

# Influence of Tool Offset Distance on Microstructure and Mechanical Properties of the Dissimilar AA2024–AA7075 Plates Joined by Friction Stir Welding

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**Abstract:** In the present study, the effect of tool offset on microstructure and mechanical properties of dissimilar friction stir welding of Al2024 and Al7075 alloys were investigated. In this regard, base metals were welded by FSW under different tool offsetting conditions, 1.5 and 2 mm shifted into Al2024 and Al7075 alloys, respectively, in addition to constant rotation rates and traverse speeds named as 710 rpm and 28 mm/min respectively. The microstructure of different welding zones and fracture surface were investigated by an Optical Microscope (OM) and Scanning Electron Microscopy (SEM), respectively. The results showed that by tool offsetting from the weld center through Al2024, an onion-shaped area has been created and mixture happens completely. However, by tool off-setting towards Al7075, onion-shaped microstructure fails to be formed in the stirred area. From the results of the tensile test, it is presented that maximum tensile strength is obtained in samples with a tool offsetting into the Al7075. With 1.5 mm tool offsetting into Al2024, first, joint tensile strength increases by 22.2 % in comparison to non-offset condition, and then, with more tool offset as much as 2 mm, tensile strength decreases by 22.2 %. In addition, by tool offsetting towards Al7075 by 1.5 and 2 mm, joint tensile strength decreases by 4.5 and 28.5 %, respectively. It is also concluded that in the offset samples towards the 7075 alloy, the microhardness in the HAZ area decreased compared to the microhardness of the offsets samples towards the 2024 alloy. Finally, the best mechanical behavior and microstructural properties were obtained in the sample with the tool offset of about 1.5 mm towards the welded Al2024 base metal (70215 samples) alloy.

**Keywords:** Dissimilar Joint, Friction Stir Welding, Mechanical Properties, Tool Offset

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## 1 INTRODUCTION

High-strength heat-treatable 2024 and 7075 Aluminum alloys have extensive use in various industries, particularly aerospace and military industries, that is due to their unique characteristics [1-2]. AA7000 – series Aluminum alloys are frequently selected due to their high strength, meanwhile, 2000-series alloys are usually selected in cases where there is a need for high resistance to fatigue, as well as for high-temperature applications [2]. The dissimilar joint of Aluminum alloys is highly important in many engineering applications. The dissimilar joint of metals has problems and constraints as well, such as lack of proper joint of parts, low strength, and improper mechanical properties as well as unfavorable microstructure [3]. In recent decades, there is an incremental trend of the joint between such alloys using conventional methods of welding, such as Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW), Electron Beam Welding (EBW), and Laser Beam Welding (LBW) [4-6]. The common problem associated with fusion welding techniques for such alloys is the inability of welding on 2000 and 7000 series alloys, which are alloys with most applications. Therefore, there is a high appeal to use solid state welding techniques [7]. In this regard, solid state welding methods are known as a common method to join dissimilar metals, and due to their specific characteristics such as negligible distortion, particularly in high length values, lack of penetration of metals into fusion area, lack of gas absorption during the process and consequently, lack of porosity, lack of environmental pollution in comparison to fusion welding techniques, lack of spraying and insignificant values of residual stress created within the part, such methods are extensively used in aerial industries, naval architecture and automobile industries [8-9]. One of the advantages of using friction stir welding in comparison to fusion welding techniques is the ability to provide low input heat [10]. Therefore, a promising method to join Al alloys together is to control progress and spin velocity and confining the mixture of Al alloys [11]. Consequently, due to asymmetric nature and reaction among dissimilar Al alloys, it would be hard to reach a

proper and effective joint. One of the effective parameters on mechanical properties and the microstructure of the joints is the deviation of the tool from the welding line [12]. Movement of tools in the interface of the parts leads to mixing equal values of two metals in the welding zone, and that is one of the main reasons for degradation in mechanical properties and microstructure of the joints. Hence, by considering the deviation of tools relative to the main path of the cut, it is possible to change the ratio of mixture between two metals and intended alloys in the combination of welding area, which leads to change in mechanical strength and microstructure of the joint.

Today, in terms of the deviation of tools and its influence on mechanical and microstructural properties, studies have been conducted [12-14]. For example, Karimi et al. [15] in their study showed that by decreasing the offset of tools in friction stir welding of Al alloy to Carbon steel towards steel zone, the tensile strength of the joint also decreases. Also, they witnessed that maximum strength of the joint in 1mm of offset is visible using HSS tool. Yogang et al. [16] examined the effect of laser offset on the performance of penetration laser for Mg Alloy and steel, and they found out that in 0.4-0.8 mm range, by increasing laser offset, the tensile strength of the joint increases at the beginning, and then decreases. Since no study has been discovered regarding the effect of tool position relocation and its deviation from joint direction on mechanical as well as microstructural properties of dissimilar joint in friction stir welding of 2024 and 7075 Al alloys in scientific literature, it is necessary to conduct a sufficient research in order to reach favorable results so that it would be possible to improve the level of strength in joint and its microstructure, and finally this will determine the value of optimum deviation (positive and negative) to reach maximum mechanical and microstructural properties.

## 2 EXPERIMENTAL PROCEDUR

In this research, two sheets of Al2024-O and Al7075-H Aluminum alloys, with chemical analysis provided in “Table 1” were used as base metals.

**Table 1** The chemical composition of base metals used in this research

	Al	Si	Mg	Zn	Cu	Fe	Ti	Mn
Al2024-O	Bal.	0.5	1.8	0.25	4.9	0.5	0.15	0.9
Al7075-H	Bal.	0.4	2.9	6.1	2.0	0.5	0.2	0.3

Elemental analysis of base metals was measured using Quant meter apparatus (Model Foundry Master UV). In this study, Al2024-O and Al7075-H Al-based metals in 100×300mm sheets, and a certain thickness of 5mm

were used. The joining of base metals was conducted using Friction Stir Welding (FSW) method with butt joints using a German-made milling machine (Model: HAKRET 315). The FSW process was applied with

rotational speed of 600 rpm and welding speeds of 20 mm/min, in 5 pin locations in clockwise form. The pin used in this research was made of H13 steel and according to the schematic diagram provided in “Fig. 1”.

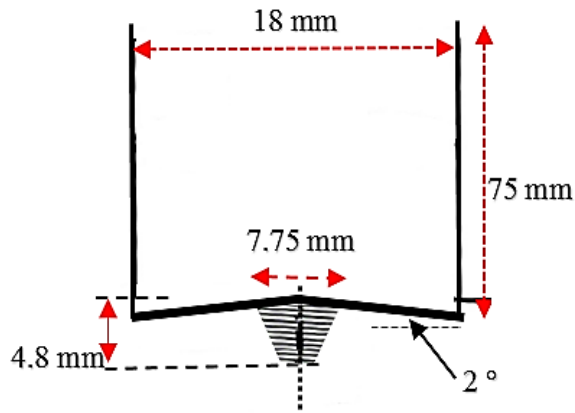


Fig. 1 Schematic of welding tool used in this research (dimension in mm).

In this research, Al2024 and Al7075 Aluminum alloys were in advanced and retreating side, respectively. Also, the position of the tool and the process of welding on samples are provided in “Fig. 2”. The parameters used in this research are also shown in “Table 2”.

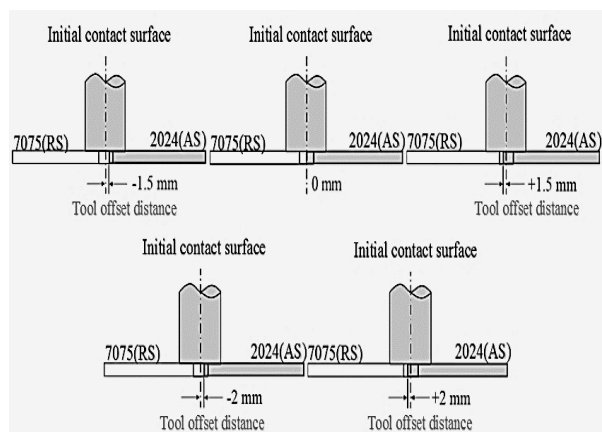


Fig. 2 Schematic illustration of friction stir butt welding of AA2024/AA7075.

Table 2 welding parameters for butt joint of AA2024/AA7075

Sample No.	Tool location	Tool offset (mm)	Sample Name
1	Al7075 (RS)	2-	RS/2
2	Al7075 (RS)	1.5-	RS/1.5
3	Center line	0	As-weld
4	Al2024 (AS)	1.5+	AS/1.5
5	Al2024 (AS)	+2	AS/2

Microstructure in different zones, as well as zone precipitates of the stirred area on the dissimilar joint in Al2024 and Al7075 alloys, were examined using metallographic test and Scanning Electron Microscope. Samples were prepared using grid papers from 60 to 3000 series alongside with following polishing process by 0.5 μm alumina solution (Al<sub>2</sub>O<sub>3</sub>). Then, in order to identify microstructure, an etchant solution containing (95 ml H<sub>2</sub>O+ 1.5 ml HCl+ 1 ml HF + 2.5 ml HNO<sub>3</sub>) in 15 to 20 seconds was used. For taking photos from etched zones and observing microstructure, an optical microscope (SA-Iran, Model: IM420) was used.

Moreover, for examining mechanical behavior of intended joint, tensile tests, microhardness tests were utilized. Test samples were prepared according to ASTM E8 [17] with a certain size (length of 15cm and width of 1.5 cm) and the test procedure was accomplished using a 30-ton tensile apparatus (Model: INSTRON-4486). Microhardness measurement process was done according to ASTM E92-82 standard following Vickers hardness test with diamond pyramid indenter using Shimadzu (Model: M) Microhardness test device and applying 100 g force in 10 seconds in 1mm distance intervals in the horizontal way from Al2024 base metal towards Al7075 base metal [18]. A schematic of the tensile test samples and the location of the microhardness test are shown in “Fig. 3”.

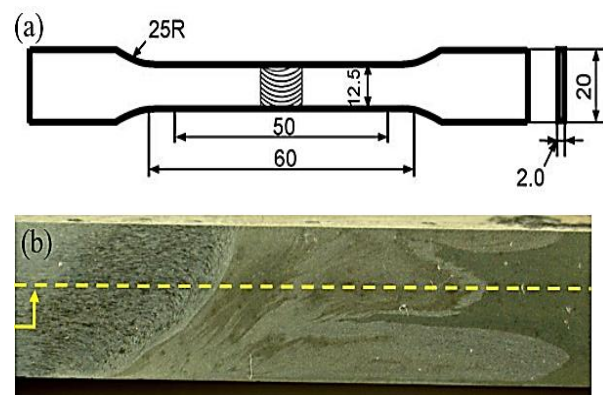


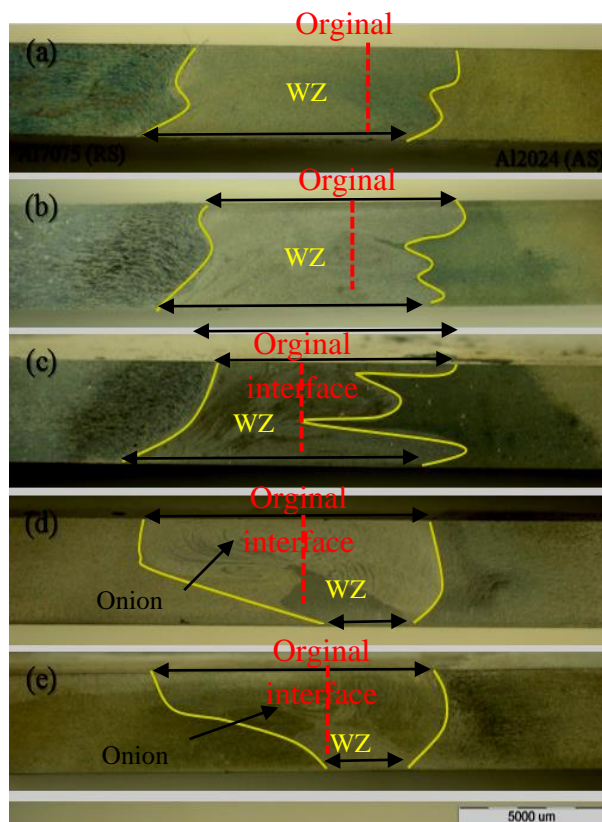
Fig. 3 Schematic of: (a): tensile test specimen, and (b): the microhardness test.

### 3 RESULTS AND DISCUSSION

#### 3.1. Macrostructure

Figure 4 shows the macrostructure of various zones in welded samples under different conditions of tool offset. In stirred zones on offset samples towards Al2024, the morphology of welding zone is observed repeatedly as an onion ring pattern, and by increasing the offset of the pin too towards this alloy, onion ring zone becomes more complete and is formed more obviously.

According to provided microstructural photos, it is observed that by offsetting pin tool towards Al2024 alloy, onion ring zone changes into the center of the joint and is formed at the center of both base metals. However, by offsetting the pin tool towards Al7075 alloy, the morphology of the microstructure in the welding zone, no onion shaped zone is witnessed. Then, in order to examine formed layers more accurately, EDX analysis was employed. According to “Fig. 4”, it is observed that in samples where the offset of pin tool is towards Al2024 alloy, the maximum width of the welding is in the upper layer of the welding (the surface of the weld) and the minimum width of the welding zone in the root of the weld.



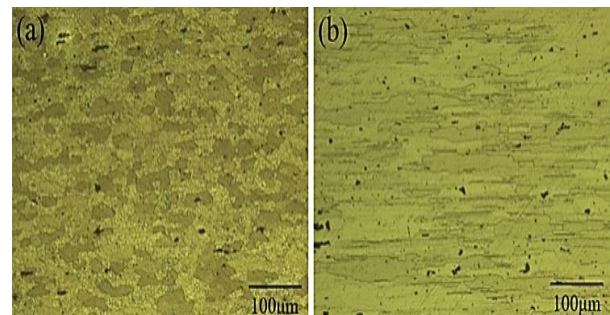
**Fig. 4** Cross section microstructure of dissimilar FSW of Al2024 and Al7075 alloys with different tool offset condition: (a): RS/2, (b): RS/1.5, (c): As-weld, (d): AS/1.5, and (e): AS/2 samples.

By the way, in samples with the offset of pin tool towards Al7075, the width of the surface and the root of the weld are similar. However, the boundary of the stirred zone (WZ), the sample without the offset of the tool in the RS side is somehow plain but in AS side, this zone is associated with significant distortion. With the offset of the tool toward the Al7075 alloy, the boundary of the stirred zone (WZ) in both sides of the AS has not changed and has distortion and this was also observed in

the RS side. The stirred zone boundary in the samples that have offset toward the Al2024 has a smooth and equal surface in both sides. The welding defects due to the welding tool offset in the weld root affect the fracture strength and load-bearing properties. When the microstructure change has distortion in the interface of the two zones, it is possible that the stress concentration increases and result in the strength decrease in this zone [19]. In the AS side, the pin tool rotation is in the same direction of the welding process and the base metal is usually under the shear process of the pin. With the rotation of the pin tool, the plastic deformation in the base metal happens in the direction of the tool movement. In the RS side, the pin tool rotation direction is contrary to the welding direction, so the Al2024 base metal is mostly affected by the extrusion of the pin. As a result, the stir in the samples with the offset of the pin tool towards the AS is more than the samples with the offset towards the RS that due to the welded samples without offset this is clearly observed. In the stir welding process, the stir happens in the WN zone and significant plastic deformation happens in this zone. Using the pin tool movement, equal stir in the base metals happens and so a proper weld structure will be obtained.

### 3.2. Microstructures

The optical microscope images of the metallographic sample's microstructure of the base metals of Al7075 and Al2024 with the same magnification is shown in “Fig. 5”.



**Fig. 5** Microstructure image of the base metals: (a): Al2024, (b): Al7075

Figure 5 (a) shows the microstructure of the AA2024 aluminium alloy that contains annealed and homogeneous microstructure with the uniform distribution of the constituent precipitates (fine-grained black and with particles). As could be seen in “Fig. 5(b)”, the Al7075 aluminium alloy has recrystallized and highly stretched or smooth grains that are related to the rolling process on the aluminium plate, that these results were observed in the previous studies [20-21]. Figure 6 and “Fig. 7” show the Scanning Electron Microscope (SEM) images of the Al7075 and Al2024 base metals. In “Fig. 7(a)”, the images of the homogeneous

microstructure of the Al2024 alloy is clearly visible. Moreover, according to “Fig. 6 (a)”, the stretched grains in the rolling direction are clearly observed. As observed in these images, the base metals have precipitates that are composed of intermetallic compounds. The SEM images of the Al7075 and Al2024 base metals with the spot Energy Dispersive Spectroscopy (EDS) analysis of the precipitates are shown in “Fig. 6 and Fig. 7”, respectively. After spot EDS analysis, it is clear that the Al2024 base metal is composed of precipitates with the composition of the AlCu and AlFeCuMgSi and the Al7075 base metal contains precipitates with the intermetallic compounds containing AlFeCrSiCu and AlCu elements.

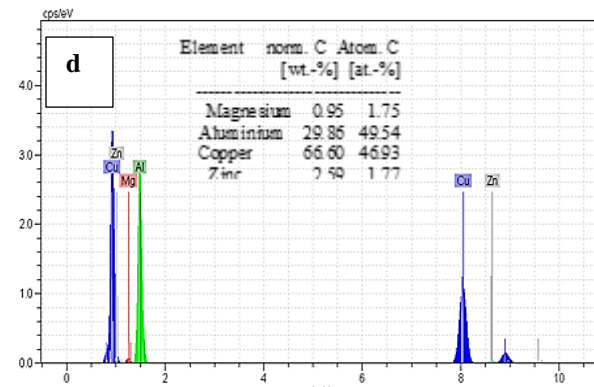
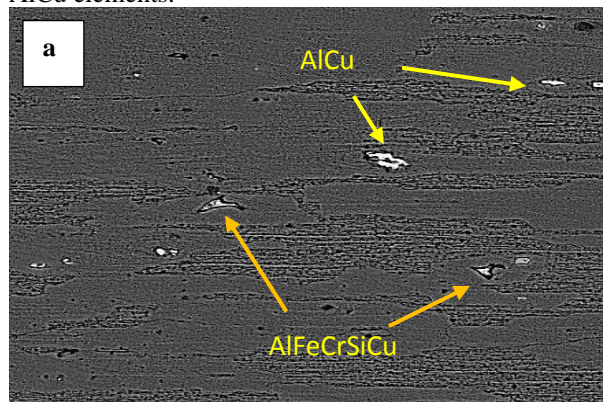
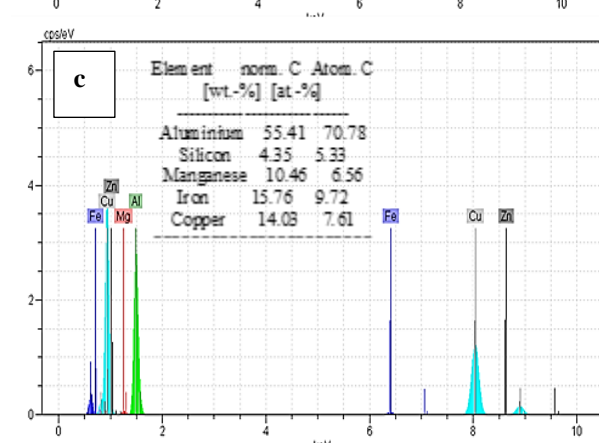
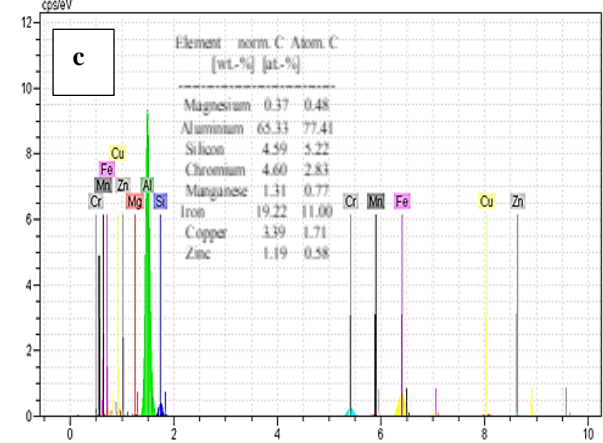
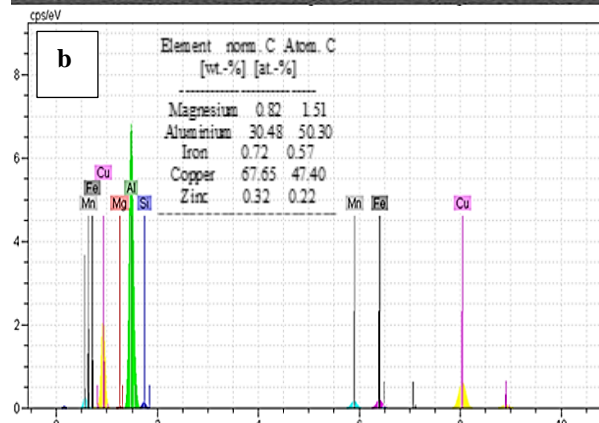
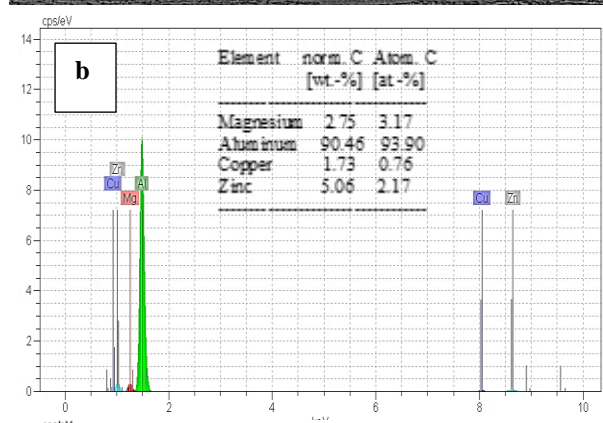
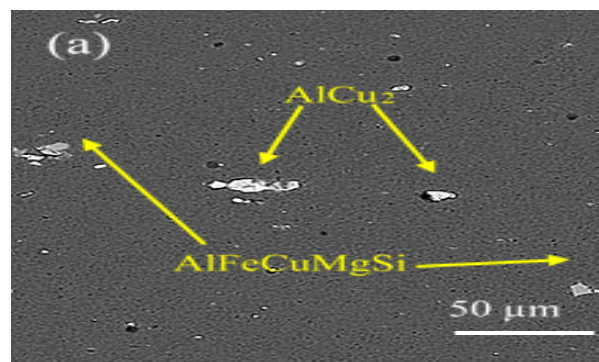
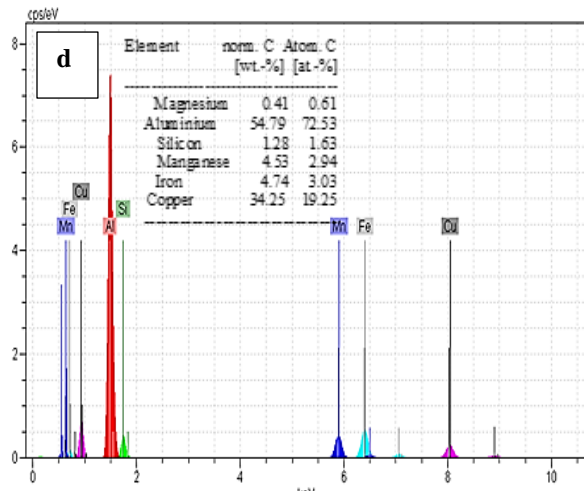


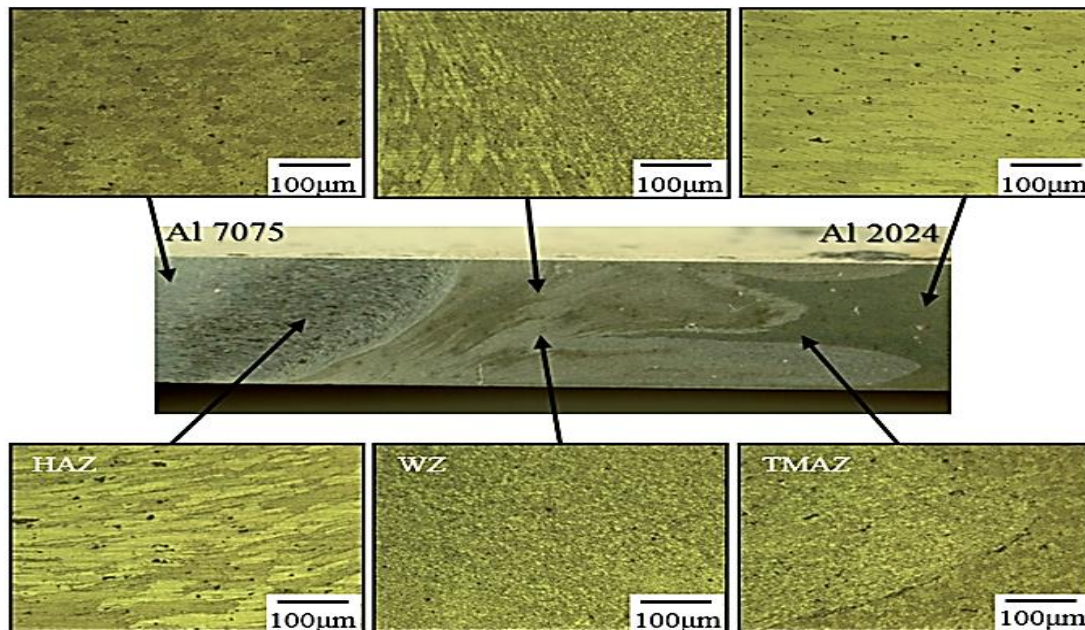
Fig. 6 (a): SEM image, (b), (c) and (d): EDS analysis of Al7075 alloy used as RS base metal.





**Fig. 7** (a): SEM image, (b), (c) and (d): EDS analysis of Al2024 alloy used as AS base meta.

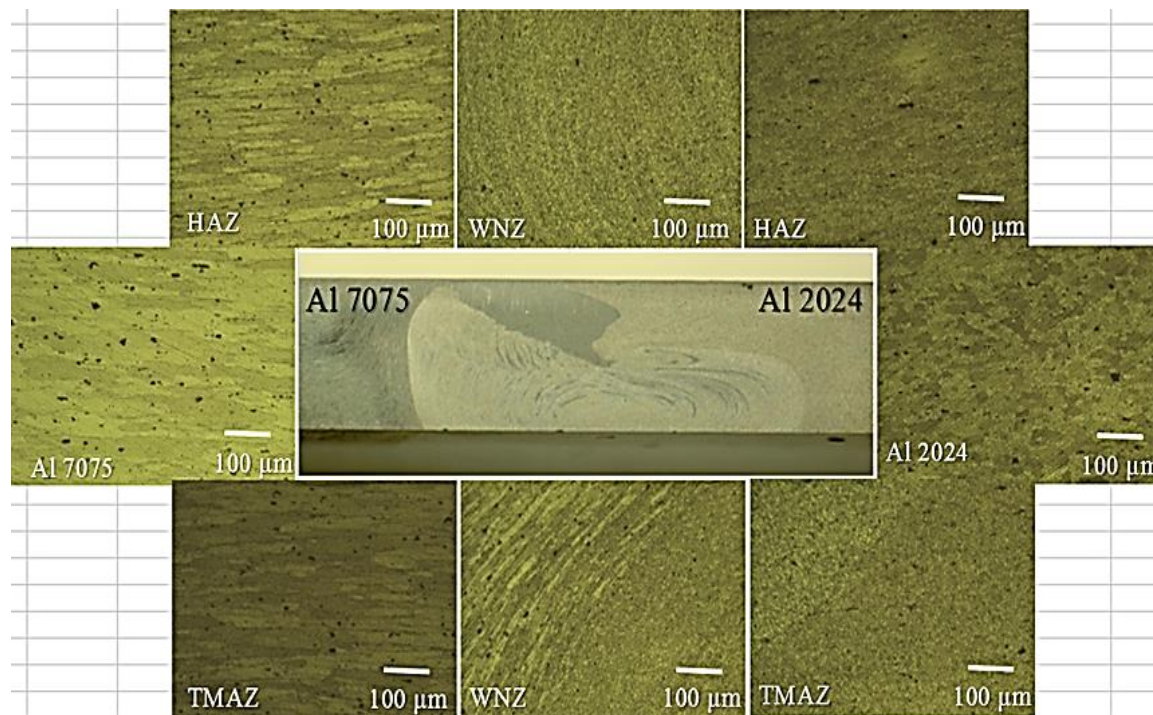
The cross section of the joint area of the without offset sample is shown in “Fig. 8”. In this figure, the Al2024 alloy in the Advanced Side (AS) and the Al7075 in the Retreating Side (RS) have butt weld. As could be seen in Fig. 8, the welded sample has various zones like base metals alloy of the Al7075 and Al2024, Heat Affected Zone (HAZ), Thermo-Mechanical Affect Zone (TMAZ) and Stirred Zone (SZ). This was also observed in the previous studies that in the welding of materials using friction stir process, a zone is formed because of mechanical process [22]. In the present study, the dissimilar welding of 7075 and 2024 aluminium alloys was successfully carried out using the FSW process. The optical microscope images of the welded samples microstructure are presented in “Fig. 4”. The results show that no porosity or microscopic defects were observed in the welded surface and the joining of the base metals was well performed.



**Fig. 8** Cross section microstructure of dissimilar FSW of Al2024 and Al7075 alloys without tool offset.

Figure 9 shows the microstructure and macrostructure of the different zones of 70215 sample. The results show that in the center of the stirred zone, the microstructure is composed of fine and homogenous grains that shows the lack of total mixing in the Al2024 and Al7075 base metals in the center of weld that could result in the uniform microstructure. However, in some zones, there is a sign of base metals presence in the beneath of the WNZ zone that has compressed some parts of the base metal zone from the AS to the RS side. The results of the optical microscope images show that the onion ring microstructure is formed in the stir zone of the offset samples towards the Al2024 alloy and dissimilar weld of the Al2024 and Al7075 alloys, that this is aligned with the microstructure with recrystallized grains. According

to “Fig. 9”, it is observed that the onion ring zone is composed of fine and equiaxed grains. With the offset of the tool towards the 2024 alloy, higher temperature and severe plastic deformation result in the formation of the higher volume ratio of the fine grains compared to base metal. According to the previous studies about the aluminium alloys joining using FSW process, the primary stretched grains in the base metal direction, due to mechanical joining process, are converted to a fine, equiaxed grains microstructure. Silva et al., [23] reported the same microstructure for the stirred zone. Khodier et al., [24] also showed that the grain size in the weld zone decreases and related this phenomenon to the low temperature due to low heat input in the FSW process.



**Fig. 9** Optical microscope image of different region for AS/1.5 sample.

By passing from the Base Metals (BM) and reaching the Initial Contact Surface (ICS), the heat of joining results in the HAZ formation. The microstructure of this zone shows the same behaviour in both directions of the weld. Because of the low heat input in the friction stir process, there is no obvious change in the microstructure in two sides of the joint. The transition zones between WNZ and BM, are TMAZ zone with more stretched grains and HAZ zone. The images obtained from optical microscope shows very fine and equiaxed grains in the recrystallized areas. In the TMAZ zone, apparently, no recrystallization has happened that is because of low temperature in the friction stir process. The microstructure in this zone is similar for all the samples but showed different behaviour in the two sides of the joint. The microstructure of the TMAZ zone in Al2024 side is finer than the base metal and minor fine graining has happened in this zone. However, in the microstructure in the TMAZ zone of the Al7075 aluminium, due to the retreating zone, the grains are more stretched. The precipitates of this zone were discussed by Muthua et al., [25]. As could be seen in “Fig. 9”, in the samples that the tool offset is towards the Al2024 base metal, the morphology of the stirred zone is composed of onion rings with the overlap of the base metals. In fact, the onion rings are in the stirred zone that the base metal flow microstructure could be clearly seen in it. In other words, the more mixed area is present in the middle part of the stirred zone that the angles of the aluminium base metals grains are mixed like onion rings and in a layered pattern. As shown in “Fig. 5”, the lighter

regions are related to the 2024 aluminium alloy and the darker regions are related to the 7075-aluminium alloy. The obtained results in this research and previous researches show that the difference between plastic flow of the materials and loading condition in two sides of the 2024 aluminium alloy (AS) and 2024 aluminium alloy (RS) is the major reason for difference and microstructure variation in the WN and TMAZ zones in the two sides of the 2024 aluminium alloy (AS) and 2024 aluminium alloy (RS).

### 3.3. EDS Analysis

According to the microstructure results presented in “Fig. 4”, in order to study the microstructure of the stirred zone, “Fig. 10” shows the SEM image of the AS/1.5 stirred zone containing EDS analysis. As could be seen in “Fig. 7”, the stirred zone is composed of two different structures and is layered. The EDS results in this zone showed that the EDS analysis of the lighter zones is in consistency with the coarser microstructure and the EDS analysis of Al7075 alloy, and the EDS analysis of the darker zones and finer structure is in consistency with the EDS analysis of Al2024 alloy. As a result, it could be said that the stirred zone is a mixture of the two Al2024 and Al7075 alloys that are formed as onion ring and layered structure. The EDS results of the stirred zone and comparing it to the base metals analysis show that this zone has layered microstructure. In such a way that a layer of the Al2024 aluminium alloy and a layer of the Al7075 alloy are formed, which in the previous papers and studies such a process is called onion ring structure [26].

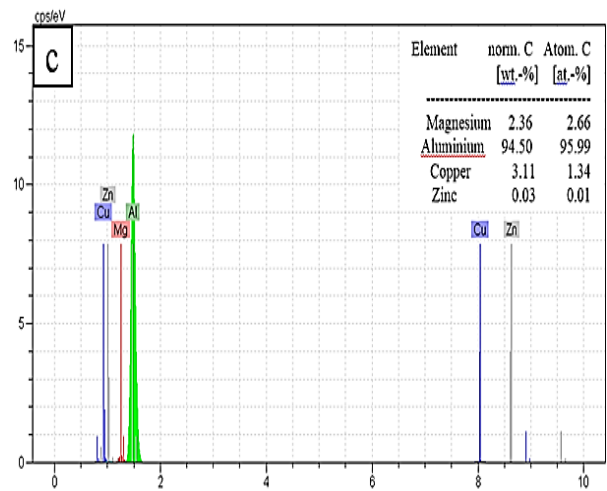
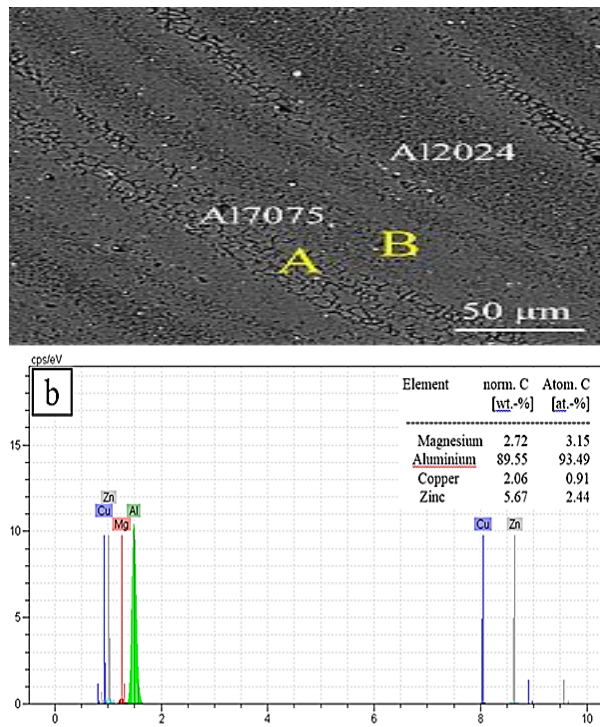


Fig. 10 (a): SEM image of WNZ zone for AS/1.5 Sample, (b): EDS Analysis for point A, and (c): point B.

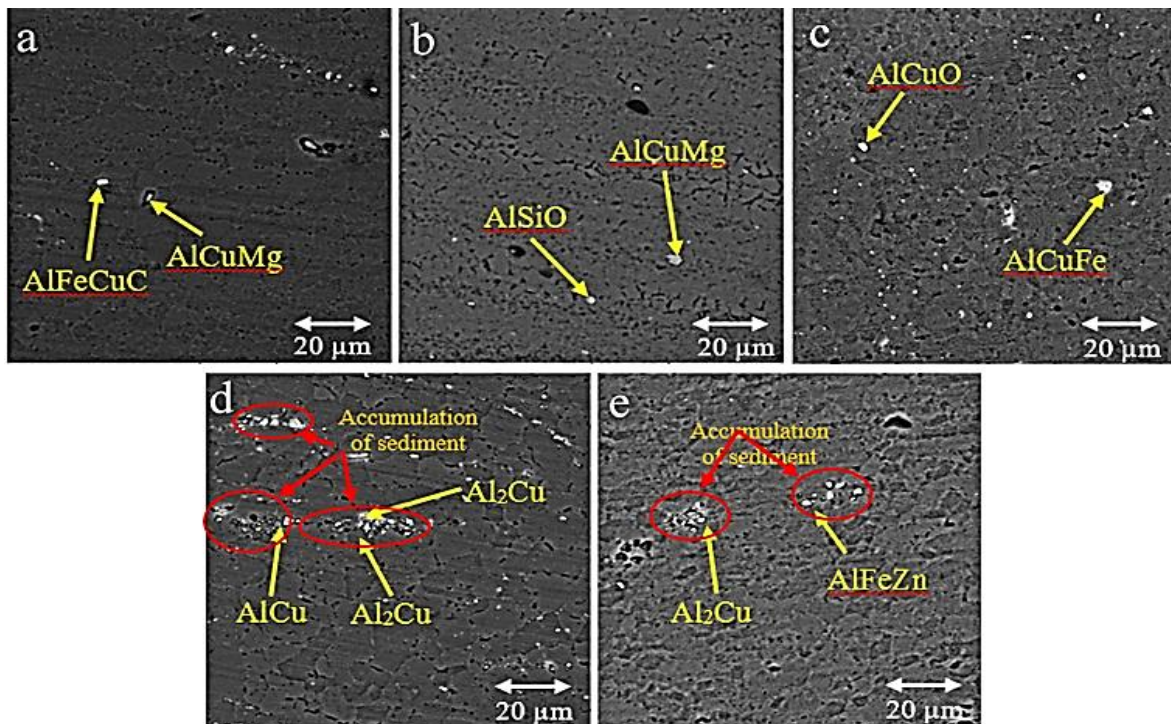


Fig. 11 SEM micrograph of WNZ for: (a): As-weld, (b): AS/1.5, (c): AS/2, (d): RS/2, and (e): RS/1.5 samples.

Figure 11 shows the SEM images of the stirred zone in welded samples with various offsets. As could be seen in the presented images, the layering behavior in the WZ zone in the welded sample with 1.5 mm offset towards the Al2024 sample is clearly observed. Also, as could be seen, in the stirred zone some precipitates with

intermetallic compound are formed. The presented results in “Fig. 11” show that in the samples which the pin tool had offset towards the Al7075 alloy, Al<sub>2</sub>Cu precipitates are formed. Moreover, according to “Fig. 11”, it is observed that the precipitates in the welded samples with pin tool offset towards the AS, are uniform



and homogeneously distributed throughout the weld zone. But in the samples that the tool offset is towards the RS, the precipitates segregation has happened that this directly affects the mechanical properties of the samples.

### 3.4. Tensile test

“Table 3” presents the results of the tensile test. As could be seen in “Table 3”, the samples in which the tool has shifted towards the Al2024 base metal have higher tensile strength compared to the samples that the tool has shifted towards the Al7075 base metal.

**Table 3** The mechanical properties of welded samples under different offset conditions.

Specimen No.	Yield Strength (MPa)	Unlimited Tensile Strength (MPa)	Tensile Strain (%)	Maximum Force (N)
Al2024 B.M	307	502	33.19	11387.57
Al7075 B.M	290	482	33.08	38544
AS/1.5	315	496	33.72	39655
AS/2	72.48	216.05	2.28	8101.77
AS-Weld	264.80	303.67	5.21	11387.57
RS/2	216.48	216.48	2.30	8117.87
RS/1.5	207.89	289.49	4.46	10856.05

As could be observed, the tensile strength of the sample without offset is nearly equal to 304 MPa. The results show that with the tool offset towards the 7075 aluminium base metal the tensile strength decreases. Also, with the tool offset towards the 2024 base metal different behavior was observed. So that, at first, the strength increases and then with the higher tool offset the strength decreased. Maximum tensile strength was observed in the 15 mm offset towards the Al2024 base metal. Moreover, the minimum tensile strength was observed in the 20 mm offset towards the Al7075 base metal. Tensile strength in the sample with the 1.5 mm offset towards the Al2024 was increased about 63% and in the 7022, 71520 and 7220 samples was decreased as about 29%, 5%, and 29%, respectively. Due to the obtained results from the tensile test, it could be concluded that the tool offset could be considered as an effective and important parameter in the tensile strength of the joint. When the welding is carried out without offset, the center of the joint is in the maximum pressure and highest temperature situation. In this case, due to the high base metal temperature, the stirred zone is in the thermoplastic situation but since the base metals are dissimilar, the stirring process does not happen in a symmetrical manner and the stirring does not fully progress. This results in the weld defects formation in the stir zone and the boundary of this zone with TMAZ zone.

The presented results in “Fig. 4 and Fig. 11” show that in a sample that the mixing is complete, the WZ zone is formed as the layered structure and the weld zone is

formed as an onion ring structure, the maximum strength is obtained and the minimum strength is related to the sample without any mixing. Furthermore, due to the presence of brittle phases like AlCu and Al<sub>2</sub>Cu in the welded samples, the difference between the tensile strength could be related to the presence of these precipitates. According to “Fig. 11”, it is observed that in the samples that the tool has offset towards the Al2024 (AS) sample, the precipitates are distributed in the weld zone, but in the samples that the tool has offset towards the Al7075 alloy (RS), the precipitates are distributed inhomogeneously in the weld surface and in some zone the precipitates segregation could be seen that this will cause strength reduction.

### 3.5. SEM Fractographs of Fractured Tensile

The SEM images of the fracture surface of the samples after the tensile test in the weld joint for all the samples are shown in “Fig. 12”. As could be seen in “Fig. 12”, the fracture surface of the weld joints in different samples has dimples, big voids, different dents, and some cleavage planes. The ductile dimple morphology is a representative for a ductile fracture that is because of nucleation and coalescence of the voids. This type of fractured surfaces was mostly observed throughout the RS/2, RS/1.5, As-weld, AS/1.5 and AS/2 samples and the only difference is the size of the dents and dimples. The results show that with the offset of the pin tool towards the 2024 aluminium alloy, the dimples, and small voids could be observed in the fracture surface and as a result, the ductile fracture happens.

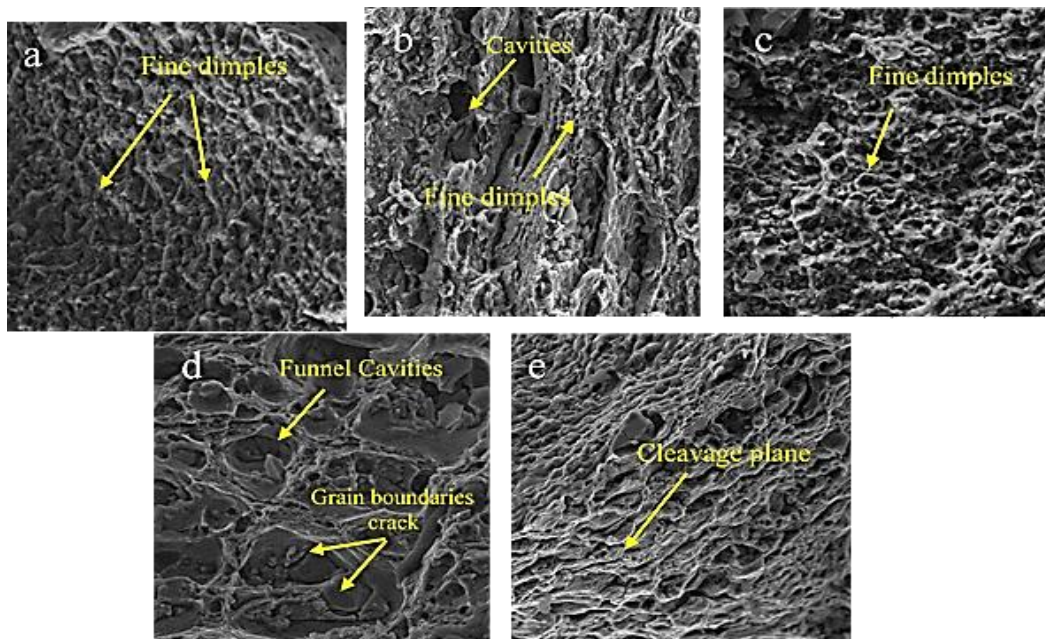


Fig. 12 SEM fractographs of fractured tensile of: (a): AS/1.5, (b): AS/2, (c): As-weld, (d): RS/1.5 and (e): RS/2 specimens.

As could be seen, with increasing the distance of the pin tool from the weld center, the porosities and coalescence and dimples get bigger. However, with the offset of the pin tool toward the 7075 samples, the cleavage surfaces in the weld joint fracture and the dimples and porosities sizes increase. Then, it could be concluded that the fracture mechanism with the offset of the pin towards the 7075 aluminium alloy tends for brittle fracture, but in some fracture surface zones, there are surfaces that show that the ductile fracture has also happened. The obtained results show that in the samples with the offset towards the 7075 aluminium alloy, the semi-brittle fracture has happened. Additionally, the fracture surface has coarse dimples and cleavage surfaces that shows the brittle fracture, but with the increase in the offset towards this alloy, the fracture surface tends to the ductile fracture.

### 3.6. Microhardness Test

In this section, the microhardness of the base metal, HAZ and TMAZ areas and also weld metal has been investigated horizontally. The results of the microhardness test for the welded samples with the tool movement towards the Al2024 alloy are presented in “Fig. 13”. As could be seen, the microhardness variation in the Heat Affected Zone (HAZ) to the stirred zone is lower in the AS side compared to the RS side.

The microhardness in the stirred zone is highly related to the base metal mixing amount in the welding process. The presented results show that the microhardness of the Al2024 and Al7075 base metals are equal to 120 HV and 130 HV that according to the previous studies are acceptable [20]. With the progress from the base metals towards the stirred zone, in the HAZ area the microhardness increases. That this microhardness

increase in two sides of the stirred zone is different. The microhardness in the HAZ area in the Al2024 alloy side is about 140 HV, while the microhardness in this zone in Al7075 alloy side is about 160 HV. This could be due to the microstructure difference of the base metals. Between the welding tool and the welded samples in the welding process, there is an indirect pressure distribution. This could be observed from the results obtained during the hardness test presented in “Fig. 13”. The pressure on the center of the welding tool is maximum and with taking some distances from the center, it reduces towards the sides.

As a result, the friction between the pin center and the base metals are maximum and the temperature in this zone is also maximum and with taking distances from the center and decreasing the friction, the temperature in both sides gradually decreases. For this reason, after the welding process, the heat arising from the welding in the HAZ area results in the grain refinement and formation of the fine grain region. In addition, in the HAZ area towards the Al2024 alloy, due to the heat because of welding, the grains are recrystallized and the microhardness increases from the base metals towards the weld center. As could be seen in “Fig. 13”, the stirred zone has the highest microhardness. In this zone, grain refinement and equiaxing have happened that will result in the microhardness in this zone. Microhardness increase in the TMAZ area and stirred zone could be because of microstructure changes due to plastic deformation and grains recrystallization. This amount of increase in the microhardness could be related to the grain growth and mixing amount of the base metals due to the plastic flow rate [27].

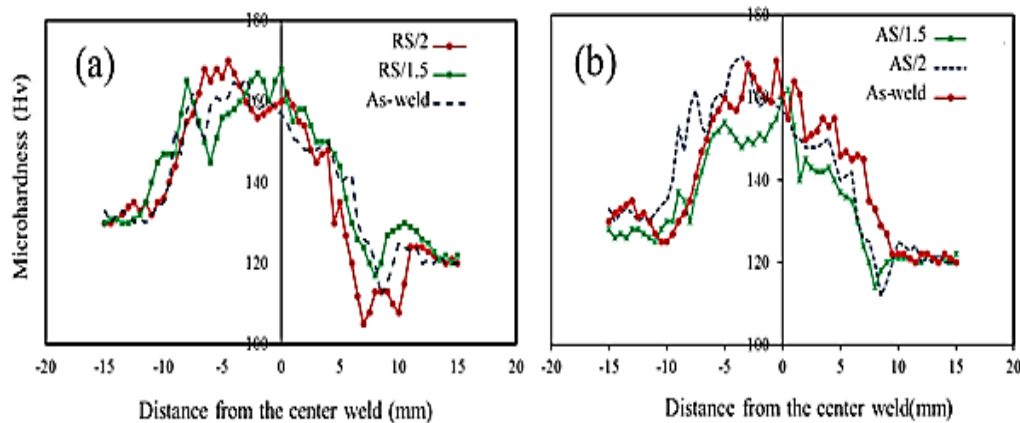


Fig. 13 Microhardness profiles of FSWed samples for tool offset to (a) RS (b) AS.

The results showed that the microhardness in the WZ zone in all the samples is almost equal and in the offset samples towards the 7075 aluminium alloy (RS) is a little higher than the microhardness of the 2024 aluminium alloys (AS) that this could be related to the hard and brittle precipitates in these samples ( $Al_2Cu$  precipitates). The presence and segregation of these precipitates in “Fig. 11” are clearly visible. Also, the microhardness in both the offset samples towards the 2024 aluminium alloy (AS) is like W that this could be related to the presence of the base metals as layered and onion ring structure in the WZ zone. Cavalier et al., [20] have reported the microhardness increase in the dissimilar weld joints of the 2024 and 7075 aluminium alloys.

#### 4 CONCLUSIONS

The FSW dissimilar welding of Al2024 and Al7075 alloy was successfully performed. In this research, the effect of tool offset on the microstructure and mechanical properties of the joint were investigated and the following conclusions were obtained:

1. The microscopic results show that the weld zone morphology in the offset samples towards the 2024 alloy is like onion-shaped ring and in the offset samples towards the 7075 alloy is as incomplete mixing.
2. The microstructural survey showed that in this joint, four zones of base metal, HAZ area, TMAZ area, and stirred zones are formed. Also, with the tool offsetting towards the Al2024 alloy, the onion-shaped ring pattern completes slowly and without any discontinuity, but with the tool offsetting towards the Al7075 alloy, the onion-shaped ring pattern did not form.
3. Tensile strength with the tool offsetting equal to 1.5 mm towards the Al2024 alloy significantly increased, and also the maximum tensile strength and elongation as

observed in the Al7075 alloy. On the top of that, the fracture type in the offset samples towards the Al2024 alloy was ductile and in the offset samples towards the Al7075 alloy was as the brittle type.

4. According to the results, it was found that with the tool offsetting towards the Al2024 alloy for about 1.5 mm, the tensile strength of the joint increased about 22.2% and with the more offset of about 2 mm, the tensile strength decreased about 22.2%. In addition, with the tool offsetting towards the Al7075 alloy for about 1.5 and 2 mm, the tensile strength of the joint decreased by about 4.5% and 28.5%, respectively.

5. The results of the microhardness showed that the microhardness of the weld zone has increased compared to the base metal and HAZ and TMAZ areas and there were little differences between the microhardness in the weld zone. However, in the offset samples towards the 7075 alloy, the microhardness in the HAZ area decreased compared to the microhardness of the offsets samples towards the 2024 alloy.

6. In this research, the best mechanical behavior and microstructural properties were obtained in the sample with the tool offsetting about 1.5 mm into the welded Al2024 base metal (70215 samples) alloy.

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