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FRICTION STIR WELDING: A REVIEW

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Abstract—This article provides an introduction to the basic principles of the friction stir welding(FSW) as well as the applications of friction stir welding in the industrial field. The basic principles covered include the terminology, joint configurations, heat generation, tool design, defects and the properties of alloy materials. In every aspect of the friction stir welding process discussed, all the information acquired by several authors are combined together in this article for easy reference purposes. All the results and conclusions from various experiments are given so that further research on this field can be initiated. The recent application of robot .i.e. automation in industrial sectors is increasing rapidly. Hence the application of automation and control architecture for FSW process is also discussed. Various methods which help in the discovery of defects in the weld products are also given. Quality testing methods of FSW process are also given in this article. Finally, the latest applications are discussed, with an emphasis on the advances in space launch vehicles, trains, aerospace, motor vehicles and marine vessels.

Keywords— Friction stir welding, Manufacturing, Robotics.

I.Introduction

The friction stir welding (FSW) technique, developed by The Welding Institute (TWI) in the United Kingdom, is a potentially attractive joining technique and has been extensively applied in many applications in the modern era. Joining of Mg alloys is complex due to their high reactive nature and high inflammability. FSW is a solid state joining technique which has emerged as a potential tool to join similar and dissimilar metals. The principle behind joint formation in FSW was explained by Mishra and Ma. FSW does not melt the base material and therefore completely eliminates the problems associated with solidification that usually appear in fusion welding. In addition, the lower temperature of the process enables joining with lower distortion and lower residual stresses. FSW is also an energy efficient process that requires no filler material and, in most cases, does not require the use of a shielding gas. Furthermore, the process lacks the fumes, arc flash, spatter, and pollution associated with most fusion welding techniques.
[1]

a) Basic principle

Although there are several process variants in the friction welding technique, the conventional FSW was the earliest demonstrated technique, and is the most widely used technique in the field of both research and industry. A rotating cylindrical tool with a profiled probe is fed into a butt joint between the two clamped workpieces, until the shoulder, which has a larger diameter than the pin, touches the surface of the workpieces. The probe is slightly shorter than the weld depth required, with the tool shoulder riding atop the work surface [1]. After a short dwell time, the tool is moved forward along the joint line at the pre-set welding speed. Frictional heat is generated between the wear-resistant tool and the work pieces. This heat, along with that generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without melting. As the tool is moved forward, a special profile on the probe forces plasticized material from the leading face to the rear, where the high forces assist in a forged consolidation of the weld.

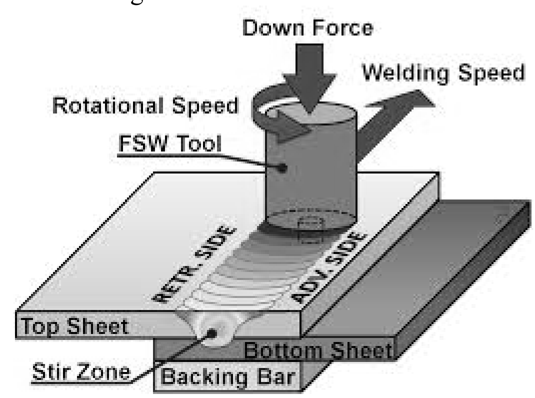

Fig. 1: FSW process

This process of the tool traversing along the weld line in a plasticized tubular shaft of metal results in severe solid state deformation involving dynamic recrystallisation of the base material [2]. Many of the authors have studied about the friction welding process and have conveyed their opinions and observations. Krishnan classified FSW as an extrusion process, saying that for each rotation of the tool, a cylindrical section of the material is extruded around the probe and a banded structure within the weld results. Krishnan coined these bands to be "onion rings", which can appear as concentric rings or semicircles depending on which cut plane they are viewed from, result from oxidation on the surface of each semi-cylinder [3]. Similarly, Yang et al. observed banded microstructure in welds of AA2024-T351 and AA2524-T351. From his

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observations he concluded by saying that it resulted from periodic variations in the size of equiaxed grains, the micro-hardness, and the concentration of base metal impurity particles [4]. A unique feature of the friction stir welding process which I observed is that the transport of heat is aided by the plastic flow of the substrate close to the rotating tool. The heat and mass transfer depend upon the material properties as well as welding variables including the rotational and welding speeds of the tool and its geometry.As discussed, the joining in the FSW process takes place by extrusion and forging of the metal at high strain rates. Kokawa et al. estimated an effective strain rates in the range 2-3 s1 [5]. Schneider et al. also studied the band formation which is quoted by Krishnan as " onion rings", which is formed by one tool rotation. However, Schneider et al. also observed a secondary phenomenon at a lower frequency that was evident in the dispersal pattern of a molten lead tracer wire in a butt weld of 2195-T81 Al-Li-Cu alloy. This phenomenon was referred as interfacial" slipping and sticking" and results from a variation in the radial distribution of the rotational field, or an oscillation in the material contact condition at the edge of the tool shoulder. This phenomenon was observed at a frequency one order of magnitude lower than the tool rotational speed [6]. Qian et al. also used this so called "slipping and sticking" terminology but did not study lower frequency oscillations, rather they studied torque oscillations that occurred at the same time [7].

b) Joint configuration

The solid-state nature of the FSW process, combined with its unusual tool shape and asymmetric speed profile, results in a highly characteristic microstructure. The microstructure can be broken up into the following zones: a)The stir zone(which is a nugget, dynamically recrystallized zone) is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller then the grains in the parent material [8]. A unique feature of the stir zone is the common occurrence of several concentric rings which has been referred to as an " onion ring" structure as Krishnan stated [3].b)The flow arm zone is on the upper surface of the weld and consists of material that is dragged by the shoulder from the retreating side of the weld, around the rear of the tool, and deposited on the advancing side.c)The thermos-mechanically affected zone(TMAZ) occurs on either side of the stir zone. In this region the strain and temperature are lower and the effect of the welding on the microstructure is correspondingly smaller. d)The heat-affected zone(HAZ) is subjected to a thermal cycle but is not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. In fact, in age-hardened aluminium alloys this region commonly exhibits the poorest mechanical properties [9].

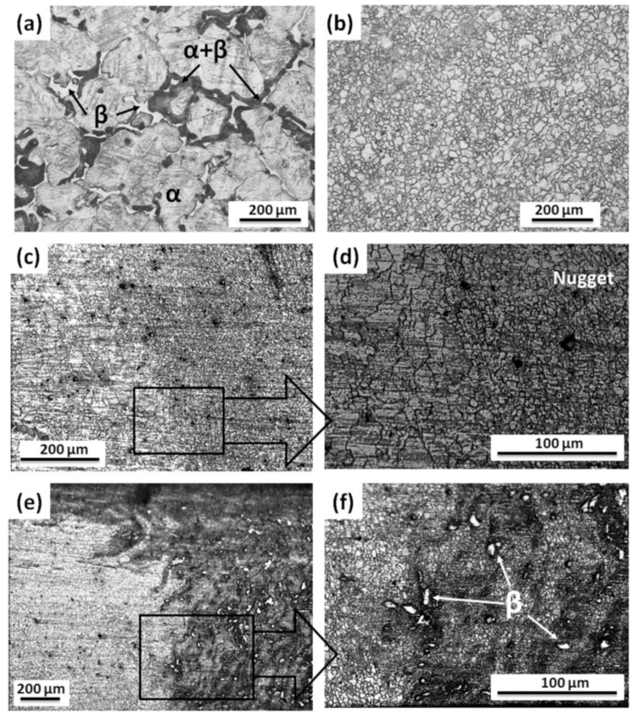

Fig. 2: Optical microscope images of the specimens AZ91 Mg and AZ31 Mg alloy base microstructure, nugget zone and base material interface [10]

c) Heat generation

An analytical model for heat generation for eccentric cylindrical pin in friction stir welding was developed that utilizes a new factor based on the tool pin eccentricity. The proposed analytical expression is a modification of previous analytical models from the literature, which is verified and well matches with the model developed by previous researchers. Results of plunge force and peak temperature were used to validate the current proposed model. The cylindrical tool pin with eccentricities of 00, 0.2 and 0.8mm were used to weld two types of aluminum alloys; a low deformation resistant AA105-H12, and a relatively high deformation resistant AA5754-H24 alloy. The FSW was performed at constant tool rotation speed of 600rpm and different welding speeds of 100, 300 and 500mm/min. Experimental results implied that less temperature is generated using eccentric cylindrical pin than cylindrical pin without eccentricity under the FSW process conditions [11]. Furthermore, numerical simulation results show that increasing the pin eccentricity leads to decrease in peak temperature. During the process of friction stir welding, heat is generated by friction between the tool and the work-piece and via plastic deformation. A fraction of the plastic deformation energy is stored within the thermomechanically processed region in the form of increased defect densities. In the weld, a mixture of recovery and recrystallisation phenomena occur simultaneously [12]. Deformation not only increases the dislocation density but also the amount of grain surface and grain edge per unit volume and by cutting precipitates may force them to dissolve [13-16].

c) Tool design

Zhao et al. studied the effect of tool pin design on the weldability and mechanical properties of welded 2014Al plates. Cylindrical and tapered tool pins did not ensure effective mixing in the vertical direction leading to wormholes at the base of the TMAZ zone. However, when tapered tools with the threads were used, defect free welds were obtained [17]. Colegrove and Shercliff used a thermal model based on FLUENT to design a tool to minimise the traversing force during FSW of aluminium alloy. They examined several tool geometries including Trivex, which is triangular in shape with convex surfaces, and MX-Trivex which had similar shape with threads. They observed that the traversing force and downward forces were considerably lower for the Trivex tools relative to those for Triflute at lower applied shear stress where considerable slip occurs between the tool and the work-piece [18,19]. Elangovan and Balasubramanian also studied probe geometry, testing the effects of straight cylindrical, tapered cylindrical, threaded cylindrical, square, and triangular probes on the microstructure, tensile strength, and microhardness of Al 2219 butt welds [20]. Scialpi et al. studied the influence of shoulder geometry on microstructure, tensile strength, and microhardness of Al 6082 butt welds. Shoulder geometries featured scrolls, a cavity, and a fillet [21]. Liu and Ma studied varying shoulder and probe diameters and their effects on the microstructure and mechanical properties of 6061- T651 butt welds [22]. Sorensen and Nielsen presented a convex scrolled shoulder tool with a step spiral probe that offered wider process windows, lower process forces, and the ability to operate at a zero degree tilt angle [23].

d) Defects

An inappropriate rate of heating can result in the formation of FSW defects such as lack of penetration, lack of fusion, tunnels, voids, surface grooves, excessive flash, surface galling, nugget collapse and kissing bonds [24]. These defects are sometimes divided into volumetric flaws and weld line flaws [25]. A more common possibility is the division of the defects based on the energy input. As it is primarily determined by the main parameters of FSW, which are the tool rotational speed (TR), the translational speed i.e. welding speed (WS), and tilt angle [26]. Voids and wormholes (single voids extending longitudinally along the weld) can be found in FSW under non-ideal process conditions. Things like insufficient forging pressure, excessive travel speed, inappropriate tool design, or an overly worn tool may cause the formation of voids [27,28]. These defects may be surface breaking or contained entirely within the volume of the weld, with the former being significantly more detrimental to mechanical properties [29]. Kahl et al. and Chimbli et al. have performed studies on the effects of non-surface breaking wormholes on mechanical properties such as tensile strength, ductility, and fatigue strength in aluminum alloys [30].

II.Properties of alloy materials

a)Aluminium alloy

P Satish studied the influence of tool revolving on the mechanical properties of the stir welded 5083 Aluminium alloy. The final result of his observation through his experiment was that to get good mechanical properties for the aluminium alloy used, it is better to set the tool speed to 710 rpm rather than using 900 rpm and the recommended welding speed is 40 mm/min [31]. Noor zamar concluded through his experiment that the FSW of similar and dissimilar alloys resulted in the significant grain refinement at the stir zone of all the joints. He also determined the tensile strength of the joints as well as the hardness values [32]. Shengchong Ma studied the corrosion behavior of the friction stir welded aluminium alloy 2219 [33].

b) Titanium alloy

By far the most dominant of titanium alloys is Ti–6Al–4V, which in its commercial condition has a mixed microstructure consisting of hexagonal-close packed a and body-centred cubic b phases, which is the stable phase at high temperatures. The usual microstructure is produced by cooling from the phase field to produce Widmanstätten b with about 50% of the a being retained in the microstructure. R. Nandan et al. / Progress in Materials Science 53 (2008) 980–1023 1009 This alloy, which accounts for about half of all the titanium that is produced, is popular because of its strength (1100 MPa), creep resistance at 300 C, fatigue resistance and castability [34].

III.Robotic welding

As FSW evolved through the two decades after its discovery, effort was placed on how best to automate the process for further adoption. Since FSW uses a rotating tool, similarly to how a milling machine uses an end mill, computer numerically controlled milling machines could immediately be used for the welding process. Thus custom built machines for the specific use of FSW emerged. These custom built machines looked similar to a milling machine, but included sensors for process monitoring capability and more control capability beyond position control.

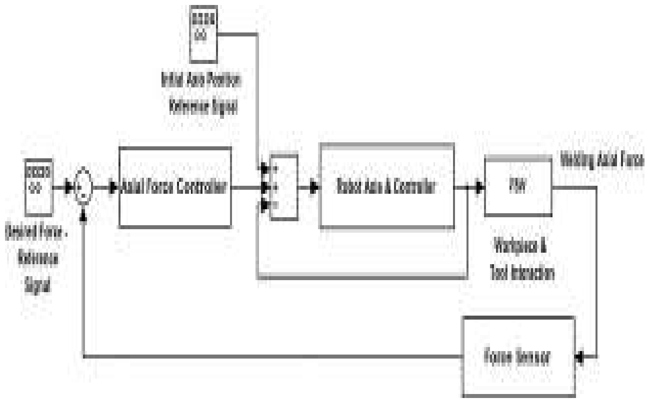

Fig. 3. Process control architecture [35]

IV.Weld quality testing

Esther conducted non-destructive testing on dissimilar friction stir welds between 5754 aluminium alloy and C11000 copper. Visual inspection of the quality of welds is improper as Esther has found out that only 44% of the welds were defect free. The optimal rotational speed required for producing defect-free welds of aluminium and copper was found to be 950 rpm [36]. Rosada prefers the advanced technique of FSW to be held in practice since in the previous methods defects were found only upto 200um but using this advanced technique defects were detected as small upto 60um [37]. The welding quality testing methods include: post-weld nondestructive testing methods such as visual testing, dye penetrant testing, eddy current testing, radiographic testing and ultrasonic testing.

V.Applications

a) Space launch vehicles

Friction stir welding has been used in many of the world's space launch vehicles, including the Space Shuttle main tank built by Lockheed Martin, Boeing USA's Delta II and Delta IV rockets, the Space X Falcon 9, the European Ariane rocket and NASA's Orion spacecraft & Space Launch System(SLS). More recently, TWI used friction stir welding to fabricate and deliver a prototype cast titanium propellant tank for the European Space Agency.

b) Trains

The rail industry was an early adopter of FSW, with Japanese manufacturers: Hitachi, KHI and Nippon Sharyo, among others, using the technique for both commuter and express trains for use around the world. The process has been used for Hitachi super-fast trains(Shinkasen) which are able to reach speeds of 320kph and on the new Virgin Azuma trains being assembled at Newton Aycliffe. Friction stir welded trains are also in operation on the UK Channel Tunnel and on the London Underground.

c) Aerospace

Aerospace has also seen a strong uptake of FSW, which allows parts to be joined without the use of riveting to create lighter components and structures for aircraft. Used by companies including Boeing, Lockheed Martin, Bae systems, and EADS, the technique was also used by Eclipse Aerospace who developed in the first friction stir welded jet aircraft, the Eclipse 500 and is used in Embrater's 'Legacy' aircraft.

d) Motor vehicles

The ability to join lightweight components with FSW has obvious advantages for the motor industry. Used by companies including Audi, Ford and Mazda, FSW has also been used by Tesla for their ground-breaking all-electric sports car. However, FSW has also seen links with more traditional car manufacture, as seen through the application of friction stir welding by Morgan Motors.

e) London stadium

Following the success of the London Olympics in 2012, there was a need to convert seating at the Olympic stadium (now 'London Stadium') to allow a transition from 'Athlete Mode' to 'Football Mode' ahead of the 2015 Rugby World Cup and before the new tenants, West Ham United, moved in. With time being a factor, FSW was used (alongside TWI's expertise) to deliver a quota of 3,500 panels for the new extruded aluminium seating decks well ahead of the schedule.

f) Nuclear waste disposal

FSW is considered so reliable a process that it will be used to encapsulate Swedish and Finnish nuclear waste in giant copper containers designed to last for 100,000 years.

g) Marine vessels

Pre-fabricated wide aluminium panels for high-speed ferryboats can be produced by friction stir welding and are commercially available. The panels are made by joining extrusions, which can be produced in standard size extrusion presses. Compared to fusion welding, the heat input is very low and this results in low distortion and reduced thermal stresses. 1700 panels with an overall weld length of 110km have been produced and delivered by Marine Aluminium in Haugesund (Norway) from 1996 to 1999.

Fig. 4: Prefabricated FSW panel for a catamaran sidewall, rolled for road transport

Fig. 5: Prefabricated FSW panel for a catamaran sidewall, straight panel for ship transportation at Marine Aluminium in Haugesund in Norway

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