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EFFECT OF OPERATION CONDITIONS ON MECHANICAL PROPERTIES OF AA7020-T53 ALLOY WELDED BY FRICTION STIR WELDING

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Abstract: Friction stir welding -FSW- is a new process of joining AA7020- T53 aluminum alloy sheet. There are few parameters which effects of FSW such as spindle speed, feed rate, tool design and tool tilt angle. In this search, the effect of tool rotational speed (spindle speed) and travel speed (feed rate) on mechanical properties are discussed. The FSW technique was performed using three different of rotational speeds and three different traverse speeds, while other parameters are kept constant to compare between joints. It was found that the best mechanical properties can be obtained from using high spindle speed and high feed rate. The ultimate tensile strength increases approximately 25% while the yield stress and elongation increases approximately 19% and 57% respectively, when used spindle speed (900r.p.m) and feed rate (50 mm/min).

Keywords: *Friction Stir Welding, Aluminum alloy 7020, Mechanical properties, Spindle Speed, Feed Rate.*

تأثير ظروف العمل على الخواص الميكانيكية لسبيكة الألمنيوم الملحومة(AA 7020-T53) بطريقة اللحام الاحتكاكي بالخلط

الخلاصة : لقد تم دراسة لحام الخلط الاحتكاكي وهي طريقه جديدة لربط صفائح من سبائك الألمنيوم AA7020-T53 وهناك متغيرات تؤثر على عملية لحام الخلط الاحتكاكي منها سرعة دوران العدة ومعدل التغذية وتصميم شكل العدة وزاوية ميل العدة. في هذا البحث درسنا تأثير سرعة دوران العدة ومعدل التغذية على الخواص الميكانيكية للملحومة وانجزنا عملية اللحام بالخلط باستعمال ثلاث سرع دورانية مختلفة للعدة وثلاث معدلات مختلفة للتغذية مع المحافظة على بقية المتغيرات ثابتة لأجراء المقارنة. وجدنا ان افضل خواص ميكانيكية سجلت باستعمال الظروف المثالية وهي أعلى سرعة دوران للعدة وأعلى معدل للتغذية .ان قوة للشدالعظمى قد ارتفعت حوالي 25%بينما اجهاد الخضوع والاستطالة قد ارتفعت حوالي 19%و57% على التوالي عندما استعملنا سرعة دوران للعدة 900r.p.m ومعدل تغذية 50mm/min.

1. Introduction

Friction stir welding -FSW- was patented and developed by Thomas in year 1991 at the welding institute, Cambridge. It can exceed many of problems in traditional welding methods and make of good quality, especially in case of hard to weld materials

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such as, copper, magnesium and aluminum alloys. Friction stir welding method is an environment friendly (no filler material and no fumes), also proven and potential process for welding high strength aluminum alloys. FSW technique is widely utilized for industry transport structures such as trucks, boats, aircrafts and trains, as in [1, 2].

FSW process is a novel solid state joining technology because of the materials can be welding without recast or melt and this process notice that many benefits over conventional fusion welding like no porosity, no crake and no problems of solidification. Moreover, this process is very useful for joining soft materials such as aluminum alloys and high-strength aluminum alloys special 7xxx and 2xxx which were considered unweldable by conventional welding methods, as in [3, 4].

In FSW method, 2 parameters are too important (rotation speed of tool r.p.m in counterclockwise or clockwise direction and travel speed mm/min along the line of joint). The tool rotation speed lead to mixing and stirring of materials about the spinning pin, also the translating of tool movements the stirred materials from the (front)to the(back) of the pin and finished FSW method. High speed of rotation tool produce high temperature due to high friction heating and lead to mixing and more intensity stirring of material, as stated in [5].Generally, lower tool rotation speeds and slower travel speeds are used for thicker sections or harder alloys. Decreasing travel speeds or increasing rotational speeds lead to increase joining temperature and heat input. However, extremely low or high rotational and travel speeds can adversely affect on mechanical properties, as mentioned in [6].

Aluminum alloys are utilized in many applications such as aerospace, automobile, bridges and ships industries because of its higher strength to-weight ratio and light weight. In manufactures welding, aluminum alloys are too prime and wide applicable metal joining method, as in [7]. Many studies in last years have been done to relating the parameters of FSW process and their effect with all output response to obtain best joint properties.

Lakshminarayanan and Balasubramanian [3] discussed the impact of tensile strength on primary parameters of FSW process such as force axial (4, 6 , 8 KN), traverse speed(22 ,45 ,75 mm/min) and rotational speed(1200, 1400, 1600 rpm) for 7039 aluminum alloy plats and found the optimum condition by using force axial 6.5KN, traverse speed(welding speed) 40mm/min and rotational speed(tool speed)1460 rpm was given maximum tensile strength 319 Mpa.

Rajakumar et al. [8] presented the use of AA7075-T6 plats as basic metal changing many parameters of friction stir welding such as welding speed or feed rate (20 ,40, 60,80 and100 mm/min),rotational speed or spindle speed(900, 1200, 1400 ,1600 and 1800r.p.m), tool hardness(33 ,40 ,45, 50 and 56 HRC), pin diameter(3, 4, 5, 6 and 7mm) and shoulder diameter(9 ,12 ,15 ,18 and 21mm) through the experimental part ,they concluded that the best joint condition, when 8KN(axial force), 60mm/min (welding speed), 1400rpm(tool rotational speed), 45HRc(tool hardness), 5mm (pin diameter) and 15mm(shoulder diameter) gave the higher tensile strength 373 MPa, higher yield strength 315 Mpa, higher hardness 203 HV and 77% efficiency of welding.

Balasubramanian and Lakshminarayanan [9] evaluated the percentage of important parameters in FSW process for 7039 aluminum alloy plats and found the traverse speed (feed rate) has33% contribution, axial (load) has 21% contribution and high percentage of tool speed (spindle speed) has 41% contribution to tensile properties of welding. The ideal values of these parameters are for traverse speed is 45 mm/min, axial force is 6KN and rotational speed is 1400 rpm.

Gaafer et al. [10] investigated the mechanical and micro-structural properties of friction stir welding process for AA7020-O plate and studied the effect of rotational speed (1120, 1400, 1800 rpm) and welding speed(20, 40 , 80 mm/min) parameters. It has been found that increasing the tool rotational speed and/or reducing welding speed increases the primary Al phase grain size as well as the size of the precipitates at the center of the stirred zone. The tensile characteristics of the friction stir welded tensile samples depend significantly on both the tool rotational and welding speeds.

Essa et al. [11] modeled the aluminum alloy of AA7020-O plate produced by FSW process. This material was annealed before welding to remove the residual stress and homogenizing. The welding process was performed using two rotational speeds of 1125 and 1400 rpm with three traverse speeds, 20, 40 and 60 mm/s and keeping other parameters of FSW process constant. It was concluded that the lower traverse speeds are accepted with two rotational speeds to produce good joints and the micro-hardness is strongly depends on the rotational tool speed. It was shown that the decrease in the rotational speed lead to increase the value of the joints hardness but slightly affected of welding speed.

Jweeg et al. [12] related the effect of tool geometry and (rotation and travel speeds) joining parameter on the mechanical properties when, used FSW process of 7020-T53 aluminum alloy. Three types of tools are used (high speed steel HSS with diameter of shoulder 15mm and inclined angle 2.5°, steel X12M with diameter of shoulder 18mm and inclined angle 8° and steel X12M with diameter of shoulder 18mm and inclined angle 2°).While welding speed mm/min(16, 25, 40) and tool speed rpm(710 ,900 ,1120,1400).It was concluded the suitable condition of FSW process (40mm/min travel speed),(1400rpm tool speed) and (83% max. welding efficiency).The micro-hardness increase when, increasing tool speed in welding zone and decrease the grain size.

Heidarzadeh et al. [13] studied the tensile properties of AA7020 aluminum alloy plate by friction stir welding (FSW) and used three parameters (axial force 5.32, 6, 7, 8 and 8.68 KN), (traverse speed 58, 75, 100, 125 and 142 mm/min) and (rotational speed 664 ,800 ,1000 ,1200 and 1336 rpm).It was found that the higher axial force, higher tool rotational speed and lower traverse speed lead to increase in heat input during friction stir welding, also the ultimate tensile stress of AA7020 increased reaching the maximum amount and then decreased. The optimal condition to obtain maximum value of tensile strength at 7.4 KN, 97 mm/min and 1055 rpm.

Tolephih et al. [14] carried out friction stir welding of AA7020-T6 aluminum alloy plate with different tool speeds (450, 560, 710 and 900r.p.m) and different transverse speeds (16, 25 and 40 mm/min) by vertical milling machine. It was estimated that the increase of UTS for FSW process was 340 MPa while for MIG welding process was 232 MPa, also; the micro-hardness was recorded 133 HV for FSW and 70 HV for MIG welding. The friction stir welding method produces 2470 N higher than the MIG method.

Liguo Zhang et al. [15] discussed the design of friction stir welding tool and concluded that that the geometry of the flute of a rotational tool during the friction stir welding process greatly influences the material flow behavior. The tool with half-screw pin and the tool with tapered-flute pin both obviously increase material flow velocity near the bottom of the workpiece and are both beneficial in avoiding root flaws.

Yang et al. [16] related the Effect of tool geometry and process condition on static strength of a magnesium friction stir lap linear weld. . Compared to the cylindrical tool, the triangular tool effectively suppresses the hook on the retreating side due to enhanced horizontal material flow. This primarily leads to a 78% increase in optimized weld strength. A ‘pure’ shear surface present on the tool pin significantly reduces weld strength.

Faleh [17] studied the mechanical properties of friction stir linear welds for 7075 aluminum alloy and the effects of tool geometry on tensile stress and shear strength of butt and lap welds, and comparing with base material. It was found that the FSW with lap joining showed good strength behavior, about 15% compared with FSW butt welds. The FSW samples machined with high revolutions for tool, about 2000 rpm, showed good strength behavior, about 15% compared with FSW of 1000 rpm .The samples of FSW by stirrer with pin, showed good strength behavior, about20% compared with FSW butt welds.

2. Experimental Procedure

2.1. Materials Used

The aluminum alloy (AA7020-T53) 5mm thickness plate was obtained from locally market. This alloy AA7020-T53 is [Al- Zn- Mg] grade alloy of (7xxx-series) heat treatable of medium strength alloys. The inspection of this alloy was carried out in Specialized institute for engineering industries by Spectra device to find the chemical composition of piece as shown in Table (1), these values are compared with the standard values from ASM standard.

The mechanical properties of aluminum alloy (AA7020-T53) as shown in Table (2). Aluminum alloy AA 7020-T53 plate of dimension (200mm x100mm x5mm) was joint parallel to the rolling direction to prepare the FSW process as shown in Figure (1).

Table (1): Actual and standard chemical composition of AA7020-T53 aluminum alloy (wt %).

	Fe	Si	Mn	Cu	Mg	Ti	Zn	Cr	Zr	Al
Actual value	0.256	0.166	0.111	0.142	1.29	0.042	4.61	0.213	0.14	Bal.
Standard value	≤0.40	≤0.35	0.05-0.5	≤0.20	1 – 1.5	0.08	4 – 5	0.10-0.35	0.08-0.2	Bal.

Table (2): Actual and standard mechanical properties of AA7020-T53 aluminum alloy.

	Ultimate stress (MPa)	Yield stress-proof stress of 0.2%- (MPa)	Elongation (%)
Actual value	400	356	16%
Standard value	393	345	15%

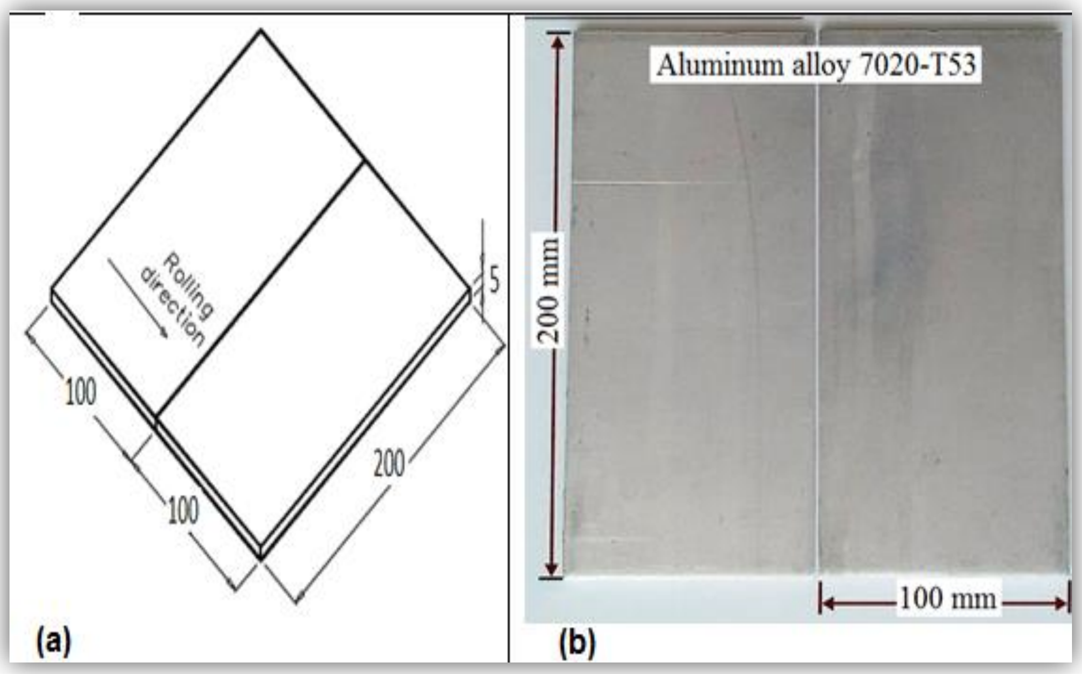

Figure (1): (a) Size and shape of aluminum alloy (AA7020-T53) rectangular-butt- joints used for FSW process. (b) Sheets preparation for welding. All dimensions in mm.

2.2. Friction Stir Welding (FSW) Technique

The FSW technique was performed by tool has hardness (56HRC) and this tool is manufactured from high speed steel (HSS). The diameter of shoulder tool was (15 mm), diameter of pin was (5 mm), while height was (4.85 mm) and cone angle was ($2.5^{o)}$ as shown in Figure (2).

All the FSW processes were carried out at vertical classic milling machine in the Technical College, Baghdad, see Figure (3). The butt-joint arrangement (specimen of welding) was occurred by supporting backing-plate made from carbon steel.

This plate was connected with table of vertical milling machine and was checked the level surface to ensure from adjusting. During process of welding, the rotating of tool was taken with clockwise-direction according to vertical-axis, and then the tool was going in the rolling-direction of the specimen.

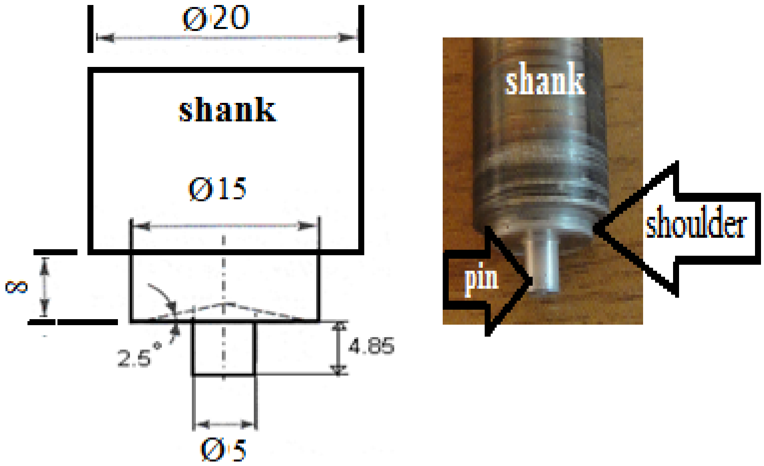

Figure (2): HSS tool of FSW. (The dimensions of tool in mm)

Figure (3): Universal of milling-machine (fixture and plate to be welded).

2.3. Process Parameters

In this work two parameters were selected: rotational speed and travel speed (feed rate) because it has main effect to quality and control of mechanical properties of joining. The parameters were chosen in consideration with the machine capabilities. The welding process was performed using three rotational speeds and three travel speeds as shown in Table (3), while the tool was rotating in counter-clockwise direction during the friction stir welding process, Figure (4) shows of aluminum welded sample.

Table (3): Parameters of FSW process for aluminum alloy (AA7020-T53).

Spindle speed (rpm)	450	710	900
Feed rate (mm/min)	20, 31.5, 50	20, 31.5, 50	20, 31.5, 50

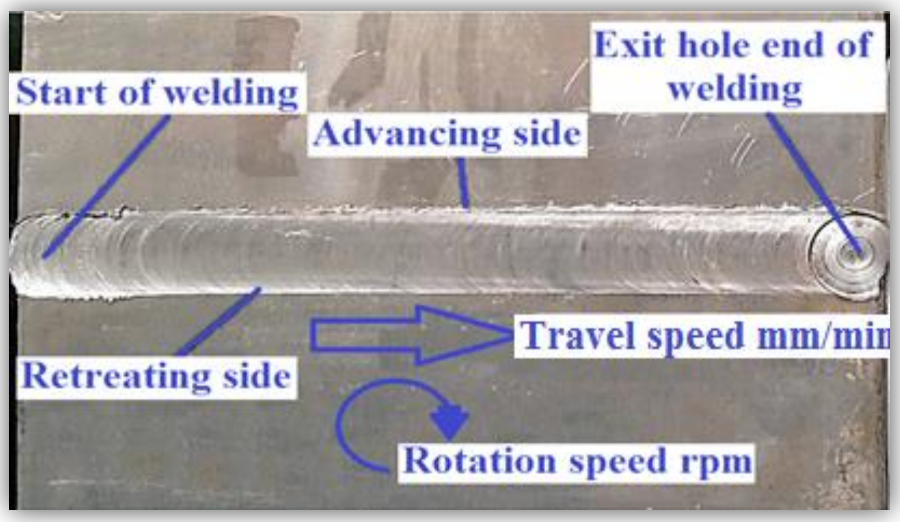

Figure (4): Welded sample explaining welding direction, start, and end of welded joint.

3. Mechanical Properties

3.1. Tensile Test

Tensile test was carried out on samples taken in a perpendicular direction to the welding line to determine the tensile properties of the welding joints. The dimensions and shape of the transverse tensile sample according to ASTM standard (B557M) are shown in Figure (5).

Tensile specimens configuration were designed and manufactured according to ASTM specifications for both parent metal and FSW plates and executed on CNC machine type TX32 in the Technical College, Baghdad / CNC Workshop, as seen in Figures (6) .

All tensile strength tests were performed at constant loading-rate (5mm/min) and room temperature by computerized universal machine, when united test 100KN in the (Institute of Technology – Baghdad) shown in Figure (7).

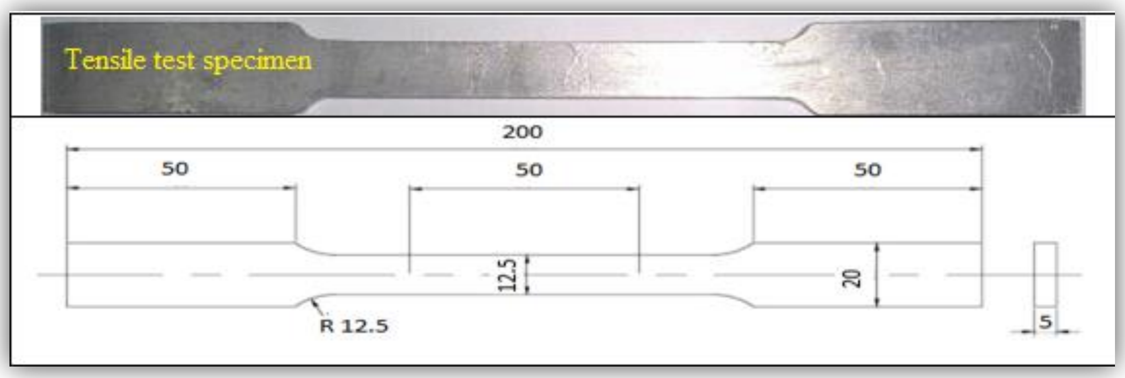

Figure (5): Tensile test specimen according to ASTM-B557M (all dimensions in mm).

Figure (6): CNC machine type TX32.

Figure (7): Universal testing machine (united test 100KN).

3.2. Bending Test

3- Point bending test was performed to estimate the maximum bending load of the welded joints. Face and root bending tests were performed with former diameter is equal to 58.1mm (1.5 in.) according to the yield strength value [for $\sigma y \leq 50000$ psi (345 MPa) $D_{=}$ 1.5in.] as shown in figure (8a). The bending test was carried out at room temperature by computerized universal testing machine (united test 100KN), in the (Institute of Technology – Baghdad) as shown in figure (8b).

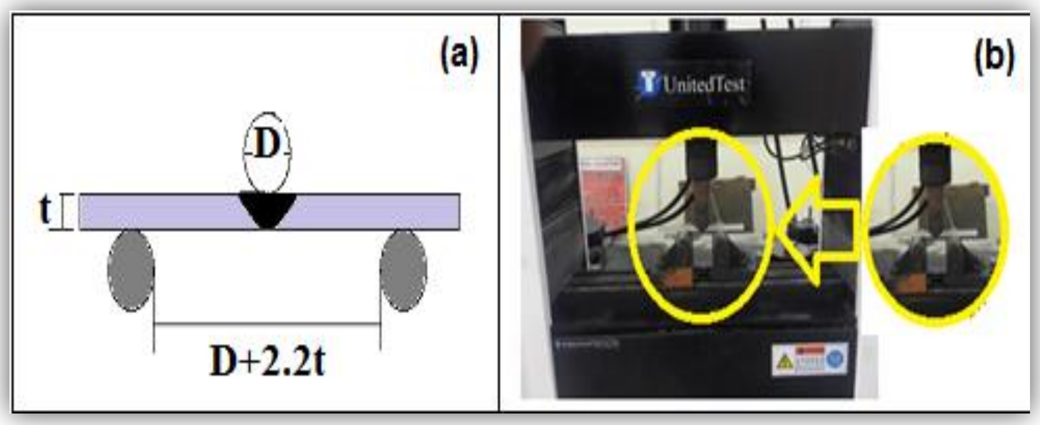

Figure (8): (a) Standard bending test according to ASME (QW-462). (b) Universal testing machine (united test 100KN) with fixture of 3-point bending.

4. Results and Discussion

4.1. Results of Tensile Test

The results of mechanical properties (tensile properties) with process parameters are listed in Table (4).

Generally, the ultimate tensile strength and yield stress decrease in the welding process compared with the base-material, because of localized deformation or re-precipitate of strengthening precipitates, coarsening and dissolution during FSW [5, 18].

Table (4): The results of tensile test for aluminum alloy (AA7020-T53).

Spindle Speed (rpm)	Feed Rate (mm/min)	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
450	20	251	278	4.65
450	31.5	246	301	5.45
450	50	244	256	3.81
710	20	231	268	4.25
710	31.5	276	287	4.71
710	50	241	314	4.95
900	20	240	269	3.31
900	31.5	280	300	4.59
900	50	289	319	5.96

4.1.1. Effect of Tool Rotation Speed

Figures (9) and (10) show the effect of rotation speed or spindle speed on ultimate tensile strength (UTS) and yield stress. In Figure (9) the result for first set of FSW parameter (450rpm) with different travel speeds show the higher UTS is (301Mpa) when the travel speed (31.5 mm/min),but the second set of FSW parameter (710r.p.m) with different travel speed seen the higher UTS is (314Mpa) when travel speed (50 mm/min),also the third set of FSW parameter (900r.p.m) with different travel speed show the higher UTS is (319Mpa) when travel speed (50 mm/min).Beside that the yield stress behavior as same as UTS behavior . It means that the ultimate tensile strength UTS, yield stress and elongation% increase with increasing the rotational speed from 450 to 900 r.p.m. That occurs because increased heat generation taken with increase in rotation speed resulting in best flow and mixing of materials, as in [19]. Comparing UTS at (450 r.p.m) and UTS at (900r.p.m) with the same travel speed (50 mm/min), the UTS with 900r.p.m increase approximately 25%, while the yield stress and elongation increase approximately 19% and 57% respectively, at the same conditions.

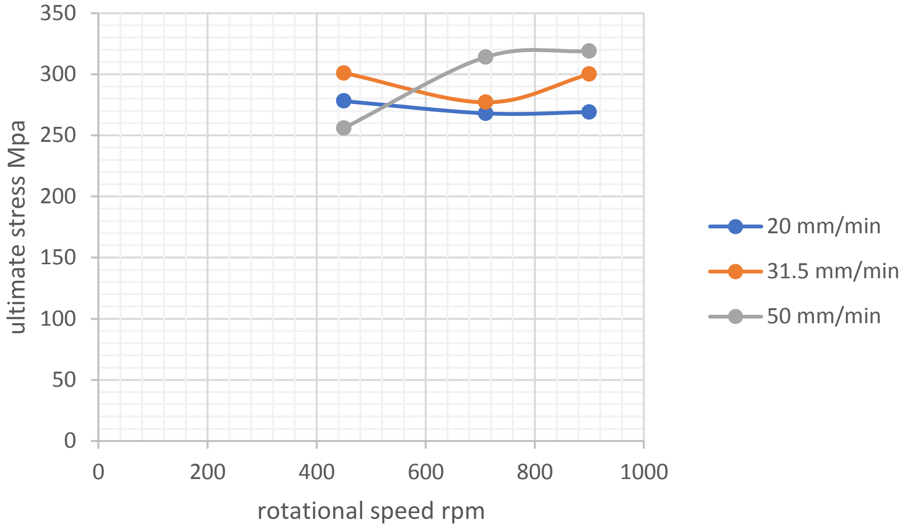

Figure (9): Effect of rotational speed on ultimate tensile strength at different travel speeds.

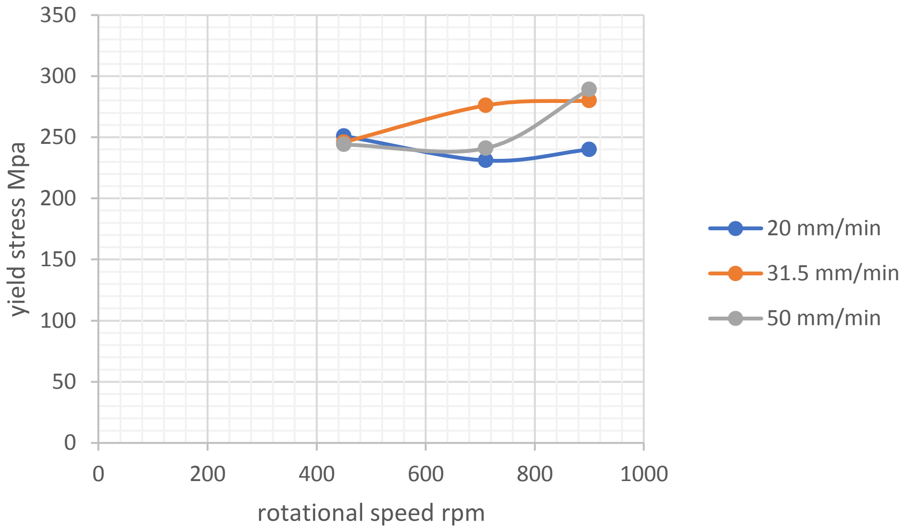

Figure (10): Effect of rotational speed on yield stress at different travel speeds.

4.1.2. Effect of Feed Rate

Figures (11) and (12) the effect feed rate or travel speed on ultimate tensile strength (UTS) and yield stress are show. The maximum value of UTS (319Mpa) was recorded at (50 mm/min) in the third set. The minimum value of UTS (269 Mpa) was recorded at

(20 mm/min) in the first set if used the same tool speed (900 r.p.m).Also the maximum value of yield (289Mpa) was recorded at (50 mm/min) in the third set and minimum value of UTS (240 Mpa) was recorded at (20 mm/min) in the first set if used the same tool speed (900r.p.m). It means that the ultimate tensile strength UTS, yield stress and elongation% increases with increase the feed rate from 20 to 50 mm/min, at low feed rate prolonged exposure of the workpieces to friction-heating and the stirring of the tool lead to the formation of flash defects results in the weak welding, as in [19]
Comparing UTS at (50 mm/min) and UTS at (20 mm/min) with the same tool speed (900r.p.m), the UTS with 50mm/min increase approximately 19%, while the yield stress and elongation increase approximately 21% and 80% respectively, at the same conditions.

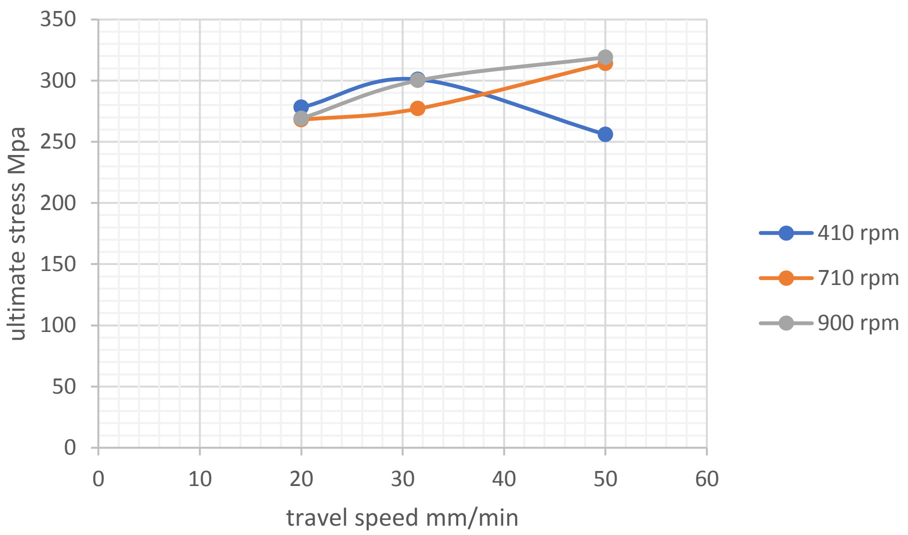

Figure (11): Effect of travel speeds on ultimate tensile strength at different rotational speeds.

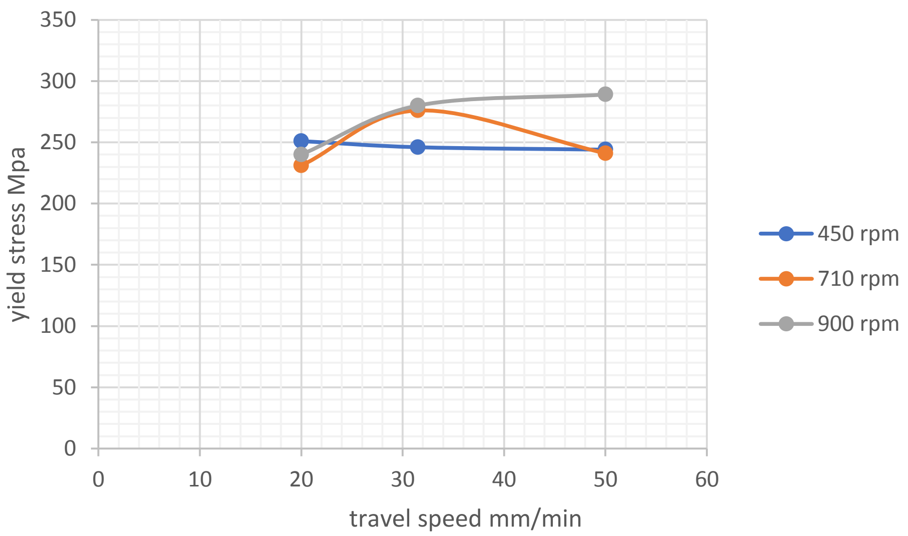

Figure (12): Effect of travel speeds on yield stress at different rotational speeds.

Moreover, to get high quality of FSW joining with best mechanical properties it means higher welding efficiency should be carefully chosen the main welding parameters (tool rotation speed and feed rate) to balance the impact of each-parameter on the amount of heat-input during FSW process.

From the location and shape of tensile samples fracture can be observed many things:

1. Most of the friction stirs welding samples failed at heat effect zone on the advancing-side because it has the lower strength.
2. Failure happened in a plane almost vertical to the tensile-axis.
3. The welding joints of high ductility and high elongation show ductile fracture and the welding joints of low ductility and low elongation show brittle fracture during the tensile testing as shown in Figure (13). All these result agree with [12, 18, 20].

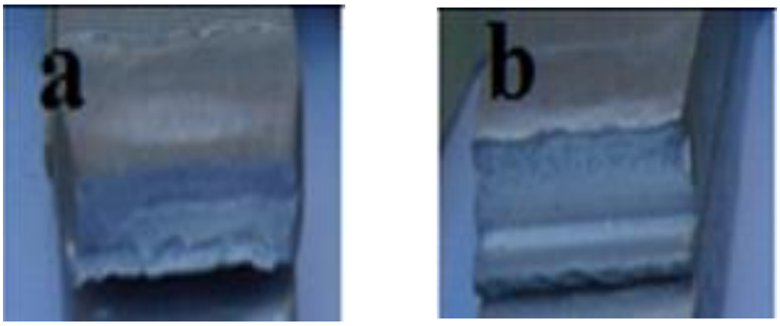

Figure (13): Type of fracture surface (a) Ductile fracture. (b) Brittle fracture.

4.2. Results Bending Test

The results of bending properties with process parameters are listed in Table (5).

Table (5): The results of bending test for aluminum alloy (AA7020-T53).

Spindle Speed (rpm)	Feed Rate (mm/min)	Bending load (kN)
450	20	4.1
450	31.5	12.1
450	50	4.8
710	20	4.9
710	31.5	7.4
710	50	12.8
900	20	8.1
900	31.5	9.2
900	50	14.9

The bending test results are nearly the same as tensile test results and the bending load increases with tool rotation speed and feed rate increment. The higher value of bending load recorded is (14.9 kN) at 900r.p.m and 50mm/min and lower value of bending load recorded is (4.1 kN) at 450r.p.m and20mm/min.

Most of the bending samples show U-shape. The bending angle reached 180° and that means no-cracking was seen in bending test of the welds in both test conditions, i.e. with the joint face and root. All these result conform to [12, 14].

5. Conclusions

1. The experimental data indicated that the rotation speed and the travel speed have significant effect on mechanical properties (the ultimate tensile strength increases approximately 25% while the yield stress and elongation increases approximately 19% and 57% respectively, when used spindle speed 900r.p.m and feed rate 50 mm/min).
2. Optimum condition of FSW has been achieved with 900r.p.m spindle speed and 50 mm/min feed rate, which produce 81% welding efficiency.
3. The maximum value of UTS is (319Mpa), yield stress is (289Mpa) and elongation (5.96%) and most of friction stir welding sample failed at heat effect zone in the tensile test.
4. The maximum value of bending load is (14.9kN) and most of friction stir welding samples gave the U-shape during bending test.

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