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Analysis of Mechanical Properties and Microstructure of Aluminum and Copper Sheet Welding Using Friction Stir Spot Welding Method

Analisis Sifat Mekanik dan Struktur Mikro Hasil Pengelasan Lembaran Alumunium dan Tembaga Menggunakan Metode Friction Stir Spot Welding

Adit Waisal, Hary Munandar*, Sofia Debi Puspa, Achdianto, Triyono
Mechanical Engineering Study Program, Faculty of Industrial Technology, Universitas Trisakti, Jakarta 11440, Indonesia

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Abstract

Welding aluminum and copper materials using friction stir spot welding (FSSW) is widely practiced. Although strong enough, it still produces keyhole and shoulder marks, which are quite large due to the large shoulder and pin sizes. This study investigates the joining of aluminum and copper panels using the FSSW technique using smaller shoulders and pins in different shoulder shapes. The study began by cutting aluminum and copper panels 150 mm long, 50 mm wide, and 5 mm thick. The joining process was carried out at rotational speeds of 900, 1200, and 1500 rpm with tools with several variations in pin length. Pin lengths of 0,5 and 7 mm with pin diameters made the same at 5 mm, shoulder diameter 20 mm. The connection was observed for macrostructure, microstructure, and hardness. Different tool geometries have the potential to be applied in FSSW joints, especially for sheets. The highest hardness value is found in Cu-Cu material welding, with an average hardness value of 101.63 HVN in the stir zone area. The lowest hardness value is located in the base metal of aluminum material, with an average hardness value of 48.37 HVN.

Keywords: FSSW, microstructure, mechanical, spot welding.

***SDGs*:**

Abstrak

Penyambungan material alumunium dan tembaga dengan menggunakan metode *Friction Stir Spot Welding* (FSSW) telah banyak digunakan. Meski memiliki tenaga yang cukup besar, namun tetap menimbulkan lubang kunci dan bekas bahu yang cukup besar karena penggunaan ukuran bahu dan pin yang besar. Penelitian ini menyelidiki sambungan panel aluminium dan tembaga menggunakan teknik FSSW menggunakan bahu yang lebih kecil dan pin dengan bentuk bahu yang berbeda. Penelitian diawali dengan pemotongan panel aluminium dan tembaga dengan panjang 150 mm, lebar 50 mm, dan tebal 5 mm. Proses penyambungan dilakukan pada putaran 900, 1200, 1500 rpm dengan *tool* yang memiliki beberapa variasi panjang pin. Panjang pin 0, 5, dan 7 mm dengan diameter pin dibuat sama yaitu 5 mm, diameter shoulder 20 mm. Sambungan diamati struktur makro, struktur mikro dan kekerasan. Geometri *tool* yang berbeda berpotensi untuk dapat diaplikasikan dalam sambungan FSSW terutama untuk lembaran (*sheet*). Dan nilai kekerasan tertinggi terdapat pada saat pengelasan material Cu-Cu dengan nilai kekerasan rata-rata sebesar 101,63 HVN pada *brewing zone*. Nilai kekerasan terendah terdapat pada material logam dasar aluminium dengan nilai kekerasan rata-rata sebesar 48,37 HVN.

Kata Kunci: FSSW, mikrostruktur, mekanik, *spot welding*.

*Correspondence Author
email : hary.munandar@trisakti.ac.id

1. INTRODUCTION

The technology known as Friction Stir Welding (FSW) is currently being utilized to weld different types of metals together. By joining dissimilar metals, like aluminum and steel, aluminum with magnesium, aluminum with copper, and steel with nickel, it is possible to maximize the strengths of both materials. This technique is beneficial in industries such as power generation, military, and electrical, where combining different materials can help reduce weight, improve corrosion resistance, and increase ductility. Fusion welding methods, which involve high heat and can lead to solidification defects and intermetallic compounds, are not ideal for dissimilar materials. However, FSW welding can reduce or eliminate these defects by utilizing a lower welding temperature than the melting point of the base metal (Esmaeili, Givi and Rajani, 2011).

During the welding process, aluminum welds can experience various welding defects like porosity, solidification, and liquidation cracking. These defects can also occur after the welding process. To overcome the lack of fusion welding, one can use friction-based solid-state welding methods such as Friction Stir Spot Welding (FSSW). FSSW replaces Resistance Spot Welding (RSW), challenging to implement on aluminum due to its high electrical conductivity, low electrical resistance, and an aluminum oxide layer on the surface with a high melting point. FSSW is a friction-based spot-welding method performed in a solid condition to avoid defects such as porosity, solidification, and liquidation cracking on the weld. This method is highly suitable for welding aluminum materials susceptible to melting (Tiwan, Ilman, and Kusmono, 2021).

Friction Stir Spot Welding (FSSW) is a process that involves generating frictional heat through the interaction of the tool pin with the material. This causes the material to become pasty and extrude vertically. The tool shoulder then applies an upsetting action on the stirred material to form the weld nut. In the case of FSSW of thermoplastics, the process consists of four phases: plunging, stirring, solidifying, and retracting. The friction between the tool and the plates generates the heat required to weld the plates (Benyerou *et al.*, 2021).

The FSSW process is a three-stage process that involves plunging, stirring, and drawing out. During the plunging stage, the rotating tool experiences high resistance from the workpiece. This resistance causes the workpiece to soften due to plastic deformation and frictional heat. In the dwell period, the heat generated by friction increases, allowing the material to flow in the weld zone. Finally, in the last stage, the rotating tool is drawn out from the weld zone. Overall, this process is a highly effective method for welding materials together, and it is widely used in various industries (Lewise and Dhas, 2022). The pinless friction stir spot welding (FSSW) process is similar to the conventional FSSW method. The welding process involves plunging the pinless tool slightly into the top sheet material, agitating it for a short dwell time, and then backing off (Li *et al.*, 2014). The tool retracts quickly and precisely once it reaches a specific depth and pause time (Venukumar *et al.*, 2014).

Research conducted by Çam at al. on advances in FSSW and FSSW plates of different Al alloys shows that applying the FSW/FSSW process on different Al alloys is relatively more accessible compared to FSW on various combinations of materials with different properties, such as alloys of Al with Mg or Al alloy with steel. The primary challenge in joining different Al alloys with FSW/FSSW is discontinuing the mechanical and technological properties (like high-temperature strength, plastic deformation capacity, viscosity, etc.) of the materials to be welded at the abutting surfaces. This discontinuity, along with the inherent asymmetry in heat generation and material flow in the FWS/FSSW process, leads to higher asymmetry in material flow behavior in different welding (Çam, Javaheri and Heidarzadeh, 2023).

A study was conducted by Andrade et al. on shoulder-related temperature thresholds in FSSW of aluminum alloys. The research results indicate that the temperature in FSSW can be regulated by using an appropriate combination of rotation speed and tool dimensions for aluminum alloys (Andrade *et al.*, 2021). The heat generation in aluminum alloy FSSW was assessed by producing bead-on-plate spot welds with a pinless tool. The study tested coated and uncoated tools with varying diameters and rotation speeds. Heat-treatable (AA2017, AA6082, and AA7075) and non-heat-treatable (AA5083) aluminum alloys were welded to analyze the possible influence of base material properties on heat generation. The study found that for rotation speeds higher than 600 rpm, the tool diameter was the main process parameter governing heat generation.

Shen et al. researched refilling FSSW Al alloy to copper via a pure metallurgical joining mechanism. Defect-free Al/copper dissimilar welds were successfully created using backfilled FSSW. The process involved inserting a tool into the top Al alloy sheet. It identified two types of continuous and ultra-thin intermetallic compound (IMC) layers across the Al/copper interface. The local area also showed strong evidence of liquefaction and solidification. The peak temperature obtained at the center of the Al/copper interface during the penetration phase of the sleeve was 591 °C, and the heating rate reached up to 916 °C/s. The FSSW backfill process produced a softened weld area, visible through the W-shaped appearance of the hardness profile along the middle thickness of the upper Al alloy. The weld lap shear load was not sensitive to the welding conditions, and the load distribution was relatively small. Under external rotational shear loading, fracture paths exclusively propagated along the Cu_9Al_4 IMC layer. The fracture surface on the copper side showed the presence of both $CuAl_2$ and Cu_9Al_4. This study demonstrated that acceptable weld strength can be achieved via a purely metallurgical joining mechanism, which has significant potential for industrial applications (Shen *et al.*, 2021).

As a relatively new welding technique, the current development of FSSW is still extensive in scope. The variables studied are very varied and exciting to develop. Aluminum (Al) and Copper (Cu) are two common materials that are widely used in the automotive and electrical industries, one of which was proposed by Mazda Motor Company Japan and then applied in its production (Shen, Ding and Gerlich, 2020). In making car bodies and batteries, several methods combine the material using welding, rivet, and adhesive bonding technology to connect different materials. Utilizing this welding technology, researchers can find out the material's mechanical properties and the lifetime of the material so that it can be applied to the body and aircraft manufacturing industry. For this reason, researchers took the connection method with the Friction Stir Spot Welding process on aluminum material (Meschut, Janzen and Olfermann, 2014).

The connection process was tested at rotational speeds of 985, 1660, and 2350 rpm with two types of tooling (shoulder angle 0° and 5°). Research results showed that all joints had brittle fractures. As the shoulder angle of the tool rotation speed increases, the size of the welding spot and welding area increases, so the tensile load capacity increases to 2116 N (Nugroho, Saputra and Budiyantoro, 2019). A joint without hook defects showed a shear-tensile load of 12 kN, higher than 6.9 kN in a joint with hook defects (Li *et al.*, 2014). Meanwhile, a study was also conducted from the use of Zn electroplating interlayer and gave optimal results in tensile testing on friction stir spot welding results of 3.8 kN while for the connection value without electroplating interlayer of 2.5 kN, as well as hardness testing which resulted in a more excellent value of 63 HV greater than without using electroplating interlayer (Saputra, Sukarno and Zulaehah, 2021). In previous research, the results of microstructure testing showed that the friction stir spot welding method could change the dimensions of the grains in the welding area (Sehono and Ardianto, 2021).

The focus of this research is to investigate the strength of welded joints made from different materials, specifically copper and aluminum. The research will involve measuring hardness and examining the microstructure. By using the FSSW process, we hope to determine how the joined material affects its mechanical properties and microstructure.

2. METHODOLOGY

2.1. Flowchart

The research flow chart is presented in Figure 1. This flow chart generally shows the steps that will be taken in this research. From the literature study, determining the materials and machines to be used, the process parameters, and the number of samples to be used. Then, the sequence of implementation of the friction stir spot welding process is followed by taking complex test data and microstructure. The last stage is to analyze the data and discuss the results of this research.

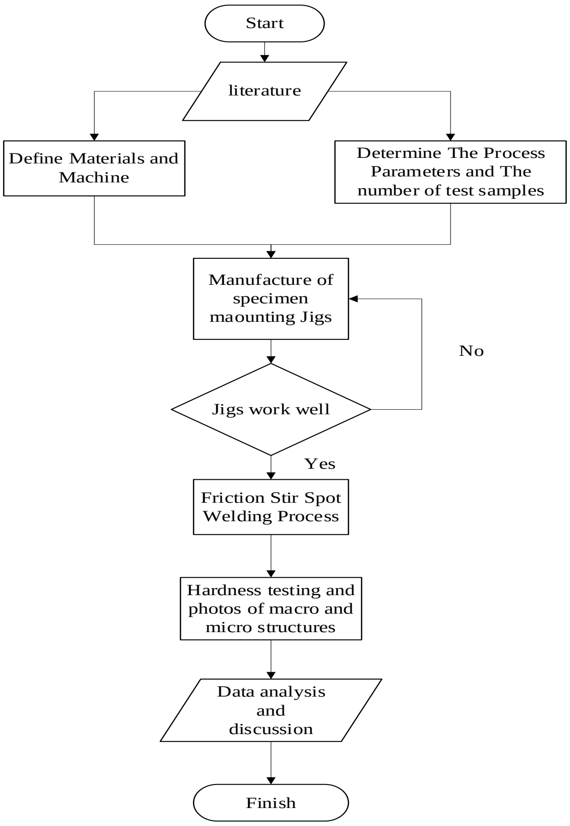


Figure 1. Research flowchart.

2.2. Research Location

In this research, the lathe and welding processes and data collection were conducted in the Production Process Laboratory and Physical Metallurgy Laboratory of the Department of Mechanical Engineering, Faculty of Industrial Technology, Trisakti University.

2.3. Research Equipment and Materials

2.3.1. Specifying Material

The materials to be welded were selected using Aluminum and Copper. Both sheets have dimensions of 150 mm x 50 mm x 5 mm in length. As for the specifications (Almaxco, 2015):

a) Aluminum:
- Material: Aluminum Alloy 1100-H14
- Density: 2.71 g/dm^3
- Hardness: 23 (500 g load; 10 mm ball)
- Tensile Stress: 75-105 MPa (Ultimate), ≥ 20 Mpa (Yield)
- Elongation: 15-28%
- Modulus of Elasticity: 68.9 GPa
- Size: 150 mm x 50 mm x 5 mm

b) Copper:
- Material: Copper Alloy
- Purity: 98%
- Density: 89.6 g/cm^3

Friction Stir Spot Welding requires tools, such as a Shoulder and Pin made of VCN steel material with specifications:
- Material: VCN 150 Steel
- Dimensions: ⌀20 mm (shoulder), 5 mm pin diameter
- Hardness: 220-250 BHN
- Heat treatment: 820-850 °C

2.3.2. Machines and Equipment

The welding process uses a vertical milling machine. The vertical milling machine is to be used with the following specifications:
- Brand: RRC Qinghai Universal lifting table milling machine.
- Model name: X61W
- Machine type: conventional
- Table size: 1000 x 250 mm
- Speed: 65 to 1800 pm
- Feeding: 12 to 980 mm/min

2.3.3. Setting Process Parameters

The process parameters used in this vertical milling machine are spindle rotation (to rotate the shoulder) of 900, 1200, and 1500 rpm. Because of spot welding, the welding is only local, or the shoulder does not move. The following test process variable is pin length, three (3) types: without pin, 5, and 7 mm, with a shoulder diameter of 18 mm. Figure 2 is the VCN material before the turning process, which will be used as a tool in the friction stir spot welding process, and Figure 3, Figure 4 and Figure 5 is a tool that has been turned.

Figure 2. VCN material before turning.

Figure 3. Tool shoulder with 7 mm pin (after turning).

Figure 4. Tool shoulder with 5 mm pin (after turning).

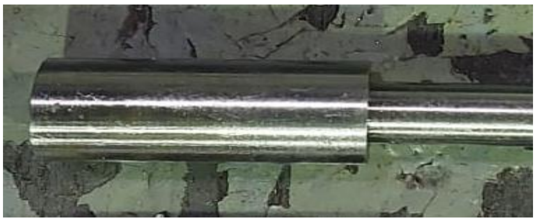


Figure 5. Tool shoulder without pin (after turning).

2.3.4. Sample Preparation using Friction Stir Spot Welding

2.3.4.1. Preparing Test Samples

The materials used are aluminum and copper sheets with a thickness of 5 mm. The sheet is then cut to 150 mm x 50 mm x 5 mm, as shown lap joint in Figure 6.

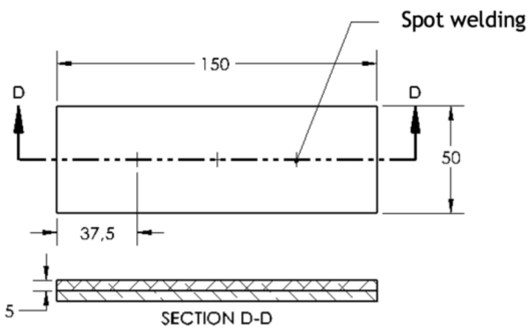


Figure 6. Lap joint aluminum and copper.

The material is used when cut into a predetermined size, as shown in Figure 7 and Figure 8.

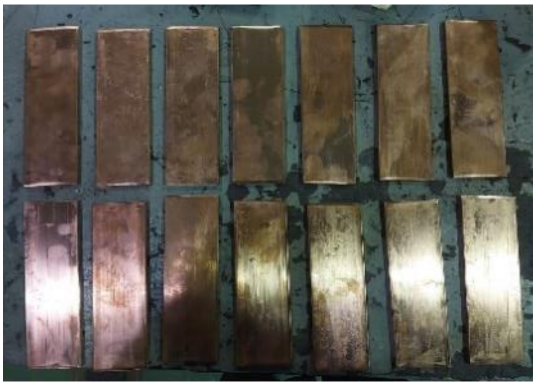


Figure 7. Copper material 150x50x5 mm.

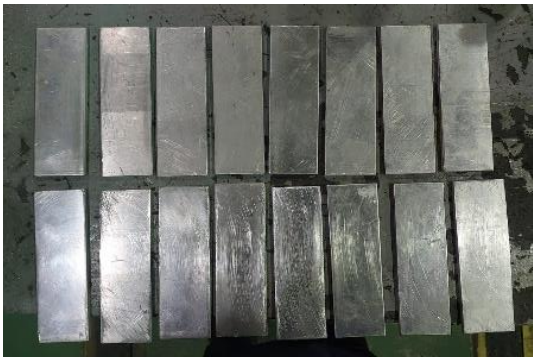


Figure 8. Aluminum material 150x50x5 mm.

2.3.4.2. Creating Tools

The VCN steel tool used has the initial shape of a solid cylinder widely available on the market. Tool making is done according to Figure 9, Figure 10 and Figure 11. The tool has several pin length variations of without pin, 5, and 7 mm, with the pin diameter made the same at 5 mm and the shoulder diameter of 20 mm.

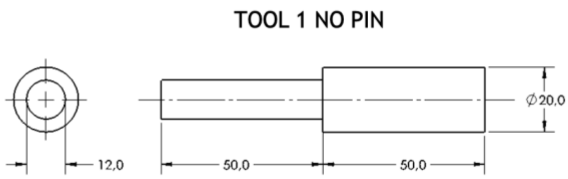


Figure 9. Pinless shoulder.

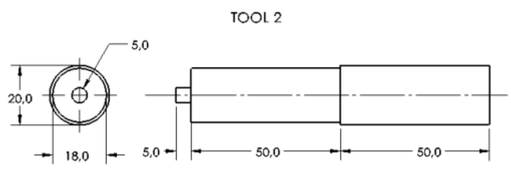


Figure 10. Shoulder with 5 mm x 5 mm pin.

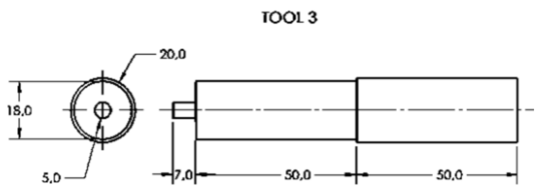


Figure 11. Shoulder with pin size 7 mm x 5 mm.

2.3.4.3. Jig Manufacturing Process

The design of jigs and fixtures is adjusted and specialized to hold and support certain workpieces. The fixture usage plan used in this research process is clamping. Figure 12 is the clam kit used in the machining process, and Figure 13 is the base kit.

Figure 12. Clamping Kit used in the FSSW process.

Figure 13. Base Kit used in the FSSW process.

2.3.4.4. Heat isolator

Gaskets are inserted on all surfaces between the bottom surface of the base kit and the milling machine table. Gaskets or packing used are non-asbestos gaskets or gaskets with a mixture of aramid/Kevlar/twain materials. Figure 14 shows the gasket before use and Figure 15 after use.

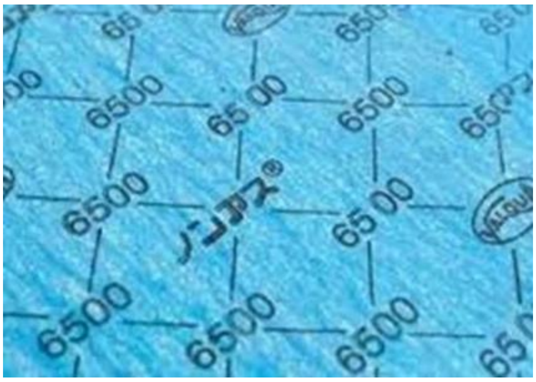


Figure 14. Gaskets used in the FSSW process.

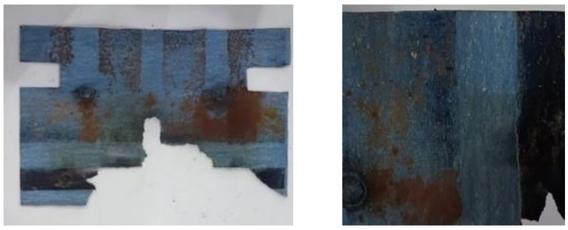


Figure 15. Condition of the gasket after being used in the FSSW process.

2.3.4.5. Proses Friction Stir Spot Welding

Friction stir spot welding uses a vertical milling machine with a 900, 1200, and 1500 rpm rotation.

2.3.5. Hardness Testing and Microstructure

2.3.5.1. Preparation of Specimens for Testing

Before testing, the research specimens were cut and cross-section into three parts. The cut parts are leveled using a file, and the welding results are smoothed using sandpaper.

2.3.5.2. Hardness Testing

Hardness testing uses the Vickers method with a Universal Hardness Tester machine. This method is appropriate for soft materials such as Aluminum. The standard used in this test is ASTM E384. The indenter used is a pyramid-shaped diamond with a loading of 294 Nf (Newton Force) or equivalent to 29.9797 kgf (kilogram-force) with a loading time (dwell time) of 15 seconds (ASTM, 2017). Figure 16 is one of the hardness test shots of FSSW material.

2.3.5.3. Microstructure Image

This test is carried out based on the intensity of the reflected light from the metal surface to the inside of the microscope, which causes different images to be seen (bright, slightly bright, dark) (Akramifard *et al.*, 2014).

Before micro photos, the material that has undergone the FSSW process is smoothed (polished) and then etched with a Nitric acid (HN03) chemical solution. Determination of parts taken for micro photos are determined in Figure 17.

Figure 16. Hardness testing.

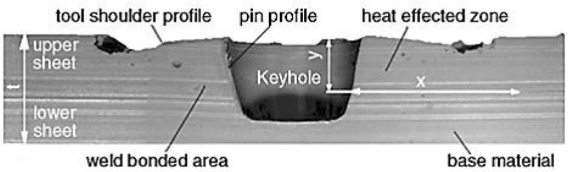


Figure 17. Microphoto position of the test sample (Bilici, 2012).

3. RESULTS AND DISCUSSION

The results and discussion present a description of the research data equipped with tables and figures. The result data obtained is analyzed and explained in detail the causes and effects of the data obtained and related to relevant reference sources.

3.1. Visual Observation of Friction Stir Spot Welding Results

The welding results with the friction stir spot welding method make different top appearances due to the influence of different rotational speeds and pin dimensions given in the welding process, which is also already stated and supported in the article that Friction stir spot welding (FSSW) is a variation of linear Friction Stir Welding (FSW) along the surface (Shen, Ding and Gerlich, 2020), as shown in Figures 18, Figure 19, and Figure 20.

Figure 18. Samples A1, A2, and A3 top view of FSSW welding results with 5 mm pin 5.1 mm welding depth.

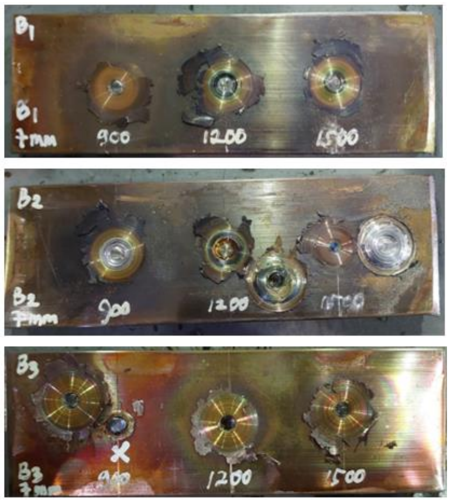


Figure 19. Samples B1, B2, and B3 top view of FSSW welding results with 7 mm pin welding depth of 7.1 mm.

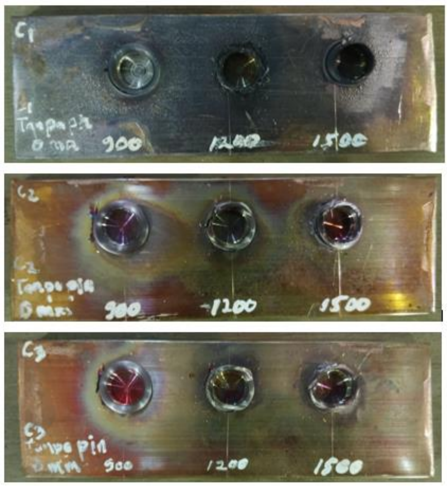
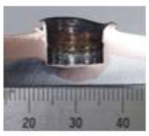
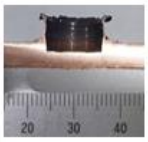
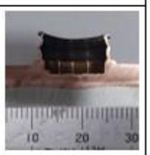
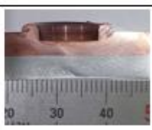
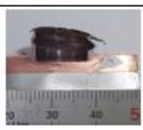
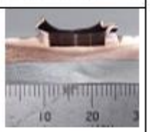
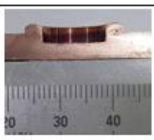
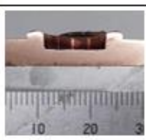
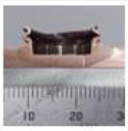
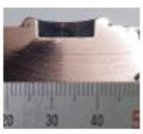
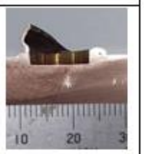


Figure 20. Samples C1, C2, and C3 top view of FSSW welding without pin (0 mm) welding depth of 2 mm.

3.2. Results of Macro Photographs of Weld Cross Sections

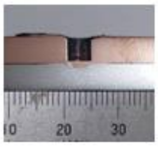
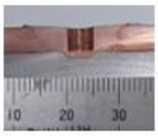
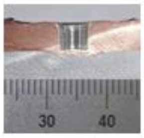
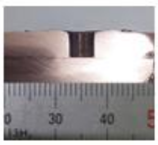
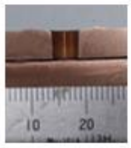
The results of welding with the friction stir spot welding method after cutting and sanding produce an appearance as in Table 1, Test sample C1 was the first trial before determining the depth of ingestion during the FSSW process, so the resulting depth differed from the other test samples samples as described in article that carbon galvanized steel using friction stir spot welding. Three conical pins with varying lengths (short, medium, and long) were utilized, along with different dwell times and rotation speeds of the tool. The objective of this research was to compare the simultaneous effects of several important process parameters on mechanical and welding properties (Feizollahi and Moghadam, 2023).

Table 1. Samples with tool without pin (0 mm).

Replication Code	Pin Length 0 mm		
	900 rpm	1200 rpm	1500 rpm
C1 Cu-Al			
C2 Cu-Al			
C3 Cu-Al			
Cu-Cu			

This different for each parameter imposed on the welding process. All welding processes show that at the initial point of welding, there are traces of initial penetration of the tool in the welded area so that the sheet widens due to the tool's pressure. This is shown in the pictures in Table 1. Starting from C1 (Cu-Al), C2 (Cu-Al), C3 (Cu-Al), Cu-Cu and Al-Al. In Figure C1 (Cu-Al), with a rotation speed of 900 rpm and a pressing depth of 6 mm, the perfect mixing of copper and aluminum is seen compared to other parameters. Along the joint, it does not connect perfectly with the visible gap from the two sides of the sheet that has been welded.

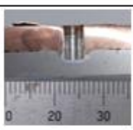
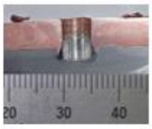
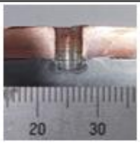
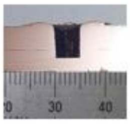
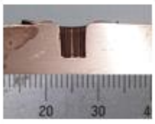
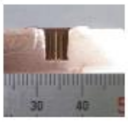
Table 2. Sample with 5 mm pin length tool.

Replication Code	Pin Length 5 mm		
	900 rpm	1200 rpm	1500 rpm
A1 Cu-Al			
A2 Cu-Al			
A3 Cu-Al			
Cu-Cu			

The results of welding with the friction stir spot welding method after cutting and sanding produce an appearance as in Table 2, which is different for each parameter imposed on the welding process. All welding processes show that at the initial point of welding, there are traces of initial penetration of the tool in the welded area due to the pressure of the tool, which is shown in the pictures in Table 2 starting from A1 (Cu-Al), A2 (Cu-Al), A3 (Cu-Al), Cu-Cu, Al-Al, and Al-Cu. Comparison of welding results between all specimens can be seen visually. There is perfect and less perfect diffusion in each test specimen, such as in test specimens rotated 900 rpm A1 (Cu-Al), A2 (Cu-Al) shows mixing between copper and aluminum, which is arguably quite good, and in test specimens with 1200 rpm on A3 (Cu-Al) shows mixing between copper and aluminum which is arguably quite good.

Meanwhile, the different parameters show fusion imperfections in the welding mixture area, which is not perfectly stirred to form a joining, which is visible in the picture in Table 2 where the welding area is included. This is because the mixture should melt and stir upwards to join and form a surface on the welded sheet.

Table 3. Sample with 7 mm pin length tool.

Replication Code	Pin Length		
	7 mm		
	900 rpm	1200 rpm	1500 rpm
B1 Cu-Al			
B2 Cu-Al			
B3 Cu-Al			
Cu-Cu			

The results of welding with the friction stir spot welding method after cutting and sanding produce an appearance as in Table 3, which is different for each parameter imposed on the welding process. All welding processes show that at the initial point of welding, there are traces of initial tool penetration in the welded area due to the tool's pressure. This is shown in the images in Table 3, starting from A1 (Cu-Al), A2 (Cu-Al), A3 (Cu-Al), Cu-Cu, Al-Al, and Al-Cu. These results are different compared to the previous results using the tool without a pin (0 mm) and the tool with a 5 mm pin. For the results of stirring with a pin length of 7 mm, there is a perfection of fusion in the weld mixture area as shown in Table 3. The size of the pin affects the perfect stirring to form the joining, which is visible in the figure in Table 3, where the weld area is formed.

3.3. Microstructure Observation

The determination of parts taken for micro photos are determined in position 1, namely the base metal (BM), position 2, namely the stir zone, position 3, namely the HAZ section as described in Figure 21 from the Cu-Al, Cu-Cu, Al-Al, and Al-Cu.

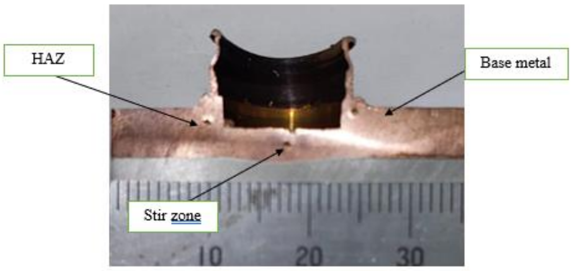
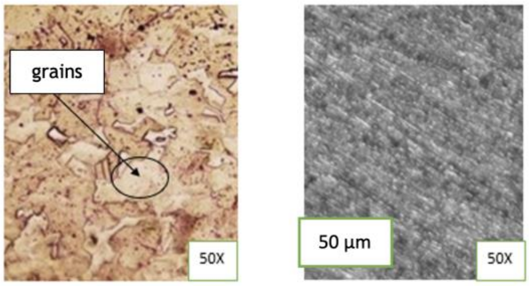


Figure 21. Position for a micro photo of the test sample.

3.3.1. Base Metal

Base metal is an area that is not affected by the welding heat of either the mortar or the heat generated.



(a) (b)

Figure 22. Microstructure of base metal material (a) Copper, (b) Aluminum.

In Figure 22, (a) the base copper base metal the black particles and square grains are Cu_2O, while in an image (b) shows aluminum base metal, and the evenly distributed black particles are $FeAl_3$.

3.3.2. HAZ (Heat Affected Zone)

The HAZ region is an area that undergoes a thermal cycle but does not undergo plastic deformation, in this area there are also changes in microstructure. The HAZ area will change grain size, where the size is influenced by material characteristics, temperature, welding process, and cooling rate.

In Figure 23, the HAZ grain size of Cu-Cu welding experiences a slight change in grain size getting bigger compared to the base metal Cu material. While in the Cu-Al and Al-Al welding HAZ area the size of the copper grain structure is smaller than the grain size in the base metal area.

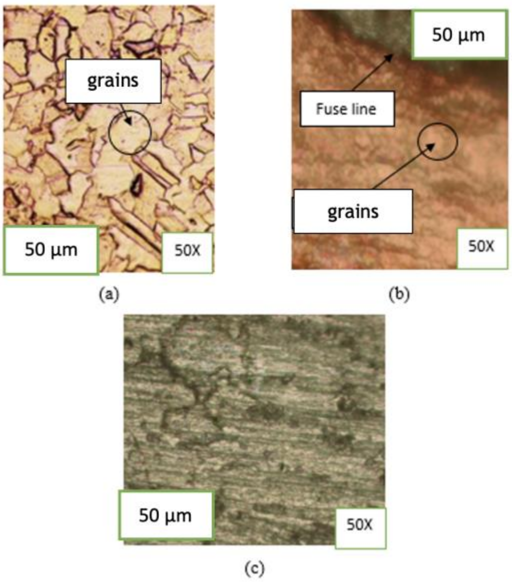


Figure 23. Microstructure of HAZ (a) Cu-Cu, (b) Cu-Al and (c) Al-Al.

The study aimed to investigate the heat generation in FSSW (Friction Stir Spot Welding) of aluminum and copper alloys. This was done by creating bead spot welds on plates using both pinless and pinned tools with the same diameter and varying rotational speeds. The results showed that tool diameter is the main process parameter governing heat generation for rotational rates higher than 600 rpm. The rotating tool transfers heat to the surface of the aluminum and copper plate material. Welding temperature thresholds were identified, depending on the rotational speed and the aluminum alloy being welded, with respect to the tool diameter. It was found that the temperature in FSSW can be controlled by using an appropriate combination of rotational speed and tool dimensions for aluminum and copper alloys subjected to temperature rise (Andrade *et al.*, 2021).

3.3.3. Stir Zone

The Stir Zone is the area directly affected by the heat generated during welding and the deformed area due to the stirring process of the pin tool. Welding and the deformed area due to the stirring process of the pin tool.

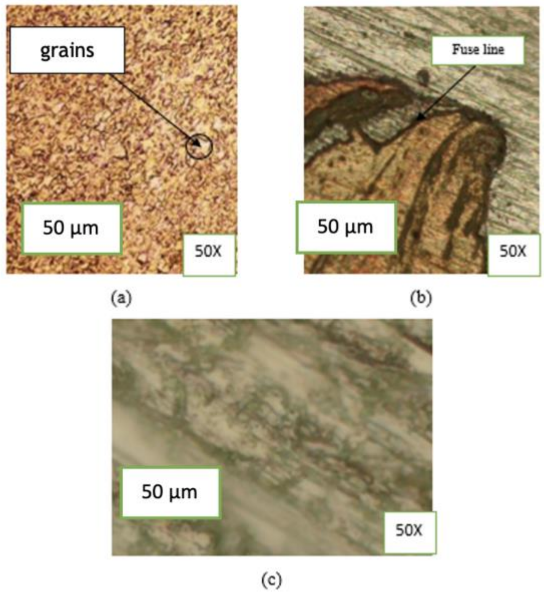


Figure 24. Microstructure of Stir Zone Region, (a) Cu-Cu welding, (b) Cu-Al welding, (c) Al-Al welding

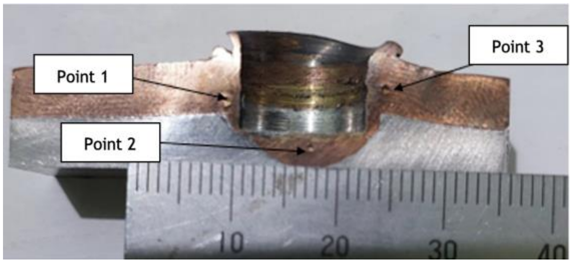
In Figure 24, it can be seen that the microstructure of the stir zone area of all welding results has changed the grain size to be very small and looks smooth compared to the HAZ and base metal areas, and also in welding Cu-Cu, Al-Al materials, this is due to the influence of high temperatures by the pin tool as a stirrer and shoulder as preheating during the welding process and for different Cu-Al materials, the grain boundaries are not very visible due to the lack of polishing so that only the stretch marks are visible in the material mixture.

3.4. Hard Test on Welded Cross Sections

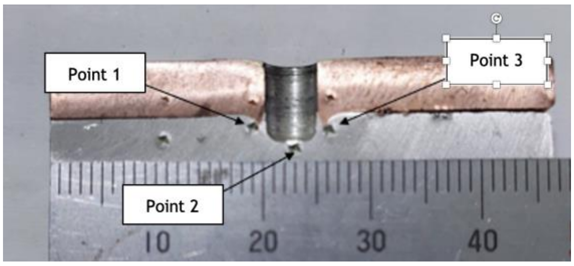
Microstructure testing was carried out at the Metallurgical Laboratory of Trisakti University. The determination of parts taken for microphotographs are determined in position 1, namely the point 1 section, position 2, namely the point 2 section, position 3, namely the point 3 section as described in Figure 25.

3.5. Hardness Test Results

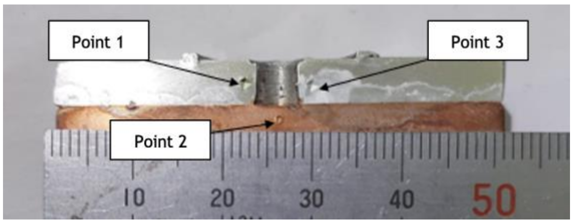
The following are the results of hardness testing on the welding results at indentation points 1, 2 and 3 with the friction stir spot welding method in Table 4 and Table 5.



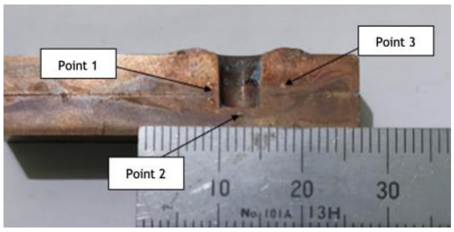
(a) Indentation points on Cu-Al material without pins



(b) Indentation point on 7 mm Cu-Al material



(c) Indentation point on 5 mm Al-Cu pin material



(d) Indentation point on 7 mm Cu-Cu pin material

Figure 25. Indentation points of samples.

Table 4 is the average hardness value obtained from several indentation points, namely at points 1, 2, and 3, each of which is taken from Cu-Cu, Cu-Al, and Al-Cu materials. Then, the average value is taken to produce a value as in Table 5.

Table 4. Hard test values of test samples in Cu-Cu, Cu-Al, Al-Cu materials.

Zone	HVN Hardness Value in Materials		
	Cu-Cu	Cu-Al	Al-Cu
Point 1	83.3	70.2	69.7
Point 1	78.1	71.4	66.1
Point 1	76	70.8	67,4
Point 3	67.8	71.7	71.1
Point 3	72.1	72.5	69.5
Point 3	71.3	72.7	73.1
Point 2	90.9	77.2	74.1
Point 2	105.9	76.6	73.5
Point 2	108.1	79.4	72.4
Point 3	73.9	50.4	66.6
Point 3	71.7	51.2	68.5
Point 3	67.5	49.6	71.2
Point 1	75.86	48.7	64.2
Point 1	75.72	48.1	65.4
Point 1	72.4	48.3	64.7

Table 5. Average values of hard test on test samples in Cu-Cu, Cu-Al, and Al-Cu materials

Materials	Point 1	Point 3	Point 2	Point 3	Point 1
Cu-Cu	79.16	70.4	101.63	71.03	74.66
Cu-Al	70.8	72.3	85.07	50.4	48.37
Al-Cu	67.73	71.23	73.3	68.76	64.76

Figure 26 as shown histogram of hard test results in the welding process produces a distribution of hardness in Vickers testing as in Figure 27 as a graph of the average value of hard test on test samples in Cu-Cu, Cu-Al, and Al-Cu materials. The average hardness test results show that the point 2 areas all have the highest hardness value compared to other areas, namely point 1 and point 3 area.

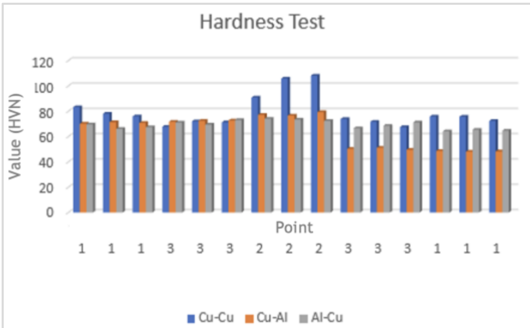


Figure 26. Histogram of hardness test.

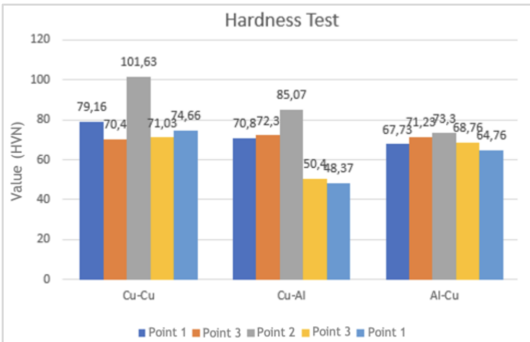


Figure 27. Average hard test results.

In the Cu-Cu specimen, there is a slight decrease in hardness from the base metal to the HAZ area, and this is because it experiences softening, which is influenced by the heat from the welding process. It can be seen from the results of the micro photo that the grain size looks more significant than the base metal grains because the smaller the grain size, the greater the hardness value and vice versa. In Figure 27 the highest hardness value is found in Cu-Cu welding, with an average hardness value of 101.63 HVN at point 2. The lowest hardness value is found in aluminum material, with an average hardness value of 48.37 HVN in point 1 area.

4. CONCLUSION

FSSW can be applied to sheets with several parameters that need to be considered. Based on observations of FSSW welding joints variations in pin tool length are very influential, the use of pin tools that are too short or without pins results in a less-than-optimal connection.

Pin tool with a length of 7 mm found the welding results are quite optimal. The rotational speed of 1500 rpm obtained the largest hook compared to the rotational speed of 900 to 1200 rpm in the pinless FSSW welding results. Then the more the rotational speed increases, the greater the Vickers hardness value on the aluminum part closest to the center of the nugget.

From the results of the distribution of hardness values, the lowest hardness was obtained by test sample A (5mm pin) at A1 900 rpm, namely 72.91 HV30, while the highest hardness value was obtained by test sample A (5 mm pin) at A3 1500 rpm, namely 76.94 HV30. The lowest hardness was obtained by test sample B (7 mm pin) at B1 900 rpm, 72.89 HV30, while the highest hardness value was obtained by test sample B3 1500 rpm, 79.33 HV30. The test result for test sample C (0 mm pin) at C1 900 rpm, namely 65.80 HV30, while the highest hardness value was obtained by test sample C (0mm pin) at C3 1500 rpm, namely 69.12 HV30.

Based on the results of hardness testing, the highest hardness value is found in Cu-Cu welding with an average hardness value of 101.63 HVN at point 2. The lowest hardness value is found in aluminum material with an average hardness value of 48.37 HVN in point 1.

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