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Research Article

Analysis of Tools used in Friction Stir Welding process

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Abstract

A relatively new joining process, friction stir welding (FSW) produces no fumes; uses no filler material; and can join aluminium alloys, copper, magnesium, zinc, steels, and titanium. FSW sometimes produces a weld that is stronger than the base material. The tool geometry plays a critical role in material flow and governs the transverse rate at which FSW can be conducted. The tool serves three primary functions, i.e., (a) heating of the work piece, (b) movement of material to produce the joint, and (c) containment of the hot metal beneath the tool shoulder. Heating is created within the work piece by friction between both the rotating tool pin and shoulder and by severe plastic deformation of the work.

Keywords: *Tool materials; Tool shoulder; Tool pin; Friction Stir Welding*

1. Introduction

Friction stir welding (FSW) is a relatively new joining process that has been used for high production since 1996. Because melting does not occur and joining takes place below the melting temperature of the material, a high-quality weld is created. This characteristic greatly reduces the ill effects of high heat input, including distortion, and eliminates solidification defects. Friction stir welding also is highly efficient, produces no fumes, and uses no filler material, which makes this process environmentally friendly.

Friction stir welding was invented by The Welding Institute (TWI) in December 1991. TWI filed successfully for patents in Europe, the U.S., Japan, and Australia. TWI then established TWI Group-Sponsored Project 5651,"Development of the New Friction Stir Technique for Welding Aluminium," in 1992 to further study this technique.

The development project was conducted in three phases. Phase I proved FSW to be a realistic and practical welding technique, while at the same time addressing the welding of 6000 series aluminium alloys. Phase II successfully examined the welding of aerospace and ship aluminium alloys, 2000 and 5000 series, respectively. Process parameter tolerances, metallurgical characteristics, and mechanical properties for these materials were established. Phase III developed pertinent data for further industrialization of FSW.

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Since its invention, the process has received world-wide attention, and today FSW is used in research and production in many sectors, including aerospace, automotive, railway, shipbuilding, electronic housings, coolers, heat exchangers, and nuclear waste containers. In FSW, a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the weld joint between two pieces of sheet or plate material that are to be welded together (Figure 1). The parts must be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart or in any other way moved out of position.

Frictional heat is generated between the wear-resistant welding tool and the material of the workpieces. This heat causes the workpieces to soften without reaching the melting point and allows the tool to traverse along the weld line. The resultant plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged together by the intimate contact of the tool shoulder and the pin profile. This leaves a solid-phase bond between the two pieces.

The function of the tool shoulder is to provide heat by application of a large compressive force and tool rotation over the surface of the material being welded and to contain the softened, plasticized metal beneath it. The compressive stress also minimizes the formation of voids or pores in the consolidated metal. In the case of welding thin sheets, almost all of the frictional heat is provided by the friction between the tool shoulder and the work piece.

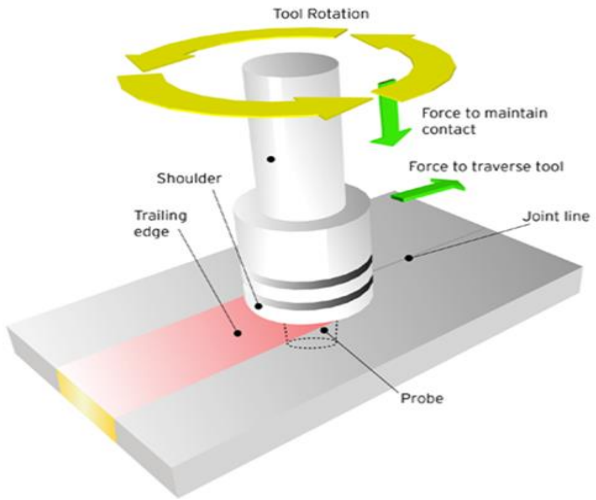

Figure 1: A schematic diagram showing FSW process

The function of the tool probe is to move the highly plasticized material from the front of the probe to the rear and also to move the material in a vertical direction. The latter movement of the plasticized material is achieved by the presence of threads or similar features on the tool probe. The probe also promotes dispersion of oxides or impurities present in the joint line. As the thickness of the plate increases, the ratio of heat input from the shoulder to heat input from the probe decreases. The schematic diagram of tool geometry is shown in the Figure 2.

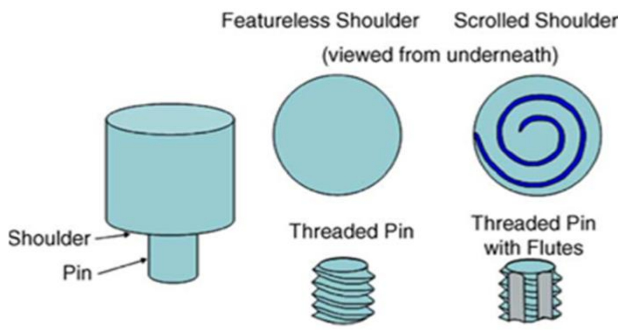

Figure 2: Schematic representation of Tool geometry

2. Tool material selection

Weld quality and tool wear are two important considerations in the selection of tool material, the properties of which may affect the weld quality by influencing heat generation and dissipation. The weld microstructure may also be affected as a result of interaction with eroded tool material. Apart from the potentially undesirable effects on the weld microstructure, significant tool wear increases the processing cost of FSW. Owing to the severe heating of the tool during FSW, significant wear may result if the tool material has low yield strength at high temperatures. Stresses experienced by the tool are dependent on the strength of the work- piece at high temperatures common under the FSW conditions. Temperatures in the workpiece depend on the material properties of tool, such as thermal conductivity, for a given workpiece and processing parameters. The coefficient of thermal expansion may affect the thermal stresses in the tool. Other factors that may influence tool material selection are hardness, ductility and reactivity with the workpiece material. The tool hardness is important in mitigating surface erosion due to interaction with particulate matter in the workpiece. The brittle nature of ceramics such as pcBN may be undesirable if there is a significant probability of breakage due to vibrations or accidental spikes in loads. Tool degradation may be exaggerated if the tool material and workpiece react to form undesirable phases.

3. Commonly used Tool materials

3.1 Tungsten based tools

Commercially pure tungsten (cp-W) is strong at elevated temperatures but has poor toughness at ambient temperature, and wears rapidly when used as a tool material for FSW of steels and titanium alloys. It is known that exposure of cp-W to temperatures in excess of 1473 K causes it to recrystallise and embrittle on cooling to ambient temperature. Addition of rhenium reduces the ductile to brittle transition temperature by influencing the Peierls stress for dislocation motion. This led to the development of tungsten–rhenium alloys, with W–25 wt-% Re as a candidate material for FSW tools, and more recently, a variant of this reinforced with 2% of HC. Steels and titanium alloys are successfully welded by W–25 wt-%Re tool. Tungsten carbide (WC) based tools have also been exploited in investigations of the feasibility of FSW of steel and titanium alloys. The toughness of WC is said to be excellent and the hardness is 1650 HV. The material is apparently also insensitive to sudden changes in temperature and load during welding trials.

3.2 Tool Steel

Materials such as aluminium or magnesium alloys, and aluminium matrix composites (AMCs) are commonly welded using steel tools. Steel tools have also been used for the joining of dissimilar materials in both lap and butt configurations. In butt joint configuration, the harder workpiece is often placed on the advancing side and the tool is slightly offset from the butt interface towards the softer workpiece. Oil hardened (62 HRC) steel tool has been used to successfully weld Al 6061z20 vol.-%Al2O3 AMC and Al 359z20 vol.-% SiC AMC. Tool wear during welding of metal matrix composites is greater when compared with welding of soft alloys due to the presence of hard, abrasive phases in the composites. For FSW of AMCs, some studies have shown that the tool wears initially and obtains a self-optimised shape after which wear becomes much less pronounced. This self-optimised final shape, which depends on the process parameters and is generally smooth with no threads, can reduce wear when used as the initial tool shape. Total wear was found to increase with rotational speed and decrease at lower traverse speed, which suggests that process parameters can be adjusted to increase tool life.

3.3 Polycrystalline cubic boron nitride (pcBN) tools

Owing to high strength and hardness at elevated temperatures along with high temperature stability, pcBN is a preferred tool material for FSW of hard alloys such as steels and Ti alloys. Furthermore, the low coefficient of friction for pcBN results in smooth weld surface. However, due to high temperatures and pressures required in the manufacturing of pcBN, the tool costs are very high. Owing to its low fracture toughness, pcBN also has a tendency to fail during the initial plunge stage. Maximum weld depths with pcBN tools are currently limited to 10 mm for welding of steels and Ti alloys. Boron nitride has two crystal structures, the hexagonal and cubic varieties. The hexagonal form has a layered structure and hence is more suited as a lubricant. The cubic (zinc blende structure) form is usually pre- pared by subjecting the hexagonal version to high temperatures and pressures, similar to what is followed in producing diamond from graphite. The cubic form is second in hardness only to diamond and has greater thermal and chemical stability than carbon. The phase is also chemically inert to iron, reportedly even up to 1573 K. Like diamond, pcBN has a high thermal conductivity which helps avoid the development of hot spots on tools. A high thermal conductivity also helps in the design of liquid cooled tools. The best properties are obtained with single phase cubic boron nitride (cBN), produced without using any binder. Such a material can be prepared by sintering commercially pure hexagonal boron nitride at high pressures (6–8 GPa) and temperatures (1773–2673 K).

4. Types of Tools

In Friction Stir Welding process there are three different types of Tools i.e. Self-reacting, fixed and adjustable as shown in the Figure 3.

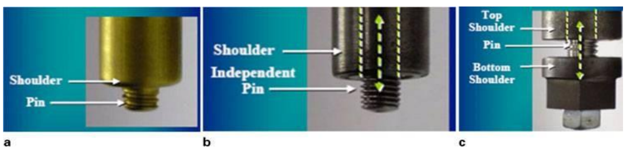

Figure 3: a) Fixed Tool, b) Adjustable tool, c) Self-reacting Tool

In fixed probe tool, shoulder and probe constitute a single unit. Due to fixed probe length, this tool can weld a workpiece which has a constant thickness. This tool undergoes whole replacement in the case of wear or breaks. While in adjustable tooling system there are two independent components i.e. separate probe and the shoulder. There are two main advantages in using the adjustable tooling system. Firstly, for fabricating this tool separate tool shoulder and probe can be used which are manufactured from different materials. In case of the wear or break, the probe can be easily replaced. Secondly, workpieces of variable and multiple gauge thickness can be easily welded using adjustable tooling system. It should be noted that both the fixed and adjustable tooling system requires a backing anvil. The self-reacting tool for example the bobbin type tool constitutes three parts i.e. tool probe, top shoulder and bottom shoulder (W. M. Thomas, 2001; M. Skinner, 2003). Multiple gauge thickness can be accommodated by this tool due to the adjustable probe length between the top and bottom shoulder (G. Sylva, 2004; F. Marie, 2004). It should be kept in mind that the fixed and adjustable tooling system can be tilted laterally and longitudinally while the bobbin type tooling system can work only perpendicular to the workpiece.

5. Shapes of Tool probe

The tool probe governs the tool travel speed and deformation (W. M. Thomas, 1991). The deformational and frictional heating is produced by the tool probe. The main function of the tool probe is to shear the material in front of the tool offers the disruption to the contacting surfaces of the workpiece. As shown in the Figure 3, the end shape of the probe is either domed or flat.

The most commonly used shape in Friction stir welding process is flat bottom probe design (T. W. Nelson, 2000; B. London, 2003). But the main disadvantage of the flat probe is the high forge force during plunging. In contrast, a round or domed end shape can reduce the forge force and tool wear upon plunging, increase tool life by eliminating local stress concentration and improve the quality of the weld root directly at the bottom of the probe (C. J. Dawes, 1995). Nowadays, cylindrical probes have been widely used for joining plates up to 12 mm thick plates. In case of the tapered probe, the higher frictional heat increases the plastic deformation because of the larger contact area of the probe with the workpiece. The tapered probe also promotes a high hydrostatic pressure in the weld zone (R. W. Fonda, 2004) which is extremely important for enhancing the material stirring and the nugget integrity.

The probe outer surfaces can have different shapes and features including threads, flats or flutes. Threadless probes are chosen for high strength or highly abrasive alloys as the threaded features can be easily worn away. The addition of flat features can change material movement around a probe. This is due to the increased local deformation and turbulent flow of the plasticised material by the flats acting as paddles (W. M. Thomas, 1996). It is also found that, reduction in transverse force and tool torque was directly proportional to the number of the flats placed on a tapered shoulder (K. J. Colligan, 2003).

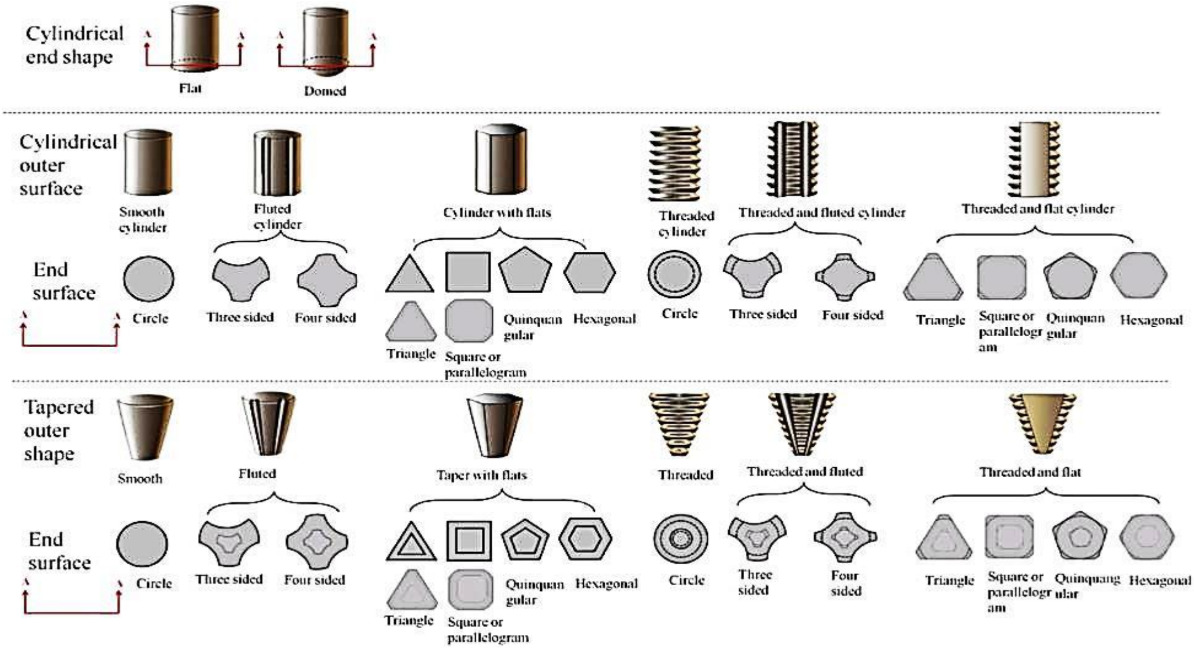

Figure 4: Various tool probe profiles in Friction Stir Welding process

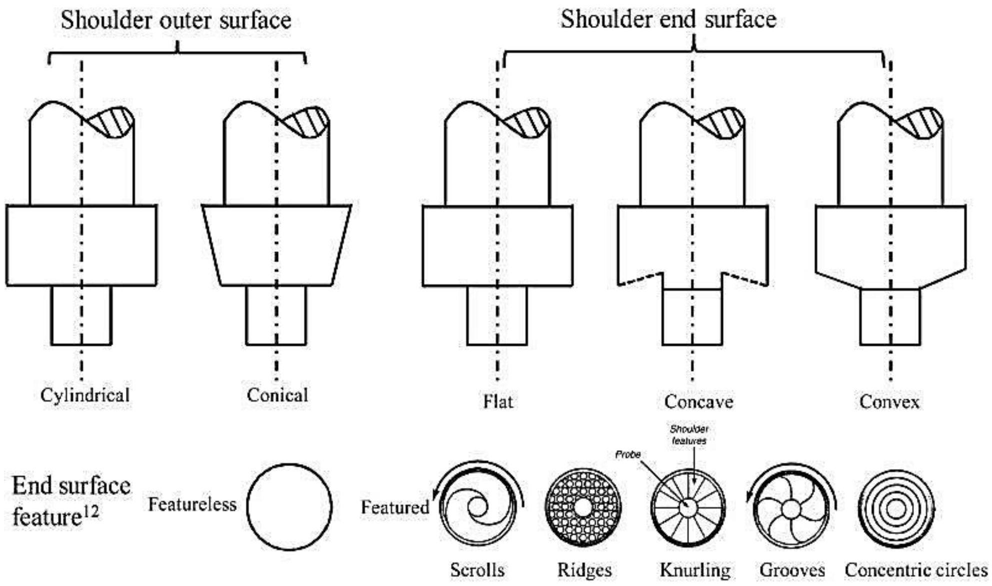

Figure 5: Design of Tool shoulder used in Friction Stir Welding

The flats on the probe act as the cutting edge of a cutter. The material is trapped in the flats and then released behind the tool, promoting more effective mixing. The addition of the flats also increases the temperature and nugget area.

6. Shapes of Tool Shoulder

Tool shoulders are designed to frictionally heat the surface regions of the workpiece, produce the downward forging action necessary for welding consolidation and constrain the heated metal beneath the bottom shoulder surface. Figure 5, summarises the typical shoulder outer surfaces, the bottom end surfaces and the end features. The shoulder outer surface usually has a cylindrical shape, but occasionally, a conical surface is also used. Generally, it is expected that the shape of the shoulder outer surface (cylindrical or conical) has an insignificant influence on the welding quality because the shoulder plunge depth is typically small (i.e. 1–5% of the gauge thickness).

The sound welds can be obtained using a probe free shoulder tool in which the bottom scrolled shoulder surface feature played a significant role in stirring the materials. In this case, the shoulder outer surface shape and feature may also become important.

As demonstrated in Figure 5, three types of shoulder end surfaces are typically used.5 Of these, the flat shoulder end surface is the simplest design. The main disadvantage of this design is that the flat shoulder end surface is not effective for trapping the flowing metal material under the bottom shoulder, leading to the production of excessive material flash. To this end, a concave shoulder end surface was designed and has now become popular for restricting material extrusion from the sides of the shoulder.

Another possible end shape of the shoulder is a convex profile. Early attempts at TWI for the convex end surface were unsuccessful because the convex profile was determined to push the material away from the probe. However, it was reported that a smooth convex end surface shoulder with a 5 mm diameter was successfully used to weld 4 mm thick AZ31 Mg alloy sheets, inevitable because of the thin gauge thickness (i.e. ,1 mm) for which the end shape of the shoulder becomes insignificant. Although the main advantage of the convex shoulder profile is that it can attain contact with the workpiece at any location along the convex end surface, and thereby, accommodate differences in flatness or thickness between the two adjoining workpieces, the inability of the smooth end surface to prevent material displacement away from probe causes weld integrity issues.

7. Contemporary Tool design in Friction Stir Welding

A variety of tool designs have been developed in order to improve the material flow and to reduce the required axial welding forces, which would ultimately lead to improved weld quality, reduced energy costs and increased utilization of the FSW process. Following are a few examples:

7.1 The Skew Stir FSW Tool

It was developed at TWI in which the shoulder face is oblique to the axis of the tool probe but normal to the axis of the machine spindle as shown in Figure 6. The probe is cut from one side to make it asymmetrical, which improves material flow. Use of this technique increases the proportion of the dynamic volume relative to the static volume of the weld. This ratio is significant in reducing void formation in the weld. Also, because a larger volume is stirred, this tool is better suited for FS processing. The following figure shows the principle of operation of a Skew-Stir™ tool.

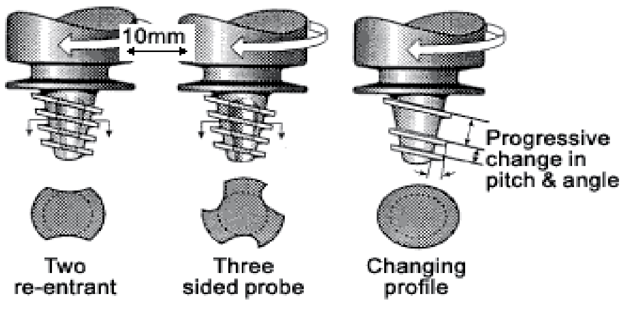

Figure 6: Skew Stir FSW Tool

7.2 The Triflute™ tool

It was recently developed at TWI. Like the Skew-Stir tool, the dynamic to static volume ratio is higher than that for a conventional tool (2.6:1 as opposed to 1:1). Investigations at TWI have shown that use of the Triflute tool gave a 100 % increase in traverse rate and a 20% reduction in the axial force.

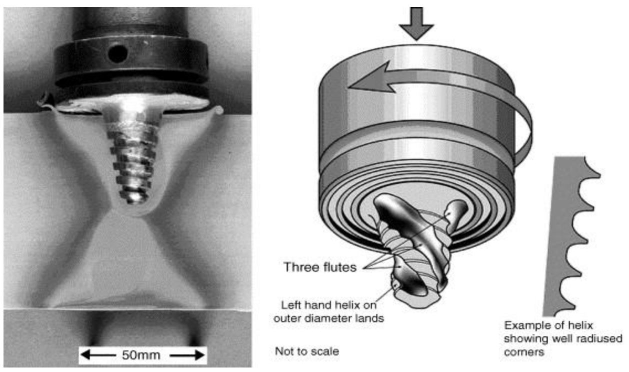

Figure 7: Triflute tooling system

Furthermore, the upper plate thinning (due to tool plunging required to achieve defect-free welds) was reduced by factor of 4. Above figure shows a design of this tool.

7.3 The Whorl™ tool

It was developed at TWI and consists of a scoop-shaped shoulder with a tapered, frustum-shaped probe which has a helical ridge with side flats which auger plasticized material downwards. For enhancing material flow, it is preferred that the distance between each ridge is greater than the thickness of the ridge itself. Some variants of this tool have a progressively decreasing pitch. This tool enables welding of thick sectioned alloys (25 to 75mm) in a single pass since it provides better frictional heating and material flow due to the design of the probe. The following figure shows variants of the Whorl™ tool.

Conclusions

Although significant efforts have been made in the recent past to develop cost effective and reusable tools, most of the efforts have been empirical in nature and further work is needed for improvement in tool design to advance the practice of FSW to hard alloys. Heat generation rate and plastic flow in the workpiece are affected by the shape and size of the tool shoulder and pin. Although the tool design affects weld properties, defects and the forces on the tool, they are currently designed empirically by trial and error. Work on the systematic design of tools using scientific principles is just beginning.

References

W. M. Thomas, E. D. Nicholas and S. D. Smith (2001): 'Friction stir welding-tool developments', Proc. Aluminum Automotive and Joining Sessions, 213–224, Warrendale, PA, TMS.

M. Skinner and R. L. Edwards (2003): 'Improvements to the FSW process using the self-reacting technology', Mater. Sci. Forum, 426, 2849–2854.

G. Sylva, R. Edwards and T. Sassa (Sept 2004): 'A feasibility study for self- reacting pin tool welding of thin section aluminum', Proc. 5th Int. Conf. on 'Friction stir welding', Metz, France, TWI.

F. Marie, D. Allehaux and B. Esmiller (Sept 2004): 'Development of the bobbin tool technique on various Al alloys', Proc. 5th Int. Conf. on 'Friction stir welding', Metz, France, TWI.

W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Temple-Smith and C. J. Dawes (1991): GB Patent no. 9125978-8

T. W. Nelson, H. Zhang and T. Haynes (June 2000): 'Friction stir welding of aluminum MMC 6061-boron carbide', Proc. 2nd Int. Conf. on 'Friction stir welding', Gothenburg, Sweden, TWI. 34.

B. London, M. Mahoney, M. Bingel, M. Calabrese, R. H. Bossi and D. Waldron (2003): 'Material flow in friction stir welding monitored with Al–SiC and Al–W composite markers', in 'Friction stir welding and processing II', 3–12, Warrendale, PA, TMS.

C. J. Dawes, P. L. Threadgill, E. J. R. Spurgin and D. G. Staines (1995): 'Development of the new friction stir technique for welding aluminum phase II', TWI member report, Cambridge, UK

R. W. Fonda, J. F. Bingert and K. J. Colligan (Sept 2004): 'Texture and grain evolutions in a 2195 friction stir weld', Proc. 5th Int. Conf. on 'Friction stir welding', Metz, France, TWI.

W. M. Thomas, E. D. Nicholas, J. C. Needham, P. Temple-Smith, S. W. K. W. Kallee and C. J. Dawes (1996): 'Friction stir welding', UK Patent Application 2306366

K. J. Colligan, J. Xu and J. R. Pickens (2003): 'Welding tool and process parameter effects in friction stir welding of aluminum alloys', in 'Friction stir welding and processing II', 181–190, Warrendale, PA, TMS.