A Review of Friction Stir Welding Process and its Variables

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Abstract: ***Friction Stir Welding (FSW) was invented by Wayne Thomas at TWI (The Welding Institute), and the first patent applications were filed in the UK in December 1991. Initially, the process was regarded as a "laboratory" curiosity, but it soon became clear that FSW offers numerous benefits in the fabrication of aluminum products. Friction Stir Welding (FSW) has become a major joining process in the aerospace, railway and ship building industries especially in the fabrication of aluminum alloys. The process uses a spinning non-consumable tool to generate frictional heat in the work piece. Worldwide, there are now over 135 licensees of FSW and new techniques and applications are being developed daily. This paper looks at the review, on friction stir welding process, various welding variables like tool rotation, transverse speed, tool tilt, plunge depth and tool design, for the welding of aluminum alloys or various dissimilar alloys. Applications, future aspects and several key problems are also described.***

Keywords: Friction Stir Welding, tool rotation and transverse speed, tool tilt and plunge depth tool design

1. Introduction

Friction stir welding (FSW) is an innovative welding process commonly known as a solid state welding process. This opens up whole new areas in welding technology. It is particularly appropriate for the welding of high strength alloys which are extensively used in the aircraft industry. Mechanical fastening has long been favored to join aerospace structures because high strength aluminum alloys are difficult to join by conventional fusion welding techniques (Pouget G. et al., 2007). Its main characteristic is to join material without reaching the fusion temperature. It enables to weld almost all types of aluminium alloys, even the one classified as non-weldable by fusion welding due to hot cracking and poor solidification microstructure in the fusion zone (Zimmer Sandra et al., 2009). FSW is considered to be the most significant development in metal joining in a decade and is a green''technology due to its energy efficiency, environment friendliness, and versatility. The key benefits of FSW are summarized in Table 1(Mishra R.S. et al., 2005).

2. FSW: The Process

The working principle of Friction Stir Welding process is shown in Fig. 1. A welding tool comprised of a shank, shoulder, and pin is fixed in a milling machine chuck and is rotated about its longitudinal axis. The work piece, with square mating edges, is fixed to a rigid backing plate, and a clamp or anvil prevents the work piece from spreading or lifting during welding. The half-plate where the direction of rotation is the same as that of welding is called the advancing side, with the other side designated as being the retreating side (Nandan R. et al., 2008). The rotating welding tool is slowly plunged into the work piece until the shoulder of the welding tool forcibly contacts the upper surface of the material.

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 (Rowe C.E.D. et al., 2005).The welding tool is then retracted, generally while the spindle continues to turn. After the tool is retracted, the pin of the welding tool leaves a hole in the work piece at the end of the weld. These welds require low energy input and are without the use of filler materials and distortion.

Table 1: Key benefits of FSW are summarized

Metallurgical benefits	*Environmental benefits*	*Energy benefits*
Solid phase process Low distortion of work piece Good dimensional stability	No shielding gas required No surface cleaning required Eliminate grinding	Improved materials use (e.g., joining different thickness) Allows reduction in

As the tool (rotates and) moves along the butting surfaces, heat is being generated at the shoulder/work-piece and, to a lesser extent, at the pin/work-piece contact surfaces, as a result of the frictional-energy dissipation (Grujicic M. et al., 2010).

The welding speed depends on several factors, such as alloy type, rotational speed, penetration depth, and joint type (Sakthivel T. et al., 2009). Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. During traversing, softened material from the leading edge moves to the trailing edge due to the tool and this transferred material, are consolidated in the trailing edge of the tool by the application of an axial force(Kumar K., et al., 2008) plasticized material around it and forging the same in place.

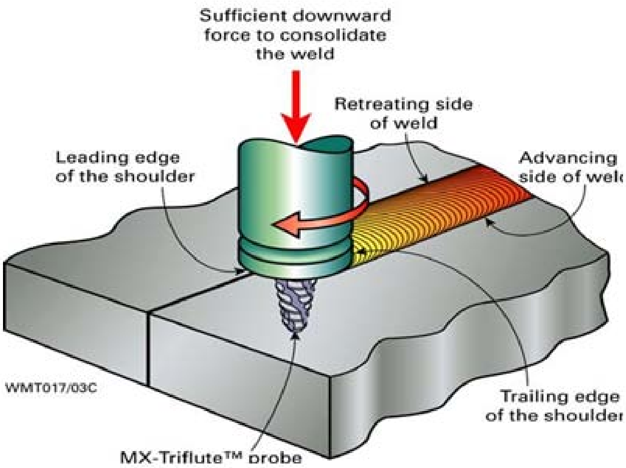

Figure 1: The principle of Friction Stir Welding (Eur. Ing. Wayne Thomas)

3. Welding Variables

FSW involves complex material movement and plastic deformation. Welding parameters, Tool geometry and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material (Mishra R.S. et al., 2005). Therefore, welding speed, the tool rotational speed, the tilt angle of the tool, tool material and the tool design are the main independent variables that are used to control the FSW process.

The main process parameters and there effects in friction stir welding are given below Table 2 (FSW-Technical-Handbook).

Table 2: Main process parameters in friction stir welding

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

3.1 Tool rotation and Transverse speed

For FSW, two parameters are very important: tool rotation rate (v, rpm) in clockwise or counter clockwise direction and tool traverse speed (n, mm/min) along the line of joint. The motion of the tool generates frictional

3.2 Tool tilt and plunge

In addition to the tool rotation rate and traverse speed, another important process parameters are tool tilt with respect to the work piece surface and plunge depth. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. The tool is usually characterized by a small tilt angle (θ), and as it is inserted into the sheets, the blanks material undergoes to a local backward extrusion process up to the tool shoulder. (Fratini L. et al., 2009). Further, the plunge depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders.

3.3 Tool Design

Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. Tool geometry such as probe length, probe shape and shoulder size are the key parameters because it would affect the heat generation and the plastic material flow (Gopala Krishnan S. et al., 2011). The tool is an important part of this welding process. It consists of a shoulder and a pin. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process. The shoulder generates most of the heat and prevents the plasticized material from escaping from the work-piece, while both the shoulder and the tool pin affect the material flow. Friction stir welds are characterized by well-defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions.

The commonly used five pin profiles i.e., straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square pins to fabricate the joints, in FSW are shown schematically in Fig. 2 (Elangovan K. et al 2009).

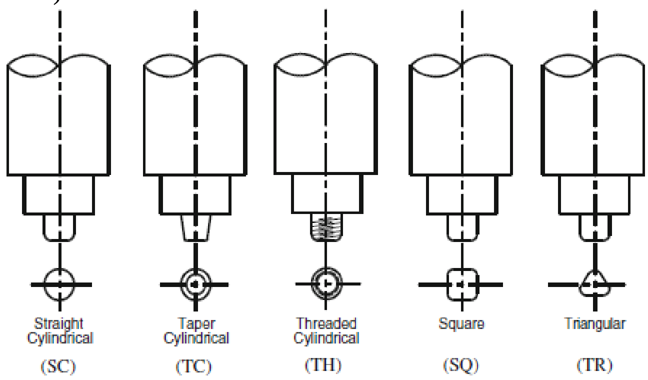

Figure 2: Schematic drawing of the FSW tool

4. Applications

Application of FSW includes various industries including few of following:

- Shipping and marine industries: - Such as manufacturing of hulls, offshore accommodations, aluminum extrusions, etc.
- Aerospace industries: - for welding in Al alloy fuel tanks for space vehicles, manufacturing of wings, etc.
- Railway industries: - building of container bodies, railway tankers, etc.
- Land transport: - automotive engine chassis, body frames, wheel rims, truck bodies, etc.

5. Current Status and Future Aspects

Friction stir welding technology has been a major boon to industry advanced since its inception. In spite of its short history, it has found widespread applications in diverse industries. Hard materials such as steel and other important engineering alloys can now be welded efficiently using this process. The understanding has been useful in reducing defects and improving uniformity of weld properties and, at the same time, expanding the applicability of FSW to new engineering alloys. Some conclusions on future work are listed below:

- The future work is to analyses the influence of the processing parameters on the transition, plunging and welding stages (Zimmer Sandra et.al, 2010).
- Future work will be to perform the analysis on other heat treatable and non-heat-treatable aluminum series. The future work will also be focused on the investigation of the thermo-mechanical phenomenon, leading to the uncharacteristic force and torque behavior, etc. (Langlois Laurent et al., 2010).
- The demand of Aircraft Industries to substitute the conventional joining technologies with low costs and high efficient processes such as friction stir welding is considered as one of the most encouraging design challenge for the future. (Cavaliere P. et al., 2006).

So, with better quantitative understanding of the underlying principles of heat transfer, material flow, tool-work–piece contact conditions and effects of various process parameters, efficient tools have been devised. At the current pace of development, FSW is likely to be more widely applied in the future.

6. Several Important Key Problems and Issues Remain to be addressed

The fundamental knowledge of the FSW process and the knowledge of the evolution of the structure and properties needs to be combined to build intelligent process control models with a goal to achieve, defect free, structurally sound and reliable welds. According to DebRoy T. et al.,

2008, an important difficulty is that the existing process models are unidirectional. In other words, the process sub-models require as input welding parameters, thermo physical properties, and tool and work–piece geometry and provide, as output, the temperature and velocity fields and the cooling rates at various locations. Success of an undertaking will ensure availability of practically the entire quantitative knowledge base of FSW to the whole FSW community for the purpose of tailoring FSW weld attributes and fabricating defect free, structurally sound, and reliable welds (Bhadeshia H. K. D. H. et al., 2008). Some of the major key problems are discussed below:

- Forming of FSW welds is still challenging due to the limit formability. The studies on the relationship between formability and microstructural stability of FSW joint are rare. (Yuan S.J. et al., 2012).
- The essential drawback of this technique, however, is the low stability of the welded material against abnormal grain growth during subsequent annealing, (Mironov S. et al., 2012).
- According to Uyyuru R.K. et al.,2006, the main limitations and areas for further research of the FSW process can be summarized as follows:

- Welding speeds are somewhat slower than those of some fusion welding processes.
- There is a keyhole at the end of each weld seam.
- The evolution of microstructure and properties of friction stir welded joints.

  So, the attainment of this milestone is well within the reach of the welding community within the next ten years.

7. Case Studies: Effect of Various Welding Parameters on FSW

Sr. No.	*Author (Year)*	*Substrate Material*	*Parameters selected for study*	*Conclusion*
1	*Elangovan K. , Balasubramanian V. ,* (2008)	AA2219 aluminum alloy	Tool pin profile and welding speed	-square pin profiled tool produced defect free FSP region, irrespective of welding speeds. - the joints fabricated at a welding speed of 0.76mm/s showed superior tensile properties, irrespective of tool pin profiles. -the joint fabricated using square pin profiled tool at a welding speed 0.76 mm/s exhibited maximum tensile strength, higher hardness and finer grains in the FSP region.
2	Chen Thaiping, (2009)	AA6061 aluminum alloy and	Lower transverse speed and rotation speed	-The lower transverse speed and rotation speed, which are the significant FSW process parameters, yield a higher C-notch Charpy impact value.
3	Patil H. S. , Soman S. N. , (2010)	AA6082-O aluminum	Welding speed and tool pin profiles	-The effect of tool pin profile and welding speed on the appearance of the weld is presented and no obvious defect was found. - It is found that the joint fabricated using taper screw thread pin exhibits superior tensile properties compared tri -flute pin profile, irrespective of welding speed.
4	Arora A. & Mehta M. & De A. & DebRoy T. ,	L80 steel and AA7075 alloy	Load bearing capacity of tool pin	A three-dimensional heat transfer and visco-plastic model is used to compute the influence of pin length and diameter on traverse force during FSW. The total traverse force increases significantly with increase in pin length

5	Reshad K., Seighalani, M.K. Givi Besharati, Nasiri A.M., and Bahemmat P. , (2009)	Pure Titanium	Tool Material, Geometry, and Tilt Angle	-Using high-speed steel (HSS) tool for FSW of titanium will result in complete failure of the pin and severe wear of the shoulder nose because of heat generation from friction between the tool and the base metal. -Using brittle WC as a pin material for FSW of the Ti-CP and because of high wear and stress concentrations developing on the root of the pins threads Macro structural analysis of the welded joints shows that
6	Kulekci Mustafa Kemal & Şik Aydin & Kaluç Erdinç, (2008)	AA 5754 aluminium alloy plates	Tool rotation and pin diameter	-Increasing tool rotation for a fixed tool pin diameter reduces fatigue strength of joints. – Increasing tool pin diameter for a fixed tool rotation, decreases fatigue strength of joints. – In FSW lap joints, an optimization between tool pin diameter, tool rotation and tool traverse speed is needed to obtain better fatigue strength.
7	Arora A., Deb A. and DebRoy T.. (2011)	AA6061 aluminum Alloys	Tool shoulder diameter	In order to determine the optimum tool geometry, the two components of the torque are used for various shoulder diameters. As the shoulder diameter increases, the sticking torque, MT, increases, reaches a maximum and then decreases. This behavior can be examined, which shows that two main factors affect the value of the sticking torque. First, the strength of the material is decreases with increasing temperature due to an increase in the shoulder diameter. Second, the area over which the torque is applied increases with shoulder diameter.
8	Cao X., Jahazi M.. (2011)	AZ31B-H24 magnesium alloy	Tool rotational speed and probe length	Tensile shear load initially increases with increasing tool rotational speed but decreases with further increase. Shear strength increases with increasing probe length and penetration depth in to the bottom sheet.

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