

ADVANCES IN TOOLING MATERIALS FOR FRICTION STIR WELDING

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ABSTRACT.

Since its invention at TWI in 1991, Friction Stir Welding (FSW) has become a major joining process in the aerospace, railway and ship building industries especially in the fabrication of aluminium alloys. The process uses a spinning non-consumable tool to generate frictional heat in the workpiece. Worldwide, there are now over 135 licensees of FSW and new techniques and applications are being developed daily. This paper looks at some current uses, variations in tool design, improved welding techniques and new tool materials being developed for the welding of more difficult aluminium alloys to give increased tool life.

1. INTRODUCTION

Friction Stir Welding was invented and patented by The Welding Institute in 1991. The process uses a spinning, non-consumable tool, similar to a taper reamer, to generate frictional heat in the workpiece. By pressing this tool into contact with a seam to be welded, the base metal heats up and once it reaches about 80% of its melting point it becomes soft and deforms easily. A typical FSW system is shown in Fig 1¹.

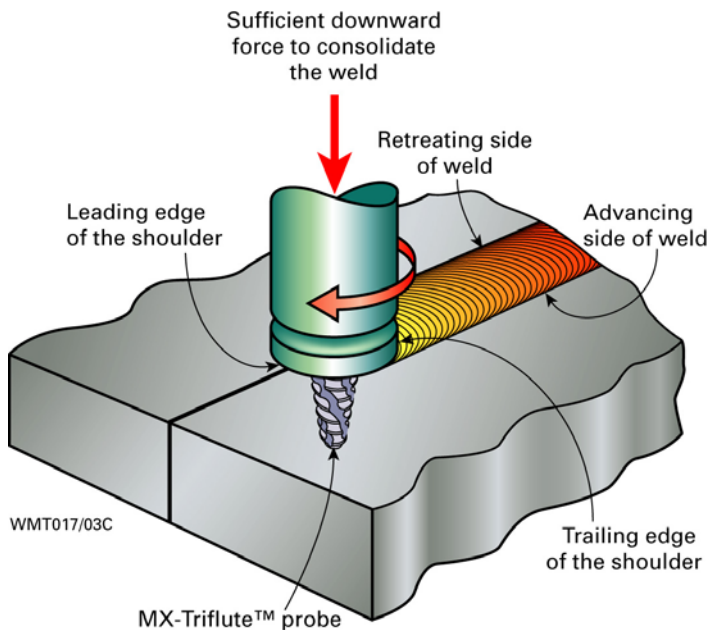


Fig 1¹
The principle of Friction Stir Welding

By keeping the tool rotating and moving it along the seam to be joined, the softened material is literally stirred together forming a weld without melting. These welds require low energy input and are without the use of filler materials and distortion. Initially developed for non-ferrous materials such as aluminium, by using suitable tool materials the use of the process has been extended to harder and higher melting point materials such as steels titanium alloys and copper. Since its conception in 1991 there have been considerable advances in process technology and there are now over 135 licensees of the process and over 1500 subsidiary patents have been filed. This paper will concentrate on improvements for tooling for the friction stir welding of aluminium alloys.

2. COMMERCIALISATION

Boeing in the USA was amongst the first companies to realise the commercial benefits of the process and used it to fabricate fuel tanks used in its space programme, Fig 2. By changing from conventional TIG to FSW for the welding of their rocket fuel tanks, Boeing achieved a staggering 99% reduction in welding costs. Clearly, the process has excellent possibilities and thus many licensees are rapidly developing improved tooling and looking for new applications. In the conventional tungsten inert gas welding process, except in the case of thin sheet, material is machined from the ends of plates to be

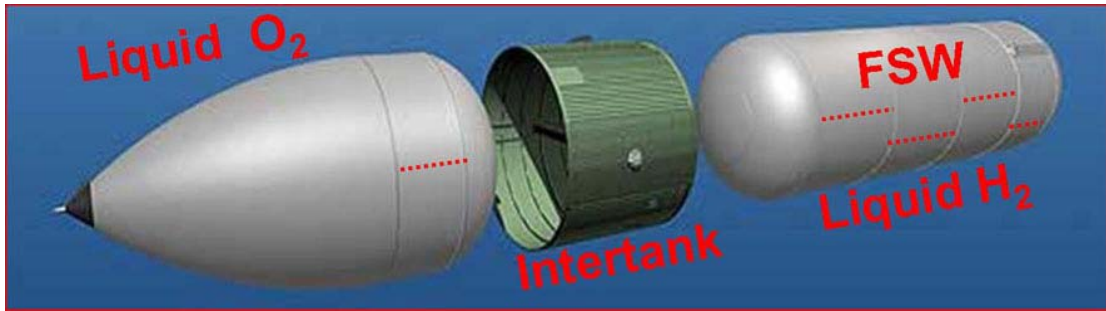


Fig 2. Rocket fuel tanks fabricated by FSW

joined to form the weld preparation only to be replaced by several runs of filler material to complete the weld. With FSW, clean cut straight edges are butted or lapped together, held in position by a suitable clamping arrangement and welded together purely by running a tool along the seam. The process is now in regular use in Japan for the production of aluminium railway rolling stock, Fig 3 and for aluminium ship construction, Fig 4. It is also used to weld sections of the latest Bang and Olufsen loud speakers.



Fig 3. Japanese railway rolling stock fabricated from aluminium by FSW.



Fig 4. Aluminium ships constructed in Japan using FSW

3. TOOL DESIGN

Tools consist of a shoulder and a probe which can be integral with the shoulder or as a separate insert possibly of a different material. The design of the shoulder and of the probe is very important for the quality of the weld. The probe of the tool generates the heat and stirs the material being welded but the shoulder also plays an important part by providing additional frictional treatment as well as preventing the plasticised material from escaping from the weld region. The plasticised material is extruded from the leading to the trailing side of the tool but is trapped by the shoulder which moves along the weld to produce a smooth surface finish. Clearly, different materials and different thicknesses will require different profile probes and welds can be produced from just one side or by welding half the thickness then turning over to complete the other side. Some typical Whorl™ type probes are shown in Fig 5² which can be designed to weld in excess of 60mm thick plate at higher speeds than conventional pin type probes.

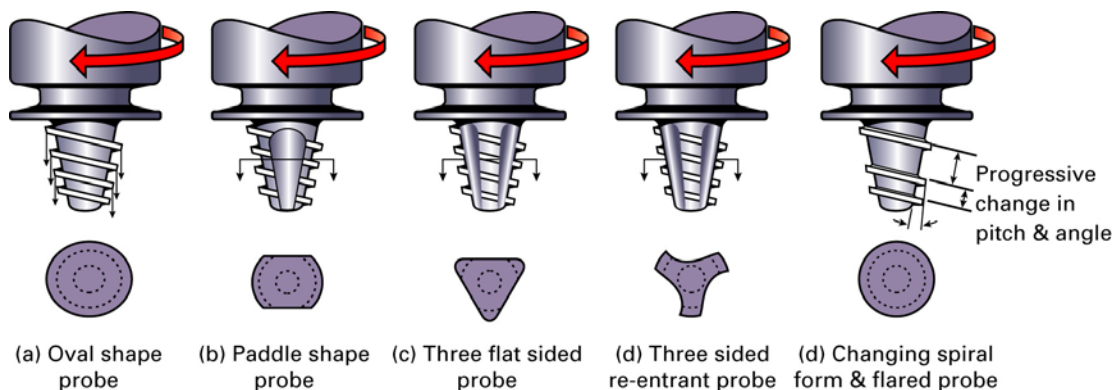
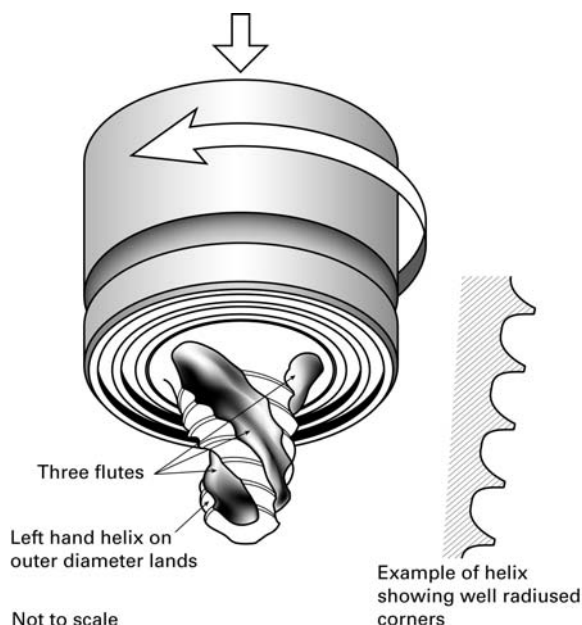


Fig 5 Basic variants on the Whorl™ type probes².

A variation on the Whorl™ probe is the MX-Triflute™ Fig 6² which can produce a better weld than the Whorl™ tool with a narrower, more parallel sided weld region.



**Fig 6.
A Typical MX-Triflute™ probe².**

The improvement can clearly be seen in Figs 7 & 8 of welds in 25mm thick 6082-T6 aluminium alloy welded at 4mm/second. The Whorl™ tool, Fig 7 tending to produce an 'union ring' effect whereas the MX-Triflute™ weld Fig 8, is narrower and more uniform².

Advancing side

Retreating Side

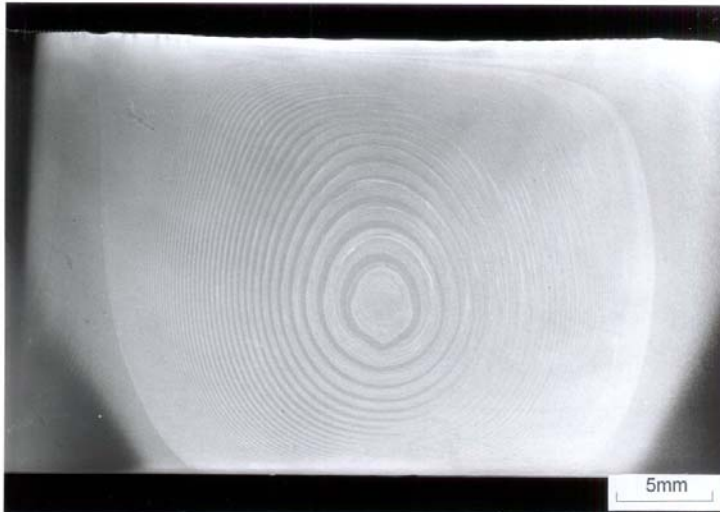


Fig 7

Macrostructural features in the weld region². Weld produced in 6082-T6 condition aluminium alloy using a Whorl™ probe at a weld travel speed of 4mm/sec.

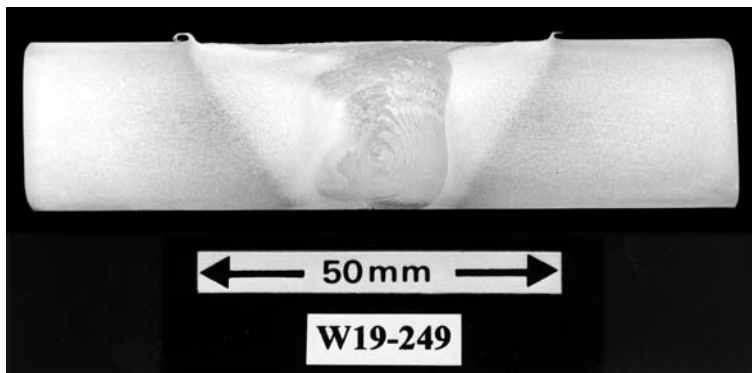


Fig 8

Macrostructural features of a weld as in Fig 7 but using a MX-Triflute™ probe a a weld travel speed of 4mm/sec.²

Retreating Side

Advancing Side

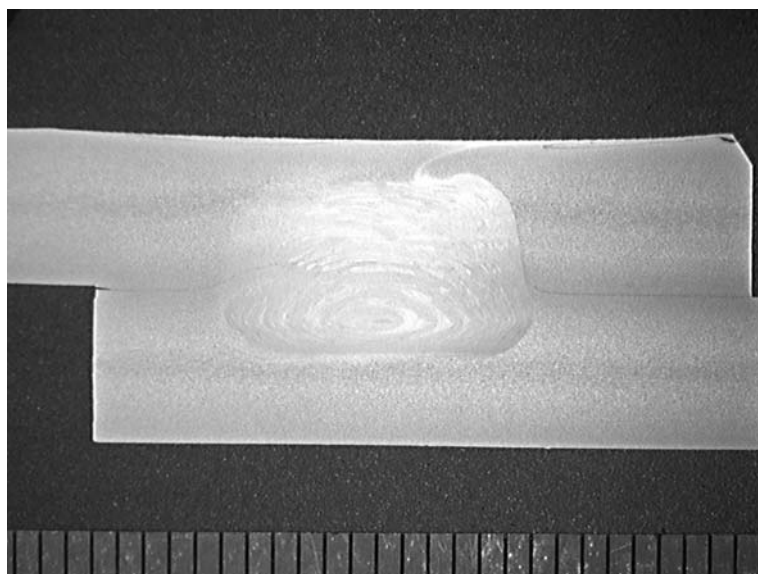


Fig 9

Macrosection of a Lap weld in 6mm thick 5083-0 condition aluminium alloy welded at 4mm/sec using a Flared-Triflute™ tool.²

Friction stir welding is also used to carry out lap welds where the plates to be joined are overlapped and the probe run through the top sheet and into the bottom as illustrated in Fig 9.

With the lap welds it is desirable to increase the width of the weld region to achieve a better bond. This is achieved by re-design of the tools as in Flared-Triflute™ as illustrated in Fig 10.

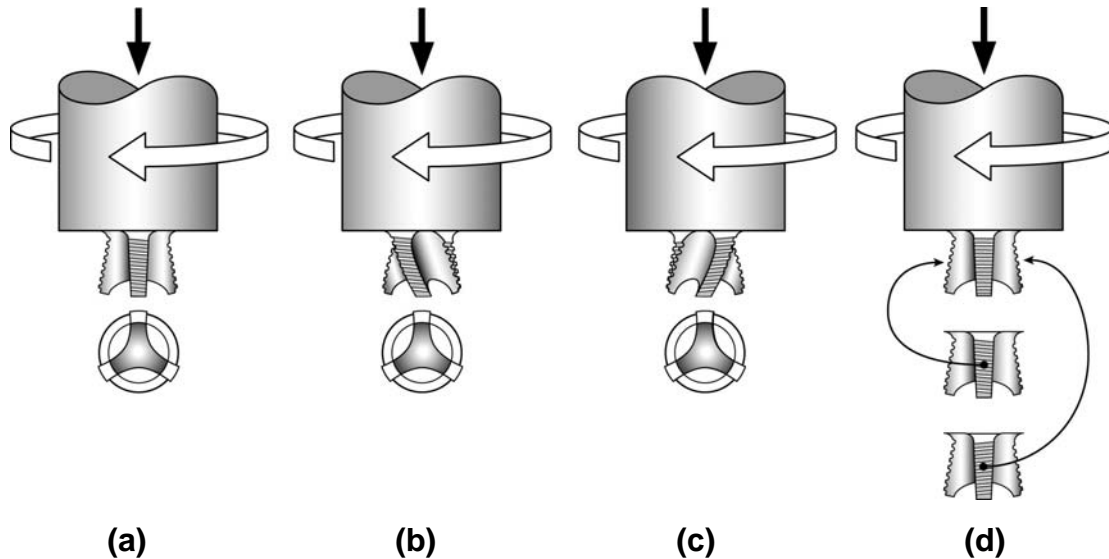
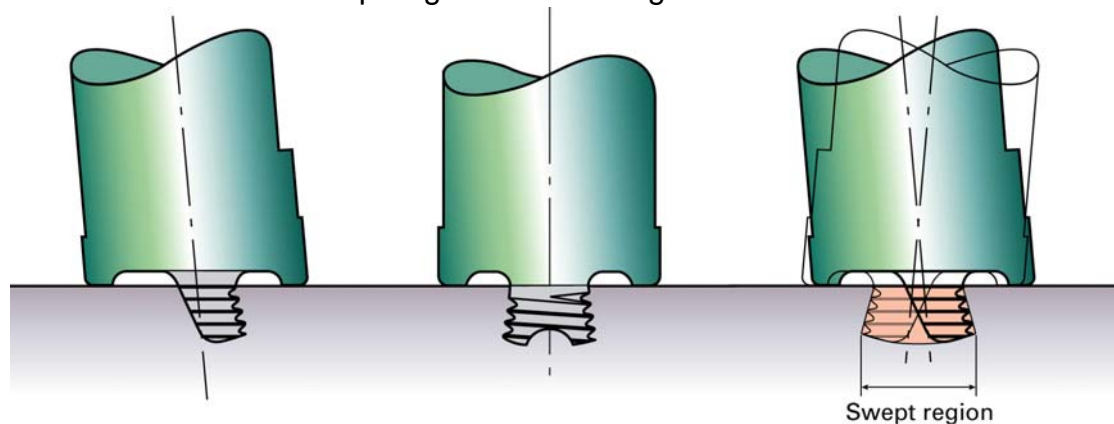


Fig 10. Basic variants of the Flared-Triflute™ type probes².

The fluted tool can have flutes neutral (a), left (b) right (c) handed as illustrated or a combination of all three at 120° intervals one neutral, one left and one right on an individual probe (d). The pitch of the ridges is also important in determining the properties of the tool. The ridges enable plasticised material to be deflected in the direction required especially to deflect oxide from the centre of the weld to the surface. To increase the spread in lap welds still further the probe was angled with respect to the tool axis in a variant of FSW known as Skew-Stir™ and illustrated in Fig 11². It will be seen that the swept region is much larger than with conventional



tooling.

Fig 11. Basic principle of Skew-Stir™ showing different focal points.²

Another variation is known as Re-Stir™ which is similar to the conventional stir welding process but the tool continually reversed throughout the welding process either within one revolution or after 1 or more full revolutions. This process is illustrated in Fig 12 and the weld produced in Fig 13.²

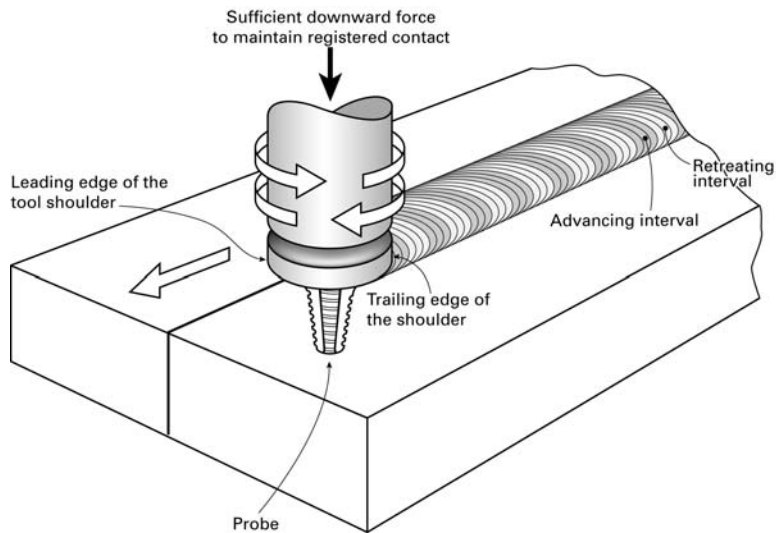


Fig 12
The basic principle of Re-Stir™ showing the reversal techniques.²

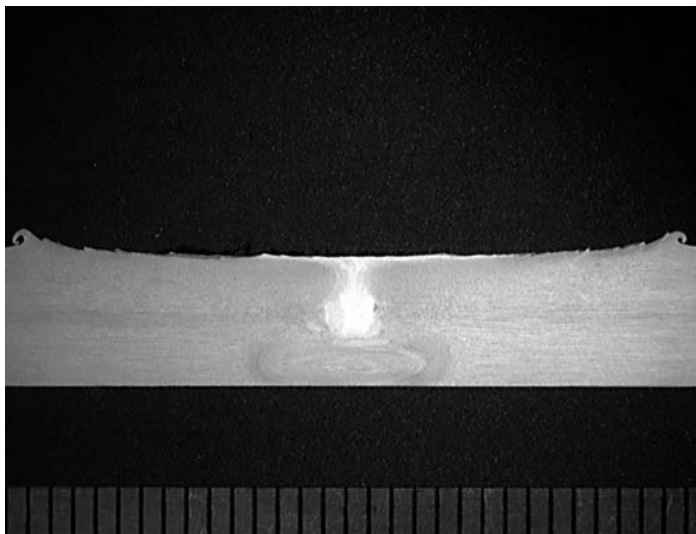


Fig 13
Macrostructure of a Re-Stir™ butt weld produced at a weld travel speed of 4.2mm/sec using 8 revolutions per interval.²

Further variations being investigated involve a separate shoulder and probe both being rotated in the same direction but at different speeds.

Clearly, the variations in tool design are infinite and combinations of shoulder diameter, shoulder profile, probe length, diameter and profile, are all important parameters in determining the speed of welding and the quality of the finished weld. Another important parameter in the determination of the suitability of a tool for a particular application is the tool material itself. Welding is carried out around 70 – 90% of the material melting point so it is important that the tool material has sufficient strength at this temperature otherwise the tool can twist and break. With conventional aluminium alloys tools made of tool steel give good results but with the harder alloys something stronger is required. Such as super alloys, oxide dispersion strengthened alloys (ODS) and refractory

metals such as molybdenum alloys. However, although these materials have superior melting properties they are more difficult to fabricate especially into some of the complex shapes described above. Difficulties in fabrication lead to increased tool cost and it is often desirable to sacrifice some durability for a reasonably priced tool. In an ideal world the user requires to produce very long welds without tool wear or degradation occurring so some of the more exotic materials and designs could see increased usage.



Fig 14
Welding 40mm thick 6082 aluminium alloy using a molybdenum probe.

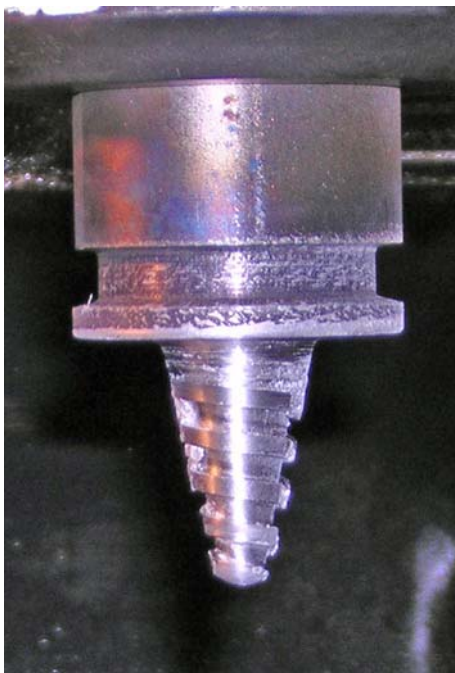


Fig 15
A molybdenum tool of basic design after welding 40mm thick 6082 alloy as in Fig 14. No tool wear occurred.

Fig 14 shows a basic molybdenum tool welding 40mm thick 6082 alloy. Because molybdenum has a fibrous structure with the fibres running parallel to the tool axis, the design of the tool must be simplified to avoid thin sections and sharp angles. However, the material shows promise and an excellent weld was produced with no tool wear being observed. The probe after removal from the weld is shown in Fig 15.

On removal of any FSW probe from the weld, a hole is left. There are several ways of dealing with this. It can be filled in with conventional TIG filler, the part of the weld with the hole can be cut off and discarded, or the weld can be run off into a scrap piece of material which is then discarded. Another method is to gradually remove the probe at the end of the weld but this is not recommended as a full penetration weld is not then produced in this region.

3. OTHER VARIANTS OR TWIN STIR™

A problem occurring with conventional friction stir welding is that the plates to be joined require extensive clamping both in the vertical and horizontal directions to prevent them being separated by the rotating probe instead of being welded. A new process has recently been invented by TWI in which two contra rotating probes are used to carry out the weld^{2,3}. These can be in tandem as illustrated in Fig 16, especially useful for lap welding or one on each side of the weld as in Fig 17.

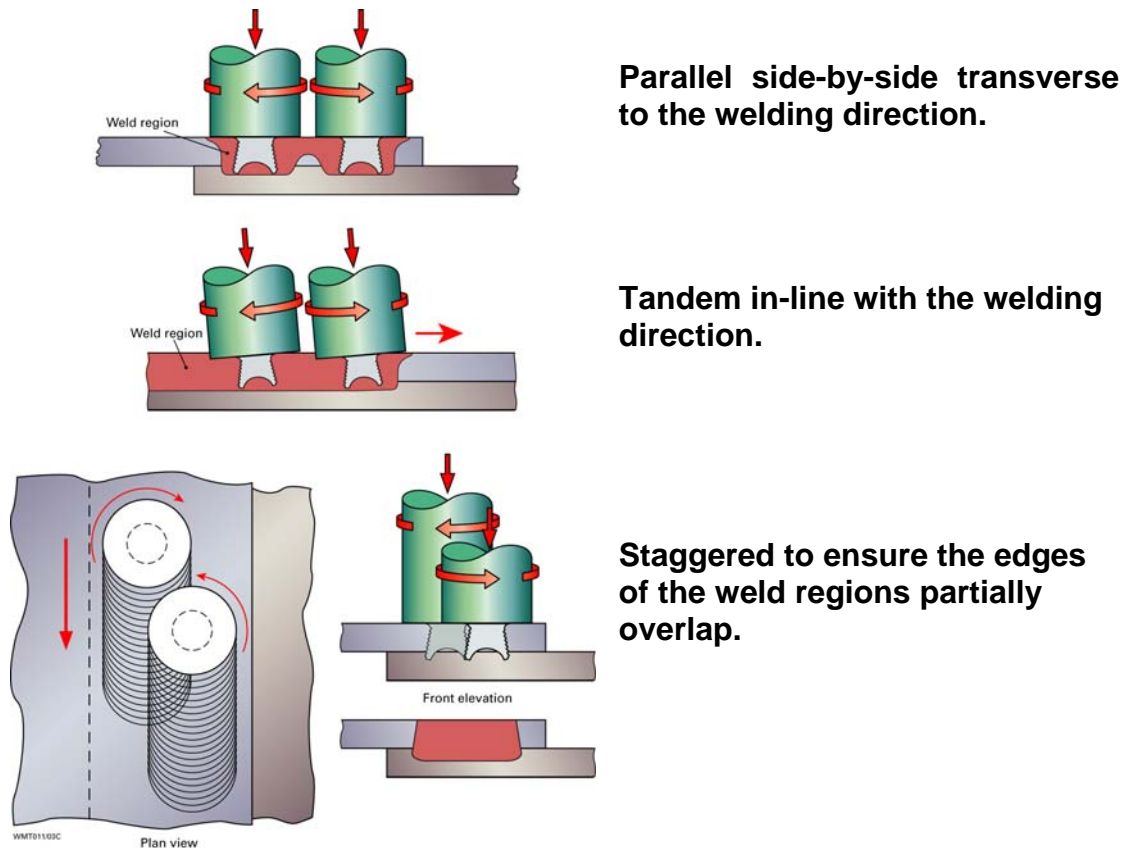


Fig 16. Twin-Stir™ variants^{2,3}.

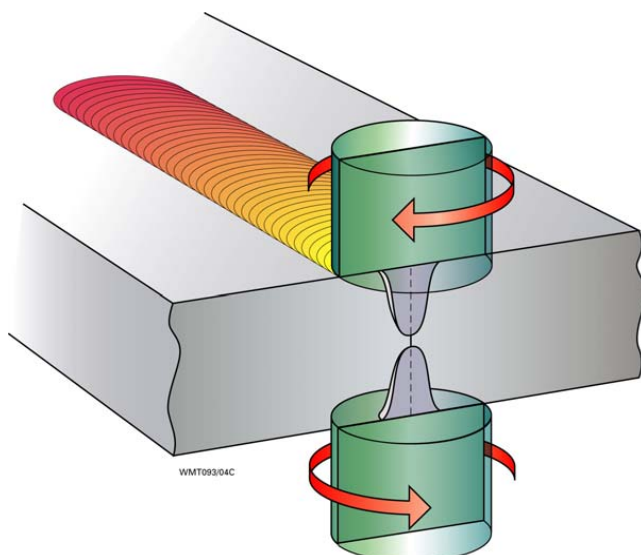


Fig 17³.
Simultaneous double side stir techniques with contra-rotating probes.

The weld head used is illustrated in Fig 18^{1,3}.



Fig 18
Twin-stir™ prototype head assembly¹.

Which ever technique is used the torque generated by one tool is counteracted by the other and very little clamping pressure is required to keep the plates in position for welding. The distance between the tools also helps to fix the position. This process is known as Twin-Stir™ minimises complex clamping arrangements and opens the door to producing very large plates, perhaps the whole plate for a ship's hull can be produced in one piece and then fabricated to shape. Currently the sizes of the clamping arrangements determine the size of welded structure and, although length of plate is no longer a problem, the plate being passed between the clamps after welding to allow location and clamping of the next section, the actual width of the clamps must be of a finite size so there is a restriction in the maximum width of plate producible. With Twin-Stir™ many of the clamps can be replaced with simple conventional tack welds. The welds produced are excellent. Fig 19¹ shows the surface of a typical Tandem Twin-Stir™ lap weld in 6083-T6 aluminium alloy and Fig 20¹ the cross section.



Fig 19³
The surface of a typical tandem Twin-stir™ weld in 6082-T6 aluminium alloy¹.

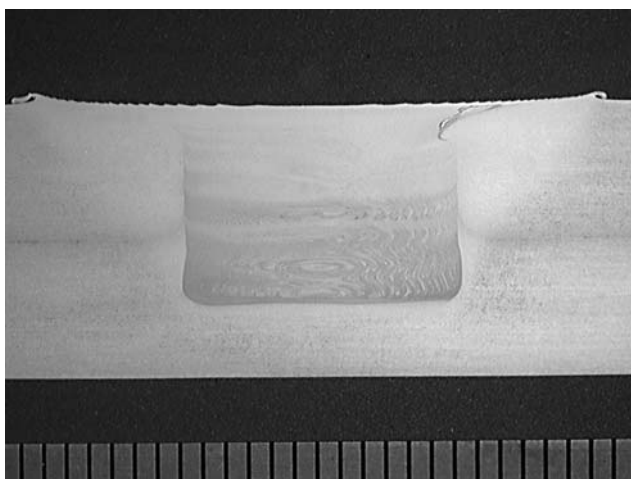


Fig 20³
Macrosection of Tandem Twin-stir™ weld in 6mm thick 6082-T6 aluminium alloy¹.

However, one disadvantage of Twin-Stir™ is that there are two exit holes produced instead of one, Fig 21^{1,3}, which require treatment as outlined above.



Fig 21^{1,3}

Tandem Twin-stir™ lead and follower exit holes¹.

4. DISCUSSION AND CONCLUSION

Friction stir welding is an exciting process for welding pieces of material together as it requires little or no weld preparation, operates at relatively low temperatures so gives off no fumes, is environmentally friendly, energy efficient and can be used by only semi-skilled personnel to produce a satisfactory weld. The process is suitable for welding plate, pipe or fabrications and has been used to build up components of complex shape but this is the topic of another paper. As TIG and MIG welding processes replaced most of the original stick welding operations in the past, it is envisaged that FSW will displace many of the current TIG or MIG welding applications with reduced costs and superior weld quality. As the welding is carried out below the melting point of the material there is minimum heat affected zone with the reduced ductility as observed with conventional techniques. This can be particularly advantageous with some aluminium alloys as segregation can occur when the material is melted using conventional welding techniques.

5. ACKNOWLEDGEMENTS

D.G Staines of TWI for help in evaluating tool designs and materials.

6. REFERENCES

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