Effect of Rotational Speed and Flat Tool Diameter on the Zn Distribution of the Dissimilar Metals Friction Stir Spot Welded between Aluminum Alloy 5083 H321 and Galvanized Steel

Bintang Adhi Guna[1], *Nurul* Muhayat[1] and Triyono[1,*]

[1]Mechanical Engineering Department, Universitas Sebelas Maret Surakarta, Indonesia

Abstract. Friction stir spot welding (FSSW) was developed to join the dissimilar materials as an alternative for replacing the resistance spot welding (RSW). In the case of dissimilar metals welded between aluminum and galvanized steel, Zn can decompose and diffuse in both steel and aluminum so it can increase the joint strength. Due to this reason, it is important to explore the Zn distribution based on the parameter of the friction stir spot welding. The lap joint configuration was used in this work where aluminum plate was placed on the top of steel. Aluminum thickness was 3 mm, while steel thickness was 1 mm. The constant depth of plunge, dwell time, and penetration rate were 2.7 mm, 3 seconds, and 0.9 mm/sec respectively. Flat tool with diameters of 10 mm, 12 mm and 14 mm were used for FSSW processes and for each flat tool diameter, four levels of the rotational speed of 1000 rpm, 1200 rpm, 1600 rpm and 2000 rpm were performed. The Zn distribution was evaluated using the SEM and EDS analysis. Due to the heat generation during FSSW process, materials around the tools will soften and then flow to follow the centrifugal force. The rotational speed and the flat tool diameter affected the distance and the shape of Zn diffusion flow. The distance of Zn diffusion both horizontal and vertical direction increased as increasing the rotational speed and the flat tool diameter.

1 Introduction

Recently, automotive industries tend to use lightweight alloy materials to replace traditional steel materials. The use of aluminum alloys has the advantage of reducing body weight which also reduces the resulting gas emissions [1]-[4]. Dissimilar metals weld between aluminum and steel has been developed because it has low density, high strength, and high corrosion resistance. It can be applied in the transportation and automotive industries, such as high-speed trains, shipyards, and aviation. Unfortunately, it has the disadvantage of forming an inter-metallic compound (IMC) in fusion welding due to the considerable differences of thermal and physical properties of both materials [5].

The resistance spot welding (RSW) process is used broadly in sheet metal joint of car body structure. Due to IMC issue in fusion welding process in which there is a metallurgical bond on the welded material, RSW is not recommended for joining dissimilar metals weld between aluminum and steel [6]. Based on the welding geometry, Friction Stir Spot Welding (FSSW) has been proposed to join dissimilar metals weld between aluminum and steel as an alternative to replace Resistance Spot Welding (RSW) [7], [8]. The advantages of the FSSW process are cheap, efficient, with no melting and solidification cycles, small residual stresses and environmentally friendly [9], [10]. Moreover, the lightweight materials can be welded using FSSW with a smaller HAZ area than TIG and laser welding processes. Inclusions and defects in FSSW joints can also be avoided [11].

During the FSSW process, the tool will rotate and scrub directly against the sheet material. The spot joint is obtained by dynamic re-crystallization occurring at the periphery of the joint hole [12]. The rotational speed and the tool diameter are the important parameters of FSSW [13]. These parameters determine the microstructure, nugget formation, mechanical properties and defects of the FSSW joint due to the generated heat, the material flow around the pin, and the joint geometry [14]-[16].

The disadvantages of the FSSW process are a lack of pin penetration depth and low joint capability because there are curves on the interface called hook region [15], [17] or hooking defect [11]. It is due to the overlapping material on the joint and affected by the character of the formed hook area [17]. The providing an interlayer material on the surface of the welded materials can minimize this defect [18].

The galvanized steel is layered by Zn (zinc) with little aluminum and magnesium. They serve to provide a protective coating and increase corrosion resistance of galvanized steel when exposed to atmospheric air. The content of aluminum and magnesium in Zn layer ranges from 0.2-11.0% to 0.1-3.0% in weight [19].

* Corresponding author: triyonomesin@uns.ac.id

In the FSSW of dissimilar metals between galvanized steel and aluminum alloy, the presence of Zn layer has many advantages. Due to the generated heat, Zn melts and moves out to the edge of the stirring zone [20]. It can decompose and diffuse in aluminum and steel materials [21], react with the magnesium to form MgZn and bonding layer at the interface joint, remove the hook defects [22], [23], change the grain size of aluminum and finally increase the joint strength [24].

It is well known that fusion joint of aluminum and steel leads the intermetallic compound (IMC) which interferes the joint strength. In case of dissimilar metals FSSW between aluminum and galvanized steel, Zn is not part of IMC, but it greatly influences and controls the IMC formation. Zn can accelerate the reaction between aluminum and galvanized steel. It may act as a flux which can solve and eliminate the impurities at aluminum and galvanized steel interface.

Based on the important role of Zn on strengthening of the joint, it is important to evaluate the Zn distribution in FSSW of dissimilar metals between aluminum and galvanized steel. There is no previous study which focused on the Zn distribution on the FSSW of dissimilar metals between aluminum and galvanized steel. In this work, the Friction Stir Spot Welding (FSSW) of aluminum A5083-H321 and galvanized steel with a variation of rotation speed and flat tool diameter was performed to evaluate the distribution of Zn in FSSW joint.

2 Methodology

Aluminum alloy 5083-H321 and hot dip zinc coated galvanized steel ASTM A653 with thicknesses of 3 mm and 1 mm respectively were used in this work. The chemical composition of both materials are shown in Table 1 and Table 2 respectively. They were cut in dimension of 35 mm x 35 mm.

Table 1. Chemical composition of AA5083.

Elements	Al	Mg	Mn	Cr	Cu	Fe	Si
%	93.45	4.4	1.0	0.25	0.1	0.4	0.4

Table 2. Chemical composition of galvanized steel.

Elements	Fe	C	Mn	P	S
%	98.31	0.20	1.35	0.10	0.04

Friction Stir Spot Welding (FSSW) was conducted in a milling machine where the end mill was replaced by the High Strength Steel (HSS) tool with the hardness of 70 HRC. The tool diameter was varied of 10, 12, and 14 mm. The rotational speeds variation of 1000 rpm, 1200 rpm, 1600 rpm, and 2000 rpm were conducted for each tool diameter level. The constant of plunge depth, dwell time and penetration rate were set of 2.7 mm, 3 s and 0.9 mm/s respectively. During FSSW process, the position of the aluminum plate was on the top of the galvanized steel plate as seen in Figure 1.

Metallography investigation standard was used to reveal the Zn distribution in FSSW joint. Sample was cut along cross section of nugget. Nugget is bonding part where the metals melt and then fuse to form the joint. The sample was then sanded with grade in the range from 240 to 2000 of sandpaper, polished and finally etched. Etching solution was Poulton reagent in which the solution composition is 30mL HCl, 40mL HNO_3, 2.5mL HF, 42.5mL H_2O, and 12g CrO_3.

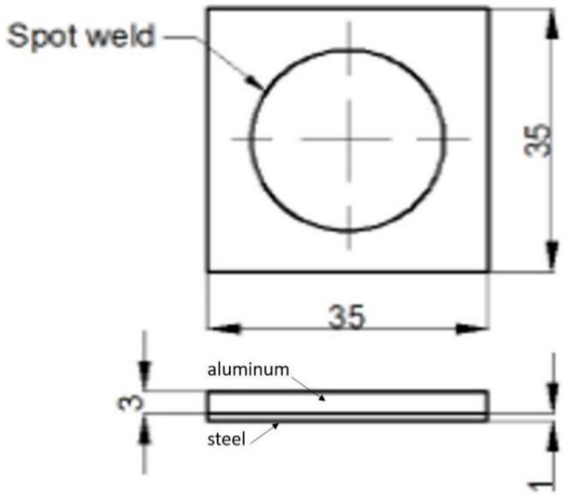


Fig. 1. The dimension of a FSSW specimen.

Macro-structure of FSSW joint was revealed under stereo zoom Olympus SZ2-ILST, while microstructure and elements mapping were examined under scanning electron microscope (SEM TESCAN Vega3 LMU) with EDS (OXFORD INCA Energy 250) attachment. Based on the result of SEM and EDS observation, the morphology of Zn distribution around the stirring zone was determined.

3 Results and Discussion

Figure 2 shows the macro structure of FSSW dissimilar metals welding between aluminum and galvanized steel. It describes the geometry and zones of FSSW joint. It can be seen, aluminum is placed on top of weld joint. A hole with the diameter equal to tool diameter is left at the weld center as result of tool penetration [25]. An area around the hole is called stir zone where during FSSW process, it experienced heating and softening due the pressure and friction of tools. Stirring zone consisted of almost aluminum while interface area was a mixing of aluminum and Zn from the steel surface. Due to the generated heat, the Zn melted, diffused in soft aluminum and then pushed up following the tool rotational. The Zn flow during FSSW process took place due to the stirring process occurring in the Zn layer [2], [6].

Figure 2 also shows the hole at the joint interface between aluminum and galvanized steel. It is called a hook defect. It occurred due to the plunging process where the tool pressed the overlapping materials and made curvature profile at interface [15]. Hook also occurred due to material flow from the center to the steering zone peripheral [28]. The hook defect reduced the joint strength since no bonding occurred on the hook [11], [17], [26].

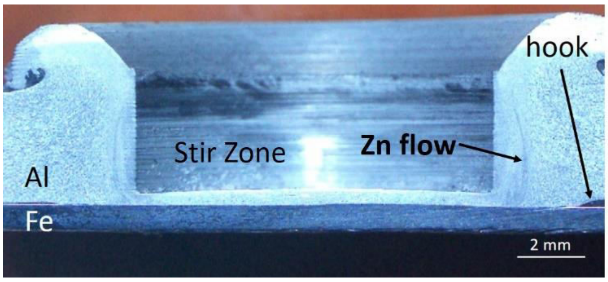
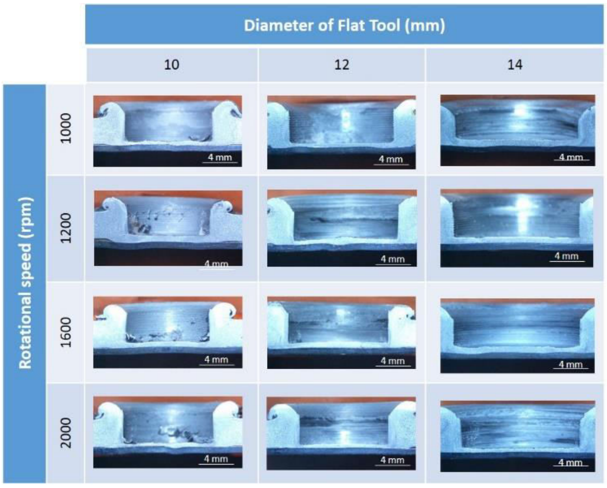


Fig. 2. Geometry and zones of FSSW joint

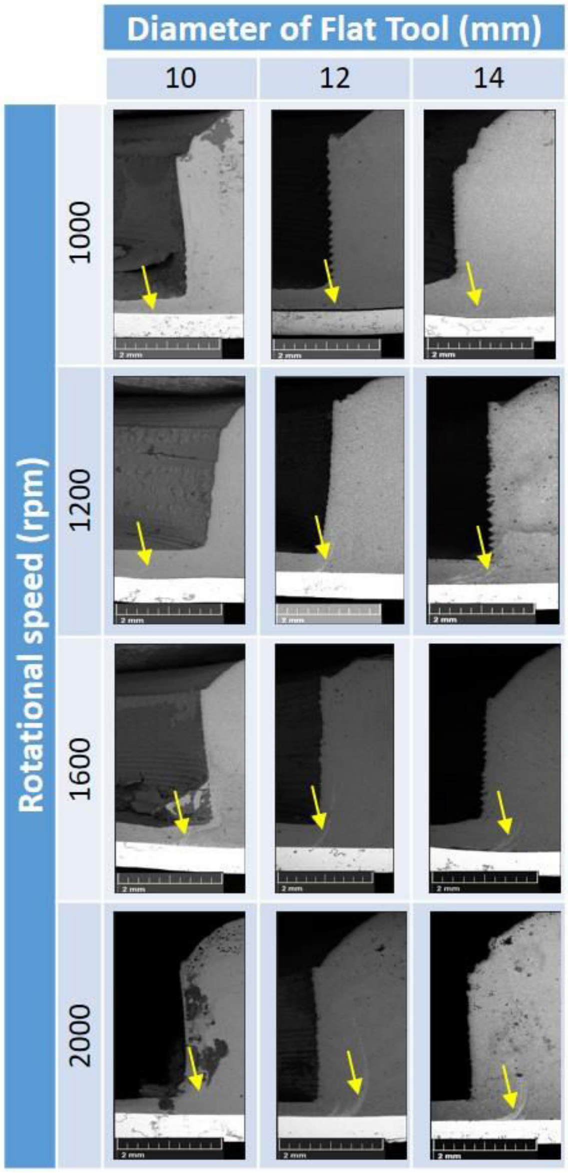
Table 3. Geometry of FSSW joint due to the variation of rotational speed and tool diameter



Effect of rotational speed and tool diameter on the joint geometry is resumed in Table 3. The area of the stirring zone increased as increasing rotational speed as well as tool diameter. The stirring zone is the zone where both galvanized steel and aluminum materials are stirred. The number of stirred materials during the FSSW process is equivalent with the welding zone. The size of welding zone affects the joint strength [27]. Based on Table 3, it is guessed the joint strength will increase if the rotational speed or/and tool diameter increase.

SEM images and elements mapping for clearly describing of the Zn flow in FSSW welding joint are shown in Table 4 and Table 5 respectively. They were taken on the one side of stirring area in Table 3. Zn flow layer is marked with a yellow arrow in Table 4 while Zn element is shown as congregated bright yellow points in Table 5. Zn rose from the aluminum and galvanized steel interface to the edge of the stirring zone and up to the top. Based on Table 4 and Table 5, it can be summarized that the flow profile of Zn material in FSSW joint including amount, distance and element intensity were influenced by the rotational speed and diameter of tool. Rotational speed affected the amount of plastic flow of material and it led to more Zn flow to the edge of the stirring zone [6], [18]. In other words, when rotational speeds increased, mount of moved Zn material would increase so Zn intensity also increased [28]. The diameter of the tool affected the generated centrifugal force [27] which affected the distance of moved Zn material. The distance of moved Zn material would increase if the tool diameter increased.

Table 4. Detail view of Zn distribution area.



There was a stirring process in the FSSW process. The stirring process at aluminum and galvanized interface was started by smoothing aluminum grain and then mixing of materials and finally plastic flow in the stirring zone. Zinc coating layer on galvanized steel was released due to the scrubbing process of tool on the galvanized steel surface. Zn melted, moved and diffused upward at softened aluminum material. Figure 3 is the results of the SEM and EDS tests of the FSSW joint. It was performed to prove that the bright line in Table 4 and Table 5 is a Zn element that flowed to the edge of the steering zone. The EDS spectra shows that Zn flowed upward from point 1 (bottom area) to point 3 (top area). Zn flowed due to the rotation of the tool on the interface during the stirring process. Zn content of 1.7% was in point 1 while that of 0.5% in point 3. The Zn material flow rate was also affected by the Zn melting point of

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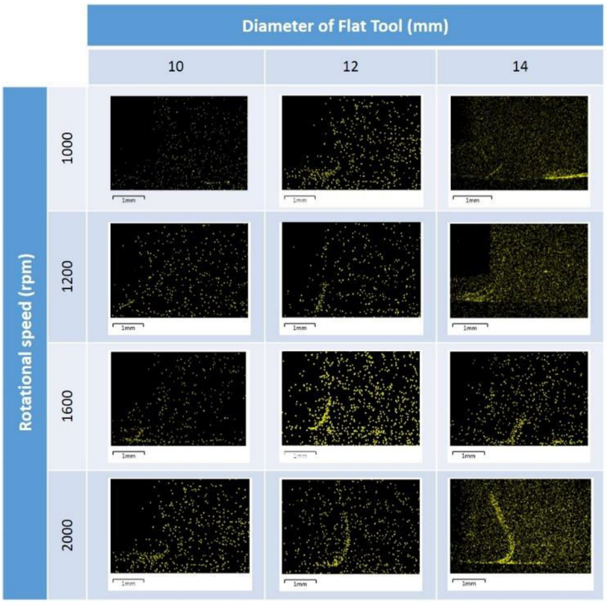
419°C. The interface temperature during the welding process was around 590°C [20]. During the FSSW process between aluminum alloys and galvanized steel, different temperatures were occurred at different part. The temperature was 430ºC at the interface and 310º C near the center and edge nugget. Based on these data, Zn layer melted or softened under the FSSW tool rotation [29], [30].

Table 5. Mapping view of Zn distribution area



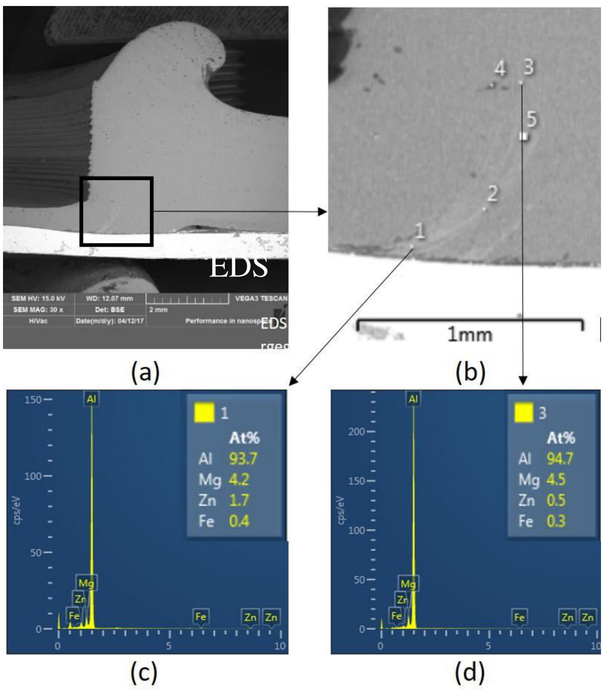


Fig. 3. SEM and EDS of FSSW joint, (a) macro view, (b) detailed view, (c) EDS spectra of point 1, (d) EDS spectra of point 3

The distribution of Zn will better if it is illustrated in quantitative measurement. In this work, Zn distribution is represented by flow in horizontal and vertical directions. The X-Y axis system as seen in Figure 4 is commonly used to describe horizontal and vertical directions. X and Y axis describes horizontal and vertical direction respectively. The origin point (0,0) is placed at cross point between galvanized steel surface and the line of stirring zone. Positive direction is defined as above of X axis and right side of Y axis, while negative direction is defined vice versa.

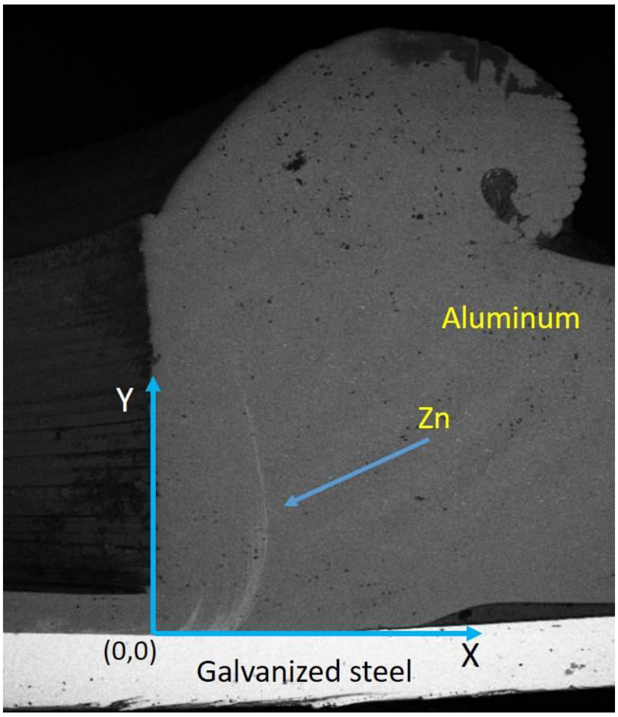


Fig. 4. The X-Y system to measure the distribution of Zn in horizontal and vertical directions.

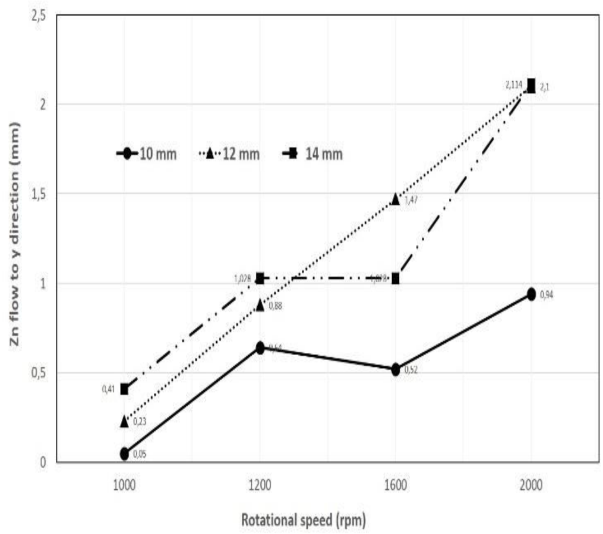


Fig. 5. The Zn flow in vertical direction.

Figure 5 and Figure 6 provide a quantitative distribution of Zn in vertical and horizontal respectively. Zn distributions both in vertical and horizontal directions were affected by rotational speed or/and diameter of tool. Previous discussion has provided reasonable proves regarding to Zn melting point, materials scrubbing, softening, melting and flow due to rotational speed and diameter of FSSW tool in dissimilar metals weld between aluminum and galvanized steel.

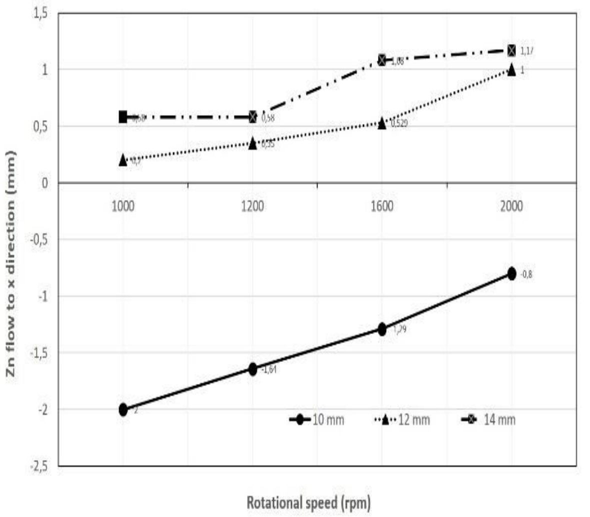


Fig. 6. The Zn flow in horizontal direction.

4 Conclusion

Effect of rotational speed and tool diameter on the Zn distribution in dissimilar metals FSSW between aluminum and galvanized steel has been investigated. Based on the results and discussion, the conclusions of this work are as increasing of the rotational speed and tool diameter, the area of stirred zone of FSSW increased, the distance of Zn dispersing increased both vertical and horizontal directions and the intensity of Zn flow distribution increased.

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