Experimental Study on Manufacturing of Tailor Friction Stir Welded Aluminium Blanks

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Abstract: Today, in sheet metal forming processes, a new concept of fabricating consolidated sheets or in other words Tailor Welded Blanks emerged. Friction Stir Welding is one method for manufacturing TWBs and has numerous advantages over fusion welding methods for joining aluminum sheets. In the present study, TWBs made by friction stir welding of 6061-T6 and 5754-O aluminum alloys were studied. The effects of different tool rotational speeds and welding speeds on the mechanical properties and microstructural characteristics of dissimilar joints were evaluated. The results showed that in an appropriate range of speeds combinations, an optimum rotational speed exists at which maximum strength is achieved. Regarding welding speed, greater strength is attained at higher speeds. The microstructural analysis confirms that an increase in welding speed will result in grain size reduction and consequently higher tensile strength. It is observed that above the optimum rotational speed, the grain size of the nugget zone increases which results in decreasing tensile strength. With regard to elongation, it is found that despite the grain growth of the nugget zone at a higher ratio of tool rotational speed to welding speed, the elongation improved due to the dominant material existing in the weld zone. Positioning Al 6061 on the advancing side of the dissimilar joints leads to improved mechanical properties compared with positioning on the retreating side. It is notable that the degree of such improvement in ductility is much more remarkable than strength, which is valuable regarding formability concerns.

Keywords: Dissimilar Friction Stir Welding, Rotational Speed, Tailor Welded Blank, Welding Speed

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1 INTRODUCTION

Tailor Welded Blanks (TWB) as a novel solution to reduce vehicle weight and manufacturing costs and improve product performance, are widely extended in car body manufacturing section [1]. Making TWBs always is a critical subject concerning appropriate joining method. Fusion welding methods have been proven that are not capable of joining some materials or it may be too hard. In practice, fusion welding for joining aluminum alloys is relatively hard and produces many kinds of defects in the weld zone which results in a drastic decrease in mechanical properties [2]. So Friction Stir Welding (FSW) as a recent and remarkable development in welding techniques has solved these problems due to the solid-state nature of the process [3]. FSW invented by TWI [4] possesses high capability of joining dissimilar alloys and exhibits superior mechanical properties of joint with respect to base materials. FSW process is of much interest for joining aluminum to copper alloys [5, 6]. Regarding dissimilar weld of aluminum alloys, Al 5083 to Al 6082 was joined by Peel et al. [7]. FSW of aluminum to magnesium alloys, e.g. Al 6061 to AZ31B alloy is also investigated by Fu et al. [8]. Because of such technical and economic reasons, nowadays, shipbuilding, aerospace and automotive industries widely use FSW to make sensitive components [9-10].

From the beginning, FSW of dissimilar Al alloys has made researchers proceeding extensive studies because of potential engineering importance and problems associated with conventional welding concerning dissimilar welds [11]. But up to now, a few researches were done in dissimilar FSW of the most common Al alloys specifically applied in automotive and marine industries, i.e., 5xxx and 6xxx series which includes joining Al 5086 to Al 6061 [12], Al 5083 to Al 6082 [13], Al 5182 to Al 6016 [14], Al 5083 to Al 6351 [15], Al 5083 to Al 6061 [16] and Al 5182 to Al 6022 and Al 5754 to Al 6022 [17].

In general, for dissimilar FSW as well as similar one, process parameters play a decisive role in welding quality and improving mechanical properties of the weld. Appropriate tool rotational speed, welding speed and tool design are the most important factors in proper feasibility of the FSW process. Until now a few investigators have focused on the effects of mentioned parameters on mechanical properties of dissimilar FSW of 5xxx and 6xxx Al alloys. Miles et al. [17] investigated the elongation of friction stir welded joint of these alloy pairs: Al 5754 to Al 5182, Al 5182 to Al 6022 and Al 5754 to Al 6022. The results showed that total elongation is a function of the weakest alloy in the welded pair. It was shown that Al 6022 sheet welded to either Al 5182 or Al 5754 does not have significantly less ductility than similar FSW joints of Al 5754 and Al 6022, but FSW joint of Al 5182 to Al 5754 showed relatively worse elongation than similar welds of both alloys.

Leitao et al. [14] studied the mechanical behavior of similar and dissimilar FSW of Al 5182-H111 and Al 6016-T4. It was found that dissimilar welds exhibit no significant decrease in hardness, and also strength efficiency is about 90%. However, the weld showed much decrease in ductility relative to the base materials.

Palanivel et al. [15] assessed the effect of three different tool rotational speeds of 600, 950 and 1300 rpm on tensile strength of dissimilar FSW of Al 5083-H111 and Al 6351-T6. It was observed that the joint welded at a rotational speed of 950 rpm leads to highest strength, due to variation in material flow behavior, loss of cold work in the HAZ of Al 5083 and dissolution and over the aging of precipitates of 6351 Al alloy.

Aval et al. [12] examined the microstructure and mechanical properties of dissimilar FSW joints of Al 5086-O and Al 6061-T6 produced at various tool rotational and welding speeds. The results of tensile tests showed that the mechanical properties of welded samples are more similar to Al 5086 base material and also the tensile strength of the joints in which Al 6061 was placed on advancing side was slightly higher than that of Al 6061 was placed on the retreating side. Ghaffarpour et al. [16] investigated the effect of tool rotational and welding speed on the tensile strength and formability of dissimilar FSW joints of 6061-T6 and 5083-H12 Al alloys. It was found that rotational speed has greater influence than the other parameters on the tensile strength of the TWB sheets.

The effect of material location on mechanical properties of dissimilar joints was also investigated by Karlsson et al. [18]. It was shown that locating Al 6082 on advancing side results in a relatively stronger weld with respect to placing Al 5083 on there. Also, Park et al. [19] examined the effect of alloy location in dissimilar FSW of 5052-H32 and 6061-T6. The results showed that the dominant material in the weld zone was 5052 and also all samples fractured at the HAZ of the 5052, with the lowest hardness value at HAZ, for both material arrangements.

Al 5754–O and Al 6061-T6 alloys are commonly used in car components and also specified for shipbuilding applications [20].

Hence, TWBs of such materials may be of interest to such applications, not only for having a good combination of strength and formability [21] but also due to superior corrosion resistance at elevated temperatures [20]. To the best of author's knowledge, there exists no research on dissimilar FSW of these two alloys until now. In the present study, the mechanical properties of the dissimilar FSW of Al 5754-O to Al 6061-T6 are considered and weld strength and ductility are compared with similar FSW. In the current extensively study, the effects of various combinations of tool rotational and welding speeds on the mechanical properties and microstructural characteristics of dissimilar FSW joints have been studied. For the first time the effect of alloy location on strength and ductility of the dissimilar joints is also assessed.

2 EXPERIMENTAL PROCEDURE

The chemical composition and hardness value of Al 6061-T6 and Al 5754-O alloys are shown in “Table 1”. Samples in dimensions 200 mm × 110 mm (7.87 in. × 4.33 in.) were cut from the 1.5 mm (0.06 in.) thick sheets of both alloys. The FSW tool made from H13 steel was hardened up to 50 RC by nitriding process. The tool shoulder diameter, pin diameter and pin length were, respectively, 12 mm (0.47 in.), 3 mm (0.12 in.) and 1.3 mm (0.05 in.). Also after some trials, the resulting shoulder plunge depth was maintained at a constant value of 0.1 mm (0.004 in.) to make sure appropriate penetration of tool pin and reducing excessive flash. The FSW process was performed by an improved numerical control milling machine. The tool is adjusted perpendicular to the work piece at zero tilt angle. The MO40 steel alloy with a thickness of 20 mm (0.79 in.) was used as a backing plate.

Table 1 Chemical composition of 6061-T6 and 5754-O aluminum alloy (wt%)

Alloy	Cu	Mg	Si	Fe	Mn	Ti	Cr	Sb	V	Al	Other elements
6061-T6	0.19	0.99	0.49	0.57	0.07	0.04	0.24	0.03	0.01	Bal	<0.02
5754-O	0.07	3.03	0.07	0.38	0.16	0.02	0.08	0.02	0.01	Bal	<0.02

The specimens from each alloy were prepared for the tensile test according to ASTM-E8 standard. The tensile tests were performed on the universal tensile test machine with a cross speed of 1 mm/min (0.04 in./min). The results are presented in “Table 2”.

Table 2 Mechanical properties of base materials

Alloy	0.2 Pct Yield, MPa	UTS, MPa	Elongation, % (50 mm (1.97 in.) gage length)	Hardness, Vickers
6061-T6	255	276.3	6.39	90
5754-O	100-110	216	18.1	68

Due to variations in metallurgical behavior of weld zone from advancing side (AS) to retreating side (RS) of weld centerline, the weld zone exhibits different mechanical properties from AS to RS. For example a rapid reduction in hardness and yield strength of Al 5083 weld material at the AS with respect to the RS was reported by Rao et al. [22]. Also the mechanical properties of the weld zone were different from AS to RS described by Lee et al. [23] due to the weld zone mainly composed of the material placed on RS. In dissimilar FSW, some researchers suggest that softer material should be placed on the AS. For example, a better intermixing of both materials in the weld zone and higher yield strength of the weld was obtained when Al 5086-O (lower strength than Al 6061-T6) was positioned at AS [12]. In the current study, based on mentioned researches, the stronger material, i.e. Al 6061 was placed on RS of the joint. Figure 1 depicts the characteristics of such dissimilar FSW process. The rolling direction of the base sheets was perpendicular to the welding direction.

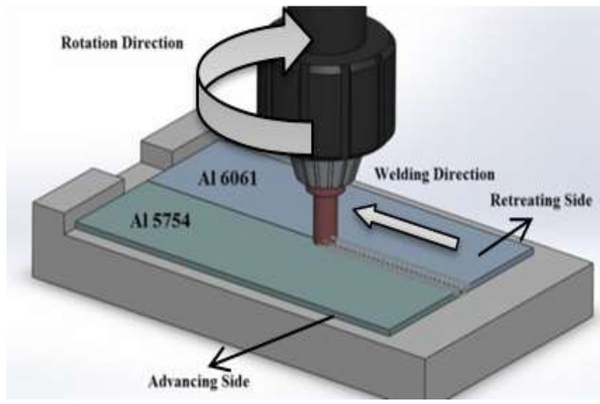


Fig. 1 Schematic view of conducted dissimilar Friction Stir Welding.

Based on the full factorial design of experiments, 36 dissimilar FSW experiments in various welding conditions have been performed. As shown in “Fig. 2”, the welding speed and tool rotational speed were selected between 25 mm/min (0.98 in./min) to 400 mm/min (15.75 in./min) and 400 rpm to 2500 rpm respectively.

Rotational speed, rpm

Welding speed, mm/min	400	800	1000	1600	2000	2500
25	×	×	×	×	×	×
63	×	✓	✓	✓	×	×
100	×	✓	✓	✓	×	×
160	×	✓	✓	✓	×	×
250	×	×	×	×	×	×
400	×	×	×	×	×	×

Fig. 2 Welding performance of dissimilar FSW joints at various FSW parameters.

The welded joints were visually inspected in terms of surface quality and macroscopic defects. The internal defects were considered by investigation of the weld cross section. The mechanical evaluation of the defect-free joints was performed using the tensile test. In order to eliminate the effect of weld thinning and consequently stress concentration, the surface of the obtained tensile samples was uniformly paper sanded.

To perform the tensile test, the samples were prepared according to the ASTM-E8 standard. The root bending test was carried out for experiments to make certain that perfect joints were produced at the selected speeds combinations.

Moreover, the effect of alloy location on mechanical properties and also on macro and microstructure characteristics of the weld zone were examined by establishing dissimilar joints at a rotational speed of 800 rpm and welding speeds of 63, 100 and 160 mm/min.

Besides the mechanical evaluation, the metallurgical investigation of the dissimilar FSW joints has been done. The transverse cross section of the welds was prepared, polished and then the samples were etched.The microstructure of the joints was revealed by an etchant of modified Poulton's reagent contains 50 mL Poulton's reagent (30 mL HCL, 15 mL HNO_3, 2.5 mL HF, 2.5 mL H_2O) + 25 mL HNO_3 + 40 mL of the solution of 3 g chromic acid per 10 mL of H_2O. (“Fig. 3”)

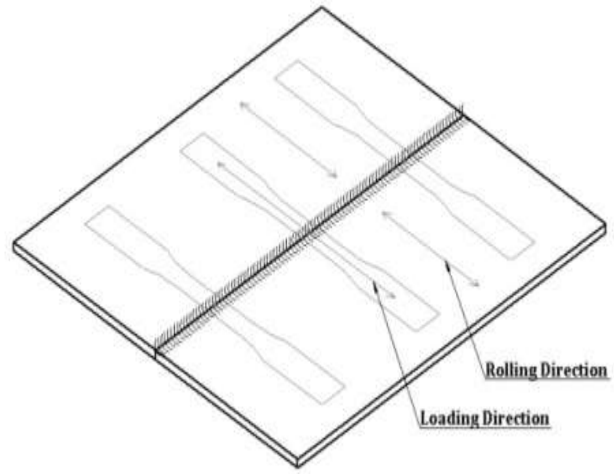


Fig. 3 Prepared tensile specimens according to the ASTM-E8 standard.

Fig. 4 Defected joint at unsuitable speeds combination.

3 RESULTS

Examination of the welded joints at welding speed below 63 mm/min (2.48 in./min) and the tool rotational speed above 1600 rpm showed that due to excessive material overflow around the tool and material over-heating, the flash defect at the weld surface appeared.

At welding speeds above 160 mm/min (6.3 in./min) and tool rotational speed below 800 rpm, insufficient material flow and little amount of generated heat input, resulted in improper material filling of the region behind the tool. The mentioned reason led to producing defects/voids and joint line remnant in the weld zone. The typical improper selection of the welding parameters is shown in “Fig. 4”.

The tool rotational and welding speeds combinations were considered regarding the fact that by increasing welding speed, rotational speed should simultaneously increase to diminish any defects in the joint [24], and also knowing that increasing tool rotational speed or decrease of welding speed will lead to enhancement of the stirring effect which results in improving the welding quality [25].

The welding quality of the joints welded at accepted speeds combinations is shown in “Fig. 5”. The visually accepted welded joints were examined using root bending test. A typical of the root bending test at the welding speed and tool rotational speed of 160 mm/min (6.3 in./min) and 1000 rpm, respectively, is shown in “Fig. 6”. All of the samples exhibited adequate strength and ductility.

“Table 3” shows the results of tensile tests as well as failure location in dissimilar FSW joints produced at various combinations of tool rotational and welding speeds.

Regarding alloy location, as seen in “Fig. 7”, the welding joints show proper mixing in both situations (Al 6061 on AS or RS) in a selected range of speeds.

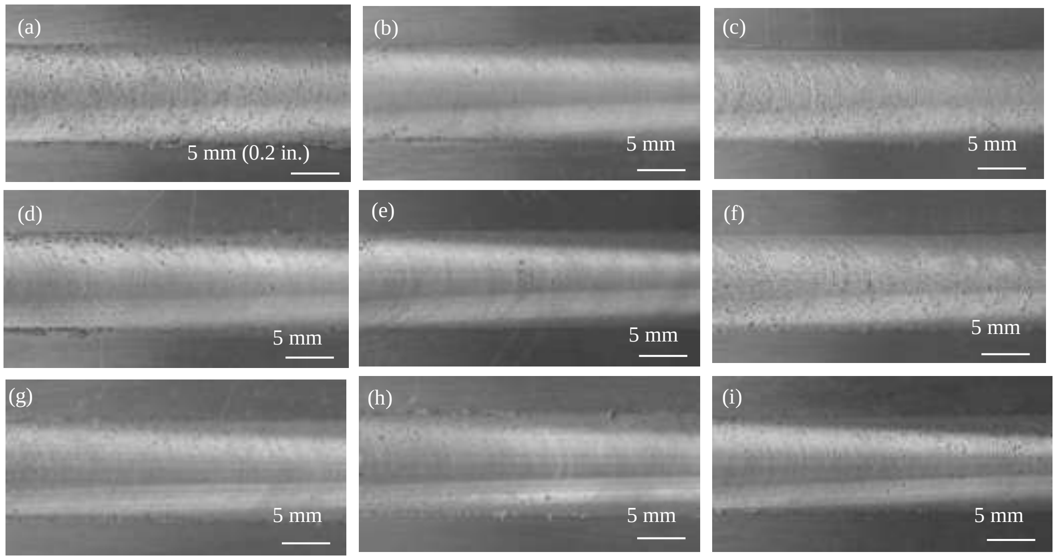


Fig. 5 Welding quality of dissimilar FSW joints at suitable combinations of tool rotational and welding speeds: (a): 800/63, (b): 800/100, (c): 800/160, (d): 1000/63, (e): 1000/100, (f): 1000/160, (g): 1600/63, (h): 1600/100 and (i): 1600/160.

Fig. 6 The typical root bending test of the dissimilar welds at the welding speed and tool rotational speed of 160 mm/min (6.3 in./min) and 1000 rpm, respectively.

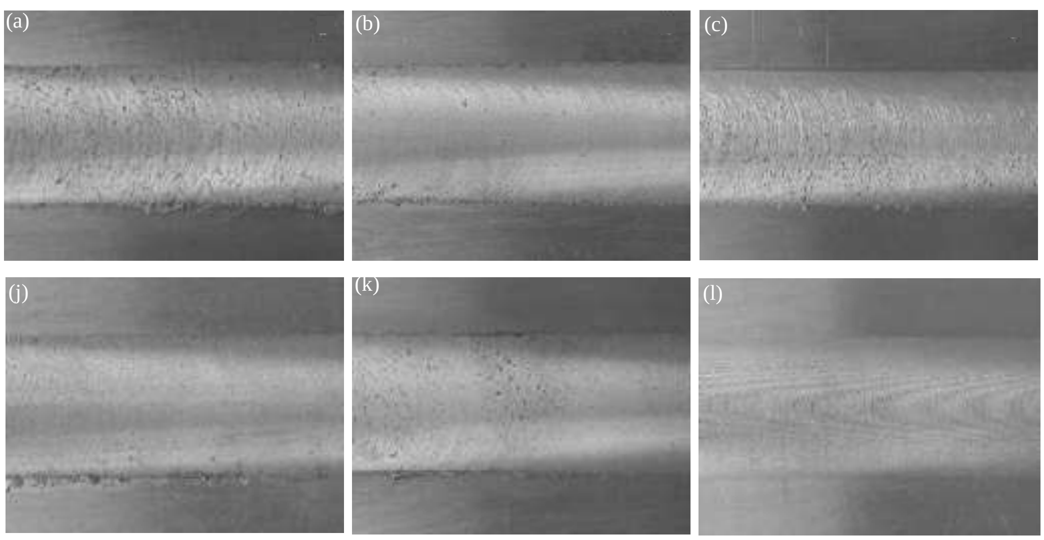


Fig. 7 Welding quality of dissimilar FSW at suitable combination of rotational and welding speeds – Al 5754 on advancing side: (a): 800/63, (b): 800/100, (c): 800/160, Al 6061 on advancing side, (j): 800/63, (k): 800/100 and (l): 800/160.

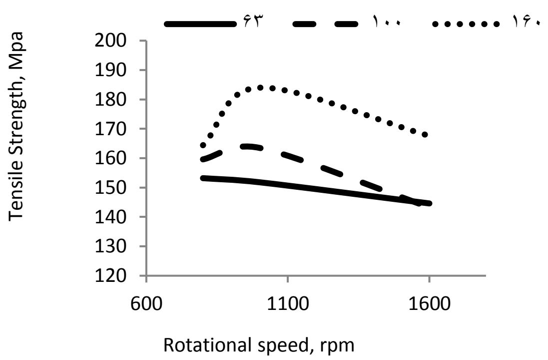
4 DISCUSSION

4.1. Mechanical Properties

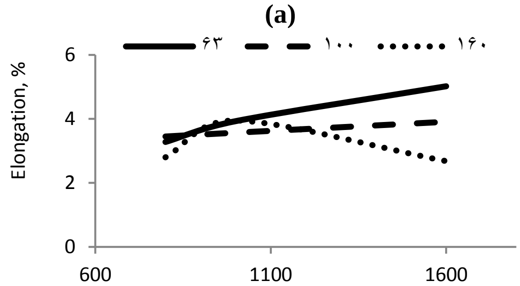
Most of the fracture locations were at HAZ of Al 6061 adjacent to TMAZ, and in some cases fracture occurred from weld nugget to TMAZ/HAZ of Al 6061, as seen in "Table 3". All joints elongated and fractured at Al 6061 side that indicates failure has occurred in the most softened zone in the weld. Figure 8 shows the trend of the tensile strength and elongation properties of dissimilar FSW joints versus rotational speed, individually.

Table 3 Average of tensile test results performed on dissimilar FSW joints at an appropriate range of tool rotational and welding speeds

Rotational Speed, rpm	Welding Speed, mm/min	UTS, Mpa	Elongation at fracture, % A-50 mm (1.97 in.)	Fracture location
800	63	153.2	3.28	HAZ 6061 adjacent to TMAZ
800	100	159.6	3.45	HAZ 6061 adjacent to TMAZ
800	160	164.4	2.93	HAZ 6061 adjacent to TMAZ
1000	63	151.8	3.93	HAZ 6061 adjacent to TMAZ
1000	100	163.5	3.57	Weld nugget extending to TMAZ 6061
1000	160	184	3.95	Weld nugget extending to TMAZ 6061
1600	63	144.6	5.02	HAZ 6061
1600	100	143.3	3.91	Weld nugget extending to TMAZ 6061
1600	160	167.6	2.68	HAZ 6061 adjacent to TMAZ



(a)



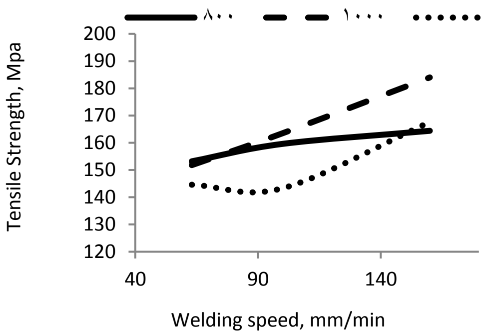
(b)

Fig. 8 (a): Tensile strength and (b): elongation property of joints versus tool rotational speed at three welding speeds of 63, 100 and 160 mm/min (6.3 in./min).

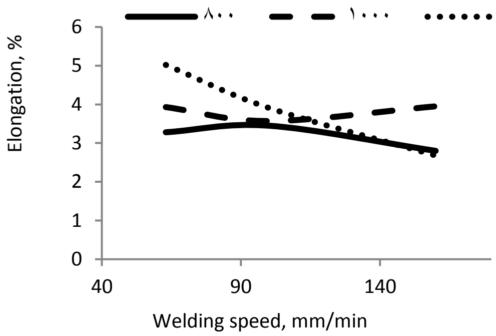
Insufficient material flow due to inadequate generated heat input happened while the rotational speed was selected below 800 rpm. Increasing rotational speed led to improve the tensile strength to a maximum value at a rotational speed of 1000 rpm. More increasing of the tool rotational speed causes the reduction of tensile strength. It may result that in higher tool rotational speed increasing the produced heat input as well as material flow occurred. Further increase in tool rotational speed produces excessive heat input. It was reported that when generated heat input is too high, changes in material flow, dissolution and over the aging of precipitates occur at the precipitation-hardenable Al alloy [15].

The higher tensile strength of dissimilar joints is obtained at a welding speed range of 63 to 160 mm/min (6.3 in./min). It was observed that by increasing the tool welding speed, the joint tensile strength improved.

Tensile strength and elongation behavior of the joints versus tool welding speed were demonstrated in "Fig. 9". As seen in "Fig. 9", the elongation property of the joint diminished by increasing the welding speed, except in the case of rotational speed of 1000 rpm. The high amount of elongation and also tensile strength, at this rotational speed may be related to the appropriate weld pitch (ratio of welding speed to rotational speed) at such speed combination. It must be noted that the joint with the lowest strength, 144.6 Mpa, i.e., 1600 rpm and 63 mm/min (2.48 in./min) has the highest elongation of 5.02 % which is fairly close to Al 6061 base material.



(a)



(b)

Fig. 9 (a): Tensile strength and (b): elongation property of joints versus welding speed at three tool rotational speeds of 800, 1000, and 1600 rpm.

4.2. Joint Efficiency

To evaluate the joint efficiency, the FSW process was implemented for similar materials i.e. Al 6061 to Al 6061 and Al 5754 to Al 5754. The joint efficiency is defined as the ratio of the joint strength to the strength of the base material [26]. The mechanical investigation revealed that the maximum joint efficiency for similar joints of Al 5754 Al and Al 6061 aluminum alloys were about 103% and 55%, respectively. For dissimilar joint of Al 6061 to Al 5754, the maximum attained joint efficiency was about 85%. The maximum joint efficiency for the dissimilar joint was reached in welding speed of 160 mm/min (6.3 in./min) and tool rotational speed of 1000 rpm.

The mechanical properties of a typical similar and dissimilar welded joint are also depicted in "Fig. 10".

It was found that, though, the tensile strength and ductility of the dissimilar joint are lower than both base materials, the related values of the dissimilar joint are greater than Al 6061 similar joint. As found in "Fig. 10a", a slight increase in tensile strength is observed in similar Al 5754 joint compared with the tensile strength of Al 5754 base material. In other words, the tensile strength of 5xxx Al alloys (in annealed condition) has improved when the welding process was applied, as mentioned in earlier studies.

For example, a significant increase in yield stress of welded Al 5182-H111 was shown by Leitao et al. [14]. A similar report demonstrated that TMAZ of the weld has at least equal mechanical properties relative to the base material of Al 5083 H111 and Al 5182 H111 [27]. In fact, in non-heat treatable Al alloys (e.g. 5xxx) mechanical properties of weld joint depend on the density of dislocations after plastic deformation and recrystallized structure appears during welding process [28]. It was shown that in both similar joints of Al 5754 and Al 5182, homogeneous dynamic recrystallization occurred and also no softened HAZ was revealed [29].

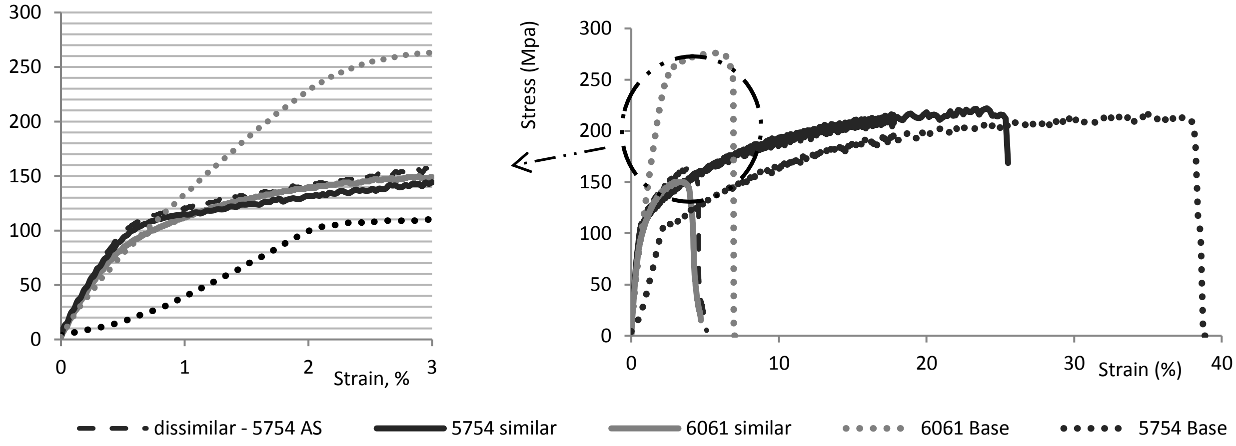
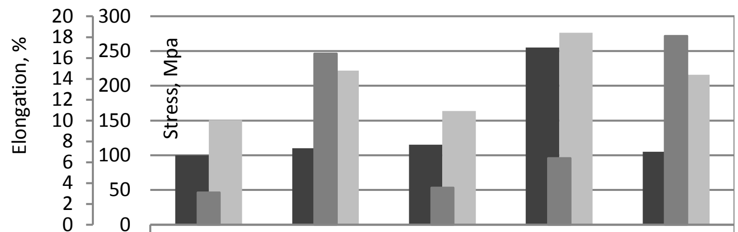


Fig. 10 The mechanical properties of the similar FSW joints at tool rotational speed of 1000 rpm and welding speed of 100 mm/min (3.94 in./min): (a): tensile strength and (b): 0.2% yield strength point.

A significant reduction in grain size and residual work hardening resulted in a slight increase in mechanical properties of Al 5182-O similar joint that has been reported by Miles et al. [30]. With regard to Al 6061 similar joint, as indicated in previous studies, in heat treatable Al alloys (e.g. 6xxx), FSW produces a softened region in TMAZ or HAZ, so tensile strength of welded joint decreases due to the dissolution and coarsening of strengthening precipitates during thermal processing. These observations were proceeded by Cabbibo et al. [31] in terms of over aging of precipitates at TMAZ of both AS and RS sides of Al 6056 weld and also explained by Leitao et al. [14] in the viewpoint of localization of plastic flow in weakest TMAZ. The current study also focuses on the yield strength of the joints and base alloys. "Fig. 10b" presents a scaled view of the stress-strain curves. As seen in "Fig. 10b", it is interesting that the 0.2% yield stress point of the specified dissimilar joint is relatively upper than the similar joints of both alloys. A comparison of strength and elongation between similar and dissimilar joints and base alloys, conducted at 1000 rpm and 100 mm/min (3.94 in./min), is outlined in "Fig. 11".

Also, 0.2% yield strength of the dissimilar joints, at different speeds combinations, can be deduced from stress-strain curves illustrated in "Fig. 12". It seems that despite the lower tensile strength of the joints welded at 1600 rpm compared with 800 rpm, the pertinent values of yield strength are noticeably greater.



	Similar 6061	Similar 5754	Dissimilar	6061 Base	5754 Base
0.2 Pct Yield (Mpa)	100	110	115	255	105
UTS (Mpa)	150.5	222	163.5	276.3	216
Elongation at Fracture %	3.1	16.42	3.57	6.39	18.1

Fig. 11 Mechanical properties of the base alloys, similar and dissimilar joints, at 1000 rpm, 100 mm/min (3.94 in./min).

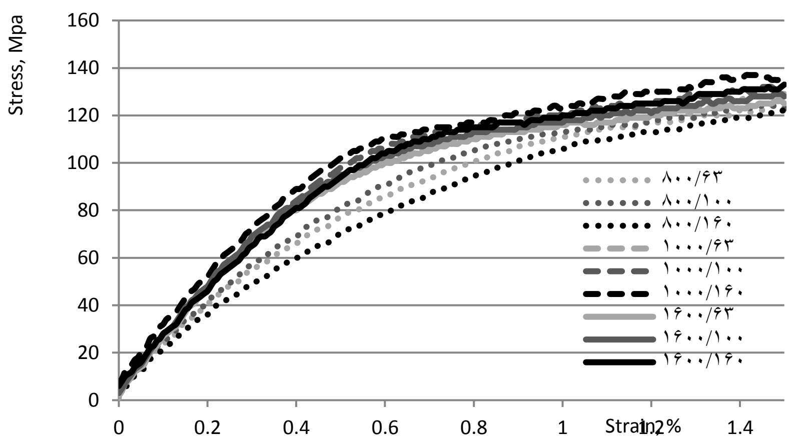


Fig. 12 Comparison of yield strength of dissimilar FSW joints at various speeds combinations.

4.3. Macro and Microstructure Characteristics

Macrostructure view of the dissimilar FSW joints at selected rotational and welding speeds is gathered in "Fig. 13". The joints exhibited proper mixing of both materials and revealed the defect-free joints. As seen in "Fig. 13", a distinct boundary between two alloys is observed. When the welding speed exceeds 100 mm/min (3.94 in./min), the shape of the nugget zone was changed. Considering the strength of the joints ("Fig. 9") and mixed boundary shown in "Fig. 13", it can be concluded that the mechanical interlock between two materials may result in increasing the joint strength at above 100 mm/min (3.94 in./min). In the welded joints at the higher tool rotational speed, i.e. 1600 rpm (see "Fig. 13"), it was found that the nugget shape is relatively different from the nugget shape of the obtained joints at lower tool rotational speeds. Also in the joint welded at tool rotational speed of 1600 rpm, the material flow of Al 6061 is evidently observed in both sides of the weld nugget.

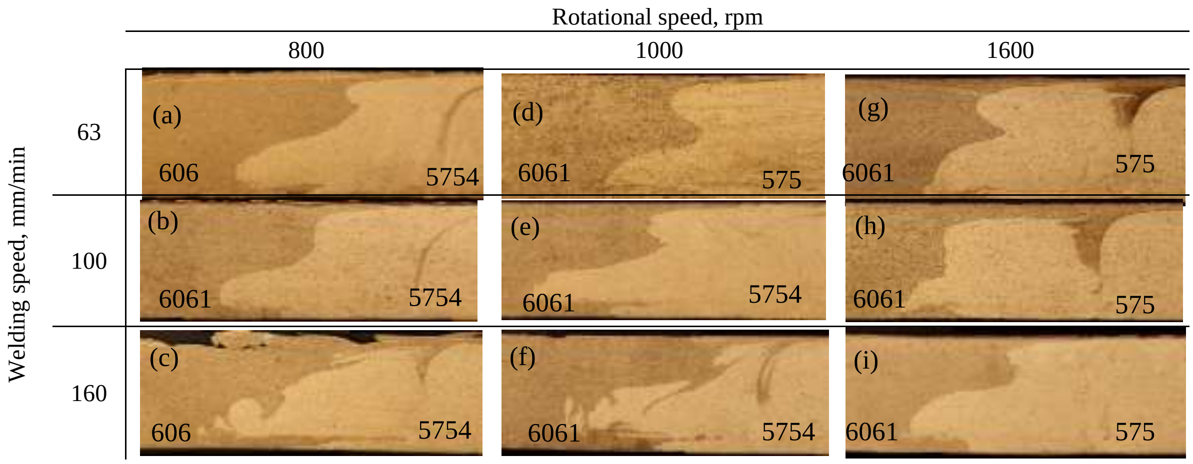


Fig. 13 Optical macrographs showing the cross section of the dissimilar FSW joints at various speed combinations etched by Modified Poulton's reagent– Advancing side on the right.

As shown in "Fig. 13", at the tool rotational speed of 1600 rpm, the weld zone dominantly consists of Al 5754. As regards the greater ductility of Al 5754 base material than Al 6061, the above mentioned reason can justify the improved ductility of the joint at such tool rotational speed, as resulting from tensile tests (see "Table 3"). Figure 14 shows the macrographic view of dissimilar joints at various welding conditions.

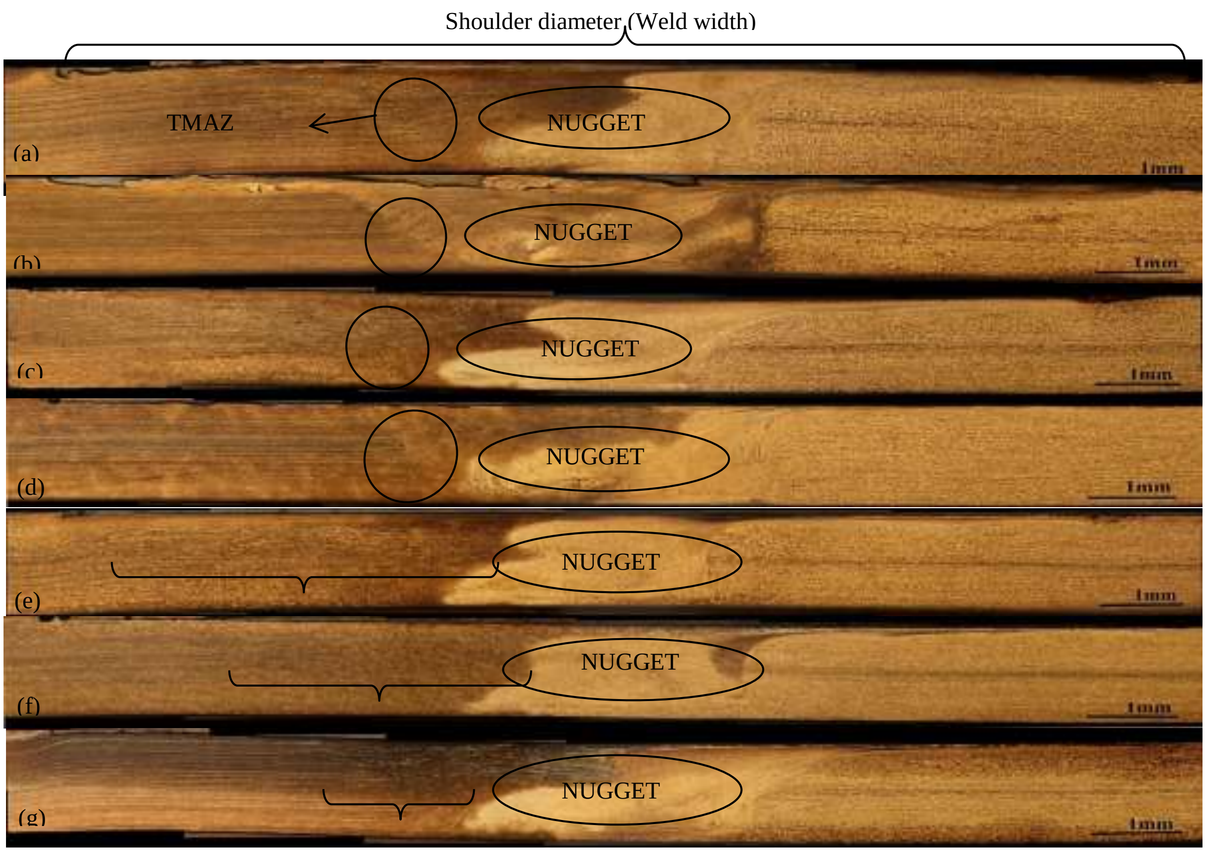


Fig. 14 Optical macrographs showing the weld zone of the dissimilar FSW joints at various speed combinations etched by modified Poulton's reagent with magnification of 50 times– Al 5754 on the right: (a): 800/63, (b): 800/160, (c): 1000/63, (d): 1000/160, (e): 1600/63, (f): 1600/100 and (g): 1600/160.

Considering previous studies on FSW, the fine-grain structure was produced in Al 6061-T6 similar welds [32] and dissimilar FSW of Al 5083 and Al 5059 [33] and also in dissimilar joints of Al 5182 and Al 6016 [14]. In “Figs. 14-16”, the fine grain structure can be seen as a result of severe plastic deformation occurred during the FSW process. Considering “Fig. 14a and b, and Fig 14c and d”, it was revealed that by increasing the welding speed from 63 to 160 mm/min (6.3 in./min), an abrupt change in material flow from HAZ to nugget zone (in TMAZ) on retreating side occurs. It indicates that when welding speed raises, the generated heat input is not enough to affect the adjacent material around the tool pin, hence not being well flowed.

More considering on “Fig. 14e-g”, appeared that decreasing the weld pitch _i.e. the increasing ratio of tool rotational speed to welding speed_ leads to a wide disturbance in rolling lines in HAZ, particularly on the retreating side. This behavior is related to the more generated heat input at higher tool rotational speed. Such fluctuation in material flow is much more considerable at lower welding speed (as seen in “Fig. 14e”). The lowest value of tensile strength of the joint welded at speeds combination of 1600 rpm and 63 mm/min (2.48 in./min), may correspond to such wide softened zone in HAZ due to the more produced heat input. Hence, the fracture location at the HAZ of Al 6061 occurred distant from the TMAZ and weld nugget.

According to “Fig. 15”, in dissimilar joints by increasing welding speed, the grain size in TMAZ and nugget zone reduces when the tool rotational speed was kept constant at 1000 rpm. As expected, the reduction in grain size results in improving the tensile strength as well as the elongation property (as listed in Table 3).

Fig. 15 Optical micrographs showing TMAZ, HAZ and nugget zone on advancing side of the dissimilar joints welded at 1000 rpm and different welding speeds: (a): 63 mm/min (2.48 in./min), (b): 100 mm/min (3.94 in./min) and (c): 160 mm/min (6.3 in./min), with a magnification of 100 times.

In “Fig. 16”, the grain size of the nugget zone and TMAZ is compared with the adjacent region (HAZ) at two tool rotational speeds of 800 and 1600 rpm at a constant welding speed of 63 mm/min (2.48 in./min). The grain size of the nugget zone increased at higher tool rotational speed due to the more generated heat input as found by Mishra and Ma [11].

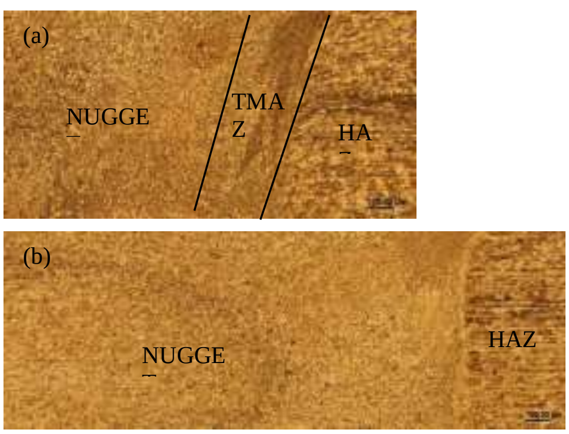


Fig. 16 Comparison of grain size between nugget and adjacent zones on advancing side: (a): 800 rpm, 63 mm/min (2.48 in./min) and (b): 1600 rpm, 63 mm/min (2.48 in./min), with magnification of 50 times.

It was expected that higher grain size results in diminishing the elongation property. Nevertheless, in the obtained sample welded at higher tool rotational speed i. e. 1600 rpm, the joint exhibited improved elongation. This occurrence may be related to the presence of the dominant material in the weld zone (i.e. Al 5754 with the much higher elongation property than Al 6061), which governs the mechanical properties of the joint (particularly in elongation) at such speeds combination. Such influence may be accompanied by the aforementioned great variation in material flow, demonstrated in “Fig. 14e and f”.

“Table 4” shows the results of changing the location of alloys in ultimate tensile strength, elongation and fracture location of welded joints at a range of welding speed with a constant amount of rotational speed. As seen in “Table 4”, most of the fracture locations happened at HAZ of Al 6061 adjacent to TMAZ, and in some cases cracked in weld nugget and then extended to TMAZ/HAZ of Al 6061. All joints elongated and fractured at Al 6061 side that indicates failure occurs in the most softened zone in Al 6061 side which accompanied by strain localization. Even at 800 rpm, 63 mm/min (Al 6061 on advancing side) that the joint elongated in Al 6061 side, eventually fractured at the weld center.

Regarding different arrangements of alloy location, it was revealed when Al 6061 was placed on advancing side, yield and tensile strength, and also elongations are better than Al 6061 placed on the retreating side, illustrated in "Figs. 17-19" and "Table 4".

Table 4 The average of tensile test results of dissimilar FSW joints in different alloy locations (at selected speeds combinations)

		Al 5754 on Advancing side			Al 6061 on Advancing side		
Rotational Speed (rpm)	Welding Speed (mm/min)	UTS (Mpa)	Elongation at fracture (%) A-50 mm	Fracture location	UTS (Mpa)	Elongation at fracture (%) A-50 mm	Fracture location
800	63	153.2	3.28	HAZ 6061 adjacent to TMAZ	158.2	3.62	Weld center
800	100	159.6	3.45	HAZ 6061 adjacent to TMAZ	165.5	4.22	HAZ 6061 adjacent to TMAZ
800	160	164.4	2.93	HAZ 6061 adjacent to TMAZ	171.7	4.31	Weld center extending to HAZ 6061

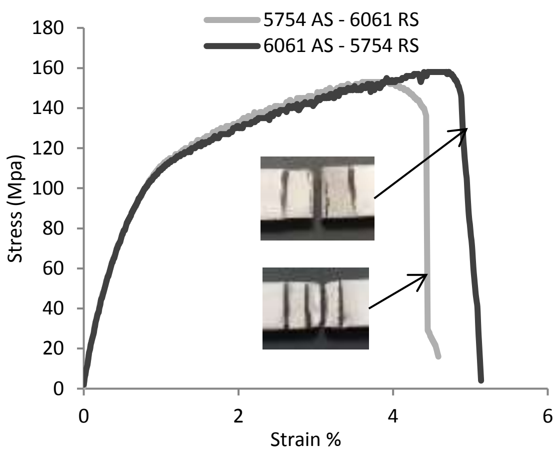


Fig. 17 Stress-strain curve of dissimilar FSW joints in two situations at 800 rpm, 63 mm/min – advancing side (AS) on the left.

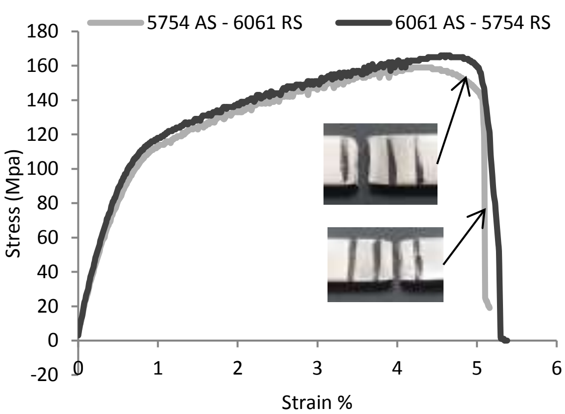


Fig. 18 Stress-strain curve of dissimilar FSW joints in two situations at 800 rpm, 100 mm/min - advancing side (AS) on the left.

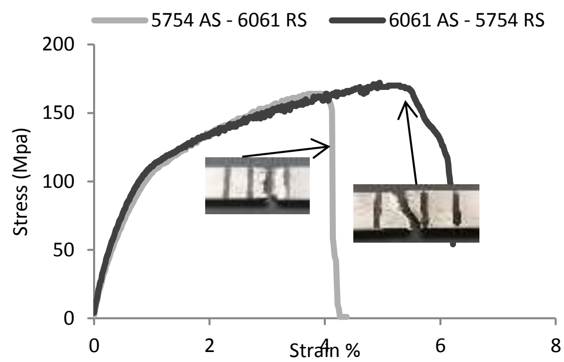


Fig. 19 Stress-strain curve of dissimilar FSW joints in two situations at 800 rpm, 160 mm/min - advancing side (AS) on the left.

Furthermore, it is interesting that when the 6061 was positioned on the advancing side, the joints exhibited better ductility at higher welding speeds compared with the related value of 6061 on the retreating side. Also the macro view and microstructure of weld zones in dissimilar joints at two different locations of alloys are demonstrated in "Fig. 20". It is apparent that the shape of mixing both alloys is completely different between two situations and also positioning Al 5754 on retreating side of the joint produces broader fine grain zone, more extended to the advancing side. That may be a reason for the relatively higher mechanical properties of the joint in this situation. As seen, TMAZ in both situations is confined to a narrow zone and has entirely a sharp boundary on advancing side, as opposed to a wider zone on retreating side that is unevenly distributed and has a diffuse boundary. It is remarkable that the HAZ of the advancing side is more constricted where Al 5754 is positioned on the retreating side. The fracture location shows failure in the softened zone on Al 6061 side in both situations.

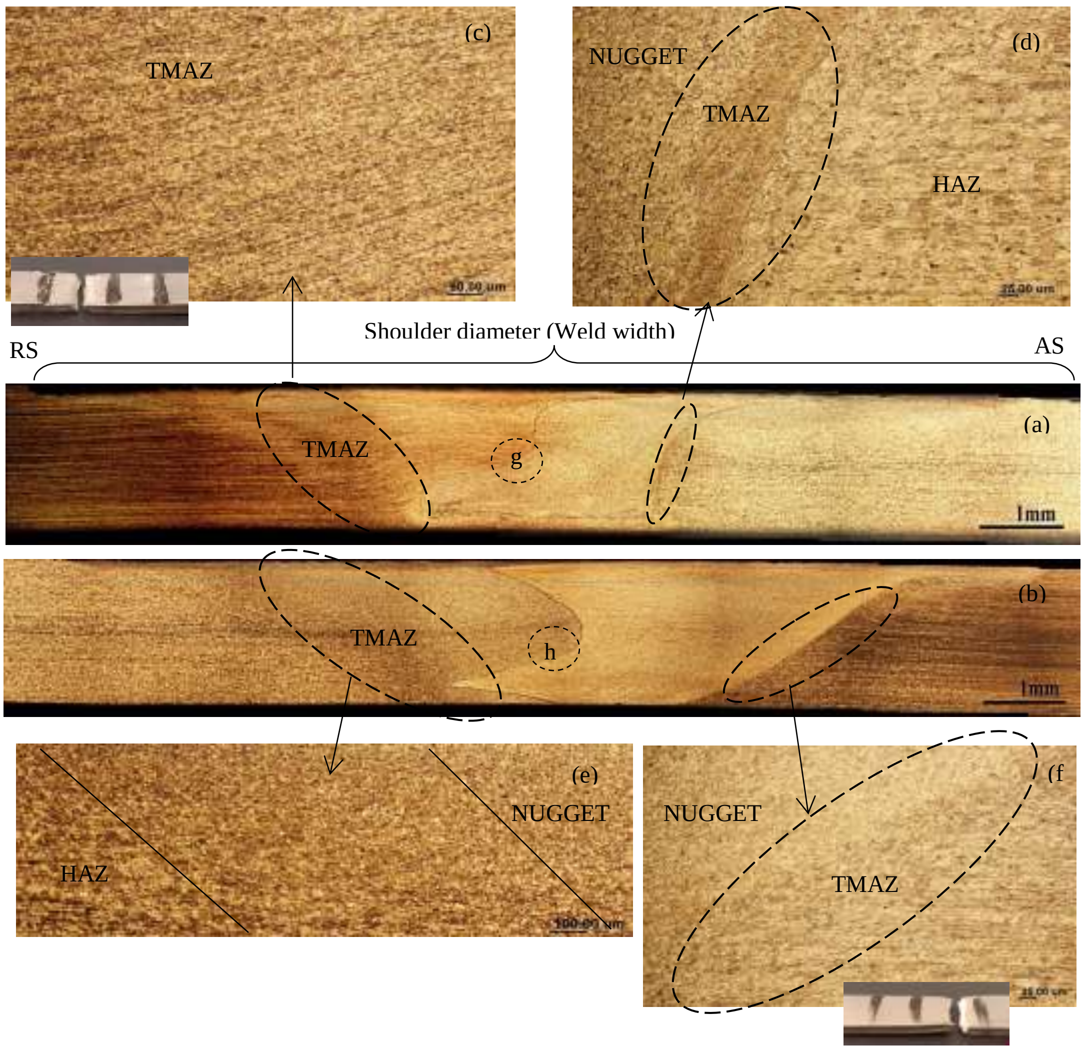


Fig. 20 Optical macro and micrographs showing weld zones of dissimilar FSW joints at 800 rpm and 100 mm/min, in two different alloy locations: (a): Al 5754 on advancing side (AS), (b): Al 5754 on retreating side (RS), ((a) and (b)): with magnification of 50 times, (c): 100 times, (d): 200 times, (e): 50 times and (f): 200 times.

Figure 21 shows the boundary between two alloys in the nugget zone in two situations. It seems the size of recrystallized grains is the same between two alloys and between two situations, as well.

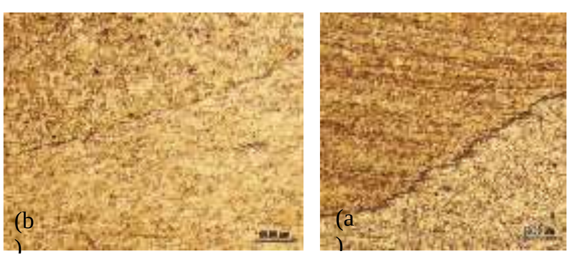


Fig. 21 The boundary between two alloys in weld nugget: (a): point g and (b): point h, in Fig 20, with a magnification of 100 times.

5 CONCLUSION

1. It was concluded that dissimilar joints were satisfactorily performed at selected tool rotational and welding speeds, having acceptable mechanical properties. In some cases, the elongation and tensile strength value were to some extent close to Al 6061 and Al 5754 base alloy, respectively.
2. In comparison with similar joints, at specified speeds combination, a higher amount of tensile strength and elongation of the dissimilar joint relative to similar Al 6061 were obtained. It is interesting that the yield strength of the dissimilar joint is slightly higher than similar FSW joints of both alloys and Al 5754 base alloy, as well.

3. In dissimilar FSW joints, increasing rotational speed results in improving the tensile strength up to the maximum value, but further increase in speed causes strength to decrease.
4. Despite the fact that in TWBs, strain deformation predominantly occurs in thinner or weaker sheet, but in dissimilar FSW of Al 6061 and Al 5754 alloys, the joints elongated at Al 6061 side (stronger material) and subsequently the fracture occurred in there, due to the softened HAZ/TMAZ that appears in Al 6061 side of the joint during FSW thermal cycle.
5. The joint efficiency of both Al 6061 and Al 5754 similar joints at 1000 rpm, 100 mm/min (3.94 in./min) are around 55% and 103% respectively. Also the maximum joint efficiency of about 85% was achieved in the dissimilar joint at speed combination of 1000 rpm, 160 mm/min (6.3 in./min).
6. Macro and micrographic analysis of the dissimilar joints at various speeds combinations implies that finer grain size of nugget zone was acquired at higher welding speed and lower tool rotational speed.
7. In spite of the lowest amount of tensile strength of the joint welded at a high ratio of tool rotational speed to welding speed, the elongation remarkably improved, because of the dominant material existing in the weld zone at such speeds combination.
8. Evaluating the effect of different alloy locations on mechanical properties of dissimilar joint shows moderately higher amount of strength and elongation where Al 6061 was placed on the advancing side. Nevertheless, the fracture locations are more inclined to the weld center in this situation relative to the joints that Al 6061 was on the retreating side.
9. Considering the results of other studies [12] shows when the 5xxx Al alloy is in work-hardened condition, locating these alloys on the retreating side will not produce higher mechanical properties than placing on advancing side. But our results show when 5xxx is in the annealed condition, the mechanical properties increase in the same alloy location.
10. Macro and micrographs of the dissimilar joints at various speeds implies that finer grain size of nugget zone was obtained at higher welding speeds. And also wider fine recrystallized zone was revealed when Al 6061 was placed on the advancing side.
11. At speeds combinations of 800 rpm with 63, 100, and 160 mm/min, the percentage of increase in mechanical properties where Al 6061 is placed on advancing side, is about 3.3, 3.7, and 4.4 % for tensile strength and 10.4, 22.3, and 47.1 % for elongation, respectively. Such a significant rise in elongation, much more than strength, highlights its desirability for making TWBs regarding formability concern.

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