REVIEW OF FRICTION STIR WELDING PROCESS

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ABSTRACT: Friction stir welding (FSW) is a rapidly growing permanent type solid state joining process for joining different metallic and non-metallic alloys in manufacturing industries, especially aerospace, marine, spacecraft, automobile, etc. In the current scenario, metal alloy welding is replaced by FSW due to its unique characteristics compared to fusion welding processes, i.e. reduced porosity defect, reduced heat affected zone (HAZ), no need protection gas, environmentally friendly, low distortion, etc. In this chapter, a critical evaluation of the critical aspects of friction stir welding, namely the principle of the process, the metallurgical and mechanical aspects; the effect of preheating and the inclusion of nano-particles were discussed. Difficulties and other issues related to FSW are also discussed to provide guidance for the global research community to conduct further research in this area.

Keywords: Solid-state welding, friction stir welding, preheating, quenching, nano- particle inclusion

INTRODUCTION

In the current scenario, transformation industries are developing rapidly in the world of work. Welding emerged as a viable manufacturing process in the mid-nineteenth century, Messler Jr, (2004); Subsequently, many fusion welding techniques evolved (eg arc welding, gas welding). Usually in fusion welding techniques, the energy density is high, and therefore the heat affected area is wider and leads to solidification defects, namely distortion, reduced mechanical properties, lack penetration, low melt rate, etc. In the mid-20th century, plasma arc welding and laser beam welding techniques were developed capable of producing a solid weld of thicker materials with a thermally affected narrow zone (Lohwasser and Chen, 2010). furthermore, these techniques are not suitable for reactive elements such as aluminum, magnesium. These drawbacks require exploration of solid state welding techniques (e.g. resistance welding, friction welding) in which the joint occurs at a temperature below the melting point of the base metals without the use of material, supply or shielding gas. In resistance welding, coalescence occurs due to heat generated by contact resistance and applied pressure and is therefore not suitable for materials with high electrical conductivity (eg copper, aluminum). In friction welding, two parts are joined by frictional heat generated when a moving part and a stationary component are pushed together to achieve the required heat and temperature for welding. The geometry of the part to be assembled limits its application in industry. To overcome the difficulties of welding aluminum-magnesium-based alloys, especially by fusion and other welding techniques, the Welding Institute (TWI) has invented a unique and innovative welding technique called friction-mix welding (FSW) after a intense research in this area. In 1991, Wayne Thomas and his colleagues invented friction stir welding and realized that the joint obtained by the process is 90% flawless and does not melt the part as in the case of fusion welding processes (Thomas et al., 1991; Dawes and Thomas, 1995). After the invention of FSW, industries began to implement this technique to manufacture aluminum components such as aluminum panels for hollow freezers for ships, fuel tanks for spaceships, etc. 50% and the manufacturing time goes from 23 days to 6 days; cost savings is up to 60%. Therefore, its ecological and energy efficient behavior makes FSW a green technology (Lohwasser and Chen, 2010).

FRICTION STIR WELDING PRINCIPLE

Friction stir welding (FSW) is a solid state joining technique in which coalescence occurs due to thermomechanical deformation of parts when the resulting temperature exceeds the solidus temperature of the parts. The basic concept of the FSW technique is shown in Figure 1. This is a non-consumable rotary tool with a specially designed shaft and shoulder for the tool. The shank of the tool sinks into the contact faces of the sheets or plates to be assembled, whereby the tool moves in the transverse direction along the length. The tool rotates clockwise and moves back and forth as shown in Figure 1. The left side where the direction of rotation of the tool is the same as the direction of travel of the tool is called the leading side. It is opposite to the flow direction of the metal. The side opposite the feed side where the tool rotation is reversed from the tool travel direction is called the reverse side. Due to the frictional heat between the tool and the workpiece, the material around the spindle softens and a solid-state seal is produced without melting (Backer and Bolmsjo, 2014; Lui et al., 1997; Mishra and Mahoney 2008).

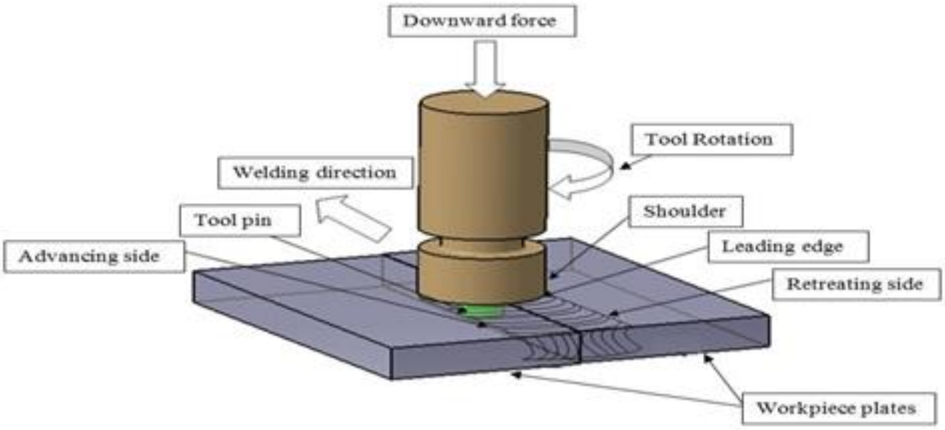


Fig. 1. Principle of friction stir welding (Backer and Bolmsjo, 2014)

In FSW joints, several microstructural regions can be observed, as shown in Figure 2. The parent metal region is not affected by heat as it is far from the recrystallized zone and therefore the microstructural properties and the mechanics of this region remain unchanged. The second region is the heat affected area that is next to the base metal and is affected by heat, but no plastic deformation occurs in this region; however, the mechanical and microstructural properties change. The next region is a thermomechanically affected area that is very close to the weld core and is plastically deformed with a tool. In this region, the material deforms without recrystallization. The next region is the nugget zone or the stirring zone or the completely recrystallized zone in which the spindle of the tool rotates and produces frictional heat; causes severe plastic deformation (Mahoney et al., 1998; McNelley et al., 2008).

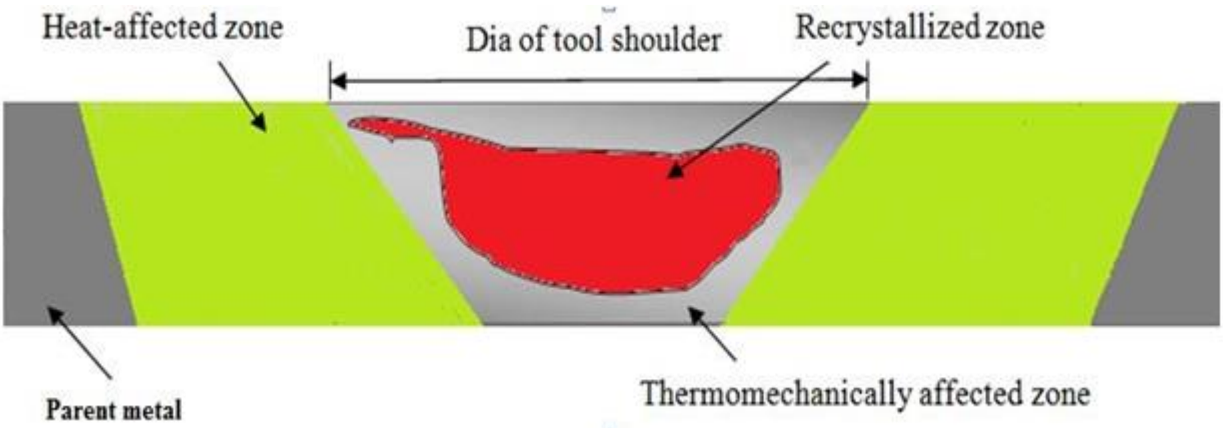


Fig. 2. Microstructural regions of friction stir welding (Mahoney et al., 1998)

PROCESS PARAMETERS

Process parameters for friction stir welding are classified into three groups: (a) Tool parameters: shoulder and pin material, shoulder diameter, pin length, pin diameter, feature geometry, pitch of thread, etc. ; (b) machine-related parameters: welding speed, immersion force or depth, spindle speed, tool tilt angle, etc. ; and (c) other parameters: anvil material, anvil size, part size, part properties, etc. (Lohwasser and Chen, 2010). The influencing process parameters are illustrated by a cause and effect diagram in Figure 3.

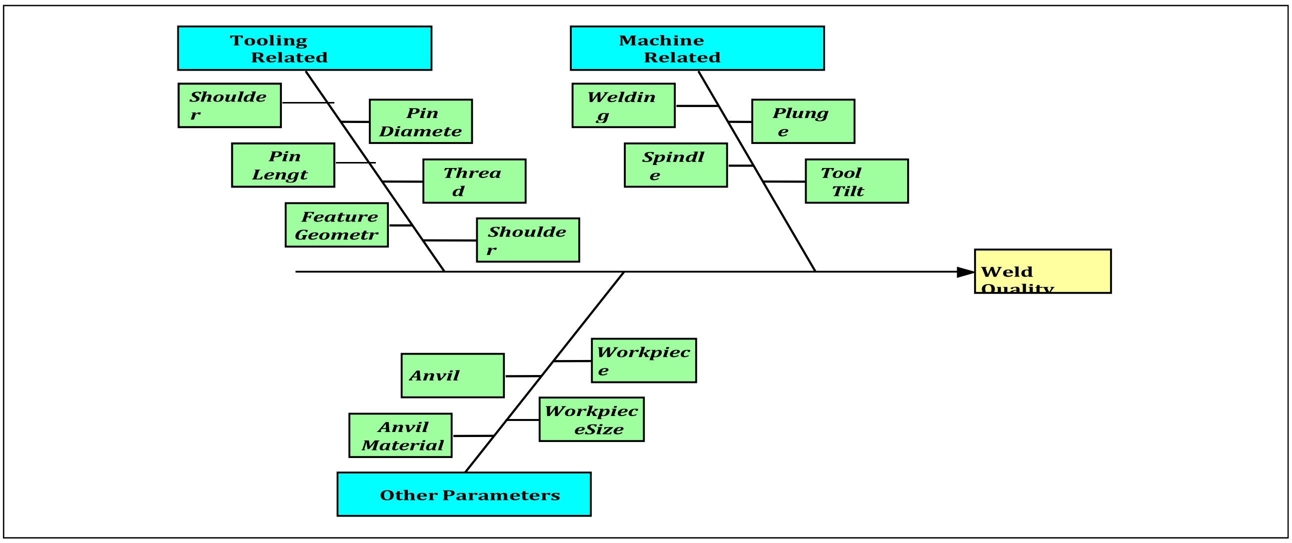
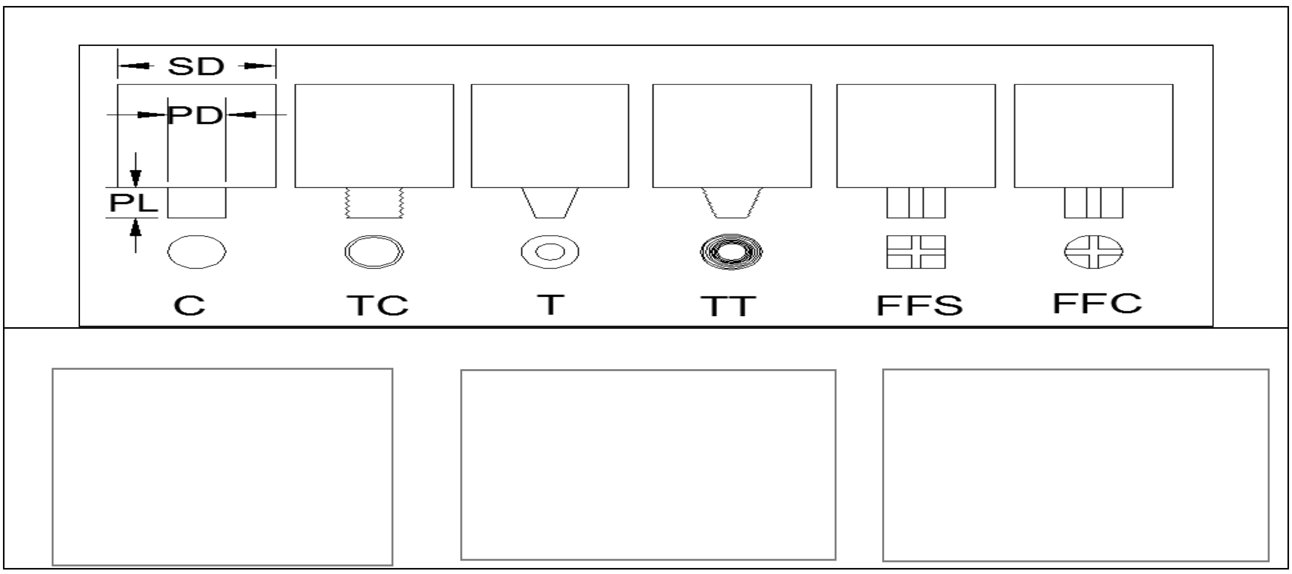


Fig. 3. Cause and effect diagram for friction stir welding process

Experimental setup

The experimental setup for the friction stir welding process consists of four major subsystems: (a) tool and tool-holding system (b) workpiece holding system (c) motion supply system (d) machine frame. FSW involves frictional heating, rotational and translational movement of tool, plunge force, etc. and hence, strength, heat resistance capability, good machinability, easy availability and low cost should be taken into consideration during selection of material for fabricating the machine setup. Tool and tool holding system consists of rotating FSW tool and a quill to hold the tool. This rotating tool is the most crucial element of FSW technique. It consists of pin and shoulder. In FSW, when rotating tool travels along the surfaces to be joined by the process, it serves primarily three objectives: heating of workpiece by friction between tool pin and solder with workpiece and resulting severe plastic deformation of workpiece material; stirring of material by simultaneous rotational and translational motion of tool to cause coalescence and to filling up the holes; and suppression of the heated metal underneath the shoulder to restrict the metal flow upto a level of frontal face of solder (Mishra and Mahoney, 2008). The common designs for pin are cylindrical with or without threads (Costa et al., 2015, Dubourg et al., 2010; Elangovan et al., 2008) conical with or without threads (Guo et al., 2013; Upadhyay and Reynolds, 2014; Ghetiya and Patel, 2015) four flute square, four flute cylindrical (Bahrami et al., 2014) etc. The tool shoulder can be a either cylindrical, with negative or positive scroll (Krasnowski et al., 2015)or it can be concave or convex (Rajakumar et al., 2011; Bahrami et al., 2014). The selection of FSW tool is a critical issue as its profile influences the stirring of material and quality of the weld to be done. The key factors in deciding FSW tool are hardness of workpiece material and amount of material to be stirred. Different FSW tool pin and shoulder geometry are illustrated in Fig. 4.



	(a)	
Flat end face shoulder	Concave shoulder	Convex shoulder

(b) Concentric circles shape shoulder	Scroll shape shoulder

Fig. 4. (a) FSW tool with different pin geometry (C: Cylindrical; TC: Threaded cylindrical; T: Tapered; TT: Threaded taper; FFS: Four flute square; FFC: Four flute cylindrical)(b) FSW tools with different shoulder geometry

The workpiece holding system contains a specially designed and shaped fixture to hold the workpieces properly. Fixture consists of base plate and clamps and it helps to keep the faying surface in contact during the process. Motion supply system consists of motors to provide rotational motion to the FWS tool and translational motion to the workpiece. Machine frame consists of bed for holding the fixture, spindle head to hold the quill, a vertical column and knee elevating screw for positioning of bed and to provide necessary support to the machine setup.

LITERATURE REVIEW

In the current scenario, the application of high strength and low weight metal alloys is increasing very rapidly in the aerospace, aeronautical, maritime industry, etc. Producing sound joints in these materials using existing welding techniques is a major concern. The FSW process due to its unique characteristics is emerging as an alternative welding technique. According to the available literature, the FSW technique is capable of joining similar or different metals or alloys and the list of materials of the parts that can be joined using the FSW technique includes aluminum, magnesium, copper, steel, zinc, nickel and their alloys. . A comparative study of published research on FSW of different materials is shown in Fig. 5. It is evident from FIG. 5 that most research work concentrates on aluminum due to its industrial applications and the difficulties researchers encounter in aluminum fusion welding. In this chapter, we have attempted to summarize the work already done and provide guidance for future research. Here is a brief description of the different aspects of the FSW process.

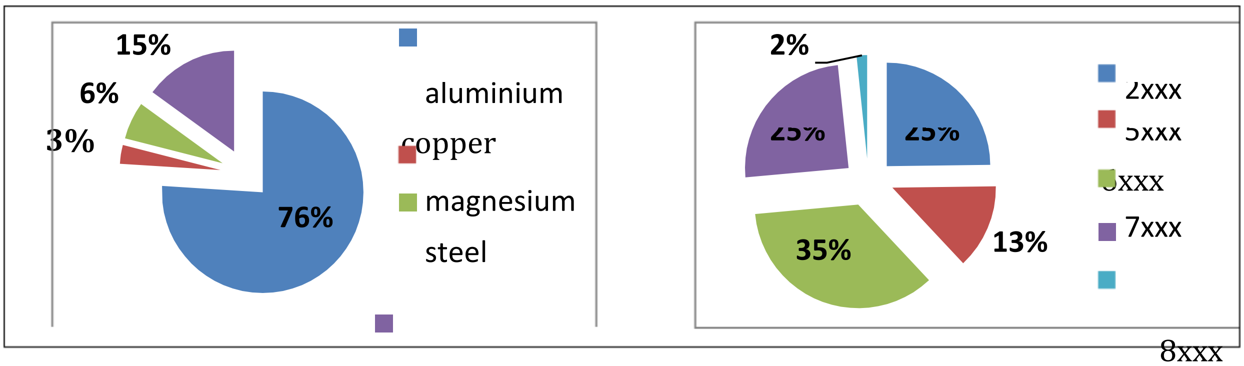


Fig. 5.Comparative study of published research work on FSW

FSW OF ALUMINIUM AND ITS ALLOYS

Aluminum and its alloys are widely used in aerospace, marine and automotive applications due to their unique characteristics: high strength-to-weight ratio, high corrosion resistance, high ductility, etc. Need for the FSW technique to join aluminum and its alloys. Rhodes et al. (1997) probably the first to take over FSW research for aerospace materials. After that, it is accelerated by Liu et al. (1997) while performing FSW to bond 6061-T6 aluminum alloy under different rotational speeds and welding conditions. The experiments show that the hardness in the zone of agitation near the crest is 55 VHN and near the depression is 65 VHN. The grain size is also changed in the seed area.

Colligan (1999) studied the plastic deformation behavior in the nugget zone during FSW and reported that the material movement in the nugget zone was partially influenced by the tool spindle. In 1999, Sato et al. examined the microstructure of friction stir welded 6063 aluminum. Formation of three types of microstructure regions: recrystallized fine grains; Equiaxed coarse grains and recovered grains are observed. The hardness is found to be reduced in the kernel area due to the low density and dissolution of the precipitates. Jata et al. (2000) examined the microstructural behavior of the nugget zone and tried to correlate it with the strain rate and the temperature of the nugget zone. They said that the size of the grain in the weld area varies with the rate of deformation and temperature. Furthermore, Jata et al. (2000) examined the effects of the post-weld condition (temperature 1210 ° C for 24 hours) on the microstructure and mechanical properties of the FSW aluminum joint. It is observed that without the post-weld condition, the tensile strength and elongation decrease and breakage occurs in the HAZ, while in the case of the post-weld condition, the tensile strength and ductility they remain constant; however, resistance to fatigue crack growth increases in ZAT and decreases in the nugget area. Charit et al. (2002) and Su et al. (2003) carried out an experimental investigation on 7xxx aluminum alloys and explained the microstructural and tensile properties of FSW joints. Charitet al. (2002) also reported that the grain exhibits a superplastic behavior in ZAT, which improves resistance. Lim et al. (2004) and Cavalière et al. (2006, 2008) applied FSW to a 6xxx aluminum alloy to evaluate the effect of rotational and translational speeds on the tensile behavior of the weld and reported that the ductility of the weld is affected by the rotation of the tool. In 2006, Schmidt applied this technique to the butt joint of 2024-T3 aluminum alloy and inserted a thin strip of copper as the marking material; Estimated average velocity of materials flowing through the shear layer. Cavaliere and Cerri (2005) used the FSW technique to join two different aluminum alloys 2024-7075 and obtained a weld without porosity defects. It is observed that in the zone of the seeds the grains are completely recrystallized and the microhardness increases as the distance from the center line increases to 2 mm on both sides. A fine-grained and more equiaxed structure is observed on the 2024 side compared to the 7075 side. It is concluded that all the samples fracture on the HAZ side around 2024 and have high ductility in relation to the original metal. . Chen et al. (2006) studied the effect of base metal conditions on the mechanical and metallurgical properties of 2219 aluminum alloys welded by friction and stirring under two conditions: 2219-O and 2219-T6. It is observed that the efficiency of the tensile strength is higher in the case of the 2219-O alloys compared to the 2219-T6 alloys. Furthermore, it is evident that the 2219-O microstructure does not have a visible interface between the nugget zone and the TMAZ.

The angle of inclination of the FSW tool also plays a crucial role in controlling weld defects. Chen et al. (2006) observed that a small angle of inclination reduces the flow of material during the process, which results in the formation of a structure similar to an embraced bond in the agitation zone, while a high angle of inclination d causes rays . The tensile strength decreases due to the formation of an enveloping joint structure. The FSW tool is one of the most important parts of the FSW setup, as the shaft profile and shoulder profile regulate the amount of material stirred. Scialpi et al. (2007), Elangovan et al. (2008) and Salari et al. (2014) described the effect of shaft and shoulder geometry on the performance of the FSW process. During the aluminum FSW 6082 Scialpi et al. (2007) reported that shoulder profiles influence the grain size in the nugget area and therefore the mechanical properties of the joints. The size of the grains in the agitation zone is observed very fine and equiax to the base metal. Elangovan et al. (2008) described the effect of tool geometries on the FSW of 6061 aluminum alloy. It is evident that the square bolt produces welds free of metallurgical defects and with high tensile strength. Subsequently, Salari et al. (2014) investigated the effect of the pin profile during friction stir welding. It is observed that the profile of the screw has a significant influence on the performance of the process. They also reported that the tapered stepped threaded pin produces a very strong seal. In addition to this, Rodrigues et al. (2009) studied the mechanical and metallurgical aspects of FSW joints using two types of tools: the conical shoulder and the spiral shoulder.

It is observed that the application of a tapered shoulder results in larger coarse precipitates in the agitation zone compared to the spiral shoulder and therefore the elongation is reduced by 30% in the shoulder, tapered and by 70% on the spiral shoulder. Furthermore, in 2012, Palanivel et al. manufactured FSW to join two different aluminum alloys (5083-6351) using four different spindle profiles at three different rotational speed levels. They reported that the screw profile influences the mixing and flow of the material during the process, resulting in a change in properties. Furthermore, it is concluded that the profile of the tapered pin produces a welding defect.

The generation of heat by friction and temperature distribution during the FSW process is another aspect to consider since it influences the microstructure and mechanical properties of FSW joints (Hwang et al., 2008; Xu et al., 2009; Lorrain et al., 2010; Al-Jarrah et al., 2014). Hwang et al. (2008) practically explored the temperature distribution and its effect on the properties of the 6061 aluminum alloy welded by friction and stirring. It can be seen that the hardness is the same on both sides (advance side and withdrawal side) but that the temperature on the advance side is slightly higher than that on the withdrawal side. In TMAZ and HAZ, both tensile strength and hardness are found to be 50% lower than base metal. On the other hand, Xu et al. (2009) conducted experiments on 2219-O aluminum alloy plates using thermocouples to determine the temperature distribution during FSW. It is evident that the stirring zone is completely recrystallized and that in the upper part of the weld the grain size is slightly coarser compared to the lower part. Xu et al. (2009) also reported that the tensile strength of the FSW joint increases with increasing rotation speed; however, elongation is adversely affected. It is observed that the fracture is ductile in nature and the toughness is improved from the bottom up. Lorrain et al. (2010) studied the effect of cooling on the microstructure and mechanical properties of the 7075 aluminum alloy plate joint.

It is observed that the nugget area is free of defects and that the strength and toughness are improved in TMAZ. Lu et al. (2011), Heidarzadeh et al. (2012) and Liu et al. (2012) carried out an experimental investigation to investigate the effect of the process parameters on the performance characteristics of the process during the FSW of alloys 2219-O, 6061 and 2219 respectively. Tensile strength is reported to improve with increasing welding speed, while feed rate negatively affects it. In addition to this, Costa et al. (2012) investigated the fatigue behavior of 6082 aluminum friction stir alloys and reported that tunneling and other serious defects affect fatigue strength. Later, Guo et al. (2014) described the effect of the process parameters on the mechanical properties of the FSW joint of two different aluminum alloys (6061-7075). It can be seen that mixing is more efficient when 6061 alloy is placed on the forward side. The grain size decreases with increasing feed rate.

Furthermore, it is evident that the fracture occurs on the 6061 side which has minimum hardness, higher tensile strength and good ductility. Fahimpour et al. (2012) compared FSW gasket with 6061 aluminum alloy GTAW gasket and concluded that FSW gasket has a property of higher corrosion resistance. Although in both cases the resistance to corrosion of the joint is lower than that of the base metal due to the size of the grain in the area of the nugget. On the other hand, Xu et al. (2012) conducted a comparative study of FSW welding and fusion welding and reported that the fatigue resistance of the lap joint by friction and agitation is lower than that of the lap joint welded by fusion due to the presence of 'lack of union'. In the most recent works, Upadhyay and Reynolds (2014) and Krasnowski et al. (2015) studied the effect of support plates and weld configuration on the metallurgical and mechanical properties of FSW, respectively joints. Upadhyay and Reynolds reported that applying a composite base plate instead of a steel base plate improves tensile strength and microhardness, while Krasnowski et al. concluded that double-sided welding has lower resistance than single-sided welding.

FSW OF STEEL

Fusion welding affects the microstructure of the steel and, due to these losses of steel, its resistance to corrosion and its toughness properties. To the best of the authors' knowledge, Thomas et al. (1999) is probably the first to verify the viability of FSW for steel. They applied the FSW technique to a 12% chromium alloy and low carbon steel on a modified vertical mill to test the joint's tensile and flexural strength. Lienert et al. (2003) experimentally analyzed the possibility of FSW of mild steel and reported the effect of the process parameters on the metallurgical and mechanical properties of the FSW joint. Thermocouples are also used to determine the temperature distribution during the process. However, very high tool wear is observed in the initial stage for the sinking action of the tool. Reynolds et al. (2003) tested the FSW for 304L and the experiments were carried out at a constant feed rate and at two different rotational speeds. It is evident that the grain size of the gasket is smaller than that of the base metal and the existence of a narrow band grain in the agitation zone for both speeds of rotation. Obviously, a joint with a greater ductility than that of fusion welding is obtained. In 2005, Sato et al. investigated the properties of friction welded super duplex 2507 stainless steel using a 25mm diameter CBN tool at a 3.5 degree rake angle. It is observed that in SZ the microstructure of the joint contains refined grains of ferrite and austenite and therefore the hardness and resistance are increased. Furthermore, it is evident that the fracture occurs between the HAZ and TMAZ lines on the withdrawal side. The percentage of carbon content is found to affect the mechanical and metallurgical properties of friction stir welded low carbon steel joints (Ueji et al., 2006). It is found that with increasing carbon content, the tensile strength increases rapidly with a small change in welding speed up to a certain limit, and then begins to decrease. With increasing carbon content, part of the austenite increases in the resulting ferrite-austenite structure. In addition, in the case of S12C steel, an austenite that has been transformed into pearlite is observed, but the distribution is not uniform. Sato et al. (2007) investigated the metallurgical properties of friction welded very high carbon steel and examined the martensitic structure in the stirred and mixed zone in the HAZ. Later in 2008, Saeid et al. described the effect of welding speed on the characteristics of stirring friction welded duplex stainless steel and stated that the stir zone microstructure consists of equiaxed grains of y-phase. Furthermore, they reported that grain size decreases with increasing welding speed and that hardness and tensile strength increase with increasing feed speed. Cho et al. (2012) and Han et al. (2014) studied the microstructure of friction and stir-welded stainless steel plates. Cho et al. observed that the hardness of the seed zone is higher due to the presence of a bainitic structure in the seed zone. On the other hand, Han et al. witnessed the formation of fine grains in the area of seeds and TMAZ due to mechanical agitation and heating. The result is a seal with superior impact resistance. In a recent work, Zhou et al. (2015) verified the possibility of filling the keyhole at the end of the process during the 316L stainless steel FSW using a 316L consumable steel bar tool. The fine-grained microstructure is obtained in the seed area. Although vacuum defects are observed on the lower surface of the keyhole. In addition to this, Sun and Fujii (2015) used a cathodic hydrogen loading method to evaluate hydrogen embrittlement during FSW of stainless steel. It is observed that due to the cathodic charge of hydrogen, no phase transformation occurs during the process. The fine particle size is obtained in the stirring zone. However, hydrogen bubbles stuck in the stirring zone cause small cracks to form.

FSW OF COPPER AND ITS ALLOYS

Copper has high thermal and electrical conductivity, excellent corrosion resistance, good strength, and good ductility that make it useful in many industrial applications. Due to its high thermal diffusivity and high oxidation rate, soldering copper by fusion welding technique is difficult. FSW is emerging as a substitute for fusion welding for copper bonding. Lee and Jung (2004) probably the first researcher to investigate copper FSW. The experiment is carried out on 4 mm thick copper plates using a steel tool. It is observed that the size of the grains in the zone of seeds is very fine and equiax with the base metal. The study shows that the resistance obtained by FSW is higher than that of electron beam welding. Khodaverdizadeh et al. (2012) analyzed the strain hardening behavior of FSW joints of pure copper alloys. The experiments are carried out at two different rotational speeds and at a constant feedrate and vice versa and it is evident that both factors influence the mechanical and metallurgical properties of the copper gasket. The grain size in SZ and HAZ decreases with increasing rotation speed and decreasing welding speed. Due to this hardening capacity it increases and the hardening exponent of the stains decreases. Lin et al. (2014) compared the properties of pure copper plates welded by friction and stirring with those of TIG and it was observed that FSW copper produced a weld 13% more efficient than TIG.

FSW OF OTHER MATERIALS

In addition to aluminum, copper, and steel, FSW has also been tested for magnesium, brass, titanium, plastics, etc. here is a brief discussion of the results. Lee et al. (2005) used FSW for the assembly of high-strength titanium alloy plates. The experiment is carried out at constant welding speed and rotation. The microstructure of titanium is different from that of friction welded aluminum alloys. In the nugget area, the presence of deformation twins with variation in density is observed. It is evident that the doubles are denser at the top due to direct contact between the workpiece and the tool and decrease at the bottom. A phase transformation is also observed in the transition zone. The tensile strength in the nugget area is slightly less than that of the base metal and a fracture has occurred in the HAZ. Later, Zhang et al. (2008) carried out an experimental investigation of friction stir butt welding of titanium alloy plates and examined the microstructure of the joint. A fine laminar structure ($\alpha + \beta$) is observed in the seed area, while a bimodal-type structure is observed in the HAZ. The hardness and tensile strength of the SZ is higher than that of the base metal, but it is lower in the case of the HAZ and, therefore, the tensile samples are fractured in the HAZ. Meran (2006) reported experimental results of FSW for brass and compared the joint with the fusion welded joint. No evaporation of zinc and copper was observed during FSW. The mechanical properties of the joint are obtained in a similar way to the base metal. Also, fewer pores are seen in the microstructure in the nugget area compared to fusion welded brass. Xunhong and Kuaishe (2006) investigated the properties of friction welded Z31 magnesium alloy at various rotational and transverse speeds with an FSW tool having a 4mm shaft and 12mm shoulder diameter. Fine grains with an intermetallic compound are observed in the seed area. The microhardness of the nugget area is greater than that of the base metal and a fracture has occurred in the HAZ. However, the tensile strength is obtained slightly lower than that of the base metal. Cao and Jahazi (2011) reported the effect of rotational speed and screw length on the Z31 magnesium friction stir welded joint. The tensile shear load is observed to increase with increasing heat input up to a limit, then begins to decrease as shear strength increases with increasing depth of immersion of the pin. Forcellese et al. (2012) also studied the mechanical and metallurgical behavior of the magnesium alloy welded by friction and stirring Z31 and the results coincide with the previous results. Payganeh et al. (2011) carried out friction and stir welding of plates made of polypropylene and studied the effect of the geometry of the tool, the angle of inclination of the tool and the speed of rotation on the strength of the joints. They also reported the existence of an optimal rotational speed for the maximum tensile strength of the weld. After that, Panneerselvam and Lenin (2014) tried the FSW technique to join two sheets of nylon with a mild steel tool. They studied the effect of tool direction in the FSW process and concluded that a left-hand threaded rod profile with a left-hand thread profile and a right-hand thread profile with a clockwise direction produces a weld of superior quality. Otherwise, small ventilation holes and a large cavity can be observed. Schneider et al. (2015) used FSW to join nickel-based alloys and reported that the joint produced by FSW is perfect compared to fusion welded joints. It is also observed that the size of the grains produced by FSW is reduced by up to 85% compared to the smelting process. However, the tensile strength is obviously slightly lower than that of the base metal.

FSW OF DISSIMILAR METALS

Each metal has its unique characteristics and due to this use of different metals it is increasing rapidly in many industrial applications. However, the welding of dissimilar metals by the fusion process is inconvenient due to the appearance of defects: porosity, inadequate fusion and mixing and low resistance, etc. Different metal FSW gasket is reported in literature to have strength equal to defective base metal compared to fusion welding techniques. Takehiko et al. (2006) examined the properties of the joints of two different metallic alloys (aluminum and steel) and observed that the maximum resistance is obtained with a displacement of the tool axis of no more than 0.2 mm towards the side of the steel. It is also reported that the resistance of the joint depends on the speed of rotation which should be optimal. Liu et al. (2008) analyzed the properties of the FSW joint when joining copper with an aluminum alloy. No intermetallic compound is observed in the stirring zone. It can be seen that the mixture of copper and aluminum towards the copper side has a laminar structure and a mixed structure on the aluminum side. During the tensile test, the sample fractures towards the copper side and the observed tensile strength is the same as that of copper and 6% lower than that of aluminum. Chen and Nakata (2009) also attempted to bond FSW from aluminum to titanium and the results are consistent with previous results.

NANOPARTICLE INCLUSIONS, QUENCHING AND PREHEATING

In today's scenario, monolithic alloys are easily replaced by Aluminum Matrix Composites (AMC) in many engineering industries such as aerospace, automotive and marine due to their superior properties. The strengthening of the hard ceramic particles in molten aluminum led to the development of AMC. It is observed that with the increase in the amount of ceramic particles, the hardness, impact resistance and density of the AMC improve while the flexural strength increases up to a certain percentage and then begins to decrease. It is evident from the available literature that the mechanical properties of FSW joints improve with increasing reinforcement fraction and negatively affect ductility. Dinaharan and Murugun (2012) experimentally investigated the effect of the inclusion of ZrB2 particles on the tensile strength of FSW joints and it was observed that due to the unique characteristics of ZrB2: strong covalent bond, high fusion, high strength and hardness , good thermal resistance conductivity and resistance to thermal shock the tensile strength of FSW joints increases significantly with the increase of the percentage of ZrB2. Bahrami et al. (2014) investigated the effect of the inclusion of SiC on the strength of FSW joints and reported that these included particles act as barriers against recrystallization during the process. It is evident that due to the inclusion of particles, the strength of the FSW joint improves to such an extent that during the tensile test the sample fractures from the base metal. However, the FSW tool experiences a higher rate of wear due to the presence of SiC. Kumar and Murugan (2014) observed an improvement in the mechanical and thermal properties of AMC due to the presence of AlNp. A similar phenomenon is observed by Misak et al. (2014) during the FSW of aluminum alloy including CNT particles.

The quality of the seals produced by FSW is highly dependent on the flow of material in the agitation zone and therefore researchers have made several attempts to increase the flow of material in the agitation zone by varying the geometry of the pins. or welds. Alternatively, you can set the room preheat before FSW. Preheating softens materials and increases material flow in the agitation zone, thereby reducing weld forces and improving efficiency (Sinclair et al. 2010). It is observed that in the FSW with preheating, the resistance of the joints increases by 8% compared to the conventional FSW. Preheating improves material flow and marginal change in deformation behavior, resulting in increased hardness of the nugget area (Yaduwanshi et al., 2014). Due to the additional heat, the HAZ increases and the TMAZ decreases. Thermal stress also increases due to the presence of additional heat in the HAZ (Yaduwanshi et al., 2013). In the case of FSW of dissimilar metals, preheating increases the flow of material in SZ and decreases the formation of voids. Yaduwanshi et al. (2014) investigated the effect of preheating during FSW of dissimilar metals and found that the developed seals are free from vacuum defects. In addition, FSW joints are obtained with better tensile and flexural strength. In addition, the additional heat reduces friction between the tool and the workpiece; results in low tool wear and longer tool life (Zargar and Kukatpally, 2013) Rapid cooling using different cooling media, i.e. brine solution, water, oil, etc. increases the elastic limit and minimizes residual stresses. In addition, slow cooling improves resistance to stress corrosion cracking. The same concept can be applied to improve the strength of FSW joints. To the best of the authors' knowledge, the available literature lacks experimental studies on the hardening of FSW joints and, therefore, this may be an aspect to be explored significantly.

CONCLUSIONS AND FUTURE SCOPE

In this chapter, a review of different aspects of the FSW technique has been illustrated. It was decided to present the main results related to FSW in one place in order to provide a clear picture to the reader. We can conclude the following points:

- Friction-stirring welding due to its unique characteristics: low deformation and contraction even in long welds, without arc, filler metal and shielding gas, low HAZ, without spattering or porosity defect, emerges as an alternative to fusion welding. FSW is suitable for joining similar or different metals or alloys, including aluminum, magnesium, copper, steel, zinc, nickel and their alloys, plastics, etc.
- Like traditional fusion welding, butt and lap joints can be made by friction stir welding. However, no special preparation is necessary. Furthermore, it is observed that FSW exhibits a significant improvement in tensile strength, ductility, fatigue and toughness over fusion welding.
- It is clear that the FSW process parameters: tool rotation speed, travel speed, spindle angle of inclination influence the mechanical and metallurgical behavior of the joints and are therefore crucial to produce a solid weld and impeccable.
- It is clear that the FSW tool regulates the amount of material stirred and the frictional heat and therefore the geometry of the spindle and shoulder is a decisive factor in achieving solid welds. Despite the considerable attention given to the FSW technique, the following issues have not received enough attention and need to be addressed:
- According to the available literature, most of the research work has focused on friction stir welding of aluminum, copper and magnesium. Friction-stir welding of alloys, plastics, composites, etc. it has ample scope for future research.
- Influences of input process parameters on process performance characteristics and interaction effects are not significantly explored. A detailed study of the contribution of individual input process parameters on the performance characteristics of the process is lacking in the literature.
- The material flow mechanism, tool geometry design, welding tool wear and force distribution during welding require special attention.
- The tribological, corrosive and topographic surface behavior of friction and agitation welded joints is not

discussed in detail in the literature.

- A detailed study is needed to explore the effect of preheating, nanoparticle inclusion and quenching on the mechanical and metallurgical behavior of FSW joints.
- There are no adequate guidelines in terms of the mathematical / theoretical modeling of the FSW process performance parameters for selecting the input parameters to achieve the desired output.

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