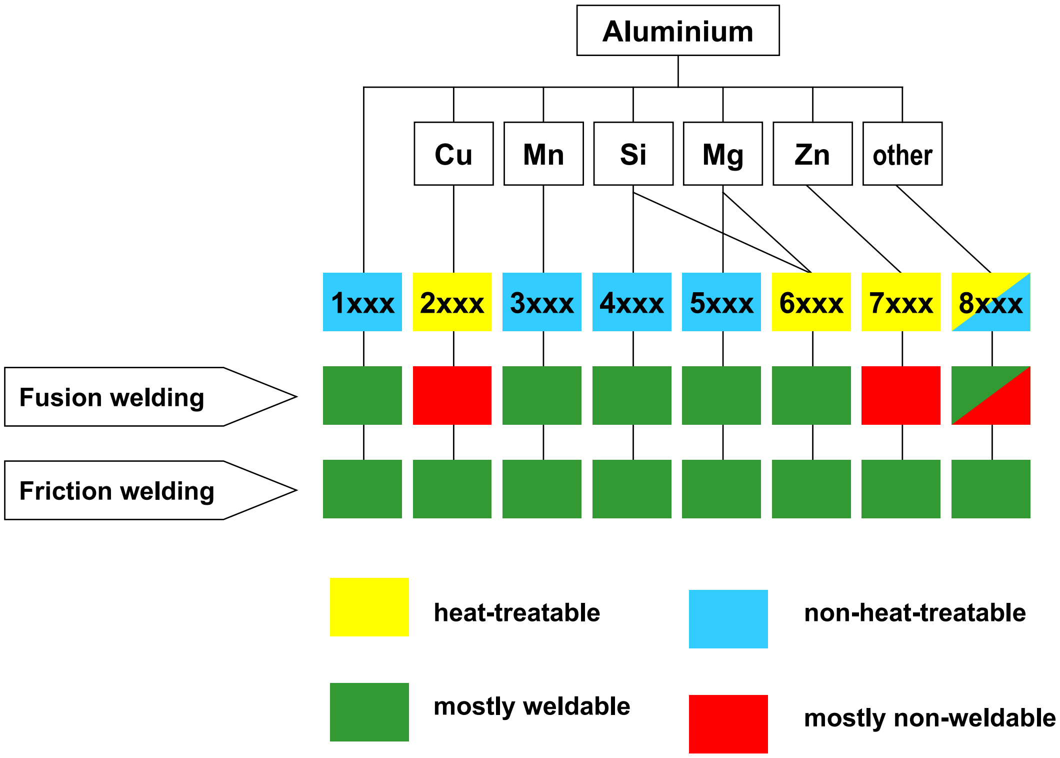


Figure 7. Weldability of various aluminium alloys. ©TWI

In the following tables a designation system for wrought and cast aluminium alloys together with temper designations is summarised. These are commonly used designations in aluminium business.

Table 3. Designation system for wrought aluminium alloys.

Alloy series	Principal alloying element
1xxx	Aluminium, 99,00 % minimum or more
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and silicon
7xxx	zinc
8xxx	Other element
9xxx	Unused series

Table 4. Designation system for cast aluminium alloys.

Alloy series	Principal alloying element
1xx.x	Essentially pure aluminium
2xx.x	Copper
3xx.x	Silicon + Copper and/or magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused series
7xx.x	zinc
8xx.x	Tin
9xx.x	Other element

Temper designations

"F" **"as fabricated"**

No special control over thermal or strain hardening conditions is employed.

"0" **"annealed"**

Applies to wrought and cast products which have been heated to produce the lowest strength condition and to improve ductility and dimensional stability.

“H" **"strain hardened"**

Strengthened by strain-hardening through cold-working.

The first digit indicates basic operations:

H1 - strain hardened only

H2 - strain hardened and partially annealed

H3 - strain hardened and stabilised

The second digit indicates degree of strain hardening

HX2 - 1/4 hard

HX4 - 1/2 hard

HX6 - 3/4 hard

HX8 - full hard

HX9 - extra hard

"W" "solution heat treated"

Applicable only to alloys which age spontaneously at room temperature after solution heat treatment. Solution heat-treatment involves heating the alloy to approximately 538 °C (1000 °F) to bring the alloying elements into solid solution, followed by rapid quenching to achieve a super-saturated solution at room temperature.

"T" "thermally treated to produce stable tempers other than F, O or H"

Applies to products, which have been heat-treated. The first digit indicates specific sequence of treatments:

T1 -	naturally aged after cooling from an elevated temperature shaping process, such as extruding.
T2 -	cold worked after cooling from an elevated temperature shaping process and then naturally aged.
T3 -	solution heat treated, cold worked and naturally aged.
T4 -	solution heat treated and naturally aged
T5 -	artificially aged after cooling from an elevated temperature shaping process
T6 -	solution heat treated and artificially aged
T7 -	solution heat treated and stabilised (over aged)
T8 -	solution heat treated, cold worked and artificially aged
T9 -	solution heat treated, artificially aged and cold worked
T10 -	cold worked after cooling from an elevated temperature shaping process and then artificially aged

The second digit indicates variation in basic treatment

Additional digits indicate stress relief.

TX51 -	Stress relieved by stretching
TX52 -	Stress relieved by compressing

Table 5. General application areas of aluminium and some of its substitutes.

Sector	Main Applications	Substitutes
Electrical	Busbars	Copper
	Transformers and generators	Copper
Transportation:		
Automobiles	See Table 6	Copper / brass
Aerospace	Structural components	Steel/Plastic/Magnesium
	Commercial Airframes	Carbon reinforced and other composite materials
Rolling stock	Freight cars	Steel
	Coaches	Steel
Marine	Boat Hulls	Timber, fiberglass, coated steel,
	Propellers	brass, stainless steel
Consumer durables	Refrigerators and freezers	Steel, plastics
	Air conditioners	Copper
Construction	Cladding	Timber, coated steel, plastic
	Roofing	Timber, galvanised steel, lead
	Window and door frames	Timber, PVC
	Fencing	Timber, concrete, steel
Industrial	Heat exchangers	Copper, stainless steel
	Hydraulic systems	Steel
Machinery and equipment	Irrigation piping	Cast iron, steel, plastic

4. Applications

4.1. Automotive industry

Automotive industry with large manufacturing batches, six sigma requirements and challenging material combinations from wrought and cast aluminium to magnesium alloys provides a perfect ground for friction stir welding applications. One of these success stories is shown on Figure 8, which shows a fully automated ESAB SuperStir™ for welding of seat frames at SAPA, Sweden. The cycle time is less than one minute / seat using dual welding heads.

Figure 8. Fully automatic manufacturing cell for production of components to a car. ©SAPA, Sweden.

Welding speed depends on the alloy to be welded and the used tool geometry. However, speeds up to 6 meters / min. on 5 mm thick AA6082 are possible. The alloys which are sensitive to heat even tend to have better mechanical properties if welded fast, since no changes in the chemical composition of the material occurs. Alloys which are difficult to join with conventional arc-welding processes can often be joined by friction stir welding providing numerous possibilities in, for example, construction of military vehicles.

Overlap and butt joints can be welded in all positions, as well as mixed welds (different thickness or different materials – 5000 series to 6000 series, for example). Even cast aluminium components can easily be welded. The microstructure and homogeneity of the cast material improves significantly when friction stir welded. The porosity typical to castings disappears. Figure 9 demonstrates an etched surface on a T-joint between two cast plates.

The microstructure on the ”stirred area” is much finer-grained than the relatively coarse as cast plate material.

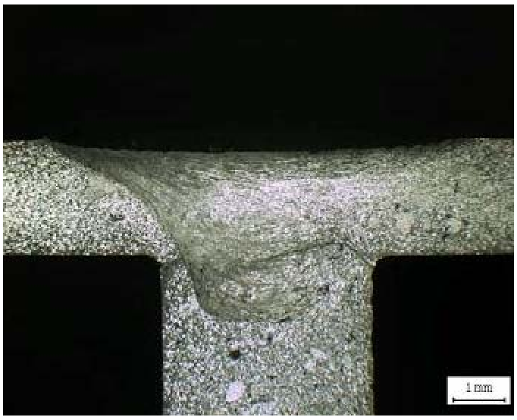


Figure 9. Etched microstructure on cast aluminium T-joint shows that the weld area has fine-grained microstructure without porosity. The fine “crack-shaped-line” coming from the right is poorly stirred oxide-layer, not a crack.

To join together two different thickness or different alloys, is a very demanding task when utilising arc- or beam welding processes. With friction stir welding, plates of different thickness can be joined securely and strongly (Figure 10.) Also overlap joints are possible with FSW providing an alternative solution to resistance spot welded or seam welded pieces. An excellent solution for making a watertight seal weld instead of spot-welding is demonstrated on Figure 4.

Figure 10. Possible applications in a car for friction stir welding: mixed joint between two thickness (1+2 mm), overlap joint on 1 mm thickness and folded seal weld. ©ESAB

4.1.1. Applications in cars and road transport vehicles

All aluminium components in a car can in principle be friction stir welded: Bumper beams, rear spoilers, crash boxes, alloy wheels, air suspension systems, rear axles, drive shafts, intake manifolds, stiffening frames, water coolers, engine blocks, cylinder heads, dash boards, rollover beams, pistons, etc… Minor modifications to the structure maybe needed in order to make it more suitable for FSW, but that should not be impossible to overcome.

In larger road transportation vehicles the scope of applications is even wider and easier to adapt – long, straight or curved welds: trailer beams, cabins and doors, spoilers, front walls, closed body or curtains, dropside walls, frames, rear doors and tail lifts, floors, sides, front and rear bumpers, chassis (Figure 11), fuel and air containers, toolboxes, wheels, engine parts, etc.

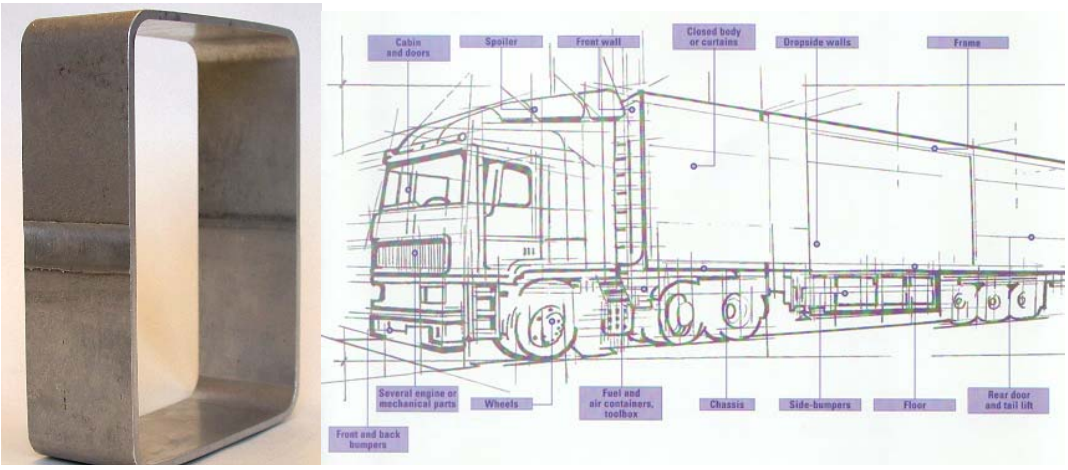


Figure 11. A longitudinal FSW weld in a rectangular profile. Beams with minimal distortion can be manufactured. On the right hand side a picture by EAA (European Aluminium Association) showing potential application areas for aluminium in a truck.

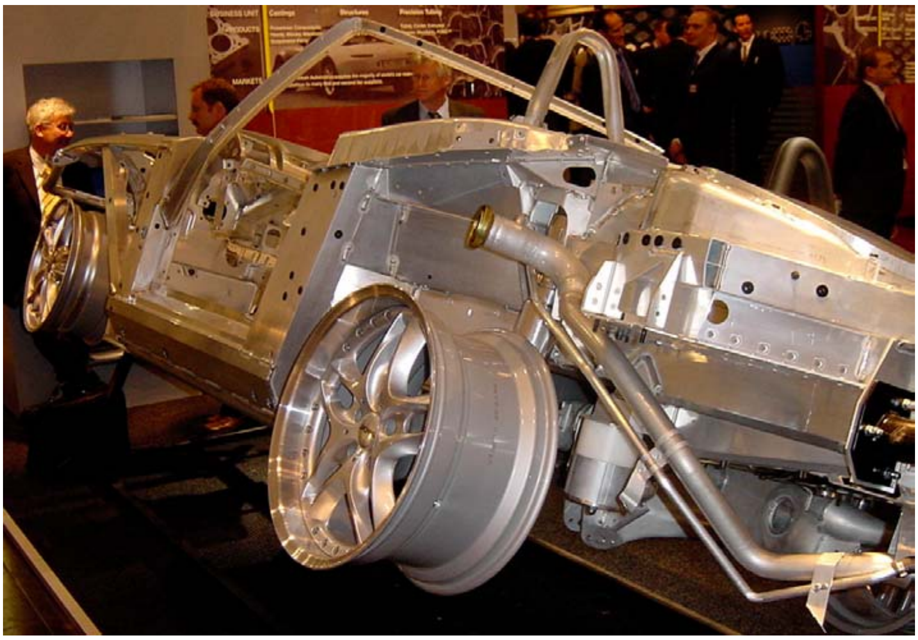


Figure 12. A car is full of application areas for aluminium as can be seen in this picture taken at the Aluminium 2002 fair in Germany at the booth of SAPA.

Table 6 . Aluminium alloys typical to automotive industry and their respective application areas. (Irving 2000)

Inner and outer body panels	2008, 2010, 2036,3004, 5052, 5182, 5754, 6009, 6010,6016, 6022, 6111
General structural components	6005, 6005A, 6009, 6061
extrusions	6063, 6082, 7005
luggage racks, air deflections	6463
space tire carrier parts	6061
Bumper components	
ace bars	5052, 6009
reinforcements	6009, 6061, 7003, 7004, 7021, 7029
brackets	6009, 7021
Seats	
shells	7036, 6010
headrest bars	7116, 7129
tracks	6010, 5182, 5754, 6009
Load floors	2036, 5182, 5754, 6009
Wheels	5454, 6061, A356.0
Suspension parts	6061 (forging)
Drive shaft	6061 (tube), aluminium metal matrix alloys
Drive shaft yokes	6061 (forgings and impact extrusions)
Engine accessory brackets and mounts	5454, 5754
Sub-frames and engine cradles	5454, 5754, 6061, 6063
Miscellaneous	
Radiator tubes; heater cores; radiators, heater and evaporator fins; oil coolers; heaters and air conditioner tubes	3003
Radiator, heater and evaporator fins	3005
Condenser tubes	3102
Condenser and radiator fins	7072

4.1.2. Suspension parts

ESAB SuperStir™ in Figure 14 was delivered to Tower Automotive in year 2000. The machine is designed for making a big profile from two or three extrusions. The welded profile is then cut into smaller widths to form a lightweight suspension link.

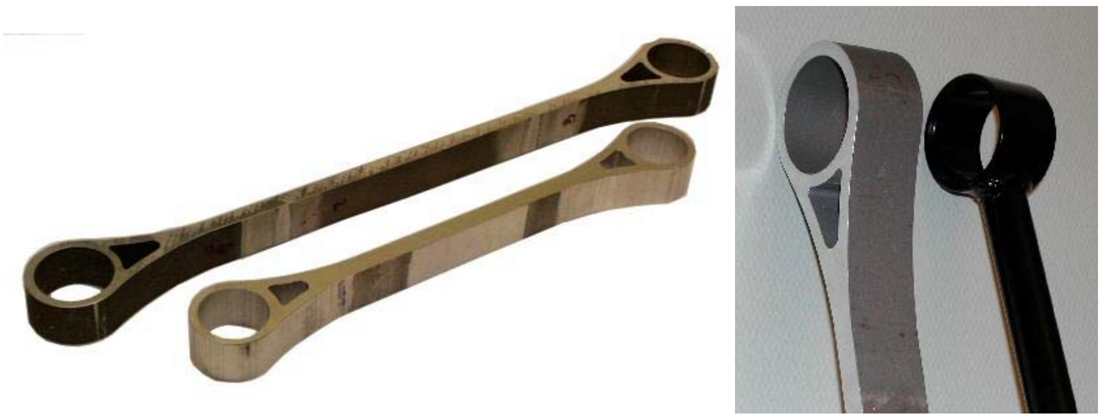


Figure 13. Suspension links by Tower Automotive. On the image to the right , the old steel based design is also shown. © Tower Automotive

The machine is equipped with two separate welding heads for simultaneous welding from top and bottom side in order to get a symmetric heat distribution and no ”root” problems. As the heat is generated on both sides, this is the fastest and most effective way to use FSW as the time consuming plunging operation (penetration to the material) only goes to half of the plate thickness and the heat is generated on both sides.

Tower lists the benefits of friction stir welding as follows:

- reduced weight – estimated 40% vs. GMAW
- improved joint efficiency (2x tensile strength of GMAW in 6000 series aluminium)
- increased fatigue life (2x to 20x GMAW)
- no consumables (no filler wire or shielding gas required)
- less distortion – low heat input
- improved energy efficiency
- environmentally friendly – no fumes or spatter

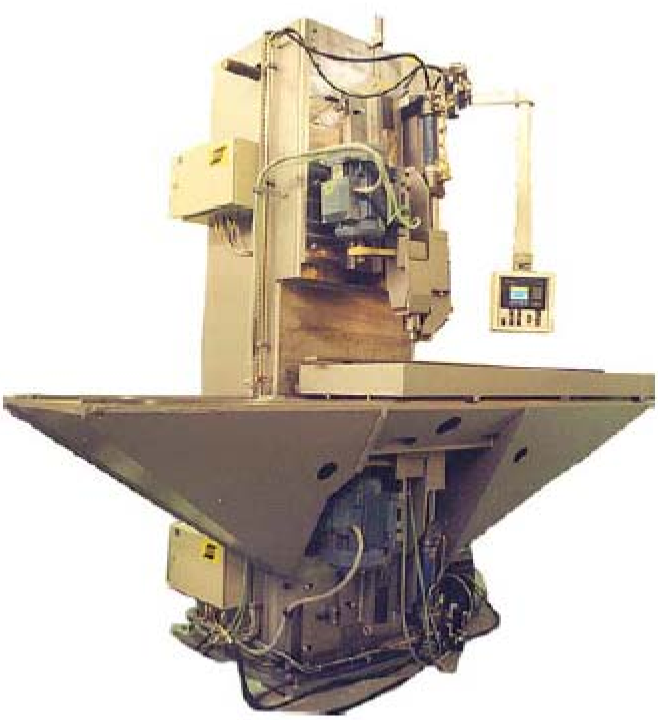


Figure 14. ESAB SuperStir™ at Tower automotive.

Tower on the press ***(Aluminum Now, 2003):***

Ford Suspension Link the First U.S. Auto Part to Be Friction Stir Welded

Tower Automotive has successfully produced aluminum suspension links for the Ford Motor Company using the friction stir welding process. It is the first time in the U.S. that friction stir welding has been used in the manufacture of an automotive component.

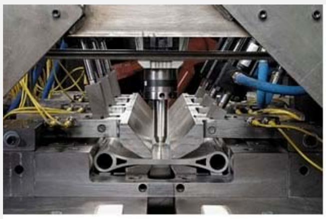
Recognizing the potential for applying friction stir welding to automotive applications, Tower purchased a license from TWI to carry out testing of the process. Those tests showed that, compared to the traditional automotive industry method of gas metal arc welding, friction stir welding could reduce weight, lower costs, increase joint efficiency, and increase fatigue life.

"This new process offers superior joining technology in all series of aluminum," said Art Scafe, Tower's product development leader for suspension components. "The quality level created by a friction stir weld is superior to other types of welding."

Tower Automotive worked with Ford to develop the friction-stir welded design for the suspension links in the company's line of Lincoln Town Car limousines. According to Scafe, friction stir welding was used to join half-inch-thick pieces of 6061 aluminum.

Within six months, Tower completed the suspension link design, analysis, welding specifications, prototyping and product testing. The first vehicles with the friction-stir welded suspension links rolled off the assembly line at Ford's Wixom, Mich., plant in October 2002.

According to Tower spokesman Kevin Kennedy, the company is looking at additional non-suspension applications in which to apply use of friction stir welding, including aluminum body panels. "*Use of friction stir welding is design-dependent and material-dependent. The process works best with a straight, flat surface to weld*."



Another application on suspension components is a 3-piece suspension arm on BMW 5 – series (Sato et. al, 1998). In their case study, they have been able to create improved properties to the suspension arm. Some of the main fields of interest for such a component is of course weight, and also road noise reduction capabilities. Also in this application it was noticed that the heat on the ball joint portion during welding was only 393K, which does not destroy the rubber bellow attached.

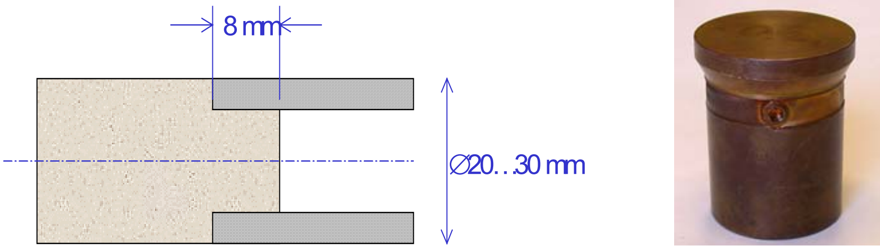


Figure 15. Drawing of the joint configuration for the suspension arm. On the right hand side is a picture showing similar joint geometry used in welding of copper.

4.1.3. Other automotive applications

Welding of aluminium wheels was one of the earliest applications on automotive industry for FSW (Simmons, Australia). It was first used for longitudinal welding of aluminium tube, which was later cut to proper length and spin-formed to right shape. Hydro in Norway has used friction stir welding in attaching the inner rim to the wheel form, Figure 16. The butt and over lap welds can be fabricated in wrought and/or cast materials (Johnson et al. 1999).

Figure 16. Friction stir welding used in joining wheel components. © Hydro, Norway.

4.1.4. Engine components

Cast aluminium components can successfully be friction stir welded or processed to improve the quality of the cast structure, or to join inserts in the piston. In friction stir processing there is no "weld joint", but the tool travels on the material and stirs it. This results in fine-grained microstructure and the porosity typical to castings will vanish. The amount of potential applications in the engine of any motor vehicle alone is incredible, not to mention the cast or forged components used in load-carrying applications. An example of a product with improved quality is shown on Figure 17.

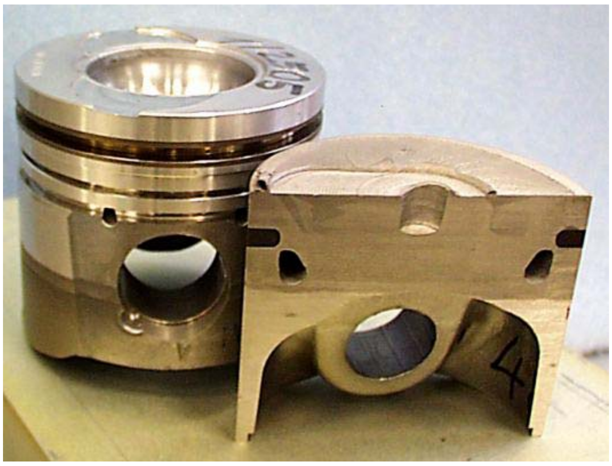


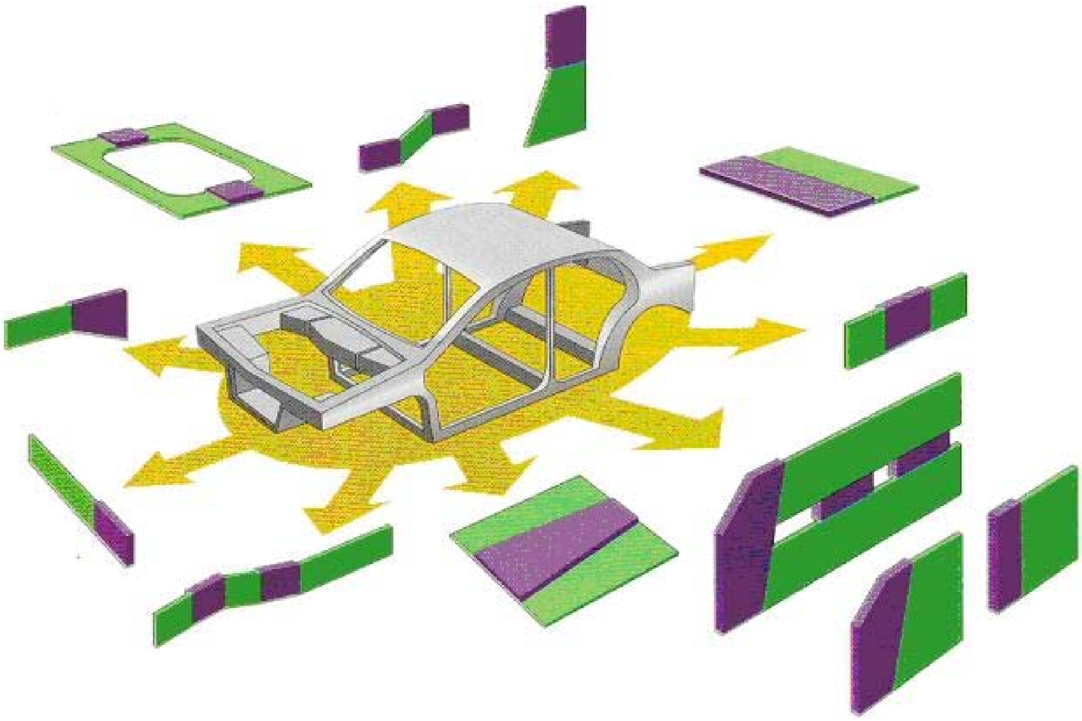
Figure 17. A friction stir processed piston. The metallographic structure was clearly improved after friction stir processing.

4.1.5. Loading bridges and tail-lifters

More and more aluminium is used in transport vehicles in order to lower the "dead-load" and hence increase the pay-load. Also the ever increasing awareness of environmental issues has put pressure to reduce weight in many road applications. A lorry is full of potential applications for friction stir welding – mainly straight linear welds in x-y plane, and materials easily weldable and thickness typically up to 5 mm. Could there be better applications for friction stir welding? Some samples are shown in Figure 18. By replacing conventional arc welding joining processes by friction stir welding, the straightness of the panels will be drastically improved and assembly times shortened to minimum.

Figure 18. Aluminium loading bridges, which could easily be made using friction stir welding.

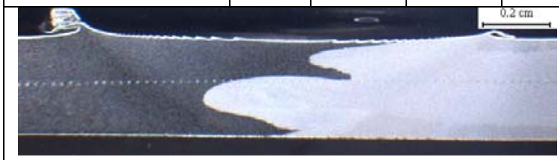
4.1.6. Tailor welded blanks (TWB's)



To combine different alloys and/or different thickness is one of the most interesting areas among automotive joining applications. Laser and laser hybrid welding have gained a relatively stable position when joining steels and stainless steels, but for aluminium joining has friction stir welding proven extremely high potential. Table 7 summarises test results from a study made for 3 mm thick tailor welded aluminium blanks. The results may speak for themselves.

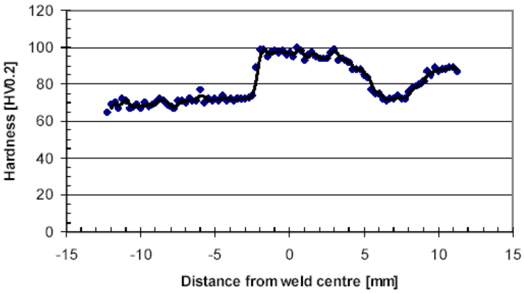
Table 7. Test results of tailor-welded joint between AA6063 and AA6082.

Alloy name	***t***	***%Si***	***%Fe***	***%Cu***	***%Mn***	***%Mg***	***%Zn***	***%Ti***	***%Cr***
AA6063-T4	3,0	0,42	0,18	<0,02	0,02	0,47	<0,02	<0,04	<0,02
AA6082-T4	3,0	0,97	0,19	<0,05	0,48	0,64	<0,05	<0,02	<0,03



Cross-section of AA6063 welded to AA6082. The markings from hardness measurements are clearly seen.

X-ray showing perfectly defect-free friction stir welded joint.

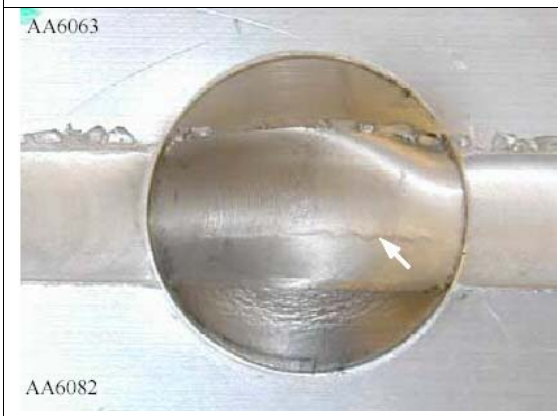


Hardness profile across the weld.

Tensile test failure is clearly on the base material side. Failure occurred always on the AA6063 side of the weld.

Average Tensile Strength R_m = 157 MPa

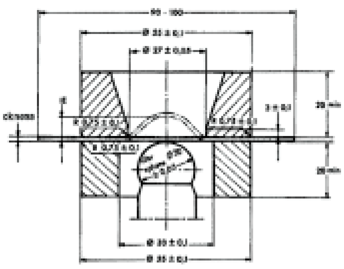
Average failure strain 18,4 %



Friction stir welded sample after Erichsen cupping test.

The top-out value was 7,9 mm, and

The root-out value was 9,2 mm.



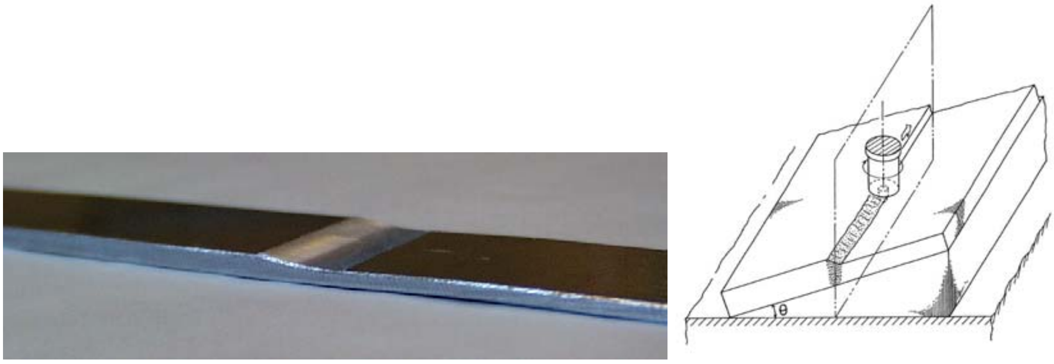


Figure 19. Tailor welded blank on AA5754 H22 on thicknesses 1 and 2 mm. Welding was done on a fixture with inclined table at a speed of 6 m/min. © ESAB

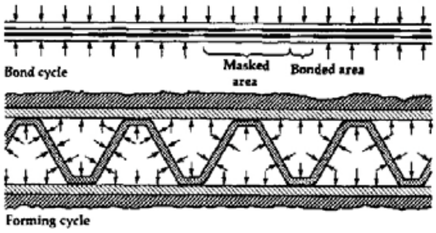
Table 8. Mechanical properties of the plates shown on Figure 19. © ESAB

AA 5754 H22	*Yield strength*	*Tensile Strength*	*Elongation*
1,0 mm plate:	$R_{p0,2}$ = 130 N/mm^2	R_m = 248 N/mm^2	A_{50mm}=18%
2,0 mm plate	$R_{p0,2}$ = 122 N/mm^2	R_m = 227 N/mm^2	A_{50mm}=17%
No porosity! No undercut or lack of penetration!			

4.1.7. Superplastic forming

The next step in exploitation of friction stir welding as a welding process will be in superplastically formed products as already demonstrated by Aston Martin in their Vanguard model, Figure 20. This technique often goes hand in hand with tailor welded blanks manufacturing and some applications from door component manufacturing are already available. In superplastic forming the final shape to products is given with help of a pressurised gas. The idea is to make connecting welds in relatively simple positions and plate shapes, as shown in Figure 21. When the gas pressure is applied, the final shape of the structure is formed. Superplastically formed 3-plate AA5083 panel construction is also shown (Pimenoff et al. 2002). Connecting welds were made with friction stir welding.

Figure 20. Aston Martin Vanguard. Significant use of superplastic forming in the hoods. © Superform



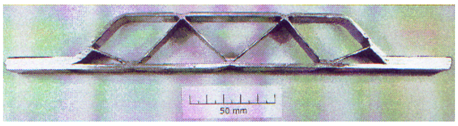


Figure 21. Basic principle of superplastic forming (left) and AA5083 superplastically formed panel. © Pimenoff 2002.

4.2. Extruders and extrusions – with special focus on rolling-stock-type panels

Welding of two or more narrow extrusions together to make a wider one is a real classic in the field of friction stir welding. It was the first industrial equipment (delivered 1996 to Marine Aluminium, Norway) which utilised this concept to full degree. The equipment has been in constant use ever since and has produced hundred of thousands of meters of defect free welds.

There are limitations in the maximum and minimum sizes in various extrusions depending if they are open, half-open or closed (hollow-profiles). This sets challenges in finding the right balance both technically and economically. It has bee reported that *Conglin aluminum Corp* in China has a 10.000 MT press capable of making extrusions as wide as 970 mm. These extrusions will be used in Levitation Train between Shanghai airport and city of Shanghai (Aluminium Extrusion, 2002). Plants capable of this size of extrusions are very rare. Sizes of typical commercially available extrusions are more like the ones shown in Figure 22.

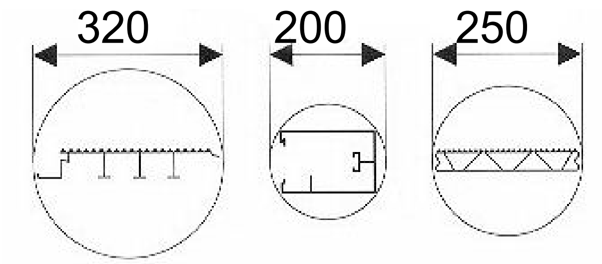


Figure 22. Typical extrusion widths for open, half-open and hollow profiles. (c) Nordic Aluminium

To join profiles with high productivity you need a "gentle giant". This means powerful and robust equipment, which has an extremely accurate control of the welding forces and the position of the tool. Also, use of multiple welding heads is a possibility to increase the flexibility and cycle time. Figure 23 shows a full automatic welding equipment with two welding heads on the upper side and one welding head on the lower side (the two upper heads are used on single skins for almost doubling the welding capacity as they both start from the middle and weld outwards, one upper and the lower head is used to weld both sides of a double skin panel). The welding length is 14,5 meters and makes it possible to manufacture very large components to, for example, rolling stock and road transport equipment.

Figure 23. A fully automatic panel welding equipment at SAPA, Sweden. The equipment has three welding heads – two on the upper side, and one on the lower side.

In order to be successful in welding of extrusions into wider plates or in joining of hollow-profiles, design of the profiles must be adapted to the requirements of the friction stir welding process. The main criteria being capability to withstand the welding forces without collapse or buckling. A profile, which is designed on the needs of GMAW, can be made a lot easier when adapting it to FSW. An excellent example is shown in Figure 24 by Hydro Marine Aluminium. The picture illustrates very clearly the difference in extrusion shape when using FSW and GMAW, respectively.   This has direct effect on weight of the structure, tooling costs, etc.

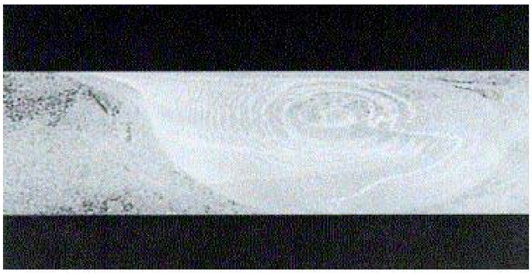
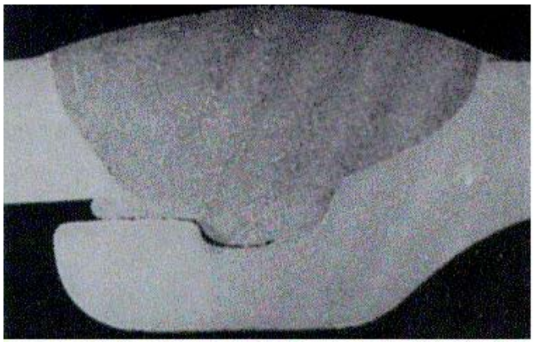
 

Figure 24. Difference in extrusions needed for making the same component by friction stir welding (left) or by GMAW (right). © Hydro Aluminium, Norway

Rolling stock, i.e., train car and coach manufacturers are very keen on using friction stir welding in various components of a train car. For example Alstom LHB has used friction stir welded floor-panels and side walls from Hydro Marine, Norway since 2001 in suburban trains (Kallee et al. 2002). Another pioneer in train industry has been Hitachi in Japan who has used friction stir pre-fabricated floor elements in their Shinkansen trains, Figure 25. Even in these cases the profiles and extrusions must be made suitable for FSW. The Shinkansen profiles used are pretty much like the ones shown later on Figure 31. In Figure 26 an example of profile design for friction stir welding is shown. The thickness on the weld area, as well as the radii on the corners are the know-how that some of the extruders have started to gain even if they don't friction stir weld themselves. This is clearly an area for future business in extrusion market.

Figure 25. Shinkansen train where friction stir welding is used in the floor panels.

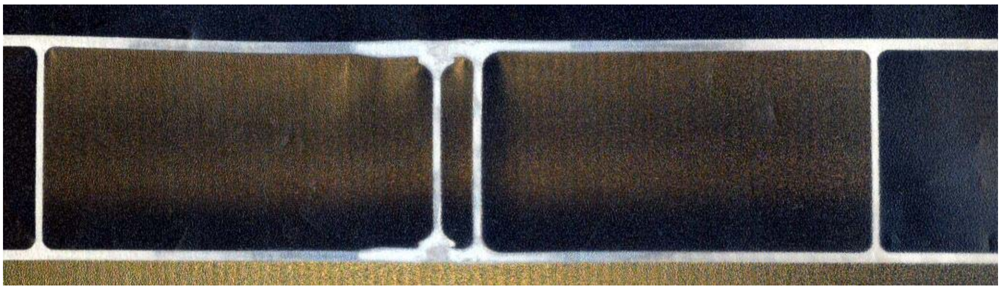


Figure 26. An extruded profile designed for friction stir welding. © Mäkelä Alu Oy, Finland.

In Figure 27 a quality inspection is performed to panels which have been welded with the big panel machines using one upper and one lower head simultaneously. The flatness is incredible!

Figure 27. Perfectly flat hollow profiles inspected after welding at SAPA, Sweden.

4.2.1. Speed of the process

Not so long ago, one of the main “excuses” for not using FSW in welding was the statement that the welding speed is too slow for production, even though the mechanical properties of the welds outperform conventional joining processes for aluminium. A typical welding speed stated for AA6082 in thickness of 5 mm was between 250 mm/min and 400 mm/min. This is a typical result when welding with a CNC machine, that not is designed for high down forces needed in friction stir welding nor the high travel speeds. With production machines the welding speeds for above mentioned alloy are and have been for a number of years almost 10 times higher – 2000 mm/min is a typical production speed in joining of extruded profiles.

In a medium size welding workshop (200…400 blue collar workers) time spent in welding and related functions represents roughly 15…20% of the total manufacturing time. Therefore the key question is actually if the productivity can be improved by:

1. increasing the welding speed with conventional processes (GMAW, GTAW),
2. introducing new welding process (FSW in this case) welding with speeds of conventional arc welding processes but resulting in significant cost savings in other phases of production, or
3. Introduce FSW, which welds 3-4 times faster than GMAW and results in significant cost savings later in the production stage.

Alternative number 3 is, of course, the most attractive. There are a few companies, which have chosen that way, and improved the economical, as well as production capacity. A Norwegian shipyard has succeeded in reducing the production time of a 60-m long catamaran hull from 10 to 6 months, which means 40 % increase in capacity. A cost saving of 10% is also reported being 10% of the total fabrication costs. This is divided into 3 different categories: 2…3% due to improved extruded profile designs and the use of friction stir welded panels, 4…5% due to improved streamlined fabrication at the yards, and 3% due to new design (Midling, 2000).

A series of test welds has been successfully welded at the ESAB Friction Stir Laboratory in Laxå Sweden with welding speeds up to 6 m/min on materials thicker than 1 mm. The tests reported here were done on AA6082 alloy with a thickness of 5 mm. The mechanical properties of the base material are presented on Table 9, and the test data on Table 10.

Table 9 . Mechanical properties of commercial alloy AA6082 T6.

	Yield strength $R_{po,2}$	Ultimate tensile strength, R_m	Hardness HV	Elongation
AA 6082 T6, AlSi1MgMn	260 MPa	310 MPa	95	9 % (A5)

Table 10. Welding parameters.

Tool:	Modified Tri-flute MX™
Forward movement *(travel speed / tool rpm)*	2,5 mm / rev
Down force	Sufficient
Preparation	Degreasing with alcohol
Welding speeds	1,0 m /min, 3,0 m/min and 6,0 m/min

Table 11. Summary of the test results on 5 mm thick AA6082 T6. The test results are based on average of 3 tests (bending test only 1 sample).

Welding speed	*$Rp_{0.2}$ [Mpa]*	*dev.*	*R_m [MPa]*	*dev.*	*Bend test [°.]*	*A25*	*Dev.*
1 m / min	155,9	0,56	256,2	0,04	180	10,76	2,72
3 m / min	171,1	1,71	268,5	0,24	180	11,46	0,75
6 m / min	173,8	1,66	268,7	1,29	180	9,20	0,46

As it is noticed, the properties of the welds are rather identical, but surprisingly enough the mechanical properties are improved by ca. 4-5% by welding faster (compare 1 m/min. to 3 m/min.). As the welding speed is further increased, the mechanical properties remain in the excellent level, but deviation in the tensile strength is slightly increased. This is mainly due to the smaller parameter box as the speed is increased. Smaller and smaller variations in the welding conditions may effect the quality more easily. Figure 28 shows an example of a typical welding fault experienced when welding outside the scope of the parameter box. The stirring was not good enough and causes a fault on the root side of the weld. Since the heat input is further decreased as the welding speed is increased, the risk of having “too cold” welds exists. Therefore a total control of the welding parameters is needed in order to make a solid, defect-free weld at high speeds.

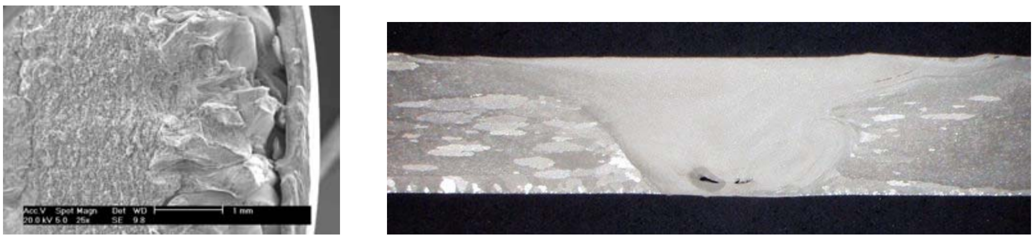


Figure 28 . Etched microstructure of AA6082 welded at 6 m/min with too low "heat input" in the root of the joint.

From the hardness curves (Figure 29) it can be seen that the curves for 1 and 6 m/min are rather identical. Curve for 3 m/min samples differs slightly even though it is taken from the same batch. This is an excellent example of the tolerance variation, which can sometimes exist even within the smallest batches. As a hardness measurement for unwelded base material on 1, 3 and 6 m/min samples was performed, the hardness was 112,102 and 115HV respectively as can easily be concluded from Figure 29, also.

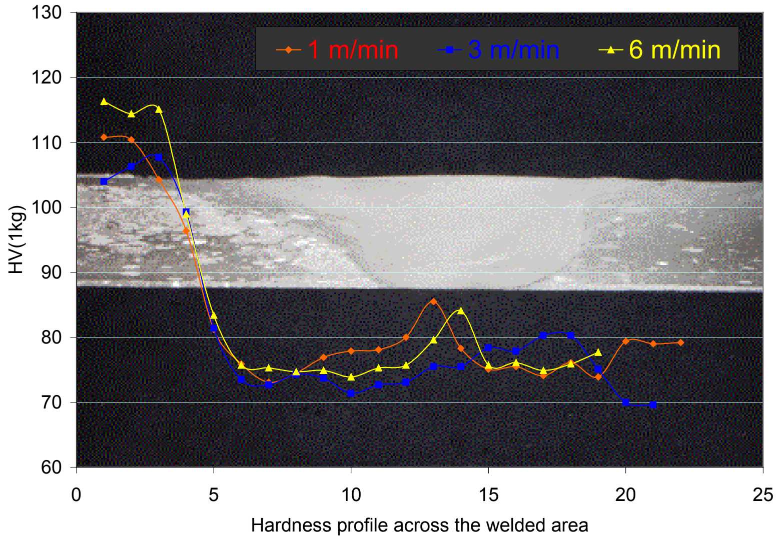


Figure 29 . Hardness profile across the weld joint on welding speeds 1, 3 and 6 m/min. The base material 5 mm thick AA6082.

4.3. Shipbuilding

Imagine if a large catamaran could be constructed from building blocks, just like a toy boat. All pieces would fit perfectly to each other and dimensional accuracy and changes could be mastered to full degree. Friction Stir Welding takes the first step towards such assembly work in shipbuilding. Due to the low heat input during joining and resulting in very low residual stresses, the welded components are accurate and minimal fit-up work is needed. The resulting savings in both time and money are obvious. Since this creates competitive advantage to the users of FSW pre-fabricates; documented information of actual savings is not very often reported. However, Midling et. al. 2000, gives an idea of the possibilities gained by friction stir welded pre-fabricated panels from a panel producer’s point of view:

- Industrial production with a high degree of completion.
- Extended level of repeatability ensuring uniform level of performance, quality and narrow tolerances.
- The flexible production equipment and capacity allows customer built solutions with reliability of delivery.

- The completed panel units are inspected and approved at present by classification authorities such as DNV, RINA, British and Germanischer Lloyds.
- The high level of straightness of the panels ensures easy assembly at yard, which means less manual welding.
- Supplementary work for the customer, such as less need for floor levelling and preparation for floor coverings also is a major cost saving with FSW panels.

One of the most attractive features of friction stir welded products is that they are ready-to-use. No time consuming post-weld treatment such as grinding, polishing or straightening is needed. With proper design the elements are ready-to-use directly after welding. However, it is important to keep in mind that designs, which are made for MIG or TIG welding, are not necessarily suitable for friction stir welding. The limiting factor often being the relatively high down-force needed when friction stir welding. A proper support in a form of backing bar or design change are often needed (Figure 30). Once done, repeatability reaches levels previously not experienced in welding.

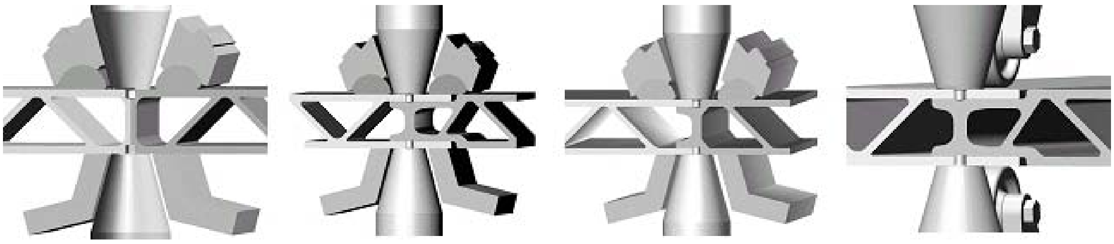


Figure 30 . Designs which make it possible to weld hollow profiles.

Figure 31. Flat panel field after welding. Instead of using wide profiles, the panel is made from relatively narrow (120 mm) extrusions. ©ESAB

When producing large surfaces like walls or floors, besides the straightness of the panels, also the resulting reflections are an important and expensive issue to consider. A lot of time is spent polishing and "making-up" surfaces, which are architecturally visible. In FSW prefabricated panels, the reflections are merely caused by the surface appearance of the aluminium plates and profiles in the as-delivered state, not by the reflections caused by welding heat input. One of the earliest examples of product where a lot of friction stir welding was used is shown on Figure 32 – Catamaran made by Kvaerner Fjaellstrand using extruded and friction stir welded profiles produced by Hydro Marine Aluminium.

Figure 32. A catamaran where a lot of friction stir pre-fabricates was used. This was actually the kick-start for the industrialisation of the process.

4.3.1. Why use aluminium instead of steel?

One excuse of not using aluminium has always been "that it is not as strong as steel." True – and not true. It, of course, depends also on the alloy to be used, and surprisingly enough, there are aluminium alloys, which are as strong or even stronger than steels. For example the so-called "ALUSTAR" has yield and tensile strengths comparable to low alloyed steel S235. AlCu4SiMg (AA2014) – an alloy typically used in aerospace applications –has significantly higher strength than alloys in 5xxx- and 6xxx series, which are typically used in shipbuilding. Some of these alloys just have not been used in shipbuilding before, due to their poor weldability! With friction stir welding, some of these barriers can be overcome – just imagine, for example, using strong alloy AA7021 for making aluminium floor panels even thinner, and gain weight savings by "thinking differently".

In Figure 7 the weldability of various aluminium alloys is shown as a reminder. The typical alloys used in shipbuilding are from 5xxx –series due to their good corrosion resistance, or from 6xxx –series due to the strength. A dissimilar combination between these two alloys is of course also possible (Larsson et. al. 2000).

4.3.2. *An easy way to make small-scale pre-fabricated panels or components*

Figure 34 gives an idea of relatively easy implementation of FSW in shipbuilding. ESAB's new LEGIO™ concept is ideal for fabrication of small batches of friction stir welded panels. The equipment is placed on the workshop right next to the assembly of the ship hull. The picture is from *Estaleiros Navais do Mondego S.A. Shipyard* in Portugal. Even small batches can effectively be welded on-site.

The main idea around ESAB LEGIO™ friction stir welding modular system is the flexibility: the welding head is selected according to the alloys to be welded and their thickness. The length of the machine is adjusted according to length of the pieces to be welded. Clamping systems and fixtures are typically made separately based on the application needs (Figure 33).

Table 12 . Performance table used for defining the size of the LEGIO™ friction stir welding machines. © ESAB

Size	Spindle effect (kW)	Vertical Down force (kN)	AA6xxxx	AA5xxx	AA2XXX AA7XXX	Oxygen free copper
FSW 1	3,5	6	3	2	1,5	0,8
FSW 2	5	12,5	5	3,5	2,5	1,5
FSW 3	11	25	10	7	5	3
FSW 4	18	60	18	10	9	7
FSW 5	22	100	35	20	18	12
FSW 6	45	150	60	40	35	25
FSW 7	90	200	100	75	70	40

Figure 33. "Home-made" clamping for welding of 5 mm thick AA5083 with LEGIO. © Estaleiros Navais do Mondego S.A., Portugal.

Figure 34. FSW LEGIO™ 3UT installed next to aluminium ship hull production line at Estaleiros Navais do Mondego S.A. shipyard in Portugal 2002.

Figure 35. Modular LEGIO 5UT friction stir welding machine for flexible manufacturing. The working envelope of this particular equipment is 6000x500x300mm (x-, y-, z- axis). Delivered to KMT –tekniikka OY, Finland December 2003.

4.4. Aerospace – civil aviation

Friction stir welding was first introduced to larger, general public in the "*Schweissen und Schneiden*" fair 1997. The equipment displayed is shown on Figure 36. It was later purchased by The Boeing Company for research and laboratory use. Besides the laboratory machine, has Boeing been a real pioneer in introducing friction stir welding into industrial manufacturing. In Delta II and IV programs friction stir welding has been widely used in manufacturing of rocket fuel tanks, used also on the latest Mars expeditions.

The production time for a typical tank has been dramatically reduced and cost savings have been gained. Price difference between friction stir welding and riveting is surprisingly big – friction stir is only 20% of the costs for riveting! More parts on rockets are constantly being evaluated for future production not only at the Boeing Company, but almost everywhere where there is manufacturing of aerospace or civil aviation equipment. A number of different applications in the commercial and military *aircraft industry* are under evaluation; they include carrier beams, floors and whole bodies and wings. (Eriksson, 2001)

A major breakthrough in the field of civil aviation has been the approval made by the FAA (Federal Aviation Association), which has approved the friction stir welding process as a joining process for aeroplanes.

Figure 36. SuperStir™ #1 - first friction stir welding machine introduced to general public 1997 in Schweissen and Schneiden fair. Currently used at Boeing laboratories for research and development work.

Figure 37. Showing to the left, one of two identical vertical welding machines at the Boeing Company in Decatur, USA. The welding length (height) is 12 meters and the diameter is 5 meters.

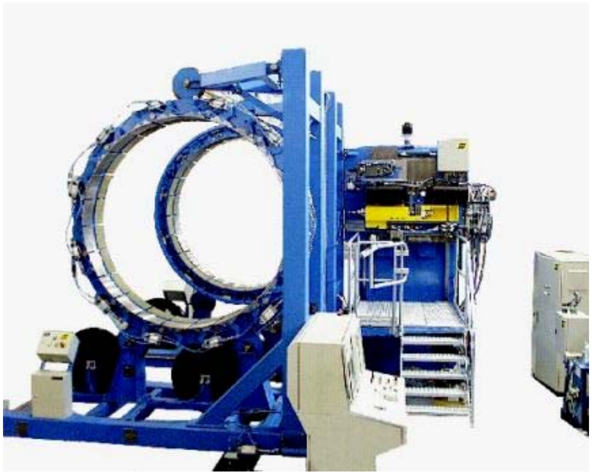


Figure 38. Circumferential welding machine which utilises the Bobbin Tool and the Plug Welding technology.

Figure 39. Longitudinal welding machine for joining of machined honeycomb-structured sections. Earlier the segments were joined by MIG or VPPAW (variable polarity plasma-arc welding).

Figure 40. Eclipse - the first commercial aircraft using friction stir welded components.

4.5. Aerospace R&D

The pressure to replace riveting by welding is very strong at the moment. Riveting is good process, but it is very time consuming in practice. Holes for the rivets are typically drilled one by one, so it is easy to imagine possible time savings if welding could instead be used. The main areas of interest are:

- overlapping joints
- welding of anodised plates
- mixed joints (different alloys)

As a curiosity it can be mentioned here that friction stir welded joints do not suffer from colour changes when anodised. An important issue when compared to conventional arc welding processes, when the matching colour is often gained by sacrificing mechanical strength or corrosion properties.

A good manufacturing unit is the basis for research work. There is no use in creating excellent test values in laboratory if the parameters and conditions can not be transferred to production. Therefore, some of the leading European aerospace research units have purchased units capable for production work for their R&D purposes, also, Figure 41.

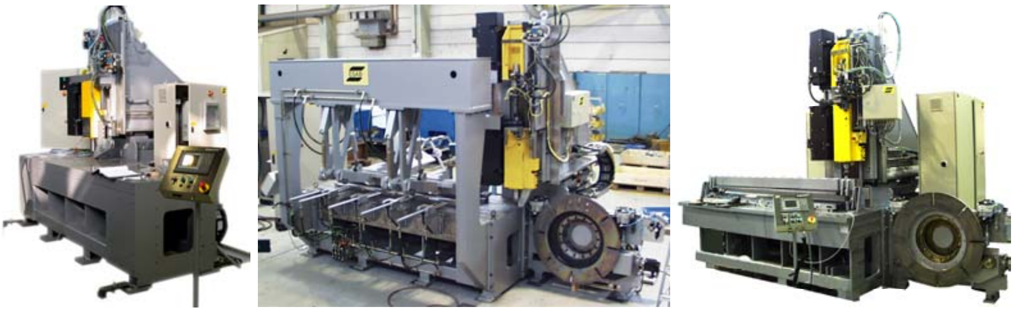


Figure 41. Research and prototype manufacturing units at, from left: EADS Ottobrunn in Germany, EADS together with Institute d'Soudure in France and Alenia Spazio in Italy.

4.6. Application examples

4.6.1. Loudspeaker frames

B&O's BeoLab 2 subwoofer is an excellent example of innovative thinking in aluminium construction. The cast subwoofer halves are joined together by friction stir welding, which results in no heat-induced deformations in the final product, and a solid structure which is good for acoustics.

Figure 42. B&O loudspeaker frame where friction stir welding is used to join the two halves together. © Temponik

4.6.2. Cooling blocks

This cooling block is used in a heavy-duty cutting machine. Instead of using one very big extrusion, the new design is to join together two profiles into one. The penetration depth on the weld is approximately 15 mm.

Figure 43. Cooling block from a heavy-duty cutting machine. ©ESAB

The following Figure (Figure 44) shows an alternative solution for attaching cooling fins together to form a cooling element. The possibilities are numerous – just free your mind!!

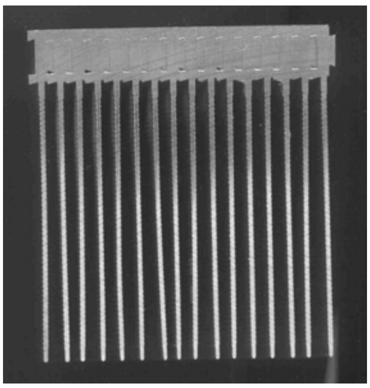


Figure 44. A potential application for welding cooling fin packages.

5. Are the welds really as good as promised?

A great number of applications have been presented in the previous chapters. It is quite obvious, that the resulting weld quality is excellent. Low quality welds would never be accepted in space!

As a summary, Table 1, a collection of published test results for various aluminium alloys is presented. Weld ratio is ca. 20% higher than for respective arc welds.

Table 13. Collection of tensile test results for various aluminum alloys.

Material	*Condition*	*t (mm)*	*Yield strength, $R_{p0,2}$ (Mpa)*	*Tensile strength, R_m (Mpa)*	*Elongation, A5 (%)*	*Weld ratio*	*Source*
2024-T3	FSW	4,0	304	432	7,6	0,87	Biallas G, et. al 1999
2024-T3	FSW	1,6	325	461	11	0,98	Biallas G, et. al 2000
2024-T3	As-welded		310	441	16,3	0,9	Magnusson & Källman 2000
2024-T3	Solution heat treated and aged		302	445	14,5	0,9	Magnusson & Källman 2001
2024-T351	Base material	6,4	310	430	12		
5083-0	base		148	298	23,5		TWI
5083-0	FSW		141	298	23	1,00	TWI
5083-H321	Base		249	336	16,5		TWI
5083-H321	FSW		153	305	22,5	0,91	TWI
6013-T6	Aged to T6		h253	291	8,3	0,75	Magnusson & Källman 2002
6082-T4	Base		149	260	22,9		SAPA profiles AB
6082-T4	FSW		138	244	18,8	0,93	SAPA profiles AB
6082-T4	FSW + heat treatment		285	310	9,9	1,19	SAPA profiles AB
6082-T6	Base		286	301	10,4		TWI
6082-T6	FSW		160	254	4,85	0,83	SAPA profiles AB
6082-T6	FSW + heat treatment		274	300	6,4	1	SAPA profiles AB
7108-T79	Base		295	370	14		
7108-T79	FSW		210	320	12	0,86	
7108-T79	FSW and aged		245	350	11	0,95	TWI
7475- T76	as welded		381	465	12,8	0,92	Magnusson & Källman 2003
7475- T76	Solution Heat treated and aged		476	512	10	0,97	Magnusson & Källman 2004

In many applications fatigue design is one of the main criteria used. Friction Stir Welded joints have proven to have good fatigue properties compared to corresponding MIG welds (Figure 45).

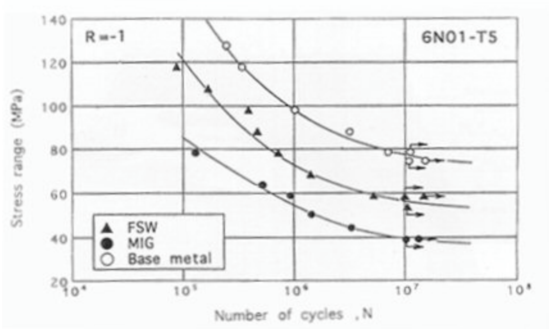


Figure 45. Fatigue curves of 6N01-T5 welds. (Kumagai & Tanaga 2002)

5.1. Heat Input

To calculate heat input in arc welding is one of the most important issues when preparing welding procedure specifications (WPS) for production. In friction stir welding, the traditional components – current and voltage – are missing. Therefore, trials to calculate generated heat must hail from the tribology, as proposed in the following Equation.

Equation 1. Heat input calculation in friction stir welding.

$$Q = \frac{\mu_{coefficientoffriction} * F_{downforce[N]} * v_{radialvelocity\left[m/s\right]}}{v_{weldingspeed\left[mm/s\right]}} = \frac{\mu_k * F_{[N]} * n_{1/s} * \phi_{shoulderdiameter[m]}}{v_{\left[mm/s\right]}} \left(J/mm\right)$$

Heat from the pin represents 2-20% of the generated heat and the rest comes from the shoulder.

6. Economics

One of the key issues when considering implementing friction stir welding in production is always money. How to justify the investment and show a reasonable return on the investment? As far as friction stir welding is concerned, the conventional way of looking at costs directly related to joining process and considering ways to reduce them is not applicable. It would be easy to state that any friction stir investment creates savings in the amount of welding wire and shielding gases not used, for example. This logic does not take one very long. The principle in calculating the return for any industrial investment should be looked at from at least the following three perspectives in order to create a sound base for the short- or long-term decision-making.

1. Payback calculated as a time period,
2. IRR – Internal rate of return, and
3. Profitability index.

The first is the simplest and most common method used. It measures how long it takes for the expenditure on an investment to be recouped and the investment will be accepted or rejected dependent on whether this is within the company's required payback period. This, however, does not take into account the time value of money or the cash flows after the payback period.

The IRR method discounts cash flows based on the companies required rate of return and equates the present value of the cash outflows associated with an investment with the sum of the present value of the cash inflows accruing from it. If the net present value of the investment is greater than 0 the investment is generating more than the company's required rate of return and is therefore viable although may be rejected due to the fact that alternative investments yield a higher return.

The profitability index (PI) is calculated by dividing the present value of future cash flows by the cost of the initial investment. If the PI is greater than/equal to one, the project is viable but again may be rejected if alternative projects produce higher PI's.

No matter which of the above methods of calculating the investment is chosen, the main issue is: Is the company capable of introducing additional positive cash-flow either through significant cost reductions or increased capacity to justify the investment?

If a company assessing a project bases its decision on reducing production costs then for friction stir welding cost reductions associated with the process would include:

- simplified pre-weld work – only degreasing of the plates needed
- no welding consumables nor shielding gas used
- no need for worker protection against open arc or welding fumes
- low energy consumption
- straight and dimension accurate products after welding – no need for time consuming and difficult straightening work

If a company is assessing a project based on increasing capacity then these cost reductions as well as the additional profit from the increased capacity of the plant directly associated with the investment should be considered.

There are no hard and fast rules, which can be applied when assessing an investment. Different methods will be applied according to the individual company's reasons for investing in capital. The same applies to the sales price of the FSW-users end products – there are different market prices in different markets. Therefore, everyone should do their homework locally in order to be able to make realistic investment calculations.

6.1. Example of cost calculation

Since people tend to be relatively lazy if not pushed constantly, to create a cost calculation model based on the ideas introduced in Table 14, Table 15, Table 16 and Table 17 is quite a challenging task. Therefore, in the following Tables an idea of calculating costs (notice!) related to friction stir welding is tried. But, please, keep in mind that this is just the beginning. Now you get an idea of costs of running an equipment and making welds. To make the investment profitable, you still need to sell your products and get paid enough to cover the costs. Please, notice also that the cost calculation is assuming full pace production. Make a realistic estimation of the total annual volume and base your sales price estimations to those like shown on

Table 14. Theory vs. practise. What really is needed in any company are the salesmen who make sure that there is enough volume to justify lower sales prices. As clearly seen from the cases below, the realistic production volumes are essential when justifying investments.

	Optimal case	***Probable case***
Number of 6 meter welds per annum	5 486 units	500 units
- costs / unit - add mark-up of 30%	41.35 €	41,35€*11 = 454,85
Net sales price per /tank (6 welds)	355 €	3 898 €

Table 15 . Investment residual value, welding capacity and additional cost calculations.

year	1	2	3	4	5	6	7	8	9	10
Investment cost	400 000									
Depreciated value / year	75 200	61 062	49 583	40 261	32 692	26 546	21 555	17 503	14 212	11 540
Residual value	50 000									
Number of useful years	10									

Welding capacity calculations

					in hour	in one-shift	in a week	in a month	in a year
- fixing and clamping prior to welding	3	min	number of finished welds		2,86	22,86	114,29	457,14	5485,71
- cleaning with alcohol 0,5 min / m	3	min							
- welding speed	0,5	m / min	(for AA5xxx series in 5 mm thickness; for AA6xxx welding speed of 2 m/min)						
"arc time"	12	min	meters of weld / year		**32 914** m				
- plate removal	3	min	capacity / year		**5 486** longitudinal welds in 6 m length				
	21	min							

Factory overheads **22 000**

- work floor costs (rental or equivalent)	12 000	(typically 120 € / m^2 in industrial parks) footprint needed for equipment 100
- share of S&A overheads / year	10 000	(sales and admistration, office overheads, telephone, etc.)

Other costs

- energy cost / kWh	0,03	(average 30 € / MWh, can vary drastically during the year - 0,03 € / kWh)
- salary incl. overheads	50	€ / h
- tool costs / tool	1 000	€ (useful lifetime of 1 tool 2000 m)

Table 16. Cost / welded meter.

Fixed costs / year	114 200,00 €
- depreciation (year 1.)	75 200,00 €
- factory overheads	22 000,00 €
- service contract	17 000,00 €
Variable costs / unit	20,54 €
- energy costs / h (consumption 0,2 kW/m)	0,04 €
- labour costs / unit	17,50 €
- tool	3,00 €
Welded meters in a product (= 1 N)	6 m

N [units]	Total costs	€ / m	economies of scale	€ / m
1	114 221	19 037		
2	114 241	9 520	114 233	9 519
4	114 282	4 762	114 266	4 761
8	114 364	2 383	114 331	2 382
16	114 529	1 193	114 463	1 192
32	114 857	598	114 726	598
64	115 514	301	115 251	300
128	116 829	152	116 303	151
256	119 457	78	118 406	77
512	124 714	41	122 612	40
1024	135 229	22	131 023	21
2048	156 258	13	147 846	12
4096	198 315	8	181 492	7
8192	282 431	6	248 785	5
16384	450 662	5	383 369	4

Table 17. Summary of the costs and sensibility analysis when welding 5 mm thick AA5xxx series. If the material to be welded was changed to AA6xxx and welded at the speed of 2 m/min, the resulting cost / meter would be ca. 4,20 €.

Summary / year 1		**sensitivity analysis** *welding speed +10%*	*labour costs +10%*	*investment -10%*
Welding Capacity / year	32 914 m	34 718	32 914	32 914
(6 meter long welds)	5 486 units	5 786	5 486	5 486
Fixed costs	114 200 €	114 200	114 200	103 440
Variable costs	112 655 €	113 567	122 255	112 655
Cost / meter	6,89 €	6,56	7,18	6,57
Cost / unit	41,35 €	39,36	43,10	39,39

6.2. Compared to Arc welding

Among the readers of this document are always people who are not that well updated on different ways of joining materials. Therefore – as a simple comparison the following tables.

Table 18. Time needed to weld 1 meter on AA6082-T6 using MIG or FSW.

AA 6082-T6	t = 5 mm	t = 5 mm	t = 10 mm	t = 10 mm
One sided welding	MIG	FSW	MIG	FSW
Preparation	V – groove, 60°	-	-	-
Cleaning with alcohol	-	0,5 min/m	-	0,5 min / m
Brushing prior to welding	2 min / m	-	2 min/m	-
Welding current	200 A	-	200/250 A	-
Shielding gas	Ar	-	Ar	-
Welding speed	0,5 m/ min	2 m/ min	0.6/0,3 m/ min	1,0 m / min
Consumable	OK 18.16 ∅1,2 mm	-	OK 18.16 ∅1,2 mm	-
Number of runs	1	1	1+1	1
Total time / one meter of weld	**4 min**	**1 min**	**7 min**	**1,5 min**

Table 19. Time needed to weld thick aluminium plates using FSW or MIG welding.

	t = 15 mm	t = 15 mm	t = 15 mm	t = 15 mm
	AA5083-O	AA5083-O	AA6082-T6	AA6082-T6
One sided welding	MIG	FSW	MIG	FSW
Preparation.	V – groove, 60°	-	V – groove, 60°	-
Cleaning with alcohol	-	0,5 min / m	-	0,5 min / m
Brushing prior to welding	2 min / m	-	2 min / m	-
Pre-heating 150 °C	10 min / m	-	10 min / m	-
Welding current	Root run 240 A Filling runs 260 A	-	Root run 240 A Filling runs 260 A	-
Shielding gas	Ar30/He70	-	Ar30/He70	-
Welding speed	0,46 / 0,14 m / min	0,15 m / min	0,46 / 0,14 m / min	0,50 m /min
Consumable	OK 18.16 ∅1,6 mm	-	OK 18.16 ∅1,6 mm	-
Grinding between runs	8 min / m	-	8 min / m	-
Grinding for root opening run	5 / min	-	5 / min	-
Number of runs	1 + 1	1	1 + 1	1
Total time / one meter of weld	**34 min**	**7,2 min**	**34 min**	**2,5 min**

N.B. normally the FSW panels and most other parts are delivered as welded, no grinding, no straightening and no cleaning afterwards

7. Conclusions

Friction stir welding is here to stay. The process has shown its' capabilities and been approved as a novel method for joining of aluminium and other metals. By friction stir welding totally new areas of welding are being explored everyday. The existing construction and structural details are improved with this welding process which leaves the weld "cold". The properties of the welds are in some cases on the same level as those of the base material if proper cautions are taken.

Anyone who is using aluminium today, could also be using friction stir welding. It is within every ones reach and it is merely a question of daring to use it and getting rid of the smoke and spatter typical to arc-welding instead of process being not suitable. Just dare to use it!

8. ESAB Reference List

Customer	Country	Equipment	Year (Order)	Remarks
Marine Aluminium	Norway	1 machine	1996	Horizontal panels
The Boeing Company	USA	1 machine	1997	Basic + circumferential
The Boeing Company	USA	1 machine	1998	Horizontal, longitudinal
The Boeing Company	USA	1 machine	1998	Vertical, longitudinal
The Boeing Company	USA	1 machine	1998	Vertical, longitudinal
SAPA	Sweden	1 machine	1999	Double heads
SAPA	Sweden	1 machine	1999	Horizontal, panels and profiles, three heads
The Boeing Company	USA	1 machine	1999	Bobbin tool lab unit
The Boeing Company	USA	1 machine	2000	Circumferential + Plug Welding unit
Tower Automotive	USA	1 machine	2000	Universal,.basic, double heads
Hydro Aluminium Profiler	Norway	1 machine	2000	Motor housings + longitudinal
The Welding Institute, TWI	U.K.	1 machine	2000	Gantry, laboratory
DanStir ApS	Denmark	1 machine	2001	Gantry,.laboratory and job shop
EADS / Institute d'Soudure	France	1 machine	2001	Basic+circum-ferencial+ RPT + Bobbin tool
EADS	Germany	1 machine	2001	Basic laboratory
Swedish Nuclear Fuel and Waste Management Co.	Sweden	1 machine	2002	Circumferencial, 50 mm copper
Alenia Spazio S.p.A.	Italy	1 machine	2002	Basic +circum-ferencial + RPT + Bobbin tool
KMT Tekniikka Oy	Finland	1 machine	2003	LEGIO 5UT 6000 mm welding length, pro-duction machine
MPA, University of Stuttgart	Germany	1 machine	2004	LEGIO 3 ST 1000mm Lab unit
Krunichev Space Center	Russia	1 machine	2004	LEGIO 5 U 1000mm, Lab unit

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