MECHANICAL PROPERTIES AND MICROSTRUCTURE OF 6061-T651 ALUMINUM ALLOY WELDED BY FRICTION STIR WELDING

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Abstract

Friction Stir Welding (FSW) is a solid –state process leads to several advantage over fusion welding methods. This process used a non-consumable tool to generate frictional heat required to performance sound joint. Tool pin profile, rotational speed, welding speed, play a major role to determine the weld quality .In this study, the effect of welding parameters (tool pin profile, rotational speed, welding speed) on mechanical properties and microstructure of 6061-T651 aluminum alloy joints are investigated. Results showed that tensile strength increases with welding speed and reaches a maximum value (235.7MPa)with welding parameters 900rpm,189mm/min threaded cylindrical pin and impact energy increased from 11J to 20j at weldingparameters:900rpm,116mm/min for threaded cylindrical pin. Also microstructure showed a fine grains with defect- free in weld zone.

Keywords: Friction stir welding, 6061-T651 Al-alloy ,Tool pin profiles

الخلاصة :-

يعتبر لحام الاحتكاك و الخلط من انواع لحام الحالة الصلبة والذي يتميز بخواص ميكانيكية متقدمة عن اللحام الأنصهاري . يستخدم في هذا اللحام عدة غير مستهلكة والتي تكون مسؤولة عن توليد الحرارة الكافية للحام و الناتجة عن الاحتكاك . (شكل العدة , السرعة الدورانية و السرعة الخطية) تلعب دور رئيسي في الحصول على نوعية جيدة للحام . في هذه الدراسة تم التعرف على تأثير كل من (شكل العدة , السرعة الدورانية , السرعة الخطية)على الخواص الميكانيكية والبنية المجهرية لسبيكة الالمنيوم 6061-T651.اظهرت النتائج بان مقاومة الشد ازدادت بزيادة السرعة الخطية ووصلت الى 235.7 MPaوبكفاءة (% 76.04) عند استخدام سرعة دورانية 900 rpm , سرعة خطية 189 mm / min وعدة اسطوانية مقلوظة المسمار , وكذلك مقامة الصدمة ازدادت من (11 J) الى (20 J)عند استخدام سرعة دورانية 900 rpm , سرعة خطية 116 mm / min وعدة اسطوانية مقلوظة المسمار . اظهر الفحص المجهري بان المنطقة الملحومة تتميز ببنية مجهرية ناعمة وبدون اية عيوب.

Introduction.

Welding is the extremely important joining method in the manufacturing process(Murr 1998), for the last years, the friction stir welding (FSW), metho has significantly increased the quality of a weld(Wang 2006). Invented by Wayne Thomas at The Welding Institute to UK (TWI), Cambridge, England in 1991(Mishra 2005).The process starts with clamping the plates to be welded to a backing plate so that the plates would not fly away during the welding process and a rotating hard steel pin can be inserted between two contacting metal plates or into a solid section of a continuous plate to create "a weld" in its walk or trailing side as illustrated in Fig. (1), it has been used most extensively on aluminum –based alloy, where in fusion welding is difficult, though this technology has also been applied to iron, titanium, copper, magnesium, nickel based alloys, tungsten carbide, and polymer(Zhang 2008).

FSW process is an emerging solid state joining process in which the material that is being welded does not melt and recast, thereby improving strength and ductility, increasing resistance to corrosion and fatigue, enhancing formability, and improving other properties. FSW can also produce fine-grained microstructures through the thickness to impart super plasticity. Essentially, (FSW) is a local thermo mechanical metal working process that changes the local properties without influencing the properties of the bulk material(Elangovan2008).This work is investigated the adaptable process ability of (FSW), butt joints, for aluminum alloy 6061-T651. It hopes that the mechanical property study could give an obvious direction for primary design and fabrication of the light weight structure.

Experimental Work

Milling Machine

Initially due to the limitation of the available equipment a vertical (AJAX) milling machine prepared to be suitable for (FSW). The milling machine with variable rotation at speed (28 to 1400) rpm and welding speed (12 to 800) mm/min.

Fixtures

Because of the milling machine is not designed for (FSW), the machine equipped with fixtures shown in Fig. (2).The fixture was a backing steel plate with a dimensions (260 mm × 220 mm × 30 mm), and machined to make internal groove with dimensions (200mm × 200mm × 3mm) to prevent slipping the aluminum plate during welding , two special steel strips, each strip was clamped down on the machine bed by using two bolts type (M16) which fix the welded plates along both sides parallel to the weld axis .The fixture plate prepared with side strip, the dimensions of strip are (260 mm X 30 mm X 10 mm), to prevent side slip during plunging the (FSW) tool between two aluminum plates. The side strip clamped by four bolts (M12).

Welding Tools

Fig. (3) shows the two welding tools used in (FSW) and the table (1) describes details of these tools. Tools were manufactured from a low alloy steel to perform the welding of the aluminum alloy plates. The welding tools consist of a cylindrical holder linked to the machine spindle.

Welded Plates

The dimension of the test plate is 200 mm in length, 100 mm in width, and 6.5mm thickness for butt joint Fig. (4) , plates are prepared by using a horizontal milling machine. Before welded, the plates were preoxidized by stainless steel brush and whipped with acetone solution. Detailed joining designs were described in Table (2). The tilt angle of welding spindle is 2°.

Microstructure Investigation of Welded Joints

To reveal the microstructure of the AA 6061-T651 mechanical grinding and polishing process . The following regime was employed:

1- Planar grinding process of the surface undertaken with 400 grit followed by 600, 800, 1000, 1200, 1500, and 2000 grit (SiC) paper until a uniform surface finish was attained. Water was used for lubrication.
2- Initial polishing was undertaken using (1 µm) diamond compound for 5 minutes. Lubricant fluid, type W, was used for lubrication.
3- Final polishing was completed using aluminum oxide (AL_2O_3) suspension for (10) minutes. The polishing conducted in one direction until all evidence of prior polishing was eliminated. The sample was then rotated 90° and the process were repeated.

4-Etching (2.5 % HNO_3, 1.5 % HCL, 1 % HF and 95 % H_2O), applied for (15) seconds. Fig. (5) illustrates the specimens prepared to the microstructure investigation.

Optical microscopy of the (FSW) samples was conducted with a (Beam engineers, India) model: beam rmm-7t (2003), equipped with camera and computer to revel the image of microstructure. The cross-section of sample is prepared using horizontal milling machine.

Mechanical Test

Tensile Test

Tensile specimens were machined from the welds according to the ASTM sub-size specimen geometry (B 557M-02a), shown in Fig. (6), such that the specimen length (transverse specimen). For each welded joints three specimens have been machined. Tensile strength was calculated from these tests for each sample and the results were averaged.

Microhardness Test

Microhardness testing was undertaken using a (Microhardness tester HV-1000) thesame specimens of metallurgical test are prepared for the microhardness. It is necessary to determine the hardness over small positions on the surface of base metal, heat affected zone (HAZ), and weld metal to indicate the variation in hardness for each position. In accordance with ASTM E3841, reading had been carried out for each 1 mm distance. A load of 500 g was employed and loading time of 10 to 15 seconds.

Impact Test

The impact tests were carried out on welded samples using an instrumented pendulum machine (FIT-300N). According to ASTM E23, Sub-size charpy V specimens (10 X 5 X 55) mm3, with 2mm deep V- notch, were used for the tests, due to the reduced thickness of the plates; the specimens were machined with the notch perpendicular to the welded line. The notch of V specimen is located in the center of the test specimen, which is supported horizontally at two points. The specimen receives an impact from a pendulum of specific weight on the side opposite that of the notch

Results and Discussion

Microstructures

Microstructure examination on the joint cross section conducted for butt welded samples with rotational speed (710 rpm), (900 rpm),welding speed (189 mm/min) ,and inclination angle 2°.

A specimen was sectioned from welded plate to reveal a plane normal to the direction of tool travel and this specimen was prepared for optical microscopy.

Fig.(7) reveal photographs of welded joint cross section, as well as to indentify voids or defects contained within lastly the examination provides insight and comparison study with reported literature.

Present microstructures agree with literature and fall within the category of basin-shaped and elliptical type depending on various factors such as process parameters, tool geometry, workpice temperature and metal's thermal conductivity. The visual examination showed defect free in all welded samples, so the basin –shaped and elliptical type ,occurs when tool No.2 and tool No.1, used respectively.

Butt Joint Microstructure

Fig. (8-b) present micrographs showing the evolution of 6061-T651 microstructure in the (FSW) region with rotational speed (710 rpm), welding speed (189 mm/min), tool No. 2 . The central portion of the weld or (nugget) location has a refined equiaxed grains. Fig. (8-c) present, large particles have been broken up to small particles and may be these small particles have been placed at the grain boundaries. The average size of particles decreases with increasing rotational speed from 710 rpm to 900 rpm. Sever plastic deformation during (FSW) is the main reason for breaking up of particles. Whereas, the recrystallization occurs simultaneously with breaking up of particles during (FSW) and then particles will place in the grain boundaries in the nugget zone.

Tensile Test Results

One of the objective of the present study is to examine the tensile strength of friction stir welded Al 6061-T651 alloy plate joined with different condition.

Table (3) summarizes the results of transverse tensile test. Test results for specimens (S1 to S16) which welded by tool No.1, tool No.2 with rotational speed (710, 900 rpm) and welding speed (69, 86, 116, 189 mm/min), demonstrating that ultimate tensile strength have been increased with increasing welding speed and maximum joint efficiency is (76.04 %) for (S12, S16) which conducted by tool No.2 with (710 rpm, 189 mm/min), (900 rpm, 189 mm/min) respectively. The results reveals that there is no significant effected for rotational speed to the tensile strength. All welded samples failed in HAZ of the advancing side similarly as (Liu 2003), Fig. (9) shows photograph of the test sample before and after tensile testing so known that the necking zone occurred generally at the HAZ. The HAZ retains the same grain size as the parent material. However, the thermal exposure results in a significant coarsening of the precipitates and development of the precipitate free zones (PFZ). Thus, the HAZ exhibits the lowest hardness and strength, and fracture in tensile test occurs usually in the HAZ(Brown 1999).

Microhardness

In order to investigate softening or hardening effects induced by (FSW) process on the aluminum alloys, microhardness measurements, with a low load (HV_{500}), were made across the two-dimensional transverse cross section at a spacing of (1 mm) from the nugget zone to the base metal. The results show that the hardness in the nugget is slightly higher respect to the (THAZ) and (HAZ) because of the finer grain size of the nugget. In the (HAZ) precipitates are not dissolved in the matrix, and consequently there is no reappearance of precipitates due to thermal cycle. This causes the lowest hardness and consequently fractures during tensile testing in the (HAZ) (Kumr 2008).

Because there is a difference in plastic deformation between advancing and retreating sides, which produce a significant difference in precipitate microstructure, and the difference in thermal cycles in both sides, unsymmetrical microhardness profile, can be pointed out Fig (10).

Table (4) shows that there are four sets of welds, the second set (S5 to S8) and fourth set (S13 to S16) at 900 rpm , joints have higher Vickers microhardness in the welding center (HV =291), and (HV =296), than the base metal (B.M.) (HV = 107) for second and fourth sets by increase percentage (271 %), (272 %) respectively.

The first set (S1 to S4), and third set (S9 to S12),for first set, there are slight reductions in hardness from 107 HV (hardness of base metal) to 99 HV. The reduction percentage is 7.5 %. The third set, the reduction in hardness from 107 HV to 105 HV. The reduction percentage is 1.9 %.The reduction in the hardness of the nugget region is expected in friction stir welded material. The overall softening of the processed region is caused by coarsening dissolution of strengthening precipitates during the thermal cycle of the (FSW). Further, within the nugget region the comparative hardness depends on the extent of coarsening / dissolution of strengthening precipitates. The amount of dissolved phases increases with increasing heat index (Basasubramaninan 2009).

Impact Test

Table (5) show that the impact energies increased in friction stir welded material respect to the corresponding base metals, from (11 J), base metal impact energy (B.M.), to (20 J) for run S15, (tool No.2, 900 rpm, 116 mm/min). This significant increase in the total absorbed impact energies can be related to the microstructural modifications induced by the (FSW) process, such as: refinement, homogeneous distribution of the precipitate particles in nugget zone, and reduction of the matrix grain size. The changes in energy absorbed are more sensitive to changes in tool pin profiles than to changes in rotational speed and welding speed. All results of energy absorbed related to the tool (No.2) are greater than the results of tool (No.1), hence, it is clearly show that the greater amount of plastic deformation in the friction stir welded materials respect to the base metals related to the increase in the total absorbed energy.

Conclusions

The following important conclusions are derived:

1. Defect free weld nugget, higher hardness of weld nugget and very fine grain size uniformly distribution of particles in the weld nugget is formed.
2. FSW lead to grain refinement, with the grain size increasing from retreating side to advance side.
3. Of the two tool pin geometry used in this investigation to fabricate the joints, thread cylindrical pin produced sound joints and more efficiency rather than flat taper pin 30°.
4. Maximum tensile strength in this study was (235.7 MPa) and (76.04 %) efficiency, obtained when using welding parameters (900 rpm, 189 mm/min and thread pin).
5. The tensile strength is increased when the welding speed increased.
6. The joint fabricated using a rotational speed of 900 rpm, a welding speed of 116 mm/min and thread pin, showed superior impact energy 20 J .
7. The maximum microhardness of nugget zone increasing from 107 HV to 296 HV with parameters 900 rpm, 116 mm/min and with thread pin used.

Table (1): Details of the tools used in (FSW)

Tool No.	Tool feature	Tool details
1	Shoulder diameter	20mm
	Concavity	10°
	Pin diameter	6.5mm , tilte angle 30°
	Pin length	6.3mm
	Material (Tested)	Low alloy steel HRC = 35 (0.35)%C,(0.33)%Si,(0.79)%Mn, (1.5)%Ni,(0.26)%Mo, (0.16)%Cu
2	Shoulder diameter	20mm
	Concavity	10°
	Pin diameter	M(6.5×1) thread
	Pin length	6.3mm
	Material (Tested)	Low alloy steel HRC =35 (0.35)%C, (0.33)%Si, (0.79)%Mn, (1.5)%Ni, (0.26)%Mo, (0.16)%Cu

Table (2): Welding variables of the FSW welding

Tool design	*Run No.*	*Weld detail*	*Rotational speed (rpm)*	*Welding speed (mm/min)*
Tool No-1 Taper pin (30°)	*S 1*	*Butt*	*710*	*69*
	S2	*Butt*	*710*	*86*
	S3	*Butt*	*710*	*116*
	S4	*Butt*	*710*	*189*
	S5	*Butt*	*900*	*69*
	S6	*Butt*	*900*	*86*
	S7	*Butt*	*900*	*116*
	S8	*Butt*	*900*	*189*
Tool No-2 Threaded pin	*S9*	*Butt*	*710*	*69*
	S10	*Butt*	*710*	*86*
	S11	*Butt*	*710*	*116*
	S12	*Butt*	*710*	*189*
	S13	*Butt*	*900*	*69*
	S14	*Butt*	*900*	*86*
	S15	*Butt*	*900*	*116*
	S16	*Butt*	*900*	*189*

Table (3) : Results of tensile test for (FSW) joints.

Tool design	Run No.	Rotational speed (RPM)	Welding speed (mm/min)	Tensile strength (MPa)	Joint efficiency %
Tool No-1 Taper pin (30°)	S 1	710	69	189.161	61.02 %
	S2	710	86	192.588	62.13 %
	S3	710	116	210.529	67.91 %
	S4	710	189	219.852	70.92 %
	S5	900	69	195.446	63.05 %
	S6	900	86	201.476	64.99 %
	S7	900	116	215.25	69.36 %
	S8	900	189	225.968	72.89 %
Tool No-2 Threaded pin	S9	710	69	207.656	66.99 %
	S10	710	86	221.428	71.43 %
	S11	710	116	221.428	71.43 %
	S12	710	189	235.714	76.04 % *
	S13	900	69	214.285	69.12 %
	S14	900	86	214.285	69.12 %
	S15	900	116	221.428	71.43 %
	S16	900	189	235.714	76.04 % *

Table (4): Illustrate the hardness number in welding center.

Tool design	Run No.	Rotational speed (RPM)	Welding speed (mm/min)	HV_{500}Number in the center welding
Tool No-1 Taper pin (30°)	S 1	710	69	89.1
	S2	710	86	99
	S3	710	116	86.6
	S4	710	189	95
	S5	900	69	291
	S6	900	86	103
	S7	900	116	224
	S8	900	189	151
Tool No-2 Threaded pin	S9	710	69	91.8
	S10	710	86	104
	S11	710	116	105
	S12	710	189	99
	S13	900	69	94.6
	S14	900	86	108
	S15	900	116	296

S16	900	189	280

Table (5):The V Charpy impact test results.

Rotational speed (rpm)	Welding speed (mm/min)	Energy absorbed (J)	
		Tool No. 1 (Taper pin 30°)	Tool No. 2 Threaded pin
710	69	14	18
	86	10	19
	116	12	19
	189	8	18
900	69	9	19
	86	12	17
	116	10	20
	189	14	18

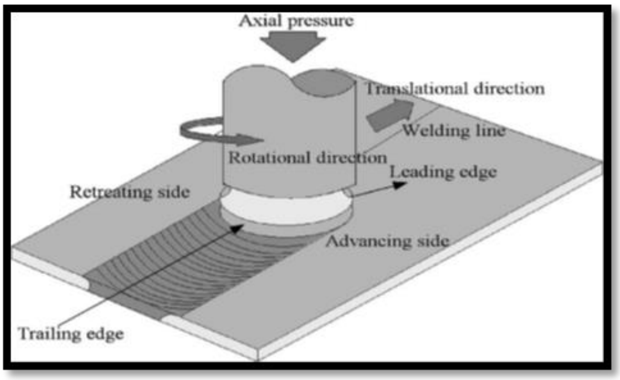

Figure (1): principle diagram of (FSW) (Zhang 2008).

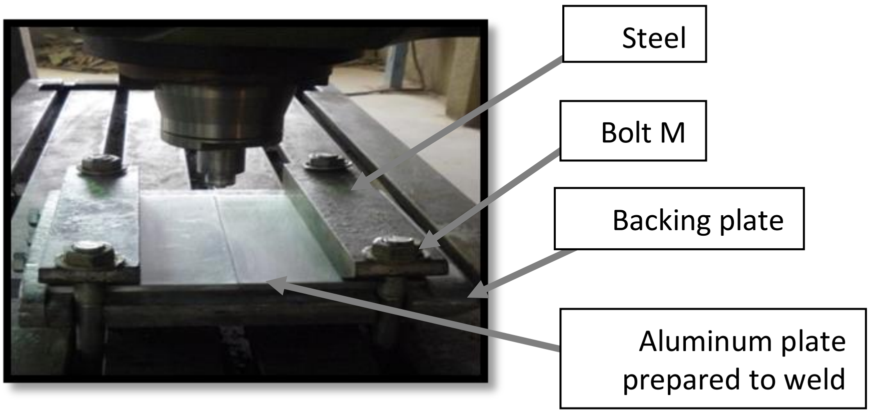

Figure (2): (FSW) fixture.

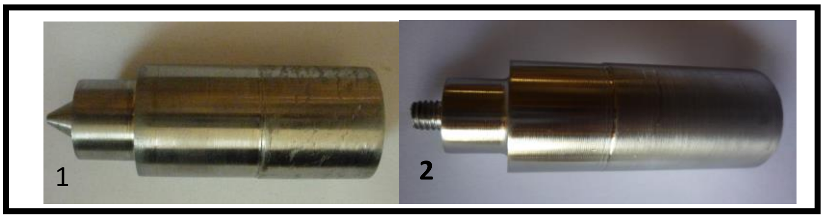

Figure (3): (FSW) tools.

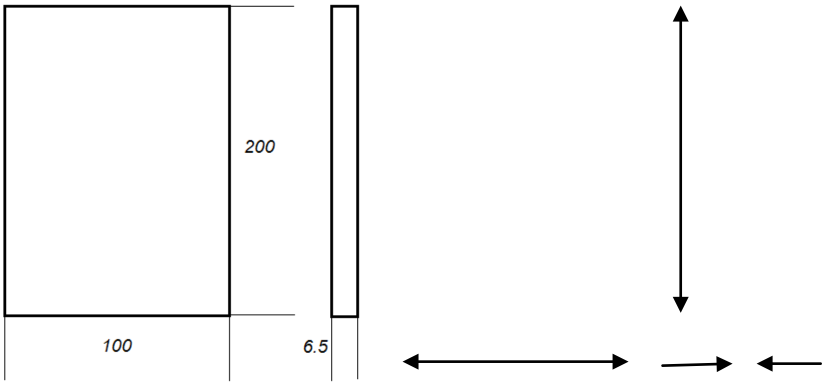

Figure (4): plate prepared for butt welding.

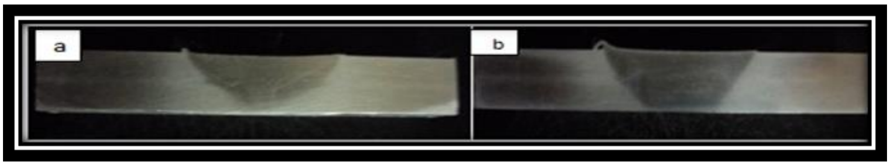

Figure (5): Specimens prepared to Microstructure investigation(X1).

a) Butt (FSW) using tool No. 1 b) Butt (FSW) using tool No. 2

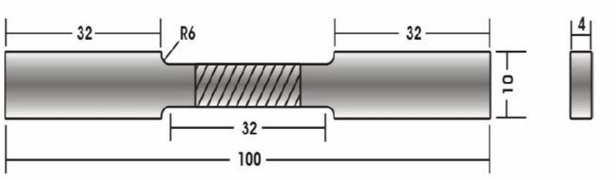

Figure (6): ASTM (B 557M-02a) sub-size sample for tensile test. Dimensions in mm.

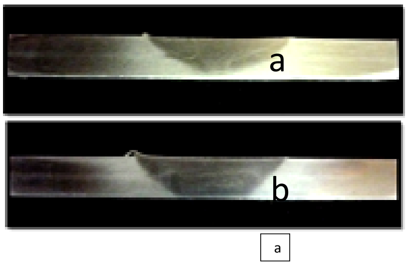

Figure (7): FSW samples (X1): (a) welded by tool No.1 (b) welded by tool No.2

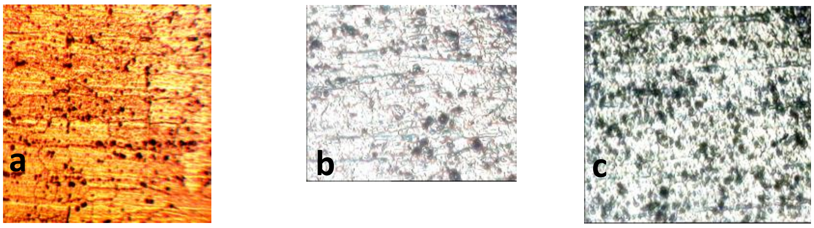

Figure (8): Butt joint microstructure

(a): Base metal, (X 150) (b): rotational speed (710 rpm) and welding speed (189 mm/min),tool No.2 (X 150) (c): rotational speed (900 rpm) and welded speed (189 mm/min),tool No.2 (X150).

Figure (9) : Tensile test samples

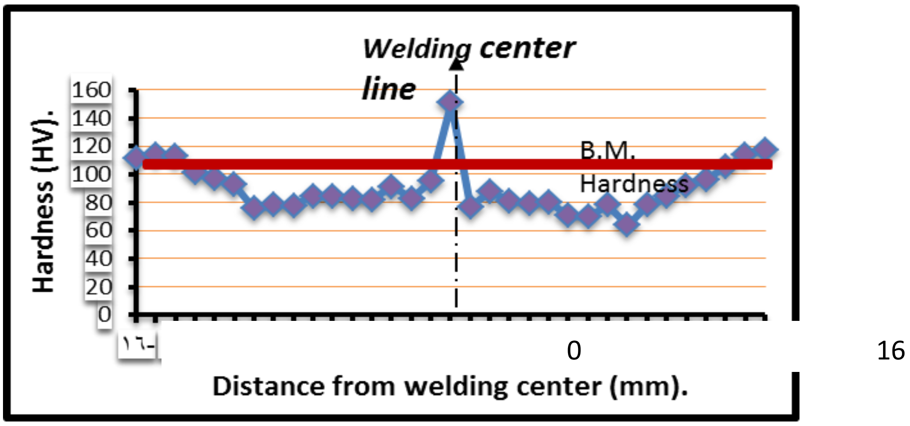

Figure (10): Micro hardness profile in joint S8.

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