Review The Common Defects In Friction Stir Welding

Abdulaziz I. Albannai

Abstract: Friction stir welding (FSW) is a solid-state weld process that broadly used by industries and preferred rather than other weld process due to its capability to weld similar and dissimilar materials under high quality. It can be used to weld high strength materials to weight ratio such as aluminum alloys, copper alloys, and magnesium alloys which are normally hard to be welded by conventional fusion welding processes. FSW has significant advantages over other weld processes, such as, automatic, used for most materials, can be carried out in all positions, low distortion, no shielding gas or filler are needed, can be employed under water, and environmentally friendly. On the other hand, FSW is like any other weld methods can produce series visualized or hidden defects if improper care used to process preparation. Of these defects are cracks, pores, voids and tunnel, fragment, lack of penetration, kissing bond, hooking, flash, and other surface defects. This paper presents the most common defects types that can be produced in FSW process and weaken the joint. The defects will be reviewed from some of significant studies made by researchers, and their results will be used to build up a guidance to detect and prevent these defects and their causes to assure producing a free defect weld joint.

Keywords: Friction stir welding (FSW); FSW defects; nondestructive evolution; FSW review

1 INTRODUCTION

Nowadays the application of aluminum and magnesium alloys offers preferable design adaptability due to their high strength to weight ration [1]. In materials fabrication processes, production of dissimilar metals and non-metals structures has been labelled as a great reputation, Steel-Mg, Steel-Al, Al-Mg, and Al-Cu are used for weight saving and corrosion resistance with high performance under high strength and fatigue resistance properties [2-4]. Their application fulfils aerospace, electric, electronics, transportation, nuclear, and marine structures [3-11]. Welding has been permanently an outstanding joining technique as compare to other fastening methods such as mechanical fasteners and other semi-joining processes [12-14]. Aluminum and magnesium alloys have some prohibited properties when conventional fusion welding processes employed, such as inherent oxide layer formation and low molten viscosity which results in poor joining and formation of hot cracking [12, 13, 15-17]. Solidification and liquation cracking are some common hot cracking associated with fusion welding processes [15-18]. Therefore, solid state welding process such as friction stir welding (FSW) is preferable and been widely expanded to light metals with lower melting points such as aluminum and magnesium alloys [7, 19-21]. FSW, which was invented and patented by The Welding Institute (TWI), London, UK in 1991 [21-26], is depending on a rotating tool which usually inserted into the interface at the butt line of the metal plates (workpiece) and produces a mixed plastically deformed zone known as a stir zone (SZ) [26, 27]. This action forces the metal plates to join when the rotating tool passes along the interface area [28]. During the weld process in FSW, when the tool rotates and passes through in the same time, a frictional heat and pressure are generated between the tool and the workpiece. This action forces to soften the materials and cause material flow and mix smoothly in the stir zone [26, 29, 30]. Thus, a weld joint with recrystallization structure is forming with better strength and toughness in comparison with the production of other conventional weld processes [12, 31, 32]. Moreover, FSW has many advantages over other weld processes, such as, weld dissimilar materials efficiently with low thermal gradient [10, 12, 20, 33], produce high weld joint quality with high surface strengthening [34, 35], autogenous process and no filler or shielding gas needed [36], continues and good repeatability [37], narrow heat affected zone [33, 38], no melting occur so no existence of solidification cracking [8], can weld almost all kind of materials and alloys (metallic, non-metallic, polymer, composite, etc.) [12, 39], and environmentally friendly [40]. Even though, FSW process has a wide range of advantages there are some significant downsides limiting its applications. High setup cost, size of the machine, noisy process, the weld should be done on the machine and hard to be done on the field, limited to material thickness, and it requires careful monitoring of welding parameters to ensure complete and consistent joining with no weld defect are some of the process downsides [12, 33, 41]. In FSW process, friction and stirring of material created by a hard non-consumable rotating tool consisting of specially designed pin and shoulder [28, 36]. During the process a tool pin (probe) is totally implanted between interface surfaces of the workpiece with appropriate rotational speed until the shoulder makes a contact with the workpiece surface and providing the right compression force (axial force) on the stir zone [42]. The action between the tool and workpiece surfaces generates large amount of frictional heat which softens the workpiece materials and stirring it to flow around the pin. The soften material flows and circulates from front to back and top to bottom of the pin when the tool is travelled along under appropriate pin rotational speed and suitable shoulder compression force [19]. Thus, with this action and after the tool passes through, the bonding of the soften materials will form the desired solid state weld joint [28, 42] as can be seen in figure (1). There are two distinct sides of a weld line will be created during FSW process, one is called the advancing side while the other is called retreating side [12, 30, 43] as can be seen in figures (1 & 2). The advancing side formed when the tool rotates in the same direction of the tool travel direction (weld direction) and generates higher frictional force, where the retreating side formed when the tool rotates in the opposite

- Abdulaziz I Albannai is a specialized trainer (C) in the manufacturing department in the college of technological studies of Public Authority for Applied Education & Training, Kuwait.
E-Mail: Al.Albannai@Paaet.edu.kw

direction of the tool travel direction creating lower frictional force.

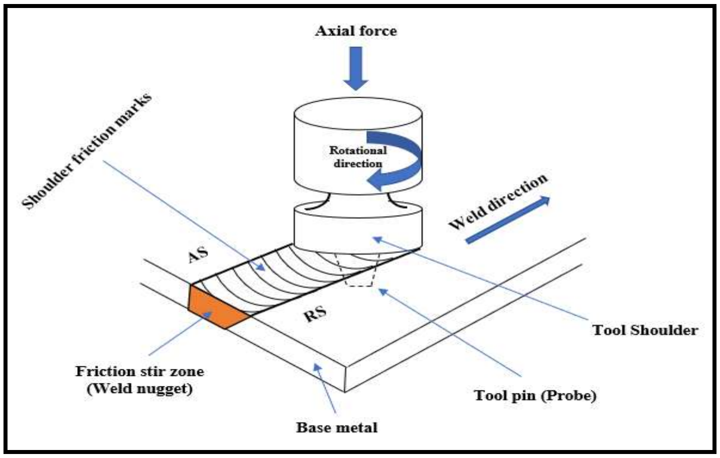

***Figure (**1): A schematic of main weld parameters used in FSW process and its tool parts*

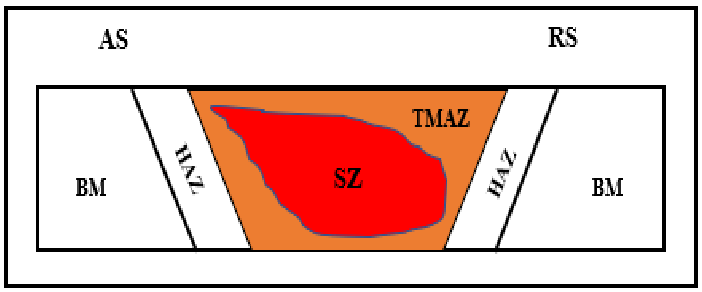

***Figure (2**): A schematic showing cross section image of FSW weld nugget and its main four regions SZ, TMAZ, HAZ, and base metal (BM) with the identification of both sides AS and RS.*

Designing tool's shape and material in FSW considering the heart of the process and governor of the weld parameters, such as tool rotational speed, weld travel speed, axial plunge load, tool offset location, and tool tilt angle [28, 33, 42, 44]. Figure (1) showing the most important FSW weld parameters and tool parts. While, figure (2) showing the four different microstructural zones produced after employing FSW process [33, 45, 46]. Stir zone (SZ) and known as dynamically recrystallized zone (DXZ) or weld nugget is where a very fine equiaxed grains can be located and resulted from high strain and thermal energies generated by weld pin motions [12, 47]. Beyond DXZ the thermo-mechanically affected zone (TMAZ) is located, where highly elongated grains can be found and no occurrence of recrystallization action. The elongated grains formed and resulted of high strain forces from the pin motions, but no enough thermal energy for recrystallization action to be reached [12]. Next to TMAZ is the undeformed region and known as heat affected zone (HAZ), where no plastically deformation can be found and the size of it depending on the amount of heat input introduced by the process [12, 48]. Farther away from the HAZ where the unaffected microstructure of the base metal can be found [20]. In FSW, if improper weld parameters and/or tool used, then weld defects and a weak weld can easily be resulted in the produced solid state weld joint [8, 12, 33]. The aim of this work is to introduce a review guide of the most common FSW defects, and their best solutions found in literatures in order to prevent weak weld and produce a good joint defect free.

2 WELDING DEFECTS IN FSW

FSW process may produce a joint not free of defects that can limit, and occasionally render weak weld joint. Several important factors can promote and assist weld defects formation during FSW process. Of these factors are; unsuitable main weld parameters such as; weld speed, rotational speed, tool design, tilt angle, plunge force and depth, pin off set, and workpiece thickness and fixing location [12, 33, 49]. If one or more of these factors used improperly then visible or blind weld defect shall be formed [8]. Micro and macro cracks, pores, voids and tunnel, fragmental, lack of penetration, kissing bond, hooking, flash, surface grooving, and end point are the most common FSW process defects [33, 50, 51]. Figure (3) showing most of the common defects' locations in FSW. The cause and prevention of each of these weld defects will be discuss and explain in this section as follow:

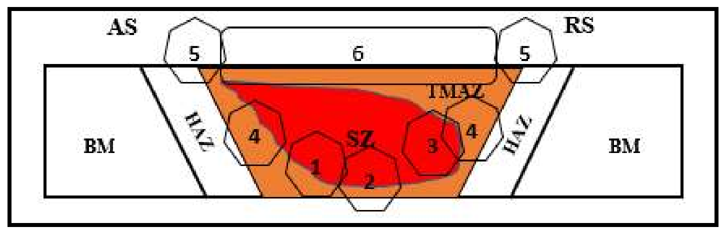

***Figure (3**): Schematic of a weld nugget produced by FSW process and its common defects' locations indicated by numbers as they follow: (1) Pores, voids and tunnel. (2) Lack of penetration. (3) Kissing bond. (4) Hooking. (5) Flash. (6) Surface defects, such as, groove, cracks and rough texture.*

2.1 MICRO AND MACRO CRACKS

This type of defect is usually found when dissimilar materials are welded due to incompatibility of materials melting points and improper flow in the stir zone. When welding dissimilar materials using FSW a critical layer with the tendency of intermetallic compounds (IMC's) is forming [12, 33]. This layer has a very hard and brittle behavior and very attractive to cracking and other defects, thus with larger size formation of IMC's layer a weaker joint will be obtained [52, 53]. High heat input which generated by low welding speed promotes forming thicker layer of IMC's [20, 33]. Also, when low heat input employed by using slow rotational speed or high welding speed an incomplete weld interfaces forms in the stir zone where inappropriate material flow consequences in micro or macro cracks and channels [12, 33, 54]. Moreover, tool design, pin offset, and material fixing location are significant and affecting the flow in the stir zone and the formation of IMC's layer in dissimilar joint [33, 55]. For example, if FSW used to weld Al and Cu, the pin offset should be located toward Al sheet to prevent process heat loss, because higher coefficient of thermal expansion of Cu can take away a minor amount of heat than Al which in turn helps to distribute thermal stresses properly and smooth mixture flow [33]. Therefore, to prevent this type of defect optimum selection of both welding and rotational speeds is necessary to limit the formation of IMCs in dissimilar weld joint [56-59]. Also, pin offset position and fixing location of the base harder material are very important to prevent expansion and its consequences in stir zone during the weld process. Additional process like cold rolling is recommended after FSW in order to partitioned IMC's layer and reduce its consequences [33, 60]. Examples of crack defects and IMC's layer formation found in dissimilar welds in FSW and presented by some researchers' work can be seen in the following figures (4, 5, & 6) [54, 61, 62].

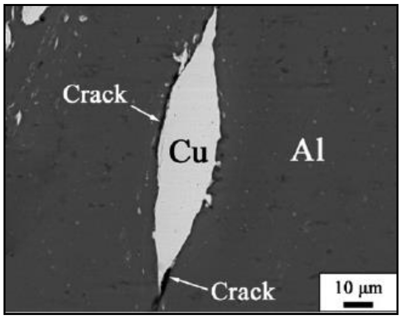

Figure (4): *showing SEM backscattered electron image of copper particle suraounded by aluminum and cracks forming barier betwwen them, this defect foundin the stir zone when welding Al to Cu in FSW when inproper weld parameters used in a research done by Xue et al [54].*

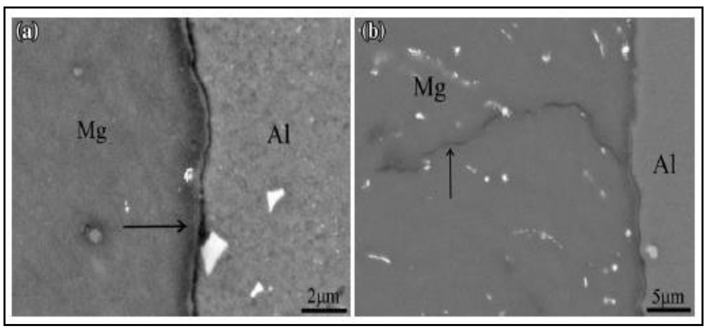

Figure (5*): Showing of micro cracks pointed by arrows in Liang et al. study [61] and found at the bottom interface of the weld zone due to insufficient materials' intermixing when welding Al to Mg by FSW.*

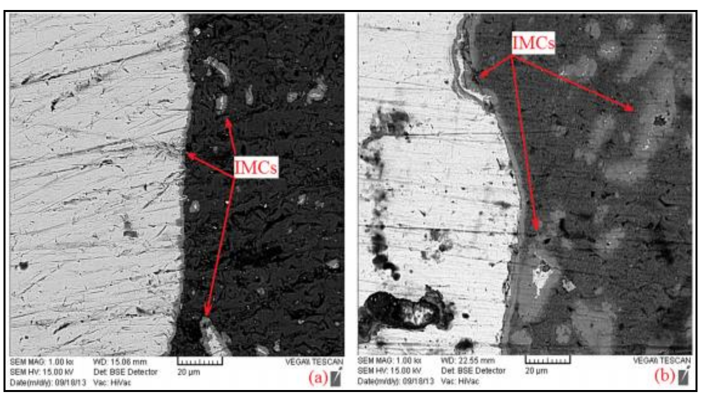

Figure (6): *Optical microscope images showing formation different sizes of IMCs in the stir zone of FSW A441 AISI to AA1100 aluminum using (a) lower tilt tool angle (b) higher tilt tool angle as Elyasi et al. presented in their work [62].*

2.2 Pores

Pores or porosity can be found in the bottom region on the advancing side of stir zone either single or in line with different diameter size appearance and common in dissimilar weld joint [8, 33]. Pores like any other defects in welding joints, if it appears in the weld joint then weak weld has been provided [63, 64]. So, improper pressure amount under small tool tilt angle, plunge depth, and excessive heat are the main reasons of forming this type of defect in stir zone [33, 65-69]. Also, a non-uniform scratching of one of the base materials particles leads to this type of defects during FSW of dissimilar system [70]. This defect result in lower heat inputs, hence reducing the plasticity and rate of diffusion in the material during the process and accordingly follow-on a weak interface [71, 72]. Moreover, existence exist of these pores creates another defect type that are called zig-zag defect [73, 74]. Examples of pores defects found by some researchers in dissimilar welds in FSW can be seen in the following figures (7 & 8) [71, 73, 75].

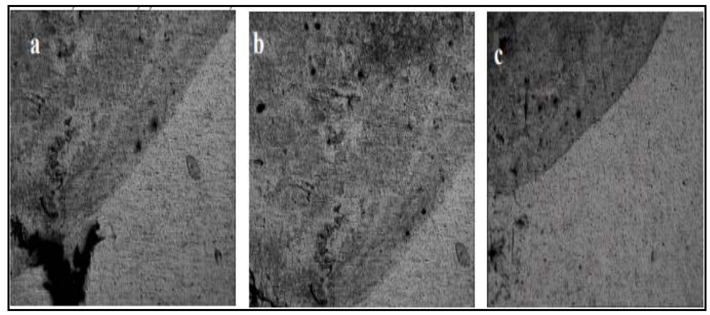

Figure (7*): Showing the stir zone with the appearance of varying sizes and amounts of pores (black dots) when powder aluminum welded with pure aluminum under varying pressure values (a) low pressure, (b) medium pressure, and (c) high pressure as Kurt et al. presented in their study [71].*

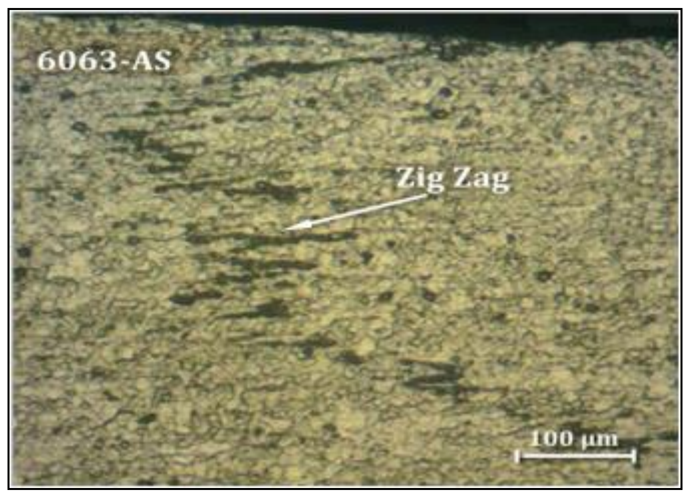

Figure (8*): Zig zag defect presented by Bayazid et al. [73, 75] in non-homogeneous connection of 7075 RS to 6063 AS.*

2.3 Voids and Tunnel

Tunnel and voids are commonly found in dissimilar weld joints at the advancing side close to the bottom of the weld zone due to insufficient material flow and poor mixing [54, 70, 76]. Also, with larger IMC's layer formation in the weld joint higher chance of this type of defect exists [49, 77]. Thus, inappropriate weld parameters leading to voids and tunnel and joint with lower ductility, while optimum weld and travel speeds and proper tool design provide higher strength weld joint with defect free [33, 50, 78, 79]. Moreover, if no enough heat produced in the stir zone or incorrect workpiece fixture used, which causes poor connection, defects such as tunnel or cavity can be formed [38, 73, 80]. Examples of voids and tunnel defects found by some researchers in dissimilar welds by employing FSW can be seen in the following figures (9 &

10) [54, 76].

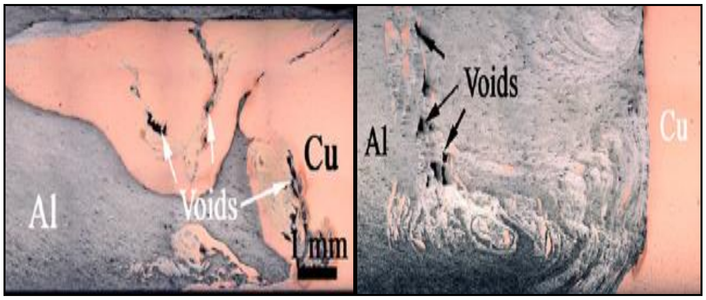

***Figure (9)**: Showing images of voids defect formation collected when Al/Cu FSW employed in a research done by Xue et al. [54] with small offset tool location on the left image while on the right voids were formed when the rotational speed was too slow.*

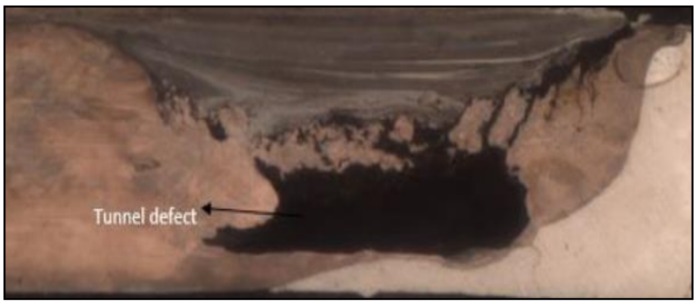

***Figure (10)**: Showing a macrograph image of a FSW with tunnel defect appearance at the bottom toward advancing side in the stir zone when aluminum alloy 5052 on retreating side and stainless steel 304 on advancing side located and joined in FSW with zero tilt tool angle, low rotational speed, and slow weld travel speed. This study made by Chitturi et al. [76].*

2.4 FRAGMENTAL

It is not possible to find this type of defect in similar material weld and it is commonly found in dissimilar weld [33, 51]. When uneven material flow appears due to differences in material thermal conductivity some hard IMC's particles (fragments) exist in the mixture [12, 65]. These fragments are unable to dispense uniformly and leaves the weld region with unfilled spots leading to form voids and micro cracks [33]. This means the fragmental defect promotes more defects in the stir zone producing a weak joint with multi issues [33, 81]. As mentioned earlier formation of IMC's puts the weld joint under high risk of defect formation. Therefore, optimum welding parameters mainly appropriate tool pin and lower rotational speed can produce more chance to eliminate such types of defects [12, 33, 76]. Example of fragmental defect formation in dissimilar weld when FSW process used shown in the following figure (11) [82].

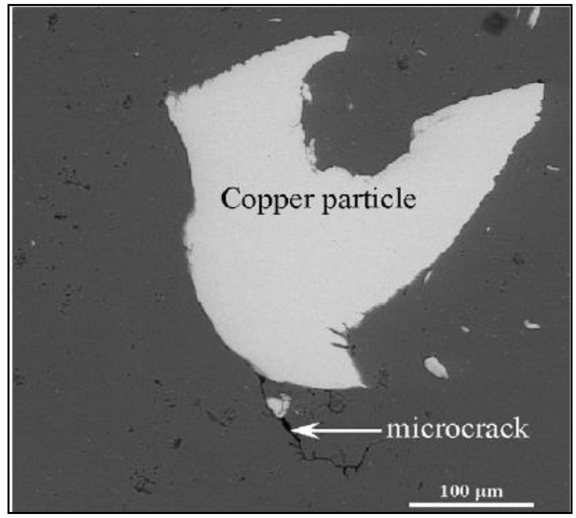

***Figure (11)**: A micrograph image showing uneven scattering copper fragments and surrounding by aluminum during high deformation and inappropriate mixing of materials in the FSW attracting cracks formation as presented by Saeid et al. [82] when Al/Cu welded in lap joint.*

2.5 LACK OF PENETRATION

If the interfaces between the plates is not completely joined at the root of the weld joint, then lack of penetration is the right name for this type of defect, and a weak joint under high stress concentration produced [83, 84]. There are primary causes behind this type of defect such as too short tool probe, too low plunge depth, unsuitable tool probe offset position, incorrect tool design, different plates thickness, and low heat input [12, 33, 85]. Therefore, lack of penetration prevention lay on proper weld parameters selection and special joint preparation would be helpful. For example, additional material with low thermal conductivity can be chosen as backing plate to save the proper heat amount in the weld zone and avoiding uneven scattering fragments in the stir zone [76]. Example of lack of penetration defect formation in butt joint weld in FSW process is shown in the following figure (12) [85].

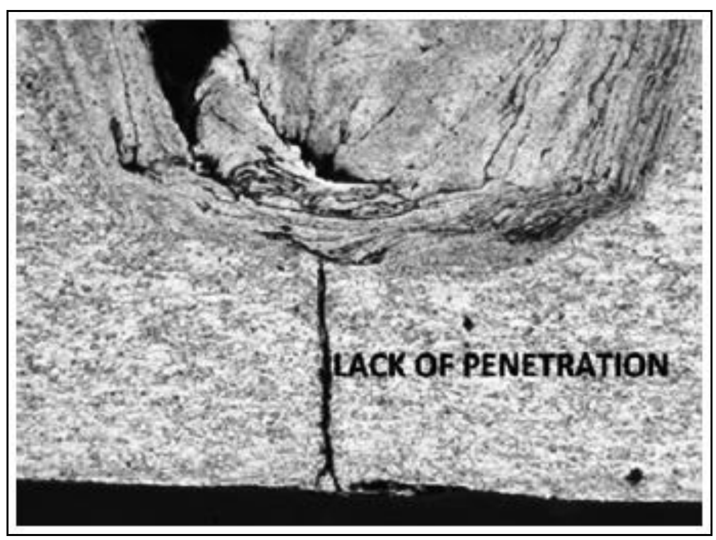

***Figure (12)**: Showing image of lack of penetration defect obtained at the bottom of butt weld joint below the stir zone, which was presented by Lacki et al. study [85].*

2.6 Kissing bond

If the tool-pin stirring is inaccessible to the bottom of the weld interfaces, significantly deficient of both heat input and material flow will encourage the formation of this defect type [12, 35]. One of the major concerns associated with FSW of Al alloys is the oxide layer and causing some types of defects, which is kissing bond one of them [86]. Kissing bond is exist only in the retreating side of the weld joint and to avoid this defect, full material mixing is essential by creating smooth material flow around the tool pin [33, 80]. Therefore, Incorrect process parameters and existence of excessive thick oxide layer prevent proper mixing of materials and enough scattering of oxides in order to obtain defect free and full bonding joint [85]. Examples of kissing bond defect formation in butt welds made by FSW process are shown in the following figure (13) [86].

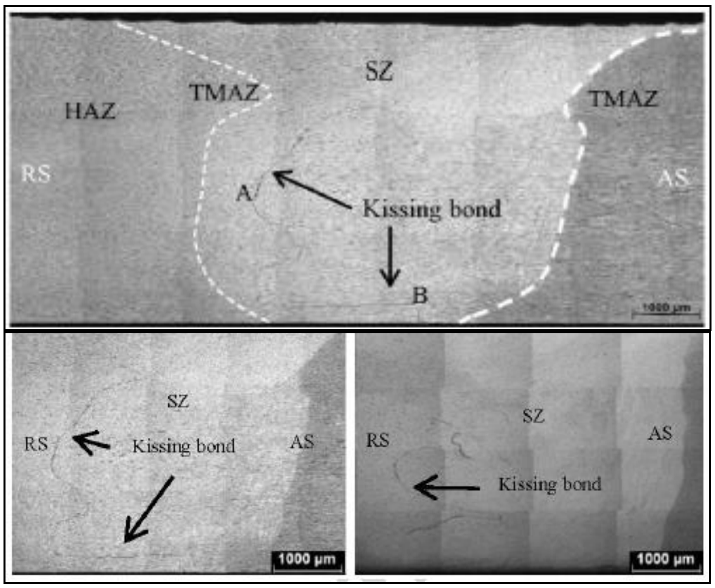

Figure (13): *Cross-section images taken from Zhou et al. study [86] showing the kissing bond defect formation at retreating side in the stir zone of AA5083-H112 friction stir butt welds .*

2.7 Hooking

Hooking defect can be found in one or both sides advancing or retreating of a lap joint in the TMAZ for both similar and dissimilar systems [12, 35], where bad tool design, incorrect tilt angle, low welding speed, high rotational speed, and unfitting workpiece fixture are the main promoting factors [87, 88]. Hooking may form because of the upward bending of the sheet interface due to the penetration force of the tool into the bottom sheet and the affiliated upward movement of the material from the lower sheet to the upper one [88, 89]. Hooking is a defect most probable defects in friction stir welded lap joints [90], which appears only in TMAZ adjacent to the weld nugget and might not appear in the HAZ where no existence of plastic deformation [12]. Thus, process settings significantly affect the hook geometry which in return affects the lap shear strength [91]. For prevention this type of defect proper weld parameters should be used attentionally. Rather than weld parameters, a stationary shoulder could be used to produce large forging force [92], or enhance the strength of friction stir lap weld joint by using an interlayer of graphene nanoplatelets at the weld interface may eliminate hooking defect [93]. Both figures (14 & 15) [89, 94] are examples of hooking defect in FSW and can only be found in lap joint.

Figure (14*): A macrograph of cross-section lap joint with hooking defect observed in Liu et al. study [94], when 2A12-T4 Al alloy was friction stir spot welded.*

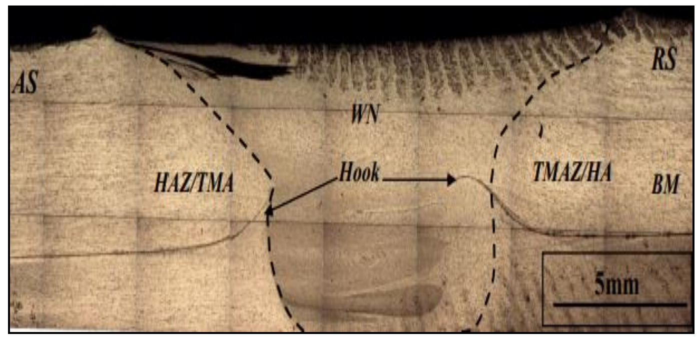

Figure (15): *A macrograph of cross-section lap joint with hooking defect observed in Salari et al. study [89], when AA5456 welded under rotational speed of 800 rpm.*

2.8 Flash

Is normally occurred by extreme heat input and/or high plunge depth, where soften weld material under tool shoulder region ejects and extrudes in huge volumes fraction on the surface sides of the weld line in the form of weld flash [12, 33, 50, 95]. Flat shoulder also tends to produce flash defect on the welded surface as the flat shoulder is not operative for trapping the flowing material under the bottom shoulder [42, 96] Therefore, in order to prevent this type of defect, optimum heat input should be used with the right tool design and correct amount of plunge force [33]. Also, appropriate tilt angle during the process assists filling up the defects through forging material downward instead of distributing it up to the surface [12]. Moreover, tool pin with zero offset setup is preferable to avoid flash defect [51, 97]. Examples of flash defect found in FSW process when welding butt joint are shown in figures (16 & 17) [50, 80, 95].

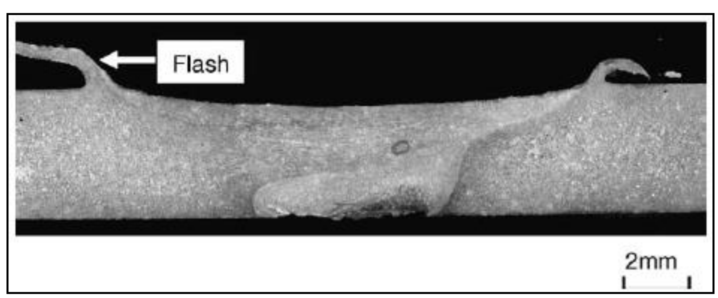

Figure (16): *A macrograph image of cross-section weld with appearance of flash defect on the surface obtained by Kim et al. [95] when excess heat used to weld ADC12 aluminum die casting alloy plates.*

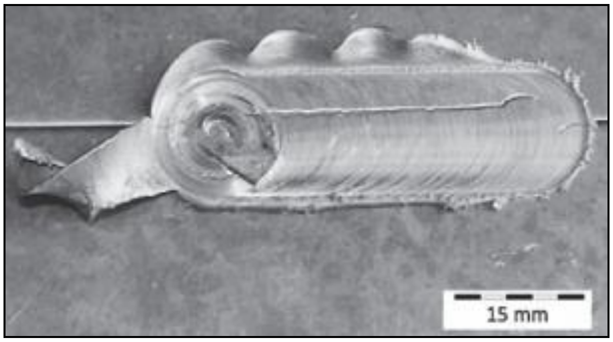

***Figure (17)**: A macrograph image top view of FSW with high fraction of flashing material on the surface [50, 80].*

2.9 Surface Defects

Surface defects like grooves, rough texture, and cracks or surface lack of fill, are common in FSW, and one of the most affecting factors is shoulder contact surface design and geometries such as concave, convex, flat with special profile features like scrolled, ridges, grooves, concentrating circles [33, 98, 99]. Surface grooves defect at upper surface of the weld usually formed in low pressure, and steady appearance of flat surface grooves defect exist by decreasing of penetration depth. Removal of surface grooves can be achieved by increasing of penetration depth and minimum critical contact between shoulder and welded materials is achieved when the friction surface makes a fully semicircle pattern [51]. Therefore, sufficient heat input is very important to prevent this type of defect [50]. Also, as the FSW tool shoulder rotates and move along the workpiece surface, it leaves behind tool markings like feed marks in machining and affecting the surface rough texture. These surface characteristics provide high surface stress concentration which may have sever impacts on the mechanical properties of the joints, particularly fatigue cycle life [100]. Thus, with producing higher surface texture a weaker weld joint will be achieved. Moreover, under cold or lack of heat processing with slippery conditions, inadequate flowing material results in surface lack of fill defect [101]. Surface cracks or tunnels can form when wrong setup preparation used in FSW, such as location of the harder material with respect to the tool rotational direction and tool off set position [54, 102]. Figures (18, 19, 20, & 21) [54, 100, 103] are some examples of common surface defects found in different researches.

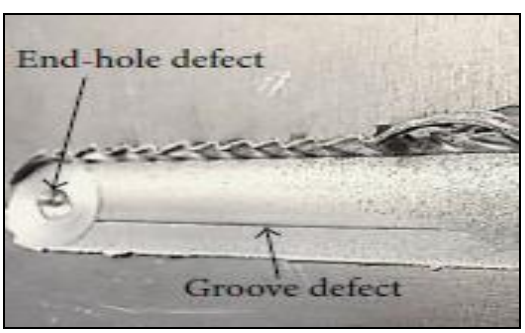

***Figure (18):** Top view image showing groove defect obtained by unstable temperature distribution and end hole defect obtained by end of weld and removing tool in FSW as presented by Hussein et al. [103].*

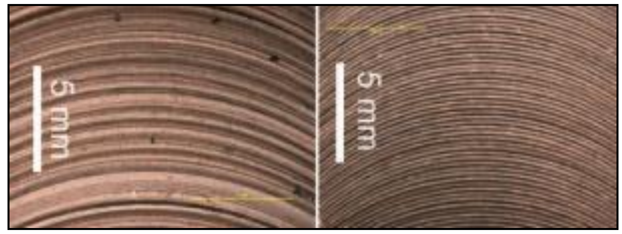

***Figure (19)**: Top view of two different weld made by FSW, on the left rougher surface texture obtained when thicker workpiece welded, and on the right smoother surface texture produced with thinner workpiece as Edwards & Ramulu presented in their study [100].*

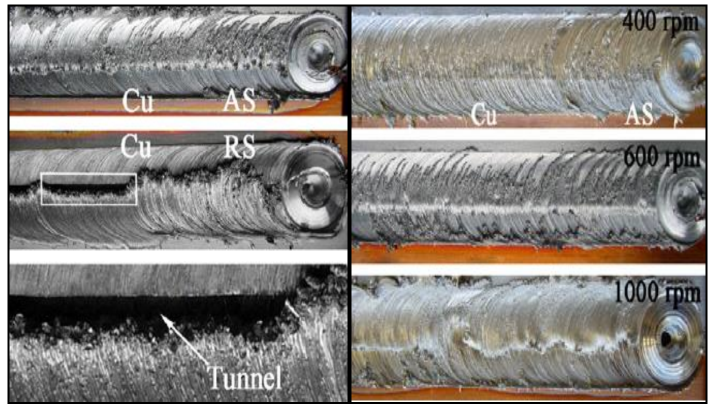

***Figure (20)**: Top view images of different produced surfaces in FSW Cu/Al butt joint, on the left showing the effect of material fixing location on the tunnel or crack defect. While on the right showing the effect of tool rotational speed on the surface grooves as Xue et al. showed in their work [54].*

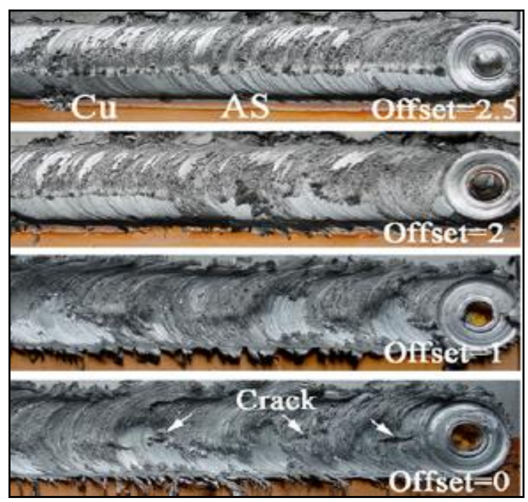

***Figure (21):** Top view images of different produced surfaces in FSW Cu/Al butt joint, showing the effect of tool offsetting positioning toward Al on the lack of filling and crack defects as Xue et al. showed in their study [54].*

2.10 Exit-hole Defect

In FSW process, after finishing the weld line a non-consumable stir-pin is pulled out from its end point location, causing a defect type known as exit-hole or end point will appear in the final location of the welding process leaving a critical hole behind [104]. This defect is unfavorable in FSW due to high stress concentration point and weaken the weld joint mechanical properties [105]. The presence of this type of defects depending on one factor only, which is pulling up the stir-pin action from the weld line. Therefore, skipping this action during the process can produce a joint with better mechanical properties and defect free weld. Thus, Leaving the exit hole in the run sacrificial plate or run off wedge [106] or using a semi-consumable stir-pin [107, 108] can solve the end hole problem in the weld joint. Example of end hole or exit hole defect can be seen in figure (18) [103] where the weld line ends in a butt joint.

3. Defects Prevention in FSW

The important components of FSW is material of the stirring tool and its two main parts design. The tool shoulder and pin dimensions such as, shoulder to pin diameter ratio, pin geometries, pin length, shoulder features and individual diameters of pin and shoulder are basic significant factors rolling the process [11, 28]. Therefore, variations in these factors consequently influence the heat input, plastic deformation, plunge force, torque and material flow of the weld joint [19, 109]. Most of the subsequent weld parameters depending on the tool used in the FSW and should be selected with respect to the tool design. Thus, proper tool design can strongly prevent FSW defects and produce defect free joint [110, 111]. Generally, higher heat input can be generated by reducing tool travel speed (weld speed) or increasing tool rotational speed. Increasing of rotational speed leads to tool wear so the flow of material will be insufficient. It is likely that voids defects form due to poor merging of the weld interface when the tool travels at higher traverse speeds, and hence lower heat inputs. Reduction in plasticity and rates of diffusion in the stir zone may results in a weak interface [112]. Also, using a water-cooled tool and other cooling system, can keep the weld stir zone below the beta transus temperature during FSW, which enables the formation of a preferable grain structure and improve tool efficiency [113]. Therefore, Tool design plays a significant role in controlling of tool wear and thus optimal tool design with respect to material and shape must be chosen. This will lead to better weld joint properties by controlling the thermal heat input and the mechanical deformation by the tool [112]. Good homogeneity and equal distribution of material flow is necessary for good weld properties. This can be achieved through increase in number of passes or changing the direction of weld after each pass. Tool shape like frustum, tapered shape or straight square also promote homogenization of the weld structure and reduce formation of fragments defect [114]. Also, double pass welds with overlapping advancing sides show better fatigue life and tensile properties by eliminating hooking formation [91]. Moreover, increasing tool travel speed to rotational speed ratio is an important variable in the formation of the wormhole and tunnels defect [26]. Moreover, under hot processing with stick conditions, excessive material flow results in flash formation and surface rough texture. While, under cold processing with slippery conditions, insufficient flowing material results in surface grooving and lack of fill defects [101] Flash defect is not always undesirable and usually is used as a visual indicator that the proper tool depth has been reached for a given application, where shoulder design and plunge force can control this defect [25]. Even though, machining the top surface after FSW was found to eliminate most of the surface defects produced during sever plastic deformation and restoring the fatigue life of weld joint [113]. It is important to know that with optimum processing conditions prevention of flow related defects occur at a temperature where stick slip rubbing flow occurs and material flowing from the region ahead of the pin tool is smoothly balanced with that flowing back into the vacated region behind the tool [101]. Also, regions where the intermetallic compounds formed seemed to be weak and a fracture paths in the joint [102]. For example, in dissimilar Al/Cu system weld, defect-free joints obtained under larger pin offsets toward the Al matrix, and a good metallurgical bonding with smaller intermetallic compound layer between the Cu bulk/pieces and Al matrix was achieved. However, defects formed easily at smaller pin offsets due to the hard mixing between the large Cu pieces and Al matrix. Sound defect free joint could be obtained only when the hard material fixed at the advancing side. While, large volume defect can be formed when the soft material was fixed at the advancing side. This is attributed that the hard material could not transport to the advancing side smoothly during FSW causing insufficient flow [54]. Mostly, the joint surface became poorer as the tool rotation rate increased. Many defects may form in the weld stir zone at the lower tool rotation rate, whereas at higher rotation rates, good metallurgical bonding in dissimilar matrix can be reached [54]. Defects formation always have deleterious effects on the mechanical properties of the welded parts and eradicating them is highly recommended [104]. In the following table (1) a guidance of some important weld parameters influences on formation types of defects in FSW as gathered from different researches.

***Table (1)**: Showing the influences of the amount of process parameters on FSW defects formation*

No	Weld Parameters / Defect Types	Rotational Speed	Travel Speed	Tilt Angle	Offset Location toward soft material	Fixing Soft Base Metal on (AS)	Main Cause
1	Micro Cracks	L	H	L	L	H	Insufficient heat & formation of IMC's [115, 116]
2	Pores	H	H	L	L	H	Insufficient heat [33, 66, 117]
3	Voids & Tunnel	L	H	L	L	H	Improper mixing & pressure [12, 33, 70, 76]
4	Fragmental	L	H	L	L	H	Uneven materials flow [33]
5	Lack of Penetration	L	H	L	H	H	Short pin length [12, 33]
6	Kissing bond	L	H	L	L	H	Insufficient material flow & oxide layer [12, 86]
7	Hooking	H	L	L	L	L	Insufficient setup Lap joint [12, 94, 118]
8	Surface Defects	H	H	L	L	H	Low heat & improper pressure [54]
9	Flash	H	L	H	L	H	Excess heat & improper pressure [66]

(H) High or increasing (L) Low or reducing

4. METHODS OF DETECTING DEFECTS

FSW is ideal for applications where higher strength properties and/or dissimilar material are mandatory along the welded seam, thus process quality assurance is very important to approve the joint strength by detecting weld defects and preventing their formation [118]. As mentioned earlier from different previous researches, there are different types of defects can be found after FSW process. Therefore, weld inspection is required for assuring and controlling the quality of the produced weld joint [119]. Accordingly, there are two kinds of evaluation or inspection methods can be applied to test the produced weld, a destructive evaluation (DE) and a non-destructive evaluation (NDE). DE of welds such as, tensile, shear, microstructure, and bending in most cases is not optional for controlling quality since they are costly, in terms of material loss and waste of time and effort [120]. While, visual, dye penetrant, magnetic particles, ultrasonic, eddy current, and X-ray are conventional NDE methods and most preferable for industries [118, 121, 122]. Unfortunately, some of the defects are extremely difficult to detect by conventional NDE methods due to defect size, location, and orientation [123-125]. Small defects such as kissing bond, micro cracks, hooking, and lack of penetration are extremely difficult to detect with any of nondestructive testing methods [8, 33, 124, 126]. In table (2) most of the conventional nondestructive testing methods and their ability of detecting the discussed defects in this work are shown as gathered from different researches, where micro-cracks, lack of penetration, kissing bond, and hooking are hard to be detected with conventional NDE.

***Table (2)**: Showing some conventional NDE methods and their ability of detecting FSW defects*

No	NDE Method / Defect Type	Visual	Dye penetrant	Magnetic particles	Ultrasonic	Eddy current	X-ray
1	Micro cracks	0	0	1	1	1	1
2	Pores	0	0	1	2	1	2
3	Voids & Tunnel	0	0	1	2	1	2
4	Fragmental	0	0	0	2	1	2
5	Lack of penetration	1	1	1	1	1	1
6	Kissing bond	0	0	0	1	1	1
7	Hooking	0	0	0	1	1	1
8	Surface defects	2	2	2	2	2	1
9	Flash	2	2	2	1	2	2
References		[25, 127]	[25, 118, 127, 128]	[129]	[25, 127]	[25, 33, 118, 125, 127]	[8, 25, 118, 12 130]

(0) Not applicable (1) Poor & depend on location and size (2) effective & ideal

5. CONCLUSION

Despite process advantages and superiority, FSW is not free of defect process and can form defects terminate its perfection. Even though, defects like solidification or liquation cracking are not able to exist during FSW since it is a solid-state welding process. On the other hand, if wrong process preparation and/or incorrect weld parameters used, then series issues can be found in the produced joint and alter the weld quality. Therefore, it is important to understand the main causes of possible process defects in order to prevent them and produce good weld quality. Also, quality assurance is not an easy task in FSW, since some defects like hooking, lack of penetration, micro cracks, and kissing bond are hard to be detected with NDE. Thus, it is helpful to have instruction and guidance to follow during FSW process to reduce and/or eliminate the chance of defect forming and save time, money, and effort.

ACKNOWLEDGMENT

The author sends special thanks to all mentioned researchers for their wonderful work and rich information, which has been gathered to assist producing this review study and building up defect prevention guidance to FSW operators.

REFERENCES

[1] Shi, L. and C. Wu, Transient model of heat transfer and material flow at different stages of friction stir welding process. Journal of manufacturing processes, 2017. 25: p. 323-339.

[2] Firouzdor, V. and S. Kou, Al-to-Mg friction stir welding: effect of material position, travel speed, and rotation speed. Metallurgical and Materials Transactions A, 2010. 41(11): p. 2914-2935.

[3] Gao, N., et al., Application of uniform design in optimisation of three stage ageing of Al–Cu–Mg alloys. Journal of materials science, 2007. 42(12): p. 4398-4405.

[4] Williams, J.C. and E.A. Starke Jr, Progress in structural materials for aerospace systems. Acta Materialia, 2003. 51(19): p. 5775-5799.

[5] Klag, O., et al., Microstructural and thermodynamic investigations on friction stir welded Mg/Al-joints. International journal of materials research, 2014. 105(2): p. 145-155.

[6] Yamamoto, N., et al., Effect of intermetallic compound layer on tensile strength of dissimilar friction-stir weld of a high strength Mg alloy and Al alloy. Materials transactions, 2009. 50(12): p. 2833-2838.

[7] Gerlich, A., P. Su, and T. North, Peak temperatures and microstructures in aluminium and magnesium alloy friction stir spot welds. Science and technology of welding and joining, 2005. 10(6): p. 647-652.

[8] Li, B., Y. Shen, and W. Hu, The study on defects in aluminum 2219-T6 thick butt friction stir welds with the application of multiple non-destructive testing methods. Materials & Design, 2011. 32(4): p. 2073-2084.

[9] Kah, P., et al., Investigation of weld defects in friction-stir welding and fusion welding of aluminium alloys. International Journal of Mechanical and Materials Engineering, 2015. 10(1): p.

[10] Taban, E., J.E. Gould, and J.C. Lippold, Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel: Properties and microstructural characterization. Materials & Design (1980-2015), 2010. 31(5): p. 2305-2311.

[11] Wang, G., Y. Zhao, and Y. Hao, Friction stir welding of high-strength aerospace aluminum alloy and application in rocket tank manufacturing. Journal of Materials Science & Technology, 2018. 34(1): p. 73-91.

[12] Singh, V.P., et al., Recent research progress in solid state friction-stir welding of aluminium–magnesium alloys: a critical review. Journal of Materials Research and Technology, 2020. 9(3): p. 6217-6256.

[13] Albannai, A.I., et al., Improving Centerline Solidification Crack Resistivity of AA 2024 Using Tandem Side-by-Side GTAW Technique. Materials Performance and Characterization, 2019. 8(4): p. 541-554.

[14] Savage, W., Joining of advanced materials. 2013: Elsevier.

[15] Kou, S., Welding metallurgy. New Jersey, USA, 2003: p.

431-446.
[16] Liu, J. and S. Kou, Susceptibility of ternary aluminum alloys to cracking during solidification. Acta Materialia, 2017. 125: p. 513-523.
[17] Lippold, J.C., Welding metallurgy and weldability. 2015: Wiley Online Library.
[18] Kou, S., Solidification and liquation cracking issues in welding. Jom, 2003. 55(6): p. 37-42.
[19] Mishra, R.S. and Z. Ma, Friction stir welding and processing. Materials science and engineering: R: reports, 2005. 50(1-2): p. 1-78.
[20] Murr, L., A review of FSW research on dissimilar metal and alloy systems. Journal of Materials Engineering and Performance, 2010. 19(8): p. 1071-1089.
[21] Threadgill, P., et al., Friction stir welding of aluminium alloys. International Materials Reviews, 2009. 54(2): p. 49-93.
[22] Thomas, W., et al., Friction stir welding. International patent application no. PCT/GB92102203 and Great Britain patent application, 1991. 9125978.
[23] Thomas, W., et al., Friction stir welding-process developments and variant techniques. 2000: Society of Manufacturing Engineers.
[24] Thomas, W.M., et al., Friction welding. 1995, Google Patents.
[25] Gibson, B.T., et al., Friction stir welding: Process, automation, and control. Journal of Manufacturing Processes, 2014. 16(1): p. 56-73.
[26] Nandan, R., T. DebRoy, and H. Bhadeshia, Recent advances in friction-stir welding–process, weldment structure and properties. Progress in materials science, 2008. 53(6): p. 980-1023.
[27] Khandkar, M., J.A. Khan, and A.P. Reynolds, Prediction of temperature distribution and thermal history during friction stir welding: input torque based model. Science and technology of welding and joining, 2003. 8(3): p. 165-174.
[28] Zhang, Y., et al., Review of tools for friction stir welding and processing. Canadian Metallurgical Quarterly, 2012. 51(3): p. 250-261.
[29] Papaefthymiou, S., C. Goulas, and E. Gavalas, Micro-friction stir welding of titan zinc sheets. Journal of Materials Processing Technology, 2015. 216: p. 133-139.
[30] Nandan, R., Computational modeling of heat transfer and visco-plastic flow in friction stir welding. 2008.
[31] Heidarzadeh, A., et al., Application of nanoindentation to evaluate the hardness and yield strength of brass joints produced by FSW: microstructural and strengthening mechanisms. Archives of Civil and Mechanical Engineering, 2020. 20: p. 1-9.
[32] Neto, D.M. and P. Neto, Numerical modeling of friction stir welding process: a literature review. The International Journal of Advanced Manufacturing Technology, 2013. 65(1-4): p. 115-126.
[33] Mehta, K.P. and V.J. Badheka, A review on dissimilar friction stir welding of copper to aluminum: process, properties, and variants. Materials and Manufacturing Processes, 2016. 31(3): p. 233-254.
[34] Zhang, H., et al., Improving the structure-property of aluminum alloy friction stir weld by using a non-shoulder-plunge welding tool. The International Journal of Advanced Manufacturing Technology, 2016. 87(1-4): p. 1095-1104.
[35] Cao, X. and M. Jahazi, Effect of tool rotational speed and probe length on lap joint quality of a friction stir welded magnesium alloy. Materials & Design, 2011. 32(1): p. 1-11.
[36] Elangovan, K., V. Balasubramanian, and M. Valliappan, Effect of tool pin profile and tool rotational speed on mechanical properties of friction stir welded AA6061 aluminium alloy. Materials and Manufacturing Processes, 2008. 23(3): p. 251-260.
[37] Heuzé, T., et al., Two experimental set-ups designed for investigation of friction stir spot welding process. Science and Technology of Welding and Joining, 2011. 16(8): p. 735-744.
[38] Franke, D., et al., Understanding process force transients with application towards defect detection during friction stir welding of aluminum alloys. Journal of Manufacturing Processes, 2020. 54: p. 251-261.
[39] Storjohann, D., et al., Fusion and friction stir welding of aluminum-metal-matrix composites. Metallurgical and Materials Transactions A, 2005. 36(11): p. 3237-3247.
[40] Thomas, W., P. Threadgill, and E. Nicholas, Feasibility of friction stir welding steel. Science and Technology of Welding and Joining, 1999. 4(6): p. 365-372.
[41] Akinlabi, E.T. and R.M. Mahamood, Introduction to Friction Welding, Friction Stir Welding and Friction Stir Processing, in Solid-State Welding: Friction and Friction Stir Welding Processes. 2020, Springer. p. 1-12.
[42] Rai, R., et al., friction stir welding tools. Science and Technology of welding and Joining, 2011. 16(4): p. 325-342.
[43] Threadgill, P., Terminology in friction stir welding. Science and Technology of Welding and Joining, 2007. 12(4): p. 357-360.
[44] Cui, L., et al., Recent progress in friction stir welding tools used for steels. Journal of Iron and Steel Research International, 2018. 25(5): p. 477-486.
[45] Salem, H.G., Friction stir weld evolution of dynamically recrystallized AA 2095 weldments. Scripta Materialia, 2003. 49(11): p. 1103-1110.
[46] Kumar, K. and S.V. Kailas, The role of friction stir welding tool on material flow and weld formation. Materials Science and Engineering: A, 2008. 485(1-2): p. 367-374.
[47] Zettler, R., et al., Dissimilar Al to Mg alloy friction stir welds. Advanced Engineering Materials, 2006. 8(5): p. 415-421.
[48] Fonda, R. and J. Bingert, Microstructural evolution in the heat-affected zone of a friction stir weld. Metallurgical and materials transactions A, 2004. 35(5): p. 1487-1499.
[49] Galvao, I., et al., Formation and distribution of brittle structures in friction stir welding of aluminium and copper: influence of process parameters. Science and Technology of Welding and Joining, 2011. 16(8): p. 681-689.
[50] Podržaj, P., B. Jerman, and D. Klobčar, Welding defects at friction stir welding. Metalurgija, 2015. 54(2): p. 387-389.
[51] Esmaeili, A., M. Besharati Givi, and H. Zareie Rajani, Experimental investigation of material flow and welding defects in friction stir welding of aluminum to brass. Materials and Manufacturing Processes, 2012. 27(12): p. 1402-1408.
[52] Shi, H., et al., Intermetallic compounds in the banded structure and their effect on mechanical properties of Al/Mg dissimilar friction stir welding joints. Journal of Materials Science & Technology, 2017. 33(4): p. 359-366.
[53] Fu, B., et al., Friction stir welding process of dissimilar metals of 6061-T6 aluminum alloy to AZ31B magnesium

alloy. Journal of Materials Processing Technology, 2015. 218: p. 38-47.
[54] Xue, P., et al., Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al–Cu joints. Materials science and engineering: A, 2011. 528(13-14): p. 4683-4689.
[55] Esmaeili, A., M.B. Givi, and H.Z. Rajani, A metallurgical and mechanical study on dissimilar Friction Stir welding of aluminum 1050 to brass (CuZn30). Materials Science and Engineering: A, 2011. 528(22-23): p. 7093-7102.
[56] Dehghani, M., A. Amadeh, and S.A. Mousavi, Investigations on the effects of friction stir welding parameters on intermetallic and defect formation in joining aluminum alloy to mild steel. Materials & Design, 2013. 49: p. 433-441.
[57] Khan, N.Z., et al., Investigations on tunneling and kissing bond defects in FSW joints for dissimilar aluminum alloys. Journal of alloys and Compounds, 2015. 648: p. 360-367.
[58] Liu, L., D. Ren, and F. Liu, A review of dissimilar welding techniques for magnesium alloys to aluminum alloys. Materials, 2014. 7(5): p. 3735-3757.
[59] Unnikrishnan, M. and D.J.E. Raja. A survey on friction stir welding of dissimilar magnesium alloys. in IOP Conference Series: Materials Science and Engineering. 2017. IOP Publishing.
[60] Kahl, S. and W. Osikowicz, Composite aluminum-copper sheet material by friction stir welding and cold rolling. Journal of materials engineering and performance, 2013. 22(8): p. 2176-2184.
[61] Liang, Z., et al., Effect of tool offset and tool rotational speed on enhancing mechanical property of Al/Mg dissimilar FSW joints. Metallurgical and Materials Transactions A, 2013. 44(8): p. 3721-3731.
[62] Elyasi, M., H. Aghajani Derazkola, and M. Hosseinzadeh, Investigations of tool tilt angle on properties friction stir welding of A441 AISI to AA1100 aluminium. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2016. 230(7): p. 1234-1241.
[63] Meran, C. and O. Canyurt, Friction Stir Welding of austenitic stainless steels. parameters, 2010. 6: p. 13.
[64] Mehta, K.P. and V. Badheka, Experimental investigation of process parameters on defects generation in copper to AA6061-T651 friction stir welding. International Journal of Advances in Mechanical & Automobile Engineering, 2016. 3(1): p. 55-58.
[65] Mehta, K.P. and V.J. Badheka, Hybrid approaches of assisted heating and cooling for friction stir welding of copper to aluminum joints. Journal of Materials Processing Technology, 2017. 239: p. 336-345.
[66] Mahto, R.P., R. Kumar, and S.K. Pal, Characterizations of weld defects, intermetallic compounds and mechanical properties of friction stir lap welded dissimilar alloys. Materials Characterization, 2020. 160: p. 110115.
[67] Mehta, K. and V. Badheka. Investigations on friction stir welding defects for dissimilar copper to aluminum materials under different process parameters. in Proceedings of International Conference on Friction Based Processes, IISc-Bangalore, India. 2014.
[68] Mehta, K.P. and V.J. Badheka, Influence of tool design and process parameters on dissimilar friction stir welding of copper to AA6061-T651 joints. The International Journal of Advanced Manufacturing Technology, 2015. 80(9-12): p. 2073-2082.
[69] Springer, H., et al., Influence of intermetallic phases and Kirkendall-porosity on the mechanical properties of joints between steel and aluminium alloys. Materials Science and Engineering: A, 2011. 528(13-14): p. 4630-4642.
[70] Xue, P., et al., Enhanced mechanical properties of friction stir welded dissimilar Al–Cu joint by intermetallic compounds. Materials science and engineering: A, 2010. 527(21-22): p. 5723-5727.
[71] Kurt, A., I. Uygur, and H. Ates. Effect of porosity content on the weldability of powder metal parts produced by friction stir welding. in Materials Science Forum. 2007. Trans Tech Publ.
[72] Zhang, H., et al., Defects formation procedure and mathematic model for defect free friction stir welding of magnesium alloy. Materials & design, 2006. 27(9): p. 805-809.
[73] Bayazid, A., M. Heddad, and I. Cayiroglu, A review on friction stir welding, parameters, microstructure, mechanical properties, post weld heat treatment and defects. Material Sci & Eng, 2018. 2(4): p. 116-126.
[74] Su, J.-Q., et al., Microstructural investigation of friction stir welded 7050-T651 aluminium. Acta materialia, 2003. 51(3): p. 713-729.
[75] Bayazid, S., H. Farhangi, and A. Ghahramani, Effect of pin profile on defects of Friction Stir Welded 7075 Aluminum alloy. Procedia materials science, 2015. 11: p. 12-16.
[76] Chitturi, V., S. Pedapati, and M. Awang, Challenges in dissimilar friction stir welding of aluminum 5052 and 304 stainless steel alloys. Materialwissenschaft und Werkstofftechnik, 2020. 51(6): p. 811-816.
[77] Akbari, M. and R.A. Behnagh, Dissimilar friction-stir lap joining of 5083 aluminum alloy to CuZn34 brass. Metallurgical and Materials Transactions B, 2012. 43(5): p. 1177-1186.
[78] Qian, J., et al., An analytical model to optimize rotation speed and travel speed of friction stir welding for defect-free joints. Scripta Materialia, 2013. 68(3-4): p. 175-178.
[79] Ajri, A., N. Rohatgi, and Y.C. Shin, Analysis of defect formation mechanisms and their effects on weld strength during friction stir welding of Al 6061-T6 via experiments and finite element modeling. The International Journal of Advanced Manufacturing Technology, 2020: p. 1-15.
[80] Soni, N., et al., Defects Formation during Friction Stir Welding: A Review. International Journal of Engineering and Management Research (IJEMR), 2017. 7(3): p. 121-125.
[81] Esmaeili, A., M.B. Givi, and H.Z. Rajani, Investigation of weld defects in dissimilar friction stir welding of aluminium to brass by radiography. Science and Technology of Welding and Joining, 2012. 17(7): p. 539-543.
[82] Saeid, T., A. Abdollah-Zadeh, and B. Sazgari, Weldability and mechanical properties of dissimilar aluminum–copper lap joints made by friction stir welding. Journal of Alloys and Compounds, 2010. 490(1-2): p. 652-655.
[83] Tabatabaeipour, M., et al., Non-destructive ultrasonic examination of root defects in friction stir welded butt-joints. Ndt & E International, 2016. 80: p. 23-34.
[84] Zettler, R., T. Vugrin, and M. Schmücker, Effects and defects of friction stir welds, in Friction Stir Welding. 2010, Elsevier. p. 245-276.
[85] Lacki, P., W. Więckowski, and P. Wieczorek, Assessment of joints using friction stir welding and refill friction stir spot welding methods. Archives of Metallurgy and Materials,

2015. 60(3): p. 2297--2306.
[86] Zhou, N., et al., Influence of the kissing bond on the mechanical properties and fracture behaviour of AA5083-H112 friction stir welds. Materials Science and Engineering: A, 2018. 719: p. 12-20.
[87] Shirazi, H., S. Kheirandish, and M. Safarkhanian, Effect of process parameters on the macrostructure and defect formation in friction stir lap welding of AA5456 aluminum alloy. Measurement, 2015. 76: p. 62-69.
[88] Kumar Rajak, D., et al., Friction-based welding processes: friction welding and friction stir welding. Journal of Adhesion Science and Technology, 2020: p. 1-25.
[89] Salari, E., et al., Influence of tool geometry and rotational speed on mechanical properties and defect formation in friction stir lap welded 5456 aluminum alloy sheets. Materials & Design, 2014. 58: p. 381-389.
[90] Bisadi, H., M. Tour, and A. Tavakoli, The influence of process parameters on microstructure and mechanical properties of friction stir welded Al 5083 alloy lap joint. American journal of Materials science, 2011. 1(2): p. 93-97.
[91] Song, Y., et al., Defect features and mechanical properties of friction stir lap welded dissimilar AA2024–AA7075 aluminum alloy sheets. Materials & Design, 2014. 55: p. 9-18.
[92] Dong, Z., et al., Friction Stir Lap Welding 0.8-mm-Thick 2024 Aluminum Alloy with the Assistance of Stationary Shoulder. Journal of Materials Engineering and Performance, 2019. 28(11): p. 6704-6713.
[93] Sharma, A., et al., Friction stir lap welding of AA6061 aluminium alloy with a graphene interlayer. Materials and Manufacturing Processes, 2020. 35(3): p. 258-269.
[94] Liu, H., et al., Microstructural characteristics and mechanical properties of friction stir spot welded 2A12-T4 aluminum alloy. Advances in Materials Science and Engineering, 2013. 2013.
[95] Kim, Y., et al., Three defect types in friction stir welding of aluminum die casting alloy. Materials Science and Engineering: A, 2006. 415(1-2): p. 250-254.
[96] Khalilabad, M.M., et al., Effect of tool geometry and welding speed on mechanical properties of dissimilar AA2198–AA2024 FSWed joint. Journal of Manufacturing Processes, 2018. 34: p. 86-95.
[97] Shankar, S., et al., Joint strength evaluation of friction stir welded Al-Cu dissimilar alloys. Measurement, 2019. 146: p. 892-902.
[98] Fuse, K. and V. Badheka, Bobbin tool friction stir welding: A review. Science and Technology of Welding and Joining, 2019. 24(4): p. 277-304.
[99] Singh, V.P., et al., Parametric effect on dissimilar friction stir welded steel-magnesium alloys joints: a review. Science and Technology of Welding and Joining, 2019. 24(8): p. 653-684.
[100] Edwards, P. and M. Ramulu, Investigation of microstructure, surface and subsurface characteristics in titanium alloy friction stir welds of varied thicknesses. Science and technology of welding and joining, 2009. 14(5): p. 476-483.
[101] Arbegast, W.J., A flow-partitioned deformation zone model for defect formation during friction stir welding. Scripta materialia, 2008. 58(5): p. 372-376.
[102] Watanabe, T., H. Takayama, and A. Yanagisawa, Joining of aluminum alloy to steel by friction stir welding. Journal of Materials Processing Technology, 2006. 178(1-3): p. 342-349.
[103] Hussein, S.A., et al., Unstable temperature distribution in friction stir welding. Advances in Materials Science and Engineering, 2014. 2014.
[104] Ghavimi, A., M. Aboutalebi, and S. Seyedein, Exit-hole repairing in friction stir welding of AA5456 pipe using consumable pin. Materials and Manufacturing Processes, 2020: p. 1-11.
[105] Peilin, L., et al., Mechanical properties and microstructure analysis of refilling friction stir welding on 2219 aluminum alloy. 金属学报英文版, 2012. 25(3): p. 225-234.
[106] Engelhard, G., et al., Method and apparatus for welding two work pieces. 2003, Google Patents.
[107] Huang, Y., et al., Interface behaviours and mechanical properties of filling friction stir weld joining AA 2219. Science and Technology of Welding and Joining, 2012. 17(3): p. 225-230.
[108] Han, B., et al., AA7075 bit for repairing AA2219 keyhole by filling friction stir welding. Materials & Design, 2013. 51: p. 25-33.
[109] Mehta, K.P. and V.J. Badheka, Influence of tool pin design on properties of dissimilar copper to aluminum friction stir welding. Transactions of Nonferrous Metals Society of China, 2017. 27(1): p. 36-54.
[110] Malarvizhi, S. and V. Balasubramanian, Influences of tool shoulder diameter to plate thickness ratio (D/T) on stir zone formation and tensile properties of friction stir welded dissimilar joints of AA6061 aluminum–AZ31B magnesium alloys. Materials & Design, 2012. 40: p. 453-460.
[111] Simoncini, M. and A. Forcellese, Effect of the welding parameters and tool configuration on micro-and macro-mechanical properties of similar and dissimilar FSWed joints in AA5754 and AZ31 thin sheets. Materials & Design, 2012. 41: p. 50-60.
[112] Peel, M., et al., Microstructure, mechanical properties and residual stresses as a function of welding speed in aluminium AA5083 friction stir welds. Acta materialia, 2003. 51(16): p. 4791-4801.
[113] Sanders, D., et al., Effects on the surface texture, superplastic forming, and fatigue performance of titanium 6Al-4V friction stir welds. Journal of Materials Engineering and Performance, 2010. 19(4): p. 503-509.
[114] Kumar, N., A. Das, and S.B. Prasad, An analysis of friction stir welding (FSW) of metal matrix composites (MMCs). Materials Today: Proceedings, 2020.
[115] Yan, J., et al., Microstructure characteristics and performance of dissimilar welds between magnesium alloy and aluminum formed by friction stirring. Scripta Materialia, 2005. 53(5): p. 585-589.
[116] Esmaeili, A., et al., The role of rotation speed on intermetallic compounds formation and mechanical behavior of friction stir welded brass/aluminum 1050 couple. Intermetallics, 2011. 19(11): p. 1711-1719.
[117] Galvão, I., et al., Influence of tool offsetting on the structure and morphology of dissimilar aluminum to copper friction-stir welds. Metallurgical and Materials Transactions A, 2012. 43(13): p. 5096-5105.
[118] Taheri, H., et al., Investigation of nondestructive testing methods for friction stir welding. Metals, 2019. 9(6): p. 624.
[119] Cerniglia, D. A Case Study on the Evaluation of

Friction Stir Welds by Ultrasonic Inspection Technique. in Proceedings of the 14th International Symposium on Nondestructive Characterization of Materials (NDCM 2015), Marina Del Rey, CA, USA. 2015.

[120] Sagar, S.P., et al., NDE of friction stir welds of Al alloys using high-frequency acoustic microscopy. Nondestructive Testing and Evaluation, 2012. 27(4): p. 375-389.

[121] Ranjan, R., et al., Classification and identification of surface defects in friction stir welding: An image processing approach. Journal of Manufacturing Processes, 2016. 22: p. 237-253.

[122] Rosado, L.S., et al., Advanced technique for non-destructive testing of friction stir welding of metals. Measurement, 2010. 43(8): p. 1021-1030.

[123] Chowdhury, S., et al., Tensile properties of a friction stir welded magnesium alloy: Effect of pin tool thread orientation and weld pitch. Materials Science and Engineering: A, 2010. 527(21-22): p. 6064-6075.

[124] Mandache, C., et al., Non-destructive detection of lack of penetration defects in friction stir welds. Science and Technology of Welding and Joining, 2012. 17(4): p. 295-303.

[125] Dos Santos, T.G., P.M. Ramos, and P. dos Santos Vilaça. Non destructive testing of friction stir welding: Comparison of planar eddy current probes. in 16th IMEKO TC4 Symposium. 2008.

[126] Chen, H.-B., et al., The investigation of typical welding defects for 5456 aluminum alloy friction stir welds. Materials Science and Engineering: A, 2006. 433(1-2): p. 64-69.

[127] Kinchen, D.G. and E. Aldahir, NDE of friction stir welds in aerospace applications. 2002.

[128] Stepinski, T., W. Ping, and E. Wennerström, Inspection of copper canisters for spent nuclear fuel by means of ultrasound. Phased arrays, ultrasonic imaging and nonlinear acoustics. 2004, Swedish Nuclear Fuel and Waste Management Co.

[129] Blitz, J., Electrical and magnetic methods of non-destructive testing. Vol. 3. 2012: Springer Science & Business Media.

[130] Santos, M. and J. Santos, Lamb waves technique applied to the characterization of defects in friction stir welding of aluminum plates: comparison with X-ray and ultrasonic C-scan. Journal of Testing and Evaluation, 2010. 38(5): p. 622-627.