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Studying the Possibility to Weld AA1100 Aluminum Alloy by Friction Stir Spot Welding

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***Abstract*—**Friction stir welding is a modern and an environmentally friendly solid state joining process used to joint relatively lighter family of materials. Recently, friction stir spot welding has been used instead of resistance spot welding which has received considerable attention from the automotive industry. It is environmentally friendly process that eliminated heat and pollution. In this research, friction stir spot welding has been used to study the possibility to weld AA1100 aluminum alloy sheet with 3 mm thickness by overlapping the edges of sheet as lap joint. The process was done using a drilling machine instead of milling machine. Different tool rotational speeds of 760, 1065, 1445, and 2000 RPM have been applied with manual and automatic compression to study their effect on the quality of welded joints. Heat generation, pressure applied, and depth of tool penetration have been measured during the welding process. The result shows that there is a possibility to weld AA1100 sheets; however, there is some surface defect that happened due to insufficient condition of welding. Moreover, the relationship between rotational speed, pressure, heat generation and tool depth penetration was created.

***Keywords*—** Friction, spot, stir, environmental, sustainable, AA1100 aluminum alloy.

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I. Introduction

THE Friction Stir Spot Welding (FSSW) is a solid-state welding process suitable for the spot joining of lightweight metals such as aluminum alloys. It uses a non-consumable tool to weld two sheets, mostly by the generation of friction and plastic deformation but with the further process development it is possible to weld four layer [1]. The process was used to joint lap sheets by using rotational welded tool to produce heat and mechanical work [3].

FSSW is a relatively new discrete process derived from the continuous friction stir welding (FSW) method invented by Thomas at The Welding Institute (TWI), United Kingdom, in 1991 [1], [2]. It has been used to produce aluminum doors of Mazda RX-8. It was saving more than 90% of energy consumption and reduced 40% of the investment cost when compared to the traditional resistance spot welding (RSW) [4], [5]. Large heat distortion, consuming power and current besides to the welding detects of traditional RSW are quite enough reasons to replace RSW with FSSW. Nowadays, FSSW has been successfully applied to aluminum alloys, aluminum-magnesium, aluminum-steel and aluminum-copper in the automotive industry and aerospace applications where weight saving is extremely important [6], [7].

The FSSW process consists of three stages; plunging and bonding and drawing out. Rotational pin tool touches the surface of upper sheet and applied force. However, the welding support under the second sheet will support these sheets and supply upward force. In order to generate the required frictional heat, the tool rotation speed together with tool downloader force is maintained for a suitable period of time to generate heat and softening the sheet metal beside the tip of the pin. The result of this process is plastic deformation of upper and lower plates. Finally, the tool is drawn out of the sheets, and a keyhole is left behind [8].

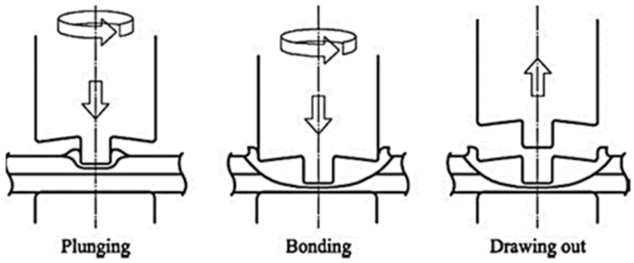

Fig. 1 A schematic illustration of the spot friction welding process [8]

Tool welding consists of shoulder and pin. It can be designed with different geometry. The shoulder can be threaded or smooth, and have a flat, convex, concave or tapered shape and the pin can be a straight cylindrical, triangular and sometimes tapered, or an inverse tapered. Tool geometry, tool rotational speed and plunge rate besides to dwell time affect the quality of welding joint. However, the tool plunge and the dwell time fundamentally detect the heat generation, material plasticization around the pin, joint geometry and thus mechanical properties of the joint [9].

Compared to the traditional welding techniques, such as RSW, Self-Pierce Riveting and laser spot welding, FSSW uses non-consumable tool and it can be done without melting the parent (base) metal [8]. FSSW process is energy efficient, the only energy consumed in FSSW is the electricity needed to rotate and drive the tool which leads to lower maintenance. FSSW can be considered as a good technique to overcome the welding defects compared to traditional welding process because it produces high joint strength without porosity, cracks and inclusions etc. [10]. It is environmentally friendly where no weld spatter, noise and reduced vapor emissions during FSSW, besides to that no preparation and consumables are needed [11]. However, one of the disadvantages of traditional FSSW is that after completing the welding process,

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a probe hole certainly created at the center of the weld nugget zone which leads to environmentally corrosion problem [12].

During the last decade, a number of studies have been reported on FSSW between Aluminum alloys. Uematsu et al. [13] joined Al–Mg–Si alloy using a double acting tool for FSSW consisting of outer flat shoulder and the inner retractable probe, which could re-fill probe hole. The microstructures were classified into three regions, mixed zone (MZ), stir zone (SZ), and parent metal (PM) where the boundaries of those three regions are clearly recognized. They further concluded that the refilling process increased the cross sectional area of the nugget which leads to increase the tensile strength [13].

Merzoug et al. [14] reported that the mechanical properties of the joint in FSSW had an excessive influence of the welding parameters and the geometry of the tool. They experimental work on AA6060-T5 show that when the rotational speed increased, the tension-shear strength was reduced. The dwell time is very important and must not exceed a certain value.

Zhang et al. [15] concluded that the joint strength decreases with increasing tool rotational speed for aluminum alloy 5052-H112 sheets of 1 mm thickness. Furthermore, hardness of heat affected zone (HAZ) is equal to 19.2 HV which is lower than the hardness of base metal.

Shen et al. [16] used 10 mm diameter concave profile shoulder to join 6061 – T4 aluminum alloys sheets of 2 mm thickness. The effects of dwell time and rotational speed on microstructure were investigated. Experimental results specify that the mechanical properties and microstructure variation depends dwell time and rotation speed. Furthermore, the Vickers hardness profile indicated that the minimum hardness occurred in the boundary HAZ and thermo-mechanically affected zone (TMAZ) where its value reaches 46.7 HV. The results show that tensile shear strength increased with increasing the dwell time and tool rotation speed.

Yuan et al. [17] stated the mechanical properties of the joints using a conventional pin tool and off-center feature tool. Increasing the plunge depth and rotational speed were considered as main influencing factors for lap-shear separation load. They found three different weld separation modes under lap-shear loading: Interfacial separation, nugget fracture separation and upper sheet fracture separation. The results indicated no direct relationship between microhardness distribution and separation locations.

II. Experimental Work

A. Materials

AA1100 aluminum alloy sheets with normal thickness of 3 mm, width of 25 mm, and a length of 100 mm have been used to be welded by FSSW process. The chemical composition and mechanical properties of AA1100 are shown in Tables I and II [18].

B. Welding Equipment

Drilling machine, type Breda R915L of spindle speed 40-2000 RPM shown in Fig. 2, has been used instead of milling machine to weld AA1100 aluminum alloy sheets as FSSW machine. The sheets were assembled as lap joint.

TABLE I
MECHANICAL PROPERTIES OF THE ALUMINUM 1100 SHEETS

Material	Hardness (HV)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
AA1100	50-65	34-150	90-165	9.9-25

TABLE II
CHEMICAL COMPOSITIONS OF USED AL ALLOYS, WT.%.

Material	Mg	Si	Mn	Cu	Fe	Zn	Al
AA1100	0.003	0.11	0.023	0.031	0.6	<0.008	99.2

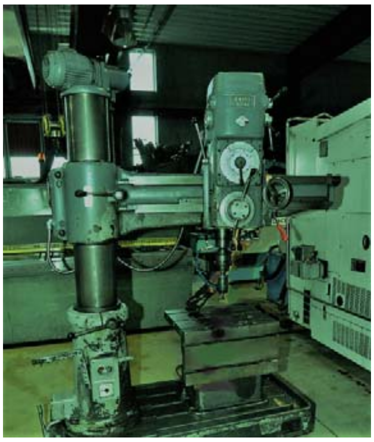


Fig. 2 Drilling machine, type Breda R915L

C. Welding Tool

Welding tool used for FSSW was made from high speed steel HSS material with taper cylinder shape. The tool consists of shoulder and pin which have the dimension and shape as shown in Table III and Fig. 3, respectively.

TABLE III
FSSW TOOL DIMENSIONS

Shoulder diameter (mm)	Shoulder length (mm)	Pin diameter (mm)	Pin Length (mm)	Tilt Angle (degree)
10	55	3	2	12
10	55	3	5	12

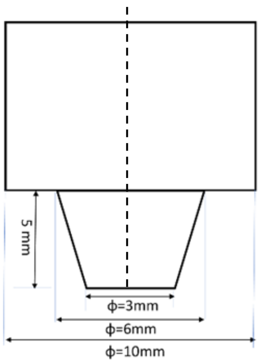


Fig. 3 FSSW tool geometry

D. Welding Process

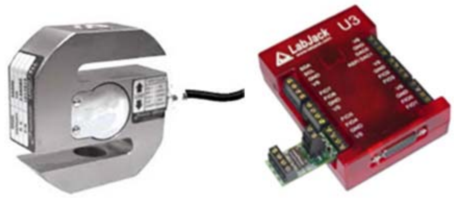
AA1100 sheets were fixed in the drilling machine anvil in the lab joint type and fixed by using rigid fixtures to prevent the movement of sheets during the welding process as shown in Fig. 4. Then welding tool was fixed in the drilling holder as shown in Fig. 5. Infrared device was fixed in the drilling machine to measure the heat that generated during the welding process and the pressure applied in this process was measured by using a load cell device fixed under the plates as shown in Fig. 6. Manual and automatic FSSW processes were used to weld the sheets with different rotational speed of 760, 1065, 1445, and 2000 RPM.

Fig. 4 FSSW specimen fixation

Fig. 5 Welding pin fixation in drilling holder

Fig. 6 Load cell and infrared temperature device arrangement

The SS300 beam load cell 50 kgf placed under the welding specimen, a signal-conditioning module (LJTIA) is used as amplifier of low-level signals produced from the load cell. The amplifier is connected to a USB DAQ device (Labjack U3) as shown in Fig. 7. The DAQ is then connected to the computer.



(a) (b)

Fig. 7 (a) SS300 load cell and (b) Labjack U3 with amplifier

Fig. 8 shows the friction stir welded sequence applied to weld AA1100 aluminum alloy sheets

Fig. 8 Sequence of FSSW for AA1100

III. Results and Discussions

The welded samples produced in this research were examined to evaluate their properties. Surface quality, depth of penetration, hardness, tensile strength and heat generation during the welding process were measured to study the effect of friction stir spot welding process on the quality of welding joint. FSSW samples were prepared according to the resistance welding handbook of American Welding Society (AWS) [19] as shown in Fig. 9.

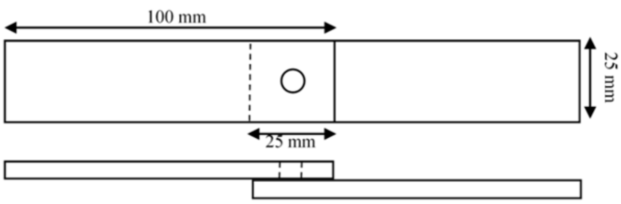


Fig. 9 Dimensions of the overlap specimen that to be welded

A. Surface Quality

Fig. 10 shows FSSW sheets welded with different rotational speed.

The results show that the welded samples have a good surface with some surface flash can be removed easily as shown in Fig. 11.

(a)

(b)

(c)

(d)

Fig. 10 FSSW sheets welded at different rotational speed (a) 760 RPM, (b) 1065 RPM, (c) 1445 RPM, (d) 2000 RPM

Fig. 11 Surface flash removal

B. Heat Generation

Heat generated during the welded process was measured by using infrared device and the results are shown in Table IV. In addition, the welded time and load applied for each sample were recorded too. The results show that heat generated increased with increasing the rotational speed and the maximum temperature was 210 °C. On the other hand, load and time were reduced with increasing rotational speed and time due the effect of heat.

TABLE IV
EFFECT OF ROTATIONAL SPEED ON THE HEAT GENERATED, TIME OF WELDING, AND APPLIED LOAD

Speed (RPM)	Time (sec)	Mean load (kg)	Max load (kg)	Max Temperature (°C)
760	64	130	230	142
760	52	134	180	146
760	35	142	239	176
760	40	126	200	124
1065	40	116	170	188
1065	44	107	200	161
1065	34	123	190	125
1065	28	125	210	110
1445	57	91	130	176
1445	50	91	140	197
1445	39	95	120	201
1445	33	95	140	99
1445	31	97	130	148
1445	27	98	160	192
1445	29	90	180	203
1445	23	106	149	210
2000	32	63	100	208
2000	40	67	110	148
2000	39	75	110	202
2000	37	68	110	200

A. Total Penetration Depth

TABLE V
DEPTH OF PENETRATION OF FSSW POINTS

Speed (RPM)	Time (sec)	Max load (kg)	Mean load (kg)	Surface flash (mm)	TPD (mm)
760	83	319	123	3.7	3.49
	96	319	121	2.34	3.81
	100	240	86	2.84	6
	131	270	137	4.75	6
1065	27	270	170	3.4	5.52
	28	270	170	4.8	6.0
	29	280	138	1.7	5.01
	78	220	105	0.88	5.77
1445	22	190	99	4	4.8
	32	180	102	2.65	5.08
	93	150	77	3.2	5.40
	94	160	90	3.3	5.47
2000	47	130	78	4.5	3.25
	75	130	72	2.81	3.69
	81	160	90	2.54	4.18
	90	150	69	2.65	3.39

Fig. 12 shows the shape of friction stir spot welded point produced in this work. Some of these points have hole in the middle happened due to high load and high heat generated during the welding process. Table V shows that the total penetration depth (TPD) is equal to 6 mm and the minimum depth of penetration is 3.25 mm depending on the load and heat. The majority of penetration depth is equal to 5 mm approximately.

The experimental work shows that load was decreased with increasing rotational tool speed due to increasing heat generation. It is equal to 319, 280, 190 and 160 kg at rotational speed of 760, 1065, 1445 and 2000 rpm, respectively.

(a)

(b)

(c)

(d)

Fig. 12 Shape FSSW welded point at different rotational speeds (a) 760 RPM, (b) 1065 RPM, (c) 1445 RPM, (d) 2000 RPM

B. Hardness

Vickers Hardness of FSSW plates have been measured by Microhardness device with load of 0.5 kg and Dwell Time of 10 s. The hardness of welded specimen was measured at different places in welded zone, TMAZ, HAZ and base metal. It is measured at distance of 2 and 5 mm from right and left of center of welded zone, respectively. The result shows that the hardness was increased at the center zone of welded joint which are higher than the hardness of base metal. The hardness was increased with range of 1.45 to 2.85 times of the base metal hardness as shown in Table VI.

The optimum tool rotational speed that can be used to weld AA1100 aluminum alloy is 1065 RPM because the hardness on the welding zone WZ and TMAZ will increase twice time comparing with the hardness of base metal. Also, the hardness of HAZ will be closed to the hardness of base metal. This is due to the value of heat generated during the welded process at 1065 RPM which are close to the recrystallization temperature of aluminum alloy. The effect of heat on the HAZ will eliminate too. In addition, the results show that the hardness and tensile strength of welded zone and TMAZ increased with increasing the rotational speed. However, the hardness of HAZ will reduce to be less than the original hardness of base metal.

TABLE VI
MICROHARDNESS OF FSS WELDED SHEET TYPE AA1100

Speed (RPM)	Hardness (HV)				
	5L	2L	2R	5R	Base
	55.7	89.6	78	50.3	
760	51	86	48	57	53.5
	56	75	99	55	
	53	63.3	48	53	
1065	53	86.6	111	51.4	53.4
	52	76	63	52	
	47.5	40.2	77	130	
1445	36.9	84.8	44.4	36.6	53.4
	38.5	66.2	35	43	
	34	53	92	33	
2000	38	150	89	38	54
	40.8	84	59.5	51.7	

C. Tensile Strength

The results show that tensile strength was increased with increasing the rotational speed as shown in Table VII. The maximum value of tensile strength was found in rotational speed of 2000 RPM which is equal to 233 MPa.

TABLE VII
TENSILE STRENGTH OF FSSW WELDED SHEETS TYPE AA1100

Rotational speed (RPM)	Tensile strength (MPa)	Elongation (mm/mm)
760	214	3.36
1065	123	5.04
1445	149	6.12
2000	233	9.9

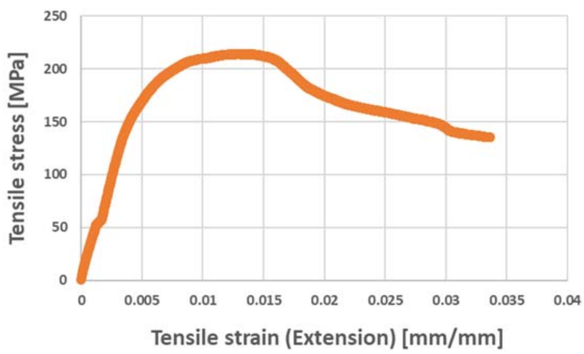


Fig. 13 Tensile strength of FSSW sheet at 760 RPM

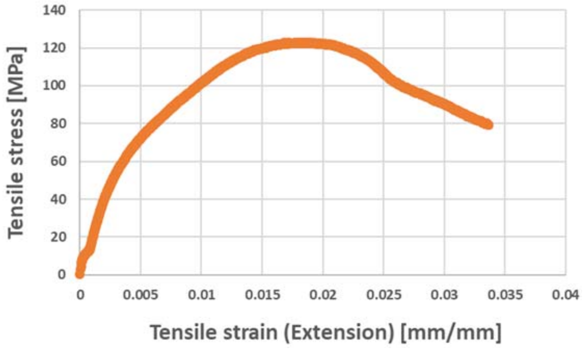


Fig. 14 Tensile strength of FSSW sheet at 1065 RPM

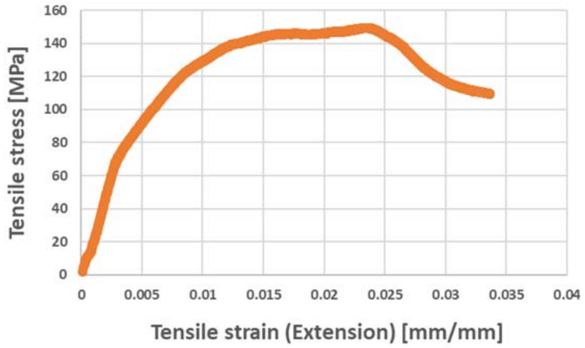


Fig. 15 Tensile strength of FSSW sheet at 1445 RPM

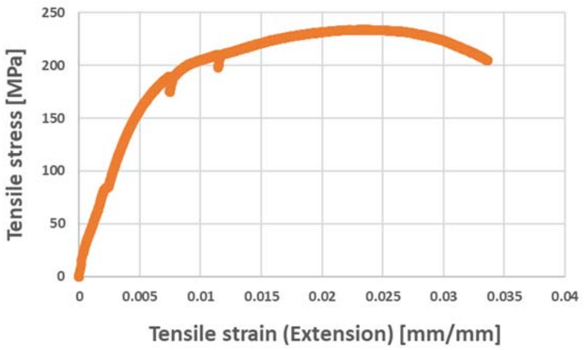


Fig. 16 Tensile strength of FSSW sheet at 2000 RPM

IV. Conclusion

The results show that there is a possibility to weld AA1100 aluminum alloy with thickness of 3 mm by using FSSW process with lap joint. Hardness was increased at the center zone of welded joint which are higher than the hardness of base metal. It was increased with range of 1.45 to 2.85 times of the base metal hardness. However, the optimum tool rotational speed is 1065 RPM. In addition, tensile strength was increased with increasing the rotational speed and the maximum value of tensile strength was obtained at a rotational speed of 2000 RPM which is equal to 233 MPa. It becomes twice of the values of base metal. The depth of penetration is in the range of 3.25 to 6 mm depending on the load and heat.

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