

EAA Aluminium Automotive Manual – Joining

7. Solid state welding

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7.0 Introduction

Solid-state welding describes a group of joining techniques which produces coalescence at temperatures below the melting point of the parent materials without the addition of third material. External pressure and relative movement may or may not be used to enhance the joining process. This group of joining techniques includes e.g. friction (stir) welding, cold pressure welding, diffusion welding, explosion welding, electromagnetic pulse welding, and ultrasonic welding. In all of these joining methods, proper control of the process parameters (time, temperature, and pressure individually or in combination) results in the coalescence of the parent materials without melting or only negligible melting at the interface. Technically, solid-state welding methods are not welding processes in the traditional sense since the materials do not reach their melting point, but can be rather compared with the traditional forging techniques.

Solid-state welding offers specific advantages since the base metal does not (or only marginally) melt and re-solidify. The parent metals essentially retain their original properties; heat-affected zone problems - which generally develop when there is base metal melting - are significantly diminished. Also the formation of intermetallic phases at the interface which can be brittle and may yield corrosion concerns is largely eliminated or minimized. Furthermore, when dissimilar metals are joined, their thermal expansion and conductivity characteristics have much less influence on the resulting joint performance than with fusion welding processes.

7.1 Friction welding

The term "friction welding" covers solid-state welding processes which lead to the coalescence of materials under the influence of the heat generated by the mechanically-induced sliding motion between rubbing surfaces. The parts to be joined are held together under pressure. Mechanical friction may be produced between a moving work piece and a stationary component, two moving components or using a moving tool.

Friction welding techniques are generally melt-free; the base materials are kept below their melting or liquidus temperatures. The frictional heat creates a plastic zone ("softens the interface") between the parts to be joined. The applied external force presses the parts together and thus creates a joint. The combination of short processing times and the development of the heat directly at the interface results in fairly narrow heat-affected zones, also caused by upsetting a portion of the interface out of the weld joint during the process. The minimal width of the heat-affected zone means that, in general, there is no need for heat treating the parts before or after joining to relieve internal stresses. Also problems like local cracking or reduced corrosion resistance in the heat-affected zone can be avoided or reduced. No filler metal or flux is used.

Another benefit is that the motion tends to "clean" the surface between the parent materials. Full-strength welds require proper boundary-layer bonding, so there can be no contamination in the interface plane. Since friction welding works by displacing the original interface materials, the parts being joined only require minimum surface cleaning or pre-treatment.

Friction welding offers the possibility to produce high quality joints with short cycle times and no additional joining elements (i.e. no additional weight and cost). An important advantage of friction welding is that it allows joining of aluminium alloys that are considered to be not fusion weldable (i.e. various EN AW-2xxx and 7xxx alloys) and of dissimilar material combinations. The strength of a friction welded joint depends on the specific joining conditions, but typically approaches that of the weaker of the two parent materials (joint efficiency ranges between 70 and 90 %). Examples of friction welded joints between dissimilar materials include combinations of aluminium/steel, aluminium/copper or aluminium/ceramic, etc.

There are different variants of friction welding techniques, but all are based on the same basic principle.

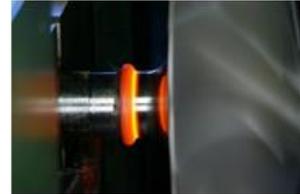
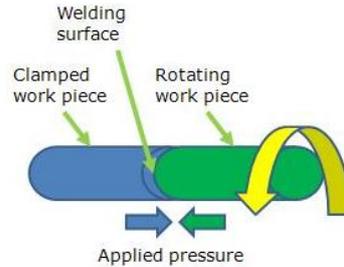
7.1.1 Friction welding of components

Net-shaped or nearly net-shaped parts can be directly joined by friction welding. The methods used in practice mainly differ in the type of the reciprocal movement of the two work pieces.

Depending on the symmetry of the individual components and the envisaged joint quality, different movement patterns are used. Consequently, the complexity of the necessary machinery can vary significantly, a fact which influences both the quality of the resulting joint as well as the productivity and the cost of the joining process.

7.1.1.1 Rotational friction welding

The rotational (or spin) friction process involves rotating one part against a stationary component to generate frictional heat at the interface. When a sufficiently high temperature has been reached, the rotational motion ceases and additional pressure is applied (“forging phase”) and coalescence occurs.



Rotational friction welding process

(Source: KUKA)

There are two variants of the rotational friction welding process. In the first (“direct-drive”) variant, the rotating part is driven by a motor which maintains constant rotational speed. The two parts are brought in contact under a defined pressure for a specified period of time. The rotating power is then disengaged and the pressure is increased. When the rotating piece stops, the joining process is completed. This process can be accurately controlled when speed, pressure, and time are properly selected. The other variant (also called inertia welding) includes a flywheel which rotates one of the pieces to be welded. After the flywheel has reached a pre-set speed, the motor is disengaged and the parts are forced together under pressure. The force is kept on the pieces while the flywheel comes to a stop and additional pressure is provided to complete the weld. Both methods produce welds of similar quality, however, slightly better control is claimed with the direct-drive process.

Rotational friction welding is a short-cycle process which can be easily automated, but requires relatively expensive machines. There are three important factors involved in the production of a high quality friction weld:

1. The **rotational speed** which is related to the material to be welded and the diameter of the weld at the interface.
2. The **pressure** between the two parts to be welded: At the start, the pressure is generally low, but it is gradually increased to create the frictional heat. When the rotation is stopped, pressure is rapidly increased so that coalescence takes place immediately before or after rotation is stopped.
3. The **welding time**: Welding time (normally few seconds) which depends on the geometrical shape of the parts and the type of materials to be joined as well as the interface area.

For rotational friction welding, at least one of the parts to be welded should be rotationally symmetrical. But depending on the specific situation, exceptions are possible. The heat, along with the perpendicular force applied to the interface, leads to the deformation and

plasticisation of the material at the interface. Much of the plasticised material is removed from the joint interface into a welding bead, due to the combined action of the applied force and movement. Along with the plasticised material, surface oxides and other impurities are also removed; allowing metal-to-metal contact between parts and the formation of a solid joint. A visual inspection of weld quality can be done based on the shape of the bead formed around the outside perimeter of the weld. Optimally, the bead should extend beyond the outside diameter of the parts and slightly curl back toward the parts. As a final operation, the bead the bead may be removed by machining depending upon the service requirements of the joint.



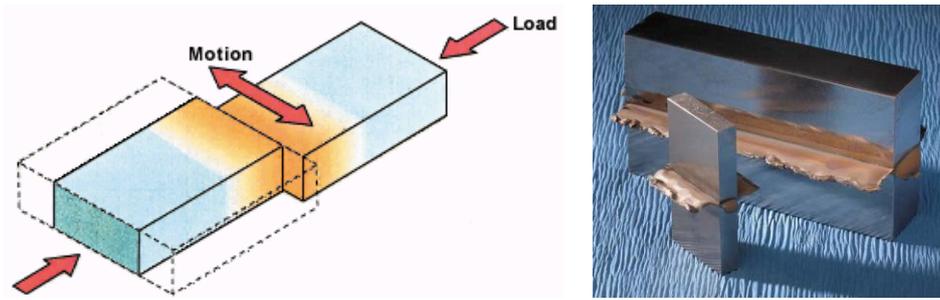
Components produced by rotational friction welding: Aluminium shock absorber (left), aluminium/steel drive shaft (centre) and aluminium/copper cable end piece (right)

(Photos: KUKA)

Parts to be joined by rotational friction welding must have a sufficiently high strength to be able to transmit the axial pressure and frictional moment as well as a sufficient hot forming capacity. Normally, the material data alone are not sufficient to indicate whether friction welding can be successfully employed. In addition, there is no straightforward correlation between the strength of the base materials and the strength of friction welded joints. Thus in general, optimum joining procedures have to be determined experimentally. Under unfavourable conditions, frictional welded joints between dissimilar materials may exhibit brittle fracture with little plastic strain at the joining plane.

7.1.1.2 Linear friction welding

Linear friction welding is similar to rotational friction welding except that the moving part oscillates laterally instead of rotating. It is also a high-quality joining process that creates a solid phase bond with parent metal properties.



4.1 Operating principle of linear friction welding

(Source: GKN Aerospace)

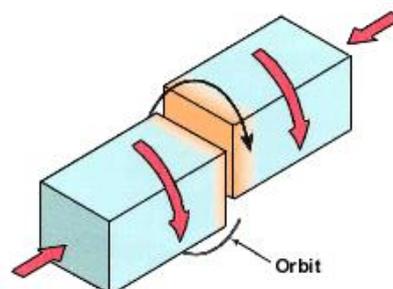
One of the parts to be joined is firmly clamped in place while the other is linearly oscillated through a small amplitude. When the work pieces are pressed together by applying a pre-set force, the frictional heat produced at the interface heats both materials to hot forming temperatures. Then the moving part is brought into alignment with the stationary part and the axial load is maintained or increased to finalise the joining process. The weld bead formed in the joint region is subsequently removed by milling.

Linear friction welding is most suited to rectangular and irregular cross-sections and is used in complex parts with a number of weld sites and multiple parts. However, it requires even more complex machinery than rotational friction welding. Also rotary friction welding can weld much larger cross sections. The high equipment and tooling cost is a major disadvantage. Thus, in the automotive industry, no application of linear friction welding is currently known.

7.1.1.3 Orbital and multi-orbital friction welding

In orbital friction welding, parts do not have to be more or less rotationally symmetric. In this case, the friction heat is the result of a relative movement of the joining parts by means of a circular vibratory motion of one or both parts. However, the parts do not rotate towards each other, i.e. the orientation of the axes remains the same. In orbital friction welding, only one of the components vibrates, whereas both vibrate in the case of multi-orbital friction welding. When the material-specific plasticizing temperature is reached, the orbital motion is stopped while both ends are pressed together, creating a high strength joint.

In contrast to rotational friction welding where the relative speed of a point on the surface depends on the diameter of the component, the speed in orbital friction welding only depends on the diameter of the orbit. Each point on the contact area moves at the same speed, resulting in a more efficient and more consistent energy input. Therefore, the joining performance is significantly improved for materials prone to internal stresses and stress cracks (e.g. ceramics) or for materials that are sensitive to temperature differences in the joining area. But also in this case, the limitations mentioned under linear friction welding apply. No automotive applications are known.



Operating principle of orbital friction welding

(Source: TWI)

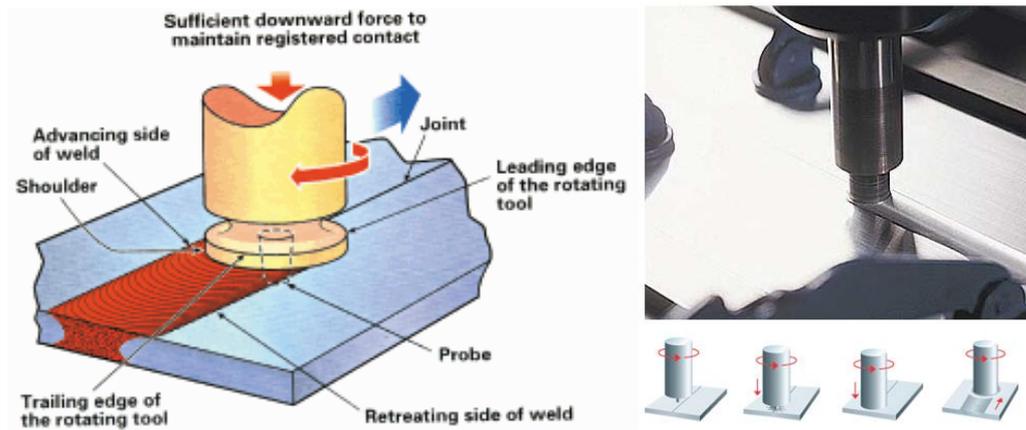
7.1.2 Linear friction stir welding

Friction stir welding is a solid-state joining process that uses a third body (“tool”) to produce the friction welded joint. Friction stir welding also employs frictional heat to plasticize the material, however, material consolidation significantly differs from the friction welding methods described above. It creates high-quality, high-strength joints with low distortion. Seam welds can be placed on either butt or overlapping joints, in a wide range of material types and thicknesses. Friction stir welding was invented by Wayne Thomas at TWI Ltd in 1991 and overcomes many of the problems associated with the traditional joining techniques.

It is a joining process which is particularly suited for aluminium alloys. Consequently, this joining method has gained significant interest within the automotive industry.

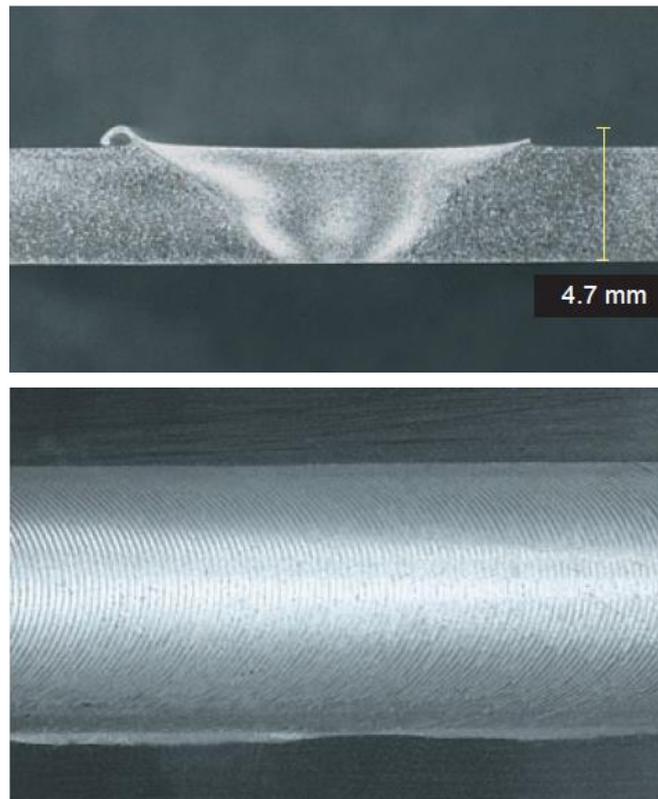
7.1.2.1 The linear friction stir welding process

In friction stir welding, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between the two work pieces. The parts are securely clamped in a fixed position to prevent the joint faces from being forced apart. The heat generated by the constantly rotating, wear resistant tool “softens” the material near the friction stir welding tool, allowing the tool to traverse along the joint line. As the pin moves forward, a special profile on its leading face forces plasticized material to the trailing edge of the tool pin (or probe) and the two work pieces are essentially forged together by the clamping forces, assisted by the mechanical pressure applied by the tool shoulder and pin profile. The probe is slightly shorter than the required weld depth, with the tool shoulder riding atop the work surface. The surface of the finished weld is smooth and more or less flush with the surface of the parts. The top surface of the weld shows the characteristic wave-marks from the rotating friction stir welding tool.



Linear friction stir welding process

(Source: TWI / Sapa)



Cross section and top view of a friction stir welded joint

(Source: Sapa)

The relevant process parameters in friction stir welding are:

- **Tool rotation speed and tool traverse speed**

These two parameters govern the heat input during welding and must be carefully chosen to ensure a successful and efficient welding cycle. It is necessary that the material surrounding the rotating tool is hot enough to enable extensive plastic flow and minimize the forces acting on the tool. If the material around the tool is too cold, voids or other defects may develop in the stir zone and, in extreme cases, the tool may break.

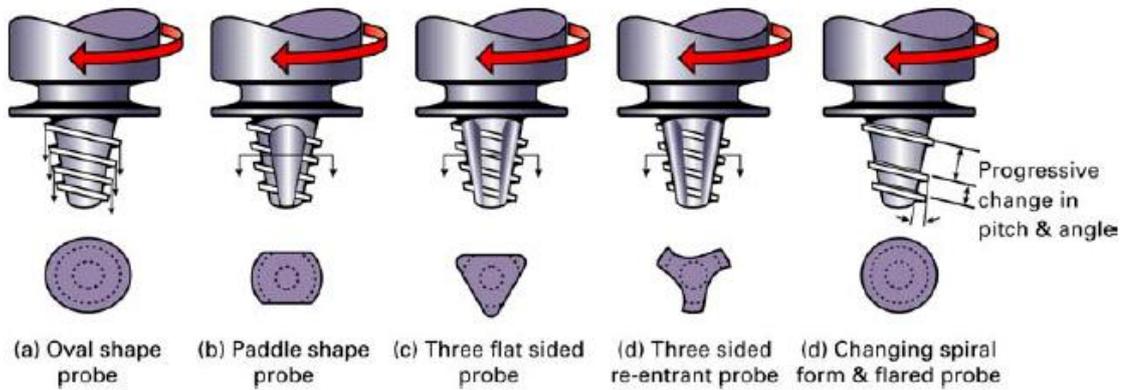
On the other hand, excessive heat input may deteriorate the final properties of the joint and could result in defects due to the liquation of low-melting phases. The relationship between the tool rotation speed, the tool traverse speeds and the resulting heat input is complex, but generally said, a faster tool rotation speed or a slower traverse speed will lead to a higher weld temperature. Consequently, tool rotation and traverse speeds must be controlled within a properly defined processing window.

- **Tool tilt and plunge depth**

Tool tilt and plunge depth have found to be additional parameters for ensuring a good weld quality. Plunging the shoulder of the tool below the plate surface increases the pressure below the tool and helps to ensure adequate forging of the material at the rear of the tool. Depending on the tool type, slight tilting of the tool such that the rear of the tool is lower than the front proved to be also beneficial regarding the effectiveness of the forging process.

- **Tool design**

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed. 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 (i.e. higher welding speed and enhanced quality).



Some basic tool shapes for friction stir welding

(Source: TWI)

The tool material must be sufficiently strong, tough, and wear-resistant at the required processing temperature. It should also have a good oxidation resistance and a low thermal conductivity to minimise heat loss and thermal damage to the machinery further up the drive train. The combination of tool and base material is therefore crucial for the operational lifetime of the tool. Hot-worked tool steels are perfectly acceptable for joining aluminium alloys, but more advanced tool materials are necessary for more demanding applications. Advanced tool designs have enabled substantial improvements in productivity and quality. Specifically designed tools allowed to increase the penetration depth and thus the successful welding of parts with higher thickness.

| Tool | Cylindrical | Whorl™ | MX triflute™ | Flared triflute™ | A-skew™ | Re-stir™ |
|----------------|--------------------------|----------------------|-------------------------------------|--------------------------------------|-----------------------------------|----------------------|
| Schematics | | | | | | |
| Tool pin shape | Cylindrical with threads | Tapered with threads | Threaded, tapered with three flutes | Tri-flute with flute ends flared out | Inclined cylindrical with threads | Tapered with threads |

Advanced friction stir welding tools developed by TWI

(Source: TWI)

During friction stir welding, different forces act on the tool:

- A downwards force maintains the position of the tool at or below the material surface. Some friction-stir welding machines are load-controlled, but the vertical position of the tool is generally preset and the load varies during welding.
- The traverse force acts parallel to the tool motion. This force is the result of the resistance of the material to the motion of the tool; it decreases when the material temperature around the tool increases.
- A lateral force may act perpendicular to the tool traverse direction.
- Torque is required to rotate the tool, the amount of which will depend on the down force and friction coefficient and/or the flow strength of the material in the surrounding region.

In order to prevent tool fracture and to minimise tool wear, the welding cycle must be properly controlled so that the forces acting on the tool are as low as possible and abrupt changes are avoided.

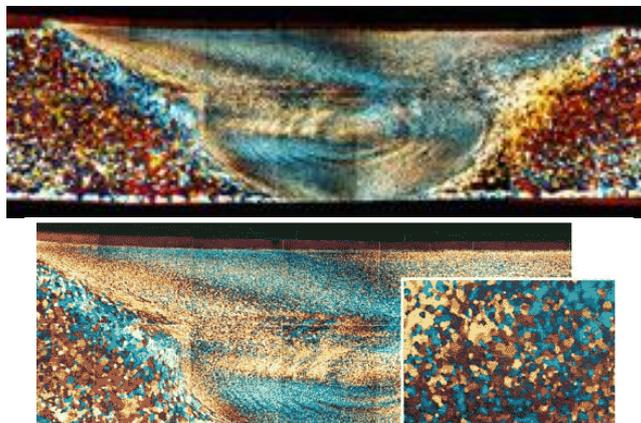
The acting forces during friction stir welding are significant, and proper fixture design is critical to the success of the joining process. The main purpose is to hold the work pieces in position and to avoid geometrical deformations of the structure during friction stir welding. Also important is a good stability during the process since any deflection or major vibration may affect the weld quality. The required fixture depends on the specific application, a sufficiently rigid construction requires only proper clamping whereas for sheet assemblies, the applied

fixtures may range from simple backing bars to specifically designed tools. The fixture design needs to take into account also potential temperature effects.

The heat generated in the joint area rises the local material temperature to about 80-90 % of its melting temperature. There are two main heat sources: the friction of the material(s) to be joined at the tool surface and the deformation of the material around the tool. Heat is predominantly produced under the tool shoulder. Heat flow and thermal profile differ during the welding cycle. In the beginning, the material is preheated by a stationary, rotating tool until the material temperature ahead of the tool allows the tool to move forward. This phase also includes the plunge of the tool into the work piece. When the tool begins to move, there is a transient period where the heat production and temperature around the tool will alter in a complex manner until essentially a steady-state situation is reached. Although fluctuations in heat generation may occur in the steady-state phase, the thermal field around the tool remains effectively constant, at least on the macroscopic scale. Only near the end of the weld, the resulting heat flow may "reflect" from the end of the plate and lead to additional heating around the tool.

The specific nature of the friction stir welding process produces in a highly characteristic microstructure:

- In the stir zone, the tool which traverses along the weld line in a plasticized tubular shaft leads to a severe deformation of the base material followed by dynamic recrystallization. The resulting grain structure is roughly equiaxed and the grain size is often an order of magnitude smaller than the grains in the parent material.
- The flow arm zone is on the upper surface of the weld and consists of material that is dragged by the tool shoulder from the retreating side of the weld, around the rear of the tool, and deposited on the advancing side.
- The thermo-mechanically affected zone is present on either side of the stir zone. In this region, the strain and temperature are lower and the effect on the microstructure is correspondingly smaller. Consequently, the microstructure of the parent material is still recognizable, but significantly deformed and rotated.
- The adjoining heat-affected zone is subjected to a thermal cycle, but is not deformed during welding. Nevertheless, the effect on the mechanical properties of aluminium alloys may be significantly.



Microstructure of a friction stir welded aluminium joint

(Source: Sapa)

7.1.2.2 Application of linear friction stir welding

In terms of materials, the focus of friction stir welding has traditionally been on non-ferrous alloys. It is almost an ideal technology to join aluminium components (sheets, extrusions and castings); without using 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.

Recent advances have challenged this assumption, enabling friction stir welding to be applied to a broader range of materials. The technology has proven to be able to successfully join numerous metals and alloys, including high-strength steels, stainless steel and titanium. A

further expansion of the application range can be expected in the future based on improvements of the existing methods and tool materials as well as new technological developments.

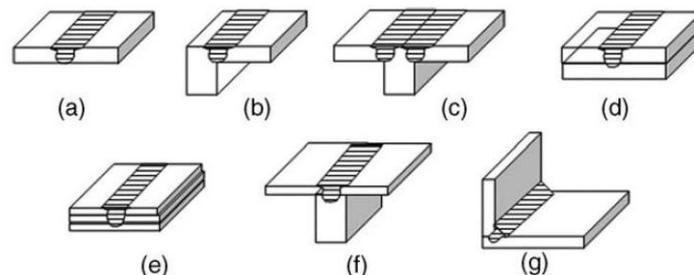
To assure high repeatability and joint quality, proper friction stir welding equipment is necessary. Most simple welds can be performed with a conventional CNC machine, but for more demanding applications, purpose-built equipment becomes essential. The relevant process parameters are purely mechanical (force, friction, and rotation). The most important control feature is the down force which guarantees high quality even where dimensional tolerances of the work pieces are relatively large. It enables robust process control as the down force ensures the generation of sufficient frictional heat to soften the material. The other process parameters to be controlled are traverse speed, rotation speed of the welding tool and its tilting angle. With production machines, typical welding speeds for aluminium alloys are about 2000 mm/min (e.g. when joining extruded profiles with wall thicknesses of about 2 mm). With increasing material thickness, the maximum welding speed will decrease correspondingly.

The quality of a friction stir welded joint is generally superior to that of conventional fusion-welded joints:

- Higher strength (in particular also fatigue resistance)
- Homogeneous joint, entirely void-free and no disruptive oxide inclusions
- Joints are - in principle - flush with material surface
- Reduced thermal deformation, tight tolerances
- Improved repeatability (few process variables)
- Little (no) effect on corrosion resistance.

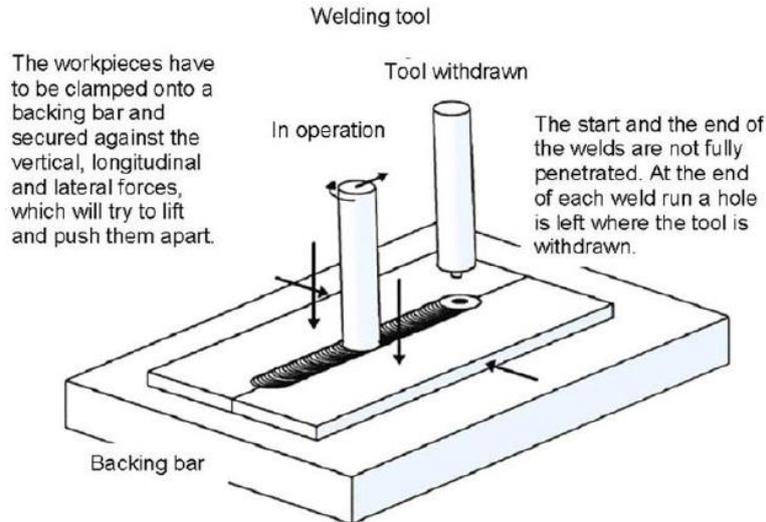
Mechanical (and corrosion) characteristics of the resulting joints depend on the specific material combination. As an example, when joining EN AW-6xxx alloys in the T6 temper, the tensile strength of the friction stir welded joint is >70 % of the base metal strength. Welding in the T4-temper condition followed by a post weld ageing could give >90 % of the base metal tensile strength in the weld. Due to the fine grained microstructure and smooth weld surface the fatigue properties are close to those of the base alloy.

The process can be applied to many joint designs. Butt and lap welds can be made even from materials with dissimilar thickness. Annular or circumferential joints can be produced by rotating the work piece underneath the friction stir welding machine, and CNC machines or robots are used for non-linear and three-dimensional joint lines.



Joint configuration for friction stir welding: (a) square butt, (b) edge butt, (c) T butt, (d) lap joint, (e) multiple lap joint, (f) T lap joint, (g) fillet joint

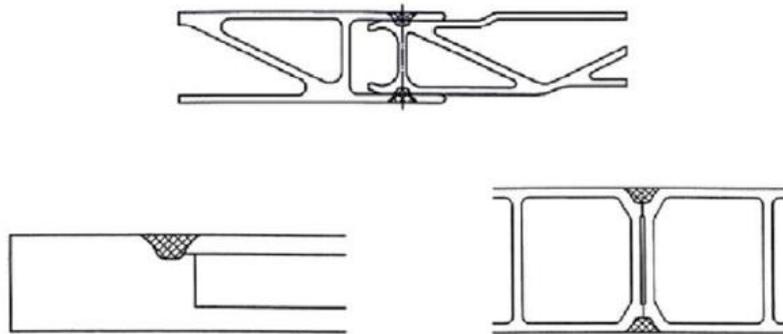
A limitation of the friction stir welding process is that the welding spindle must have access to all the joints to be welded. Other limitations include the effects observed at the start and end of the welds and the required fixtures and clamping.



Limitations of the linear friction stir welding process

The work pieces are usually clamped onto a backing bar and secured against the vertical, longitudinal and lateral forces, which will try to lift and push them apart. Normally a gap of up to 10 % of the sheet thickness can be tolerated before weld quality is impaired. In general, no specific surface preparation is necessary. However, depending on the actual surface condition, the application of a suitable part cleaning process may be considered (e.g. heavily lubricated components should be washed).

Most interesting possibilities are offered by the aluminium extrusion technology. Hollow profiles can be designed with internal backing by locating material or supporting legs in proper positions.



Joint design for friction stir welding of hollow profiles (top and right) and weld design of a plate cover to a cavity (left)

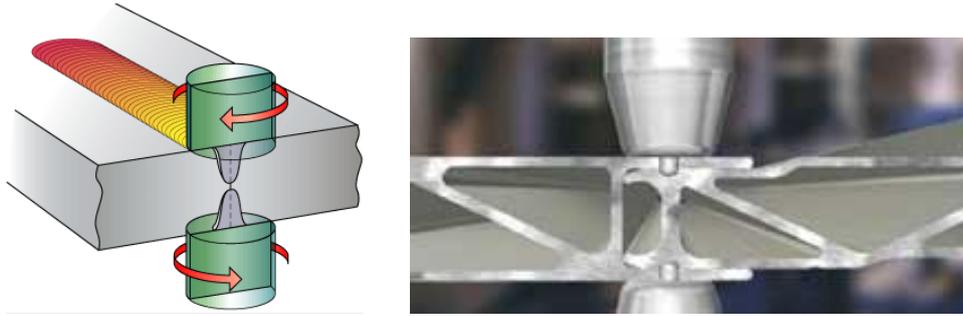
7.1.2.3 Variants of the linear friction stir welding technique

The systematic development of the friction stir welding technology has led to a number of process variants, covered by multiple patents. Development activities are on-going, thus further progress can be expected.

These process variants offer either improvements in quality, productivity or optimised performance for specific joining tasks. However, since the equipment cost for such single-purpose machines rises drastically, cost efficiency will have to be carefully examined in each application.

a) Twin-stir™ welding techniques

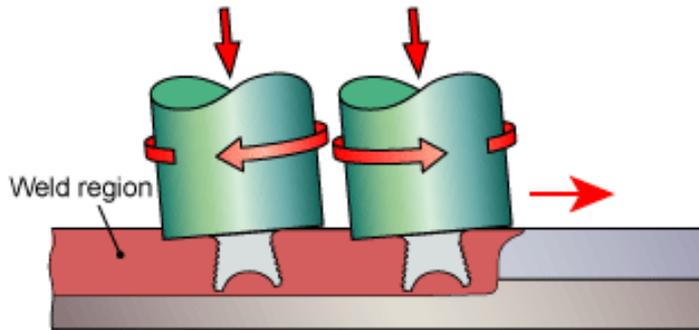
The simultaneous use of two or more friction stir welding tools acting on a common work piece was evaluated using different configurations. An early concept involved a pair of contra-rotating tools applied on opposite sides of the work piece. The simultaneous double-sided operation with combined weld passes reduces the reactive torque and results in a more symmetrical weld and heat input. The probes need not touch each other, but should be positioned sufficiently close that the softened material around the two probes overlaps to generate a full through-thickness weld. In order to avoid any problems associated with a zero velocity zone in mid-thickness, the probes can be displaced slightly along the direction of travel.



Simultaneous double-sided friction stir welding with contra-rotating tools (left) applied to a hollow extrusion (right)

(Source: TWI / Sapa)

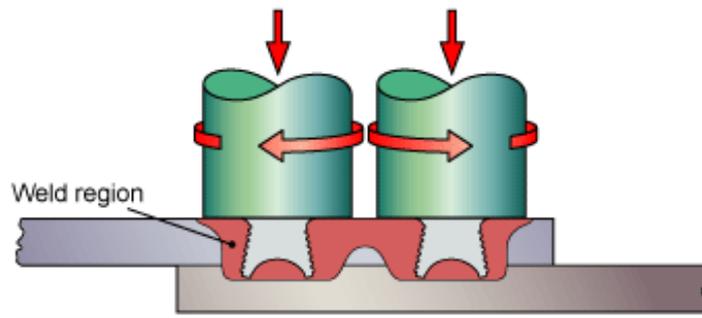
Another approach used a preceding friction pre-heating tool which is followed in line by the actual friction stir welding tool. The “tandem” technique can be applied with both tools rotating in the same direction, but more interesting is the contra-rotating variant. The Twin-stir™ tandem contra-rotating variant can be applied to all conventional friction stir welded joints and will reduce reactive torque. This has benefits in terms of simplification of clamping and jiggling for holding parts to be welded. More importantly, the tandem technique will improve the integrity of the weld by disruption and fragmentation of any residual oxide layer remaining within the first weld region by the following tool.



In-line contra-rotating tandem concept with the welding direction

(Source: TWI)

The Twin-stir™ parallel contra-rotating variant enables the positioning of defects associated with lap welding between the two welds. Owing to the additional heat available, increased travel speed or lower rotation process parameters will be possible in parallel overlap welding.



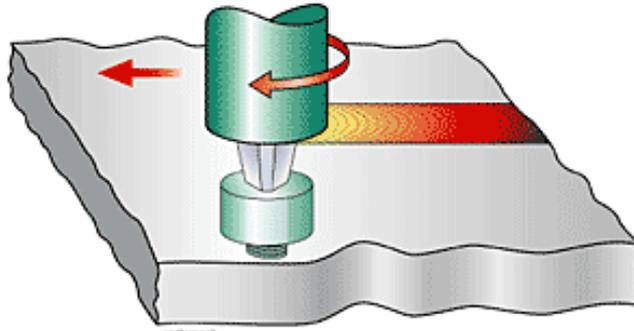
Parallel side-by-side configuration transverse to the welding direction

(Source: TWI)

A further development of this method is the staggered tool arrangement. In this case, the tools are positioned with one in front and slightly to the side of the other so that the second probe partially overlaps the previous weld region. This means that an exceptionally wide weld region can be created. Residual oxides within the overlapping region of the two welds are fragmented and dispersed.

b) Bobbin stir welding

A disadvantage of the friction stir welding process is the need for a backing bar or advanced fixtures. The bobbin tool which enables double-sided welding eliminates this problem ("self-reacting friction stir welding") and avoids the risk of root defects. It consists of two shoulders, one on each side of the work piece to be joined. The two elements of the tool are connected with the pin, which runs through the material.



Bobbin friction stir welding

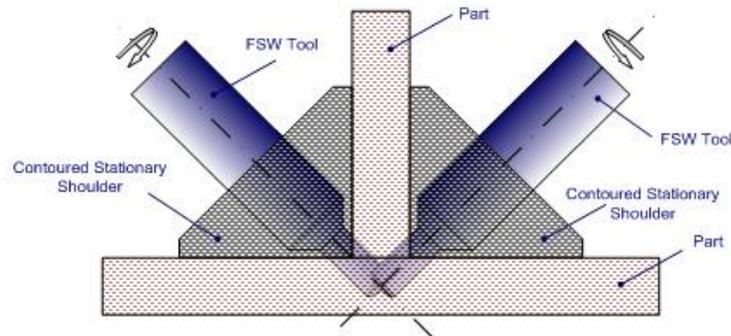
(Source: ESAB)

The bobbin technique provides a fixed gap between two shoulders, while the adaptive technique enables adjustment of the gap between the shoulders during the welding operation. The first variant offers a simple mechanical solution for the welding head since the fixed bobbin tool does not differ from a conventional tool at the tool interface. In contrast, the adaptive tool allows an independent control of the contact conditions for the two shoulders to compensate for variations in material thickness. 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 self-reacting principle of the bobbin technique means that the normal down force required by conventional friction stir welding is reduced; the reactive forces within the weld are contained between the bobbin shoulders. For certain applications, also bobbin tools that are driven from both ends are envisaged. The concept of a double driven bobbin also includes a double adaptive technique where both shoulders can be adjusted independently and a load can be applied from both ends.

c) Corner welding and dual-rotation friction stir welding technique

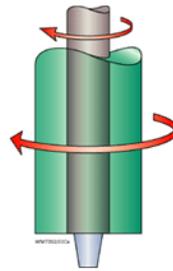
TWI also developed a technique called stationary shoulder friction stir welding mainly for welding low heat conductivity materials where a more uniform heat input into the weld is beneficial. It consists of a rotating pin located in a non-rotating shoulder component which slides over the surface of the material during welding.



Schematic of the corner welding technique applied to a T joint configuration

(Source: TWI)

This concept offers the potential to join plates which are positioned in different angular planes (e.g. T joints) by using a stationary shoulder shaped according to the internal corners of the specific weld configuration. The shaped shoulder contains the stirred material and slides over the surface of the material during welding.



Dual-rotation friction stir welding with rotation of the probe and shoulder in the same direction

(Source: TWI)

A further development of the stationary shoulder concept is the dual-rotation friction stir welding technology. The dual-rotation technique allows for a differential in speed and/or direction between the independently rotating probe and the rotating surrounding shoulder. It can be used, for example, to reduce the shoulder rotational speed as appropriate in order to reduce any tendency towards over-heating or melting, while maintaining a higher rotational speed for the probe. Thus it is possible to lower the welding temperature and minimise the thermal softening of the weld region of certain heat-treatable aluminium alloys.

d) Retractable pin friction stir welding

Friction stir welding has two major drawbacks. At the end of the weld, the single-piece pin tool is retracted and leaves a "keyhole" which is unacceptable when welding cylindrical objects such as drums, pipes and storage tanks. Another drawback is the requirement for different-length pin tools when welding materials of varying thickness.

At NASA's Marshall Space Flight Center, an automatic retractable pin tool was designed that uses a computer-controlled motor to automatically retract the pin into the shoulder of the tool at the end of the weld, preventing keyholes. This design allows the pin angle and length to be adjusted for changes in material thickness and results in a smooth hole closure at the end of the weld.



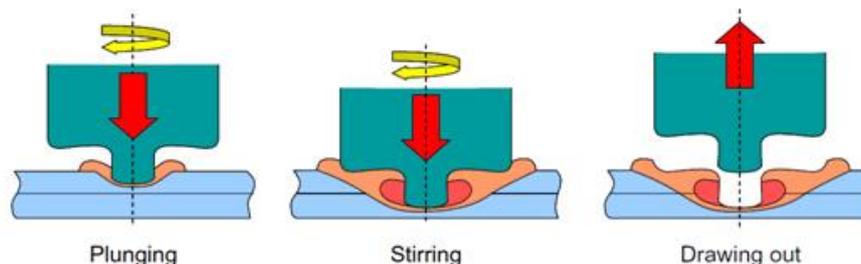
Retractable pin friction stir welding tools
(Source: NASA Marshall Space Flight Center)

7.1.3 Friction stir spot welding

Recently, friction stir spot welding, a variant of linear friction stir welding technique (invented by Mazda Motor Corporation in 1993) has received considerable attention from the automotive industry. It shows great potential to be a replacement of single-point joining processes like resistance spot welding and riveting and further developments are ongoing.

7.1.3.1 The friction stir spot welding technique

Friction spot joining is similar to friction stir welding, although generally applied as an overlap sheet joining technology. Both techniques use a rotating tool with a specially designed pin and shoulder. However, whereas in linear friction stir welding, the tool traverses along a seam between two metal plates, the tool keeps to one spot in friction spot joining. The configuration and dimensions of the tool, especially the pin, vary depending on the material, the thickness of the sheets, and the strength requirements of the joint.



Friction stir spot welding process
(Source: Kawasaki Heavy Industries Ltd.)

The friction spot joining process consists of four steps. First, the tool is positioned perpendicular to the work surface and starts to rotate at a high angular speed. Then the tool is plunged into the work piece materials to be joined until the tool shoulder touches the surface of the top sheet. Friction heats the materials, and the pin enters the softened metal. After the pin has plunged completely into the work piece, the tool continues to spin and apply pressure for a set length of time. More heat is generated by friction and plastic deformation between the tool and materials as the locally softened material moves along the pin and the shoulder under the applied stress. This causes the formation of a strong

metallic bond between the sheets at temperatures below the melting point of the work piece materials. After a sufficiently long dwell time, the joining process is complete and the tool is retracted from the work piece materials. The entire process takes approximately two seconds. A backing bar prevents denting and ensures that the tool does not simply plunge straight through the sheets. The top side of the joint has a circular indentation (keyhole or exit hole) in the centre and a small ring-shaped projection along its outer edge. The surface that was pushed against the backing bar is unblemished. Because the process does not apply excessive heat, warpage of the sheets is minimal.

The key parameters of the process are the rotational speed of the tool, the axial force, and the duration of the force. The speed of the tool is usually kept constant. Once the pin contacts the work piece, the axial force rapidly increases. When it reaches a set point, the force is held constant. The speed at which the tool enters the sheets is fairly constant until the shoulder contacts the work surface. At that point, the plunging speed decreases and stops. All three variables can be monitored for quality control.

The depth to which the tool penetrates depends on the length of the pin, i.e. the sheet thickness cannot be changed without changing the tool. Thicker sheets require a longer pin. The pin is generally made of tool steel with tapered threads like a screw. When joining sheets of different thicknesses, the thicker sheet should be placed on the bottom.

Friction spot joining has been used on aluminium sheets ranging from 1 - 3 mm thickness. It is possible to weld thicker sheets, but the longer plunge time may become an issue. Although the technique was originally developed for aluminium, it can also be applied to other lightweight metals such as magnesium and for aluminium/steel joints. The possibility of using the friction stir spot welding technology to join high strength steels has also been demonstrated, but this application is more problematic due to the higher forces and processing temperatures.

A friction spot joining system includes two servomotors; one spins the joining tool and the other pushes the tool against the work piece. The joining tool is positioned opposite the backing bar, which is fixed to the end of a C-shaped frame. The joining system can be operated as a stand-alone pedestal machine or integrated with a six-axis robot.

Joint strength with friction spot joining is comparable to resistance welding (better than clinching, but less than self-piercing rivets). A disadvantage of this technique is the characteristic keyhole in the spot centre, which significantly decreases the mechanical properties of the joints.



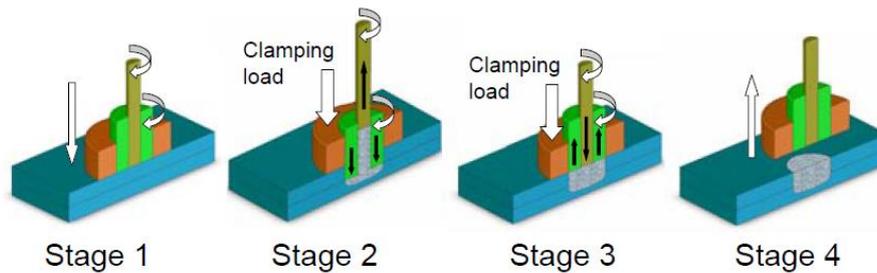
Application of the friction stir spot welding technique
(Source: Mazda)

7.1.3.2 Further developments of the friction stir spot welding technique

Several process variants have been proposed in order to eliminate the keyhole or increase the strength of friction stir spot welded joints.

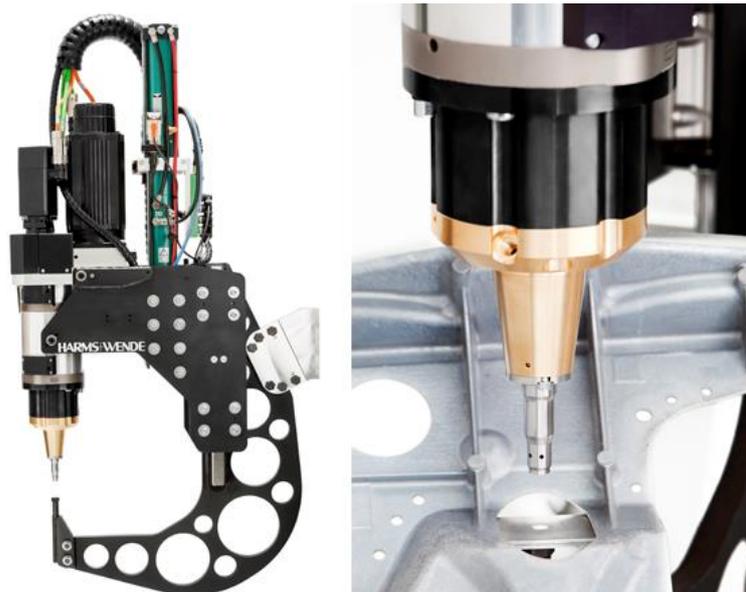
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The **refill friction stir spot welding process** developed by Helmholtz-Zentrum Geesthacht, Germany is used to join two or more sheets in the overlap configuration. The key element is a three-component tool comprising a pin, a sleeve and a clamping ring. The clamp holds the sheets firmly against a backing plate and also constrains the material flow during the process. In a first phase, the pin and sleeve begin to rotate in the same direction and simultaneously press onto the upper surface ("friction"). The pin and the sleeve then move in the opposite direction (i.e. one is plunged into the material while the other moves upwards), creating a cavity where the plasticised material is accommodated ("first extrusion"). After reaching the pre-set plunge depth, the pin and sleeve return to their initial position forcing the displaced material to completely refill the keyhole ("second extrusion"). Finally, the tool rotation is stopped and the tool is withdrawn from the joint leaving a flat surface with minimum material loss ("pull-out").



Refill friction stir spot welding process

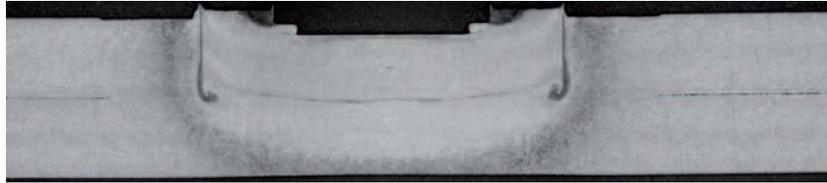
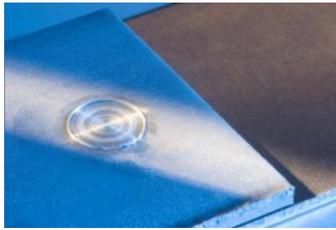
(Source: GKSS Forschungszentrum)



Refill friction stir spot welding machine

(Source: Harms+Wende)

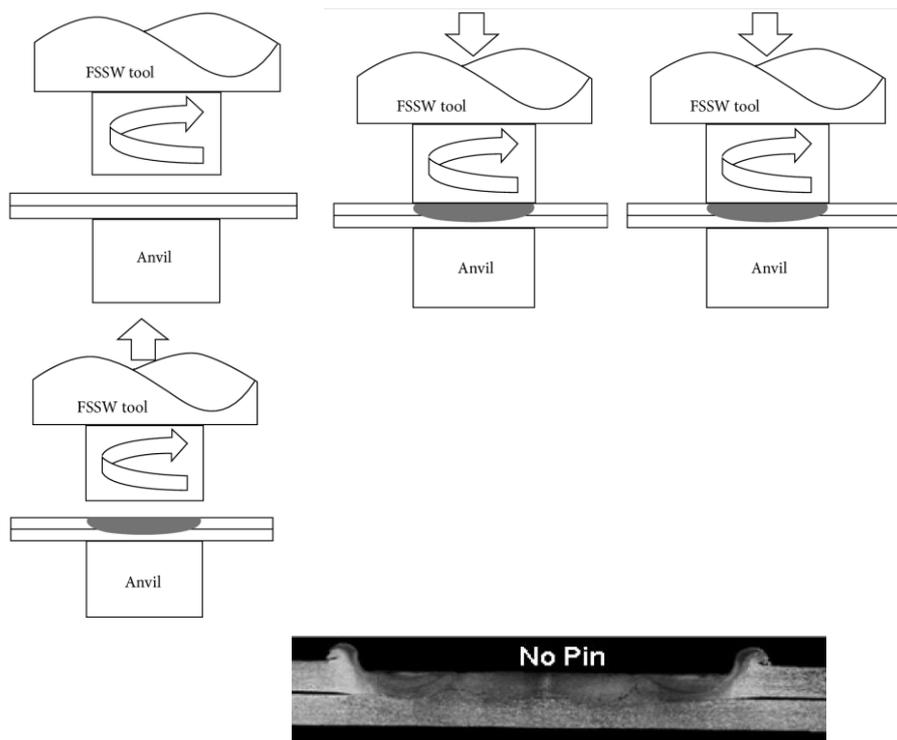
The disadvantages of this process are the more complicated procedure, a relatively long dwell time and higher cost. However, the keyhole can be eliminated, and the weld strength and appearance is significantly improved.



Joint produced by the refill friction spot welding technique

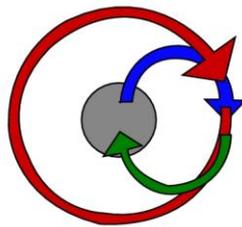
(Source: Riftec GmbH)

The **pin-less friction stir spot welding process** was invented by Tazokai et al. in 2009. It is a variant of the friction stir spot welding process where the tool has no pin, but includes a scroll groove on its shoulder surface. In thin aluminium sheets (~1 mm) where the deformation zone from the shoulder penetrates sufficiently into the bottom sheet, a pin-less tool provides excellent results because it contacts more uniformly across the tool surface. If either a steel or ceramic anvil is used (to reduce heat loss at the bottom face), welds can be produced which are as strong as those produced with an optimum pin length. Preliminary data have shown that this approach can be used to produce high-strength welds with a short dwell time.



Pin-less friction stir spot welding process

The **swing friction stir spot welding process** was developed by TWI. In this process, the tool moves along pre-set path after plunging. This process increases the actual area of weld and the strength of joints, while it cannot eliminate the keyhole.



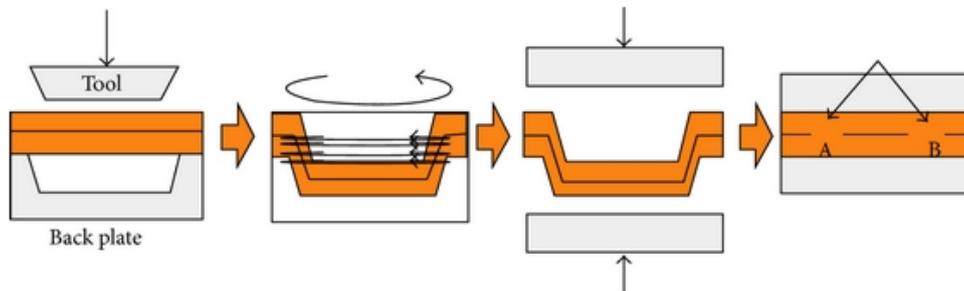
The "squircle"

-  Start/end point
-  Start arc (0.5 mm radius)
-  Circular path (1 mm radius)
-  End arc (0.5 mm radius)

Principle of swing friction stir spot welding

(Source: TWI)

A further variant of the friction stir spot welding process was proposed by Sun et al. in 2011. In the first step, a specially designed backplate containing a round dent is used for conventional friction stir spot welding. A keyhole is formed in the joint, along with a protuberance on the lower sheet due to the flow of materials into the dent. In the second step, a pinless tool and a flat backplate are employed to successfully remove both the keyhole and the protuberance.



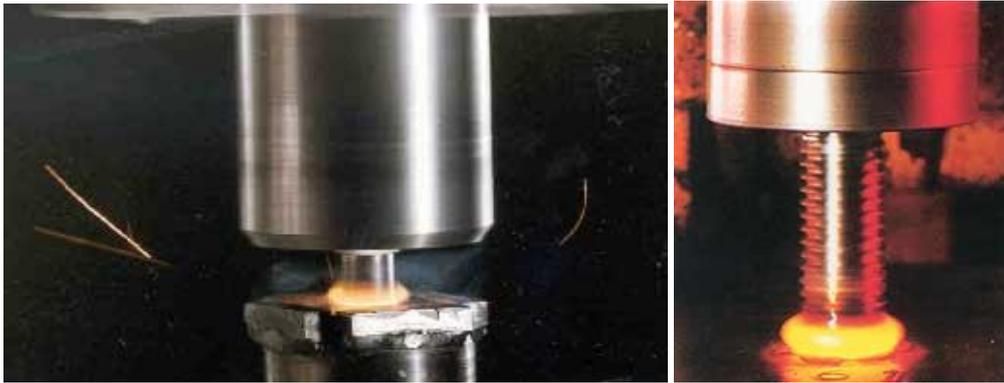
Friction stir spot welding process

(Source: Science and Technology of Welding and Joining, vol. 16, no. 7, pp. 605–612, 2011)

7.1.4 Friction stud welding

In its simplest form, friction stud welding involves rotating a stud in the form of a solid rod and forcing it onto the surface of a work piece. Rotation and downward force create frictional heat which causes the materials to plasticise in the region of contact. Rotation of the stud is then stopped and the axial force either maintained or increased to consolidate the joint.

The weld time is very short, around four seconds for a 10 mm diameter stud. The weld quality is consistently high, and when tested to destruction, failure invariably occurs in the weaker parent material and well away from the weld. A number of material combinations can be joined using friction stud welding, in particular dissimilar metals. An important limitation of the friction stud welding process is that it can only be applied when the work pieces have different forging temperatures. In general, the optimum processing conditions have to be determined experimentally depending on the application. Practical tests may be also necessary to evaluate whether applying a high rotation speed can reduce the forging force.



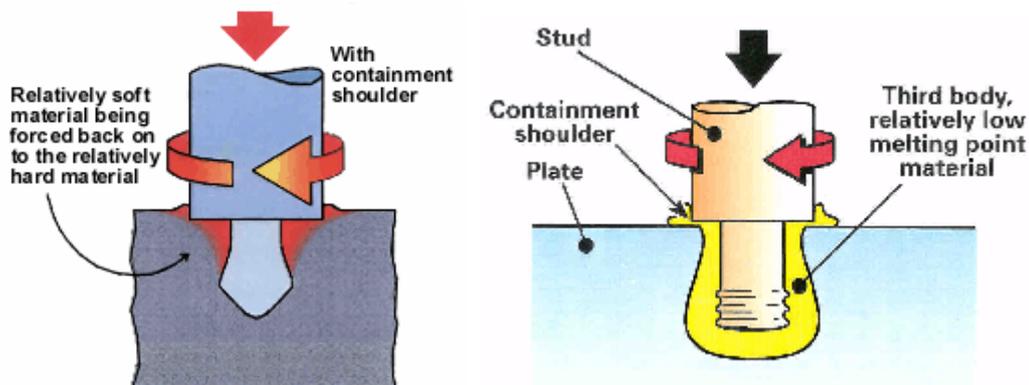
Friction stud welding

(Source: TWI / IEV Group)

For welding small diameter studs to thin sheets, small portable friction stud welding machines are available, which can be operated either attached to a robot or hand held.

In some cases, a mechanical interlock between the stud and the work piece may be required. When dissimilar materials are joined, the friction plunge welding process can fulfil this requirement. A pin with a recessed area and a containment shoulder has to be machined from the harder material. This pin is then rotated until the plasticised material of the softer work piece is forged into this recess by the forces generated by the shoulder. The process offers significant technological benefits for safety-relevant parts.

In cases of similar hardness, the use of an interlayer with a relatively low melting point can be considered. The interlayer is softened and extruded during processing. The presence of re-entrant features promotes a good mechanical lock, even when a true metallurgical bond is not achieved. This process is known as third body friction joining.



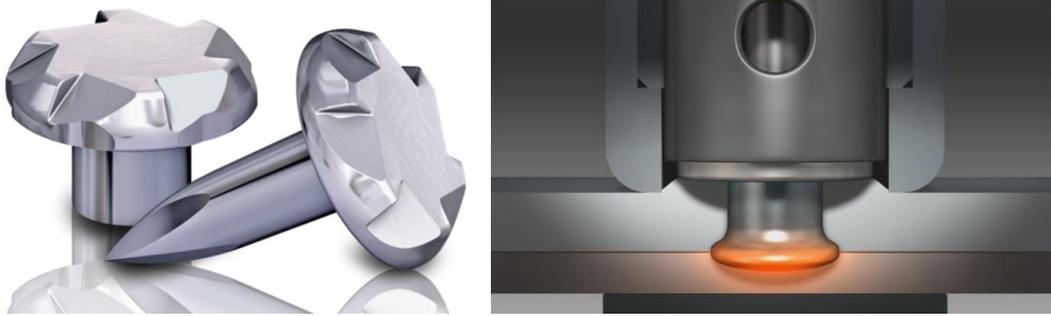
Friction plunge welding (left) and third body friction joining (right)

(Source: TWI)

7.1.5 Friction element welding

EJOWELD® friction element welding offers the possibility to join different materials (lightweight materials and high strength steels) without any pre-treatment (cleaning, de-coating, pre-drilling). The friction element welding technology combines thermal and mechanical welding principles by the use of an auxiliary joining element.

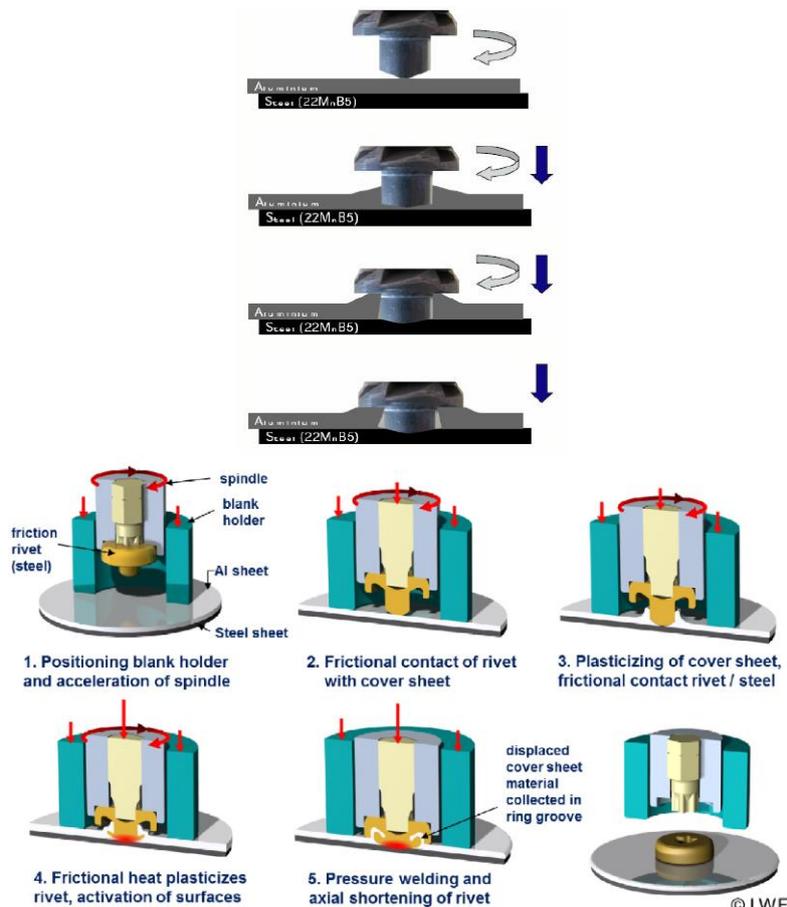
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EJOWELD® friction welding process

(Source: Ejot)

The two work pieces to be joined are placed in an overlap configuration with the softer material on top of the harder material. The joining process starts with the acceleration of a rotationally symmetrical joining part (“friction element”) to a high rotation speed (10’000 – 20’000 rpm). The rotating friction element is then pressed against the surface of the upper joining partner. The resulting frictional heat causes a plasticisation of the cover sheet and allows to penetrate the upper joining partner without any pre-hole operation or melting. When the friction element contacts the surface of the harder underlying base sheet, the friction and therefore the temperature of the friction element increases significantly. Thus also the joining element plasticises and forms the characteristic “upset”. The sliding surface of the upset cleans and activates the surface of the lower sheet. After a pre-set reduction of the length of the friction element, the rotation is stopped and the axial force is increased for a specified holding time. As a result of this “forging” process, the cleaned surfaces of the friction element and the bottom sheet form a rigid metallic bond.

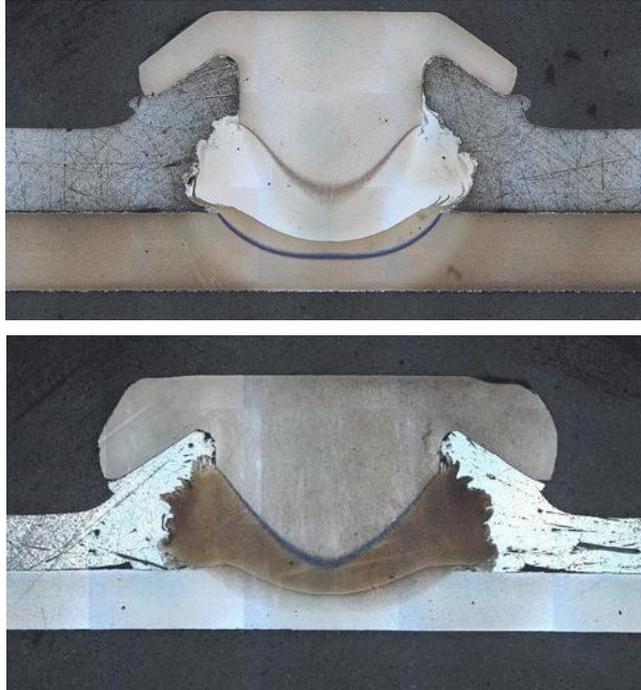


Process principle of friction element welding

(Source: LWF Paderborn)

The decreasing temperature after the completion of the friction element/base metal joint causes axial shrinking of the friction element, creating a force-lock between the friction

element and the cover sheet. In addition, the radially displaced material from the plasticised cover sheet fills the under hand groove of the friction element causing a solid positive lock. The main process parameters are the tip geometry of the friction element, its penetration depth, the force, the rotation speed and friction time.



Aluminium/steel joints produced by friction element welding

(Source: LWF Paderborn)

Compared to the existing mechanical and thermal joining processes, new fields of application arise for friction element welding with the use of highest-strength sheet metals with a tensile strength of around 1500 MPa. But also other multi-material connections will be possible using this technology.

7.2 Pressure welding processes

Different pressure welding processes are possible and have been tested. The applied pressures vary within a very wide range. In addition, also heat can be used. But except for special applications, pressure welding has found little use in industrial practice.

Forge welding is the oldest solid-state welding process. Two pieces of metal are heated to a high temperature and then joined by hammering them together. It is one of the simplest methods of joining metals, but also very versatile as it is able to join a host of similar and dissimilar metals. However, in industrial practice, forge welding has been largely replaced today by other joining technologies.

Forge welding between similar materials is caused by solid-state diffusion. This results in a weld that consists of only the welded materials without any fillers or bridging materials. Forge welding between dissimilar materials is caused by the formation of a lower melting temperature eutectic between the materials. The temperature required to forge weld is typically 50 to 90 % of the melting temperature.

7.2.1 Contact and cold pressure welding

Cold or contact welding is a solid-state welding process in which joining takes place without any fusion or heating at the interface of the two parts. In the 1940s, it was discovered that two clean, flat surfaces of similar metal would strongly adhere if brought into contact under vacuum. In practice, however, bonding is virtually impossible under most conditions, because of surface irregularities, organic surface contamination and chemical films such as oxide films.

In order to obtain proper weld efficiency, any form of contamination must be reduced to a minimum, while the contact area must be made as large as possible.

In contrast, cold pressure welding uses very high pressure at room temperature to produce coalescence of metals with substantial deformation at the joint interface. Welding is accomplished by using very high pressures on extremely clean interfacing materials. The process is readily adaptable to join ductile metals like aluminium or copper. Both butt and lap joints can be realized. But in practice, this joining method is usually limited to the realization of electrical contacts. Other applications include aluminium clad cookware although in this case, some heat (but relatively low) is applied.

Significantly improved butt welds are possible using the “multi upset principle” developed by GEC. The materials to be joined are inserted in a die and each time the machine is activated, the material is gripped by the die and fed forward. Thus, the two opposing surfaces are stretched and enlarged as they are pushed against each other. Oxides and other surface impurities are forced outward from the core of the material and a proper bond is achieved. A minimum of four upsets is generally recommended to ensure that all impurities are squeezed out of the interface.



Cold pressure welded copper/aluminium rods

Cold pressure welding is restricted to nonferrous materials. It offers a most satisfactory way of joining copper to aluminium without the formation of brittle inter-metallic phases. The joint quality is excellent because it produces a worked structure as opposed to the cast structure obtained in fusion welding. Also, there is no heat-affected zone.

7.2.2 Diffusion and hot pressure welding

Diffusion welding is a solid state welding process by which two metals (which are usually dissimilar) can be bonded together. The necessary diffusion processes involve the migration of atoms across the interface due to the existing concentration gradients. The two materials - whose surfaces must be machined as smooth as possible and kept free from contaminants - are pressed together at an elevated temperature; usually between 50 and 70 % of the melting point. The pressure is used to relieve the void that may occur due to the different surface topographies. The process does not involve plastic deformation, melting or relative motion of the parts. A filler metal may or may not be used (e.g. in form of electroplated surfaces). Once clamped, pressure and heat are applied to the components, usually for many hours; preferably under vacuum or inert atmosphere. When a layer of filler material is placed between the faying surfaces of the parts being joined, the term “diffusion brazing” is generally used.

Hot pressure welding, on the other hand, is a solid state welding process where coalescence occurs due to the application of heat and sufficient pressure to produce substantial plastic deformation at the interface. The deformation of the faying surfaces induces cracks in the surface oxide films and increasing areas of “clean” metal are developed. Welding is accomplished by diffusion across the clean regions of the faying surfaces. This type of operation is normally carried out in closed chambers where vacuum or an inert atmosphere can be used. The parts are brought to contact and upset together under pressure, usually by hydraulic equipment.

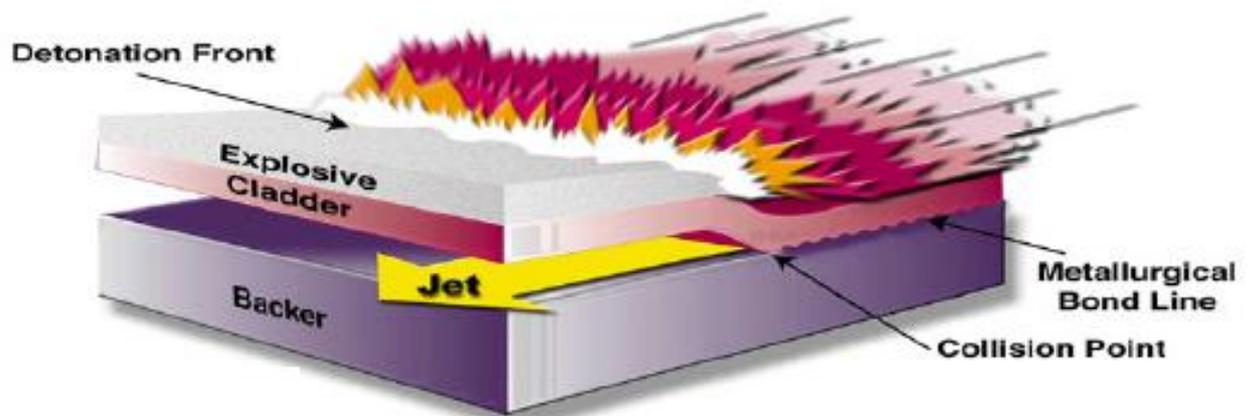
A variation is the hot isostatic pressure welding method. In this case, the pressure is applied by means of a hot inert gas in a pressure vessel.

7.2.3 Explosion welding

Explosion welding is a solid state welding process where coalescence is accomplished by the high-velocity impact of one of the components onto the other part. The moving part is accelerated by the controlled detonation of chemical explosives. Due to the nature of this process, the producible joint geometries must be simple (typically plates or tubes).

The impact energy plasticises the materials, forming a weld. Although the explosion generates intense heat, there isn't enough time for the heat to transfer to the metals, i.e. there is no significant increase in the metal temperature and, thus, no significant change in the material characteristics.

The generated heat originates from several sources. One source is the energy expended in the collision. Another source are the shock waves associated with the impact which produce extremely high pressures. The shock waves spread out and create a "material wave" at the joining plane. Heat is also released by the plastic deformation associated with jetting and ripple formation at the interface between the parts being welded. At the collision point, a thin jet of material is heated to a high temperature, causing melting and mechanical mixing at the interface. Surface jetting leads to pronounced plastic interaction between the two metals, a necessary condition for a high quality weld.



Explosion welding process

(Source: Dynamic Materials Corporation)

Explosion welding creates a strong weld between almost all metals. The surfaces have to be simply ground to achieve a smooth finish, oxides and other impurities are expelled, leaving the surfaces metallurgically pure and creating the metallurgical bond. Aluminium can be effectively joined with itself and also with other metals, e.g. steel and copper. The strength of dissimilar weld joints is equal to or greater than the strength of the weaker of the two metals.

Explosion welding is only used in a few applications. Most important is the cladding of a thick base metal plate with another metal. Also bimetallic inserts between dissimilar metals are often produced by explosion welding.

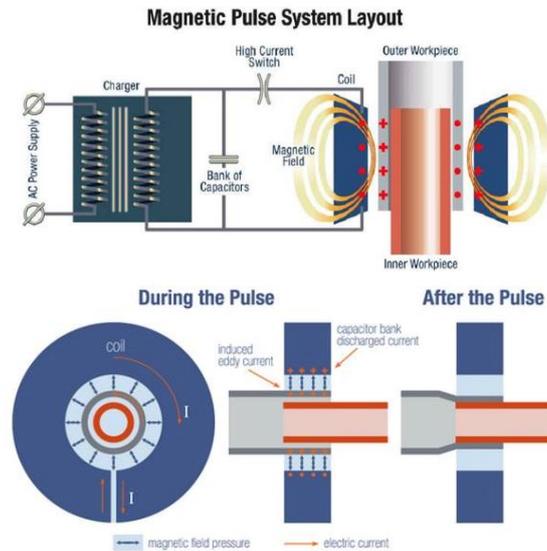
7.2.4 Electromagnetic pulse welding

Electromagnetic pulse welding uses electromagnetic forces to deform and join the work pieces. It is an automatic welding process which can be used for tubular and sheet metals placed in the overlap configuration. It is a process similar to explosion welding, both techniques rely on a high impact rate to create the bond and the joint boundary display a ripple effect.

A typical magnetic pulse welding system includes a power supply, which contains a bank of capacitors, a high-speed switching system and a coil. The power supply is used to charge the

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capacitor bank. When the required amount of energy is stored in the capacitors, it is released into a coil during a very short period of time (typically 10 - 15 μ s). The discharge current induces a strong transient magnetic field in the coil, generating a short, but high magnetic pressure which causes one work piece to impact onto the other work piece. Extremely high velocities (600 – 1000 m/sec) can be produced over a distance of a few millimetres.

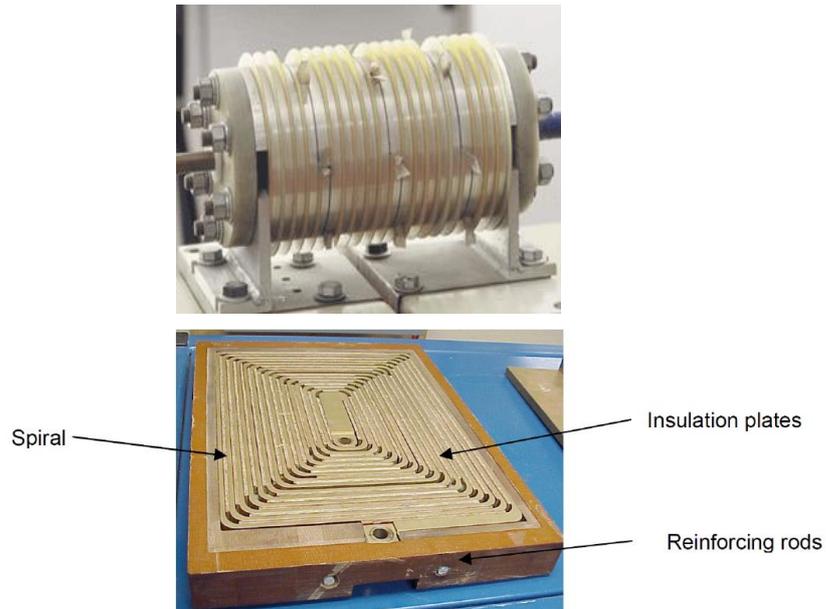


Electromagnetic pulse welding of tubular work pieces

(Source: PST)

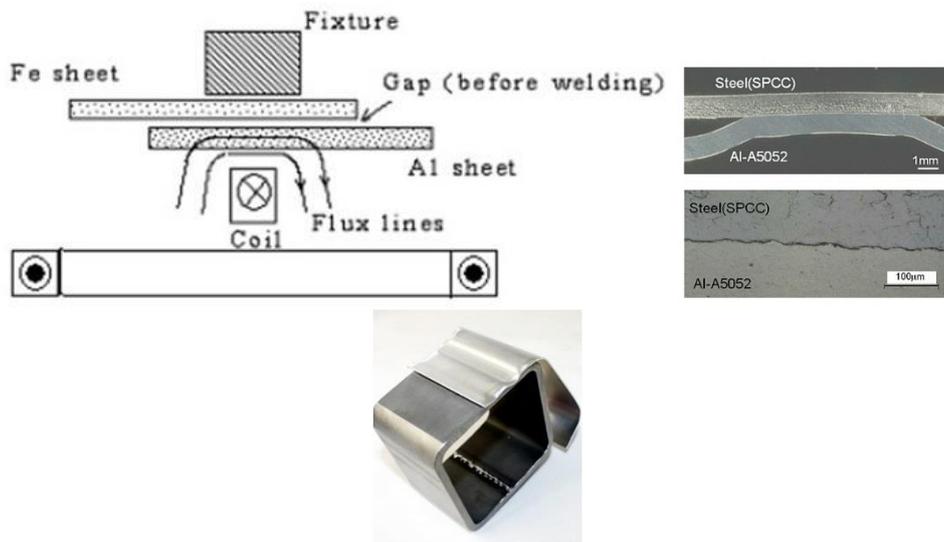
The process parameters of the magnetic pulse welding process are the geometrical parameters (air gap between both parts, axial position of the work pieces in the coil or overlap distance of the work pieces) and electrical parameters (charging voltage and discharge frequency). Magnetic pulse welding needs on average a 1 mm gap between the tube surfaces to achieve a successful weld. The reason is that the metal needs time to build up to its terminal speed at impact. If the metals are too close, a good crimp can be achieved, but not a weld. Also a minimum of two to three times the thickness of the outer material is needed to achieve a weld. Standard cleaning is generally sufficient for magnetic pulse welding as the speed of the created wave breaks down light oxide layers and ejects any dirt from the weld area.

Magnetic pulse welding is a "cold" joining process. The temperature increase is very local (in the order of 50 μ m), i.e. the temperature of the outer surface of the work pieces reach no more than 30 - 50 $^{\circ}$ C. There is no heat affected zone is created, and the metal is not degraded. The weld becomes the strongest part of the assembly. Another advantage of magnetic pulse welding is the contact-free operation: there are no marks of the forming tools.



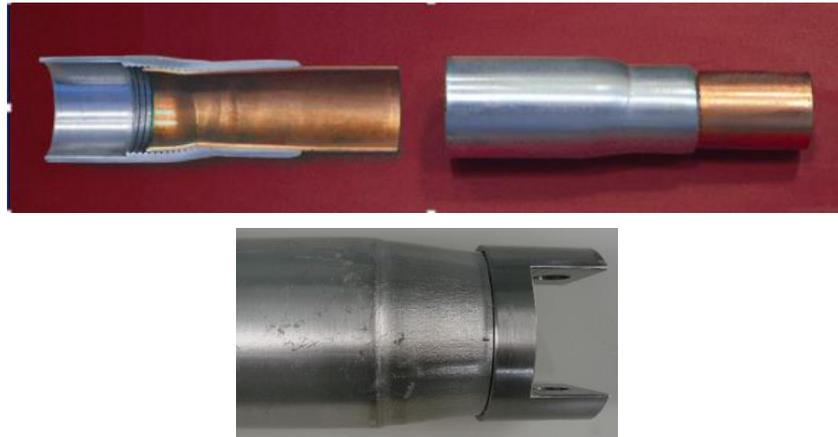
Coil for forming or welding tubular (left) and sheet work pieces (right)
 (Source: PST)

The process is commercially used for joining cylindrical work pieces in the overlap configuration, but it can also be used for sheet overlap welding. Tubular joints are the easiest task, from both the energy consumption and coil design viewpoints. The joint area needs sufficient clearance for the coil to surround the joints. Most commonly are closed coils where the part is inserted, i.e. at least one end should not have a diameter much larger than the joint diameter. But also swivelling coils have been developed which can clamp over parts that cannot be inserted into a closed coil. A critical aspect is always the lifetime of the relatively expensive coils, i.e. there are today few practical applications.



Electromagnetic pulse sheet welding
 (Source: PST)

The magnetic pulse welding technique is adaptable to a wide variety of electrical conductive metals, however, for joining materials with a lower electrical conductivity, a higher energy is required. Similar and dissimilar metals have been successfully welded. The cross section of a weld shows many resemblances with this of an explosion weld.



Aluminium/copper (left) and aluminium/steel joints (right) produced by magnetic pulse welding

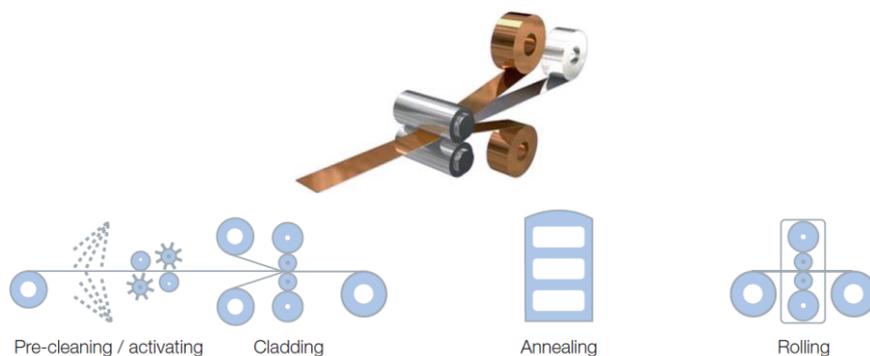
(Source: PST)

The magnetic pulse technology also can be used for joining or crimping parts that do not necessarily need a metallurgical bond, such as a metal to a non-metallic part. It can create a mechanical lock on ceramics, polymers, rubber, and composites, so adhesives, sealants, and mechanical crimps are not necessary. With the process, metal is basically shrink-wrapped over the components.

7.2.5 Roll bonding

Roll bonding (or roll welding) is a solid state welding process which joins two or more metals by rolling. The starting materials are generally pre-heated and sufficient pressure must be applied by the rolls to cause deformation at the faying surfaces. Coalescence occurs at the interface between the two parts by means of diffusion at the faying surfaces. Thus a subsequent diffusion anneal is often added. Surface cleanliness of the starting materials is most important, i.e. the individual strips are usually chemically or mechanically cleaned to provide contaminant-free surfaces. The plates or strips then pass through either a hot mill (e.g. for the production of aluminium brazing sheets) or a highly customized cold rolling mill designed specifically for cladding.

In practice, roll bonding is exclusively used in the fabrication of semi-finished products. Apart from roll bonded aluminium brazing sheets, there are also roll-clad plates and sheets combining aluminium with with other metals, in particular copper and steel.



Production of clad metals by roll bonding

(Source: Wickeder Westfalenstahl)

7.2.6 Co-extrusion welding

Co-extrusion welding is a solid-state process that produces a weld by forcing both materials together through an extrusion die. The process is typically carried out at elevated temperatures to improve welding, but mainly to lower the necessary extrusion pressure.

The extrusion technology is widely used to produce aluminium profiles with different cross sections. Extruded profiles consisting of aluminium and another metal (e.g. steel or copper) can be produced by the introduction of a designed metal strip or wire into the extrusion chamber. Proper control of the extrusion conditions leads to the formation of a metallic bond when the plasticised aluminium and the solid additional material are simultaneously pressed through the extrusion die. Also in this case, coalescence occurs at the interface between the two materials by diffusion at the faying surfaces.

7.3 Ultrasonic welding

Ultrasonic welding differs from the pressure welding technique described above in that the applied pressure is relatively small, i.e. the contact pressure between the parts being joined is significantly lower than either in friction welding or pressure welding processes. Ultrasonic welding creates a solid state weld by the local application of high-frequency vibrations as the work pieces are held together under pressure. It is a cold welding process, since the heat generated by the ultrasonic energy is not essential to the formation of the joint. Welding occurs when the ultrasonic tip that is clamped against the work pieces oscillates in a plane parallel to the weld interface.

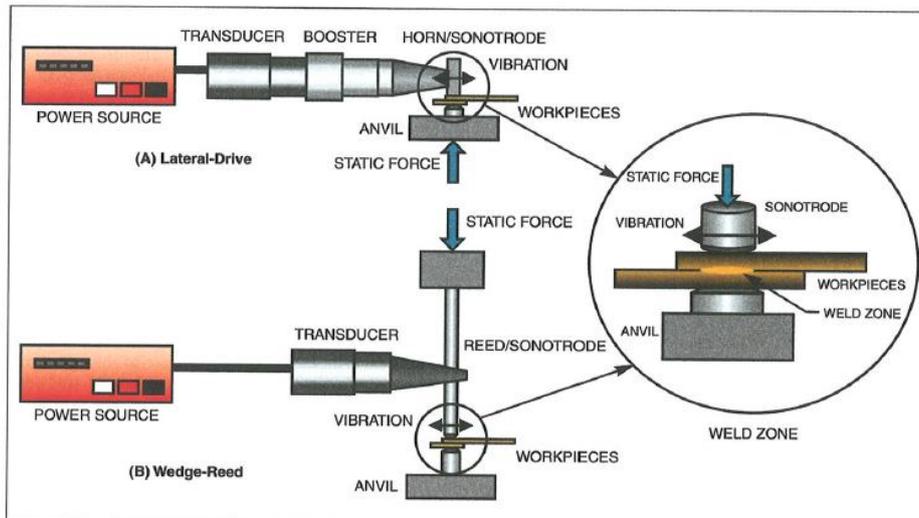
Ultrasonic welding has been used to join metals since the 1950s. It is a flexible and fast joining process, characterised by low energy consumption and capital cost. Typical weld times range from 0.25 - 2.0 seconds, while the cycle time (including tool actuation) ranges from 1 - 3 seconds. Whereas the lap shear strength values are slightly below that achieved in conventional resistance spot welding, the cross tension strength values are significantly lower. A longer welding time results in a more even welded connection, a higher yield limit and a higher fracture strength.

Soft, low-yield strength materials work best with ultrasonic welding. It is particularly suited for joining aluminium and its alloys with each other as well as for joints with other metals, in particular copper. The process is restricted to relatively thin materials (wires and thin foils). However, it has been shown that ultrasonic welding performs well on aluminium materials with thicknesses up to 1.0 mm. The process would be also capable of joining thicker materials; but due to power limitations of the commercially available systems, consistent high quality welding of thicker aluminium sheets (1 mm or higher) is today not yet possible.

Prior to welding, the welding system clamps the work pieces between weld tip and anvil. The static pressure force is then superimposed by a high frequency oscillating shearing force. However, as long as the forces within the work pieces are below the limit of linear elasticity, the pieces do not deform. The shearing forces break and disperse contaminants and oxide layers at the weld interface. Thus, mechanical and chemical surface cleaning is not necessary (except removal of excessive oil or other lubricants). Surface coatings (e.g. coated wire) and impurities behave in a similar manner. At the same time, local asperities are deformed and sheared due to the friction-like motion; clean metal surfaces are exposed and a solid-state bond forms as a result of atomic diffusion. The further oscillation leads to the growth of the deformed zone at the interface until a large welding area has been produced.

The minute deformations lead to a moderate temperature increase at the interface. But there is no fusion as long as the pressure force, the amplitude and the welding time are properly adjusted. It is estimated that local peak temperatures of 35 – 50 % of the melting point of the parent metal are reached.

The vibratory energy that produces the minute deformation comes from a transducer which converts high-frequency alternating electrical energy into mechanical energy. A number of methods, such as spot, torsion, seam, and micro welding, exist to deliver ultrasonic energy to a weld joint.

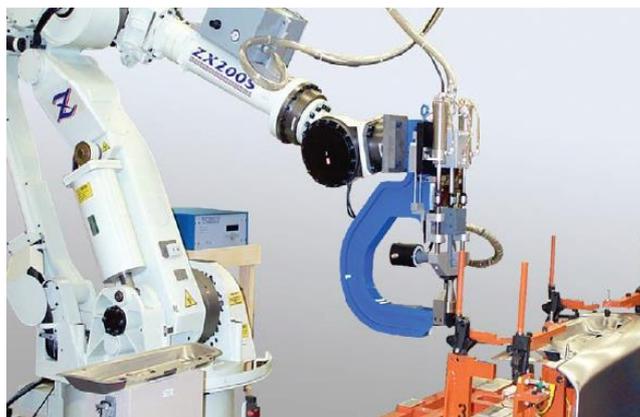


Lateral drive and wedge-reed ultrasonic welding systems

(Source: EWI)

The most relevant method is spot welding using either the lateral-drive or the wedge-reed system. The sonotrode couples with the work pieces in a manner sufficient to transmit vibratory energy. In the lateral drive system, this task is accomplished using a knurled surface which is machined into the tip of the sonotrode that presses into the work piece when a force is applied. The anvil which has a knurled surface similar to the sonotrode is commonly used to hold the other work piece stationary. The anvil and its support structure must be strong enough to resist both the static clamping force and the shear forces generated at the weld interface during a weld cycle.

In the wedge-reed system, the transducer and the wedge vibrate in a longitudinal mode, but drive the reed into a bending vibration mode. The tip is replaceable and contains a knurl pattern used to grip one work piece. The design of the anvil is usually rigid, but the anvil can also vibrate in a bending mode out of phase with the reed to increase the net relative motion between the work pieces. Wedge-reed systems have been adapted to C frames to improve access and automation integration for automotive applications.



WELDMASTER™ C frame ultrasonic spot welder

(Source: Sonobond Ultrasonics)

The parameters commonly used for ultrasonic welding are:

- **Vibration frequency**
The frequencies used in ultrasonic welding typically range from 15–60 kHz, but can be several hundred kHz for micro-welding applications. However, frequencies above 20 kHz may not provide the power required for joining aluminium sheets of 0.8 mm or greater.
- **Vibration amplitude**
The vibration amplitude is the linear motion of the weld tip, parallel with the faying surfaces. Typical peak-to-peak displacements are of the order of 20 - 100 µm. As the

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amplitude increases, so does the power requirements to drive the system. In most systems, amplitude is a controlled variable, able to be set on the power supply. In some systems, input power is the controlled variable, with the resulting amplitude dependent on part and material conditions.

- **Static weld force**

Typically, the static force which clamps the faying surfaces together ranges from 500 - 5000 N. It is generally delivered by a pneumatic cylinder.

- **Welding power, energy and time**

Power, energy and time during a welding cycle are interdependent. Typically, one of these three variables is chosen as the process control variable, while the other two variables are monitored for weld quality control.

- **Tooling**

Ultrasonic welding schedules are generally developed on a case-by-case basis. Weld tip designs vary widely in terms of the design of the knurl features, so that a change in process parameters is typically required if tip designs change. Generally speaking, as the footprint of the knurl area increases, so do the power requirements of the weld system for achieving an acceptable weld.

Ultrasonic welding requires the use of a lap joint. The overlap can be minimized because only a few millimetres of material around the weld tip are required for a suitable weld. A disadvantage is that the welded parts have markings on both sides of the joint due to the weld tip and the anvil knurl indentations. The spot welds can be overlapped or spaced at virtually any interval.

When considering joint design, the thickness of the thinner work piece is most critical. Dissimilar thickness joints can be achieved if the thinner work piece does not exceed the force and power capabilities of the welding system. As a work piece thickness increases, more static clamping force and higher peak powers are required to produce an acceptable weld. If possible, the thinner work piece should be next to the weld tip. Transferring vibration energy into the work pieces is inherent to the ultrasonic process and work piece resonance must therefore be considered. If resonant vibrations exist, they can be minimized by different measures.

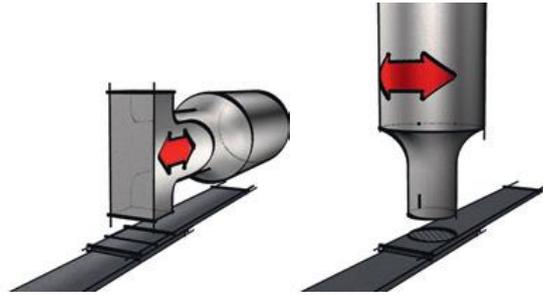
The most important practical application of ultrasonic welding in the automotive industry is making electrical connections between aluminium or copper wires /cables and end pieces, e.g. to be used in battery cables and wire harnesses.



Aluminium cable (cross section 120 mm²) ultrasonically welded to a Ni-plated copper end piece

(Source: Telsonic)

A new development for such applications is the PowerWheel® technology where the sonotrode is excited by a torsional oscillator. The welding action is carried out in a rocking movement directly at the weld. This means that the maximum amplitude is always at the centre of the weld area and the power output can be precisely focused. Due to the new construction of the sonotrode and its movement, it is possible to transfer significantly more energy into the weld than by using the conventional linear movement.



High frequency longitudinal movement in the linear axis (left) and oscillating movement around a central axis (right) in the μm range

(Source: Telsonic)