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RESEARCH ARTICLE - ENGINEERING

Investigation of Using the IL-FSSW Technique to Weld AA5052-H112 Alloy with Copper: Experimental Study

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Abstract

In this research, a developed welding technique (IL-FSSW) was used to bond alloys from Aluminum with pure Copper. Aluminium alloy AA5052-H112 and pure copper with an intermediate layer from the same base metal with a thickness of 2mm were used in the present study. The mechanism of achieving spot welding in this process differed from that of the conventional FSSW process in terms of introducing the Intermediate layer (IL) and using a pinless tool to solve the keyhole problem, and get a flat surface for the welding spot, thus increasing the tensile shear strength of the joints which makes it suitable for engineering applications. In addition, the work is based on the use of solid-state welding to eliminate the problems of conventional fusion welding methods, and this reduces the additional operations or subsequent treatments of welding and makes them unnecessary. The work was evaluated by examining the tensile shear strength and analysing the microstructure using light microscopy. The results showed a good joint appearance with shallow keyholes. The failure load value from the shear tensile test was 5008 N, obtained at a Rotating speed of 1400 rpm, feeding 20 mm/min, soaking time 20 sec, and preheating 20 sec, which was higher after comparing with the required strength value by the requirements of the American Welding Society. The microstructure images of the cross-section of the sample showed a change in the size of the crystalline grains between the welded zone and the base metal.

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Keywords: Aluminum Alloys; Pure Copper; Friction Stir Spot Welding; Keyhole Problem; IL-FSSW.

1. Introduction

Currently, some structures need a range of attributes and useful features that let them adapt to different service requirements. Therefore, the joining of different materials is essential in mechanical and electrical structures. The need for dissimilar couplings has accelerated the creation of technology for bonding different materials [1, 2].

Aluminium alloys are characterised by their lightweight, low density, high strength, good plasticity, and corrosion resistance. These properties have made them the focus of Engineers for use in constructing structures [3]. The researchers worked on connecting Aluminum with other metals such as steel and Copper, to achieve a high-quality joint [4]. Friction technology was also used in the formation of discs from Aluminum foil [5].

High thermal conductivity, good corrosion resistance, excellent electrical conductivity. These characteristics of copper have made it an important metal in industrial applications [6, 7].

Due to the multiple uses of Aluminum and copper in the refrigeration and electrical industries[8, 9], their interconnection has become a hot topic of research due to their great importance in promoting industrial development[10].

In the production of Aluminum and Copper lap joints, it is typical to use fusion welding and mechanical bonding. Bolt joining is used as a mechanical bonding process. In addition to, rivet joining[11, 12]. Pre-drilled holes will result in stress concentration and impact the performance of the structure, and the weight of the structure will increase due to the use of additional materials that are different from the alloys to be bonded. In addition, a mechanical connecting method is unlikely to produce the reliable electrical conductivity of Al-Cu joints [13].

Due to the significant differences between Aluminum and Copper's physical and thermal properties, it is difficult to obtain good metal joints when using Fusion welding techniques, due to the formation of hard and brittle metal compounds at the interface. [14, 15]. To avoid the problems mentioned above when welding Aluminum and Copper, solid-state welding processes were used such as FSW, FSSW, USW, etc. [10].

Nomenclature & Symbols			
Al	Aluminum	RPM	Rotation Per Minute
Cu	Copper	SZ	Stir Zone
FPS	Flat Pin Shoulder	TMAZ	Thermomechanical Affect Zone
FSW	Friction Stir Welding	HAZ	Heat Affect Zone
FSSW	Friction Stir Spot Welding	BM	Base Metal
IL-FSSW	Intermediate Layer Friction Stir Spot Welding	mLSFF	Minimum Lap Shear Failure Force
HSS	High – Speed Steel	IMCs	Intermetallic Compound Structures
DOE	Design of Experimental	USW	Ultrasonic Welding
CCS	Conical Pin, and a Concave Shoulder		

The process used FSSW instead of FSW, after being developed by the Japanese company Mazda, and was applied in production processes [16, 17]. There are three stages to the FSSW procedure. The tool begins to rotate and descend toward the sheets in the initial phase. The rotating tool hits its lowest point and maintains a dwell time in the second step. The spinning tool withdraws at the end of the process, and the FSSW procedure is finished. The rotating tool in the FSSW process does not maintain a tilt angle or transverse movement, in contrast to the FSW process. As a result, it is necessary to study the temperature distribution and material flow behavior in the FSSW process separately from those in the FSW process [18, 19].

The use of FSSW in connecting Aluminum and Copper, has many promising application prospects, due to its effective properties in the production of joints with high strength as well as great productivity.

In FSSW, the heat generated is influenced by the welding tool, and the microstructure of the joint is influenced by the material flow. Therefore, Mubiayi et al.[18] They studied the effect of welding tool geometry on Al-Cu joints produced by FSSW, where a flat pin and a flat shoulder (FPS), a conical pin, and a concave shoulder (CCS) were used. The results indicated that the use of FPS gave the highest shear load at the parameters of 800 rpm, and 1 mm plunge depth, while the use of CCS gave the lowest force at the same parameters. The joints produced by the conical pin have a low microhardness value below the keyhole area, which is close to the average value of Copper hardness. In addition to the geometry, the size of the welding tool is also a main factor affecting the strength of the Al-Cu FSSW joint. When the top sheet does not penetrate, the bonding between the alloys depends mainly on the metal bonding that occurs at the interface. The relatively high pressure and temperature of the Weld would produce a strong joint. Therefore, the use of welding tools with a large diameter is preferable in FSSW.

Garg et al.[19] studied the influence of the diameter of the pin tool on the strength of Al-Cu joints in FSSW, and used tools with diameters of 3.3 mm and 4.95 mm, having flat shoulders and short pins. The results indicated that the maximum shear force of the joint was when using a pinless, due to the lack of metal compounds formed. The strength of the Joint increased as the diameter of the pin increased. In the FSSW process of materials dissimilar to Al-Cu, sufficient heat is produced and material flow can form a joint with a good surface. The surface of the joint formed by a cylindrical pin at 2250 rpm appeared smooth and shiny, and this is considered a typical characteristic.

In addition, In the study conducted by Colmenero et al. [20]. To obtain a good plastic flow of the copper material, the temperature had to be raised, due to the high melting point of the Copper, especially when the Copper sheet is at the top when bonding. The researchers developed The conventional FSSW welding, to a new welding process called IL-FSSW to remove the keyhole defect associated with FSSW and therefore Increase joint strength.

This research focuses on the bonding of dissimilar Aluminum alloys with pure copper using the IL-FSSW technique, instead of the FSSW conventional to eliminate the accompanying keyhole defect. the IL part used will be of the same alloy and polygonal shape instead of the traditional round shape, this means that there is no need to manufacture a special mold for cutting the middle layer, thereby reducing the overall operation costs. The mechanical properties such as shear tensile strength as well as the microstructures of the bonding zones will be evaluated based on the experimental results.

2. Experimental Methods

2.1. Welding procedure

The conventional FSSW is modified by adding an IL part, which is placed at the center between sheets. This part is used to elevate the surface of the upper sheet in the spot welding zone and create a convex protrusion that encloses the IL part inside. This protrusion causes early friction between the welding tool and the upper surface of the upper plate. When the welding tool starts rotating and drops, friction occurs first at the top of this convex protrusion. Rises the temperature when the tool descends, causing the upper and lower sheets to be stirred with the (IL) part. Whenever the welding tool reaches the protrusion at the upper sheet's original surface level, a joint occurs due to the plasticization of the materials, leaving a welding spot with a shallow keyhole. The shape of the IL parts were Polygonal and with dimensions (8x8x2 mm). Fig. 1 displayed the fundamentals of this novel welding methods [21]. The IL part is located at the center between the metal sheets. The holding fixture first affixes the sheets with the IL part and from the other side the anvil pressure. To establish a clearance fit between the rotating tool and the stationary shoulder, the stationary shoulder has a hole that is 0.1 mm bigger in diameter than the rotating tool (Fig. 1b). The welding tool presses on the upper sheet by the shoulder to paste the upper and lower plates with the intermediate layer (IL), thereby preventing these parts from heritage during welding (Fig. 1b and c). To create a concave protrusion the interlayer is used, by raising the surface of the upper sheet in the weld zone Due to the resulting protrusion from the interlayer, friction between the welding tool and the metal is produced at a level higher than the upper surface of the working sheet. Frictional heating occurs at the top of the protrusion once the welding tool begins to rotate and fall toward the workpiece, (See Fig. 1d). When the welding tool drops, and comes into contact with the workpiece, the temperature rises, as a result of which the plasticization of the materials at the contact point, and this leads to the formation of a zone called the nugget zone (Fig. 1e). The tool retracts after it has taken the specified time to come into contact, leaving behind a connecting point between the two metals with a shallow keyhole, as seen in Fig. 1f.

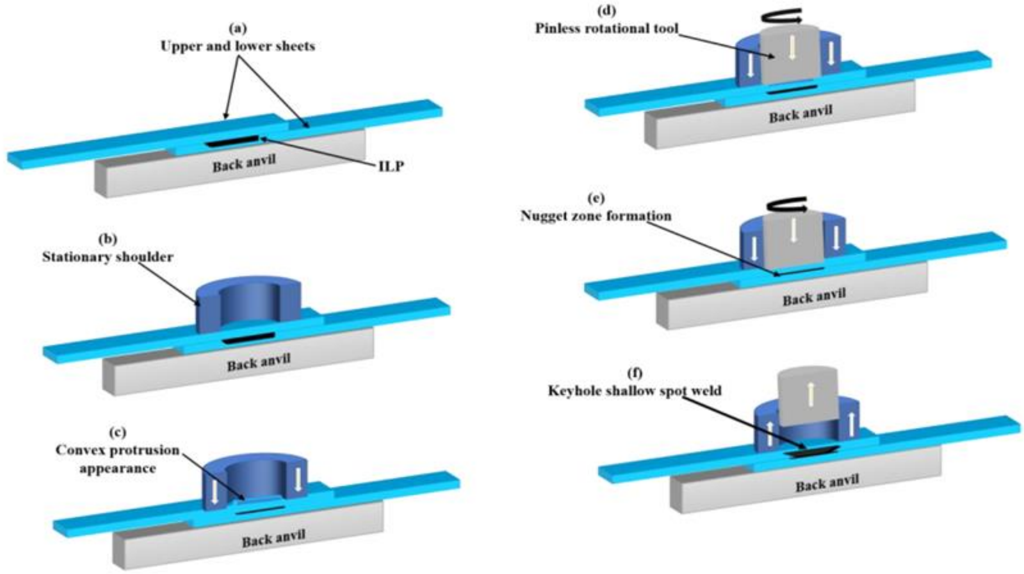

Fig. 1. Shows in this schematic the IL-FSSW process; (a) the workpieces utilized, (b) the clamp of the workpiece, (c) the formation of protrusions, (d) the tool descent, (e) the formation of the nugget zone, (f) retracted the tool [21]

2.2. Materials used and parameters

The welding samples consist of Aluminum sheets AA5052-H112, and pure Cu with a thickness of 2 mm. Their chemical composition and mechanical properties are Mentioned in Tables 1, 2, 3, and 4.

Table 1. Chemical composition of Aluminum (AA5052-H112) ASTM B209

Elements wt. Material	Si %	Fe %	Cu %	Mn %	Mg %	Cr %	Zn %	Ti %	Other	Al %
Standard [22]	0.25	0.4	0.10	0.10	2.2-2.8	0.15-0.35	0.10	0.05	0.15	remainder
Actual	0.344	0.4	0.1	0.117	2.57	0.0189	0.1	0.0144	0.11	96.3

Table 2. Chemical composition of pure Copper, S-Cu-5 DIN EN 12861

Elements wt. Material	Zn %	Pb %	Sn %	P %	Mn %	Fe %	Ni %	Sb %	S %	Al %	Bi %	Ti %	Cu%
Standard [22]	----	----	----	0.0003	----	----	----	----	----	----	----	----	99.9
Actual	0.00030	0.0079	0.0386	0.0449	0.0004	0.0158	0.0092	0.0073	0.0024	0.0013	0.0012	0.0002	99.9

Table 3. Mechanical properties of AluminumAA5052-H112 (ASTM B209)

Material	Property	Ultimate stress σu (MPa)	Yield strength σY (MPa)	Elongation %
AA5052-H112	Standard [22]	193	110	7
	Actual	226.41	126.49	26.25

Table 4. Mechanical properties of pure Copper (S-Cu-5 DIN EN 12861)

Material	Property	Ultimate stress σu (MPa)	Yield strength σY (MPa)	Elongation %
Cu-pure	Standard [22]	220	69	45
	Actual	240.57	110	45

The pinless welding tool of 12 mm in diameter, made of high–speed steel (HSS), and the modified vertical milling machine were used to make the welds in this project. Several exploratory investigations are carried out to determine appropriate process parameter ranges. Three parameters of the joining process were used (Rotating Speed, Feed, Socking Time, and Pre-Heating) shown in Table 5, While the Plunging Depth was fixed at 2mm. To study all the possibilities, four experimental cases were taken for the joints, as follows:

- Group A-1, Upper sheet AA5052-H112, Lowe sheet Cu pure, IL-part AA5052-H112 (8x8x2 mm)
- Group A-2, Upper sheet AA5052-H112, Lowe sheet Cu pure, IL-part Cu pure (8x8x2mm)
- Group A-3, Upper sheet Cu pure, Lower sheet AA5052-H112, IL- part AA5052-H112 (8x8x2 mm)
- Group A-4, Upper sheet Cu pure, Lower sheet AA5052-H112, IL-part Cu pure (8x8x2 mm)

Table 5 shows the parameters and levels used in this experiment:

Table 5. Shows the parameters and their levels used

Parameter	Level 1	Level 2	Level 3
Rotation speed, N (RPM)	1120	1400	1800
Feed mm/min	15	20	25
Socking time (s)	10	15	20

2.3. Design of experiment

The design of experiments is achieved by the Taguchi method in a nine-level or Orthogonal Array (L9) with the aid of (the Minitab 18 software). Each of the above groups was welded according to the (L9) orthogonal array design of the experiment, as shown in Table 6. Preheating is used to raise the temperature of the sheets to be welded, and this heat is obtained through the rotation of the welding tool after contact with the top sheet and without plunge depth. As for the Socking time, it is the time the welding tool remains rotating for a certain period after the end of the tool sinking in the welding sample to achieve sufficient mixing between the materials to be welded after the plastic deformation occurs. In this study, the preheating time was adopted the same as the Shocking time, therefore it was not included in the design of the experiment using the Taguchi method. Fig. 2 shows the method of fixing the samples on the machine by fixture dies manufactured for this purpose.

Table 6. Experimental design of L9 orthogonal array

Experimental NO.	Rotation speed, N (RPM)	Feed	s. time	Preheat time
1	1120	15	10	10
2	1120	20	15	15
3	1120	25	20	20
4	1400	15	15	15
5	1400	20	20	20
6	1400	25	10	10
7	1800	15	20	20
8	1800	20	10	10
9	1800	25	15	15

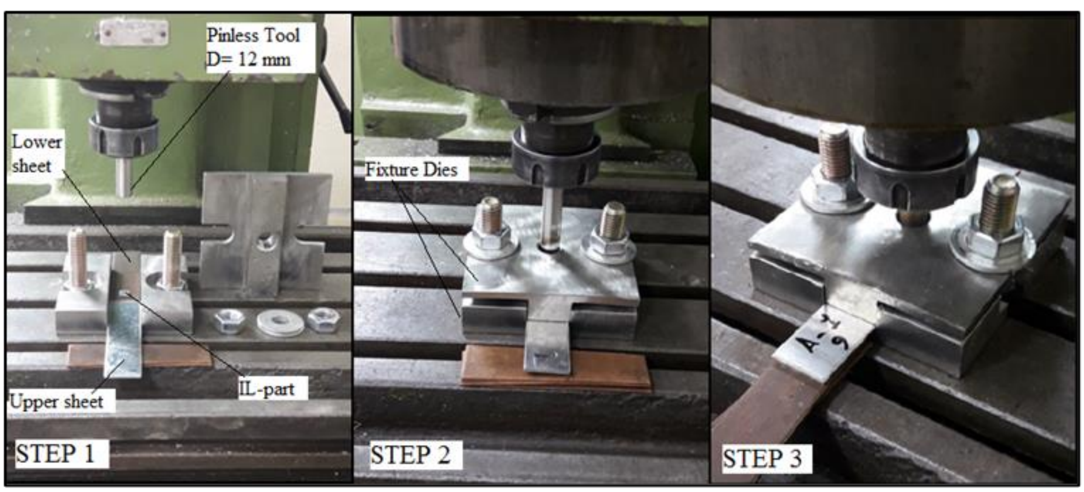

Fig. 2. Schematic Representation of the Welding Procedures

The welding samples are prepared according to the AWS standard for the tensile test [23]. The overlap spot joint sample alignment and dimensions are shown in Figs. 3, 4 and 5.

GroupA-1 did not achieve any bonding and the reason is the low melting point of Aluminumas well as its thermal conductivity compared to copper, which led to the concentration of heat resulting from friction in the Aluminum sheet and its consumption in the annealing of the metal and the intermediate layer, and it did not have enough time to reach the Copper sheet and thus achieve a welded joint. While the other groups A-2, A-3, and A-4 achieved bonding between Aluminum and Copper with varying bonding strengths, Group A-3 achieved the highest shear strength when performing the tensile test, While the A-2 and A-4 groups achieved a lower shear strength, which will be mentioned later.

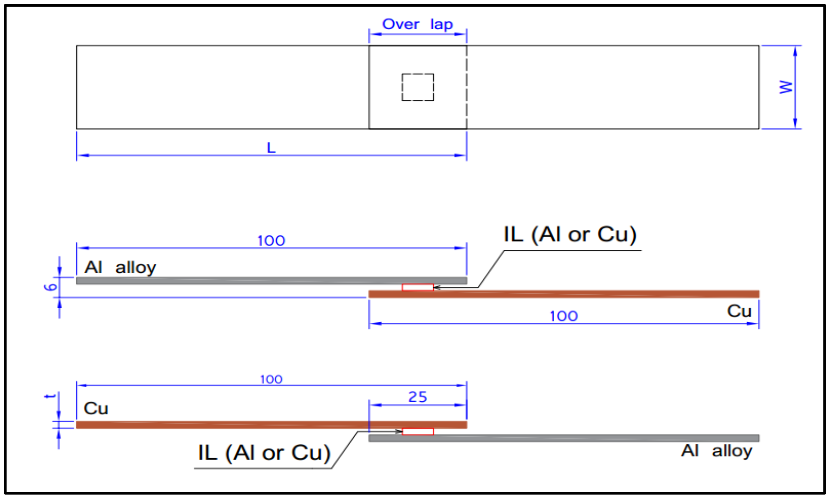

Fig. 3. Arrangement of sheets with interlayer

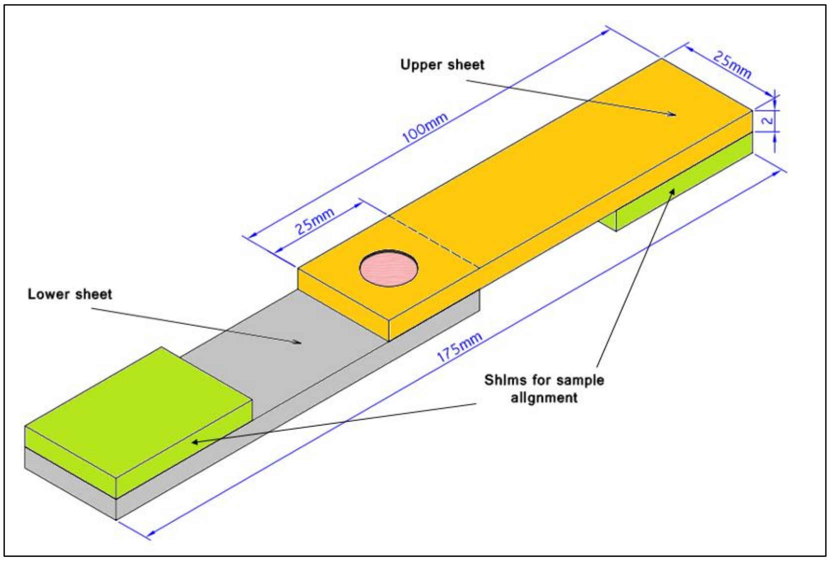

Fig. 4. The tension test sample, geometry, and dimension

Fig. 5. The surface of the spot joint of the sample lap shear test after the welding process

3. Results and Discussion

3.1. Shear test

The process of evaluating the strength of the joint was done by preparing tensile samples and testing them under shear load and head velocity 1 mm/min. Fig. 4 indicates the form of the spot welding joint. The examination was carried out in the laboratory of the Materials Department, Engineering at Technical College – Baghdad. The welded overlay sample, dimensions are (25 mm wide and 175 mm long), with additional pieces installed at the edges of the sample to prevent slippage and the same thickness of the base metal. Through the tensile test results, it was found that group A-3 (5 samples) Achieved the highest results. While Group A-2 achieved a shear strength of (2559 N), and Group A-4 (4255 N), that is, Group A-3 was superior by 48.18% to Group A-2, and by 15% to Group A-4. Table 7 displays tensile shear force (N) results, and Fig. 6 shows the shape of the sample that achieved the highest tensile shear strength.

Table 7. Values of the tensile-shear force of dissimilar weld (Cu-pure to AA5052-H112, with IL-part from AA5052-H112)

Sample NO.	RPM	Feed	S. time	Preheat time	Tensile Shear force (N) with IL
1	1120	15	10	10	2701
2	1120	20	15	15	3708
3	1120	25	20	20	4001
4	1400	15	15	15	3476
5	1400	20	20	20	5008
6	1400	25	10	10	4148
7	1800	15	20	20	4504
8	1800	20	10	10	3454
9	1800	25	15	15	3438

Fig. 6. The surface of the spot joint of the sample lap shear test

The shallow keyhole and the semi-flat surface shown in Fig. 6, which resulted from the use of the IL-FSSW technique, had the positive effect of increasing the shear strength of the joint because the keyhole is a stress concentration area and therefore led to a decrease in shear strength. The effect of a shallow keyhole in this study is evident in the results obtained and compared with the results of conventional FSSW in Table 8.

Table 8. Comparisons of the maximum failure load of FSSW Aluminum for different process conditions

	Reference	Lap configuration	Auxiliary process	Shear load (KN)	Research Year
1	Li et al. [13]	Al / Cu	FSSW	2.152	2019
2	Zhou et al. [26] Zhou et al. [14] Siddhartha et al.[27]	Al / Cu	-	2.52	2018 2019 2017
3	Heideman et al.[28]	Al / Cu	-	1.89	2010
4	Zuo et al.[29]	Al / Cu	(RFSSW)	2.35	2020
5	Manickam et al. [30]	Cu / Al	FSSW	2.395	2020
6	Zuo et al. [31]	Cu / Al	Ultrasound	3.96	2021
7			-	2.58	
8	Muna Khethier.[32]	Al/Cu	FSSW	2.29	2021
9	Hua et al. [33]	Cu / Al	Zn interlayer	3.32	2022
10	current study	Cu /Al	IL- FSSW	5.0	----

3.2. Microstructural analysis and weld geometry

The welding process starts with the contact of the welding tool with the upper sheet and preheating by rotating the tool, Before the feeding process to obtain the specified plunging depth of 2 mm. Preheating was necessary to achieve bonding, due to the difference in thermal conductivity between Aluminum and Copper[(Al 237 w/mk, Cu 401 w/mk) [22], and Copper's high ability to dissipate heat. Through experiments, the bonding preference was when the copper sheet was placed on the top and the Aluminum sheet on the bottom, and this is evident from the results of the tensile test.

The samples were prepared by a cutting wire machine to obtain as a smooth cross-section as possible for the dissimilar materials (pure Copper to AA5052-H112) and with the use of an alight microscope (Opitika) connected to a computer. The samples were prepared by wet grinding using grinding paper (Sic) with different roughness numbers (400,800,1000,2000,3000, and 4000), The samples were then polished with and finally 0.5 µm alumina solution with a particular cloth, which was used to obtain the polished surface. To examine the microstructure of the sample in the different zones such as the mixing zones, an etching solution containing was used (0.3ml distilled water + HCl 3.5 ml + HNO_3 4ml + CrO_3 1.2 g) for the Al Alloy and Copper sheet, The immersion time is 30 seconds. The images of the cross-section and microstructure represent the welding zones of the samples welded under ideal conditions, which gave the highest readings in shear forces, see Fig. 7, and 8.

As shown in the figure above, the distribution of areas on the weld sample, namely, Stir zone (SZ), Thermomechanical affect zone (TMAZ), Heat affect zone (HAZ), and Base metal (BM).

Fig. 8 displays images (A-E) of the microstructure of the sample in different areas along the interface of the cross-section of the sample, which describes the state of bonding between the IL part and the lower sheet. The images show a clear difference in the microstructure between the BM and the interlayer as a result of the pressure and temperature conditions during the welding process, dendritic growth is also formed in the stir zone. While the microstructure of the base mineral is coarser and larger. As a result of the difference in the granular size, and to clearly show the microstructure of the interlayer, we used two magnification powers, 10x for the base metal and 20x for the interlayer, as shown in Fig. 8.

The area at the bottom of the IL-part fraction at the interface line with the bottom sheet is defined as the recrystallization layer. The grain refinement can be seen as shown in Fig. 8 (A, E) and it tends to form the dendritic as we get closer to the stir zone, because the materials in this area have undergone large amounts of plastic deformation, and this is shown in Fig. 8 (B, C, D). the base metal A slight change in its microstructure, as the granules became soft in the mixing area.

Fig. 8 displays the change in the grain size of the IL part in the stir zone and other areas, like TMAZ, HAZ, and BM. Where pictures represent C, D, and E bonding areas (SZ), It is evident that the formation of the grains on shape dendritic. As for pictures A and B small crystals are visible in the remainder of the cross-section of the sample. Dendritic growth can occur at recrystallization temperature upon rapid cooling [24], or when the metal has a high potential for heat dissipation, this leads to the formation of dendrites due to the rapid drop in temperature [25]. The dark-colored spots in the pictures indicated to be intermetallic compound structures (IMCs).

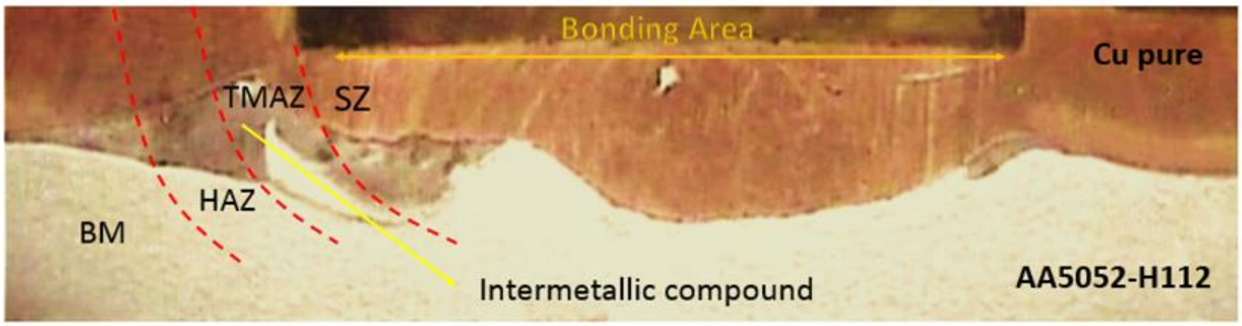

Fig. 7. Macroscopic show of the weld cross-section

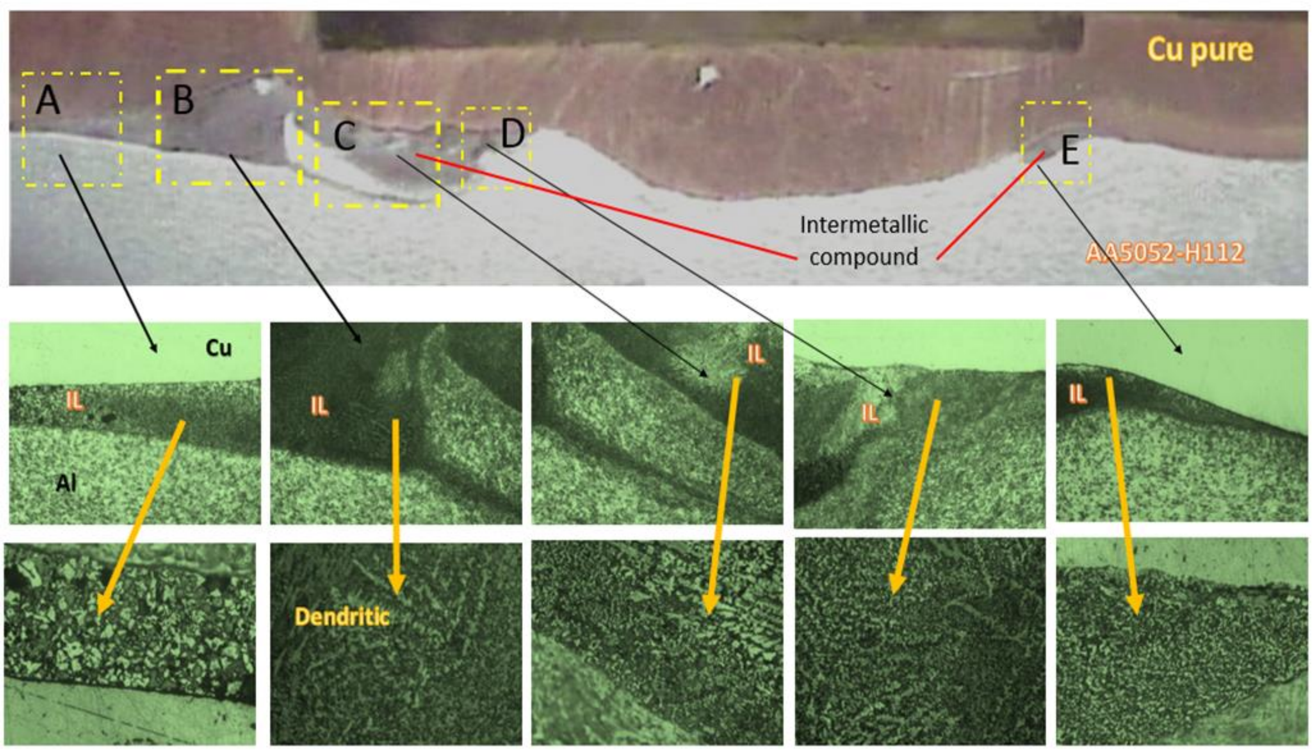

Fig. 8. Distribution of microscopic image areas on the examination sample

3.3. Joint lap shear failure force

The strength of the joint lap shear tensile should be checked out According to failure stress friction stir spot welds on Criteria AWS or Society of Automotive Engineers standards [24]. According to AWS, the minimum lap shear failure load (mLFF) for spot welds produced can be computed using the equation 1 [25]:

$$\text{mLSFF} = \frac{(-6.36\times10^{-7}\times S^2+6.58\times10^{-4}\times S+1.674)\times S\times 4\times t^{1.5}}{1000} \quad (1)$$

Where S: tensile stress of the base metal (the softer sheet)

t: sheet thickness.

Table 8 shows the UTS obtained experimentally of the base metals used [21].

Table 8. UTS of base metals used

Base Metals Used	UTS (KN)
AA5052-H112	4.585
Cu pure	4.886

The AA5052-H112 / pure Cu dissimilar welds should possess a minimum joint strength of 4.58 KN based on this equation. As shown in Fig. 9, the mLSFF value of the joint fabricated by IL-FSSW is 5 KN, which is almost similar to that required according to the equation.

Table 8, the weld strength load produced in this study is compared with the welds produced using other conventional and advanced FSSW techniques. The joint strength achieved in this study is competitive. When compared to conventional FSSW processes, the IL-FSSW method produces a high lap shear force. It is noteworthy, that group A-2 (Al / Cu, with IL – pure Cu), in which the panels were arranged to place Aluminum on top of Copper and an intermediate layer of pure Copper, gave higher results than the research results listed in Table 8 which had the same arrangement of sheets, but the advantage remains in the work when placing Copper over Aluminum.

According to Fig. 9, the welds from IL-FSSW show a large bearing capacity compared to those reported in other studies on FSSW techniques.

The bonding mechanism used in this method gave a clear indication of improving the performance of the bonding joint, which allows for avoiding the formation of keyholes in the welded samples.

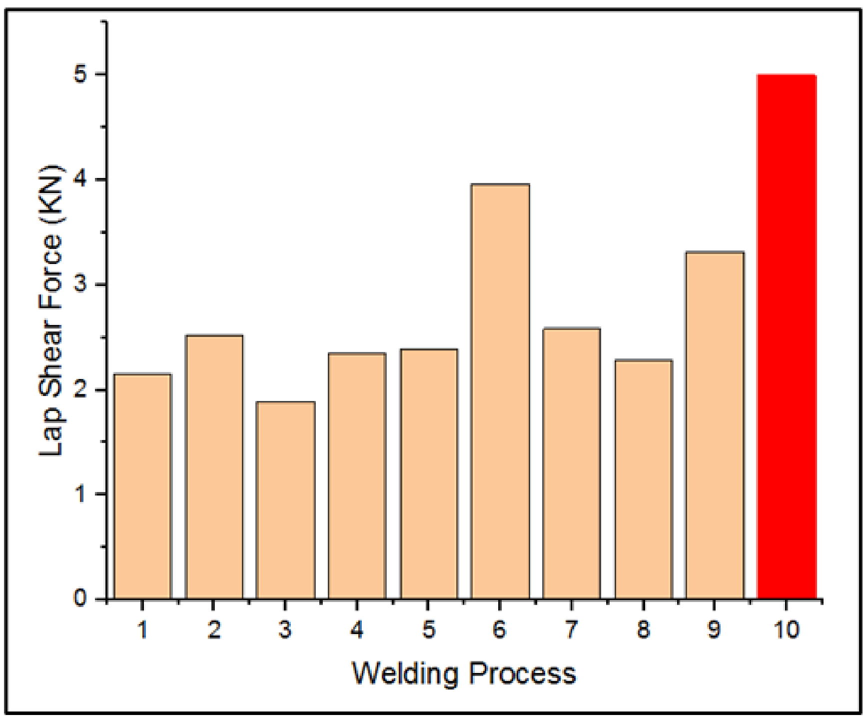

Fig. 9. The comparison of the failure load values of different welded samples

4. Conclusion

The following conclusions can be drawn from this study:

- When the IL-FSSW technique was used, the resulting Keyhole was shallower compared to the conventional FSSW technique, because the intermediate layer (IL) located between the sheet in the center of the welding spot leads to welding tool friction and the metal at a higher level than the upper sheet level.
- The keyhole that formed after the completion of the welding process by IL-FSSW was shallow, and the welding surface had an almost flat appearance.
- The intermediate layer (IL) has been greatly affected by the action of stirring and the pressure force generated by the welding tool and it has completely transformed into an intermetallic compound inside the Aluminum sheet.
- Shear tests show that the achieved shear strength is higher than the requirements of the AWS.
- Microstructure analysis revealed a difference in the size of the crystal grains in the bonding region from other regions between the IL and the BM. The pictures also showed the formation of dendritic grains in the area of NZ, which indicates the occurrence of recrystallization in this region due to the high potential of the metal to dissipate heat and rapid cooling.

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