

The background of the page is a close-up photograph of a friction stir welding process. A central, polished metal tool (the stirrer) is shown in the process of joining two metal plates. The tool is positioned vertically, and its tip is in contact with the metal. The metal plates are held together, and a bright, glowing area at the point of contact indicates the heat and friction generated during the welding process. The lighting is dramatic, highlighting the metallic surfaces and the intense heat at the weld site.

Friction Stir Welding

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Introduction to the FSW Technical Handbook

Friction Stir Welding (FSW) was invented by Wayne Thomas at TWI (The Welding Institute), and the first patent applications were filed in the UK in December 1991. Initially, the process was regarded as a “laboratory” curiosity, but it soon became clear that FSW offers numerous benefits in the fabrication of aluminium products.

Friction Stir Welding is a solid-state process, which means that the objects are joined without reaching melting point. This opens up whole new areas in welding technology. Using FSW, rapid and high quality welds of 2xxx and 7xxx series alloys, traditionally considered unweldable, are now possible.

In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two pieces of sheet or plate material. The parts have to be securely clamped to prevent the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the workpieces causes the latter to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticised material,

transferred to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling, a solid phase bond is created between the workpieces.

Friction Stir Welding can be used to join aluminium sheets and plates without filler wire or shielding gas. Material thicknesses ranging from 0.5 to 65 mm can be welded from one side at full penetration, without porosity or internal voids. In terms of materials, the focus has traditionally been on non-ferrous alloys, but recent advances have challenged this assumption, enabling FSW to be applied to a broad range of materials.

To assure high repeatability and quality when using FSW, the equipment must possess certain features. Most simple welds can be performed with a conventional CNC machine, but as material thickness increases and “arc-time” is extended, purpose-built FSW equipment becomes essential.

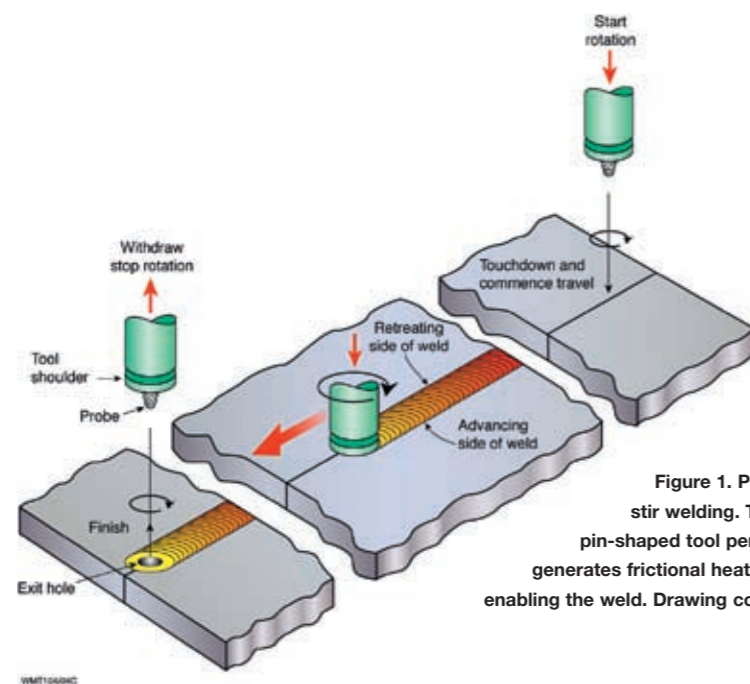
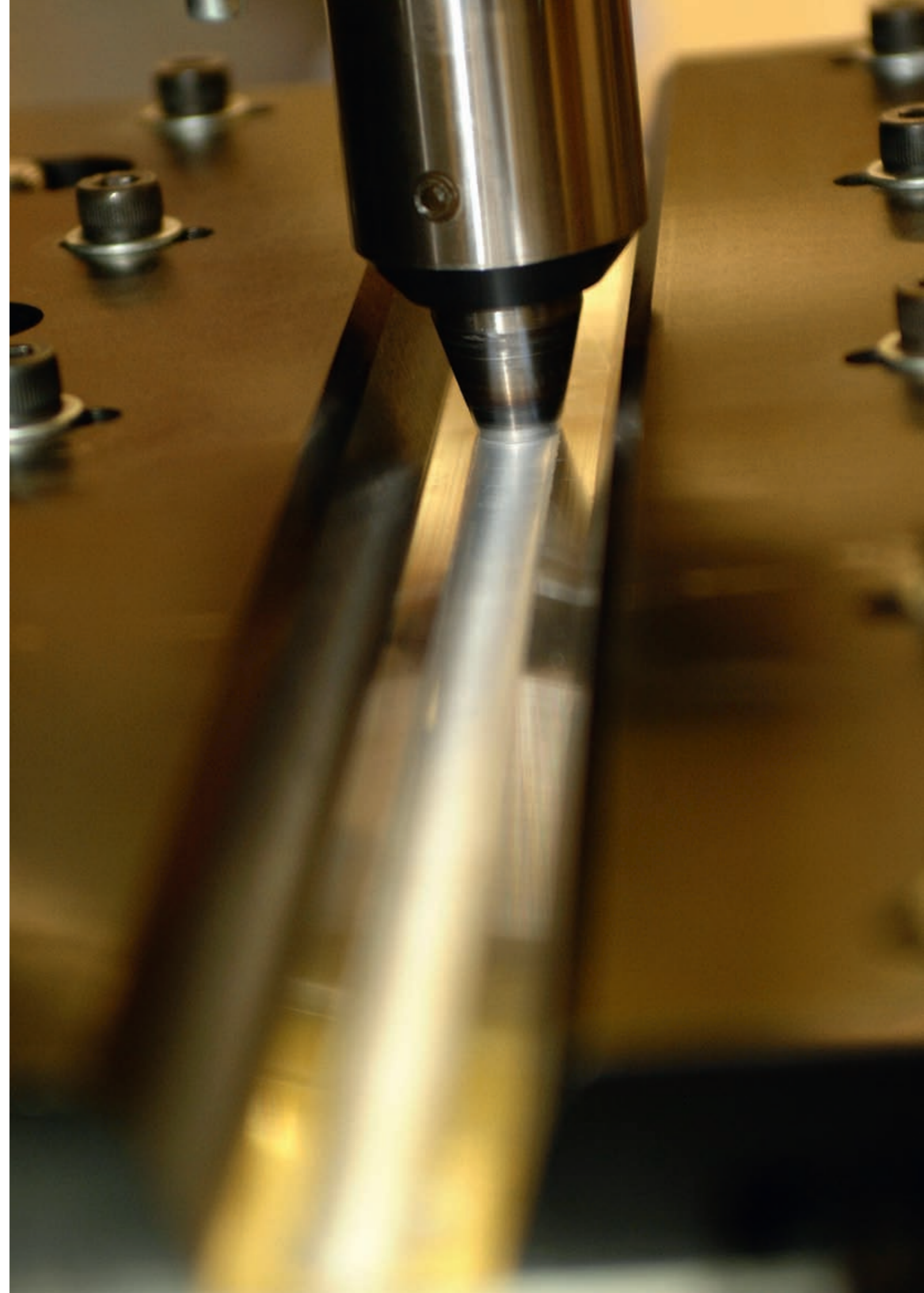


Figure 1. Process principle for friction stir welding. The rotating non-consumable pin-shaped tool penetrates the material and generates frictional heat, softening the material and enabling the weld. Drawing courtesy of © TWI.



Process principles

Weldable alloys

In terms of high-temperature materials, FSW has been proven successful on numerous of alloys and materials, including high-strength steels, stainless steel and titanium. As what is weldable refers to the material by which the welding tool is made and how the process is applied there are really no limits to what can be achieved. Improvements on the existing methods and materials as well as new technological development, an expansion is expected.

Process characteristics

The FSW process involves joint formation below the base material's melting temperature. The heat generated in the joint area is typically about 80-90% of the melting temperature.

With arc welding, calculating heat input is critically important when preparing welding procedure specifications (WPS) for the production process. With FSW, the traditional components – current and voltage – are not present as the heat input is purely mechanical and thereby replaced by force, friction, and rotation. Several studies have been conducted to identify the way heat is generated and transferred to the joint area. A simplified model is described in the following equation:

$$Q = \mu\omega FK$$

in which the heat (Q) is the result of friction (μ), tool rotation speed (ω) down force (F) and a tool geometry constant (K).

The quality of an FSW joint is always superior to conventional fusion-welded joints. A number of properties support this claim, including FSW's superior fatigue characteristics. Figure 3 clearly demonstrates the improved performance of FSW compared to a MIG-welded joint on the selected base material.

Tensile strength is another important quality feature.

Table 1 shows a collection of published results from tensile strength tests.

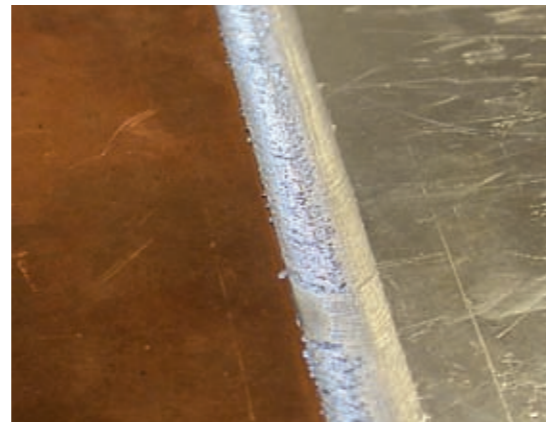
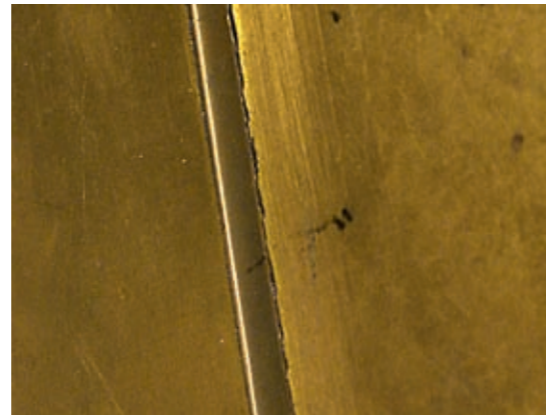
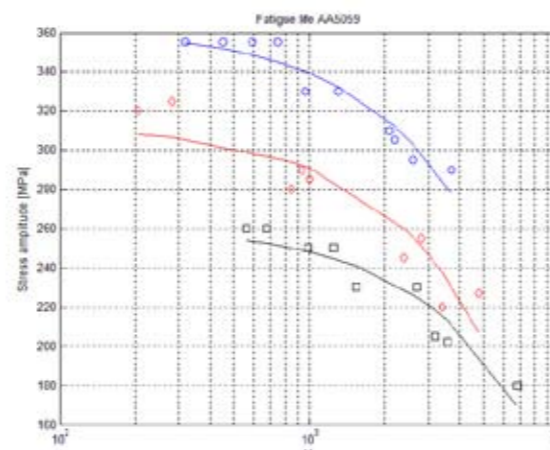


Figure 2. Brass, as well as mixed copper/aluminium joints, can be friction stir welded. © ESAB



Blue = base material Red = FSW Black = MIG

Figure 3. Fatigue life evaluation of AA5059.

Material	Condition	t (mm)	Yield strength, Rp0,2 (Mpa)	Tensile strength, Rm (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	FSW		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	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	FSW		381	465	12.8	0.92	Magnusson & Källman 2003
7475-T76	Solution heat-treated and aged		476	512	10	0.97	Magnusson & Källman 2004

Table 1. Collection of tensile test results for various aluminum alloys.

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

Table 2. Main process parameters in friction stir welding.

Alloy group	Temperature range in °C
Aluminium alloys	440...550
Magnesium alloys	250...350
Copper alloys	600...900
Carbon and low-alloy steels	650...800
Titanium alloys	700...950

Table 3. Welding temperature range of various alloys.

Welding parameters

In providing proper contact and thereby ensuring a high quality weld, the most important control feature is down force (Z-axis). This guarantees high quality even where tolerance errors in the materials to be joined may arise. It also enables robust control during higher welding speeds, as the down force will ensure the generation of frictional heat to soften the material.

When using FSW, the following parameters must be controlled: down force, welding speed, the rotation speed of the welding tool and tilting angle. Only four main parameters need to be mastered, making FSW ideal for mechanised welding.

Tools

Welding tool design is critical in FSW. Optimising tool geometry to produce more heat or achieve more efficient "stirring" offers two main benefits: improved breaking and mixing of the oxide layer and more efficient heat generation, yielding higher welding speeds and, of course, enhanced quality.

The simplest tool can be machined from an M20 bolt with very little effort. It has proved feasible to weld thin aluminium plates, even with tooling as simple as this,

although at very slow welding speeds. However, tool materials should feature relatively high hardness at elevated temperatures, and should retain this hardness for an extended period. The combination of tool material and base material is therefore always crucial to the tool's operational lifetime. Table 3 illustrates the forging temperature range of different alloy groups. Note what useful tools forging tables are in the FSW context.

Design principles

The simple pin-shaped, non-profiled tool creates frictional 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, welding heat at the lower part of the joint may be insufficient.

With parameter adjustment and tool geometry optimisation, the oxide-layer could be broken more effectively. The need to generate more frictional heat and break the oxide-layer more effectively has been a driving force in tool development for light-metals. In Figure 4 different pin-tools are displayed showing differences in shape, size and geometric features, to match the needs of specific applications. Tool materials for mild and stainless steel have been added to the list. Figure 5 illustrates some standard tools trademarked by TWI (The Welding Institute). Triflute MX™ has proven to be a very capable multipurpose tool for welding all aluminium alloys.

Tools for steels

To apply FSW in steel or other high-temperature materials, the difficulty is mainly associated with finding proper tool material; a material that can withstand the high temperatures that are experienced during the process. Resistance to wear (durability) is one important aspect, especially as many of the intended applications are considered critical; hence there can be no traces of the tool left in the seam. One of the most promising tool materials so far is the so called PCBN



Figure 4. Pin-tool geometries for FSW tools.

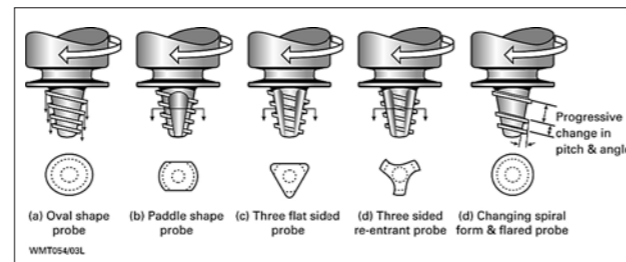


Figure 5. Some of the basic tool shapes for friction stir welding. © TWI.

(polycrystalline cubic boron nitride), which is manufactured by MegaStir (Figure 6).

Retractable pin tool

The Retractable Pin Tool (RPT) or Adjustable Probe Tool is a machine feature in which the pin of the FSW tool may be moved independently of the tool's shoulder. This permits adjustments of the pin length to be made during welding, to compensate for known material thickness variations or to close the exit hole of the weld.

The advantages of RPT may be summarized as follows:

- Ensures full root closure of the weld
- Increases joint quality properties at the exit
- Increases the joint's aesthetic properties.

This feature is available for the ESAB LEGIO™ and SuperStir™ units.



Figure 6. Tools for welding steels. Tip material is polycrystalline cubic boron nitride (PCBN).

Bobbin tool

The bobbin tool employs a technique that enables double-sided welding. The solution is a special designed tool, consisting of two shoulders, one on each side of the workpiece to be joined. The two elements of the tool are connected with the pin, which here runs through the material.

Bobbin tool welding can be applied in several ways, but there are two main alternatives:

- Fixed bobbin tool, in which the distance between the two shoulders is fixed.
- Self-reacting bobbin tool, in which a retractable pin feature allows the distance between the two shoulders to be adjusted during the weld.

There are, of course, benefits and drawbacks with both solutions. The first offers a simple mechanical solution (for the welding head), as the tool differs in no way from a conventional FSW tool at the tool interface. In contrast, the second allows us to control the contact conditions for the two shoulders independently, to compensate for variations in material thickness.

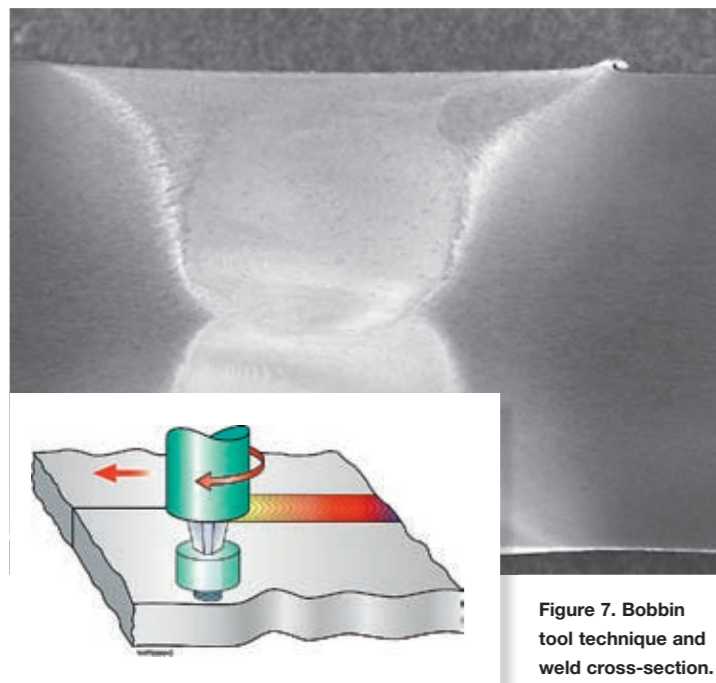


Figure 7. Bobbin tool technique and weld cross-section.

Initiating a bobbin weld either involves first drilling a hole in the material in which the tool is inserted, or by employing a run-on preparation of the material. The end of the weld is normally welded through, leaving the exit un-bounded, for removal at a later stage.

The bobbin tool is typically used to join extruded profiles, where the technique eliminates the need for a backing bar or advanced fixtures.

To summarize the advantages of bobbin tool welding, we find:

- No backing bar needed.
- Less complex fixtures.
- No root flaws from incomplete penetration.
- Less (or zero) down force needed.

Process speed

Not so long ago, one of the main “excuses” for not using FSW was the claim that its welding speed was too slow for production, even though the mechanical properties of FSW welds outclass conventional joining processes for aluminium. The typical stated welding speed for 5 mm AA6082 was between 250 mm/min and 400 mm/min. This was typical for a CNC machine, not designed for the high down forces needed in FSW or the high travel speeds. With production machines, welding speeds for the above-mentioned alloy are (and have been for a number of years) almost ten times higher – with 2000 mm/min a typical production speed when joining extruded profiles.

In a medium-size welding workshop (between 200 and 400 blue-collar workers), time spent in welding and related functions represents roughly 15% to 20% of total manufacturing time. This suggests three alternatives for improving productivity:

1. increase the welding speed of conventional processes (GMAW, GTAW),
2. introduce a new welding process that offers a speed similar to conventional arc welding but that generates significant cost savings in other aspects of production, or

	Yield strength $R_{p0.2}$	Ultimate tensile strength, R_m	Hardness HV	Elongation
AA 6082 T6, AlSi1MgMn	260 MPa	310 MPa	95	9 % (A5)

Table 4. Mechanical properties of commercial alloy AA6082 T6.

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 5. Welding parameters.

Welding speed	$R_{p0.2}$ [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

Table 6. Summary of the test results on 5 mm AA6082 T6. The test results are based on an average of three tests (bending test only one sample).



Figure 8. Etched microstructure of AA6082 welded with inadequate “heat input” in the root of the joint.

3. introduce FSW, which welds 3-4 times faster than GMAW and generates significant cost savings at a later phase of the production process.

Alternative number 3 is the most attractive, of course.

A number of companies have chosen this alternative, for improved economy and increased production capacity. A Norwegian shipyard has reduced production time for a 60-m long catamaran hull from ten to six months, boosting capacity by 40%. This yielded cost savings of 10%, equivalent to 10% of total fabrication costs. These savings derive from three different improvements: 2% to 3% due to improved extruded profile designs and the use of friction stir welded panels, 4% to 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 conducted at the ESAB Friction Stir Laboratory in Laxå Sweden, noting welding speeds of up to 6 m/min on materials thicker than 1 mm. The test results were achieved on 5 mm AA6082 alloy. The mechanical properties of the base material are presented in Table 4 and the test data in Table 5.

As can be seen, the properties of the welds are fairly similar but, surprisingly, the mechanical properties are improved by some 4-5% by welding faster (compare 1 m/min. to 3 m/min.). As the welding speed is further increased, the mechanical properties remain excellent, although there is a slight deviation increase in tensile strength. This is mainly due to the reduced parameter box as speed is increased. Smaller and smaller variations in welding conditions may affect the quality more easily. Figure 8 shows a typical welding fault experienced when welding outside the scope of the parameter box. The stirring was not good enough and has caused a fault on the root side of the weld. Since the heat input is further decreased as the welding speed is increased, there is a risk that welds can be “too cold”. Total control of welding parameters is essential to ensure a solid, defect-free weld at high speeds.

From the hardness curves (Figure 9), it can be seen that the curves for 1 and 6 m/min are almost identical. The curve for 3 m/min samples differs slightly, even though taken from the same batch. This is an excellent example of tolerance variation, which can sometimes exist even within the smallest batches. The joint hardness profile recorded for samples of unwelded base material welded at 1, 3 and 6 m/min was 112, 102 and 115HV respectively.

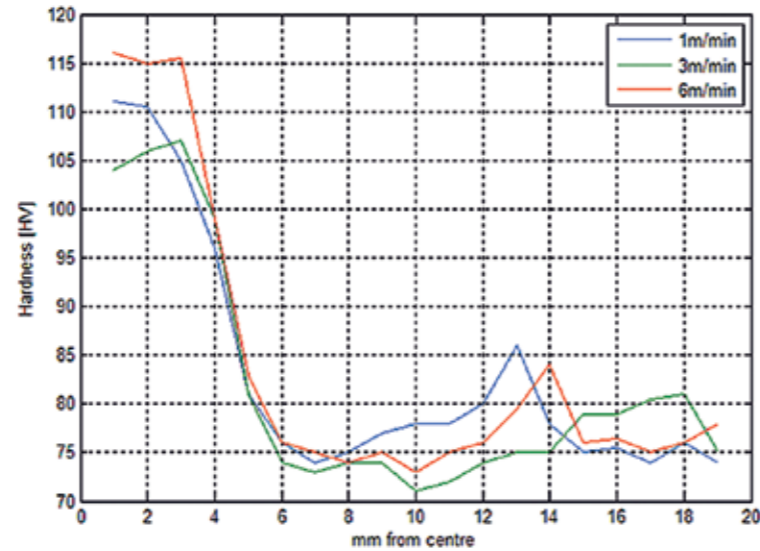


Figure 9. Hardness profile across the weld joint at welding speeds of 1, 3 and 6 m/min. Base material: 5 mm AA6082.

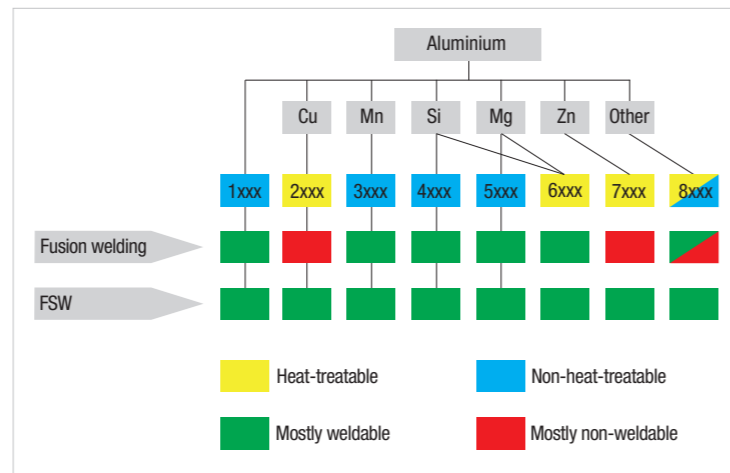


Figure 10. Weldability of various aluminium alloys. ©TWI

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 7. Designation system for wrought 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

Table 8. Designation system for cast aluminium alloys.

Temper designations

"F" "as fabricated"

No special control of thermal or strain-hardening conditions.

"O" "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** - 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 transform the alloying elements into a 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 (overaged)
- 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

Aluminium

As an engineering alloy, aluminium has been competing with steel for several years now. It is approximately three-times lighter and three-times “weaker” (elastic modulus 70 GPa), with a thermal co-efficient three-times higher than steel (the rule of three threes). To avoid unnecessary reduction in strength, however, weight savings must often be compensated through improved design.

High thermal conductivity combined with the protective oxide-layer of aluminium makes fusion (e.g. MIG) welding of this type of alloy difficult. The oxide-layer must be broken and removed and heat applied rapidly, to avoid unnecessary thermal expansion of the products. FSW avoids such problems.

Table 7 through 9 feature a summary of a designation system for wrought and cast aluminium alloys, together with temper designations. These are commonly used designations in the aluminium business.



Application areas

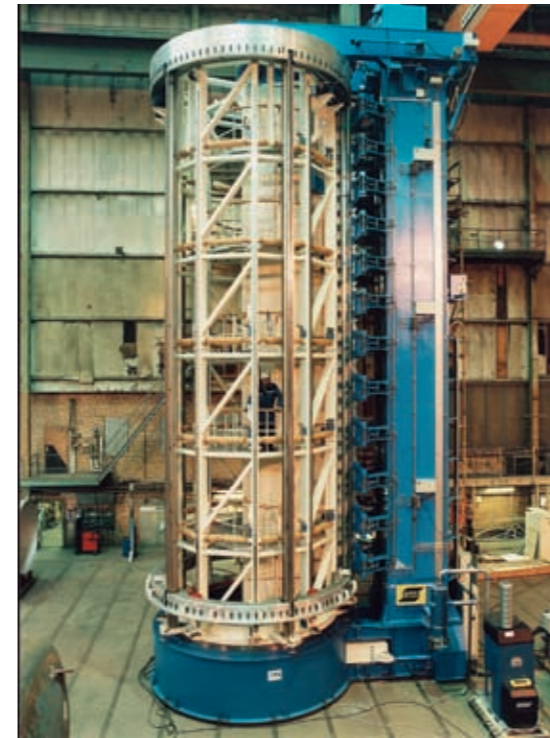


Figure 12. Longitudinal welding machines for joining of machined isogrids, vertically and horizontally. Previously, these segments were joined using MIG or VPPAW (Variable Polarity Plasma-Arc Welding) technology.

Figure 11. Nobel Peace Centre, Oslo Norway. The canopy is a temporary installation by David Adjaye that serves as a gateway between Oslo City Hall where the Peace Prize Ceremony takes place and the Nobel Peace Center. The canopy has been manufactured with the FSW process. Photo: Timothy Soar / Adjaye Associates.

Sector	Main Applications	Substitutes
Electrical	Busbars	Copper
	Transformers and generators	Copper
Transportation:		
Automobiles	See Table 10	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

Table 9. General application areas of aluminium and some of its substitutes.

Aerospace

Space industry

Friction stir welding was first introduced to a larger, general public at the Schweissen & Schneiden Fair in 1997. The equipment displayed is shown in Figure 13. It was later purchased by The Boeing Company for research and laboratory use. Besides the laboratory machine, Boeing has been a real pioneer in introducing FSW into industrial manufacturing. In the Delta II and IV programs, FSW has been widely adopted and used for manufacturing rocket-fuel tanks, Figure 12.



Figure 13. SuperStir™ #1 - first friction stir welding machine introduced to general public 1997 at the Schweissen & Schneiden Fair. Currently used at Boeing laboratories for research and development work.

Production time for a typical tank has been dramatically reduced and a number of cost savings have been achieved. At about 20% of the cost of riveting, FSW offers surprisingly significant cost gains. Not just at the Boeing Company, but almost anywhere aerospace or civil aviation equipment is being manufactured, FSW production technology is being considered for future designs. A number of different applications in the commercial and military aircraft industry are under evaluation, including carrier beams, floors and complete fuselages and wings (Eriksson, 2001).

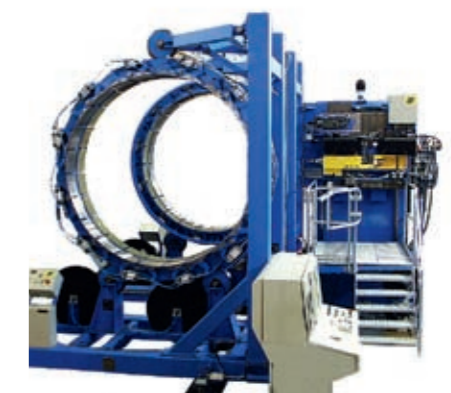


Figure 14. Circumferential welding machine, featuring Bobbin Tool and Plug Welding technology.

Civil aviation

The main rationale for employing FSW (or welding in general, for that matter) in the manufacture of aerospace components is weight savings, which translate directly into cost savings. Reducing weight enables higher speeds and/or reduced fuel consumption.

Friction Stir Welding not only eliminates rivets and fasteners, but the need for an overlap sheet configuration. The butt-joint configuration also facilitates joint evaluation and quality assurance, because a homogeneous joint with full penetration eliminates crack formation.

The fact that FSW offers the means to join previously unweldable Al-Li (e.g. AA2195) alloys has attracted growing interest from the civil aeronautics and aerospace industries. High strength and low weight is always a desirable combination. When allied to a robust welding method, this opens a whole new field of possibilities.

Approval by the FAA (Federal Aviation Association), which has certified the friction stir welding process as a

joining process for aircraft, signifies a major breakthrough in the field of civil aviation. The Eclipse 500 business-class jet is one example where FSW is used in the production of civil aircraft.

Aerospace R&D

Many may believe that the traditional metals for airframe structures are being pushed aside by the recent advances in composites. Major breakthroughs have certainly been achieved in these alternative materials, but important ongoing R&D, in which FSW plays a vital role, continues. Several such R&D programmes are funded by the European Commission.

The great mechanical properties of FSW have always been the key justification for adopting the process. Research, driven primarily by the aerospace industry, has shown that post-weld ageing treatments can even improve these properties. In one example, material welded according to T4 status (heat-treatment), then aged to T6 status, regained 100% of the parent material's ultimate tensile strength.

The maturity of the technique has led to broader acceptance within companies such as EADS and Boeing, where FSW is now a qualified and certified process. Numerous applications are being considered, for both thin and thick sections of aluminium. Given its elimination of the need for fasteners, the future looks bright for ongoing development of FSW in the aerospace industry.

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

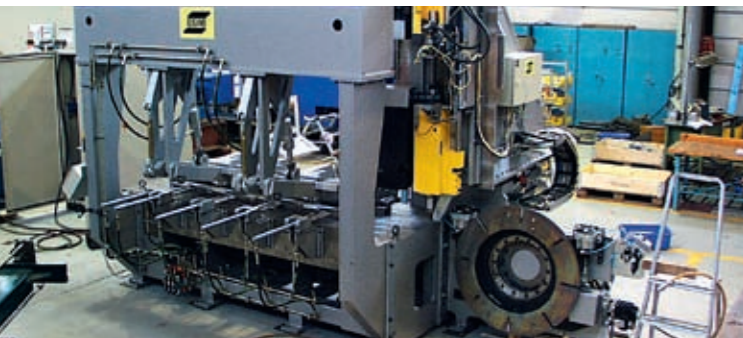


Figure 15. Research and prototype manufacturing units at EADS in association with L'Institute d'Soudure in France, Alenia Spazio in Italy and EADS Ottobrunn in Germany.



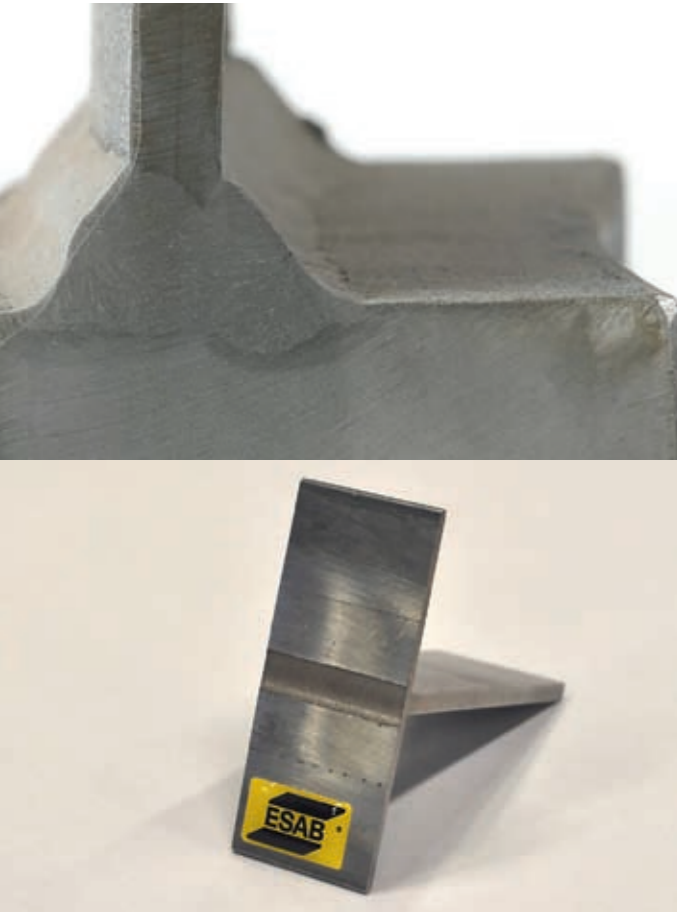


Figure 16. A traditional fillet joint versus FSW T-joint geometry.

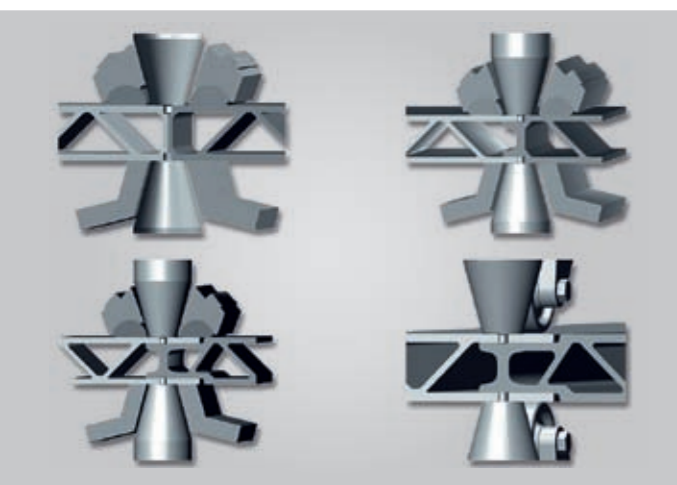


Figure 17. Designs which make it possible to weld hollow profiles.

Shipbuilding

Application advances

Imagine a large catamaran that can be constructed from building blocks, just like a toy boat. All the pieces would fit perfectly together, ensuring mastery of dimensional accuracy and simplifying any necessary modifications. FSW represents a first step towards this type of construction approach in shipbuilding.

The low heat input during joining assures less residual stress, resulting in precisely welded components that require minimal fit-up work. The resulting savings, both in time and money, are obvious. This offers users of FSW pre-fabricates a clear competitive advantage, although documented data on actual savings is seldom reported. However, the following gives an idea of how panel producers (Midling) can benefit from the production of friction stir welded pre-fabricated panels:

- Industrial production featuring a high degree of completion.
- Extended level of repeatability, ensuring uniform level of performance, quality and narrow tolerances.
- The flexible production equipment and capacity permits customized solutions without compromising delivery reliability.
- The completed panel units have been inspected and approved by classification authorities such as DNV, RINA and Lloyd's Register.
- The panels' high degree of straightness ensures easy assembly at the yard, reducing the need for manual welding.
- Less supplementary work for the customer, such as floor levelling and preparation for floor coverings, offering major cost savings.

Parts and components

One of the most attractive features of friction stir welded products is that they are ready-to-use. Normally, time consuming post-weld treatment such as grinding, polishing or straightening is not needed. With proper design, the elements are ready-to-use directly after welding. However, it is important to keep in mind that designs intended for MIG or TIG welding are not necessarily suitable for FSW. A fillet-joint geometry, often applied with MIG, may not be suitable for FSW, for which T-joint geometry is much more suitable (Figure 16).

One limiting factor, often mentioned when discussing FSW, is the relatively high down-force needed when performing the weld. One issue is the machine's capacity to apply such a high force, another is its ability to support and firmly clamp the workpiece. With a traditional butt-joint a backing bar supports the root side of the joint. The surface finish should be of high quality, as the aesthetic properties of the root side of the joint will follow the backing bar.

Another solution to the fixture issue is to modify to an 'FSW-friendly' design, eliminating the need for a backing bar. One application where such an approach is appropriate is in the manufacture of extruded profiles (Figure 17).

When producing large components, like walls or floors, panel straightness is not the only

issue to consider: the resulting reflections are also important. A lot of time is spent polishing and "making-up" surfaces, that are architecturally visible. In FSW prefabricated panels, the reflections derive merely from the surface appearance of the aluminium plates and profiles in the as-delivered state, not from the reflections caused by welding heat input. One of the earliest examples of a product where FSW was extensively used is shown in Figure 19 – Catamaran made by Fjellstrand AS, using extruded and FS welded profiles, produced by Marine Aluminium AS.

One excuse for not using aluminium has always been "it's not as strong as steel." True – and not true. It depends on the alloy used, of course, and surprisingly there are aluminium alloys that are as strong or even stronger than steel. "ALUSTAR", for example, has yield and tensile strengths comparable to S235 low-alloyed steel. AlCu4SiMg (AA2014) – an alloy typically used in aerospace applications – is significantly stronger than alloys in the 5xxx and 6xxx series, typically used in shipbuilding. *Some of these alloys have never been used in shipbuilding, because of their poor weldability!* With friction stir welding, some of these barriers can be overcome. Imagine using the strong AA7021 alloy for making aluminium floor panels even thinner, generating weight savings by "thinking differently".



Figure 18. Flat panel field after welding. Instead of using wide profiles, the panel is made from relatively narrow (120 mm) extrusions. ©ESAB



Figure 19. The first vessel in world history made from FS-panels was built by Fjellstrand AS in 1996. The panels were made by Marine Aluminium. This was what actually kick-started the industrialisation of the process.



Figure 20. FSW LEGIO™ 3UT installed next to the aluminium ship hull production line at Estaleiros Navais do Mondego S.A. shipyard in Portugal, 2002.



Figure 21. 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-teknikka OY, Finland, December 2003.

In Figure 10, the weldability of various aluminium alloys is shown as a reminder. The typical alloys used in shipbuilding are from the 5xxx series, due to their good corrosion resistance, or from the 6xxx series, due to their strength. Other combinations of these two alloys are also possible, of course (Larsson et al. 2000).

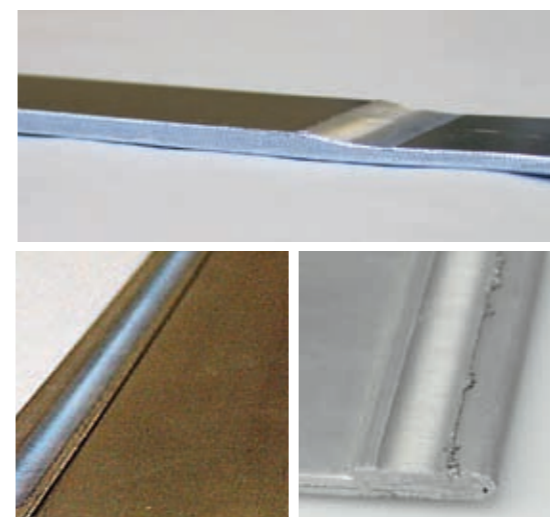
Figure 20 gives an idea of relatively easy implementation of FSW in shipbuilding. ESAB's new LEGIO™ concept is ideal for fabrication of small batches of friction stir welded panels. The equipment is placed in the workshop right next to the assembly of the ship's hull. The picture is from Estaleiros Navais do Mondego S.A. Shipyard in Portugal. Even small batches can be effectively welded on-site.



Figure 22. Fully automatic manufacturing cell for production of car components. ©SAPA, Sweden.



Figure 23. 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 indicates a poorly stirred oxide-layer, not a crack.



Automotive industry

The automotive industry, featuring large manufacturing batches, six sigma requirements and challenging material combinations, from wrought and cast aluminium to magnesium alloys, provides a perfect field for FSW applications. One good example is illustrated in Figure 22, which shows a fully automated ESAB SuperStir™ machine for the welding of seat frames at SAPA, Sweden. The cycle time is less than one minute per seat, using dual welding heads.

Welding speed depends on the alloy to be welded and tool geometry. However, speeds up to 6 metres/minute on 5 mm AA6082 are possible. The alloys, which are sensitive to heat, actually tend to demonstrate better mechanical properties when welded rapidly, since changes in the chemical composition of the material are avoided. Alloys which are difficult to join using conventional arc-welding processes can often be joined by FSW. This offers numerous possibilities, as in the construction of military vehicles.

Overlap and butt joints can be welded in all positions, as well as mixed welds (different thicknesses or different materials – the 5000 to 6000 series, for example). Even cast aluminium components are easily welded. The microstructure and homogeneity of the cast material improves significantly when FS welded. The porosity that is typically present in castings disappears. Figure 23 shows an etched surface on a T-joint between two cast plates. The microstructure of the stir-zone is much finer-grained than the relatively coarse cast plate material, which is typical with FSW.

Joining components of different thicknesses or dissimilar alloys is a very demanding task when utilising arc or beam welding processes. With FSW, plates of different thicknesses can be joined securely with a high quality weld (Figure 24.) Overlap joints are also possible with FSW, providing an alternative solution to resistance-spot-welded or seam-welded pieces. An excellent alternative to spot-welding to achieve a watertight seal may be seen in Figure 24.

Figure 24. Possible automotive applications for friction stir welding: mixed joint between two thickness (1+2 mm), overlap joint on 1 mm thickness and folded seal weld. ©ESAB.

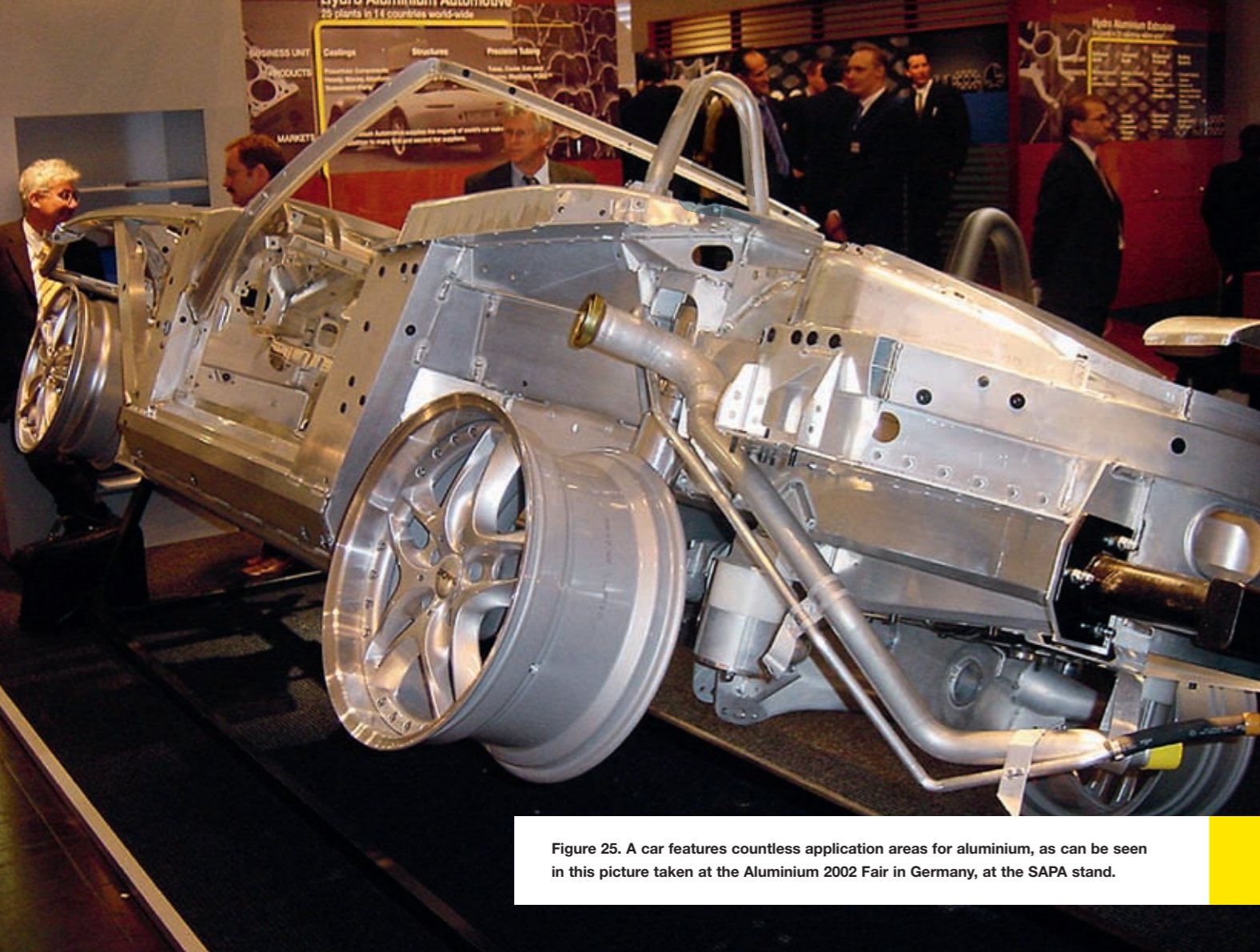


Figure 25. A car features countless application areas for aluminium, as can be seen in this picture taken at the Aluminium 2002 Fair in Germany, at the SAPA stand.

Automotive applications

In principle, all aluminium components in a car can 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, dashboards, roll-over beams, pistons, etc. Minor modifications to the structure may be needed in order to make it more suitable for FSW, but these should not be insurmountable.

In larger road transport vehicles, the scope for 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 25), fuel and air containers, toolboxes, wheels, engine parts, etc.

The ESAB SuperStir™ unit shown in Figure 26 was delivered to Tower Automotive in 2000. The machine is designed for making a large profile from two or three extrusions. The welded profile is then cut into smaller widths to form a lightweight suspension link.



Figure 26. ESAB SuperStir™ unit at Tower automotive.

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

Table 10. Aluminium alloys typical for the automotive industry and its respective application areas (Irving 2000).

The machine is equipped with two separate welding heads for simultaneous welding from top and bottom, to ensure symmetric heat distribution and avoid “root” problems. As the heat is generated on both sides, this is the fastest and most effective way to use FSW. The time-consuming plunging operation (penetration of the material) is halved (half the plate thickness), with heat generated on both sides.

Tower lists the benefits of FSW 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 27. A longitudinal FSW weld in a rectangular profile. Beams can be manufactured with minimal distortion.



Figure 28. Suspension links by Tower Automotive.

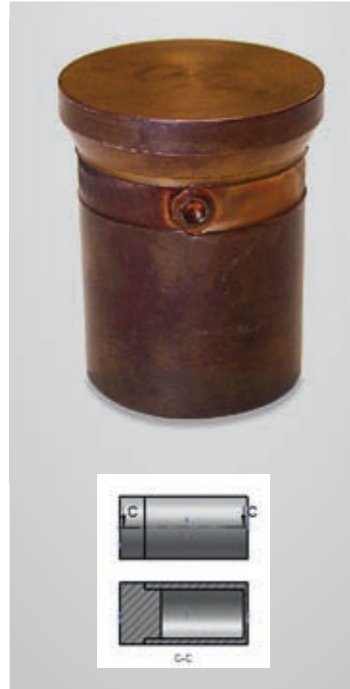


Figure 29. A butt and overlap weld of circular canister.

Another application for suspension components is a three-piece suspension arm on the BMW 5-series (Sato et. al, 1998). In their case study, they have been able to improve the properties of the suspension arm. Some of the main areas of interest for such a component are of course weight, and road noise reduction capabilities. In this particular application, it was noticed that the heat imparted to the ball joint portion during welding did not exceed 120°C, leaving the rubber bellows attached to this component unaffected.

Welding aluminium wheels was one of the earliest automotive applications for FSW. FSW was first used for longitudinal welding of aluminium tube, which was later cut to the proper length and spin-formed to the right shape. Hydro in Norway has used FSW in attaching the inner rim to the wheel form (Figure 29). The butt and overlap welds can be fabricated in wrought and/or cast materials (Johnson et al. 1999).

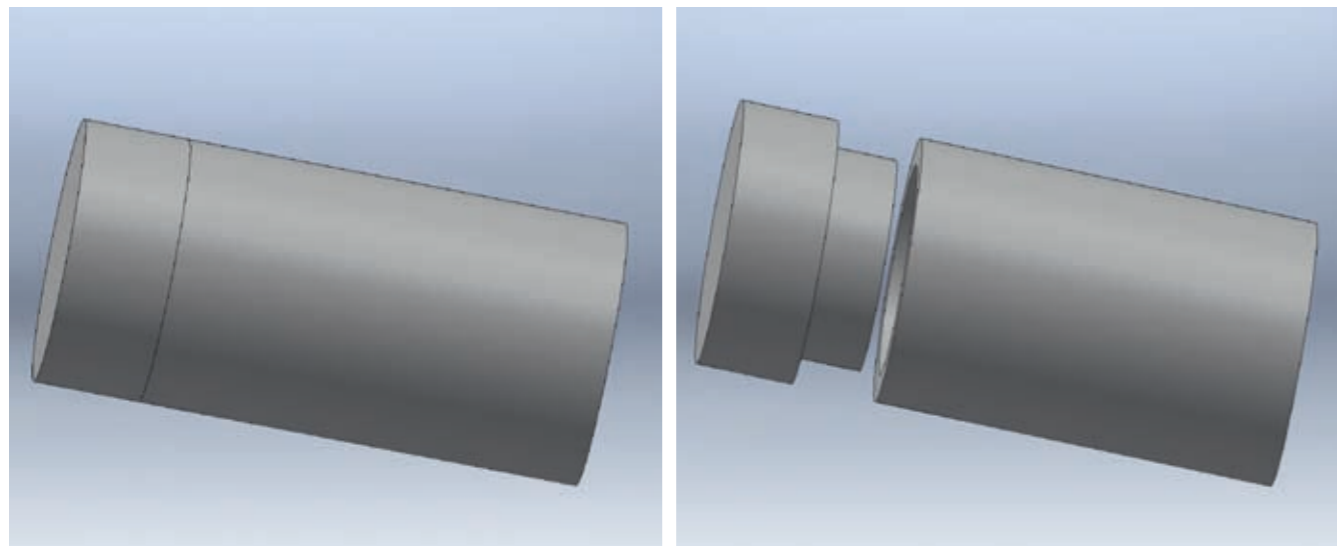
Cast aluminium components can successfully be friction stir welded or processed to improve the quality of the cast structure, or to join

inserts in the piston. In Friction Stir Processing there is no “weld joint”, but the tool travels on the material and stirs it and 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 improved product quality is shown in Figure 30.

More and more aluminium is used in transport vehicles to lower “dead load” and increase payload. The ever increasing awareness of environmental issues has also placed pressure on weight reduction in many road applications. A lorry offers countless potential applications for FSW – mainly straight linear welds in the x-y plane, with easily weldable materials and thicknesses typically of up to 5 mm. Replacing conventional arc welding joining processes with FSW can lead to a dramatic improvement in panel straightness and reduce assembly times to a minimum.



Figure 30. A friction stir processed piston. The metallographic structure was clearly improved after friction stir processing.



Tower on the press (Aluminum Now, 2003):

Ford suspension link the first US 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 US 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. These 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 aluminum series,” says Art Scafe, Tower’s product development manager 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 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.”





AA 5754 H22	Yield strength	Tensile strength	Elongation
1.0 mm plate:	$R_{p0.2} = 130 \text{ N/mm}^2$	$R_m = 248 \text{ N/mm}^2$	$A_{50mm} = 18\%$
2.0 mm plate	$R_{p0.2} = 122 \text{ N/mm}^2$	$R_m = 227 \text{ N/mm}^2$	$A_{50mm} = 17\%$

No porosity! No undercut or lack of penetration!

Table 11. Mechanical properties of the plates shown on Figure 31. © ESAB

Figure 31. Tailor-welded blank on AA5754 H22, employing thicknesses 1 and 2 mm. Welding was carried out using a fixture featuring an inclined table at a speed of 6 m/min. © ESAB



Tailor welded blanks (TWB's)

Combining different alloys and/or different thicknesses represents one of the most interesting areas in automotive joining applications. Laser and laser-hybrid welding have achieved a relatively unchallenged predominance in the joining of steels and stainless steels, but FSW offers considerable potential for aluminium joining.



Figure 32. Machined heat zinc for electrical components to be used for e.g. automotive applications.

Superplastic forming

The next step in exploitation of FSW as a welding process will be in superplastically-formed products, as already demonstrated by Aston Martin in their Vanguard model. This technique often goes hand in hand with the manufacturing of tailor-welded blanks, and some applications are already available for manufacturing door components. In superplastic forming, pressurised gas is employed to impart the product's final shapes. Connecting welds are sited in relatively simple positions, using simple plate shapes. When gas pressure is applied, the final shape of the structure is formed.

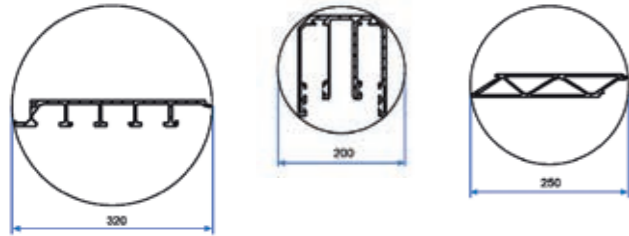


Figure 33. Typical extrusion widths for open, half-open and hollow profiles.



Figure 34. Fully automatic panel welding equipment at SAPA, Sweden. The equipment features three welding heads – two on the upper side, one on the lower side.



Figure 35. An extruded profile designed for friction stir welding.

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

Welding of two or more narrow extrusions to create a single broader extrusion is a classic FSW application. The first industrial-scale equipment to utilise this concept in full was delivered to Marine Aluminium, Norway, in 1996. The equipment has been in constant use ever since and has produced hundreds of thousands of metres of defect-free welds.

Maximum and minimum size limits apply to the various extrusions, according to their hollow profile (open, half-open or closed). This poses challenges concerning the optimal balance, technically and economically. Conglin Aluminum Corp in China has a 10.000 MT press capable of manufacturing extrusions up to 970 mm in width. These extrusions are used in constructing the Levitation Train scheduled for service between Shanghai Airport and the city of Shanghai (Aluminium Extrusion, 2002). Plants capable of this size of extrusion are very rare. The more typical widths for commercially available extrusions are shown in Figure 33.

To achieve high productivity in joining profiles requires a “gentle giant”, powerful and robust equipment that ensures extremely accurate control of the welding forces and position of the tool. Multiple welding heads also promote increased productivity and reduced cycle times. Figure 34 shows fully-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 to almost double welding capacity, starting from the middle and welding outwards, upper and lower heads being used to weld both sides of a double skin panel. The welding length of 14.5 metres enables the production of very large components used in the manufacture items such as rolling stock and heavy goods vehicles.

To weld extrusions into wider plates or join hollow-profiles, the design of the profiles must be adapted to the requirements of the friction stir welding process. The main criterion is the ability to withstand the welding forces without suffering collapse or buckling. A profile designed for the GMAW process can be welded much more easily when adapting for FSW.

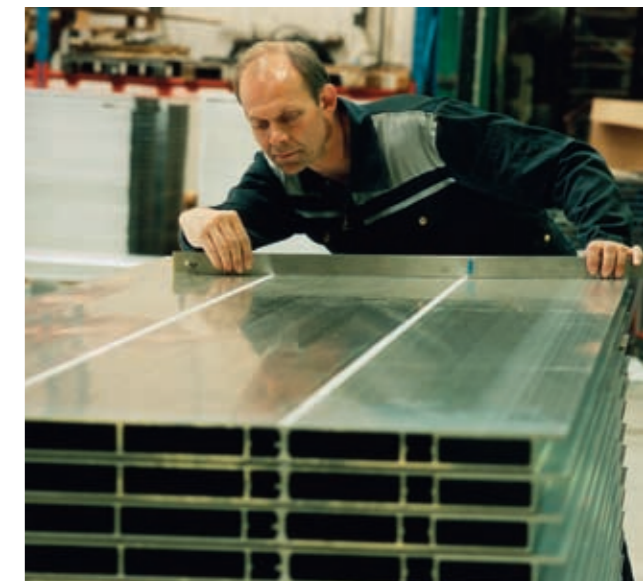


Figure 36. Shinkansen train. Friction stir welding is employed for the floor panels.

Manufacturers of rolling stock (rail cars and train carriages) are extremely keen to use FSW to manufacture a range of components. Alstom LHB, for example, has used FS welded floor and wall panels supplied by Hydro Marine, Norway, since 2001, in the construction of its suburban trains (Kallee et al. 2002). Hitachi of Japan, another train-industry pioneer, has used friction stir pre-fabricated floor elements for its Shinkansen trains (Figure 36). Here too, the profiles and extrusions must be designed for FSW. An example of an FSW profile design is shown in Figure 35. The thickness of the weld area, as well as the radii on the corners, demonstrate the know-how that some extruders have started to accumulate, even if they do not friction stir weld themselves. The extrusion market offers clear opportunities for future business.

Figure 37 shows a quality inspection being performed on panels welded using large panel machines featuring simultaneous welding with one upper and one lower head. The flatness is incredible!

Figure 37. Perfectly flat hollow profiles inspected after welding at SAPA, Sweden.



Steel and other High Temperature Materials (HTM)

Introduction - Weld characteristics of High Temperature Materials (HTM) FSW

The weld quality of steels exposed to FSW is much the same as that of aluminium. Both involve a solid-state joining process that produces a fine grain microstructure and, because of the low heat input, the HAZ shows less degradation.

Steels that are considered unweldable can be joined with full penetration in a single pass. They are a bit more complicated than aluminium, as the phase transformations can be complex. Different metallurgical properties can be achieved by varying the process. When applied to an HTM alloy, the FSW process will also require a liquid-cooled tool holder and the addition of a shielding gas (Ar).

The variables that govern the FSW process are temperature, load, tool travel speed, spindle RPM, tool design, tool thermal conductivity, material flow stresses, material thermal conductivity, the melting point of the material and the heat transfer characteristics of the system. Aluminium alloys can be friction stir welded using a broad range of process parameters because of their low strength, high ductility and high thermal conductivity. Successful FSW of ferrous, nickel base and other high melting temperature alloys requires careful control of the process variables discussed above.

Weldable materials

A number of high melting temperature alloys have been successfully joined using FSW. Many other applications are still to be explored. Alloys already successfully joined using FSW include:

1. Carbon steels, including high strength steels, pipe steels, and Dual-Phased/TRIP steels
2. Stainless steels, including Super Duplex, Super Chrome and Ferritic. These alloys exhibit a refined grain structure in the weld zone. Friction Stir Welding of these alloys offers numerous benefits, such as
 - Critical Pitting Temperature (CPT) is 20° C higher than arc-welding processes
 - FSW does not introduce harmful intermetallics
 - FSW retains the proper ratio of austenite and ferrite

- FSW does not form excessive amounts of martensite
 - FSW creates a matching fusion zone without reinforcement
3. Ni-based alloys
 4. Other non-weldable alloys.

System components for HTM FSW

To weld high temperature materials such as ferrous, nickel base and titanium alloys is merely a question of finding the proper tool materials that can withstand the high temperatures (approx. 1200° C) and high forces experienced during welding in all axes (Z and X- or Y-axis). The tool must also be designed to produce consistent weld properties and maintain high abrasion resistance

Polycrystalline Cubic Boron Nitride (PCBN) is used for the tip of the tool because of its thermal stability, hardness and strength at elevated temperatures. PCBN is classified as a super-abrasive material and is fabricated in a two-step ultra high temperature/high pressure (UHT/HP) process. CBN is the second hardest known material and its synthesis mimics the graphite to diamond conversion process. PCBN's low coefficient of friction minimizes material adhesion to the tool surface during FSW and reduces spindle horsepower requirements. The high thermal conductivity of PCBN reduces temperature gradients within the tip and helps minimize temperature gradients and residual stresses in the base metal being welded. The high hardness values of PCBN limit tool abrasion during the FSW process. Fracture toughness values of PCBN are low relative to metals but the polycrystalline nature prevents cleavage planes and minimizes crack initiation sites. An insulating material is used between the PCBN tip and the tungsten carbide shank to maintain the proper amount of heat at the tip.

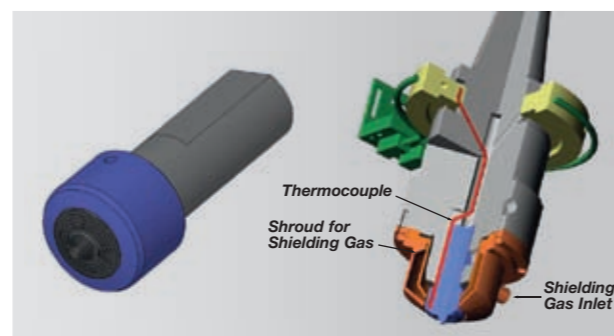


Figure 38. HMT FSW Pin Tool and Weld Head assembly.

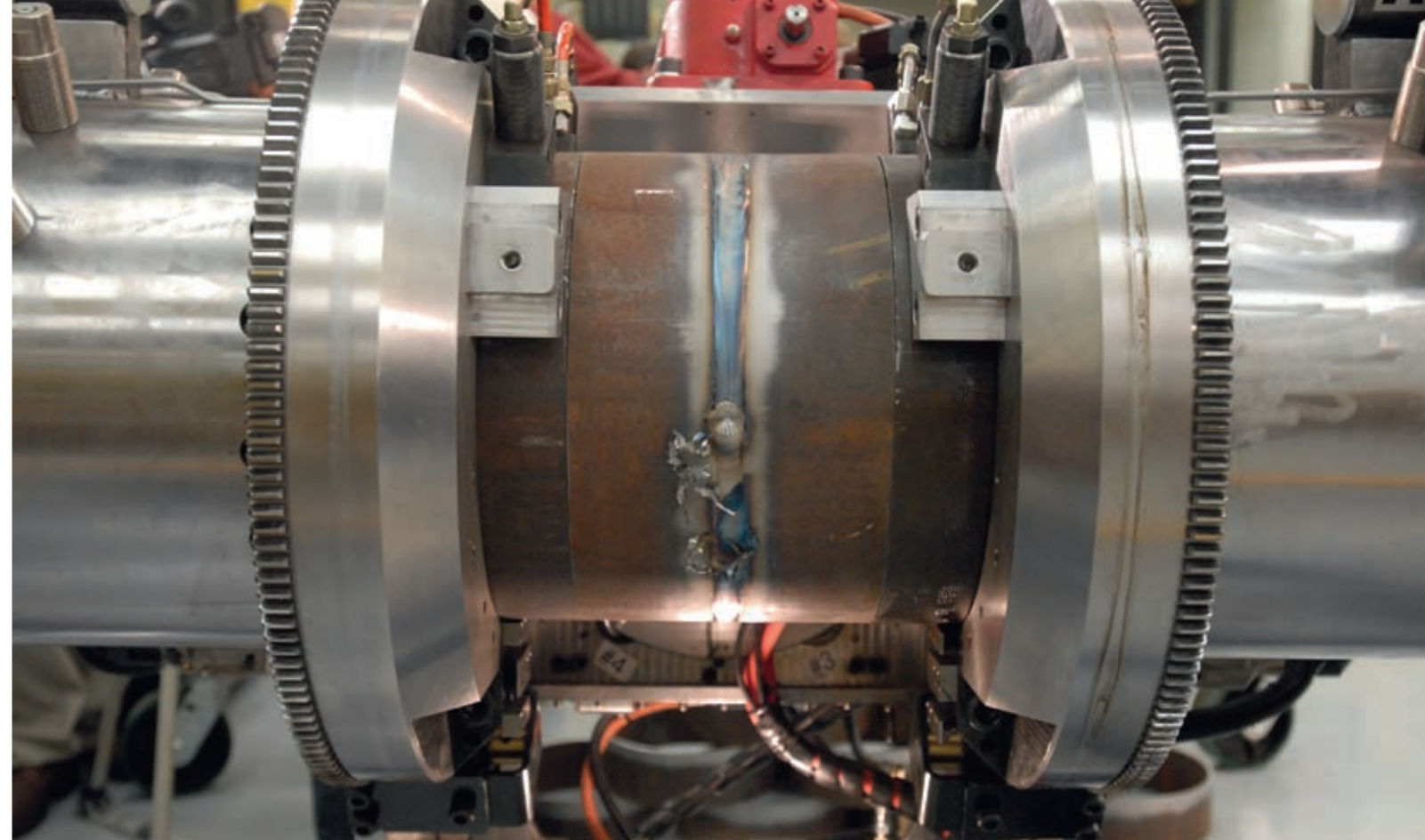


Figure 39. Orbital friction stir welding of steel pipe.

In addition to the HTM FSW tool, a patented temperature control assembly has been designed to function with any rigid load control machine to friction stir weld HTM alloys. Two additional components make up this system including a liquid-cooled tool holder, and a telemetry system consisting of a transmitting or telemetry collar and loop antenna. The liquid-cooled tool holder manages heat removal from the FSW tool and protects the machine spindle bearings. The telemetry system is a wireless temperature acquisition system required for continuous real time temperature data control, thereby prolonging tool life and indirectly managing the target material temperature.

Applications

Potential winning applications include:

Oil and gas - With the development of portable equipment specific to FSW, orbital welding can now perform girth welds for land and offshore pipelines in the field. This further enables this useful technology to be applied for pipe welding where welding repair and direct costs are high. From a mechanical capability standpoint, FSW welding of up to 1/2 inch (12.7mm) maximum on X65 - X100 steels is highly repeatable and development is currently underway to expand this capability for X120 up to 3/4 inch (19 mm). For the pipeline industry in particular, FSW is advantageous because, compared to conventional fusion welding

processes such as arc and laser welding, FSW is highly energy efficient, with reduction in energy usage by 60 to 80% not uncommon. FSW offers better weld quality because it is immune to the welding defects caused by solidification in fusion welding. It offers high weld joint strength, is a highly productive method of welding and can join dissimilar materials and composites:

Nuclear & Refinery - where low-corrosion stainless steel closure welds are required.

Drill Pipe Casing - where weld certifications are not a requirement and cost savings are high.

Friction Stir Processing and cladding of high melting temperature materials are also very attractive processes because base metal dilution problems are eliminated. Corrosion properties of the lap joint are much better than those found in arc welding processes, and the resulting weld shows excellent abrasion resistance and toughness. A lap joint simply consists of penetrating the top corrosion resistant material into the subsurface material. Due to its resultant high strength and lower hardness properties, HTM FSW has been shown to be a great joining process for *Coil Joining* where formed finished goods (i.e. tubes, stainless-steel sinks etc.) cannot tolerate fatigue related failures.



Figure 40. Copper canister with cast iron insert for nuclear fuel produced at SKB, featuring a lid sealed using ESAB Friction Stir Welding SuperStir™ equipment.



Figure 41. Cross section area of the FSW welded lid for the copper canister with a corrosion barrier thickness of 5 cm.

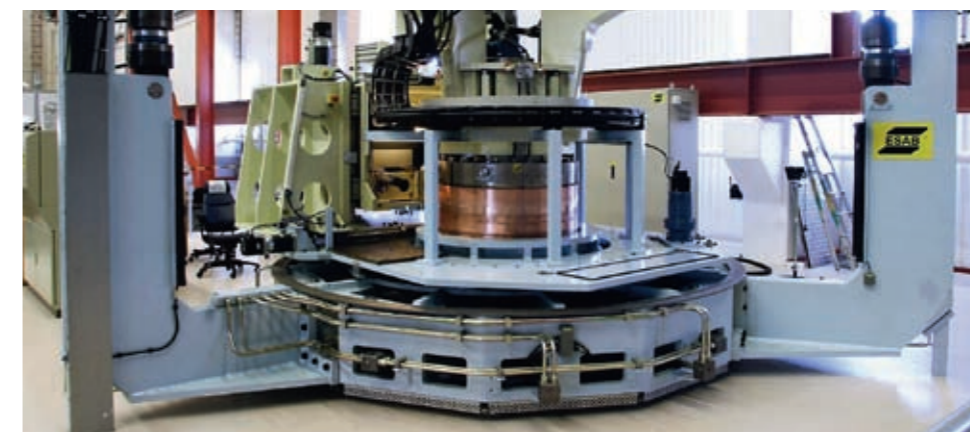


Figure 42. ESAB SuperStir™ installed and ready for welding in the Canister Laboratory at the Swedish Nuclear Fuel and Waste Management Co (SKB) in 2003.

As a result of the excellent quality and high integrity demonstrated by a large number of test welds over several years, SKB have selected friction stir welding as the welding method for this application in the encapsulation plant. ESAB's SuperStir™ equipment has proved the viability of Friction Stir Welding. It also demonstrates that ESAB is a reliable and professional partner and supplier of FSW equipment, possessing the highest levels of FSW competence, able to provide the advanced level of service essential when working with such complex and demanding applications. When it comes to sealing nuclear waste, only the best will do.

Reprinted with the permission of Swedish Nuclear Fuel and Waste Management Co (SKB), Oskarshamn, Sweden.

Application examples

Case study: Swedish Nuclear Fuel and Waste Management Co (SKB)

The Swedish Nuclear Fuel and Waste Management Co (SKB) has been tasked with managing Sweden's nuclear and radioactive waste since the merger of the country's nuclear power companies in the 1970s. In the almost 40 years since nuclear power has been generated in Sweden, much effort and R&D has been expended on finding a final repository for the waste and a reliable way of encapsulating and sealing the copper canisters of spent nuclear fuel, which must remain intact for some 100 000 years. The copper canisters (~ 5 m long) for spent nuclear waste are cylindrical, featuring a 5-cm-thick copper corrosion barrier and a cast iron insert for mechanical strength. The canister, with an outer diameter of 105 cm, must be sealed using a welding method that ensures extremely high joint quality and integrity. The only viable method when tests started in 1982, when

the canisters were being developed, was high power electron beam welding (EBW). In 1997, SKB decided to also investigate and evaluate a newly invented welding method for sealing the canisters: Friction Stir Welding.

In January 2002, SKB ordered an FSW machine from ESAB that was ready for welding at SKB's Canister Laboratory in Oskarshamn, Sweden, by April 2003. The production machine has an effect of 110 kW, making it one of the most powerful welding machines in the world. Even so, only 45 kW is actually used, to be able to control the heat input with extreme precision. Heat input and welding temperature are controlled using custom-built software, to ensure high reliability and repeatability. The challenges posed in welding this thick copper application are the high welding temperatures (up to 950° C), the high welding forces and the duration of the weld (up to one hour), placing severe demands on the tool (both in terms of the material selected for the probe and tool geometry).



Figure 43. ESAB SuperStir™ FSW equipment installed at Marine Aluminium for welding panels.



Case study: Marine Aluminium a.s, Norway

Marine Aluminium is one of the world's leading companies within the engineering, design and fabrication of aluminium structures and products for the offshore and shipbuilding industry, as well as other segments. With more than 50 years in the business, it offers special competence in material technology, extrusion tooling and welding techniques.

Marine Aluminium is located on the west coast of Norway, with easy access to the open sea. The site includes spacious indoor facilities for building and assembling a wide range of products, as well as a deepwater quay, enabling loading of large structures and modules.

During the autumn of 1995, the Marine Aluminium board discussed the possibility of broadening the company's manufacturing programme, preferably within the shipbuilding/offshore segment, and started looking for a new complementary aluminium product. Marine Aluminium visited ESAB in Laxå to discuss welding equipment for the production of aluminium panels using extruded profiles. During the visit, ESAB took the opportunity to demonstrate a new welding method called Friction Stir Welding, developed by TWI, in the UK. This demonstration led to the signing of a contract between Marine Aluminium and ESAB at the end of 1995.

In 1996, ESAB designed, manufactured, tested, installed, commissioned and placed in operation the first purpose-built FSW unit at Marine Aluminium's production facility in Haugesund, Norway. By adopting this unique process, Marine Aluminium is able to weld extruded aluminium profiles using friction, eliminating the need for shielding gas and filler material. The lower heat requirement for welding the profiles means less distortion, and the FSW technique produces panels with mechanical properties superior to their fusion welded counterparts.



Figure 44. A cruise ship, a typical application for FSW welded panels



Figure 45. An over-hull structure at Marine Aluminium.

Marine Aluminium is one of the few companies operating commercial-scale Friction Stir Welding units in Northern Europe. Continuous improvement in the technology in recent years has resulted in improved welding speeds, logistics and QA systems. The Friction Stir Welding machine, by welding several profiles together, can produce panels in thicknesses from 1.8 to 12 mm, up to a maximum size of 16x20 metres.



Equipment

Full-scale automation for high-volume applications

The ESAB SuperStir™ range is purpose-built for high-volume production of large aluminium panels, girders and trusses. These large custom-designed units offer a safe, clean and simple welding process that can be fully automated, dramatically reducing production costs.

Whatever your requirement – operator-controlled units for the workshop, fully-automated industrial scale units for the heavy engineering industry or robotic units for the components industry – ESAB Friction Stir Welding is the answer.

Modular flexibility for “standard” applications

A modular concept, the ESAB LEGIO™ system offers optimum flexibility and economy. Comprising five basic designs, available in seven sizes, this FSW system enables welding depths from 0.5–65 mm. Designed for “standard” applications, a broad range of supplementary equipment is available to further enhance flexibility. Combining the latest technology with proven quality, the modularity of the ESAB LEGIO™ concept makes the most varied friction stir welding applications possible – including small batches in varied sizes.

The S and U models are designed for ease of integration with larger fixtures, rotary units and exchangeable clamping systems. For the production of smaller workpieces, UT or ST models are recommended. These models have tables with pre-cut hole patterns, for attaching fixtures.

Robotised for more complex applications

Designed for complex joints, particularly in the aluminium 6000 series, the ESAB FSW robot system, Rosio™, features full integration of the Friction Stir Welding equipment, for flexibility and unrestricted reach up to 2.5 metres.

The latest IRC5 control system, featuring embedded force control, ensures high accuracy in-contact motion. The upgraded motion software permits linear welding in arbitrary patterns, as well as circular and square paths. Additional functionalities, to support customized path programming and spindle operation, permit advanced welding, even with limited programming skills. A user-friendly HMI extends the IRC5 interface, providing full operator feedback via a Flex Pendant.



Quality and environmental aspects

Environmental aspects of Friction Stir Welding

Today, any new industrial process needs to be thoroughly assessed regarding its impact on the environment. Careful consideration of HSE (Health, Safety and Environment) issues at the workplace is of crucial importance to any company currently investing in new processes. It is also increasingly common for manufacturers to monitor a product's environmental impact throughout its life cycle

Friction Stir Welding offers numerous environmental advantages compared to other joining methods. Furthermore, "green thinking" is cutting edge in the industrial sector and of considerable marketing value.

Less weld-seam preparation

Butt, overlap and blind welds are the main weld applications for the FSW process. To prepare the right bead configuration, workpieces featuring greater wall thicknesses often require a special cutting or milling process.

Fewer resources

The FSW Process needs no shielding gas and therefore no gas supply or plant investment such as pressure tanks, pipe fittings and gas regulators, as long as it is applied to low melting temperature materials such as aluminium.

No need for consumables, eliminating the need for their storage and transport inside the production area, and avoiding the need for their production elsewhere.

An FSW unit means less investment in the workplace. No need to protect workers/users against UV or IR radiation. The FSW process generates no smoke and, unlike arc welding processes (especially with aluminium), an exhaust system is not necessary.

Noise, an underestimated health threat

The commonest welding processes for aluminium are the MIG-pulse or TIG square-wave techniques. When used for workpieces of medium thickness, both processes require a lot of energy. Furthermore, the pulse or square-wave frequencies make noise protection for the worker a must, although this is often ignored.

Due to its electric spindle drive and hydraulic unit for axial pressure, an FSW unit generates consistently less noise, comparable to a standard milling machine.

Energy saving FSW process

When considering energy consumption, three factors must be assessed: how much energy is required to perform the weld, what is the total energy required to operate the machinery and ancillary equipment, and how much energy is required for post treatment (grinding and cleaning). Generally, FSW demands less energy input to the weld than MIG and TIG, but more than laser welding. Total energy input depends on the size of the equipment being used and the thickness of the joint, depending on whether single-pass or multi-pass welding is used. FSW is always single pass, offering the greatest energy savings at higher wall thicknesses.

Less post-treatment and impact on the environment

With most other welding processes, the weld requires weld and root reinforcement. In the latter case, this means grinding, with a negative impact on the workplace environment, as well as increased energy consumption and additional investment in equipment.



Figure 46. SuperStir™ installation at DanStir ApS, Copenhagen, Denmark.

Economics

A key issue to be addressed when considering implementing FSW in production is cost. How can the investment be justified, and how can a reasonable return be generated? When it comes to FSW, the conventional approach to cost assessment, where costs are related directly to the joining process and ways of reducing them, does not apply. The savings in welding wire and shielding gases when using FSW are obvious, of course. When calculating both the short and long-term return on such an industrial investment, however, any decision should take at least three factors into account.

1. Payback calculated over time
2. IRR – Internal Rate of Return
3. Profitability index.

The first is the simplest and most common method used. It measures the time it takes before expenditure on an investment can be recouped. Approval depends on whether this is within the company's required payback period or not. However, this ignores the value of money over the period and the cash flows after the payback period.

The IRR method discounts cash flows based on the required rate of return and equates the present value of 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 required rate of return and is therefore viable. Of course, it may be rejected if 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. Yet again, this conclusion may be rejected if alternative projects produce higher PI's.

No matter which of the above methods is chosen, the main question remains the same. Can the company introduce additional positive cash-flow, either through significant cost reductions or increased capacity, to justify the investment?

For a company seeking to reduce production costs, FSW offers the following cost-reducing benefits:

- simplified pre-weld work – plate degreasing the only requirement
- no welding consumables or shielding gas
- no need for worker protection from open arc or welding fumes
- low energy consumption
- straight and precisely dimensioned products as welded – no need for time-consuming and difficult straightening work.

A company seeking to increase capacity must consider these cost reductions as well as the additional profit from the increased plant capacity deriving from the investment.

No hard and fast rules can be applied when determining the viability of an investment. Different methods will be applied, according to the individual company's reasons for investment. The same applies to the sales price of the FSW-user's end products – different market prices apply in different markets. To conduct a realistic investment analysis, companies must include all relevant local factors.

MIG welding of aluminium usually involves some spatter, which needs post-treatment that partly destroys the surface. The arc welding process also generates many oxidation particles, adjacent to the melting zone, where gas protection is not effective. These oxidation particles require removal with toxic liquids, further impacting on the work environment and contributing to the plant's overall environmental impact. With the FSW process, heat input to the workpiece is limited to a temperature below melting point. This means less distortion and shrinkage of the material compared to all other welding processes. In environmental terms, FSW requires less energy and resources to achieve the workpiece's desired geometry.

Friction Stir Welded components offer through-life environmental gains

Friction Stir Welded products are less heavy, compared to other joining methods. Especially with products such as cars, lorries, trains and aircraft, that are constantly accelerating and decelerating, FSW offers lower energy consumption, while reducing the requirement for powerful engines and brakes.

Over a product's entire life cycle, this constitutes the greatest positive impact.

Quality

This innovative solid-state method opens up a whole new range of welding possibilities – the low melting points of soft non-ferrous metals no longer pose a problem. Bending and tensile tests have confirmed superb rigidity and excellent fatigue resistance. Post-treatment is minimal, thanks to a perfect root surface and virtually stress-free weld. And the finished joint comprises original material only – no inclusions or impurities.

Weld quality is unrivalled. The complete lack of voids and impurities and the fact that the material has been plasticized – not melted – ensures exceptional weld strength. This makes the technique especially suitable for the volume production of flat or curved panels, where safety-critical welds must be flawless – as in the shipping, offshore, rail and aerospace industries.

ESAB's ongoing development programme is producing an ever-expanding range of applications. Friction Stir Welding is ideal for joining straight profiles and flat plates. With larger and more powerful welding heads and improved rotating tools, our latest FSW machines can weld flat plates in thicknesses from 0.5-65 mm, with full penetration.

Example of cost analysis

Creating a cost analysis model based on the ideas introduced in Table 12, Table 13, Table 14 and Table 15 is quite a challenge. To help, the following tables present an approach for calculating the costs associated with friction stir welding. However, this is just the beginning, to provide an idea of the costs of operating the equipment and making welds. To make the investment profitable, the products must still be sold at a price high enough to cover the costs. Note also that the cost analysis assumes full capacity utilisation.

	Optimal case	Probable case
Number of 6-metre 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 12. Theory v. practice. What a company needs is salesmen who ensure there is enough volume to justify lower sales prices. As clearly seen from the cases below, realistic production volumes are essential when justifying investment.

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 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 administration, office overheads, telephone, etc.)

Other costs	
energy costs/kWh	0.03 (average 30 €/MWh, can vary drastically during the year – 0.03 €/kWh)
salary incl. overheads	50 €/h
tool costs/tool	1000 € (useful lifetime of 1 tool: 2000 m)

Table 13. Residual investment value, welding capacity and additional cost calculations.

Fixed costs/year	114 200.00 €	N [units]	Total costs €/m	€/m	economies of scale	€/m
depreciation (year 1.)	75 200.00 €	1	114 221	19 037		
factory overheads	22 000.00 €	2	114 241	9 520	114 233	9 519
service contract	17 000.00 €					
		4	114 282	4 762	114 266	4 761
Variable costs/unit	20.54 €	8	114 364	2 383	114 331	2 382
energy costs/h (consumption 0.2 kWh/m)	0.04 €	16	114 529	1 193	114 463	1 192
labour costs/unit	17.50 €	32	114 857	598	114 726	598
tool	3.00 €	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
Welded meters in a product (= 1N)	6m	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 14. Cost/welded metre.

Summary/year 1	Sensitivity analysis			
	Welding speed +10%	Labour costs +10%	Investment -10%	
Welding Capacity/year (6 meter long welds)	32 914m 5 486 units	34 718 5 786	32 914 5 486	32 914 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

Table 15. 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/metre would be ca. 4.20 €.

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.

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 Ø1.2 mm	-	OK 18.16 Ø1.2 mm	-
Number of runs	1	1	1+1	1
Total time/one metre of weld	4 min	1 min	7 min	1.5 min

Table 16. Time needed to weld 1 metre on AA6082-T6 using MIG or FSW.

	AA5083-O (t=15 mm)	AA5083-O (t=15 mm)	AA6082-T6 (t=15 mm)	AA6082-T6 (t=15 mm)
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 Ø1.6 mm	-	OK 18.16 Ø1.6 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 metre of weld	34 min	7-2 min	34 min	2-5 min

NB: Normally, FSW panels and most other parts are delivered as welded – no grinding, no straightening and no post-cleaning.

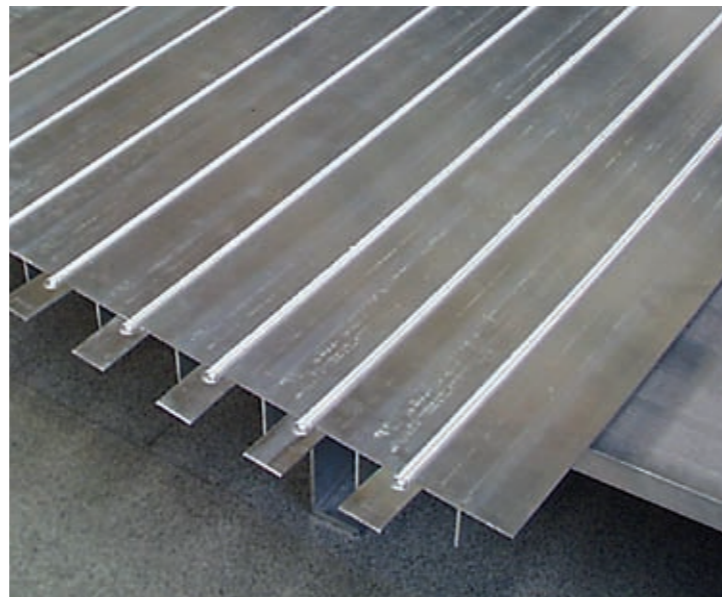
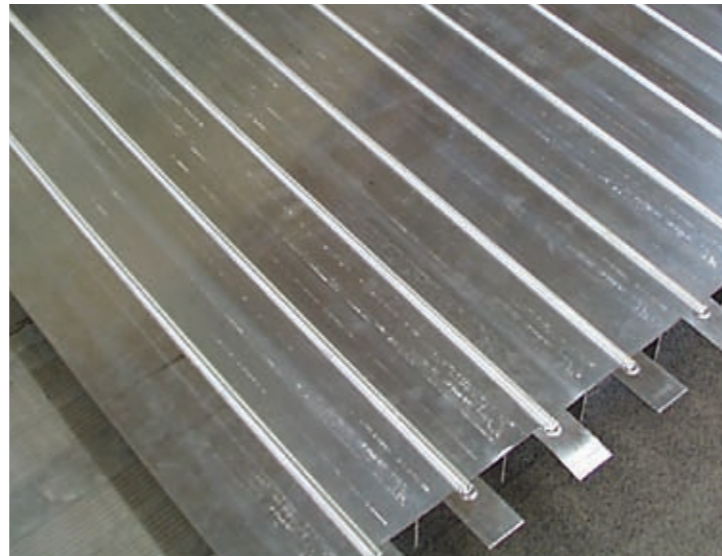
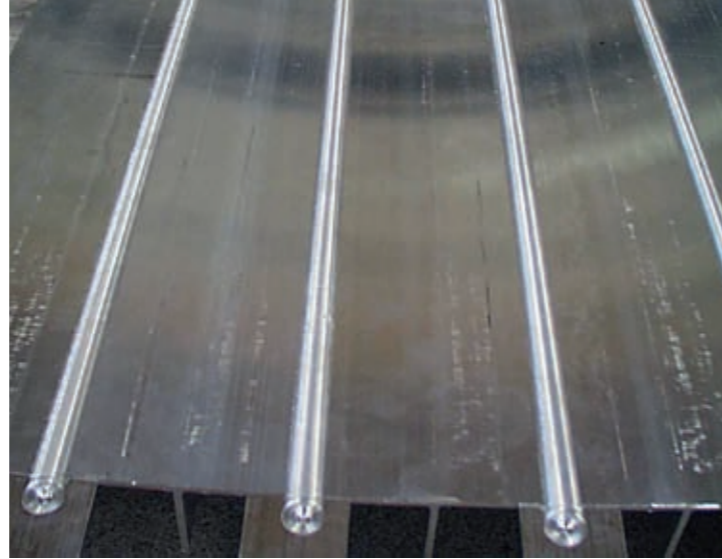
Table 17. Time needed to weld thick aluminium plates using FSW or MIG welding.



Conclusions

FSW is here to stay. The process has demonstrated its capabilities and been approved as a novel method for joining aluminium and other metals. FSW is opening up totally new areas of welding daily. The welding process improves existing structural properties and leaves the weld "cold". In some cases, if proper care is taken, weld properties equal those of the base material.

Anyone currently working with aluminium could be using FSW. It is within everyone's reach. It is just a question of daring to use it, eliminating the smoke and spatter typical of arc-welding. The choice is yours!



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World leader in welding and cutting technology and systems



ESAB operates at the forefront of welding and cutting technology. Over one hundred years of continuous improvement in products and processes enables us to meet the challenges of technological advance in every sector in which ESAB operates.

Quality and environment standards

Quality, the environment and safety are three key areas of focus. ESAB is one of few international companies to have obtained the ISO 14001 and OHSAS 18001 standards in

Environmental, Health & Safety Management Systems across all our global manufacturing facilities.

At ESAB, quality is an ongoing process that is at the heart of all our production processes and facilities worldwide. Multinational manufacturing, local representation and an international network of independent distributors brings the benefits of ESAB quality and unrivalled expertise in materials and processes within reach of all our customers, wherever they are located.

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