

*Micro-friction stir spot welding ( $\mu$ FSSW) is one type of welding that is suitable for joining lightweight materials. One of the challenges in joining lightweight materials with  $\mu$ FSSW is that the material is easily perforated, or the joint is not strong enough, so it is necessary to select the right  $\mu$ FSSW parameters. In this article discusses about investigates the micro-Friction Stir Spot Welding ( $\mu$ FSSW) parameters on weld geometry, mechanical properties, and metallography on dissimilar materials of AZ31B and AA1100. The material thickness of the AZ31B and AA100 is 0.5 mm and 0.32 mm, respectively. The  $\mu$ FSSW tool is made of high-speed steel (HSS) with a pin diameter of 0.25 mm and a shoulder diameter of 0.5 mm. The constant process parameters of the  $\mu$ FSSW joint used, i. e., plunge depth, dwell time, plunge rate, and high tool rotational speed of 33,000 rpm. Welding test results include weld geometry, mechanical properties, and metallography. Weld geometry testing to determine the weld nugget diameter. The mechanical properties test was shear tensile test and cross tensile test, while the metallographic test included macrostructure and microstructure observations. The results of the FSSW weld geometry show that at a dwell time of 700 milliseconds and a plunge depth of 600 microns, the weld pin diameter and weld shoulder diameter are close to the pin diameter and the diameter of the shoulder tool used. Dwell time and plunge depth has a significant effect on tensile strength. The maximum shear and cross loads achieved were  $387 \pm 17$  N and  $29 \pm 2$  N, respectively. Intermetallic compounds (IMC) are observed at the interface of the two materials, while a dwell time of 700 milliseconds give the effect of cracks on the inside of the weld*

**Keywords:** *micro-Friction Stir Spot Welding ( $\mu$ FSSW), dissimilar material, AA1100, AZ31B*

# IDENTIFYING THE EFFECT OF MICRO FRICTION STIR SPOT WELDING ( $\mu$ FSSW) PARAMETERS ON WELD GEOMETRY, MECHANICAL PROPERTIES, AND METALLOGRAPHY ON DISSIMILAR MATERIALS OF AZ31B AND AA1100

**Semuel Boron Membala**  
Doctoral Student\*

**Onny Sutyono Sutresman**  
Doctorate, Professor\*

**Hairul Arsyad**  
Corresponding author

Doctorate, Assistant Professor\*

**Muhammad Syahid**  
Doctorate, Assistant Professor\*

**Agus Widianto**  
Doctorate, Head of Autobody Workshop and Painting Laboratory  
Department of Automotive Engineering Education  
Faculty of Engineering  
Universitas Negeri Yogyakarta

Jl. Colombo No. 1, Karang Gayam, Caturtunggal, Kec. Depok,  
Kabupaten Sleman, Daerah Istimewa Yogyakarta, Indonesia, 55281  
E-mail: aguswidianto@uny.ac.id

\*Departement of Mechanical Engineering  
Faculty of Engineering  
Hasanuddin University

Jl. Poros Malino KM., 6, Bontomarannu Gowa,  
Sulawesi Selatan, Indonesia, 92171

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## 1. Introduction

Lightweight materials often used as structural materials for manufacturing a vehicle are aluminum alloys and magnesium alloys. The properties of aluminum alloys include lightweight materials, high strength, and easy to form. In comparison, the properties of magnesium alloys include having a lower density than aluminum alloys and being the lightest material for structural materials. Combining these two materials is a promising

alloy if appropriately manufactured for structural materials in automotive applications [1]. Several researchers have carried out various welding technologies to unite these two materials. Liquid-state welding is considered less suitable for welding these two materials because it can damage the mechanical properties, solidification cracks, high residual stresses, and high levels of intermetallic compounds in the weld [2, 3].

The FSW process is widely used for its excellent strength and ductility and for minimizing residual stresses and warp-

ing of base metals. FSW has been recognized as the most important development of metal welding technology in 10 years and is a “green technology” due to its energy efficiency, environmental friendliness, and versatility. Compared to traditional welding processes, FSW consumes much less energy. In addition, this is an environmentally friendly process as it does not use any inert gas or flux. So far, the process of welding aluminum with a thickness of less than 1,000  $\mu\text{m}$  is still under development [4].

Using inappropriate parameters in the Micro Friction Stir Weld ( $\mu\text{FSW}$ ) welding process may not optimize the mechanical properties, residual stresses, and defects such as: B. Defects of hooks [5]. The friction stir welding process between AA2024 and AA7075 using a lap joint type connection produces voids when the AA2024 series is on the top (front), while the AA7075 series has stronger mechanical properties voids occur at (front). This is not the case. The shear stress in the welded joint increases with increasing welding speed [6]. Friction stir welding (FSW) is superior to fusion welding when welding dissimilar metals. FSW offers many advantages in reducing welding defects such as punching, segregation, cracking, and IMC formation [7]. Due to these attractive advantages, FSW is widely used for welding dissimilar metals [8]. A lot of research has been done on FSW for aluminum and steel.

The key to success in FSW welding lies in the tool design, and welding parameters used [9]. In addition, the type of material and thickness are also other factors for the success of FSW welding. The most commonly used material is aluminum. FSW welding on aluminum material with a thickness of  $<1$  mm has been successfully carried out using the high-speed tool rotation method [10]. Joining dissimilar materials does have its challenges. First, where must understand each material's mechanical and thermal properties. From several studies related to the joining of dissimilar materials using the FSSW method, it is still relevant to use today. Therefore, the research shown to investigate the welding parameters of FSSW on aluminum and magnesium materials is still relevant.

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## 2. Literature review and problem statement

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Friction stir welding (FSW) is solid-state welding that can connect aluminum alloy materials and magnesium alloys well. FSW with the material below 1000 microns is also called Micro Friction Stir Welding ( $\mu\text{FSW}$ ), which was first discovered by TWI 1991 [9]. FSW has been proven to be able to join several similar materials such as aluminum alloys [10, 11], steel alloy [12], magnesium [13], copper [14] dan titanium [15]. Paper [10] reports on using FSSW to weld aluminum materials with a thickness of less than 1 mm. FSSW welding parameters such as plunge rate and dwell time are investigated for their effect on weld quality. The results showed that the dwell time did not significantly influence the maximum temperature in the center of the weld. However, the plunge rate affects the material's hardening and softening.

The steel alloy material can also be connected using FSSW. The paper [12] examines microstructure evolution after the FSSW welding process. The results showed that the Stir Zone (SZ) area had a finer grain size than other areas. Subsequent research used AZ61 magnesium material with a thickness of  $>1$  mm [13]. The varied FSSW welding param-

eters are rotational speed and dwell time tools to see their effect on mechanical and microstructure properties. Increasing the dwell time can improve its mechanical properties while the grain size formed in the SZ area is always small.

In addition, FSW is also effective for welding dissimilar materials such as Mg/Al [1], Al/steel [16], Mg/steel [17], Al/Cu [18] dan Al/brass [19]. The joining of dissimilar materials between Al 6061 and AZ31B has been successfully carried out with a thickness of  $>1$  mm with the formation of intermetallic compounds (IMCs) in the weld zone [1]. Another study between magnesium and steel coupled with zinc between the two materials can improve weldability and quality [17]. FSSW is also effective for joining different materials between aluminum and steel. From several journal reviews [16], it is stated that there are at least three techniques that can be used to connect Al-steel with FSSW, including the annealing technique, plunging technique, and diffusion technique. Other FSSW studies using different materials are aluminum and copper [18]. This study's results indicate the presence of IMCs at the interface of the two materials. In addition, increasing the dwell time can increase the heat input while the hardness value increases in the SZ area.

Several researchers have conducted several studies on dissimilar materials between aluminum and magnesium [1, 20]. The paper [21] reported that intermetallic compounds (IMC) were formed between the surfaces of the two materials, increased welded joints, and decreased weld cracking occurred at low tool speeds. Lap joints are often used for FSW, where the tensile strength of the welded joint increases with increasing tool rotation and travel speeds [1]. In other research [22] used AZ31B-O and A5052P-O materials, where rotation speeds of 1000 rpm produce a maximum tensile strength of 132 MPa.

The paper [23] presents the results of research friction stir spot welding of AZ31 to microstructure and mechanical properties. Shown, that the rotation speed and residence time are increased, the depth of the stirring zone gradually increases. Defects in the hook extend from the interface between the two plates to the surface of the top plate. But there are unresolved problems related to mechanical properties which are still low. The reasons for this may be (objective difficulties related to rotational speed and tool dimensions and tool materials which make relevant research impractical, etc.). The way to overcome these difficulties can be done by using a higher tool rotation speed and a variety of FSSW welding parameters. This approach is used in [10] but the material used in this study is aluminum. All this indicates that it is advisable to carry out a study to investigate the effect of FSSW parameters on dissimilar materials between AZ31B and AA1100.

Many researches on micro Friction Stir Welding ( $\mu\text{FSW}$ ) has been carried out for similar materials such as aluminum alloys [10]. There are several parameters to consider in  $\mu\text{FSW}$ , such as tool geometry, tool rotation, travel speeds, and downward force [23]. However, from several studies that have been carried out,  $\mu\text{FSW}$  research on spot joints with dissimilar materials between magnesium and aluminum has not been widely carried out. So, this study aims to determine the effect of micro-Friction Stir Spot Welding ( $\mu\text{FSSW}$ ) process parameters on weld geometry, mechanical properties, and metallography of aluminum and magnesium alloys with high tool rotation speed. Weld geometry is indicated by the diameter of the weld nugget and the penetration depth, while the welded joint's strength indicates the mechanical properties.

Metallographic observations included macrostructural and microstructural tests by a cross-section of the specimen.

**3. The aim and objectives of the study**

The aim of the study is identifying the effect of micro-Friction Stir Spot Welding ( $\mu$ FSSW) parameters such as dwell time and plunge depth on weld geometry, mechanical properties, and metallography. This will make it possible to join dissimilar materials between magnesium (AZ31B) and aluminum (AA1100).

To achieve this aim, the following objectives are accomplished:

- to investigate the weld geometry produced after the welding process;
- to investigate the weld's mechanical properties (shear tensile and cross tensile);
- to investigate the macrostructure and microstructure welds results.

**4. Material and method of experiment**

This study uses dissimilar materials between aluminum AA100 and magnesium AZ31B in micro-Friction Stir Spot Welding ( $\mu$ FSSW) with plate thicknesses of 0.32 mm and 0.5 mm, respectively. Chemical composition tests for AA100 and AZ31B materials have been carried out using an optical emission spectrometer (OES), and the results are shown in Table 1. Before welding, both materials were cleaned using acetone to remove any remaining dirt or dust on the plate surface.

Table 1

Chemical composition (wt %) of AA1100 and AZ31B

AA1100	Al	Zn	Mn	Fe	Si	Cu	Ti	Mg
	99.1	0.070	0.043	0.471	0.109	0.057	0.012	0.019
AZ31B	Al	Zn	Mn	Fe	Si	Cu	Ni	Mg
	3.10	0.99	0.30	0.0029	0.014	0.0009	0.00063	Balance

The welding joint used is spot welding on  $\mu$ FSSW. Specimens were prepared for three tests (shear load, cross tensile load, and metallography) with different dimensions. The dimensions of the specimen for the shear load test are shown in Fig. 1, *a*, with a length of 50 mm and a width of 25 mm. Fig. 1, *b* shows the dimensions of the specimen for the cross tensile load test with a length of 125 mm and a width of 25 mm. Meanwhile, the specimen dimensions in Fig. 1, *c* are 30 mm long and 25 mm wide for metallographic testing. Each test specimen was replicated three time.

The tool used for  $\mu$ FSSW is shown in Fig. 2. The tool material used is made of HSS, which is prepared by turning machining, which has a shoulder diameter of 4.95 mm, pin diameter of 2.54, and pin height of 0.65 mm. The friction stir spot welding machine in this study uses a tensile test machine, a modified result of the EMCO CNC TU-3A milling machine, with an accuracy of 0.01 mm. In contrast, the spindle used comes from a Maktec turner drill machine type MT912 with a die grinder specification of 6 mm, and the spindle rotation speed without load is 33,000 rpm. Table 2 shows the parameters of the  $\mu$ FSSW welding process used in this study.

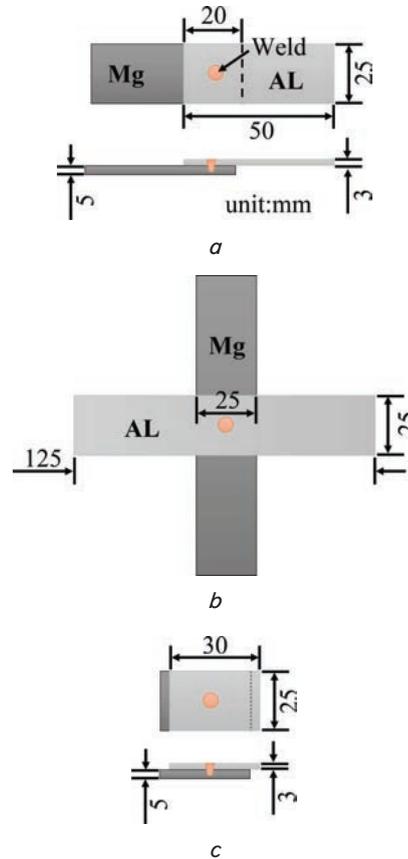


Fig. 1. Dimensions of the specimen for testing: *a* – shear load; *b* – cross tensile load; *c* – metallography

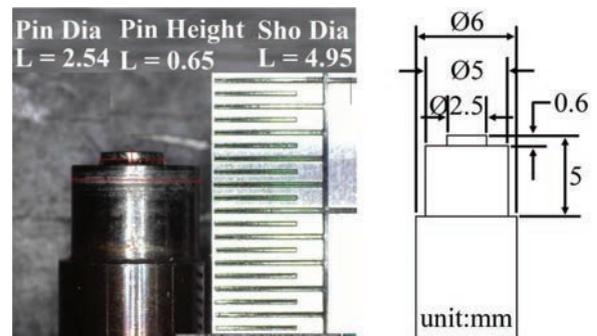


Fig. 2. Dimension tool of micro-Friction Stir Spot Welding

Table 2

Parameter process of  $\mu$ FSSW

No.	Dwell time (milliseconds)	Plunge depth (microns)	Plunge rate (mm/s)
1	300	400	0.4
2	300	500	
3	300	600	
4	500	400	
5	500	500	
6	500	600	
7	700	400	
8	700	500	
9	700	600	

Weld geometry testing is done by measuring the diameter of the weld nugget, the area of Thermo-Mechanically Affected

Zone (TMAZ), and the depth of penetration. Measurement of weld nugget diameter and area of TMAZ using a digital microscope (Dino-Lite AM 4115 Series) while measurement of penetration depth using caliper and caliper attachment. Shear tensile and cross tensile tests were carried out CNC machine A&D tension machine with a capacity of 50 KN using a displacement rate of 0.2 mm/min and 3 mm/min for shear tensile test and cross tensile test, respectively. Metallographic observations were made by cutting the weld crosswise, and then the specimen was mounted with resin. Furthermore, the specimens were sanded to a roughness of 2000 and polished using TiO<sub>2</sub>+acetone solution to bring out the microstructure of the welding results using etching with Keller's reagent. The macrostructure was observed using a digital microscope (Dino-Lite AM 4115 Series), while the microstructure was observed using the Oxion Inverso OX 2153-PLM optical microscope.

**5. Results of experiment the weld quality of dissimilar material AZ31B-AA1100 using micro-Friction Stir Spot Welding**

**5.1. Result of weld geometry**

The results of the  $\mu$ FSSW weld are shown in Fig. 3. There are three samples for the test specimen, including shear tensile (Fig. 3, a), cross tensile (Fig. 3, b), and metallography (Fig. 3, c). Each specimen was replicated three times for each parameter variation.

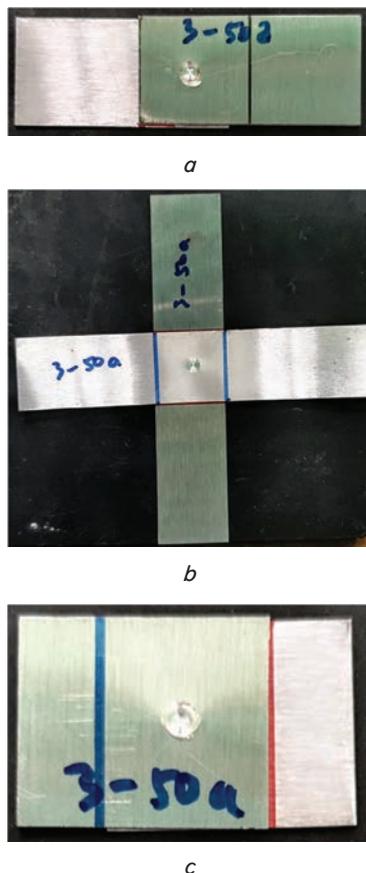


Fig. 3. Micro-Friction Stir Spot Welding weld results for test specimens: a – shear tensile; b – cross tensile; c – metallography

Weld geometry testing on  $\mu$ FSSW can be seen from the nugget diameter (pin diameter and shoulder diameter), measured plunge depth, and TMAZ area. Variations of  $\mu$ FSSW parameters used are dwell time (DT) in milliseconds and plunge depth (PD) in microns. Fig. 4 shows the results of the  $\mu$ FSSW weld on the top view and the measurement of the nugget diameter. At the same time, the results of  $\mu$ FSSW on the back view and TMAZ area measurements are shown in Fig. 5.

DT (ms) \ PD (micron)	300	500	700
400			
500			
600			

Fig. 4. Weld results from micro-Friction Stir Spot Welding on top view and nugget diameter measurement

DT (ms) \ PD (micron)	300	500	700
400			
500			
600			

Fig. 5. Welding results from micro-Friction Stir Spot Welding on back view and Thermo-Mechanically Affected Zone area measurement

Visually it can be seen that increasing the plunge depth can widen the diameter of the shoulder. However, increasing the dwell time in welding has no significant effect on the diameter of the nugget. This is due to the height of the pin tool used being 654 microns so if the plunge depth is increased, it will hit the shoulder part of the tool, which has a diameter of 4.954 mm. Adding the plunge depth and dwell time greatly affects the TMAZ area. It can be seen that the longer the

welding takes place, the wider the TMAZ area will be more visible and larger on the back of the weld.

The results of the measurement of the  $\mu$ FSSW weld geometry can be seen in Fig. 6. Fig. 6, *a* shows the results of measuring the diameter of the pin, where there is a trend of increasing the diameter of the pin when increasing the plunge depth and dwell time. The measured pin diameter is close to the diameter of the pin tool used. However, the dwell time of 700 milliseconds produces a weld pin diameter relative to the tool pin diameter. The diameter of the largest welding pin is 2.57 mm with an error of 0.11 % at the dwell time parameter of 700 milliseconds and the plunge depth of 600 microns. This is due to if the welding process lasts longer, it will generate more heat so that it can increase the diameter of the welding pin.

Meanwhile, the measured shoulder diameter is still below the shoulder pin diameter (Fig. 6, *b*). The largest diameter of the weld shoulder is 4.77 mm with an error of 0.13 % at the dwell time parameter of 700 milliseconds and the plunge depth of 600 microns. This is because of the influence of the depth of the plunge used. A low plunge depth will cause the diameter of the shoulder pin not to rub completely against the material so that the diameter of the weld shoulder will be smaller and vice versa. Dwell

time and tool geometry have an effect on weld geometry in  $\mu$ FSSW [24]. The weld geometry will be bigger if the dwell time is increased, as well as changing the tool geometry can also increase the weld geometry.

The measured plunge depth with the plunge depth set on the tool shows a difference, especially at a dwell time of 300 milliseconds (Fig. 6, *c*). However, for a dwell time of 700 milliseconds, the result of the measured plunge depth with the plunge depth set in the dial is appropriate. This is because at a dwell time of 300 milliseconds, the heat generated due to friction between the tool and the specimen is still lacking so that the depth of the plunge that is formed is not maximized. It is different from the dwell time of 700 milliseconds, at this dwell time, the heat received by the specimen is higher because the friction that occurs is longer so that the depth of the plunge is maximized. The TMAZ area is influenced by the depth of the plunge and the dwell time, where both parameters have a straight ratio to the TMAZ area (Fig. 6, *d*). The longer the friction between the tool and the specimen, the greater the heat, causing the TMAZ area to increase. This is also supported by the plunge depth that is getting deeper. The area of TMAZ formed from 5.13 mm<sup>2</sup> to 9.28 mm<sup>2</sup>, with the largest error being 1.24 %.

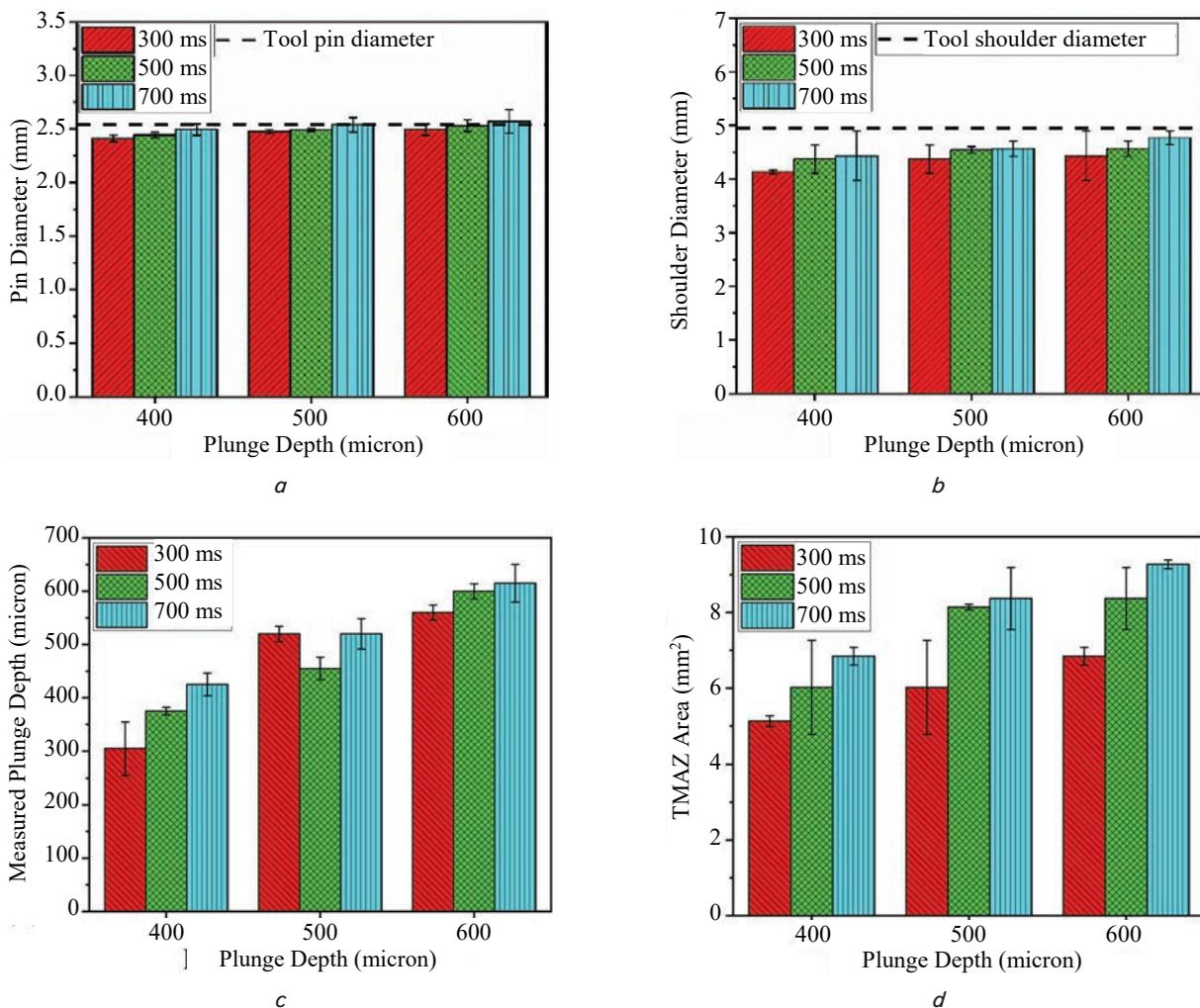


Fig. 6. Weld geometry micro-Friction Stir Spot Welding of: *a* – pin diameter; *b* – shoulder diameter; *c* – measured plunge depth; *d* – thermo-mechanically affected zone area

**5. 2. Result of tensile test**

Mechanical properties testing carried out is a shear tensile test and cross tensile test. The fracture results from the shear tensile and cross tensile tests are shown in Fig. 7 *a, b*, respectively. The results of the tensile test fracture showed a hole in the aluminum specimen. This shows that the joints between dissimilar materials between aluminum and magnesium can be welded using the  $\mu$ FSSW method.

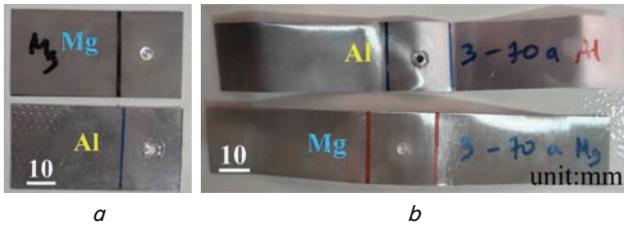


Fig. 7. Fracture modes micro-Friction Stir Spot Welding: *a* – shear tensile; *b* – cross tensile

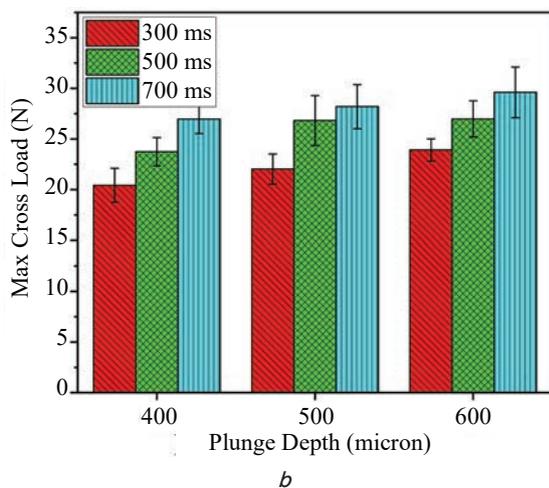
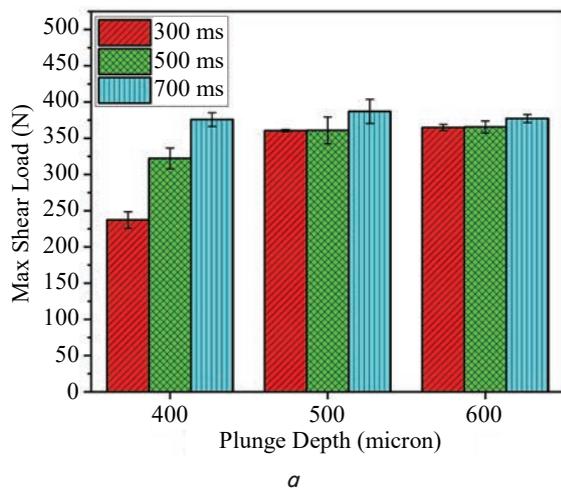


Fig. 8. Tensile test micro-Friction Stir Spot Welding of: *a* – max. shear load; *b* – max. cross load

The tensile test resulted in the maximum shear and cross loads shown in Fig. 8, *a, b*, respectively. The maximum shear load is 387.09 N at a dwell time of 700 milliseconds and a plunge depth of 500 microns with an error of 16.71 %. In comparison, the dwell time of 700 milliseconds and a plunge depth of 600 microns produce the largest maximum cross load of 29.61 N with an error of 2.50 %. Increasing

the plunge depth can increase the maximum load as well as increasing the dwell time can also increase the maximum load of the weld.  $\mu$ FSSW parameters such as dwell time and plunge depth influence the maximum load. By increasing the plunge depth, the joint between the two specimens will be stronger in this case also depending on the thickness of the plate used and the tool. Then the longer the friction between the tool and the specimen will affect the heat and the weld joint’s quality [23]. Dwell time does affect the increase in tensile strength [24].

**5. 3. Result of metallography**

Metallographic testing was carried out on several parameters by cutting the specimen crosswise. Fig. 9 shows the results of metallographic observations at a dwell time of 300 milliseconds and a plunge depth of 600 microns. Aluminum AA100 is placed on the top sheet, while magnesium AZ31B is placed on the bottom sheet. The macrostructural observations are shown in Fig. 9, *a*, which does not show the formation of flashes. However, the plunge depth that is seen still looks very shallow. The dwell time used is still too short, so the welding is not maximized. Furthermore, microstructural observations were carried out in region *b* and region *c* from the results of macrostructural observations.

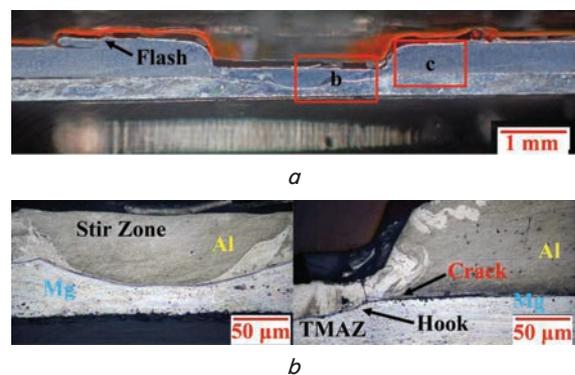


Fig. 9. Metallography of Al-Mg at dwell time 300 milliseconds: *a* – macrostructure; *b* – microstructure of area *b*; *c* – microstructure of area *c*

Fig. 9, *b* shows the microstructure observation in the weld center, where the stir zone is seen on the aluminum sheet. The weld bond between the two dissimilar materials appears to be partially bonded. However, the short dwell time parameter causes less heat input to the stir zone so that the structure formed is not clearly visible and is not fully bonded. Microstructural observations in the weld side area are shown in Fig. 9, *c*. The hook is formed pointing upwards because, during the idle time process, the rotating pins tear the material on the bottom, moving up towards the material on the top sheet. Hook formation or partial metallurgy is generally caused by tearing and breaking of the oxide layer at the interface between two sheets of discontinuous material particles that form the hook [25].

Metallographic observations at a dwell time of 500 milliseconds and a plunge depth of 600 microns are shown in Fig. 10. Macro structurally, a relatively low flash formation can be seen in Fig. 10, *a*. The joint between the two dissimilar materials appears to be well-related macro structurally. Region *b* and area *c* in the observation of the macrostructure will be further observed. Region *b* is located in the middle of the weld (Fig. 10, *b*), while region *c* is located on the side of

the weld (Fig. 10, c). Based on microstructural observations in the center of the weld, it can be seen that the tool penetrates the magnesium material so that the pin diameter causes the aluminum material to run out. In addition, the stir zone is seen on the magnesium sheet with large grains. This excessive depth is caused because the dwell time used is long enough so that the heat input that occurs is relatively high. This causes the aluminum material to run out on the tool pin diameter.

Furthermore, on the side of the weld, a hook is formed in an upward direction. The stir zone can also occur on aluminum sheets and TMAZ on magnesium sheets in this region. The grain size seen in aluminum is smaller than in magnesium. The region of intermetallic compounds (IMC) was also observed to be thin between the two materials. IMC that appears at the interface of magnesium and aluminum alloys [21].

Fig. 11 shows the results of metallographic observations carried out at a dwell time of 700 milliseconds and a plunge depth of 600 microns. Based on the results of macrostructural observations (Fig. 11, a), it can be seen that flash occurs in the side region of the weld. In addition, it is also seen that the aluminum sheet on the side is also lifted up so that the displacement is relatively high. This happens because the dwell time used is very long, causing an increase in heat input between the tool and the workpiece. Due to the heat, the area next to the weld will also be lifted up. The b and c regions of the macrostructural observations were further investigated in Fig. 11, b, c, respectively.

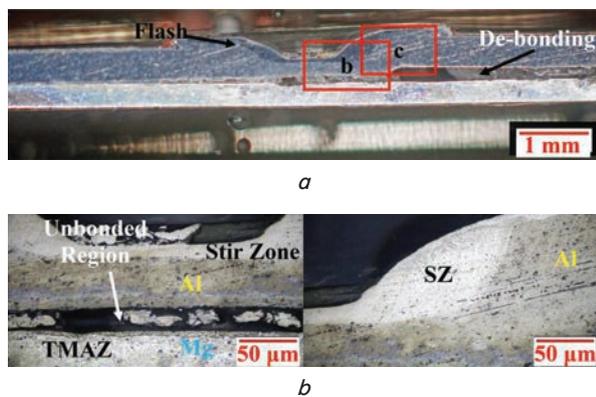


Fig. 10. Metallography of Al-Mg at dwell time 500 milliseconds: a – macrostructure; b – microstructure of area b; c – microstructure of area c

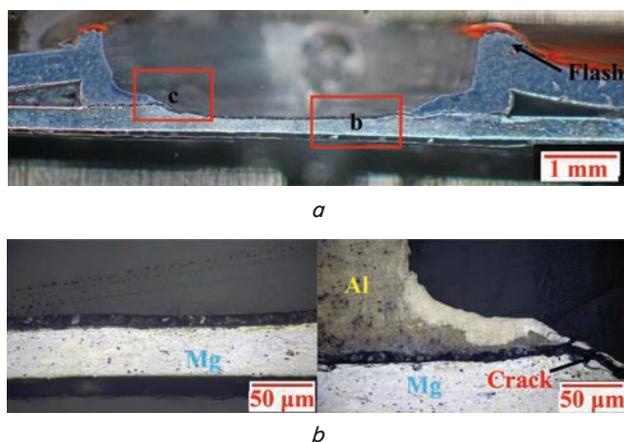


Fig. 11. Metallography of Al-Mg at dwell time 700 milliseconds: a – macrostructure; b – microstructure of area b; c – microstructure of area c

Microstructural observations show a fracture in the stir zone in the center of the weld. The cracks are straight along the stir zone, but there are no cracks in the magnesium sheet. Meanwhile, there are also quite large cracks in the area beside the weld. The observed IMC between the two materials is quite visible, with a fairly strong bond in the middle region of the weld. However, on the side of the weld, the bond is less than perfect due to the cracks that occur. This is because the tool stirs the workpiece for too long, causing cracks to occur in the aluminum sheet. The heat input and grain size in the stir zone are affected by the dwell time of the AZ31 magnesium alloy [26].

## 6. Discussion of the experimental results of the variation parameter micro-Friction Stir Spot Welding for weld geometry, mechanical properties and metallography

The weld shape is checked by measuring the diameter of the weld nugget, which consists of the shoulder diameter and pin diameter. Diameter measurements were carried out using Dino-Lite. Measurements are made at the top and back of the weld. This method has also been used by researchers in previous research on orbital pipe welding [27]. At the top of the plate, it can be seen visually that the shoulder diameter begins to form at a plunge depth of 400 microns and increases at a plunge depth of 600 microns. Mixing time also affects the size of the diameter of the formed shoulder. The two materials were stirred for a long time, increasing heat [10]. The friction between the shoulder and the material creates the weld nugget. Area measurements were carried out on the backside of the plate to see how large the TMAZ area was formed due to changes in dwell time and plunge depth. The deeper the tool is used, the larger the TMAZ area at the back of the plate [24].

The weld shape in the form of pin diameter tends to increase with increasing plunge depth and dwell time. The pin diameter measured is close to the diameter of the pin tool used. The longer the welding process, the more heat is generated and the larger the diameter of the welding pin [22]. The measured shoulder diameter is still below the tool shoulder pin diameter. This is due to the effect of the depth of the seam used. Due to the shallow depth of the plunge, the pin shoulder diameter does not rub completely against the material [13]. Therefore, the diameter of the weld shoulder is smaller and vice versa. The seam depth measured against the seam depth set by the tool makes a difference, especially with a downtime of 300 ms. Due to the dwell time of 300 ms, the heat generated by the friction between the tool and the specimen is insufficient, and the weld depth is not optimal. In contrast to a hold time of 700 ms, this hold time results in longer friction and maximum weld depth, resulting in higher heat absorption of the specimen. In addition, the area of the TMAZ is affected by the plunge depth and dwell time, where these two parameters have a straight ratio to the area of the TMAZ. The longer the friction between the tool and the test object, the greater the heat that will occur, causing the TMAZ area to be larger [1]. A deeper depth of plunge also supports this.

The tensile test provides maximum shear load and maximum cross load. Increasing the penetration depth can increase the maximum tensile strength and increasing the dwell time can also increase the maximum tensile strength of the weld. FSSW parameters such as dwell time and pen-

etration depth affect the maximum tensile strength. As the depth of the plunge increases, so does the joint between the two specimens, depending on the plate and the thickness of the tool used. In this case, the friction between the tool and the specimen has a longer effect on heating and thus on the quality of the weld joint [22]. Dwell time affects the increase in tensile strength [24]. In another study using pipe material with the FSW method [28], adding friction time to a certain value can increase its tensile strength.

The plunge depth phenomenon, which has unique properties mentioned in macrostructural analysis, helps to explain hook formation. It was also previously explained that the hook formation is closely related to the hook formation. Material flow, i. e., spotting during welding. Hooks are also associated with strength. Therefore, it can be discussed in detail about the ultrastructure of each existing tool to find out why this phenomenon occurs. For embedded tools based on the journal [26] and the researcher assumed that there was a maximum weld seam strength [24]. A schematic of the formation of the hook and extrude zone on the plate can be seen in Fig. 12. The shape of the tool with pins produces a strength that varies with the value of the height of the tool. If the height of the tool shape pin is  $X$ , then the  $X+Y$  depth results in the maximum weld strength. This is one of the  $Y$  variables, the maximum strength threshold depth, which can be used to further investigate the maximum strength value for the tool shape with pins or other shapes.

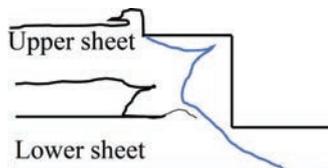


Fig. 12. The schematic of the formation of the hook and extrude zone on the plate [10]

The application of  $\mu$ FSSW welding has been widely applied in several industries, for example the automotive industry in the manufacture of vehicle cabins and bodies. Applications of different materials have also been widely applied. However, if this research is applied in practice, it still has some limitations. These limitations include the need for  $\mu$ FSSW mechanism that is smaller and difficult to use in a narrow space. However, the  $\mu$ FSSW method is very promising to produce better weld quality for different materials with thickness  $<1$  mm.

In this research, no numerical/simulation studies have been conducted. Simulation studies need to be carried out to determine the initial characteristics of several variations of the  $\mu$ FSSW parameter. In addition, this study also has not analyzed the distribution of temperature and axial force that occurs during the welding process. This can actually be done with a simulation study that can be done before taking experimental data. Research development that can still be developed further is to compare the results of simulation studies and experiments on the distribution of temperature, axial force and weld geometry formed after the welding process. This research is one of the opportunities that can be done in further research.

## 7. Conclusions

1. The weld geometry formed in  $\mu$ FSSW is influenced by dwell time and plunge depth, where at a dwell time of 700 milliseconds and a plunge depth of 600 microns the weld pin diameter and weld shoulder diameter are close to the pin diameter and the diameter of the shoulder tool used.

2. Maximum shear load and cross load are strongly influenced by dwell time and plunge depth. The maximum shear load reached  $387 \pm 17$  N at a dwell time of 700 milliseconds and a plunge depth of 500 microns, while the dwell time of 700 milliseconds and a plunge depth of 600 microns produced the largest maximum cross load of  $29 \pm 2$  N.

3. Macrostructural observations show that there is a thin flash at the weld edge while a layer of intermetallic compounds is observed at the interface of the two materials. In addition, a dwell time of 700 milliseconds gives the effect of cracks on the inside of the weld.

## Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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