THE PRESENT AND FUTURE PROSPECTS OF FRICTION STIR WELDING IN AERONAUTICS

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Abstract

Since its invention friction stir welding as a solid state joining method was considered primarily for aluminium alloys in the aerospace industry. Years of intense research and development were necessary to introduce the process for fabrication of aerospace components. It was necessary to accumulate sufficient information about process parameters, tooling and machinery for process specification, certification and design allowables. Friction stir welding was first used in space vehicles and in military aircraft, later it was used in civil aviation. Aircraft manufacturers such as Boeing, Airbus, and Embraer use this technique for components such as floor panels, fuselage panels, and wing ribs among others. This process allows for the introduction of new structural solutions in the same way that the development of advanced alloys also permits similar advances.

Keywords: friction stir welding, solid state joining, aerospace structural application, high strength Al alloys

1 Introduction

The process of friction stir welding (FSW) was invented by W. M. Thomas in 1991 and patented worldwide by The Welding Institute (TWI), Ltd, Cambridge, United Kingdom [1-3]. Since then hundreds of related patents have been filed to include improvements, particular applications, and products etc. The interest in its industrial application is reflected by a steadily increasing number of organizations holding FSW licenses of the TWI.

FSW is a solid-state joining process. The energy necessary to join objects comes from the friction heat produced by the motion of a special tool in contact with them. The heat produced is sufficient for plasticization of the material of the objects but not for its fusion. This means that it has the potential to be more energy efficient, more environmentally friendly, along with fewer health and safety concerns while producing strong welds at a lower cost. The principle of the FSW process is presented schematically in **Fig.1**. A cylindrical shouldered tool with a profiled pin is rotated in the joint area between the two pieces that have to be securely clamped together to prevent them from being forced apart by the action of the rotating tool. The plasticized material of the joint area is intermixed by the pin while the shoulder of the tool produces a smooth surface along its path.

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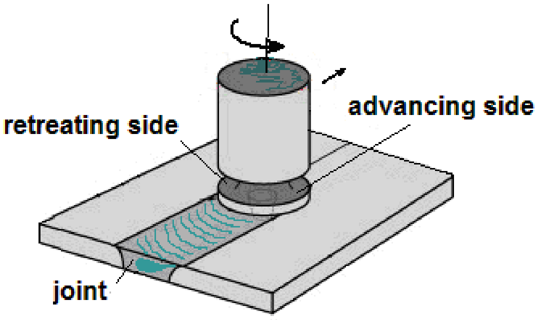

Fig. 1 Scheme of the friction stir welding process

Friction stir welding has been considered primarily for welding aluminium alloys which in fusion welding present a series of problems such as hydrogen embrittlement, porosity, liquation cracking etc. The composition of the weld metal is usually different from the base material in aluminium fusion welds resulting in significant differences in the properties of the weld and the base material. High strength precipitation strengthened aluminium alloys can be welded by FSW, so it can be used for joining structural aerospace and marine-grade aluminium alloys. Other metallic alloys that are difficult to weld by conventional fusion welding can be successfully joined by FSW. Dissimilar alloys of the same metal as well as alloys of different metals can be welded together [4-6]. Plastics also can be successfully welded by this method [7]. Today, for aeronautical applications the FSW process is used mostly for the production of individual components. Applications for major component assembly and on the final assembly line, may require substantial changes in design and modifications in existing means of production.

2 Thermo-mechanical characteristics of the process

The heat generated by the friction of the tool along with the energy release caused by plastic strain increases the temperature in the joint area to about 70-90% of the melting point resulting in a high degree of plasticization. The joint is a result of mechanical deformation and may be characterized by a combination of two hot working processes: forging and extrusion. The tool movement along the joint line results in the extrusion of the material around the weld tool probe. At the same time, the weld tool shoulder exerts pressure on the surface forging the joint together. This means that the shoulder of the tool in contact with the material of the joint generates the heat and maintains the plasticized material in the process area while the plastic flow of the material is produced both by the shoulder and the pin.

The principal process parameters include tool rotation speed, translation speed, axial pressure and tilt angle, as shown in **Fig. 2**.

Increasing rotation speed and vertical pressure increases the temperature resulting in lower torque and a better flow of the material. Insufficient heating causes voids, while overheating due to excessively high pressures leads to thinning in the joint area. The torque depends also on the tool design, the tilt angle, the vertically applied stress, and on the conditions in the contact area [8,9].

Fig. 3 shows a schematic of the transversal cross-section of a FSW joint. Four zones can be observed in this cross-section: a) the base material, b) the heat affected zone which does not suffer plastic deformation but which changes in its microstructure and properties due to the heat generated by the tool, c) the thermo-mechanically affected zone that is exposed to heating and suffers partial plastic deformation d) the stirred zone, where the material of the two welded objects is intermixed and suffers significant heating and plastic flow. It has to be pointed out that due to the rotation of the weld tool the joint structure appears to be asymmetrical in the stirred and thermo-mechanically affected zones. The heat affected zone tends to be symmetrical.

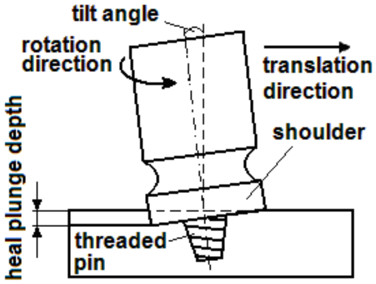

Fig. 2 The shape and the movements of the friction stir welding tool

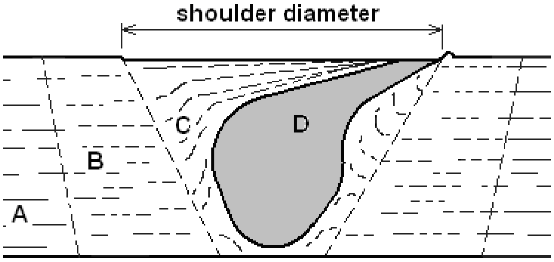

Fig. 3 Schematic of the transversal section of a FSW joint. A – base metal, B – heat affected zone, C – thermo-mecanically affected zone, D – stirred zone (nugget).

Many thermal and thermo-mechanical models have been developed to simulate the various aspects of this complex process. It has to be emphasized that a numerical simulation of every welding process requires a long list of input parameters: material properties (density, Young‘s modulus, Poisson‘s ratio, yield strength, work hardening coefficient) for the calculation of the stresses and distortions; thermo-physical properties (thermal conductivity, specific heat capacity, thermal expansion) for the temperature field calculations [10].

Another thermal model [11] based on a pseudo-steady-state heat transfer using the finite element method considered that the total heat generated is a sum of the friction heat and the heat of plastic deformation. This model also considered the material flow and the contact conditions between the tool and the material. The thermal model from ref. [12], using the finite element method, suggested that temperature gradients are higher at the leading edge than at the trailing edge. The same is true for the gradient away from the interface between the shoulder and the plate.

The fully coupled thermo-mechanical model in [13] is based on solid mechanics relating to the inter-dependent factors influencing material flow, strain distribution and microstructural evolution. In the thermo-mechanical model of [14] the tool/work-piece interfacial friction-sliding is treated as the principal heat source while the heat dissipation is treated in association with plastic deformation as it relates to the effect of the temperature on the mechanical response of the material.

3 Tooling and machinery

The tool for FSW is, in principle, a bar with a shoulder and a centrally positioned probe (a profiled pin) at its extremity. The shoulder and probe geometry is very important for the success of the technique. Since the probe generates heat and stirs the material of the objects, its design depends strongly both on the composition of the material and its thickness.

The authors in ref. [15,16] emphasize the great influence of tool geometry on heat generation, plastic flow and the power required for the process. On the other hand, Colegrove and Shercliff [17,18] on the basis of an exhaustive study of the tool geometry concluded that for practical purposes, the tool design does not influence the heat input and the power required.

The material of the tool has to resist stresses at the temperatures generated by friction without being distorted. For aluminium alloys steel tools are the first choice. Alternatives for welding harder materials include superalloys, dispersion strengthened alloys and refractory metals. However, it is difficult to fabricate the complex shapes of probes using these materials. While basic information on simple FSW tools is available [19,20,21], detailed information about advanced tools and the appropriate welding parameters for industrial production is considered confidential, and is usually only provided by tool fabricants to their customers.

FSW machines for industrial applications are mostly custom-built and designed based on the customers´ requirements for full-scale automated production. Flexibility can be achieved by robotic systems able to perform welds in an arbitrary direction in a three-dimensional workspace. Universities involved in research and companies engaged in FSW process competence, are usually interested in small-batch fabrication machines coupled with different types of accessories to suit their specific needs [22]. As of February 2014, fourteen companies located in North America (6), Europe (4) and the Far East (4) were licensed by TWI to supply FSW equipment [23].

4 Routine Aerospace applications and future prospects

The principal advantages of friction stir welding from the point of view of aircraft applications are:

a) in design and manufacturing:
  - weight savings – through the elimination of the use of rivets and fasteners, also eliminating sheet-overlap configurations,
  - joining unweldable alloys by fusion methods – class 2000 e class 7000 alloys as well as the newly developed high strength Al-Li alloys,
  - higher reliability of the joint – by higher strengths than riveted joints, by improved fatigue performance through elimination of stress concentrators, by reduction of crack formation and through easier testing,
  - environmental demands – reduced energy usage and reduced waste.

b) in operation
  - reduced fuel consumption – by weight saving
  - reduced maintenance costs -by easier testing
  - extended part life
  - simpler recycling/disposal

Weight reduction is one of the principal driving factors in the aerospace segment and the term that refers to it is the Buy-to-Fly ratio. The Buy-to-Fly ratio is given by the weight of the raw material used for the component and its final weight. For flying components, this ratio can be as high as 15-20 due to the importance of weight optimization, elevating the cost both of the material and the manufacturing. As an advanced manufacturing process, FSW has the potential to significantly decrease the Buy-to-Fly ratio.

Since its invention, FSW has been considered primarily as an attractive alternative to riveting in aircraft construction. The principal benefits include weight reduction, lower levels of stress concentration, and higher process efficiency. Together, these factors optimize manufacturing and joint strength for the modern joint designs (e.g. butt joint).

The traditional design of outer panels of the fuselage is composed of aluminium plate reinforced by stringers (usually an extruded L profile), joined together by rivets. In spite of its wide use riveting has such problems as local stress concentration and permeability by fluids. Eliminating these problems, the FSW process also offers such improvements as higher joint strength, better fatigue resistance, corrosion resistance and higher productivity.

A comparison of the traditional and a possible new approach using FSW for the stringer-plate joint is shown in **Fig. 4**. This approach yields lower weight, impermeability, lower production costs and higher production speed.

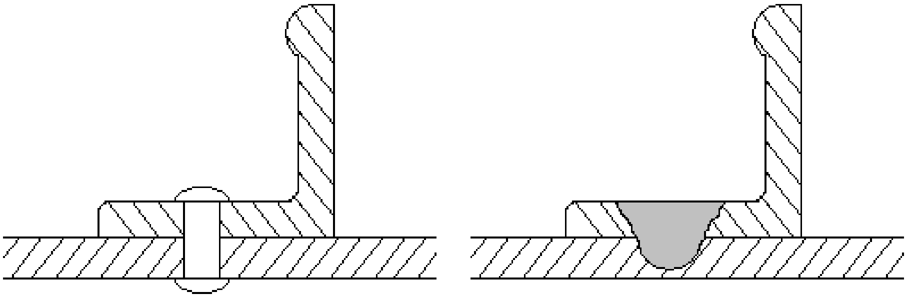

Fig. 4 Traditional (a) and friction stir welded (b) plate-stringer joint configuration solution

Fig. 5 shows the substitution of overlap plate joint configuration by friction stir welded butt joint configuration

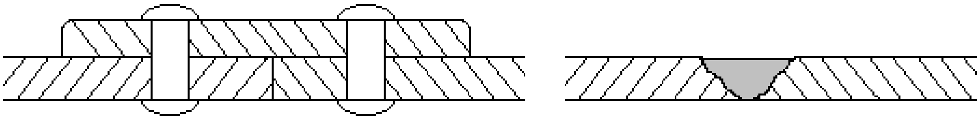

Fig. 5 Substitution of overlap plate configuration by FSW butt joint

The butt-joint configuration achieves homogeneous joints with full penetration. This solution reduces the possibility of crack formation eliminating local stress concentration, facilitating quality assurance and joint evaluation using non-destructive testing methods.

High strength and low weight is always a desirable combination in aeronautics. For structural design statistically calculated minimum strength values of the FSW joint are needed. The statistical procedure has to be based on the understanding of the expected strength variation. Random variations and process-controlled variations have to be considered when calculating the design allowables. To achieve the necessary confidence for the process reliability, a sufficient number of representative samples has to be collected.

NASA started a Process Specification for FSW in 2000 with the first version issued in 2002, since then, periodically revised. FSW is now certified by the FAA (Federal Aviation Administration) and was initiated in cooperation with Eclipse Aviation in 2001 [24,25]. Now, FSW is certified for aircraft applications as a joining process. This means that it can be used in the manufacturing of structural aerospace components.

Airbus also edited its Process Specification of friction stir welding in “Process and material Specification” [26].

Contrary to civil aviation, neither military nor space applications require FAA certification. This is the reason why friction stir welded components first appeared in these areas. Boeing started using FSW in 1999 for its Interstage module of the Delta II and Delta IV expendable launch vehicles. Other FSW applications include the external tank of the Space Shuttle, the Falcon 1 and Falcon 9 rockets.

Boeing has adopted friction stir welding on the cargo barrier beams for the Boeing 747 Large Cargo Freighter (the first commercially produced aircraft parts). FSW was used on the fabrication of the C-17 Globemaster III large transport aircraft for the toe nails of the ramp and floor, delivered to the U.S. Air Force in June, 2005. Airbus adopted FSW for the welded floor panels in the A400M military aircraft made by Pfalz Flugzeugwerke.

Lockheed Martin has applied friction stir welding for the fabrication of the floor in the C-130 aircraft.

The first commercial application in civil aviation was introduced by Eclipse Aviation, using FSW on 259 Eclipse 500 business jets. FSW was adopted instead of riveting in the body skin, wing rib, chord supports, aircraft floor and assembly of structures, replacing approximately 7000 rivets with a weld whose total length was 128m [27].

Airbus uses FSW for fuselage panels and wing skins of the A380 aircraft. Embraer uses FSW for the forward fuselage panels in the Legacy 450 and 500 Jets.

It seems to be obvious that future airframe structures will be built from many different materials in order to take advantage of the best properties of each of them. Advanced manufacturing processes will be introduced that allow for tailored structural characteristics and flexible manufacturing techniques that attend all airframe requirements. Metallic materials continue to be an important part of aircraft structures in spite of the competition with composites, the preeminent threat to the metallic fuselage. This competition has resulted in research and development of new advanced alloys and joining methods to produce lightweight aerostructures based on damage tolerant design philosophies. New structural solutions with optimized design and properties are possible using different alloys joined by solid state weld processing [28,29]. The expected benefits are reduced material usage, lower costs and reduced environmental impact.

5 Conclusions

Friction stir welding as a solid state joining method has been considered for aeronautical applications to substitute the riveted joints with such advantages as weight savings, better strength, improved impermeability, and easier testing.

Data continues to be collected about the process and the properties of the joint to elaborate Process Specifications for aeronautical applications. For civil aviation, the certification of the FAA was obtained. Continuous work is being done to determine the design allowables.

Major aircraft manufacturers such as Boeing, Airbus, and Embraer already use the process commercially.

Friction stir welding has the potential to introduce new structural solutions for future lightweight airframes.

References

[1] W. M. Thomas et al.: *Friction Stir Butt Welding*, International Patent Appl. n°. PCT/GB92/02203 and GB Patent Appl. n°. 9125978.8”, 1991, U.S. Patent no 5,460,317

[2] W. M. Thomas et al.: *Improvements relating to friction welding*, European Patent Specification EP 0 615 480 B1

[3] O. T. Midling, E. J. Morley, A. Sandvik: *Friction stir welding*, European Patent Specification EP 0 752 926 B1

[4] V. Sinka: Acta Metallurgica Slovaca, Vol. 16, 2010, No. 2, p. 116-121

[5] M. Aonuma, K. Nakata: Materials Transactions, Vol. 52, 2011, No. 5, p. 948 – 952, DOI: 10.2320/matertrans.L-MZ201102

[6] T. Chen: Journal of Material Science Vol. 44, 2009, No.10, p. 2573–2580

[7] M.J. Troughton (Editor): *Handbook of Plastics Joining: A Practical Guide*, William Andrew Publishing Inc., Norwich, 2nd. ed., 2008

[8] Y. Sato, M. Urata, H. Kokawa: Metallurgical & Materials Transactions A, Vol.33, 2002, No. 3, p. 625-635

[9] M.J. Peel et al.: Metallurgical and Materials Transactions A, Vol. 37 A, 2006, No. 7, p. 2183 -2193

[10] C. Schwenk, M. Rethmeier: Welding Journal, Vol. 90, 2011, No. 11, p. 220s-227s

[11] A. Simar et al.: Progress in Materials Science, Vol. 57, 2012, No. 1, p. 95–183

[12] K. Uyyuru, S. V. Kailas: Journal of Materials Engineering and Performance, Vol. 15, 2006, Issue 5, p. 505-518

[13] Z. Zhang, H.W. Zhang: International Journal of Advanced Manufacturing Technology, Vol. 37, 2008, No. 3, p. 279-293, DOI:10.1007/s00170-007-0971-6

[14] M. Grujicic, G. Arakere, C.-F. Yen, B.A. Cheeseman: Journal of Materials Engineering and Performance, Vol. 20, October 2011, Issue 7, p 1097-1108

[15] W. M. Thomas, K. I. Johnson, C. S. Wiesner: Advanced Engineering Materials, Vol.5, 2003, Issue 7, p.485–490, DOI: 10.1002/adem.200300355

[16] R.S. Mishra, Z.Y. Ma: Materials Science and Engineering R: Reports, Vol.50, 2005, No.1-2, p. 1–78, DOI:10.1016/j.mser.2005.07.001

[17] P. A. Colegrove, H. R. Shercliff: Science and Technology of Welding and Joining, Vol. 9, 2004, No.4, p. 345–351, DOI: 10.1179/136217104225021670

[18] P. A. Colegrove, H. R. Shercliff: Science and Technology of Welding and Joining, Vol. 9, 2004, No. 4, p.352–361, DOI: 10.1179/136217104225021661

[19] H. Fujii, L. Cui, M. Maeda, K. Nogi: Materials Science and Engineering A, Vol. 419, 2006, No. 1-2, p. 25-31

[20] D. G. Hattingh, C. Blignault, T. I. van Niekerk, M. N. James: Journal of Materials Processing Technology, Vol. 203, 2008. No.1-3, p. 46-57

[21] D. Venkateswarlu, N. R. Mandal, M. M. Mahapatra, S. P. Harsh: Welding Journal, Vol. 92, 2013, Issue 2, p. 41- 47

[22] [04.02.2014], http://www.esab.com/automation/en/products/FSW-programme.cfm, *Welding Automation*, ESAB FSW Programme

[23] [04.02.2014], http://www.twi-global.com/services/intellectual-property-licensing/friction-stir-welding/equipment/, *Friction stir welding* - Licensing

[24] D. Lohwasser, Z. Chen: Standards for friction stir welding. In: *Friction Stir Welding: From Basics To Applications*, Editors: D. Lohwasser, Z. Chen, Woodhead Publishing Ltd.,Cambridge, UK., p.10 -12

[25] [11.02.2014], http://www.ffjournal.net/item/6624-stirring-up-a-new-airplane.html, FF Journal, R. Olexa: *Stirring up a new Airplane*

[26] *AIRBUS Process and Materials Specification*, Process Specification 01-04-06, Friction Stir Welding of Aluminium Alloys, Published and distributed by: AIRBUS S.A.S. ENGINEERING DIRECTORATE, 31707 BLAGNAC Cedex, FRANCE

[27] [10.03.2014]http://www.twi.global.com/industries/aerospace/joining-of-airframe-structures/friction-stir-welding-of-airframe-structures, *Friction Stir Welding of Airframe Structures*

[28] M. Pacchione, J. Telgkamp: Challenges of the metallic fuselage, In: 25th *International Congress of the Aeronautical Sciences-ICAS*, Hamburg, CD-ROM, Paper ICAS 2006-4.5.1, 2006

[29] S.M.O. Tavares, P.P. Camanho, P.M.S.T. de Castro: Materials selection for airframes assessment based on the specific fatigue behavior. In: P.M.G.P. Moreira, L.F.M. da Silva, P.M.S.T. de Castro (Eds.): *Structural Connections for Lightweight Metallic Structures*, Springer, 2012, p. 239–261