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Effect of Tool Rotational Direction and Welding Speed on the Quality of Friction Stir Welded Al-Mg Alloy 5052-O

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Abstract: A study of the friction stir welding process was carried out in order to evaluate the influence of rotational tool direction and welding speed on the quality of aluminum alloy plates 5052-O with thickness of 14 mm. Welds were made by taper cylindrical pin tool at constant rotational speed of 1120 rpm and different welding speed of 10, 14, 21, 45 and 66 mm/min. Visual inspection, micro hardness test and bending test were done for welded samples. The result shows that friction stir welding with counterclockwise direction of rotational tool produced good welding process. However, with anticlockwise direction welding does not happened and cutting process take place. Moreover, the majority of samples exhibited smooth surface with excessive thinning flash deformation and exit pin hole which can be removed easily from the work piece. In addition, the hardness of welded plates decreased with increasing the welding speed. Friction stir welded plates produced with rotational speed of 1120 rpm and welding speed of 10 mm/min have a good resistance for bending strength which bended without any cracking. Furthermore, the best quality of friction stir welding Al-Mg alloy plates can be obtained at rotational speed of 1120 rpm and welding speed of 10 mm/min.

Key words: Friction stir welding, aluminum alloy, hardness, heat, direction, produced, inspection

INTRODUCTION

Friction Stir Welding FSW is a solid state joining process innovated by Wayne Thomas at The Welding Institute (TWI) in 1991 and overcomes many of problems associated with the traditional joining techniques (Cederqvist and Reynolds, 2001; Anonymous, 2015; Moshwan *et al*., 2015). It is a relatively novel solid state welding process which has proved to have great potential for different materials (Tufaro *et al*., 2015). Moreover, friction stir welding is a solid state thermo mechanical joint process that mainly used for making butt and lap joints with single pass weld process and single layer (Cederqvist and Reynolds, 2001).

Aluminum alloys have gathered wide acceptance in the fabrication of light weight structures requiring a high strength to weight ration and good corrosion resistance (Moshwan *et al*., 2015). Therefore, friction stir welding process can be used for welding similar and dissimilar materials. It is promising joining process with potential to joint low melting point materials such as aluminum and magnesium alloys.

Friction stir welding is an effective process which has been systematically developed for joining aluminum alloys, especially, alloys that usually considered as a non-weldable or difficult to weld such as 2, 5 and 7xxx series alloys (Ravikumar *et al*., 2014). Important advantages can be developed comparing with fusion welding processes due to very low welding temperature, minimum heat affected zone, excellent surface finish and low mechanical distortion (Serio *et al*., 2016). In addition, FSW is environmental friendly joining technology that capable of providing welds that do not have defects normally associated with fusion welding processes such as solidification defects, low distortion and residual stresses (Moshwan *et al*., 2015; Ravikumar *et al*., 2014; Muruganandam *et al*., 2015). Friction stir welding has many advantages such as distort from high heat input is minimized, improved mechanical properties in the nugget zone with correct combination of parameters lead to defect free welds and refinement of grain size in the nugget zone. In addition, heat affected zone is smaller and the chemistry of parent metal is retaining. It is quiet operation, minimum post weld cleaning required, little energy input, and no need to use filler materials. Therefore, the process can be called as a non-conventional welding process or sustainable welding process that will reduce materials, methods, machining, men and money which called 5MS (Jassim and Hamood, 2014).

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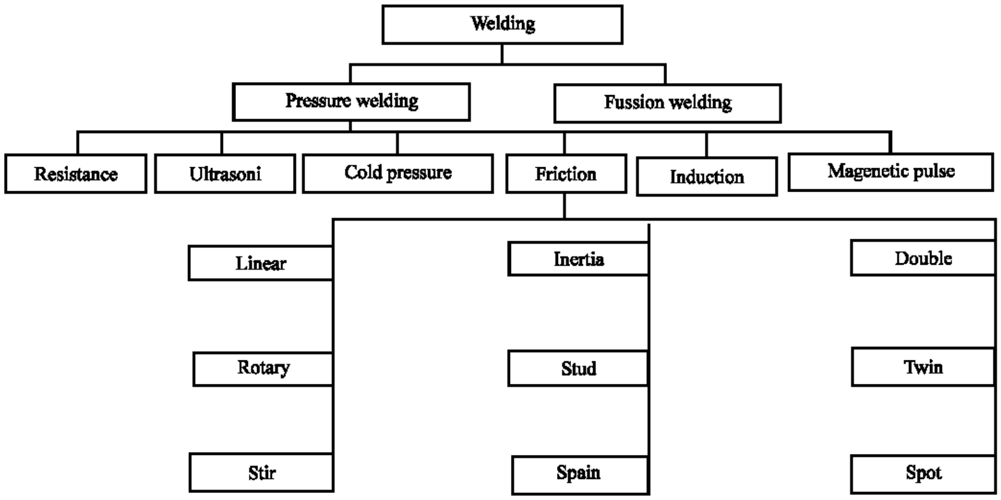

Fig. 1: Classification of welding process and friction welding

Nowadays, research is still in progress on friction stir welding of aluminum 5xxx series. Currently, aluminum alloys are used as alternative to steel in many applications because of their light weight, good weldability, good formability, good strength and corrosion resistance. The growth applications have been added challenges for improvement the welding process (Ravikumar *et al*., 2014; Romhanji and Popovic, 2006).

Moshwan *et al.* (2015) have been investigated the effect of five tool rotational speeds on the joining performance of the friction stir welded AA 5052-O plates with thickness 3 mm. The longitudinal, transverse and vertical forces acted on the welding tool during the process was evaluated. Moreover, the thermodynamic effect on intermetallic phases and the subsequent effects on the corrosion resistance of the welded joints were discussed. The results show that AA 5052-O alloy plates was successfully joined by the friction stir welding process. The welded joint produced at 1000 rpm gave a maximum tensile strength of 132 Mpa which was 76% of the base material (Moshwan *et al*., 2015).

Solid state welding process can be considered as a group of joining processes that created coalescence at temperatures below the melting point of the base materials without any additional filler metal and with or without pressure. It is called solid state bonding processes that include cold welding, diffusion welding, explosion welding, forge welding, friction welding, hot pressure welding, roll welding and ultrasonic welding.

Welding can be classified into fusion and pressure welding. However, pressure welding can be classified into different types one of them is friction welding as shown in Fig. 1. Friction stir welding is unique among the deformation based solid state processes because of the way material flows and comes together to produce the joint. It is successfully implemented in numerous industrial applications such as aerospace, automotive and shipbuilding (Mishra and Mahoney, 2007).

Tool design influences heat generation, plastic flow, the power required and the uniformity of the welded joint. The shoulder generates most of the heat and prevents the plasticized material from escaping from the work piece while both the shoulder and the tool pin affect the material flow. In recent years several new features have been introduced in the design of tools. It was found that cylindrical tool designs are suitable for butt welding and not useful for lap welding process where excessive thinning of the upper plate can occur together with the trapping of adherent oxide between the overlapping surfaces (Nandan *et al*., 2008).

MATERIALS AND METHODS

In this resaerch, aluminum magnesium alloys that cover wide use in marine and industrial applications are used to weld by using friction stir welding process as a non-conventional forming process. The selected alloy is 5052-O which belong to Al-Mg alloys type 5xxx was used as rolled plates with thickness of 14 mm. Plates chemical composition that shown in Table 1 was cut by reciprocating saw machine to a dimensions of 200 mm× 100 mm×14mm.

Friction stir welding machine: Milling machine was used after being prepared for friction stir welding. It has rotational speed in the range of 28, 35, 45, 56, 71, 90, 140, 180, 224, 280, 355, 450, 650, 710, 900, 1120 and 1400 rpm with welding speed of 10, 14, 21, 45, 66, 97, 142, 208, 444,

Table 1: Chemical composition of Al-Mg alloy type 5052-O plates

Element	Percentage
Al	96
Si	0.16
Fe	0.4
Cu	0.02
Mn	0.07
Cr	0.2
Mg	2.5
Ni	0.5
Others	<0.15

Table 2: Dimensions of friction stir welding tool

Name	Detail	Name	Detail (mm)
Shoulder diameter	18 mm	Pin diameter	6
Convexity angle	18°	Pin length	8
Tool material	HSS		

Table 3: Friction stir welding condition for welding Al-Mg alloy 5052-O

Rotational speed (rpm)	Welding speed (mm/min)
1120	10
1120	14
1120	21
1120	45
1120	66

and 650 mm/min. Fixtures were used with four strips and bolts to prevent aluminum welded plates from slipping during the welding process. Welding tool was made from high speed steel material to be used in friction stir welding process. It is consisting from shoulder and pin with dimension shown in Table 2.

FSW procedure: Friction stir welding is a solid state joining technique in which the joined material is plasticized by heat generated by friction between the surface of the plates and the contact surface of a special tool, composed of two main parts: shoulder and pin. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone while pin mixes the material of the components to be welded, thus, creating a joint. The shape and dimensions of the weld depend on the shape and size of the stirring tool and applied welding parameters (Dickerson *et al*., 2003; Adamowski and Szkodo, 2007). Different welding speed were used with constant tool rotational speed as shown in Table 3. Which were applied in counterclockwise and anticlockwise direction to study their effect on the quality of friction stir welded plates.

RESULTS AND DISCUSSION

Visual inspection: Figure 2 and 3 show samples that welded by using friction stir welding process with counterclockwise and anticlockwise direction of rotational welding tool. The welded process was done by applied constant rotational tool speed which is 1120 rpm with different welding tool speed of 10, 14, 21, 45 and 66 mm/min at counterclockwise and anticlockwise rotational tool direction. The visual inspection shows that welding joint surface has smooth surface in the counterclockwise direction with some thinning flash surface due to the excess heat input which can be removed easily. However, in anticlockwise direction welding not happened and the cutting process take place instead of welding as shown in Fig. 3.

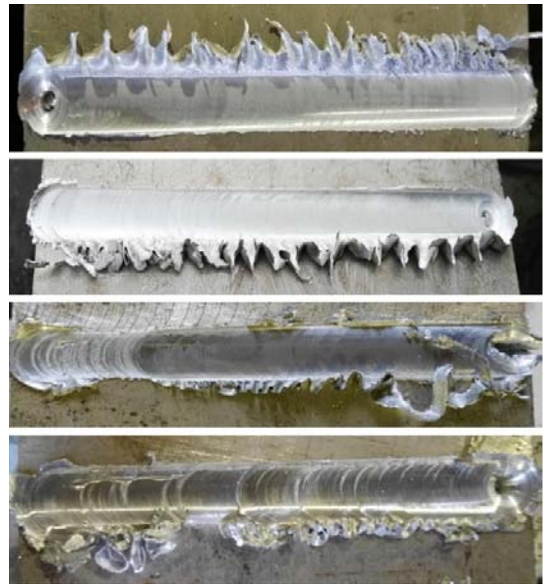

Fig. 2: FSW plates welded in counterclockwise direction at rotational speed of 1120 rpm and welded speed of 14, 21, 45 and 66 mm/min

Fig. 3: FSW Plates welded in the anticlockwise direction with rotational speed of 1120 rpm in the anticlockwise and welded speed of 10, 14 and 21 mm/min

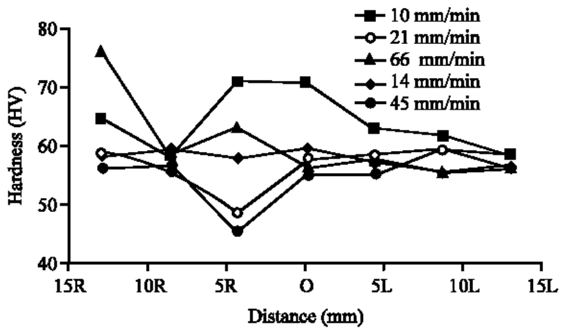

Fig. 4: Hardness of FSW plates at 1120 rpm with 5, 10 and 15 mm from the center of welded zone

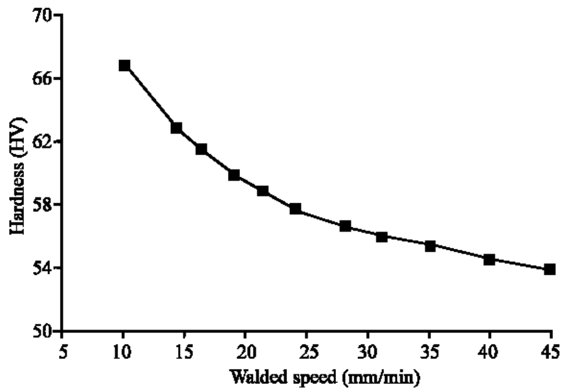

Fig. 5: Relationship between welding speed and hardness at rotational speed of 1120 rpm

Microhardness test: Hardness test is a means of determining resistance of materials to penetration and it is a function for wear resistance. Hardness was measured from the center of the welding zone at middle and then far from the center of welded zone at distance of 5, 10, 15 and 20 mm from right and left side. Seven reading of hardness has been recorded for each welded samples on the different distance from center of welded zone as shown in Fg. 4. However, Fig. 5 shows the relationship between welding speed and hardness at constant rotational speed of 1120 rpm.

The result shows that the hardness decreased with increased the welding speed due to insufficient heat input. The maximum hardness at welding zone was obtained at welded speed of 10 mm/min which equal to 70.93 HV. In addition, it was found that the hardness at thermos-mechanical affected zone TMAZ is closed to the hardness of welded zone. On the other hand, the hardness at heat affected zone HAZ is slightly less than the hardness of welded zone and closed to the hardness of base metal.

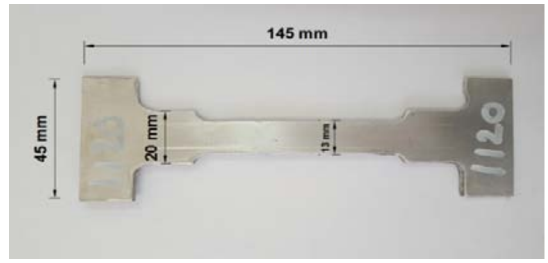

Fig. 6: ASTM (A370) sample for tensile test

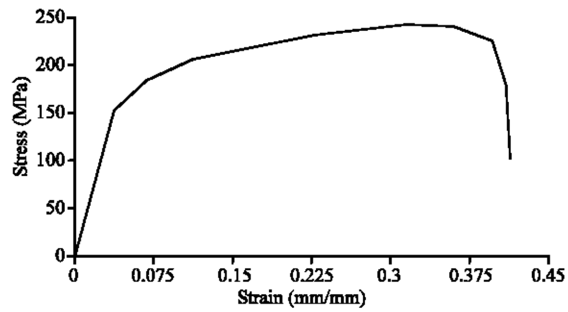

Fig. 7: Tensile stress for 5052 Al-Mg alloy base metal plates

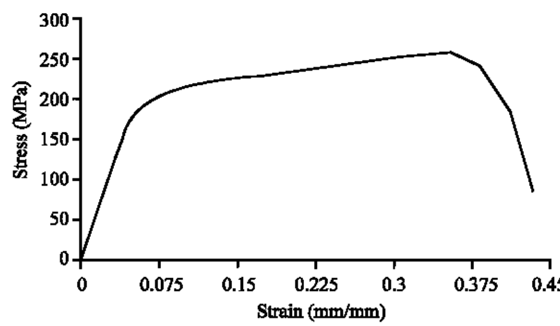

Fig. 8: Tensile stress for FS welded plates at 1120 rpm and 10 mm/min

Table 4: Tensile strength for friction stir welded plates welded at 10 mm/min

Variables	Values
Rotational speed (rpm)	1120
Welding speed (mm/min)	10
UTS For welded plate (MPa)	254
UTS For base metal (MPa)	230

Tensile test: Specimen was prepared according to ASTM (A370) with dimension shown in Fig. 6 to be ready for exam its tensile strength. The result shows that tensile strength of friction stir welded plate is higher than the tensile strength of base metal as shown in Table 4 and Fig. 7 and 8. The ultimate tensile strength of friction stir welded plates was improving with 110% which equal to 254 MPa.

Fig. 9: Bending test for specimen produced at; a) 1120 rpm and b) 10 mm/min

Table 5: Maximum heat generated and recrystallization temperature

Variables	Values
Rotational speed (rpm)	1120
Max.temperature (°C)	230
Recrystallization temperature (°C)	150

Table 6: Temperature distribution during FSW at 1120 rpm and 10 mm/min

Base metal	Temperature of welding zone	Pin	Bas metal	Temperature of welding zone	Pin
85	95	156	102	169	177
122	127	158	113	151	163
114	127	153	138	147	161
134	141	167	158	160	177
112	133	172	167	168	230
126	130	164	145	173	199
122	132	189	129	183	215
119	138	151	142	180	205
109	135	169	102	169	177
127	135	198	148	158	200
107	143	109	129	164	214
111	155	209	109	131	221

Bending test: Bending test was done for specimen and the result shows that welded plates has been successfully bended without any crack as shown in Fig. 9. It is blended with angle of 180° without any defects.

Heat generated: During the welded process, heat generated were measured at three positions in base metal, welding zone and friction stir welding tool pin as shown in Table 5 and 6. The results show that the maximum temperature at tool pin then welding zone and the lowest temperature at base metal. However, the maximum heat generated were closed to recrystallization temperature of Al-alloy which equal to 40% of Al-alloy melting point.

The mean feature of friction stir welding process is to produce solid state welds where the maximum temperatures attained during the process are about 80% of the melting temperature of the base materials. A recrystallization grain structure has been generated in a welded zone by stirring and forging process during friction stir welding. On the other hand, temperature remaining below the melting point during the welded process which lead to result low shrinkage phenomenon (Arora *et al*., 2010). In this research found that, the maximum temperature that generated during the welded process are <50% of melting temperature of base metal and the welding was happened easily.

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Fig. 10: a) Cavity formed (void) defect; b) Thinning flash formation defect and c) exit pin hole defect

FSW defects: There are some defects were appeared in the welded joints due to unsuitable rotational speed combined with welding speed. The most defects that appeared can be summarized as cavity, worm hole, thinning flash formation and exit pin hole. The defects were happened due to the excessive heat input or insufficient heat input, abnormal stirring and mismatch as shown in Fig. 10. Moreover, the above defects were formed due to too hot welding which cause by improper parameters setting that cause too much thermal softening. The excessive heat generated can lead to thermal softening in the work piece materials beyond the boundary of tool shoulder. For that reason, tool shoulder is giving rise to material removal in the form of excessive flash formation. In addition, too much thermal softening can also lead to the thinning of the work piece.

When the tool rotational speed is high, an excess heat input take place which increase the fluidity of metal and make turbulence flow in the welded zone which is resulted in the possibility of the formation of cavities. The result was agreeing with the result of Raza *et al.* which found that defect free welded joints were successfully obtained at tool rotational speeds of 800, 1000, 1500 and 2000 rpm (Moshwan *et al*., 2010). On the other hand by increasing he traverse speed (welding speed) an increase of the roughness of the joints surface occurred.

Advantages of FSW: FSW process has low distortion and shrinkage even in long welds, excellent mechanical properties and energy efficient. In addition, there is no arc or fumes, no filler wire required, no gas shielding for welding and no grinding or brushing required in mass production. Moreover, it is a fully automated method Robotic welding which has the ability to weld materials with low weldability and used in all welding positions. Furthermore, it is not need any special preparation of the workpieces and has lower setup costs and less training. Environmentally friendly and safer process than conventional welding techniques due to the absence of toxic fumes and porosity.

Limitations of FSW: Same as any other welding process, friction stir welding process has some disadvantages which included exit hole left when tool is withdrawn. In addition, large down forces are required especially with low rotational speed and high welding speed. Heavy-duty clamping is necessary to hold the plates together and lower welding speed than some conventional welding techniques. It is very expensive equipment and low wear resistance tool when welding high strength alloys.

CONCLUSION

There is a possibility to weld 5052 Al-Mg alloy plates with thickness of 14 mm by using friction stir welding process with welded tool made from high speed steel HSS material with taper pin shape without using filler metal. Welded tool (pin) has the higher heat generation which is higher than welded zone and base metal, therefore, tool must be make from suitable tool materials.

It is possible to weld plates with different rotational speed and welding speed with counterclockwise direction. However, it is difficult to weld with anticlockwise direction and the cutting process will take place instead of welding.

FSW zone has slightly high hardness compare with the base metal. On the other hand, TMAZ and HAZ zone have closed hardness to the base metal. Although, the majority of published papers showed that the hardness at TMAZ is lower than the hardness of base metal and HAZ has the lowest hardness.

The optimum value of tensile strength was obtained at rotational speed of 1120 rpm and welding speed of 10 mm/min which equal to 254 MPa. It is equal to 110% of tensile strength of base metal and the fracture angle was equal to 45°.

Friction stir welded plate that welded with rotational speed of 1120 rpm and welded speed of 10 mm/min has good resistance to bending strength which bended at 180° without any crack.

There is no smoking generated during friction stir welding process, however, the fumes and gas emission were generated during electric arc welding process. In addition, electric arc welding can be flying metal and dirt with arc rays which can be injury the welder and burn it is eyes with skin. Also, it may be produced sparks and made explosion or overheating or fire in the workshop place which are not appeared in friction stir welding process. Therefore, friction stir welding process is environmentally friendly process.

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