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Effect of shoulder to pin ratio on magnesium alloy Friction Stir Welding

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Abstract. This study focuses on the effect of shoulder to pin diameter ratio on friction stir welding of magnesium alloy AZ31. Two pieces of AZ31 alloy with thickness of 2 mm were friction stir welded by using conventional milling machine. The shoulder to pin diameter ratio used in this experiment are 2.25, 2.5, 2.75, 3, 3.33, 3.66, 4.5, 5 and 5.5. The rotational speed and welding speed used in this study are 1000 rpm and 100 mm/min, respectively. Microstructure observation of welded area was studied by using optical microscope. Equiaxed grains were observed at the TMAZ and stir zone indicating fully plastic deformation. The grain size of stir zone increased with decreasing shoulder to pin ratio from ratio 3.33 to 5.5 due to higher heat input. It is observed that, surface galling and faying surface defect is produced when excessive heat input is applied. To evaluate the mechanical properties of this specimen, tensile test was used in this study. Shoulder to pin ratio 5.5 shows lowest tensile strength while shoulder to pin diameter ratio 3.33 shows highest tensile strength with weld efficiency 91 % from based metal.

1.Introduction

Weight reduction in automotive and aircraft industries is a main concern in improving fuel economy and reducing environmental pollutions [1]. Recently, magnesium alloys are constantly gaining importance as lightweight structural materials for automotive applications [2]. The Mg alloys are especially attractive due to their low density, high specific stiffness and strength and also the recycling ability [3]. There have some problem in welding magnesium using conventional fusion welding. Conventional fusion welding methods for joining magnesium alloys produce some defects such as porosity and hot crack, which deteriorate their mechanical properties due to the melting material [4]. Friction stir welding (FSW) is a welding method under solid state joining that involves no melting, i.e. welding below melting point and it can eliminate problem related to solidification.[5]. The advantages of FSW compared to other method are low distortion and shrinkage even in a long weld, excellent mechanical properties in fatigue, tensile and bend test, no arc or fume, can weld in all position, no filler wire needed, weight reduction because no usage of filler, can weld aluminum and copper more than 75 mm with only one pass and uses consumable tools, which means that the tool can used for many times [6].

In FSW, the non-consumable tool plays an important role in generating heat by means of friction to plasticize the materials to be welded. FSW tool have three different portions such shank, shoulder and pin. The pin diameter and shoulder diameter decide the quantum of heat generated during FSW [7]. The tool shoulder diameter is having directly proportional relationship with the heat generation due to friction [8], [9]. The pin of the tool generates the heat and stirs the material being welded but the



shoulder also plays an important part by providing additional frictional treatment as well as preventing the plasticized material from escaping from the weld region [10]. From the heating aspect, the relative size of pin and shoulder is important. The heat generation is related to the mechanical and microstructure properties of welding that affect the quality of the welding. Vijayavel et al. (2014) investigated the effect of five different shoulder diameters to pin diameter (D/d) ratio on tensile properties and hardness of the friction stir processed welding of metal matrix composite [11]. Another researcher, Noor Zaman Khan et al. (2015) also investigate the effect of D/d ratio on joint quality but done at AA6063 [12]. Both researcher used fix shoulder diameter for the experiment. Some question appear would the result same if use vary shoulder and pin diameter for the ratio and applied at AZ31B magnesium alloy. It was found that not many studies regarding the ratio of tool shoulder diameter with pin diameter on tensile properties, macrostructure, microstructures and hardness of FSW joints of AZ31B with varying both shoulder and pin diameter. This study investigates the effect of shoulder to pin ratio on magnesium alloy AZ31 friction stir welding.

2. Experimental Procedure

Experiment was performed on plate of AZ31 magnesium alloy with 2 mm thickness. The dimensions of base metal plate were 50 mm (width) \times 60 mm (length) and the plate was longitudinally butt welded using conventional milling machine. Table 1 shows the chemical compositions of AZ31 alloy that was checked using Foundry Mass Spectrometers machine. The process parameters used for this experiment are given in Table 2 and the parameters are set from pre experiments, aiming at defect free specimens. The tilt angle was held constant at 3° based on several papers [13]–[16] and pre-tests. The welding tool material used is H13 steel with a taper cylindrical pin shape. The tool was processed by using a conventional lathe machine.

Table 1. Chemical compositions of AZ31 (wt.%).

Element	Al	Zn	Mn	Si	Cu	Ca	Ni	Mg
AZ31	2.87	0.99	0.239	0.0137	0.0183	0.0026	0.0015	Balance

Table 2. Welding parameters and tool dimensions for FSW.

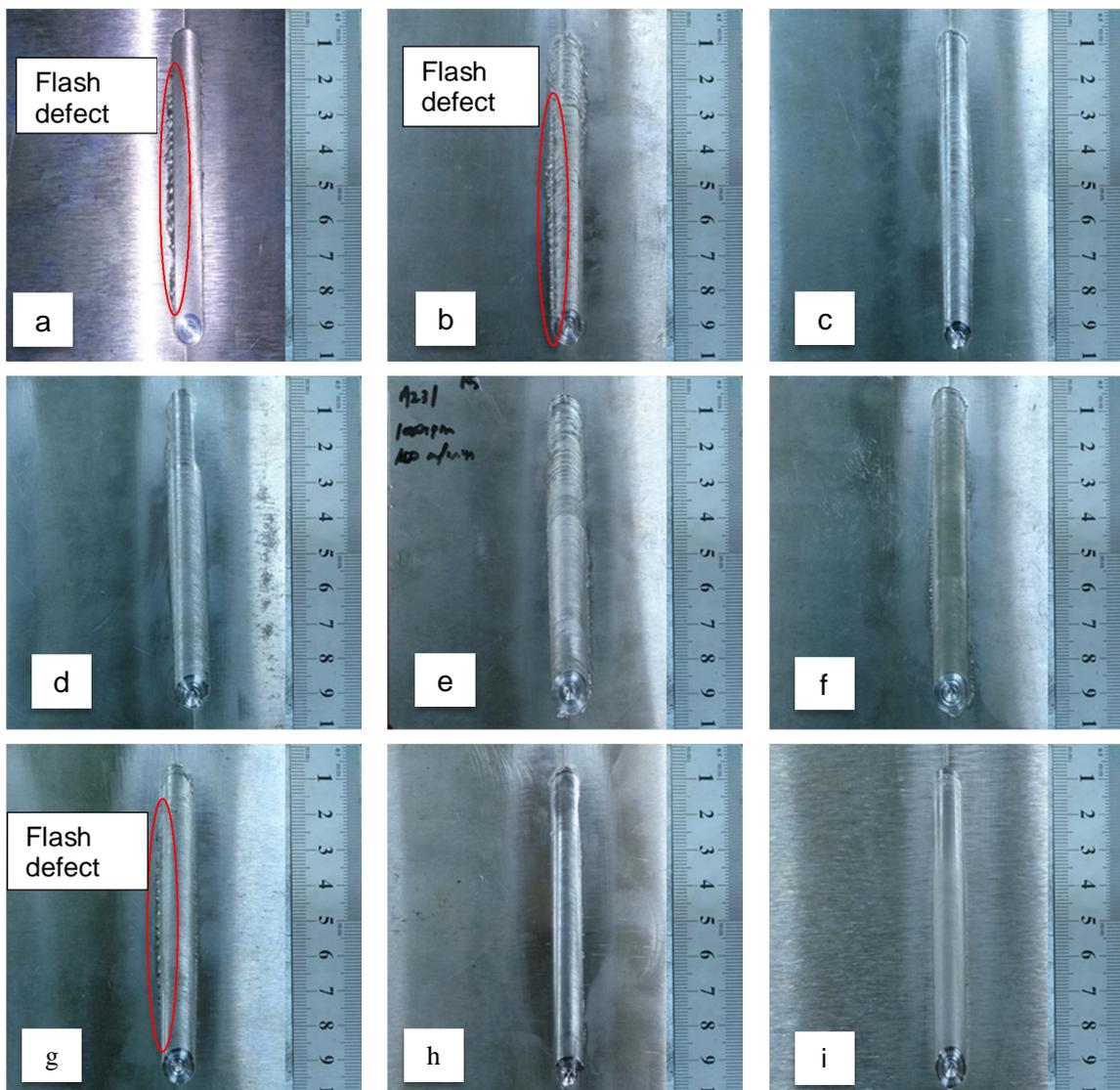
Process parameters	Values
Rotational speed(rpm)	1000
Welding speed (mm/min)	100
Pin length, l (mm)	1.8
Tool shoulder diameter, D (mm)	9, 10, 11
Pin diameter, d(mm)	2, 3, 4
Pin taper angle	10°
Tool ratio, D/d	2.5, 2.75, 3, 3.33, 3.66, 4.5, 5 and 5.5
Holder diameter, a(mm)	20
Holder length, b(mm)	20
Shoulder length, c(mm)	24

Mechanical characterizations were conducted using tensile test. The tensile test was prepared according to the ASTM-E8 standard. The tensile test was conducted with three repetitions and the average values were then presented in result and discussion. The data were recorded and analyzed accordingly. Cross-sectional samples were then cut and mounted to analyze their microstructures. The mounted sample was ground manually using 240, 320, 400 and 600-paper grid, successively. After the grinding process, the specimens were polished using 1, 3 and 6 μ m DIAMAT Polycrystalline diamond to remove the major scratches and finally etched using 4.2 g picric acid, 10 ml acetic acid, 10 ml H₂O and 70 ml ethanol. The microstructure of the weld specimens was observed using an optical microscope.

3. Results and Discussion

3.1. Weld appearance

Visual inspection was used to characterize the weld bead defect and appearance. From figure below, observed that Figure 1 (i)-(m) shows smooth weld appearance while (a) ,(b) and (g) shows small flash at retreating side. Specimen with pin ratio 4.5, 5, and 5.5 shows flash defect. Most experiments that have flashed come from large tool ratio with small pin area that is 2 mm pin diameter. This is due to the higher heat generation at the weld center. This statement also support by Saravan et al. 2016 that shoulder give more friction resulting in higher heat generation while small pin diameter affect the splitting microstructure into fine grain size [17]. Experiment no 2 shows surface galling defect due to the sticking material at the pin [18] and ribbon flash is due to the over dwell time. When a longer time is taken after the initial plunge of the tool pin, it induces more heat to the specimen and increases the fluidity. The extra fluid (metal) will split out of the weld area, causing this defect [19]. All the defect will degrade the mechanical properties [18].



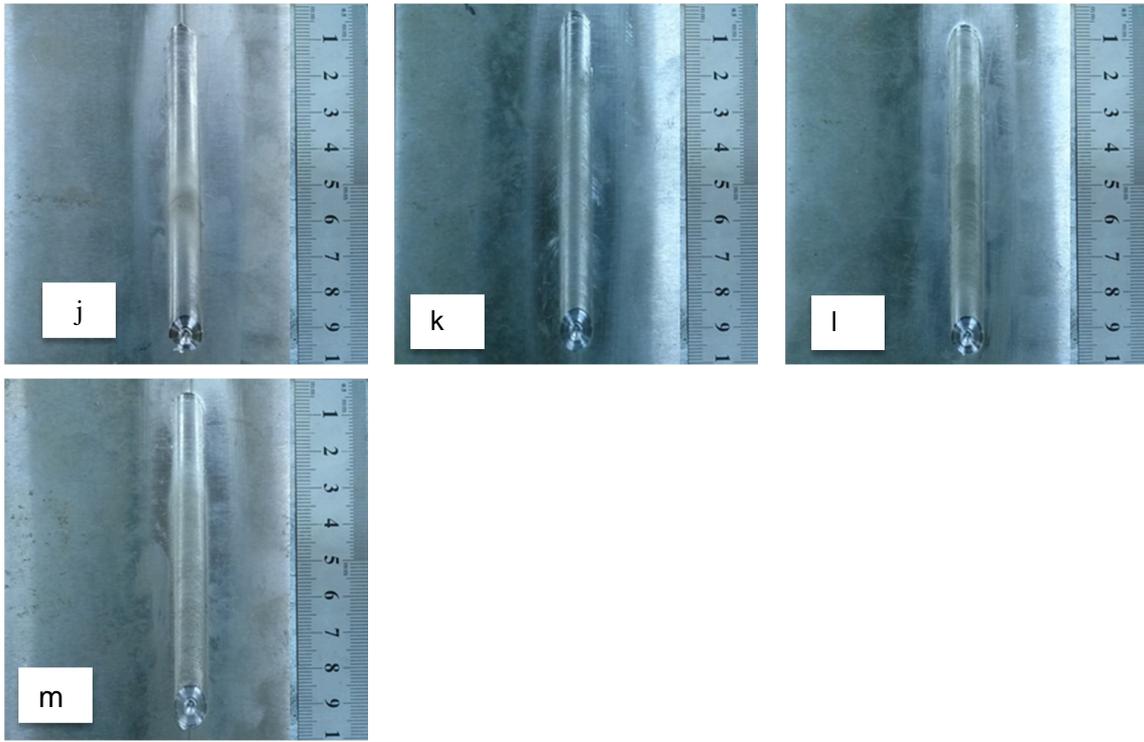


Figure 1. Weld appearances for shoulder to pin diameter ratio D/d on friction stir welding. a) ratio 4.5 , b) ratio 5.5 ,c) ratio 2.25, d) ratio 2.75 ,e) ratio 3 ,f) ratio 3.66 ,g) ratio 5, h) ratio 2.5 , i) ratio 3.33 ,j) ratio 3.33 , k) ratio 3.33 ,l) ratio 3.33 ,m) ratio 3.33.

3.2. Tensile properties of welded joint

The tensile test was conducted and the ultimate tensile strength (UTS) data shown in Table 3. The median from three samples for each specimen was taken to avoid the outliers from the overall samples.

Table 3. Ultimate tensile strength for shoulder to pin ratio friction stir welding.

Exp. No.	Shoulder Diameter	Pin Diameter	Tool Ratio	Ultimate tensile strength (MPa)
1	9	2	4.50	164.236
2	10	2	5.5	158.105
3	9	4	2.25	194.275
4	11	4	2.75	192.078
5	9	3	3	221.674
6	11	3	3.66	219.399
7	10	2	5	179.350
8	10	4	2.5	212.413
9	10	3	3.33	241.391
10	10	3	3.33	236.019
11	10	3	3.33	241.149

12	10	3	3.33	239.630
13	10	3	3.33	237.347

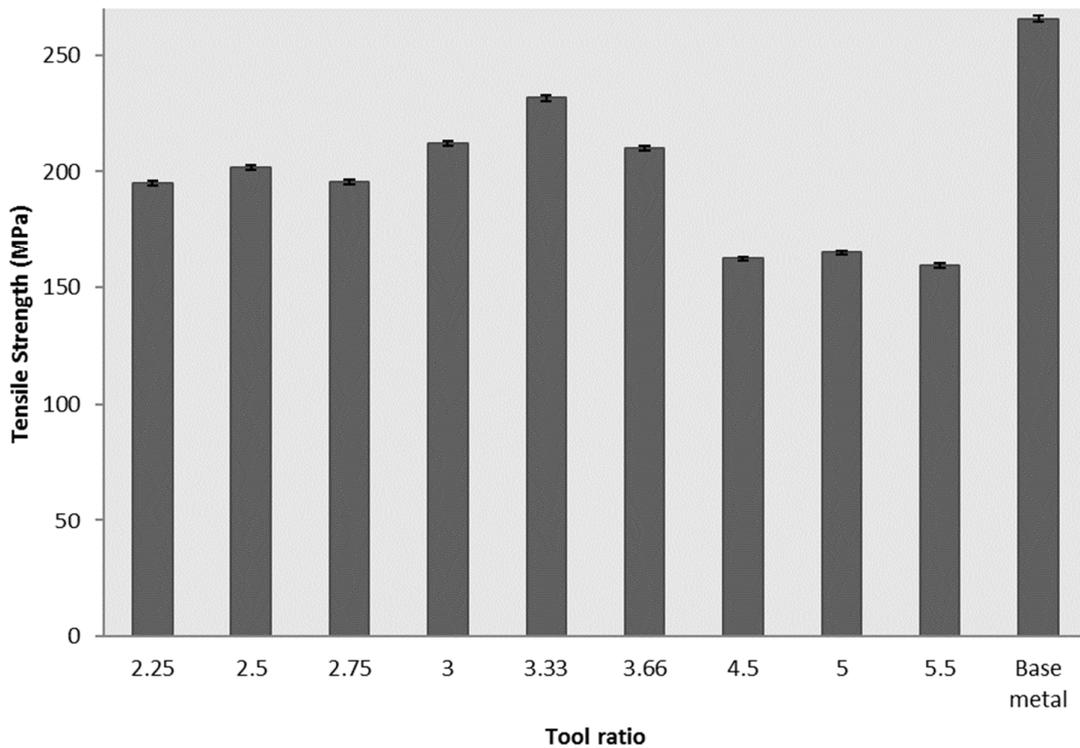


Figure 2. Ultimate tensile strength of different pin ratio.

According to the table, specimen 2 and 9 show the lowest and the highest UTS, respectively. The shoulder to pin ratio (D/d) 5.5 with shoulder diameter 11 and pin diameter 2 resulted in the lowest UTS value of 158.105 MPa. The shoulder to pin ratio (D/d) 3.3 with shoulder diameter 10 and pin diameter 3 resulted in the highest UTS value of 241.391 MPa. This value is near to the base metal UTS which is 265.6 MPa with 91 % weld efficiency.

Figure 2 shows the UTS of the welding joint and the base metals. The tensile strength trend shows that the strength are increase with increasing the tool ratio until tool ratio 3.33 and it decrease with increasing tool ratio after tool ratio 3.33. Tool ratio 4.5, 5 and 5.5 shows low tensile strength due to the flash defect shows in Figure 1. Flash may occur due to the improper parameter setting [20] that cause thinning the weld and result in decreasing the mechanical properties [18].

3.3. Metallurgical analysis

The weldability of magnesium alloy by using friction stir welding was achieved through the excellent mechanical properties. Besides the mechanical properties, macro and microstructure of the welded area are also an important characteristic in identifying the ability of the material to form a good weld.

The sample for macrostructure observation was taken based on the tensile strength results; the lowest UTS and the highest UTS. The microstructural image was taken by using an optical microscope with $\times 50$ magnifications. The cross sections of the welded area for lowest and highest tensile sample are shown in Figure 4 and Figure 6, respectively. It was observed that all specimens show the complete penetration. However, there were several defects that can be identified through the cross

section of the completed penetration specimen such as surface galling of weld surface and faying surface defect, as well as the porosity existing in the welded area as shown in Figure 3. Excessive hot weld is one of the factors existing surface galling and faying surface defect. Thus, the proper combination shoulder to pin diameter ratio are important to make sure the heat generation are sufficient for the welding.

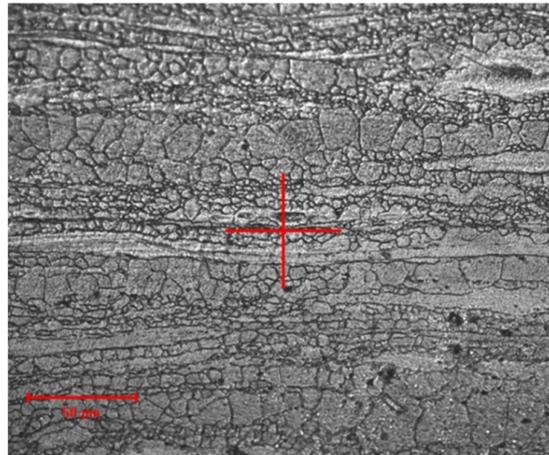


Figure 3.Microstructure of based metal (BM) AZ31 Magnesium alloy.

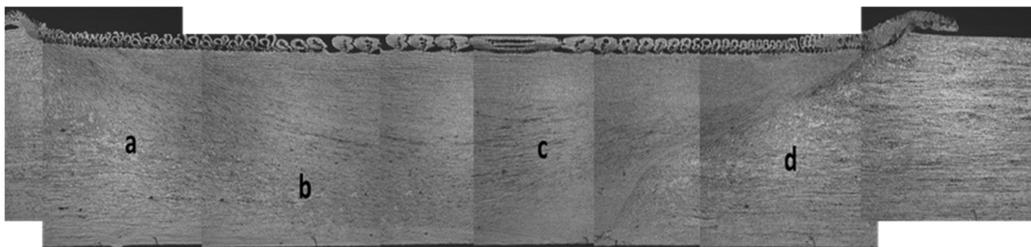


Figure 4.cross sectional macrostructure for ratio 5.5 with lowest Ultimate Tensile Strength. a) location retreating side HAZ, b) location TMAZ , c) location SZ , d) location advancing side HAZ.

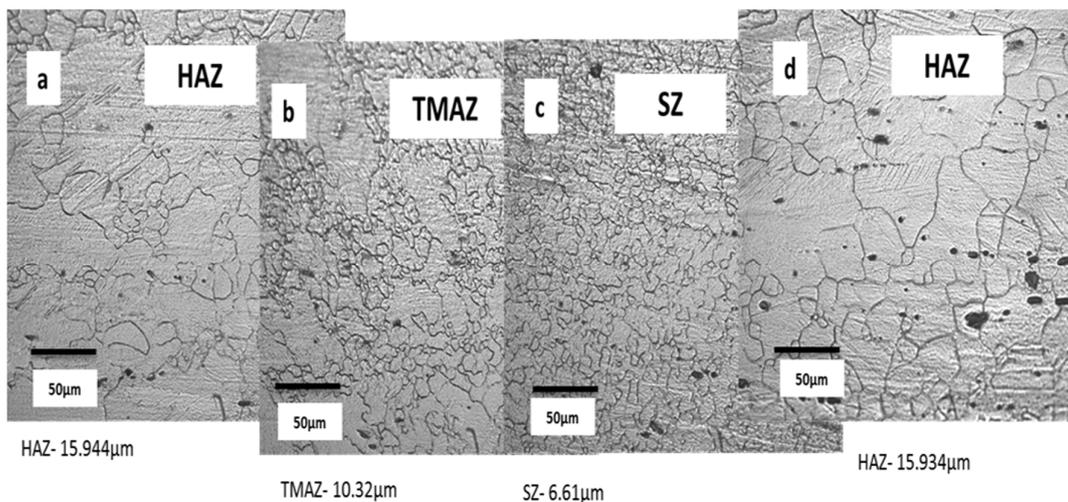


Figure 5.Microstructure of ratio 5.5 (a) Retreating side HAZ (b) TMAZ (c) SZ and (d) Advancing side HAZ.

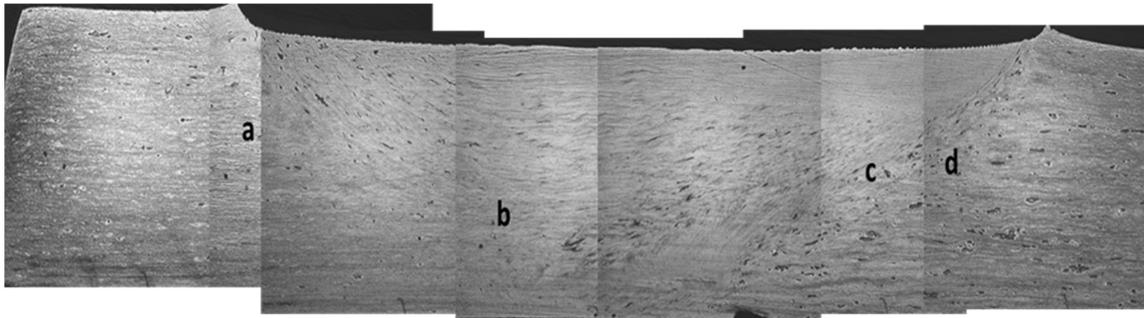


Figure 6. Cross sectional macrostructure for ratio 3.33 with highest Ultimate Tensile Strength a) location retreating side HAZ, b) location SZ, c) location TMAZ, d) location advancing side HAZ.

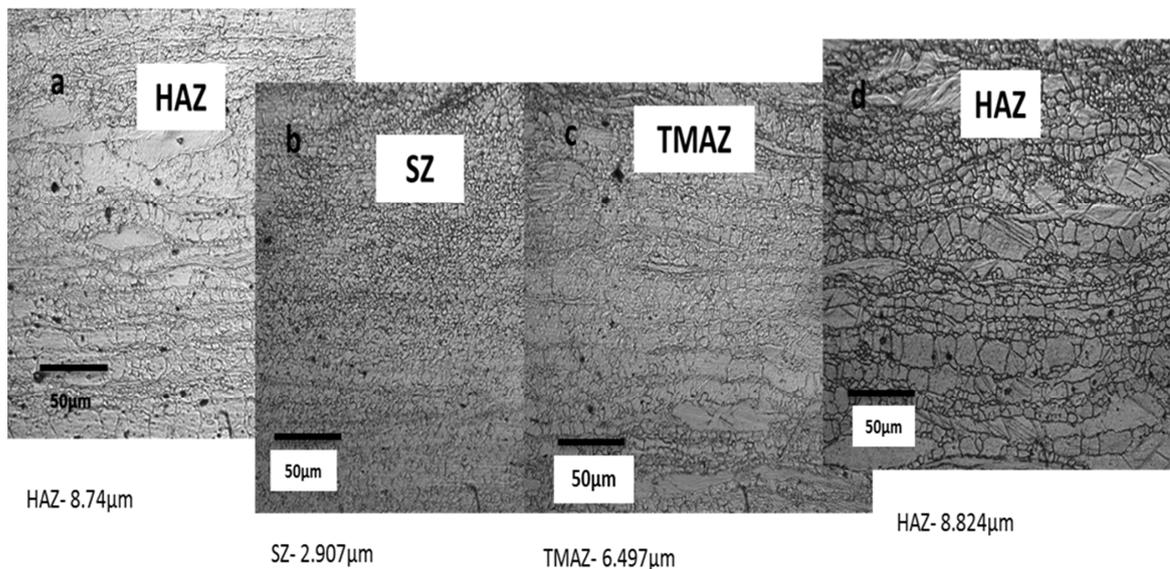


Figure 7. Microstructure of ratio 3.33 (a) Retreating side HAZ (b) TMAZ (c) SZ and (d) Advancing side HAZ.

The major FSW regions can be observed, namely the base metal (BM), heat affected zone (HAZ), thermo mechanically affected zone (TMAZ) and weld zone (WZ). Figure 3 shows typical microstructure of base metal (BM) before friction stir weld. The base metal exhibit coarse microstructure with elongated and pancake grain size. Figure 5 (b) and (c) shows the TMAZ and SZ for the lowest tensile strength. The grain size at SZ shows fine grain size. TMAZ shows elongated grain compare to SZ with average grain size 10.32 μm for TMAZ and 6.61 μm for SZ. HAZ shows uneven grain boundary with average grain size 15.944 μm . Shoulder give more friction resulting in higher heat generation but the small pin diameter affect the splitting microstructure into fine grain size [17]. Figure 6 shows cross sectional microstructure for ratio 3.33 with highest tensile strength. SZ and TMAZ at ratio 3.33 consist of fine and equiaxed grains which show that recrystallization already occur. Small grain size affect the tensile strength due to the homogeneous in whole area and crystal orientations of such grains are rather randomly distributed [21]. TMAZ shows elongated grain compare to SZ with average grain size 6.497 μm and 2.907 μm respectively. HAZ shows coarser and elongated grain size compare to SZ and TMAZ but small HAZ grain size compare to tool ratio 5.5.

The stir zone exhibit fine grain compared to base metal which is coarse grain. This behavior is due to dynamic recrystallization from the simultaneous deformation and heat input during welding process where the heat generated from the interaction of the pin tool deformed the grain boundaries [22] lead to the higher tensile strength of specimen. Grain structures for TMAZ in Figure 7 have slightly changed in grain structure due to the heat input that is sufficiently heated to undergo deformation from its original grain boundaries. TMAZ region undergo plastic deformation but recrystallization did not take place in this region due to inadequate deformation strain [23]. In HAZ, the magnesium alloy experienced thermal cycle but only little plastic deformation occurred. The increase in grain size consequently decreased the tensile strength [24]. Smaller grain size will affect the tensile strength due to the dislocation movement in the material. By reducing the dislocation movement of grain (fine grain size), the mechanical strength of material can be improve due to the metal plastically hard to deform [25].

4. Conclusion

1. Thickness of 2 mm magnesium alloy AZ31 plates were successfully welded by using friction stir welding process with shoulder to pin diameter ratio 2.5, 2.75, 3, 3.33, 3.66, 4.5, 5 and 5.5 with 1000 rpm rotational speed and 100 mm/min welding speed
2. All specimen produce sound quality joints with minimal defects. The best weld appearance can be observed in small ratio from 2.25 till ratio 3.33. Ratio 3.66 until 5.5 shows some defect such as little flash defect. Fine grain size can be seen in WZ and TMAZ and coarser grain size can be seen in the HAZ. The average grain size for D/d ratio 3.33 shows smaller grain size compare to other tool ratio. Smaller grain size will affect the tensile strength of the specimens. The D/d tool ratio 3.33 yielded the highest tensile value of 241.391 MPa due to the fine grain size and good weld appearance. Therefore the optimum D/d shoulder to pin ratio for magnesium alloy AZ31 are at ratio 3.33 gives better weld appearance and high tensile strength.

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