Effect of Taper Pin Ratio on Microstructure and Mechanical Property of Friction Stir Welded AZ31 Magnesium Alloy

N. H. Othman, N. Udin, M. Ishak, L. H. Shah

***Abstract*—**This study focuses on the effect of pin taper tool ratio on friction stir welding of magnesium alloy AZ31. Two pieces of AZ31 alloy with thickness of 6 mm were friction stir welded by using the conventional milling machine. The shoulder diameter used in this experiment is fixed at 18 mm. The taper pin ratio used are varied at 6:6, 6:5, 6:4, 6:3, 6:2 and 6:1. The rotational speeds that were used in this study were 500 rpm, 1000 rpm and 1500 rpm, respectively. The welding speeds used are 150 mm/min, 200 mm/min and 250 mm/min. 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. Tool pin diameter ratio 6/1 causes low heat input to the material because of small contact surface between tool surface and stirred materials compared to other tool pin diameter ratio. The grain size of stir zone increased with increasing of ratio of rotational speed to transverse speed due to higher heat input. It is observed that worm hole is produced when excessive heat input is applied. To evaluate the mechanical properties of this specimen, tensile test was used in this study. Welded specimens using taper pin ratio 6:1 shows higher tensile strength compared to other taper pin ratio up to 204 MPa. Moreover, specimens using taper pin ratio 6:1 showed better tensile strength with 500 rpm of rotational speed and 150mm/min welding speed.

***Keywords*—**Friction stir welding, magnesium AZ31, cylindrical taper tool, taper pin ratio.

I. Introduction

FRICTION stir welding (FSW) is a welding method under solid state joining that involves no melting, i.e. welding below melting point [1]. 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 [2]. FSW tool consists of three parts; namely shank, shoulder and pin. The shank is part that is attached to the milling machine while shoulder is the part that touches the material surface, while the pin is the part that plunges into the material and is used for stirring the material. They are several types of tool profile such as cylindrical [3], threaded pin [4], and taper pin profile [5]. Taper pin ratio has shown to have a higher tensile strength compared to cylindrical [6] and threaded pin tool [7]. However, each study uses different taper pin ratio and it can affect the strength and microstructure of the specimen. Furthermore, there are limited studies done on taper pin ratio. This study investigates the effect of taper pin ratio on magnesium alloy AZ31 friction stir welding.

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II. Experimental Method

Experiment was performed on plate of AZ31 magnesium alloy with 6 mm thickness. The dimensions of base metal plate were 50 mm (width) × 60 mm (length) and the plate was longitudinally butt welded using PARTNER VMM3917 conventional milling machine. Table I 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 II and the parameters are set from pre experiments, aiming at defect free specimens. The tilt angle was held constant at 3º based on several papers [8]–[11] 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 I
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 II
WELDING PARAMETERS AND TOOL DIMENSIONS FOR FSW

Process parameters	Values
Rotational speed(rpm)	500, 1000, 1500
Welding speed (mm/min)	150, 200, 250
Pin length, l (mm)	5.7
Tool shoulder diameter, (mm)	18
Pin diameter max, D(mm)	6
Pin diameter min, d (mm)	5, 4, 3, 2, 1
Pin ratio, D/d	6:6, 6:5 ,6:4, 6:3, 6:2, 6:1
Holder diameter, a(mm)	10
Holder length, b(mm)	20
Shoulder length, c(mm)	24

Mechanical characterizations were conducted by 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 µm DIAMAT Polycrystalline diamond to remove the major scratches and finally etched using 4.2 g picric acid, 10 ml acetic acid, 10 ml H_2O and 70 ml ethanol. The microstructure of the weld specimens was observed by using an optical microscope.

III. Results and Discussion

A. Weld Appearance

Fig. 1 shows the weld appearance for taper pin ratio with various parameters by using different welding speed (WS) and rotational speed (RS). Figs. 1 (a)-(c) produced excellent weld appearance compared to others. No outer defects can be seen by the naked eyes such as ribbon flash, surface galling and lack of fill.

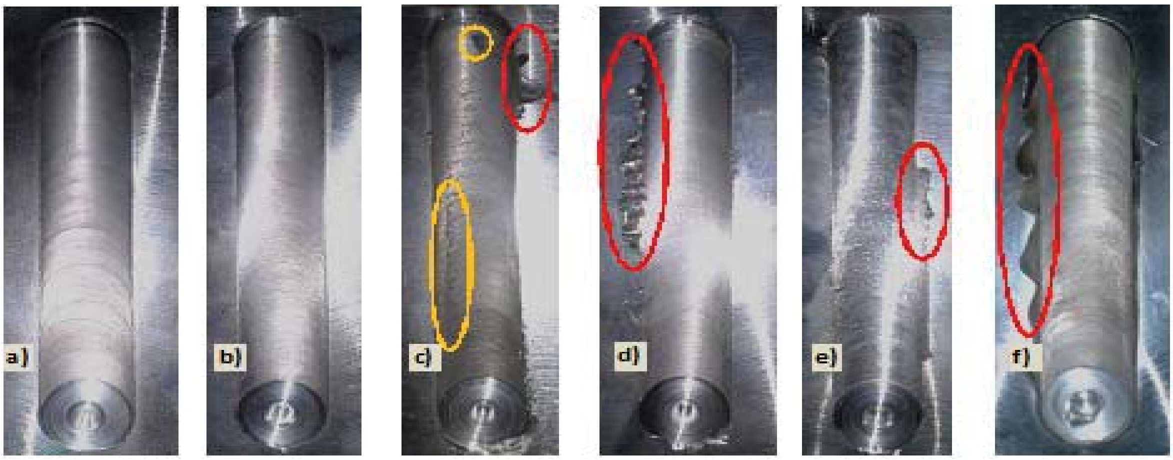

Fig. 1 Weld appearance for each taper pin ratio. a) 6/1 WS 150 mm/min RS 500 rpm, b) 6/2, WS 250 mm/min RS 1500 rpm c) 6/3, WS 200 mm/min RS1500 rpm d) 6/4, WS 250 mm/min RS 1000 rpm, e) 6/5, WS 150 mm/min RS 1000 rpm, f) 6/6, WS 250 mm/min RS 1000 rpm

Figs. 1 (c)-(f) produced some defects such as surface galling and ribbon flash. Surface galling is due to the sticking material at the pin [12] 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 [13]. It also occurs when the revolutionary pitch of an FSW is too low. Revolutionary pitch is calculated by dividing welding speed with rotational speed that used to characterize the variation of heat input qualitatively.

Based on Fig. 1, specimens under tool 6:1, and 6:2 show the very good weld appearance with no defect. The other specimen gives a poor and medium weld appearance, contains several defects that will degrade the mechanical properties [12].

B. Tensile Test

Table III shows the data for tensile strength. All specimens fractured at the heat affected zone (HAZ). The highest tensile strength obtained is 204 MPa from the best weld appearance (specimen number 1) with rotational speed of 500 rpm, welding speed 150 mm/min and taper pin ratio 6:1. The second highest value is from sample 2 (tool ratio 6:2) with tensile strength value of 186 MPa. On the other hand, the lowest tensile strength is obtained from sample 12 with tool ratio 6:3 and tensile strength value of 85 MPa due to the wrong combination of welding speed and rotational speed

It can be seen that specimens with higher taper pin ratio (6:1 and 6:2) show higher tensile strength and good weld appearance. Lakshminarayanan et al. also reported that, the tapered pin gives better joint strength because easy penetration of the pin inside the steel plate with reduced pin failures [14], [15]. Other than that, taper pin angle is beneficial in producing the plastic flow conditions that are conducive to high strength welds [16].

TABLE III
Data Tensile Strength

Experimental run	Parameters			Tensile strength (N/mm^2)
	D/d	Weld speed (mm/min)	Rotational speed (rpm)	
1	6/1	150	500	204
2	6/1	200	1000	130
3	6/1	250	1500	154
4	6/2	150	500	147
5	6/2	200	1000	186
6	6/2	250	1500	148
7	6/3	150	1000	120
8	6/3	200	1500	163
9	6/3	250	500	85
10	6/4	150	1500	145
11	6/4	200	500	125
12	6/4	250	1000	157
13	6/5	150	1000	176
14	6/5	200	1500	121
15	6/5	250	500	133
16	6/6	150	1500	144
17	6/6	200	500	116
18	6/6	250	1000	158

C. Microstructure Analysis

Fig. 2 shows the cross section of the FSW joint of taper pin ratio (6:2) for the higher tensile strength. The microstructural image was taken by using an optical microscope with ×50 magnifications. 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). Fig. 2 (c) shows typical microstructure of base metal (BM) before friction stir weld. The base metal exhibits coarse microstructure with elongated and pancake grain size. Figs. 2 (b) and (d) show the TMAZ and SZ, respectively. SZ and TMAZ consist of equiaxed grains which shows that recrystallization already occur. The HAZ consists of equiaxed grains near the TMAZ and exhibit some elongated grains near the base metal side indicating partial recrystallization has taken as shown in Fig. 2 (a). The stir zone exhibits 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 [17] lead to the higher tensile strength of specimen. Grain structure at TMAZ (Fig. 2) has slightly changed due to the heat input that is sufficiently heated to undergoes 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 [18]. In HAZ, the magnesium alloy experienced thermal cycle but only little plastic deformation occurred. The increase in grain size consequently decreased the tensile strength [19].

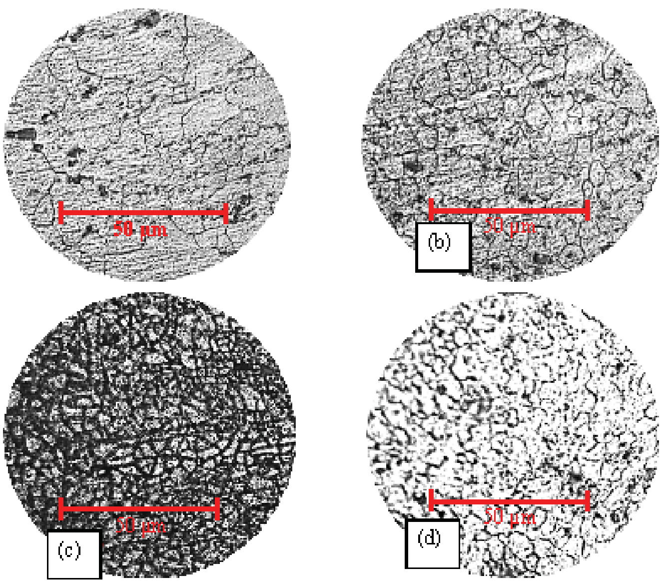

Fig. 2 Cross section FSW taper joint for higher tensile strength. Macro View tool 6:1. Welding speed 150mm/min and 500 rpm (a) HAZ, (b) TMAZ, (c) BM and (d) SZ

IV. Conclusions

6 mm thick magnesium alloy AZ31 plates were successfully welded by using friction stir welding process with taper pin ratio 6:1,6:2, 6:3, 6:4, 6:5, 6:6 method with 500, 1000, 1500 rpm rotational speed and welding speed 150, 200, and 250 mm/min.

All specimens produce sound quality joints with minimal defects. The best weld appearance can be observed in small taper pin diameter (d) which is 1 mm to 2 mm. The specimen microstructure shows similar result for specimens. 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 taper pin ratio 6:1 shows smaller grain size compare to other taper pin ratio. Smaller grain size will affect the tensile strength of the specimens. The taper pin ratio 6:1 yielded the highest tensile value of 204 MPa due to the fine grain size and good weld appearance. Therefore, the small taper pin diameter (d), larger taper pin ratio (D/d) with low welding speed (mm/min) and low rotational speed (rpm) gives better weld appearance and high tensile strength.

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