A Review-"Friction Stir Welding of AA6061 Aluminum Alloy using Drilling Machine."

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Abstract- **Friction stir welding is a solid state welding technology used for welding low melting point metals, such as Al,Mg and its alloys. The comprehensive body of knowledge that has built up with respect to the friction stir welding(FSW) of aluminum alloys since the technique was invented in 1991 is reviewed on this paper. The basicprinciples of FSW are described. Tooldesign and welding parameters contributes a major role for producing a better weld. Material flow and friction heat arethe factors that the internal factor for the formation of weld.FSW of aluminum alloys have the potential to hold good mechanical and metallurgical properties. The aim of this study was to investigate the effect of process parameters on the tensile strength of the welded joints.**

Keywords - Friction stir welding, metal flow, process parameters, mechanical properties.

I. INTRODUCTION

Friction stir welding (FSW) was invented in 1991 at The Welding Institute (TWI) of Cambridge, England[Thomas, W.M][1]. FSW is a solid-state joining technique that has grown rapidly in popularity in a wide variety ofindustries including the aerospace, railway, land transportation, and marine industries. Most often used on lowmelting point alloys such as aluminum, FSW has many advantages over fusion welding techniques. Becauseprocess temperatures remain below the melting point of the welded material there is no need for either shielding gasor filler material; low distortion and low residual stresses are inherent to the process FSW is also an energy efficientprocess that produces no fumes, arc flash, or spatter[Cook, G.E][2]. Perhaps the most significant advantage of FSW isthat the technique allows for the joining of dissimilar materials or materials that are nearly impossible to fusionweld.The FSW process includes three phenomena: heating, plastic deformation, and forging [Longhurst, W.R][3]. Anon-consumable rotating tool, consisting of a probe and shoulder, is plunged into the materials to be joined and thentraverses the joint line. Heat is generated through both friction and plastic deformation of the welded material. At elevated temperatures, the material plasticizes and is sheared at the front of the probe and it is rotated to the rear ofthe probe where it is forged together under significant shoulder pressure. The FSW process is illustrated in Figure 1.

The advancing side is the region in which the traverse velocity and the tangential velocity of the rotating tool are inthe same direction. The retreating side is the region in which the traverse velocity and the tangential velocity of therotating tool are in opposite directions. This advancing or retreating phenomenon leads to different mixingcharacteristics within the weld seam, depending on location. These characteristics will be discussed further in thematerial flow section of the introduction. FSW can be performed on a variety of joint configurations, including buttjoints, lap joints, and T-joints.[Mishra R.S][4]

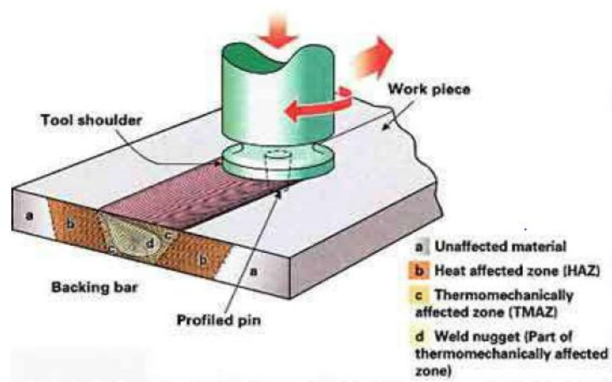

Figure-1: Friction stir welding principle and microstructure

Friction stir welding techniques have developed to a stage, in the early 21st century, where they are appliedin small-scale production. FSW uses a non-consumable tool to generate frictional heat at the point of welding,inducing gross plastic deformation of the work piece, resulting into a complex mix across the joint. The plates to bejoined are placed on a rigid backing plate and clamped in a manner that prevents the abutting joint faces fromseparating. A cylindrical-shouldered tool, with a specially projecting pin (probe) with a screw thread, is rotated andslowly plunged into the joint line. The pin length is similar to the required weld depth. The development of the FSWmachine will be made possible by converting a conventional milling machine into an adequate, functional,workstation where experimental friction stir welded joints may be performed on various base materials. Friction stirwelding is a solid state joining technique, which has made possible the welding of a number of materials that werepreviously extremely difficult to weld reliably without voids, cracking or distortion. The method was derived fromconventional friction welding. [Calvin Blignault][5]

The microstructure of a friction stir weld is unlike that of a fusion weld in that no solidification productsare present and the grains in the weld region are equiaxed and highly refined. Indeed, the FSW microstructure is thatof a wrought rather than a cast product.

The first attempt at classifying microstructures was made by [Threadgill P L][6]. His work was based solelyon information available from aluminum alloys. However, it has become evident from work on other materials thatthe behavior of aluminum alloys is not typical of most metallic materials, and therefore the schemecannot be broadened to encompass all materials. It is therefore proposed that the following revised scheme is used. This has been developed at TWI, but has been discussed with a number of appropriate people in industry andacademia, and has also been provisionally accepted by the Friction Stir Welding Licensees Association. The systemdivides the weld zone into distinct regions as follows:

II. WELD ZONE CHARACTERISTICS

Figure 2&3 shows the four visually distinct micro structural zones in which welds in aluminum aretypically divided into: (A) unaffected parent material, (B) heat affected zone, (C) thermo-mechanically affectedzone, and (D) weld nugget. In the heat affected zone, properties and microstructure are affected by the heat from theweld, although there is no mechanical deformation. This zone retains the same grain structure as the parentmaterials. The thermo-mechanically affected zone shows characteristics that suggest that it underwent plasticdeformation but recrystallization did not occur in this zone due to insufficient deformation strain. In weld nuggetzone, intense plastic deformation and frictional heating during FSW result in recrystallized fine-grainedmicrostructure.[Threadgill P L][6]

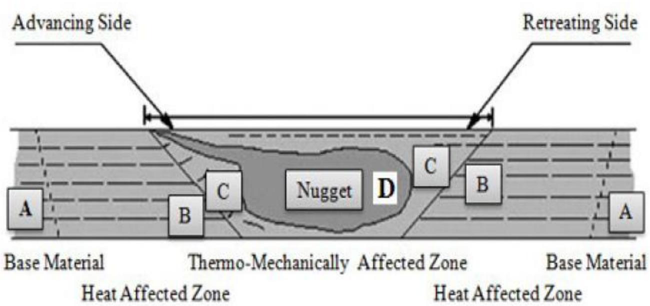

Figure-2: Schematic diagram of micro structural zones in friction stir welds in aluminium

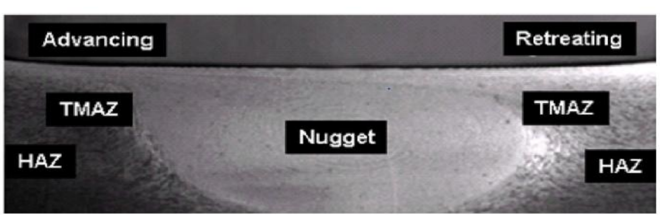

Figure 3: micrograph showing various micro-structural zones [Threadgill 1999][7]

Flow during friction stir welding is driven mainly by the rotation of the tool shoulder. Therefore, wedevelop and test an approximate analytical technique for the calculation of this flow in three dimensions, based onviscous flow of an incompressible fluid induced by a solid rotating disk. The computed velocity fields for thewelding of an aluminum alloy, steel and a titanium alloy are compared with those obtained from a well tested and comprehensive numerical model. We also present an improved non-dimensional correlation to estimate the peaktemperature, and an analytical method to estimate torque. The proposed correlation for the peak temperature istested against experimental data for different weld pitch for three aluminum alloys. The computed torque values are tested against corresponding measurements for various tool rotational speeds. The hardness in the TMAZ has alsobeen correlated with the chemical composition of aluminum alloys.

Unaffected material or parent metal: This is the material remote from the weld, which is not deformedand which, may have experienced a thermal cycle from the weld, is not affected by the heat in terms ofmicrostructure or mechanical properties.

Heat affected zone (HAZ): The material in this region lies close to the weld center and experiences athermal cycle used for modifying the micro structure and/ or mechanical properties. However, there is no plasticdeformation occurring in this area. In the previous system, this was referred to as the "thermally affected zone". Theterm heat affected zone is now preferred, as this is a direct parallel with the heat affected zone in other thermalprocesses, and there is little justification for a separate name.

Thermo-mechanically affected zone (TMAZ): In this region, the material has been plastically deformedby the friction stir welding tool, and the heat from the process exerted some influence on the material. In the case ofaluminum, it is possible to get significant plastic strain without recrystallization and there is a distinct boundarybetween the recrystallized zone and the deformed zones of the TMAZ. In the earlier classification, these two subzoneswere treated as distinct microstructural regions. However, subsequent work on other materials has shown thataluminum behaves in a different manner to most other materials, in that it can be extensively deformed at hightemperature without recrystallization. In other materials, the distinct recrystallized region (the nugget) is absent, andthe whole of the TMAZ appears to be recrystallized. This is certainly true of materials, pure titanium, b titaniumalloys, austenitic stainless steels and copper, which have no thermally induced phase transformation, but induce
recrystallisation without strain, r. In materials such as ferritic steels and ab titanium alloys (e.g.Ti-6Al-4V), theunderstanding of the microstructure is made more difficult by the thermally induced phase transformation, and thiscan also make the HAZ/TMAZ boundary difficult to identify precisely.[Terry Khaled][8]

Weld Nugget: The recrystallized area in the TMAZ in aluminum alloys has traditionally been called thenugget. Although this term is descriptive, it is not very scientific.

However, its use has become widespread, and asthere is no word, which is equally simple with greater scientific merit, this term has been adopted. It has beensuggested that the area immediately below the tool shoulder (which is clearly part of the TMAZ) should be given aseparate category, as the grain structure is often different here. The microstructure here is determined by rubbing bythe rear face of the shoulder, and the material may have cooled below its maximum. It is suggested that this area istreated as a separate sub-zone of the TMAZ.

III. ALUMINUM ALLOYS

Table: 1 Chemical composition of AA6061-T6

Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
0.9	0.62	0.33	0.28	0.17	0.06	0.02	0.02	Bal

Table: 2mechanical properties of AA 6061-T6

Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Cross section area(%)	Hardness (VHN)
302	334	18	12.24	105

Table: 3 Physical properties of AA 6061-T6

Physical properties	Density(g/ cm^2)	Melting point(^{0}C)	Modulas of Elasticity(GPa)	Poison ratio
AA 6061	2.7	580	70-80	0.33

Since the majority of work reviewed in this document pertains to aluminum alloys, it is important todiscuss some of the heat treatment aspects of these alloys. A three-step sequence is used to heat treat 2xxx, 6xxx and7xxx series and other heat treatable aluminum alloys, to higher strength levels.

Aluminum alloys are designated based on international standards. These alloys are distinguished by a fourdigit number which is followed by a temper designation code. The first digit corresponds to the principal alloyingconstituent. The second digit corresponds to variations of the initial alloy. The third and forth digits correspond toindividual alloy variations. Finally the temper designation code corresponds to different strengthening techniques.Aluminum alloy reinforced with 10% vol. SiC particles with an average size of 15 microns has been joined usingfriction stir welding method. The joining process were carried out at rotation speed 560 rpm and linear velocity of355 mm/min and the temperature was lower than 793 K. Microstructures of joined materials were observedaccording to the light and scanning electron microscopy. Changing of distribution of reinforcement particles wereanalyzed by new RVE theory. Experimental procedure for the tests showed the composite cast aluminum alloy matrix reinforced SiC particles with an average size 15 microns and a volume share of 10%. [KurtykaP.][9]The dynamic development of many industries was possible as a result of technical progress in the creationof new materials, new technologies for their preparation and permanent welding. One of the many problemsrequiring urgent solutions is to develop effective technologies permanent welding to the aluminum alloys andaluminum matrix composites. Solving this problem requires an identical strength base material and weld material,so they require unchanged the reinforcing particle size and their distribution. In the case of non-fulfillment of thiscondition is expected reduce mechanical properties of joints, as well as other adverse effects on the physical andchemical properties of the weld.

Research carried out on the selected composites reinforced with particles of oxides or carbides revealedthat FSW process significantly affects the distribution of the reinforcing phase in the matrix material; it greatlyimproves [Uzun H., Amirizad M., Flores O.V.][10,11,12]. It also leads to fragmentation of the particles [Fernandez G.J.][13]. Atthe same time it was found that the distribution of reinforcing phase in the stir zone is uniform. This has aconsequential change in mechanical and tribological properties, since the final number of particles of the reinforcingphase increases significantly and the distribution is close to isotropic. In this study it is also found that the process ofa very significant impact on the structure of the matrix material affecting the separation and homogenization of thesilicon needles present in the cast material [Shinoda T., Amirizad M., Storjohann D.][14,15,16]. The variation of transienttemperature in a FSW plate of 5mm work piece thickness is observed. Based on the experimental records oftransient temperature at several specific locations during the friction stir welding process for the AA 7020-T53, andcomparing with the temperature measured by the thermocouples records, the results are shown from the presentnumerical simulation [Muhsin J. J][17]Given the complexity and resource requirements of numerical models of FSW, well-tested analyticalmodels of materials flow, peak temperatures, torque, and weld properties are needed. Here an approximateanalytical technique for the calculation of three-dimensional materials flow during FSW is proposed considering themotion of incompressible fluid induced by a solid rotating disk. The accuracy of the calculations is examined forthe welding of three alloys. For the estimation of peak temperatures, the accuracy of an existing dimensionlesscorrelation is improved using a large volume of recently published data. The improved correlation is tested againstexperimental data for three aluminum alloys. It is shown that the torque can be calculated analytically from theyield stress using estimated peak temperatures. An approximate relation between the hardness of the thermo mechanicallyaffected zone and the chemical composition of the aluminum alloys is proposed.

IV. PROCESS PARAMETERS

The friction stir welding process is dominated bythe effect associated with material flow and largemechanical deformation, which in turn is affected byprocess parameters such as rotational speed, weldingspeed and axial force. A.K Lakshminarayanan*et al.*(2009)[18] described friction stir welding by optimum processparameter of 1200 rpm rotational speed, 75 mm/minwelding speed and 7 KN axial force, this process exhibitedyield strength of 224MPa, and tensile strength of 248MPa,which are 34% more than other welding joints and themicrostructure contains very fine, equiaxed grains andthus may be due to the dynamic crystallization thatoccurred during FSW process. Based on the experimentalstudy done by Mustafa Kemal Kulekci*et al.*, (2010)[19] FSWprocess carried out at a constant tool rotation of 1600 rpmand welding speed of 200mm/min and observed that theaverage tensile strength of the base metal is 290MPa andfor FSW is 270MPa, it seen 7% lower than base metal andstirring effect of the FSW process gives a finermicrostructure to the weld. N. T. Kumbhar*et al.*, (2008)[20] explained friction stir welding by employing toolrotational speeds of 710, 1120 and 1400 rpm and weldingspeeds of 63, 80, and 100 mm/min. It is seen that the weld nugget consists of fine equiaxed grains of an order less inmagnitude to that of the parent material ranging between15-20 μm. This small grain in the weld nugget zone is dueto stirring action of the tool. M. Iordachescu*et al.*, (2007)[21]explained friction stir process with rotational speed of1120 rpm, welding speed of 320mm/min and axial force orfriction pressure of 25 KN. They observed refined grainsin a discrete series of bands and some precipitates mainlydistributed at the grain boundaries as well as coarsenedgrains in heat affected zone regions. AnandC.Somasekharan*et al.*, (2004)[22] have taken optimum toolrotational speed of 800rpm and welding speed of 90mm/min to perform the welds of AA6061 aluminiumalloy. The base material revealed grains of unequal sizesand was seen distributed in the matrix with the grainstending to be rather elongated. The frictional heat providedby the rubbing of the tool shoulder and the mechanicalstirring of the material by the tool nib, the adiabatic heatarising from the deformation induced dynamicrecrystallization. And result shows the transitioning ofaluminium from the base material to the FSW zone with aclean decrease in grain size.

V. THE BASIC GEOMETRY FOR FSW TOOL

The basic geometry for a FSW tool is shown in Fig. 4 shows the variousnomenclature where: Rs is the shoulder radius, Rp is the pin base radius, Rpt is the pinpoint radius L pin is the pin height and a is a tap angle. According to Edwards andRamulu [23] a conical tool is needed because of the low thermal conductivity oftitanium. A cylindrical pin tool is not indicated for titanium because the heat generatedin the shoulder is not able to flow to the root of the joint, allowing the mixing ofmaterial in the lower plate. Simple geometries are generally used on pin tool fortitanium alloys. In all FSP experiments tool rotation rate, traverse speed and tilt of thespindle towards trailing direction has been defined differently in many studies byvarious authors, also the rpm of tool, feed rate and angle of tool need to be set upbefore experimentation.

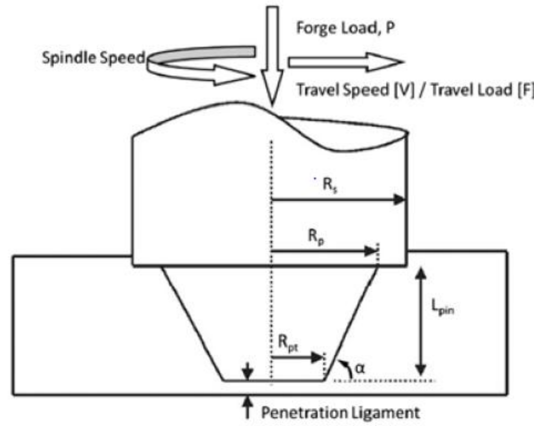

Figure.4 : Basic geometry for a FSW tool [23]

The basic concept of FSW is a rotating tool, made of non-consumable material,especially designed with a geometry consisting of a pin and recess (shoulder). Thistool is inserted spinning on its axis at the adjoining edges of sheets or plates to bejoined, and then it travels along the joining path line. Fig. 5 illustrates the process forthe tool and the plate, typical steps of the process: (i) downward motion to penetratethe material; (ii) penetrating the material; (iii) time for the heat generation fordeformation; (iv) linear movement on the part toward the processing direction; (v) endof processing and tool retraction [24].

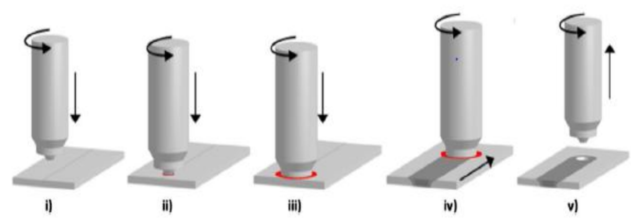

Figure. 5: FSW process steps [24].

VI. VARIOUS TOOL MATERIALS

Tool steel is the most common tool material used in friction stirring. This is because amajority of the published FSW literature is on aluminum alloys, which are easilyfriction stirred with tool steels. The advantages to using tool steel as friction stirtooling material include easy availability and machinability, low cost, and establishedmaterial characteristics. AISI H13 is a chromium-molybdenum hot-worked airhardeningsteel and is known for good elevated-temperature strength, thermal fatigueresistance, and wear resistance. In addition to friction stir welding aluminum alloys,H13 tools have been used to friction stir weld both oxygen-free copper (Cu-OF) andphosphorus-deoxidized copper with high residual phosphorus (Cu-DHP).However, thelimited travel speed in Cu-DHP would limit the production use of H13 .Shoulderinserts consisted of mainly Inconel 718, Nimonic 105 and Pins made from Nimonic 90,Inconel 718. Nimonic 105 was able to produce 20 m (66 ft) long friction stir weldswith no fracture or change in dimensions. Selection of Nimonic 105 was attributed togood creep rupture strength up to 950 °C (1740 °F) and consistent ductility up to 900°C (1650 °F). Densimet was selected as the shoulder material based on higher thermalconductivity (130 W/m°C) than nickel-base (10 to 20 W/m°C) and cobalt-base alloys(70 W/m°C), where the author assumed that faster heating of the tool shoulder ispreferred in FSW. The evaluated tool materials included H13 tool steel, IN738LC,IN939, IN738LCmod, sintered TiC:Ni:W (2:1:1), hipped TiC:Ni:Mo (3:2:1), puretungsten, and PCBN [25].

VII. CONCLUSION

The present review has demonstrated the extensive research effort that continues to progress the understanding of FSW of aluminium alloys and its influence on their microstructure and properties. It identifies a number of areas that are worthwhile for further study. From an engineering perspective, there is a need to investigate the occurrence and significance of flaws in friction stir welds. In particular, the influence of tool design on flaw occurrence and the development of nondestructive testing techniques to identify flaws in both lap and butt welds would be beneficial. The tensile strength of AA 6061 Aluminium alloy is discussedfor optimum process parameters of rotational speed, welding speed and axial force. Superior tensile properties of FSW joints were observed, this is due to the formation of fine equiaxed grains and uniformly distributed very fine strengthening precipitates in the weld region. The material flow within the weld nugget during FSW is very complex and still poorly understood. Compared to traditional fusion welding, FSW exhibits a considerable improvement in strength, ductility and fatigue properties.

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