Advances in FSW and FSSW of Dissimilar Al-Alloy Plates

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Abstract
Numerous industrial applications, particularly those in the transport industry, require the joining of dissimilar materials which offers considerable benefits in terms of low cost, design flexibility, and weight reduction for overall structures. The problems associated with conventional fusion welding processes have stimulated researchers in recent years to develop new joining methods for dissimilar materials which are particularly difficult to join. Friction stir welding (FSW) originally developed for joining difficult-to-weld Al-alloys and FSSW (a variant of FSW for spot welding) have exhibited great potential for obtaining sound joints in various dissimilar alloy systems in different configurations namely butt-, lap- and spot-welding, particularly in dissimilar Al-alloys systems with different properties, which are very difficult to weld using conventional fusion welding techniques. A major difficulty in joining dissimilar Al-alloys by FSW/FSSW lies in the discontinuity in mechanical and technological properties (such as high temperature strength, plastic deformation capacity, viscosity, etc.) of the materials to be welded across the abutting surfaces. This discontinuity as well as inherent asymmetry in heat generation and material flow of FWS/FSSW processes causes a higher asymmetry in materials flow behavior in dissimilar welding. However, it is relatively easier to implement the FSW/FSSW process to dissimilar Al-alloys in contrast to FSW of dissimilar materials combinations with very differing properties, such as Al-alloy to Mg-alloy or Al-alloy to steel.

Keywords: Friction stir welding (FSW); friction stir spot welding (FSSW); Aluminum alloys; Dissimilar welding; Butt joint; Lap joint; T-joint.

1. Introduction
Several joint types can be fabricated by friction stir welding (FSW), namely butt-, lap- (overlap-) and T-lap joints (Fig. 1) along with the lap joint in the form of spot welding by friction stir spot welding (FSSW). FSSW is a variant of FSW where a rotating tool is plunged into the plates positioned in lap joint configuration to a predetermined depth to generate frictional heat and join the workpieces by plastic deformation of the heated regions. Fig. 2 presents a schematic illustration of the FSSW process which consists of three stages namely plunging, stirring (also called dwelling), and drawing out (also called retraction).

Critical weld parameters vary depending on the process used, i.e. FSW or FSSW, as well as the joint type produced by FSW. The main preliminary parameters that are quite influential for the FSW of dissimilar materials combinations in butt-joint configuration are the base plates' positioning, the tool rotational speed, welding (travel) speed, and tool position. There are also some other parameters like tool geometry (shoulder diameter to pin diameter ratio), pin profile (cylindrical, conical, polygonal), and tool tilt angle which affect the microstructural evolution in the weld region and thus the mechanical properties of the fabricated welded joints. The placement of the base plates affects material flow while rotational and welding speeds control the heat input. All these variables affect the welding process and thus the microstructural and mechanical characteristics of the dissimilar fabricated joint. However, higher material is generally placed on the top in lap configuration in contrast to butt-joints where higher strength material is placed on the retreating side (RS). On the other hand, the T-lap joints composed of the stringer and skin parts are one of the common connections in the structures of aircraft wing-box, railway tankers, and structural panel plates. In this application, a stronger material is used for the stringer while the skin is designed for a lower strength plate. Thus, lower strength material is placed on the top in FSW of T-lap joints.
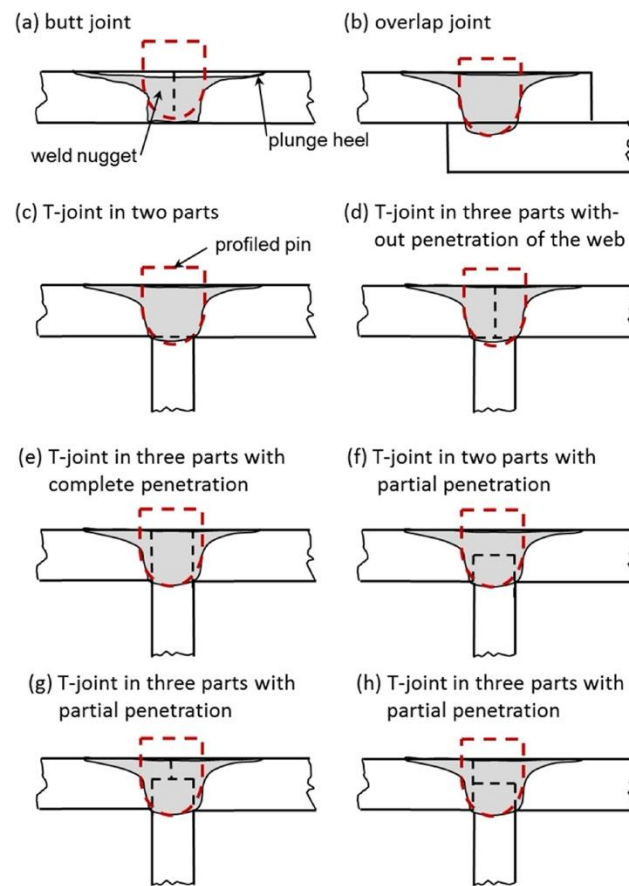

Fig. 1. (a)-(b) Typical joint configurations and (c)-(j)) design solutions to produce T-joints by FSW [1].

On the other hand, critical weld parameters in FSSW are plunging speed, plunging depth, dwell time, and rotational rate. There are also other parameters, such as tool geometry and tool tilt angle which affect the plasticization and upward material flow and thus the mechanical properties of the fabricated welded joints.

In the case of similar material friction stir welding, the stir zone (SZ) usually undergoes extensive grain refinement, resulting in fine-grain microstructures, due to dynamic recrystallization. The microstructural evolution in dissimilar friction stir welds strongly depends on the welding parameters, as the material flow plays a significant role in the case of dissimilar material combinations compared to similar joints. The appropriate selection of all process parameters leads to a sufficient material mixing of the materials and produces a sound weld.
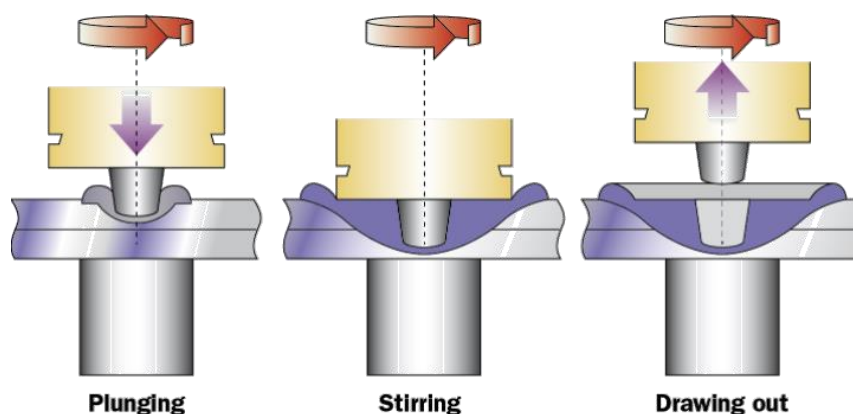

Fig. 2. Schematic illustration of friction stir spot welding (FSSW) [2].

The welding variables affecting the quality of the dissimilar Al-alloys joints fabricated in different configurations by FSW/FSSW and their microstructural aspects are discussed below.

2. The Influence of Weld Parameters in Butt Joints
Plate positioning, tool rotational and welding speeds, tool geometry that is, shoulder diameter to pin diameter ratio, and pin profile (cylindrical, conical, polygonal), and tool tilt angle are the most influential welding parameters on the joint performance of FSWed dissimilar Al-alloys butt welds.

2.1. Effect of Plate Position
The material flow during FSW is quite complex. The positioning of the two base metals during FSW of dissimilar materials welding is very influential in terms of material flow as it strongly determines material stirring and mixing [3,4]. This can particularly be crucial in the final joint microstructure when the materials combination selected have significantly different mechanical properties [5-9]. Thus, the positioning of base materials becomes an important parameter in welding, similar to the importance of the rotation and the welding speeds.

It was originally proposed by Larsson et al. [3] that the lower strength material should be placed at the advancing side (AS) side in order to achieve a better material flow and mixing in the SZ. In several other researchers the influence of the placement of lower strength material on material mixing in dissimilar Al-alloys welding has been investigated [3-38]. The results indicated that when the lower strength alloy is placed at the AS a better material flow and mixing is achieved. In this way, a sound dissimilar joint with better properties in FSW of dissimilar Al-alloys can be achieved. For instance, Yan et al. [7] investigated the effect of plate configuration on the mechanical properties of the joints produced for the Al-Zn-Mg and the Al-Mg-Si dissimilar Al-alloys combination. They reported that the changing of the plate configuration led to very different material flow behaviors due to different flow characteristics of the alloys, i.e., the lower strength Al-Mg-Si alloy displays a higher flowability while the high

strength Al-Zn-Mg alloy possesses higher resistance to flow. Thus, when Al-Zn-Mg was placed at the advancing side (AS), a limited flow of the Al-Mg-Si alloy material to the AS side took place due to its higher ability to flow as shown in Fig. 3a. On the other hand, when Al-Mg-Si alloy was placed at AS, high material flow resistance at the retreating side (RS) limits the material at RS (Al-Zn-Mg alloy) to flow into the AS. Hence, no Al-Zn-Mg alloy was observed at the AS, as shown in Fig. 3b.

Similarly, Niu et al. [8] studied the influence of base plate positioning on the material flow for the AA2024-AA7075 Al-alloys combination and observed that the upper part of the SZs of the dissimilar joints consisted mainly of the base material (BM) in RS as shown in Fig. 4. This can be attributed to the driving force generated by the horizontally rotated tool shoulder. On the contrary, the middle and bottom parts of SZs contained more AS BM than RS BM.
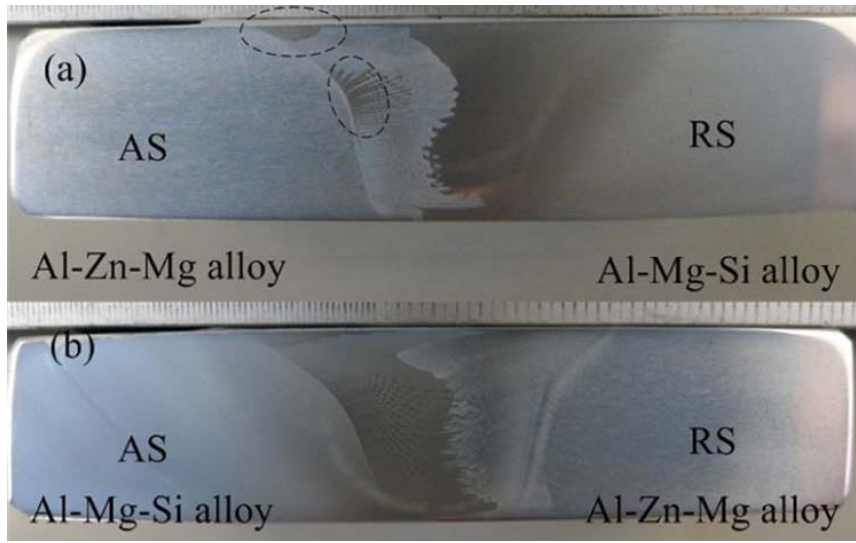

Fig. 3. Cross-sections of the dissimilar Al-alloys joints: (a) the joint produced by placing Al-Zn-Mg on the AS side (Al-Zn-Mg-AS joint), and (b) the joint produced by placing Al- Mg-Si on the AS side (Al-Mg-Si-AS joint) [7].
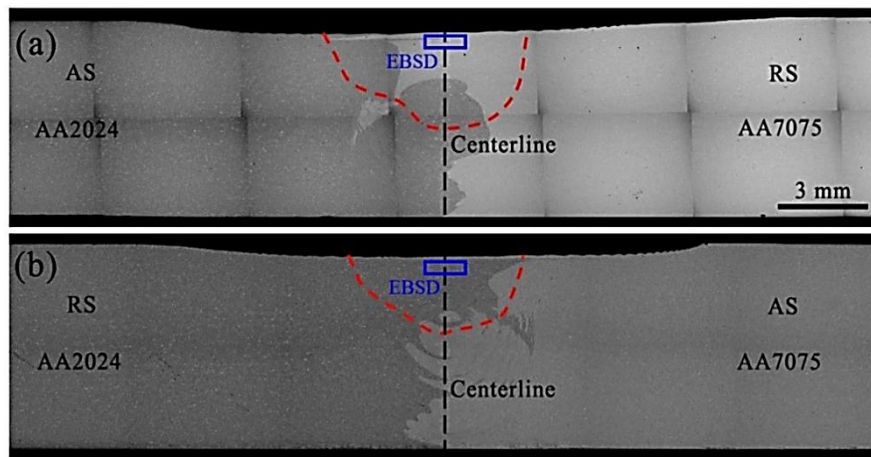

Fig. 4. SEM macrostructures showing the cross-sections of the AA2024-AA7075 joints: (a) AS: AA2024 and (b) AS: AA7075 [8].

Kim et al. [9] also clearly demonstrated that the base plate positioning significantly affects the material flow such that by placing the high strength Al alloy on the AS excessive agglomerations and defects generated due to limited material flow. Similarly, Kalemba-Rec et

al. [10] reported that a better mixing of both base materials took place when the softer base material was placed at the AS side in FSW of dissimilar AA5083-AA7075 alloys. A very limited mixing occurred if the higher strength material (i.e., AA7075) positioned at the AS side as shown in Fig. 5.
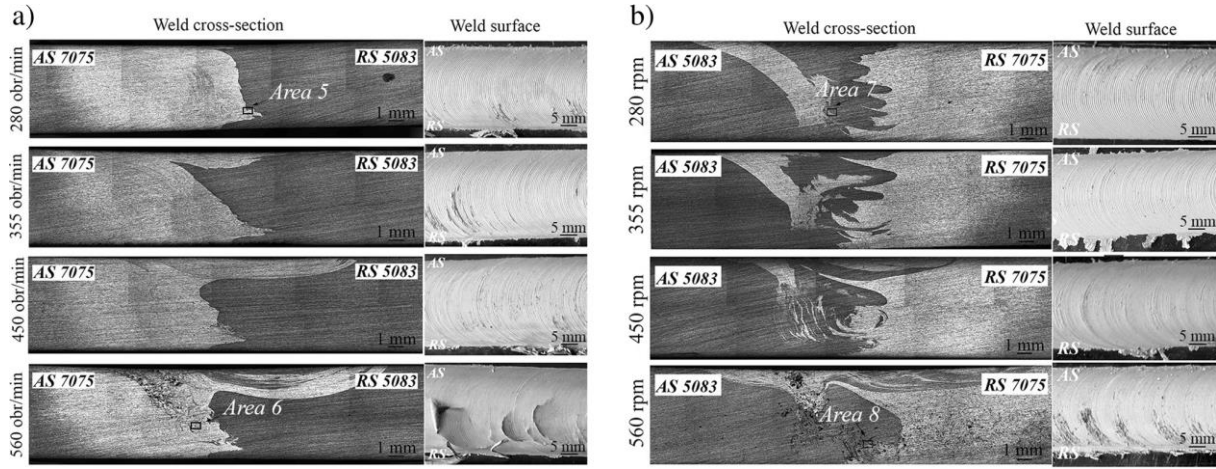

Fig. 5. Macrographic view of the cross-section and top surface of a) AS 7075-RS 5083 welds and b) AS 5083-RS 7075 welds, with marked areas of microstructural analysis (tool geometry used: threaded taper pin) [10].

İpekoğlu ve Çam [11] also well demonstrated that a better mixing of base materials takes place if the lower strength alloy is placed at the AS side and the SZ consists of predominantly lower strength AA6061 alloy, Fig. 6. Similarly, Guo et al. [13] also clearly showed the better mixing of materials when the lower strength AA6061 alloy was placed at the AS side in FSW of AA6061-AA7075 dissimilar welding as shown in Fig. 7. Park et al. [15], Aval et al. [16] and Murr et al. [17] also investigated the effect of base materials' locations on FSW of AA5052-AA6061, AA5086-AA6061, and AA2024-AA6061 dissimilar Al-alloys combinations, respectively, and revealed that more efficient materials mixing was obtained when the softer AA5xxx aluminum alloy was in the AS and the harder AA6xxx aluminum alloy was in the RS. Moreover, Khodir and Shibayanagi [18] investigated the effect of the material location prior to welding on the joint properties of dissimilar AA2024 and AA7075 aluminum alloys and observed that the maximum tensile strength of 423 MPa obtained when the AA2024 is located in the AS of the joint. Similarly, Cavalier et al. [6] also conducted a study investigating the effect of plate position on the mechanical properties of the dissimilar AA6082-AA2024 joints and reported that the best tensile and fatigue properties were obtained for the joints with the AA6082 (that is the lower strength alloy) on the AS and welded with a travel speed of 115 mm/min. Peel et al [19] also studied the influence of plate position on joint performance of dissimilar friction stir welds in AA5083-AA6082 and they reported that the highest tensile strength was exhibited by the joint produced by placing the lower strength AA5083 at the AS using rotation and traverse speeds of 840 rpm and 300 mm/min, respectively. Similarly, Robe et al [20] investigated microstructural and mechanical characteristics of a dissimilar friction stir welded butt joint made of AA2024-T3 and AA2198-T3 by placing the lower strength AA2198 at the AS. They reported that a joint efficiency of about 91% of the AA2198 alloy was obtained. Furthermore, Dinaharan et al. [35] studied the effect of material location on the joint strength of dissimilar friction stir welded Al-alloys, namely cast AA6061 and wrought AA6061 alloys, fabricated using a tool with a hexagonal profile. The results they obtained indicated that the plate position and tool rotational speed significantly influenced the material flow behavior. The material placed in the advancing side occupied the major portion of the weld zone at higher tool rotational speeds. They also reported that the dissimilar joints displayed higher tensile strength

values when lower strength cast aluminum alloy was placed in the advancing side prior to welding at all tool rotational speeds.
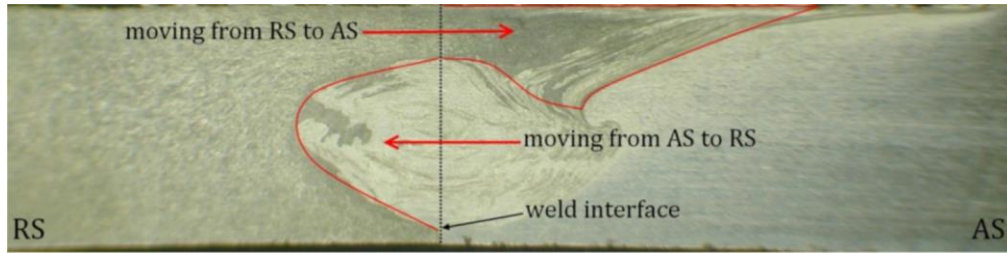

Fig. 6. Weld cross-section of the AA6061-AA7075 dissimilar joint produced by placing the lower strength AA6061 alloy at the AS side showing that the SZ consists of predominantly lower strength AA6061 alloy [11].
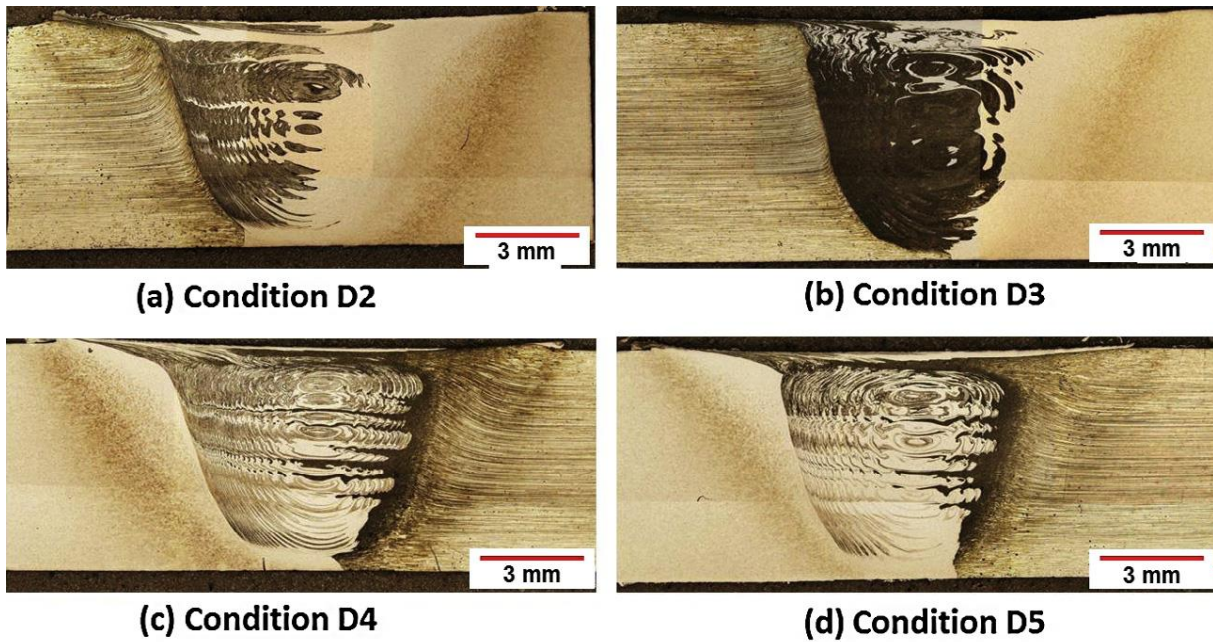

Figure. 7. Macro-views of the cross-sections of joints produced at a rotational rate of 1200 rpm under different conditions: a) AA7075 placed at the AS and a welding speed of 3 mm/s used, b) AA7075 placed at the AS and a welding speed of 5 mm/s used, c) AA6061 placed at the AS and a welding speed of 3 mm/s used and d) AA6061 placed at the AS and a welding speed of 5 mm/s used [13].

In general, it is widely accepted that the higher strength (the higher hot-strength) Al should be placed at the RS to minimize the resistance to the material flow in FSW of dissimilar Al-alloys combinations. However, it was also suggested that the higher strength alloy should be placed in the AS provided that the peak temperature achieved high enough for sufficiently plasticizing the material at the AS for increasing the strength of FSWed dissimilar Al-alloys joints [17,39-65]. For instance, Aliha et al. [39] investigated the influence of material position on the strength of the FSWed AA6061-AA7277 dissimilar joint and reported that the dissimilar joints exhibited higher tensile strength values (i.e., 78 % of the base alloy AA6061-T6) when the higher strength AA7277 alloy was placed at the AS side. Amancio-Filho et al. [40] also investigated the effect of the plate position on the joint performance of AA2024-AA6056 dissimilar Al-alloys joints and the highest joint performance was obtained, i.e. about 90% of the lower strength AA6061 base material, when the higher strength alloy 2024-T351 was placed on the AS. Similarly, Lee et al [41] studied the effect of plate position on the material mixing in the SZ of dissimilar cast

A356-AA6061 Al-alloys welds by changing the base alloy placed at the AS. They demonstrated that the SZ contained predominantly A356 Al alloy when A356 Al-alloy was fixed at the RS. However, when 6061 Al-alloy was fixed at the RS, the microstructure of the SZ was mainly composed of that of 6061 Al-alloy. Therefore, the macrostructure of the stir zone was predominantly determined by the materials fixed at the RS.

Similar results were also reported by Dilip et al. [44] who investigated the influence of plate positioning on the material mixing in dissimilar FSW of AA2219-AA5083 Al-alloys. They observed that the SZ was primarily composed of alloy 2219 which was placed on the AS. They also described that a joint efficiency of around 90%, which is substantially higher than what can be achieved with conventional fusion welding. Bahemmat et al. [12] also investigated the influence of plate positioning on the joint strength in dissimilar AA6061-AA7075 Al-alloys joints and pointed out that if the lower strength alloy is located at the RS the fabricated weld will display better tensile strength than when the lower strength alloy is at the AS. Similarly, Dong et al. [45] showed that by placing the harder 7003 alloy on the AS, sound joints were produced in AA6061-AA7003 dissimilar combination, the stir zone of which composed of predominantly AA7073 material. Thus, they reported a joint efficiency of about 78.2% of BM 6060-T4. Moreover, Song et al. [46] investigated the effect of plate position on weld formation and mechanical properties of dissimilar AA5052-AA5J32 welds. They observed that when the higher strength 5J32 was placed on the AS, defect-free welds were obtained under all the studied welding conditions. It was also reported that the average tensile strength approached approximately 90% of that of the 5052 alloy, regardless of the plate position, but the tensile strengths of the AS5052-RS5J32 joints were slightly higher than those of the AS5J322-RS5052 joint. Hassan et al. [49] also conducted FSW of dissimilar A356 and A319 cast Al-alloys by placing the higher strength alloy (i.e., A319) at the AS and reported that the peak hardness in the SZ increased by increasing the rotational speed and/or reducing the traverse speed. It was also observed that the as-welded dissimilar FS joints exhibited better mechanical properties than both base alloys. Similarly, Khan et al. [51] investigated the joint performance of FSWed dissimilar AA2219-AA7475 joints produced by placing the higher strength alloy (i.e., AA7475) on the AS and reported that the joints exhibited a tensile strength of about 97% of parent alloy AA2219. However, Azeez et al. [64] studied the influence of the plate position prior to joining on joint quality in friction stir welding of dissimilar AA6082 and AA7075 alloys and reported that the positioning of the AA7075-T6 alloy on the AS results in poor welds, unlike when it is on the RS.

On the other hand, Jonckheere et al. [66] showed that regardless of material placement material flow and joint quality mainly depend on the processing conditions and their effects on heat input and weld nugget temperatures. They proposed that there is no significant effect of the alloys' placement or the tool shift on the joint properties. Similarly, Sato et al. [67] investigated the influence of plate position on the joint behavior of dissimilar AA7075-AA2024 joints and no difference was observed by inverting the alloys' positions. Simar et al. [68] also reported a slightly better mixing of the materials in the SZ in dissimilar AA6005-AA2017 joints produced by placing the lower strength alloy (i.e., AA6005) at the AS. In contrast, they also observed that the dissimilar joint produced by placing the higher strength AA2017 at the AS displayed better strength, but they also pointed out this is dependent on the welding conditions. Similarly, Pabandi et al. [69] also studied the influence of plate position on the joint performance in dissimilar AA2024-AA6061 Al-alloys and they reported that the dissimilar joints displayed a joint efficacy of about 60% regardless of alloys location.

It was however clearly demonstrated that the weld is formed mostly by AS material in FSW because the stirring tool drags mostly the material located at AS into the weld seam. Thus, the hardest material can be placed in the AS in order to increase the weld hardness. However, the other weld parameters should be adequate in order to achieve a peak temperature as high as possible to sufficiently soften and plasticize the higher strength material located at AS. Moreover, it is also worth pointing out that it is difficult to conclude about the optimal material position for dissimilar welding since the positioning and mixing abilities appear to be highly materials and process parameters dependent.

2.2. Effect of Tool Rotation and Welding Speeds

Weld parameters, such as tool rotation and welding speeds, control heat generation or heat input as well as material plastic flow during FSW [10,26,27,31,37,55,61,70-78]. The tool rotation speed affects the intensity of plastic deformation and through this affects material mixing as it determines the heat generated which softens the surrounding materials. This is thus totally applicable to material mixing in dissimilar Al welds. Material flow is accomplished better by either increasing the rotational speed and/or reducing the welding speed. The former, however, has a significantly greater effect as reported by Peel et al. [26,27]. For instance, Hamed [31] weld demonstrated that the increasing heat input results in better mixing of the materials in dissimilar FSW. Kalemba-Rec et al. [10] also described a proportional relationship between material mixing and tool rotation speed for a dissimilar AA7075-AA5083 joint. Similarly, Rodriguez et al. [61] reported that the increasing tool rotational speed improved material intermixing and joint strength in friction stir welded dissimilar AA6061-AA7050 joints. Ipekoğlu and Çam [11] also showed that the dynamically recrystallized zones (DXZs) of FSWed AA6061-AA7075 dissimilar joints displayed the complex materials flow patterns (onion rings) and is dominated by the BM placed in the AS, i.e., AA6061, and the amount of RS BM (i.e., AA7075) increases in the weld region as the rotation rate increases due to better mixing of BMs at higher rotational rates as shown in Fig. 8.
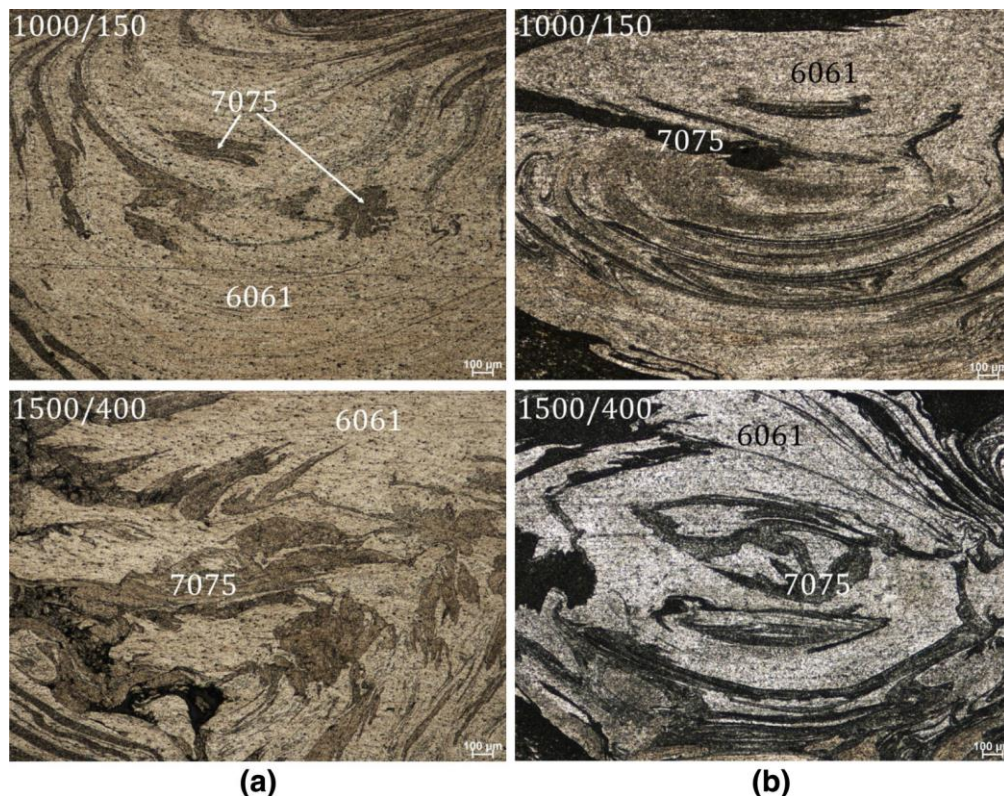

Fig. 8. Dynamically recrystallized zones (DXZs) of the as-welded dissimilar joints:

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(a) O joints and (b) T6 joints [11].

Palanivel et al. [55] also observed that the tool rotational speed and pin profile considerably influenced the microstructure and tensile strength of the joints. Similarly, Ravikumar et al. [37] also studied the effects of rotational and traverse speeds with the pin profiles for dissimilar friction stir welded but joints between AA6061 and AA7075 fabricated by keeping lower strength AA6061 alloy on the AS. They reported that higher rotational and lower weld speeds promoted intermixing of both alloys.

A low rotational speed or a higher traverse speed cause tunneling defect and kissing bond due to insufficient material mixing as the heat input is too low and the material is not soft enough [72]. On the other hand, the high heat input results in an SZ containing onion ring patterns (consisting of alternative bands of alloys welded), whilst low heat inputs lead to an SZ clearly divided into regions of base plates and a clear boundary between two alloys can be distinguished [21]. Zhang et al. [73] also investigated the effect of rotation speed on the joint properties of dissimilar AA7075-AA2024 welds. They reported that the rotational speed remarkably influenced the degree of mixing in the joints. Whilst low rotational speeds resulted in limited materials mixing, the typical onion ring type mixing pattern can be acquired at high rotational speeds. Correspondingly, other researchers reported that better materials mixing can be achieved when high rotation speeds are used [16,27,47,74,75]. However, a combination of high rotational and welding speeds causes cavities in the SZ due to abnormal stirring [76]. In the range of optimized welding parameters, increasing the travel speed at a constant rotational rate improves joint mechanical properties [77], while increasing the rotational speed at constant weld speed leads to higher heat input and thus lower mechanical properties in the joints [13,47,78].

An increase in the tool rotational speed or welding speed led to improvement of tensile strength until a certain level and then a decrease after reaching a maximum value [18,35,36,38,53,56). For example, Shanmuga Sundaram and Murugan [52] reported that an increase in tool rotational speed or welding speed leads to an increase in tensile strength; so that it reaches to a maximum value and then decreases by increasing the both speeds. Palavinel et al. [55] also observed that the increasing weld speed increases the tensile strength, but again after a maximum value further increase in weld speed results in diminishing the tensile strength of the joint. Moreover, Dinaharan et al. [35] observed that increasing tool rotational speed enhanced the joint strength of dissimilar friction stir welds irrespective of the prior alloy position. Similarly, Raturi et al. [36] concluded that tool rotational speed and tool pin profile are the most prevailing factors affecting the quality of dissimilar FSW joints between AA6061 and AA7075 alloys. However, they pointed out that very high rotational speeds may result in inferior nugget shape and inadequate joining of dissimilar metals due to excessive heat generation that leads to intense material softening, in turn poor joint strength. High traverse speeds can also result in inferior strength of the dissimilar friction stir welded joints. The preheating has been also proposed to be used to improve the material intermixing and thus the joint strength slightly. However, very large rotation speeds lead to numerous imperfections such as poor surface (flash), voids, porosity, tunneling, or formation of wormholes because of the excessive heat input [62,76,79,80]. Moreover, low welding speeds increase heat input and are associated with defects like tunneling [55,76,80-83]. Thus, an appropriate combination of tool rotation and welding speed should be selected for a defect free joint having a good metallurgical bond and mechanical properties.

2.3. Effect of Stirring Tool Geometry

The geometry of the shoulder and the pin profile govern heat generation and material flow during welding [84-99]. The shoulder contributes to a large extent to heat input due to its size. The common shoulder profiles employed are the flat, the concave, and the convex. The pin profile greatly affects material stirring and mixing. Cylindrical or conical pin profiles that may have features like threads or threads with flats have been used for dissimilar Al alloy combinations. When pins used without threads are used a smaller surface is provided to the material. Thus, additional features on the pin such as a spiral or a groove improve frictional behavior as well as material flow [4,10,58,94]. Shanmuga Sundaram and Murugan [52] investigated the effects of various process parameters including tool pin profile (namely tapered cylinder with grooves, tapered square, tapered hexagon, paddle shape, and straight cylinder), tool rotational speed, and welding speed on mechanical properties of the dissimilar joints between AA2024 and AA5083 Al alloys. They showed that dissimilar joints fabricated using tapered hexagon tool pin profiles have the highest tensile strength and tensile elongation, whereas the straight cylinder tool pin profile has the lowest tensile strength and tensile elongation. Palanivel et al. [54] also investigated the effect of pin profile on the joint performance of dissimilar FSWs in AA5083-AA6351 Al-alloys. They selected five different tool pin profiles including straight square, straight hexagon, straight octagon, tapered square, and tapered octagon. It has been observed that the joint fabricated using tool rotational speed of 950 rpm and straight square pin displayed the highest strength level of 273 MPa. Ilangovan et al. [58] also studied the influence of pin profile on joint performance of dissimilar AA5086-AA6061 joints. First, they have determined that the surface defect free joints were fabricated using a tool rotational speed of 1100 rpm and a welding speed of 22 mm/min, irrespective of tool pin profile. Hence, these parameters were kept constant for making the dissimilar joints using three different pin profiles consisting of straight cylindrical, threaded cylindrical, and tapered cylindrical. It was reported that the threaded pin profile of the tool contributes to better flow of materials between two alloys and the generation of defect free stir zone. Palanivel et al. [87] investigated the effect of different shoulder profiles, namely the partial impeller (PI), the full impeller (FI), and the flat grove (FS) on the FSW of AA5083-AA6351 alloys. They reported that the full impeller shoulder tool produced the optimum mechanical strength due to the enhanced material flow it produced. On the other hand, Koilraj et al [88] investigated the effect of weld parameters on the joint performance of the AA5083-AA2219 dissimilar welds. They found that the cylindrical threaded pin tool profile was the best and the D/d ratio plays a vital role. The optimum levels of the rotational speed, transverse speed, and D/d ratio were determined to be 700 rpm, 15 mm/min, and 3, respectively. A joint efficiency of around 90% (based on alloy AA5083) was achieved from the dissimilar joints. Similarly, Sadeesh et al. [48] studied the influence of weld parameters, such as tool shoulder diameter/pin diameter ratio, and pin profiles (cylindrical threaded pin, cylindrical pin, squared pin, tapered pin, and stepped pin), and they inferred that a combination of cylindrical threaded pin and the rotational speed of 710 rpm, traverse speed of 28 mm/min and D/d ratio of 3 is the most efficient. They also proposed that tool shoulder diameter to pin diameter ratio is the most dominant factor.

Masoumi Khalilabad et al. [89] also investigated the effect of tool geometry and welding speed on mechanical properties of dissimilar AA2198-AA2024 FSWed joints. Different tool geometries including three shoulder profiles (flat, raised spiral, and raised fan) and five different pin profiles (cone, half threaded cylindrical, straight cylindrical, tapered cylindrical, and square) were employed in their research. They carried out preliminary investigations by moving the tool into a seamless sheet of the AA2024-T3 in order to select the tools that produce defect-free joints. These preliminary investigations showed the raised fan shoulder profile facilitates a better material flow in comparison with flat and raised spiral shoulder profiles. They also observed that pins with a minimum diameter equal to half the plate thickness produced a lack

of penetration (LOP) defects while increasing minimum pin diameter to the plate thickness eliminates the LOP defects. Moreover, while half-threaded cylindrical pin produced tunneling defects, straight cylindrical, tapered cylindrical and cubic pin profiles produced defect-free joints. Also, Salari et al [90] observed that adding a step to a conical pin eliminated the cavity defect and increase the joint mechanical properties. Similarly, Ji et al [91] reported that a half-screwed pin also eliminated the cavity defect and increase the joint mechanical properties in comparison to a full-screwed pin. Venkatesh Kannan et al [92] also studied the influence of tool profile, i.e. cylindrical, cylindrical-threaded, squared, tapered, and stepped types, on the joint properties in dissimilar AA2024-AA5052 welds and reported that defect free joints were obtained by both newly designed stepped pin tool and cylindrical-threaded pin tool. However, the joint performance of the dissimilar joint produced with the stepped pin tool was much better. In another recent work, Hou et al. [93] investigated the FSW of dissimilar AA2024-AA6061 Al-alloys combination employing a novel dual-pin tool and clearly demonstrated that this novel tool resulted in better mixing of both materials in the SZ and thus yielded better joint performance.

Moreover, it was pointed out by Patel et al [95-97] that the polygonal pin profiles generate pulses in the flow during material stirring and mixing, resulting in material adhering to the pin. This pulsating effect hinders material flow significantly in the case of dissimilar Al alloy combinations. Thus, it is recommended to use a cylindrical or a conical pin profile with various surface features in the dissimilar Al alloy joints for good material flow to produce sound joints. Although it is well known that in FSW, the material is transported from the leading face to the retreating edge, it was just recently showed by Colligan [98] that with a threaded tool, material from the upper part of the parent plate is forced down into the weld, whereas material from the lower part of the parent plate is moved toward the top surface.

There are also other investigations to evaluate the influence of using a stirring tool with a non-rotating shoulder on the joint properties for dissimilar Al-alloys. In this direction, Barbini et al. [99] investigated the influence of a stationary shoulder on heat generation, microstructure, and mechanical properties of dissimilar AA2024/AA7050 FSW joints. They reported that the torque applied is less in FSW with stationary shoulder than that in conventional FSW. This reduces microstructural changes across the joint and allows the production of good quality welds with low heat input. Thus, the joints produced using stationary shoulder FSW (SSFSW) exhibited relatively higher joint efficiency values, i.e., 94% of the AA2024-T3 base plate strength, compared to 86% obtained for FSW.

2.4. The Effect of Tool Position
There is a very limited number of optimization studies to analysis the effect of tool offset on dissimilar Al-alloys welding. For instance, Cole et al. [14] investigated the influences of tool offset and tool-workpiece interface temperature during dissimilar FSW of AA6061-AA7075. They reported that the weld tool offsets into the higher strength AA7075 side increases the number of AA7075 stirred into the nugget, thus leading to higher tensile strength. Similarly, Cavaliere and Panella [100], studied the effect of the tool position concerning the weld line on the properties of AA2024-AA7075 dissimilar welds and found that a tool offset of 1mm into the AA2024 side (AS) resulted in a good intermixing 'n the SZ while the SZ was characterized by bands of different grain size due to the non-optimal mixing of the two different alloys when the tool offset was 1.5 mm into the AA2024 alloy as shown in Fig. 9. They also reported that offsetting the tool 1 mm into the AA2024 side significantly improved the joint fatigue properties and further tool offsetting did have an adverse effect.
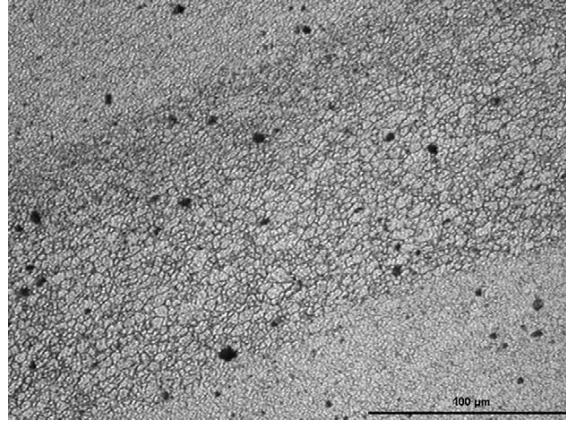
Fig. 9. Band formation in the SZ of the welds produced with a distance from the weld line of 1.5mm [100].

2.5. Microstructural Evolution in Butt Welding

Typical microstructures observed in friction stir welded joints of similar materials are two types as schematically shown in Fig. 10 [101]. In the first type, the weld area consists of three distinct zones, namely onion structure-like stirred (nugget) zone (also called a dynamically recrystallized zone, DXZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ), as seen in Fig. 10(a) [102-109]. This three-zone weld area is typically observed in FSWed materials with slower rates of recrystallization, such as Al-alloys. However, the second type exhibits a weld cross-section consisting of only two regions, namely stirred zone (also called dynamically recrystallized zone) and HAZ, as shown in Fig. 10(b). This is the case in materials with faster rates of recrystallization.
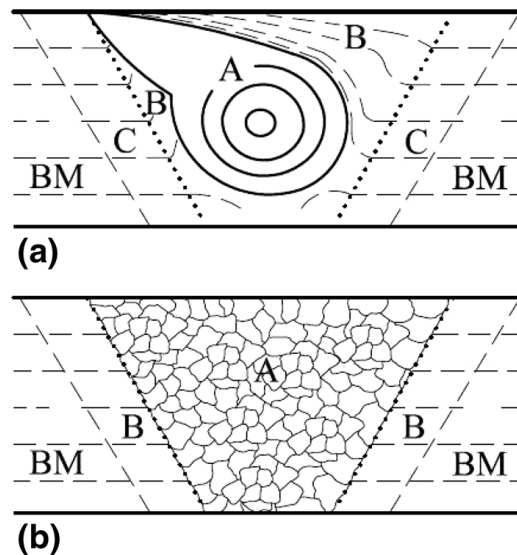

Fig. 10. Schematic presentation illustrating the cross-sections of the joint area obtained in friction stir welding: (a) in materials with slower recrystallization rate (e.g., Al-alloys) and (b) in materials with faster recrystallization rate (e.g., austenitic stainless steels or Ti-alloys). A: stirred zone (SZ), B: thermo-mechanically affected zone (TMAZ), C: heat-affected zone (HAZ) [102].

However, complex material movement occurs in dissimilar FSW depending on the welding conditions and parameters, resulting in the formation of a complicated microstructure in the SZ.

The microstructure evolving in the SZ of dissimilar FS welds may vary from lamellar structure to complex intercalated lamellar structure (vortex-like cell structure or onion ring) with single (Fig. 6) or double cell appearance (Fig. 8b) provided that a sufficient intermixing of both base materials is achieved [10,11,13,75]. As discussed in the previous section, the microstructural evolution depends on the welding variables since the material flow plays a more important role in the case of dissimilar material welding compared to similar joints. If the weld parameters are inappropriate, then the intermixing of the materials does not take place sufficiently as shown in Fig. 7a. On the other hand, the appropriate selection of all process parameters results in excellent material mixing on both sides (AS and RS) of the joint and produces a sound weld with a somewhat more symmetric weld zone, as shown in Fig 7c. When the intermixing of abutting base materials is good then a typical weld cross-section similar to the one shown in Fig. 10a is obtained whereas more asymmetric weld regions are observed if the intermixing is not sufficient.

Speaking about the similar friction welded joints, the SZ undergoes extensive grain refinement, producing fine-grain microstructures, while the TMAZ has an elongated grain structure [11,101-121]. The grain refinement in the SZ depends on the original grain size of the materials to be welded and the welding variables. The grain refinement occurring within the weld zone of friction stir welded joints is primarily caused by shear deformation processes and dynamic recrystallization [114,115]. For instance, Bala Srinivasan et al [111] reported that a very fine and recrystallized grain structure was developed in the SZ of friction stir welded dissimilar AA6056-AA7075 joints, as shown in Fig. 11. They also observed that the flow and mixing of materials during the FSW resulted in a wavy interlocking structure within the SZ, Fig. 12. Although a grain refinement was evolved in the weld nugget region, there exist differences in the grain size. The region marked 'a' corresponding to AA7075 layer in Fig. 12 shows a much finer recrystallized grain structure compared with the light etched region marked 'b', which corresponds to the layer of AA6056, and the higher magnification micrographs (Fig. 13) clearly indicate the differences in the grain size in the respective regions. They also pointed out that the differences in the grain size within the nugget could be attributed to the initial grain sizes of the respective base materials.
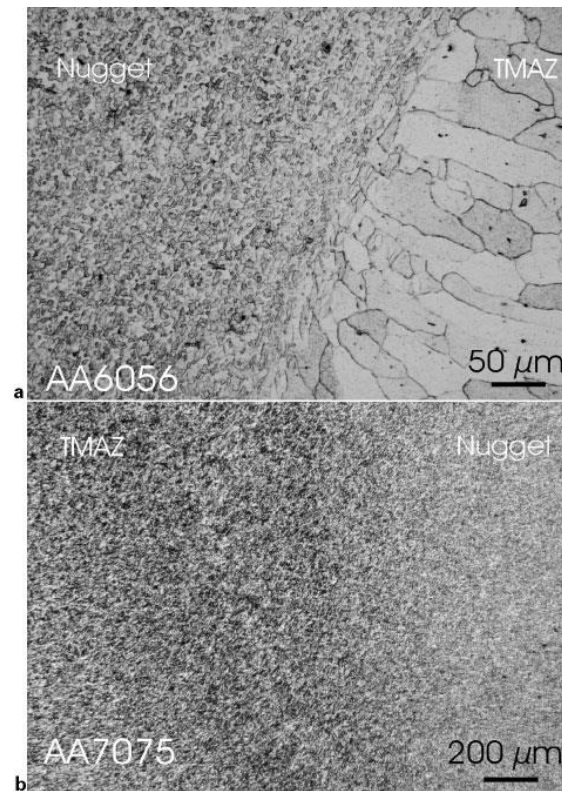
Fig. 11. Grain refinement in the SZ of FSWed 6056-7075 dissimilar joints: a) SZ-TMAZ interface on 6065 alloy side and b) SZ-TMAZ interface on 6065 alloy side [111].
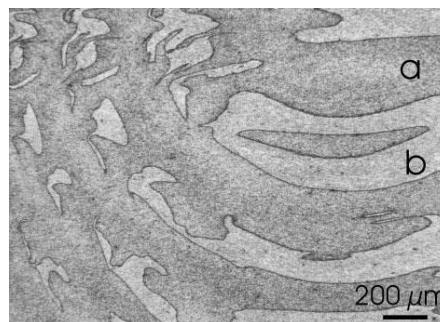

Fig. 12. Optical micrograph showing a wavy interlocking structure within the SZ of FSWed 6056-7075 dissimilar joint [111].
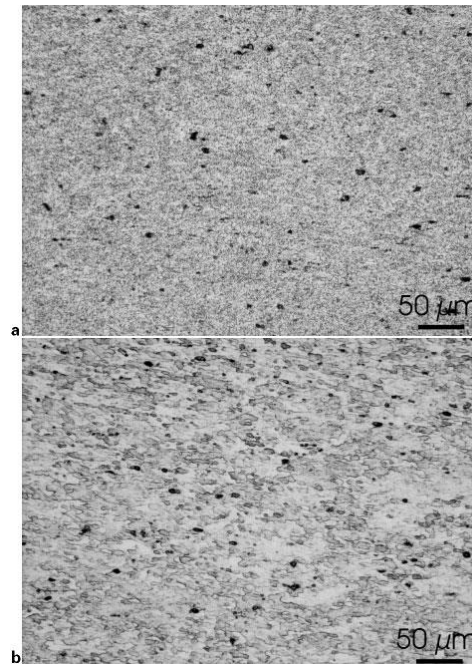
Fig. 13. Higher magnification micrographs of regions marked in Fig. 10: a region 'a'; b region 'b' [111].

Recently, Niu et al. [53] reported that highly inhomogeneous microstructures were evolved across the friction-stir welded AA5083 to AA2024 dissimilar joint. They conducted a comprehensive EBSD investigation across the AA5083-AA2024 joint cross-section, as shown in Fig. 14. As seen from the EBSD orientation maps (Fig. 14a-d), tilted and elongated grains in the TMAZ and fine grains in the SZ were developed due to dynamic recrystallization in accordance with the Zener-Hollomon parameter. Grain boundary orientations also varied in all three zones as shown in Fig. 14(e-h). A higher fraction of large (>10) angular grain boundaries was present in the SZ, while more of the low (2-10) angular grain boundaries were in the HAZ. Moreover, a more intense texture in the SZ was formed compared to other zones.

In what precipitation is concerned, to the authors' knowledge, no special precipitates have been found at the interface between dissimilar Al alloys. Precipitates are similar to the SZ of a given band with the usual precipitate evolution. For example in a 7003-T4 to 6060-T4 dissimilar weld by Dong et al. [45] coarser and a low number density of η' precipitates are observed in the weld nugget in a band made of 7003 alloy. In a 6082 to 7075 weld by Aval [84], post-weld natural aging also revealed the classical β' precipitates in the 6082 side of the SZ and the η' precipitates in the 7075 side of the weld.
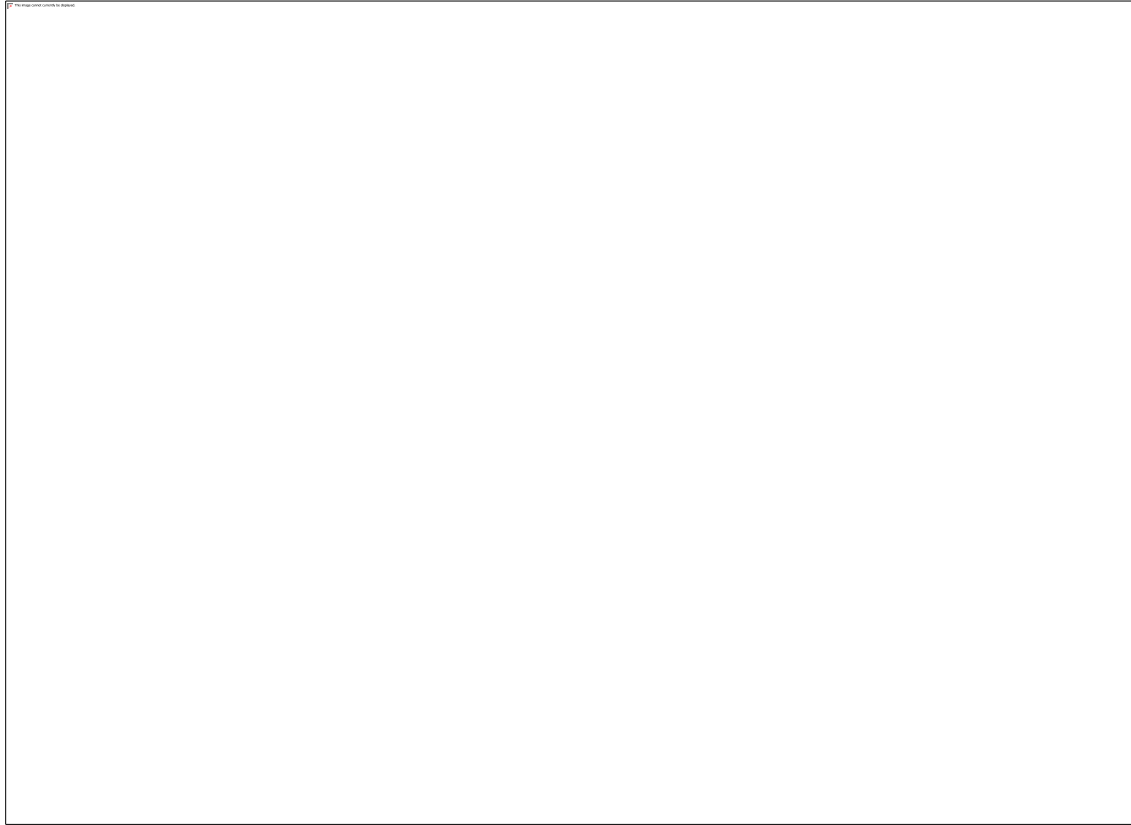
Fig. 14. EBSD orientation maps and grain boundaries of the dissimilar AA5083-AA2024 aluminum alloy joint on the AA5083 side: (**a,e**) BM, (**b,f**) HAZ, **g**) TMAZ-SZ interface and (**d,h**) SZ [53].

3. The Effect of Weld Parameters in Lap- and T-Lap Joints

All the weld parameters which affect the joint behavior of FSWed butt welded dissimilar Al-alloys welds except tool position are also influential on the performance of FSWed lap welded dissimilar Al-alloys welds. These are plate positioning, tool rotational and welding speeds, tool geometry, and tool tilt angle. Moreover, tool geometry plays an even more significant role in the performance of lap welds as discussed below.

3.1. Effect of Plate Position

The relative plate positioning is also influential in determining the strength of the friction lap joints of the dissimilar Al-alloy plates as the case in dissimilar Al-alloys butt-joints. This issue was already addressed by several researchers who studied different material combinations and welding conditions. For instance, Song et al. [122] studied the effect of weld speed and plate positioning on the joint performance of friction stir lap welded dissimilar AA2024-AA7075 aluminum alloy sheets. They reported that no voids are formed in AA7075/AA2024 joints where higher strength AA7075 alloy placed as the top sheet, whereas the lap joints fabricated by placing lower strength AA2024 alloy on the top exhibited voids. They also observed that the hook geometry varies with welding speed as well as the sheet positioning, the hook size was increased when AA7075 alloy was placed as the top sheet. They also reported that defect free joints can be obtained by both plate positioning and the joints fabricated by placing higher strength AA7075 alloy as top sheet show higher failure load than the joints produced by placing AA 2024 alloy as the top sheet at lower welding speeds while the opposite result appears at higher welding speeds. Similarly, Soundararajan et al. [123] also reported superior performance for the welds performed with the higher strength AA6022 alloy on the top, for dissimilar friction

stir lap welds between AA 5182 and AA 6022. They also highlighted the importance of the base materials' thermal properties on weld quality. In accordance with Soundararajan et al. [123], Lee et al. [124] also reported higher mechanical strength for welds performed with the higher strength AA6061 alloy placed on the top of AA 6061-AA 5052 alloys FSW lap joints. Finally, Costa et al. [125] conducted dissimilar lap welding of 1 mm thick plates of AA 6082-T6 and AA5754-H22 Al-alloys by FSW and investigated the influence of base materials relative positioning on welds strength. They reported that the plate positioning has a strong influence on material flow during welding and, in this way, on hooking formation. Thus, superior welding properties were obtained by placing the AA 6082-T6 alloy as the top plate in contact with the tool shoulder, regardless of the tool geometry.

3.2. Effect of Tool Rotation and Welding Speeds
Since weld parameters, such as tool rotation and welding speeds, control heat generation or heat input as well as material plastic flow during FSW as already discussed earlier, they also affect the joint performance in dissimilar lap joints. The influence of welding parameters in conjunction with probe design has been found to produce a very strong impact on hook formation and an effective sheet thickness of the joints which greatly influence the properties of the joints. Generally, when the rotation speed is high and the welding speed is low, the weld nugget takes on an onion ring shape, while if the rotation speed is low and the welding speed is high, void-type defects occur on the advancing side or center of the nugget [126]. In this respect, Urso and Giardini [127] studied the effects of FSW parameters for two different tool geometries on the aluminum friction stir lap joints. They observed that rotation speed and welding speed play a significant role the joint strength. The joint strength decreased with increasing the rotation speed and decreasing the welding speed due to an increase of hooking length. Thus, the weld pitch (WP) defined by dividing the rotational rate (N) and the travel speed (V) of the tool also affects the dissimilar lap joint performance. For instance, Park et al. [128] proposed that decreasing the WP transforms the height of the deformed interface from a hooked shape to a simple interface while higher WP produces a larger bonded area and thus higher weld performance.

Similarly, Aldanondo et al. [129] conducted FS lap-welding of dissimilar AA6082-T6 and AA5754-H22 alloys to determine the influence of the weld parameters on microstructural aspects and mechanical properties. They reported that the use of optimum welding parameters improves the weld strength. Similarly, the FSW processing parameters namely tool rotational rate and weld speed were also reported to have an influence on the quality of dissimilar AA2198-AA6082 friction stir lap joint [130]. As regards, the increase in the welding speed leads to inferior joint quality due to insufficient material mixing and the occurrence of hooks and other defects. On the other hand, increasing tool rotational rate generates more heat, leading to better material softening and less resistance during FSW, thus enhancing joint performance. Masoumi Khalilabad et al. [131] also studied the influence of weld parameters on the joint performance of friction stir dissimilar lap joints between AA2198 and AA2024 alloys. They suggested that tunneling and kissing bond defects are more prone to form with higher rotational and traverse speeds and they recommend the usage of the tool with longer pins for such circumstances. Moreover, Yoon et al. [132] proposed that a void nugget, which is a typical defect, formed because of the remaining interface line after FSLW in the case of low heat input.

3.3. Effect of Stirring Tool Geometry
The tool geometry also plays a role in determining the joint performance in dissimilar friction lap welds as the case in dissimilar butt welds. For example, Buffa et al. [133] investigated the influence of the probe geometries (cylindrical and conical probe) on the mechanical properties of the FSLW joint of AA2198-T4 sheets. The larger probe (pin) angle significantly increases

the nugget area, which leads to enhanced joint performance. However, if the pin has no angle and its length is longer, typical void defects occur in the stir zone. Similarly, Costa et al. [125] investigated the influence of tool geometry on welds strength in addition to the plate positioning for dissimilar lap welding of 1 mm thick plates of AA 6082-T6 and AA5754-H22 Al-alloys. They investigated three different tools in this respect, namely cylindrical and two conical tools (taper probe) with different taper angles. They clearly demonstrated that the cylindrical tool produced a hooking defect due to the vertical flow of material from the lower plate, whereas the use of the taper tool eliminated the formation of hooking defect since the taper tool has less vertical flow. They also reported that better quality welds may be obtained by employing conical tools with a low shoulder/pin diameters ratio. Moreover, Aldanondo et al. [129] analyzed the influence of the process variables on microstructural aspects and mechanical properties of FS welded AA6082-T6 and AA5754-H22 dissimilar lap welds. They proposed that appropriate tool design in conjunction with the calibration of welding parameters improve plasticized materials flow, prevent undesired weld defects, and enhance joint performance. Similarly, Park et al. [128] investigated the effects of the shoulder diameter (SD) on the tensile shear load for FSW of AA6111-T4 and AA5023-T4 in a lap joint configuration. They demonstrated that the larger SD produced a higher peak load because of widened bonded area. Furthermore, Masoumi Khalilabad et al. [131] reported that the employment of tools with longer pins in friction stir lap welding of dissimilar Al-alloys plates enhances the joint performance.

A modification of the friction stir lap joint is the friction stir T-lap joint which is composed of the stringer and skin parts. The T-lap joint is one of the common connections in the structures of aircraft wing-box, railway tankers, and structural panel plate, such as the skin-stringer connection of an aircraft fuselage structure. The skin-stringer connection can be done by mechanical fastening such as riveting or fusion welding techniques such as laser welding as schematically shown in Fig. 15.
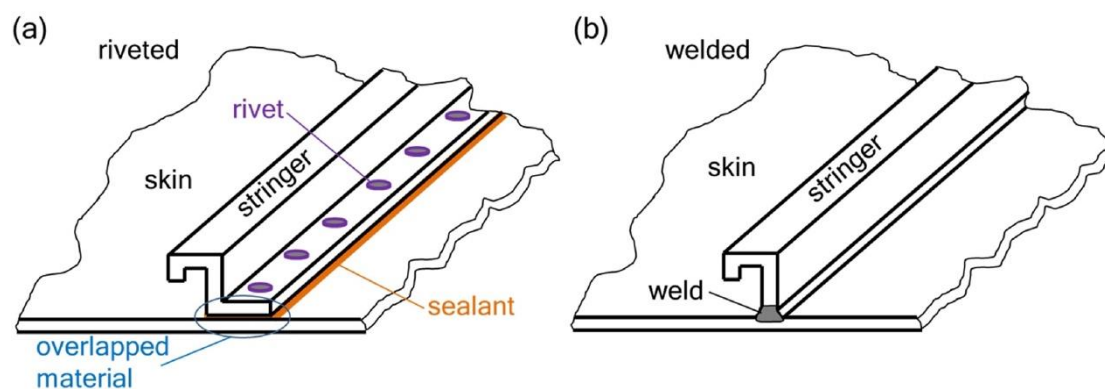

Fig. 15. The skin-stringer connection of an aircraft fuselage structure: (a) Conventionally riveted and (b) welded T-joint [1].

The FSW technology is recently being considered as a potential candidate to fabricate this type of T-lap joints. However, the joint performance of single-pass FSWed T-lap joints in literature is not satisfactory due to the presence of the kissing bond defects, especially in the stringer-directional loading test [134-138]. The geometry and orientation of kissing bonds (KBs) have an important role in the joint performance of the T-lap joints including the fatigue failure behavior. There are two approaches to eliminate weld defects in FSWed T-lap joints. First, hooking defects that are generally observed in the single-pass FSWed T-lap joints can be removed by the double pass as demonstrated by Dubourg et al. [139]. Second, hook and cold

lap defects can be eliminated by optimizing the tool geometry. For instance, Huang et al. [140] proposed a novel multi-functional tool with circumferential notches shape probe for friction stir lap welded dissimilar Al-alloys, namely 6082-T6 and 2A12-T4. Fig. 16 shows this novel tool as well as a more traditional conic tool. They reported that the novel probe produced a larger turbulent flow region (strain rate ≥ 10 s^{-1}) by 185% and converged the plasticized materials below the probe top. Thus, the employment of this novel probe eliminated general hook and cold lap defects and led to a larger metallurgical bonding area. The tensile shear load of the dissimilar lap joint reached 85% of the base 6082-T6 alloy. These results clearly demonstrate that the kissing bond defects can be eliminated by optimizing the geometry of the stirring tool and the strength of dissimilar lap joints can be enhanced.
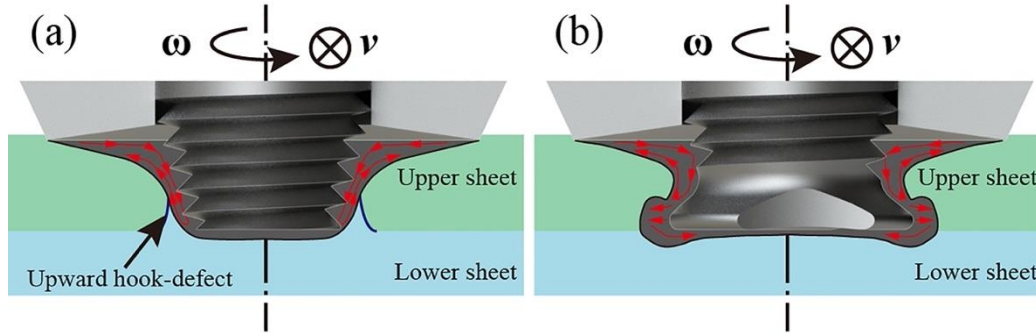

Fig. 16. Schematics show two friction stir welding tools: (a) more conventional taper-threaded probe and (b) novel circumferential notches shape probe [140].

3.4. Microstructural Evolution in Lap Welding

Microstructural evolution in friction stir lap welds does somehow differ from those observed in friction stir butt welds. Fig. 17 shows the cross-section of a typical dissimilar friction stir lap weld (FSWLW) indicating different zones namely WN (also called nugget zone or dynamically recrystallized zone, DXZ), thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ), and base metal (BM) [141].
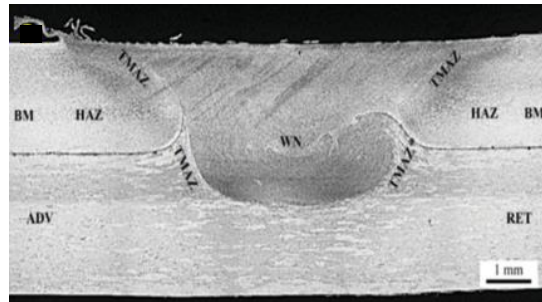
Fig. 17. Macrograph illustrating the cross-section of a typical dissimilar friction stir lap weld (FSWLW) indicating different zones weld nugget - WN (also called nugget zone or dynamically recrystallized zone, DXZ), thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ), and base metal (BM) [141].

4. The Influence of Weld Parameters in Friction Stir Spot Welding

In addition to tool geometry, tool tilt angle, and weld parameters such as rotational rate and weld speed, there are other critical weld parameters intrinsic to FSSW. These are plunging speed, plunging depth, and dwell time, in friction stir spot welding (FSSW) [142,143]. In this section, the most important of these parameters, namely plate positioning, rotation and weld

speeds, stirring tool geometry, plunging speed, plunging depth, and dwell time will be discussed.

4.1. Effect of Plate Position

As opposed to friction stir butt- and lap-welding, the plate positioning (alloy combination) is not too crucial. However, it does play a role in material flow, and thus on the weld performance in FSSW. For instance, Bozkurt et al. [144,145] conducted FSSW of AA 5754-H22/2024-T3 Al-alloys and they changed the plate positioning to investigate the effect of plate positioning on the joint strength. They observed that the plate positioning is not very influential on the strength of the joints fabricated by FSSW. They specified that both lap joints fabricated by placing the higher strength alloy (AA2024-T3) and lower strength alloy (AA 5754-H22) on the top display good lap-shear strength provided that the weld parameters are suitable [144,145]. Similarly, Jeon et al. [146] studied the effect of plate positioning in FSSW of dissimilar AA6061-T6 and 5052-H32 alloys. They stated that FSSW joints of both dissimilar combinations have similar maximum shear loads, and displacements in the lap-shear test, indicating that the plate positioning is not very influential provided that the weld parameters are sufficient.

In another study, Piccini and Svoboda [147] investigated the influence of relative plate position on the joint performance of FSSWed dissimilar AA5052-H32/AA6063-T6 sheets. They proposed that tool penetration depth is more critical than plate positioning although the plate positioning also affects plastic flow for a set of other weld parameters. They reported that the fracture loads in PT increased with the tool penetration depth for both material positions, although being higher when AA6063 was the upper material. Similarly, Zhang et al. [148] friction stir spot welded dissimilar AA2024-T3/AA7075-T6 Al alloy sheets by placing the lower strength AA2024-T3 alloy as the top sheet and obtained good tensile-shear strength, indicating that the plate positioning is not critical as long as suitable weld parameters are employed. Moreover, Tran et al. [149] also studied the influence of plate positioning on the joint performance of FSSWed dissimilar AA5754-O/AA7075-T6 sheets. The results they obtained indicated that the lap-shear strength of the welds increases when the processing time increases for the given ranges of the processing time, regardless of the plate positioning. However, they also concluded that 7075/5754 welds require a larger optimal processing time than that of the 5754/7075 welds do. Thus, the top plate determines the heat input required for achieving a successful joint, therefore the optimum weld parameters for each plate positioning should be employed.

4.2. Effect of Tool Rotation and Welding Speeds

Another influential parameter in the FSSW of dissimilar Al-alloys is tool rotation rate. In all variations of FSW including FSSW, tool rotation is the most critical parameter for heat generation [142]. For instance, Tozaki et al. [150] reported that the combination of lower rotational speed and higher dwell times was crucial for obtaining sufficient material mixing at the weld interface and thus for achieving better joint performance values in FSSWed dissimilar Al-alloy joints.

In good agreement with this, Moreover, Kim et al. [151] also reported poor material mixing at the weld interface for the FSSWed dissimilar Al-alloys (AA5052-H32 and AA6061-T6) joints produced at higher rotational speeds. Gerlich et al. [152] also pointed out that a rotation rate of more than 750 rpm is usually needed for achieving adequate mechanical properties in FSSW. Moreover, Bozkurt and Bilici [144] employed the Taguchi technique to optimize the process parameters in dissimilar FSSW of Al 5754 and Al 2024 and reported that the rotational speed

was observed to have a maximum contribution to the joint strength, followed by tool tilt angle, plunge depth and dwell time.

4.3. Effect of Stirring Tool Geometry
Tool geometry is also an important parameter that plays a significant role in the mechanical performance of the joints fabricated by FSSW. For instance, Badrinarayan et al. [153] studied the effect of tool geometry on material flow and thus variations in the hook morphology in using a triangular tool and cylindrical tool. They observed that the asymmetric shape of the triangular pin leads to increased plasticization and sufficient material flow to produce the discontinuous hook at the weld interface, and thus to produce a stronger weld joint. On the other hand, the threaded cylindrical pin results in a continuous hook due to the increased upward and outward flow of the plasticized material. The formation of continuous hooks leads to weaker welded joints.

Moreover, Kim et al. [151] investigated the influence of a convex tool on material flow in FSSW of dissimilar AA5052-H32 and AA6061-T6 alloys and reported that it produces a wider nugget as it provides an outward material flow. The increased outward flow with the convex tool was credited to the larger axial force and torque induced by the tool during FSSW.

4.4. Effect of Plunging Speed, Plunging Depth, and Dwell Time
Plunging speed is extremely critical in friction stir welding of dissimilar Al-alloy sheets. For instance, Suryanarayanan and Sridhar [154] determined the effect of plunging speed on tensile shear strength of friction stir spot welded Al 5754–Al 6061 joint. They clearly demonstrated that the lower plunge rates enhance material mixing and provide sufficient heat input and thus improve the weld joint strength. Similarly, Su et al. [155] also investigated the heat generation during FSSW and observed that the stir zone width decreases when the tool penetration rate increases, and thus the joint performance is negatively affected.

Plunging depth, which determines the weld macrostructure, has thus an effect on the joint quality of FSSWed dissimilar Al-alloy joints. Piccini and Svoboda [147] investigated the influence of tool penetration depth in addition to the relative plate position on the joint performance of FSSWed dissimilar AA5052-H32/AA6063-T6 sheets. They claimed that the fracture loads in peel testing increased with the tool penetration depth for both material positions, indicating that plunging depth is very influential. Similarly, Zhang et al. [148] also reported that the increasing plunging depth increased tensile-shear strength of the friction stir spot welded dissimilar AA2024-T3/AA7075-T6 Al alloy joint. The shoulder plunging depth is also influential since increasing shoulder plunge depth expands the stir zone and increases the upward material flow of the lower sheet significantly [156]. However, excessive shoulder penetration (higher than about 0.2 mm) extrudes a large portion of the top sheet material, causing an excessive thinning of the top sheet [142].

Another parameter that has an influence on the quality of FSSWed dissimilar Al-alloy joints is dwell time since the heat generation contribution from the tool shoulder is rather low during FSSW in general. For instance, Su et al [157] described that intermixing of materials cannot be formed using a threaded tool without the application of a dwell period in FSSW of dissimilar alloys. Lee et al. [158] also proposed that the use of higher dwell times during FSSW resulted in better material mixing that contributed to the increase in joint strength. Similarly, Siddharth et al. [159] observed that weak joints were obtained at low dwell time and rotational speed due to poor material mixing. The combination of high dwell time and high rotational speed led to increased thermal exposure and thus increase the weld strength. However, it should be kept in

mind that the width of the softened region produced when heat treatable Al alloys are FSSWed is significantly affected by the dwell time [152].

4.5. Microstructural Evolution in Spot Welding

The weld macrostructure obtained in FSSW depends on the process parameters, namely tool geometry, tool rotation, and travel speeds, and workpiece material properties such as thermal conductivity and external cooling conditions [142]. The cross-sections of the FSSWed joint usually display basin-like morphologies and the microstructure of an FSSWed joint commonly consists of four regions namely SZ, TMAZ, HAZ, and BM as the case in FSWed butt- or lap-welds. For example, Fig. 18 shows the effect of plunge depth on the macrostructure evolved in FSSWed dissimilar AA6061-T6/AA7075-T6 Al-alloys sheets [160]. As clearly seen from Fig. 18, adequate material mixing occurs with increasing the plunge depth. In addition, the lower sheet material tends to flow upwards, and the height of the upward flowing lower sheet material increase with the increasing plunge depth.
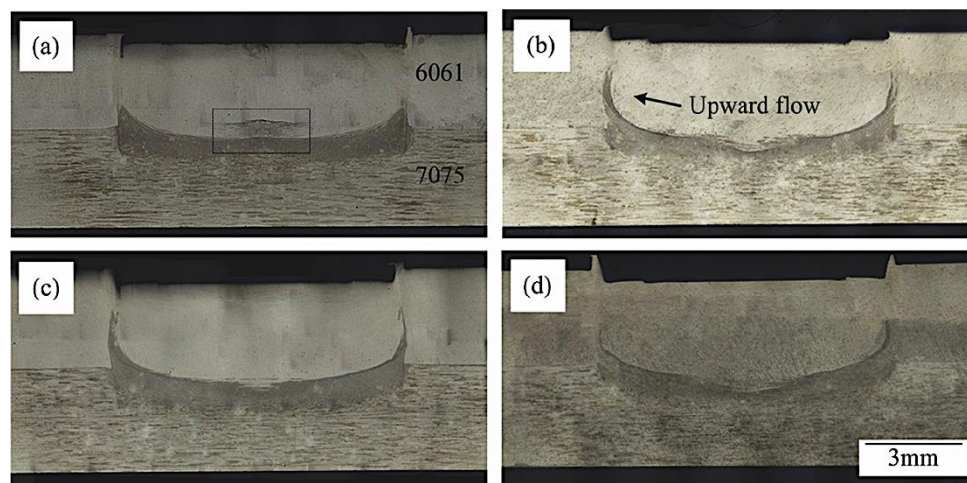

Fig. 18. Optical micrographs showing the cross-sections of FSSWed joints obtained in dissimilar Al-alloys (AA6061-T6/AA7075-T6) using various plunging depths: (a) 3.4 mm, (b) 3.5 mm, (c) 3.6 mm and (d) 3.7 mm [160].

5. General Remarks and Outlook

FSW/FSSW of dissimilar materials including joining of dissimilar Al-alloys is of particular interest, which is very difficult to conduct by conventional fusion welding processes due to the formation of porosity and cracking. The main difficulty in FSW/FSSW of dissimilar Al-alloys is the lack of homogeneous mixing of materials and thus the formation of inhomogeneous structure in the stir zone. Inhomogeneous mixing occurs due to the insufficient heat input and thus low plasticity of the materials to be welded. Thus, the FSW butt and lap joining of dissimilar Al-alloys is a very challenging task that requires the choice of optimum weld parameters such as optimum heat input (i.e., tool rotation and transverse speeds), suitable plate positioning, and tool position, and optimum shoulder geometry and pin profile. In addition, tool position is also critical in butt welding of dissimilar Al-alloys.

On the other hand, other parameters such as tool plunge speed, tool plunge depth and dwell time are influential in the FSSW of dissimilar Al-alloys. Thus, optimum tool plunge speed, tool plunge depth, and dwell time should be employed in order to achieve good quality spot welds. The studies conducted on FSW/FSSW of dissimilar Al-alloys to date have, however, well shown that these joining techniques can successfully be used for achieving defect-free joints with good properties between numerous dissimilar Al-alloys combinations in butt-, lap- and spot-weld configurations.

In summary, FSW/FSSW offers significant advantages over conventional fusion welding in terms of the materials that can be welded and the degree of microstructural control that can be achieved. As structural designs of various systems including transportation systems become more optimized for weight or performance there will be an increasing need for dissimilar materials joining. Thus, it is very likely that the use of FSW/FSSW will increase every day in the future to achieve hybrid structures involving multiple alloys traditionally thought of as difficult or impossible to join. However, there is still a need for further work to optimize the joint performance of FSWed/FSSWed dissimilar Al-alloys joints.

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