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The study of tool shape effect on the mechanical properties of friction stir welding joints of 2024-T4 aluminum alloy

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***Abstract*— Friction stir welding is a new method of solid state welding. This method is of high energy efficiency and good compatibility with the environment. Also, in aerospace and other sensitive industries, it can be used to weld high-strength aluminum-based alloys which cannot be welded easily using conventional method. In the past decade, friction stir welding has a great development in joints and connections. This research investigates the effect of tool shape on the microstructure and mechanical properties of the weld zone in 2024 aluminum alloy, with a choice of two tools with threaded profiles with a 1.25 millimeter step and a square profile of a 5-millimeter diameter. To weld the Samples, the tool's rotational speed of 1200 rpm and linear speeds of 25, 50, 75, 150 and 200 millimeters per minute were selected. Microstructural analysis of welded samples were examined using optical microscope in different conditions. Mechanical tests were performed on the samples. The results shows that by reducing the linear speed of welding and tools deformation from threaded to square, the mechanical properties of samples improved.**

***Index Terms*— Friction stir welding, Tool shape, Threaded, Square**

I. Introduction

Considering different series of aluminum alloys used in the aerospace industry which have excellent properties such as high strength, fatigue failure resistance, welding these alloys, such as 2000, 6000 and 7000 alloy series are very difficult. If the fusion welding is used therefore the connection band will have a very week freezing with plenty cavities and holes [1]. In aerospace industry the purpose of welding these alloys is to achieve the joints and connections with desirable metallurgical and mechanical properties. Due to the limitations in welding the use of this kind of alloy is limited in a wide range of aerospace structures [2]. Aluminum alloys using friction stir welding may have a special implementation in military industry, aerospace, railway and nuclear industries.

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II. Friction stir welding process

The basic concept of FSW welding is quite simple. The fundamental concept of friction welding is the change of mechanical energy into heat energy [3]. The process begins in this way that the unusable tool point (pin) with a proper design, sufficient downward force, and rotational movement descends and touches the edges of two sheets or plates and because of the applied force it moves down and penetrates into the piece until tool shoulder contacts the piece and heat energy is generated due to friction (figure 1).

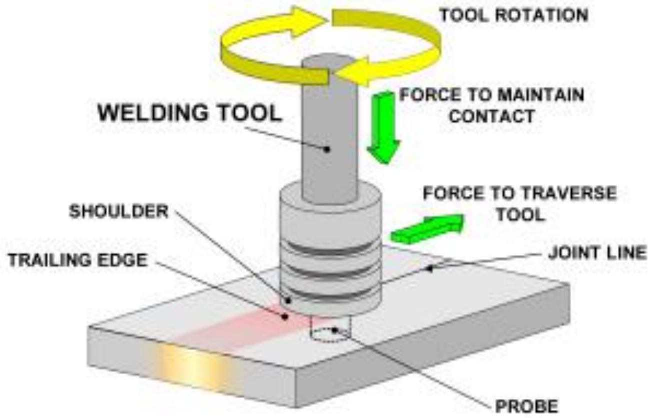

Fig 1: Schematic figure of the friction stir welding process

As the pin penetrates and more force applied, due to the friction between the tool surface and the top surface of the piece, the generated heat will increase. Increasing the heat which caused by the friction, reduce metal strength and the tool's linear movement along the intersection of two metals leads to their connection, and since the connection achieved without metal melting it is called the solid-state friction stir welding [4].

III. Effective Parameters in Friction Stir Welding

There are 3 important parameters for friction stir welding: spindle rotational speed is the welding engine's driving transmission force to the weld line by pin and shoulder, and in fact, it is the power required for welding. Output spin of the welding machine can play an important role in the quality and defects of welding operations. The friction varies with the engagement of pin and joining line and the change in rotation speed.

Traverse speed along the connecting line; In order to achieve a high quality and precision welding, it is required for the tool to move in 3 axial direction of x, y, and z. At first it is necessary for the tool to move towards the piece and placed on top of the piece, then after rotation begins in the tool, it moves towards the desired direction and welding line. Geometrical shape of tool for materials with high melting point such as steel and titanium or materials with high thermal conductivity such as copper is important [5]. In addition to the tool's rotational speed, traverse speed and geometrical shape of tool, another very important parameter in the process is the tool's inclination angle relative to the work-piece surface. Inclination angle is suitable for the angular tools which can transfer the stirred and mixed material from pin's front to its back by the shoulder. In addition, the amount of pin penetration into the work-piece (also known as target depth) to produce a flawless and smooth welding with the tool shoulder is very important. Target depth (penetration depth) depends on the pin's height.

IV. RESEARCH METHOD

To study the effect of rotation speed, the H13 hot work steel tool with threaded cylindrical profile and square profile of 5mm diameter, height of 4mm, and 12mm shoulder was designed and produced and after heat treatment was used as illustrated (figure 2).

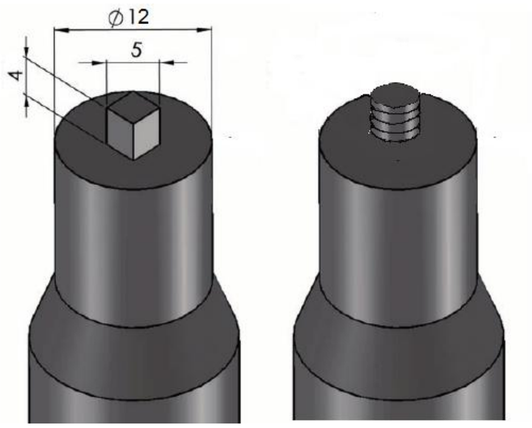

Fig 2: square and threaded profile Tools made of H13 hot work steel

According to the table 1and 2 analysis and Mechanical Properties of 2024 aluminum sheets with the size of 200 × 50 mm and thickness of 3 mm were chosen [6].

Table I: Chemical composition of 2024 aluminum based on weight percentage

Element (%)	Alloy 2024
Cu	3.80 - 4.90
Mg	1.20 - 1.80
Mn	0.30 - 0.90
Si	0.50 (Max.)
Fe	0.50 (Max.)
Zn	0.25 (Max.)
Ti	0.15 (Max.)
Cr	0.10 (Max.)
Others	0.05 (Max.) each 0.15 (Max.) total
Remainder	Aluminium

Table II: Mechanical Properties of 2024 aluminum

Hardness, Vickers	Tensile Yield Strength (Mpa)	Ultimate Tensile Strength (Mpa)	Aluminum Alloy
137	324	469	2024-t4

After preparation and milling both sides of sheets and thermocouples placement in suitable locations of work-piece, were fixed on jig and fixture platform system. For welding in fixed rotational speed of 1200 rpm by means of a square and threaded pin tool at linear speed of 25, 50, 75, 150 and 200 mm / min have been chosen and microstructure and mechanical properties were studied after welding was performed and the results of the study were collected in table (3) and (4).

Table III: Comparison of mechanical properties for rotational speed of 1200 rpm with threaded tools

Hardness, Vickers	Tensile Yield Strength (Mpa)	Ultimate Tensile Strength (Mpa)	linear speeds (mm/min)
98	**210.2**	**380.5**	**25**
102.3	**214**	**386**	**50**
106.5	**217.3**	**388.6**	**75**
109	**220**	**391**	**150**
104.7	**222.7**	**392.4**	**200**

Table IV: Comparison of mechanical properties for rotational speed of 1200 rpm with square tools

Hardness, Vickers	Tensile Yield Strength (Mpa)	Ultimate Tensile Strength (Mpa)	linear speeds (mm/min)
106.2	218	**387.5**	**25**
96.2	223.3	392	**50**
98.5	227	398.2	**75**
102	231	402	**150**
104.7	235.6	405.6	**200**

V. Discussion

To investigate the effect of the welding operation by two threaded and square profile tools in welding line against the thermo-mechanical changes, 80 MPa difference is quite evident. As known, the 2024 aluminum has a specified thermal grade which has gone under heat treatment with relevant regime and at specified times and temperatures has been subject to aging treatment, until the 469 MPa tensile strength is obtained. During the welding operation welding line temperature rises to 400 ° C, so as the temperature increases the welding area will not be as strong and hard as it was. Also, the amount of ductility (resistance to shock) also will go up. Of course, the tool's shape will not have any effect on this strength and hardness change and the impact will be minor. According to the phase diagram (fig 3), reduction in ultimate tensile strength of these alloys due to their hard sediment feature can be justified. Thus, with decreasing temperature the intermetallic compound solubility of Cu is reduced, and as the temperature decreased from eutectic temperature to room temperature intermetallic compound solubility of Cu decreases.

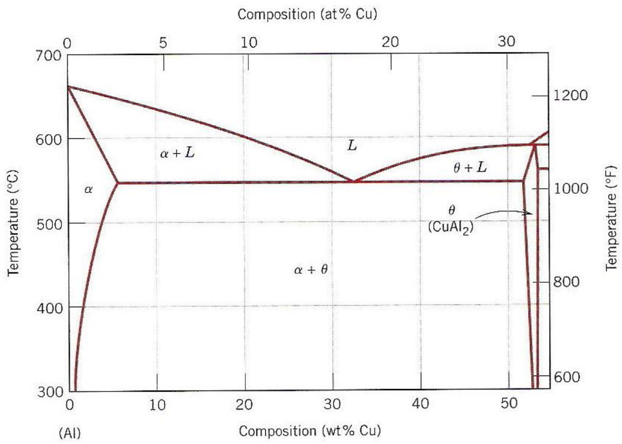

Fig 3: phase diagram of Cu-Al

To examine the effect of linear speed, and tool shape on the Ultimate Tensile Strength, Tensile Yield Strength and hardness diagrams were drawn in Figure 4 to 6.

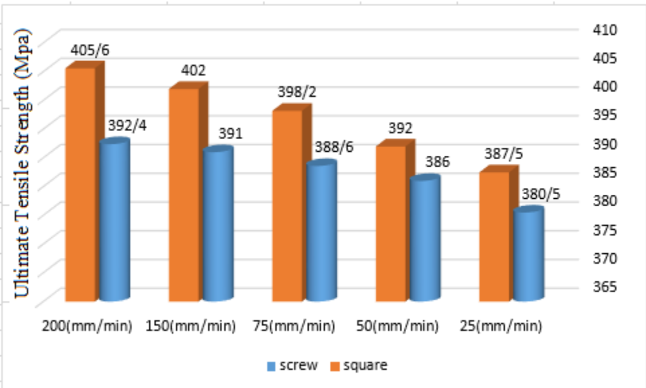

Figure 4: Comparison of Ultimate tensile strength for threaded and square pin for 2024 aluminum at rotational speed of 1200 RPM

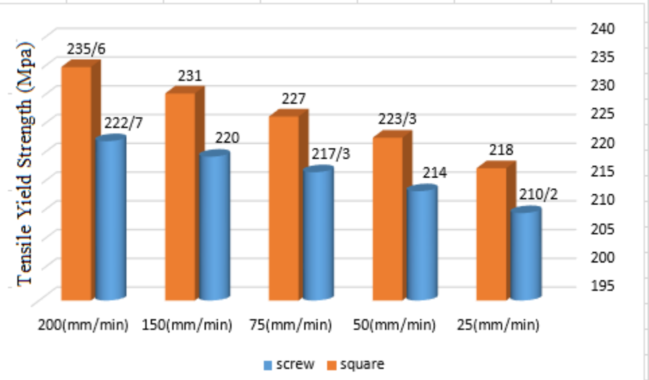

Figure 5: Comparison of Tensile Yield Strength for threaded and square pin for 2024 aluminum at rotational speed of 1200 RPM

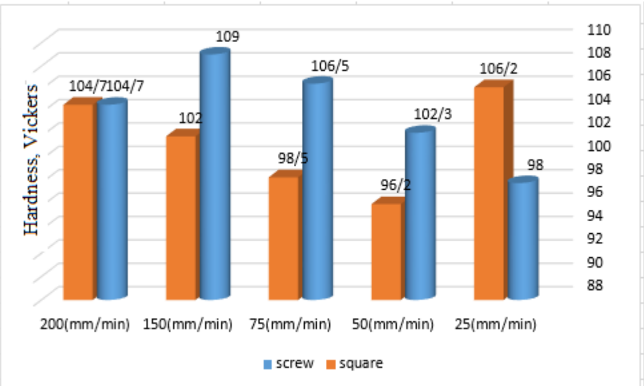

Figure 6: Comparison of Hardness for threaded and square pin for 2024 aluminum at rotational speed of 1200 RPM

During the friction stir welding of this alloy, by reducing the linear speed and consequently increasing the temperature of the welding area the present Cu4Mg1 sediments in the area gradually dissolve (of course, the finer sediments are dissolved in the field or absorbed by larger sediments.). As a result, the sediments concentration will decrease in the area or grow in size. Therefore, as a result of change in concentration and size of sediments, the mechanical properties will change, too

By reducing the lower linear speed and dissolving the Cu4Mg1 particles in the field at high temperatures, the mechanical properties of the welding area will be dropped. Of course, these mechanical properties do not include impact resistance, because by reducing sediment concentration in the welding area this area will get softer and its impact resistance will increase. Linear speeds lower than 25 mm / min and higher than 200mm / min will generate cavities or holes and in order for reducing the cavities at linear speed higher than 200 mm/min the downward force on the welding line must increase.

Area of pin stir operation, which is larger in square pin due to its big sector, is half the size of step in threaded pin. However, in square pin as illustrated in figure 7, it equals with the area outside the square and inside the circle with diameter of 5 mm, i.e. if we want to calculate the sector of square pin's stir region, the height of each sector will be 1 mm per sector, whereas, this amount for threaded pin with 1mm equals 2.5-1.765= 0.735 mm.

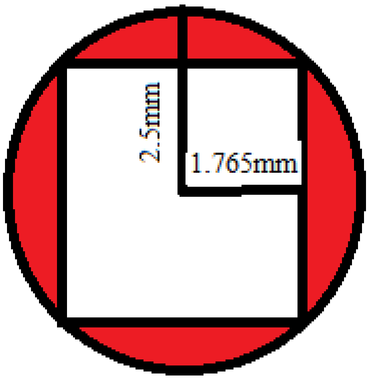

Figure 7: Area of pin stir operation

Applied force from the tool machine to welding chamber is bigger in threaded pin due to the sward moving downward in left-handed screw, whereas if the right-handed screw steps are selected less force is required. The difference is that soft materials were transferred to the upper welding seam and the canal defects is created continuously in welding root. But in the left-handed screw holes directed to the surface of the work-piece is actually transferred to the welding surface (Figure 8).

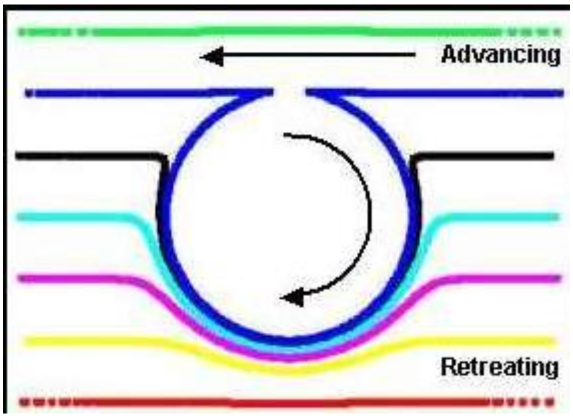

Figure 8: Performance of screw pin

Since there is no conductor screw for material flow in the square-shaped pin, therefor, the material flow will be just around the pin. However, in the screw pin, materials are directed upward or downward about the size of a pin step and eventually these materials are compressed above or below the welding band. In fact, the best welding will be for threaded pin with left-handed step and the amount of step can be varied according to the thickness of the piece. As a result, in square pin the required downward force will be more than threaded pin with left-handed step and will be lower than threaded pin with right-handed step.

The amount of downward energy required to penetrate the welding chamber, in the threaded pin is lower than the square pin which is due to directing the steps downward. Therefor the amount of stir and heat in threaded pin will be lower than square pin. The amount of compressive force in the square pin is larger than the threaded pin. Mechanical agitation of the material by pin rotation generates a hydrostatic pressure behind the pin resulting from pressure from the shoulder edges on the working surface.

The edges of the two pieces are compressed between the pin and the back strap sheet and the hydrostatic pressure is the result of this compression which is referred to as forge pressure.

VI. RESULTS

According to the results of Figure (4) and (5) it can be concluded that the tool with a square pin have better mechanical properties, especially better tensile strength than the threaded profile pin. If the impact process and the procedure of the welding operation are reviewed, it is realized that after tool penetration to the wall between the two pieces and the generating some heat, due to tool's move the pin's advancing side will apply pressure on softened material. As the tool moves forward, the material in front of the pin is being compressed, also a hollow space is created behind the pin, then due to the applied pressure the softened material moves backward in the direction of tool's rotation from the pin's front to its back, extruded and fills the empty space behind the pin. If you pay attention to the shape of square pin and threaded pin, several factors can affect the difference between these two.

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