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Effect of tool pin eccentricity on mechanical properties and microstructure of friction stir welded 5754 aluminum alloy

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ABSTRACT

The effect of smooth tool pin eccentricity on mechanical properties and microstructure of 5 mm thick friction stir welded aluminum alloy AA5754-H24 was investigated. Three different tools were used in friction stir welding (FSW), cylindrical tool pin without eccentricity (T0), two cylindrical tool pin with eccentricity of 0.2 mm and, 0.8 mm (T2, T8) were used to weld AA5754-H24 aluminum alloy. The FSW was performed using tool rotation speed of 600 rpm and different welding speeds of 100, 200, 300, and 500 mm/min. After FSW the joints were investigated using tensile testing, hardness testing and optical microscopy. The use of FSW tool pin eccentricity 0.2 mm produces a friction stir weld joint with higher mechanical properties and finer precipitates. The tensile strength increases with increasing welding speed with maximum at 500 mm/min. However, the case is reversed in case of FSW tool pin eccentricity of 0.8 mm, the tensile strength decreases with increasing welding speed.

Keywords: Friction stir welding, Tool design, Tool pin eccentricity, Mechanical properties, Microstructure.

1. INTRODUCTION

There is no doubt that the friction stir welding tool is a point of much research nowadays. In friction stir welding (FSW) a non-consumable, cylindrical, and shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together [1]. The parts have to be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. Frictional heat is generated between the wear resistant welding tool and the material of the work piece [2]. This heat causes the latter to soften without reaching the melting point and allows the tool to traverse along the weld line [3]. The plasticized material is transferred from the tool leading edge (advancing side) to its trailing edge (retreating side) and is forged by the intimate contact of the tool shoulder and the pin profile, and leaves a solid phase bond between the two pieces [4-6].

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Since 1991, the tool geometry has evolved appreciably and the tool material properties have become better and better. However, the evolution is not ended; further improvements are needed in this field. There is a growing demand of welding high melting temperature, and high strength, as well as hardening materials. The key is the tool design and the tool itself [7].

The rotation and movement of the tool through workpiece result in its wear. It may also deform plastically at elevated temperatures. Friction stir welding of hard alloy is limited today by the high cost and short life of tools [8]. The effect of tool shape on friction stir welding has not yet been systematically classified. The tool shape should be as simple as possible to reduce the cost, and the stirring effect should be sufficient to produce sound welds [9]. The primary function of the rotating tool pin is to stir the plasticized metal and move the same behind it to have good joint [10]. Elangovan et al [11] studied the influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone, and reported that the pin profile plays a crucial role in material flow. Accordingly, it regulates the welding speed of the FSW process. The pin is generally cylindrical, frustum tapered, threaded or flat. Pin profiles with flat faces (square or triangular) are sometime associated with eccentricity, which allows incompressible material to pass around the pin profile.

Thomas and Nicholas [12] reported that the tool pin eccentricity is associated with a dynamic orbit, which becomes a part of the FSW process. They found that, the ratio between the static and dynamic volumes determines the path of the plasticized material from the leading edge to the trailing one. They concluded that, the ratio is 1.0 for straight cylindrical, 1.09 for tapered cylindrical, 1.01 for threaded cylindrical, 1.56 for square and 2.3 for triangular pin profiles. Besides, a pulsating stirring action is caused by triangular and square tool pins. They referred such stirring action to pin flat faces. Furthermore, Tomas et al [12] stated that, a square pin produces 80 Pulses/s, and a triangular pin produces 60 Pulses/s at 1200 rpm tool rotation speed. In the case of cylindrical, tapered and threaded pin profiles, there is no such pulsation [11]. Research modern trends involve the effect of tool eccentricity in friction stir welding [13, 14]. More recently, Mao Yuqing et al [15] investigated the influence of pin eccentricity in a more detailed study. In such cases, they found that the material flow path is not clear, and the microstructure and mechanical properties of friction stir welded aluminum alloy thick plate joints is lacking. The effect of tool pin eccentricity on microstructure and mechanical properties in friction stir welded 7075 aluminum alloy thick plate was investigated, using a tapered threaded pin. Tool pins with four eccentricity values of 0.1, 0.2, 0.3, and 0.4 mm were applied. It has been found that, the maximum weld nugget zone area was obtained using a tool with pin eccentricity of 0.2 mm. Also, highest mechanical properties of FSW joints were those produced using 0.2 mm pin eccentricity [15].

The aim of this paper is to investigate the effect of tool pin eccentricity on the mechanical properties and microstructure of friction stir welded 5754-H24 Al alloy. In this study, three cylindrical tools were designed, fabricated and applied. The first is a tool pin without eccentricity, i.e. the pin and shoulder axes are aligned. The other two tools are of pin eccentricities 0.2, and 0.8 mm.

2. EXPERIMENTAL PROCEDURE

2.1. DESIGN AND PREPARATION OF FSW TOOLS

The tools used for welding were cut from 40 mm diameter W302 cold worked tool steel rod (0.39% C, 0.1% Si, 0.40% Mn, 5.2%Cr, 0.95% V, 1.4% Mo, and 90.6 wt% Fe), and heat-treated to HRC62. Tools with three different designs were prepared, Fig.1. The first, was with a cylindrical tool pin without eccentricity, in which the pin and shoulder axes are aligned and is referred to as "T0", Fig.1a. The second was also with a cylindrical pin but with 0.2 mm eccentricity, i.e. the pin axis is shifted by 0.2 mm from the tool axis, and is referred to as "T2", Fig.1b. The third tool was with a cylindrical pin with eccentricity of 0.8 mm, and was referred to as "T8", Fig.1c. In all cases, the smooth 19 mm diameter shoulder is with 2^{o} concavity, and the pin was 4.6 mm long with 6 mm diameter.

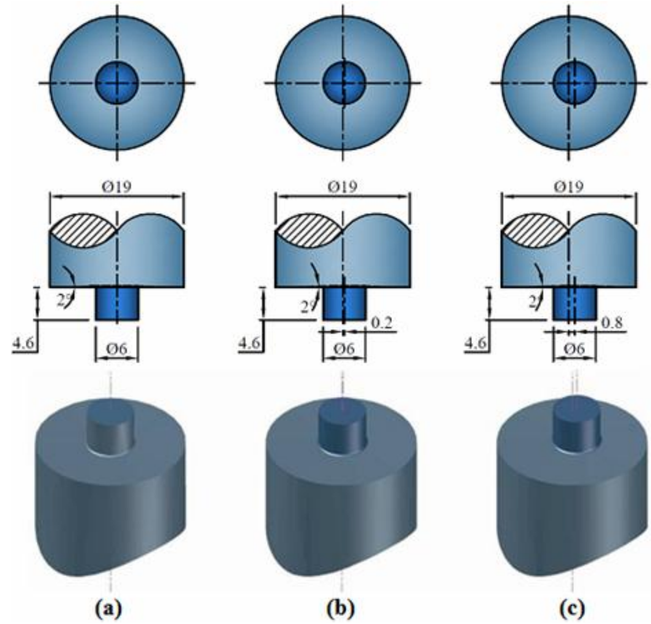

Fig.1. FSW tools: (a) T0,(b) T2, (c) T8 (Dimensions in mm)

2.2. WELD JOINT PREPARATION

Friction stir welding of butt joints of 5754-H24 aluminum alloy is performed using an FSW machine for research and development. The chemical composition of 5754-H24 aluminum alloy is listed in Table1. The weld samples are made of two 5 mm thick, 100 mm wide, and 120 mm long plates. Measured mechanical properties of used Al alloy is listed in Table2.

Table 1: Chemical composition of 5754-H24 aluminum alloy

wt.%								
Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
0.4	0.4	0.1	0.5	2.6-3.2	0.3	0.2	0.15	rest

Table 2: Mechanical properties of 5754-H24 aluminum alloy

Tensile Strength (MPa)	Proof Stress 0.2% (MPa)	Elongation (%)
260.57	205	12.93

2.3. FSW CONDITIONS

The FSW process for 5754-H24 aluminum alloy was performed at weld speeds of 100, 200, 300, and 500 mm/min. In all cases, the applied rotation speed was 600 rpm, and the tool plunge-depth (shoulder penetration) was 0.2 mm, and a tilt angle of 3^{o} is applied.

2.4. WELD JOINT EVALUATION

The FSW joints were assessed using visual inspection, macroscopic investigation of various weld zones, measuring joint tensile properties, and by determining the joint cross-section Vickers hardness profile. Macroscopic examination of weld joint cross section is carried out after conventional polishing of the surface and etching with 10 g NaOH in 90 ml distilled water.

Samples for metallographic analysis are cut from welded plates. Then, surfaces perpendicular to the welding direction are ground and polished using standard metallographic techniques, and etched with 10g NaOH in 90 ml H2O, to observe the microstructure of the weld in different regions. Tensile testing is carried out on 250 KN capacity "Instron" tensile testing machine. It can be used at a rate of 0.0005:1016 mm/min over a stroke of 1430 mm. Flat tensile specimens are cut perpendicular to the welding direction with the dimensions shown in Fig.2. According to ASTM, the velocity of the moving head of the machine is 0.1 mm/s. Vickers hardness profiles on cross sections perpendicular to the welding direction are measured. All measurements using 1 Kg load are near the section centerline.

Moreover, the peak temperatures were measured on top surface of advancing side of weld joints using "IR Thermometer", to measure the difference in the temperature between the three tools.

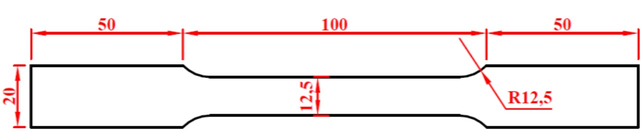

Fig. 2. Tensile test specimen

3. RESULTS AND DISCUSSION

3.1. TOP VIEW AND TRANSVERSE CROSS SECTIONS

Fig.3 shows the top view of 5754-H24 FSW joints at constant rotation speed of 600 rpm, different welding speeds of 100, 200, 300 and 500 mm/min and using the previously described FSW tools T0, T2 and T8. The top surface is mainly affected by the shoulder and so that the appearance in joints is almost similar except that the top surface of 5754-H24 FSW joints is more smooth and has little flash in the advancing side (AS) and the retreating side (RS), this is mainly due to the high strength of this alloy. In terms of welding speed, it can be observed that the welding speed is clearly affecting the appearance of the top surface of welded joints and at high welding speeds starting from 300 mm/min the semicircular banding features is noticeably getting wider. According to Krishnan [16] the measured semicircular banding features spacing was matching the calculated ones. The measured semicircular spacing in this work is 0.167 mm, 0.33 mm, 0.5 mm, and 0.83 mm for the welding speeds of 100, 200, 300 and 500 mm/min respectively. This spacing is almost matching the spacing appearance as it can be observed from Fig. 3.

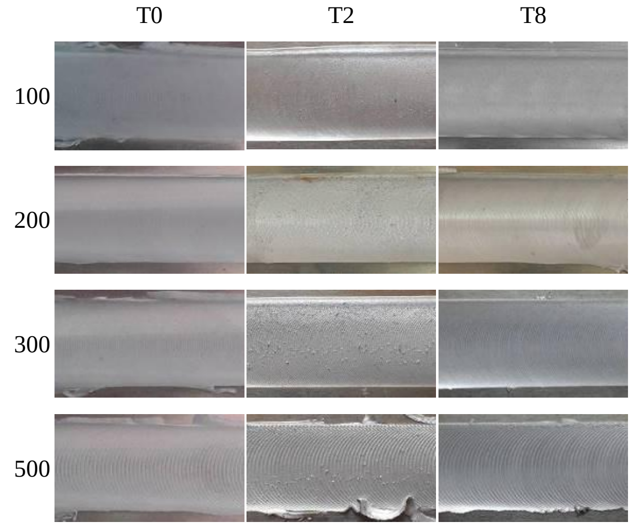

Fig. 3. Top surface view of 5754-H24 FSW joints at 600 rpm rotation speed, different welding speeds of 100, 200, 300 and 500 mm/min and using the different FSW tools T0, T2 and T8.

The macrostructure of friction stir welded 5754-H24 aluminum alloy joints using different tools at a rotation speed of 600 rpm and different welding speeds (100, 200, 300, and 500 mm/min.) are presented in Fig.4. The retreating and advancing sides of the friction stir welded joint are denoted by R and A, respectively. It is found that, defect-free weld joints produced by T0, T2 tools. However, when the welding speed is greater than 200 mm/min, some tunnel defect is more easily formed in the joints using the tool T8 with pin eccentricity 0.8 mm. On the other hand, when the welding speed is equal to or below 200 mm/min, the weld zone using the tool without eccentricity is similar to that using the other tools with pin eccentricity of 0.2, 0.8 mm. Meanwhile, the area of weld nugget zone A_{NZ} is measured for FSW joints produced by different tools at a welding speed of 500 mm/min. Using T2 FSW tool the area A_{NZ} is 39.45 mm^2, while using T0 and T8 it is 37.17, and 35.34 mm2, respectively.

Moreover, in FSW joints welded by different tools T0, T2, and T8, the interface between the weld nugget zone (WNZ) and the thermo-mechanically affected zone (TMAZ) is discernible on the advancing side, but not clear on the retreating side. The reason is related to the temperature and cooling rate in this region, because the speed of pin in the retreating side is lower than that in the advancing side, this decreases the heat input in this side.

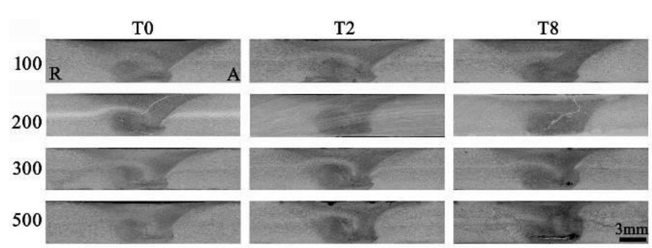

Fig. 4. Macrostructure of 5754-H24 FSW Joints.

3.2. OPTICAL MICROSTRUCTURE

To evaluate and analyze microstructural changes of 5754 FSW joints welded by different tools, a friction stir weld joint is conventionally divided into distinct regions. There are three zones at which different levels of material flow and temperature changes. The center of the weld joint, commonly referred to as “nugget zone”, is characterized by a very fine grained microstructure. The majority of grain boundaries within the nugget zone are high angle boundaries (misorientation between grains being greater than 15°). High angle boundaries of the nugget zone are believed to form through dynamic recrystallization during stirring [17]. In the region immediately surrounding the nugget zone, the parent alloy grain structure is heated and deformed, however to a less extent than that of the nugget zone. This zone surrounding the nugget zone is referred to as the thermo-mechanically affected zone (TMAZ). This often leads to a partially re-crystallized region in which fibrous grains, which are normally aligned in the rolling direction, are rotated. This can be very dangerous as the newly aligned high angle grain boundaries can become susceptible to stress corrosion cracking. Sometimes, the whole TMAZ can be re-crystallized, with no apparent distinction between that region and the nugget zone. This is a feature of materials such as pure titanium, copper and austenitic stainless steels, which perform no thermally induced phase transformation, and which would make transformation in the absence of strain. Thermally induced phase transformation can make the analysis of microstructure, and a precise definition of TMAZ/HAZ boundary; difficult. Surrounding TMAZ is the heat affected zone, which for the high strength 2xxx and 7xxx series aluminum alloy consists of a coarse microstructure [18].

The microstructures at the centre of the weld nugget zone, welded by three different tools T0, T2, and T8, are shown in Fig. 5. It is observed that the particles size of precipitates in the FSW joints produced by tool T2 with pin eccentricity of 0.2 mm is smaller than that of the joints produced by the other tools for all joints. This is due to the temperature and cooling rate in this region, which arises from the stirring effect and plastic deformation [19-20].

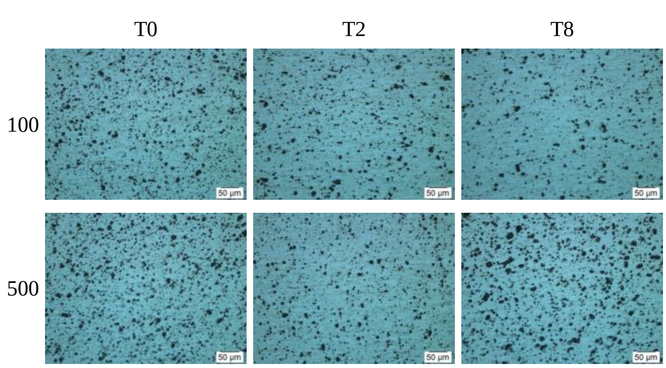

Fig. 5. Microstructure of 5754-H24 FSW Joints.

The temperature results of 5754-H24 FSW joints on the top surface of advancing side shown in Fig. 6 demonstrate that the peak welding temperatures during FSW decreases with the welding speed. The peak temperature for tool T8 with pin eccentricity 0.8 mm is lower than that for the others. Because the area of stir for tool T8 is greater than that for the other tools.

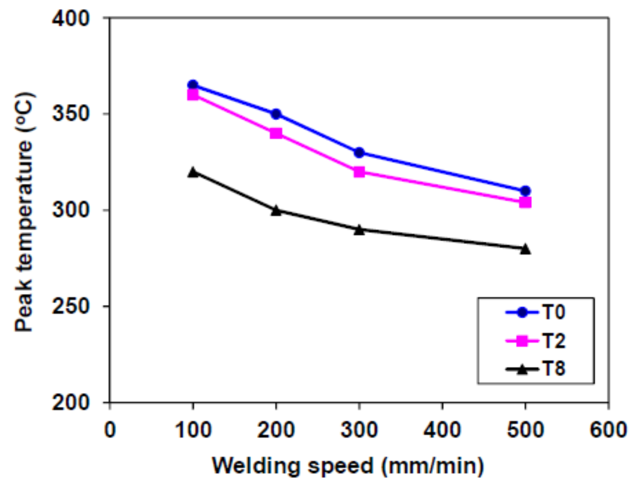

Fig. 6. Peak temperature of 5754-H24 FSW joints measured on top surface of advancing side.

This could be clarified by determining the path of a hypothetical point "a" on pin surface produced by T0, T2, and T8 tools at welding speed 500 mm/min, rotation speed 600 rpm, and revolutionary pitch of 0.83 mm/rev (for one revolution), as shown in Fig.7. The figure indicates clearly, that the path of point "a" produced by tool T8 is longer than the corresponding paths produced by the other tools, and the stir area by tool T8 is greater than the stir area by the other tools. The heat generated by tool T8 is greater than the heat generated by the other tools, and the cooling rate in weld joints welded by T8 is higher than that in weld joints welded by the other tools. This can explain the lack of the interface clarity between WNZ and TMAZ in weld joints welded by tool T8, and may affect the recrystallized grains. The path of point "a" and stir area by tool T0 are smaller than those by the other tools, so the heat generated by T0 is smaller than by the other tools. However, the cooling rate of joints welded by tool T0 is lower. Also, the dead zone around the pin of tool T0 may not be found around the pin of T2 and T8. However, the pin of T2 can generate suitable heat and cooling rate, additionally to the good movement of stir by eccentricity. This may lead to the fine recrystallized grains of the weld nugget zone, i.e. may enhance grain refining. This can explain the fine structure of the weld nugget zone produced by tool T2.

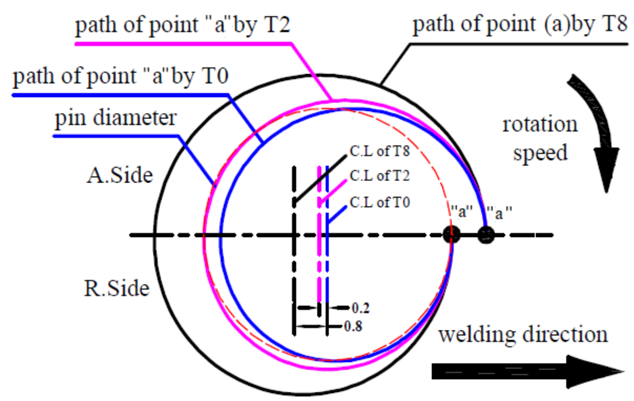

Fig. 7. Paths of point "a" on pin surface, at 500 mm/min welding speed, produced by T0, T2, and T8 tools.

Figure 8 shows the different zones in FSW joint produced by T2 at a welding speed of 500 mm/min and a rotation speed of 600 rpm. Figures 7a, b, and c illustrate the weld nugget zone, the thermo mechanical affected zone TMAZ, and base metal BM, respectively.

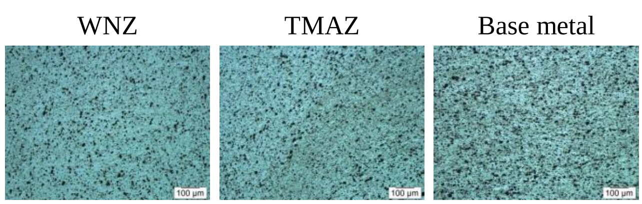

Fig. 8. Microstructure of 5754-H24 FSW Joints produced by tool T2 at rotation speed 600 rpm and welding speed 500 mm/min.

3.3. HARDNESS AND TENSILE PROPERTIES

Figure 9 shows the hardness distribution through the cross section of the 5754-H24 FSW joints produced by different tools at 600 rpm rotation speed and 500 mm/min welding speed. The hardness reaches minimum values in the weld zone varying from approximately 74 HV at the weld zone centre to approximately 81 HV. Such trend agrees well with previous results [17, 21-22]. Hardness of the stir zone is lower than that of the base metal. In 5754-H24 Al alloy, the mechanical properties of the weld zone depend mainly on the plastic deformation during thermal cycles of friction stir welding [22]. This may explain the lower hardness of the stir zone. The stir zone shows more scattered hardness values for all produced joints, which may be attributed to microstructure non-homogenous distribution [22]. Moreover, it is noticeable from Fig.9 that, the width of the stir zone depends on the applied FSW tool. Compared with a tool pin without eccentricity T0, stir zone width does not change much when a pin eccentricity of 0.8 mm (T8) is applied. However, the stir zone is appreciably wider, when a pin eccentricity of 0.2 mm is applied (tool T2). This may explain the higher values of the tensile strength of FSW joints produced by pin eccentricity of 0.2 mm (tool T2) at high welding speed of 500 mm/min because the stir zone is characterized by a fine grain structure.

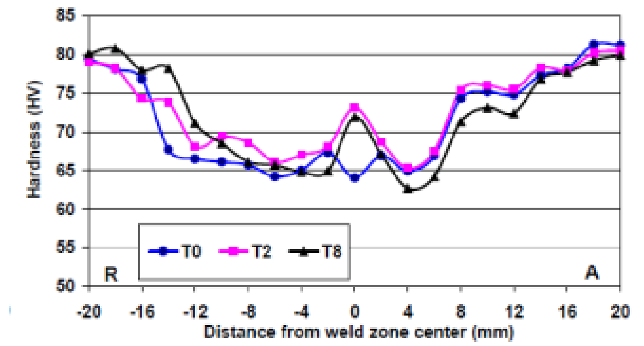

Fig.9. Vickers Hardness profiles cross section of 5754-H24 FSW joints at 600 rpm rotation speed and 500 mm/min weld speed.

The ultimate tensile strength of FSW joints using different tool designs (T0, T2, and tool T8) is plotted against welding speed, as shown in Fig.10. It is observed that, the tensile strength increases with the increase of the welding speed for FSW joints produced by T0, T2 tools. For FSW joints produced by tool T8, the tensile strength decreases with the increase of the welding speed, and the maximum tensile strength is achieved at 100 mm/min welding speed (lower welding speed). This may be due to the rate of heat input, which controls the degree of plastic deformation. Moreover, a tool pin with eccentricity over 0.3 mm generates a higher heat input rate, and forms a worse interface, where crack initiation becomes possible. This leads to stress concentration, which significantly degrades the mechanical properties of the weld joint [15, 23]. Moreover, appreciably lower tensile strength is at a lower welding speed of 100 mm/min. Besides, the defect-free FSW joints produced using tool T2 with 0.2 mm pin eccentricity shows the highest tensile strength at higher welding speed of 500 mm/min.

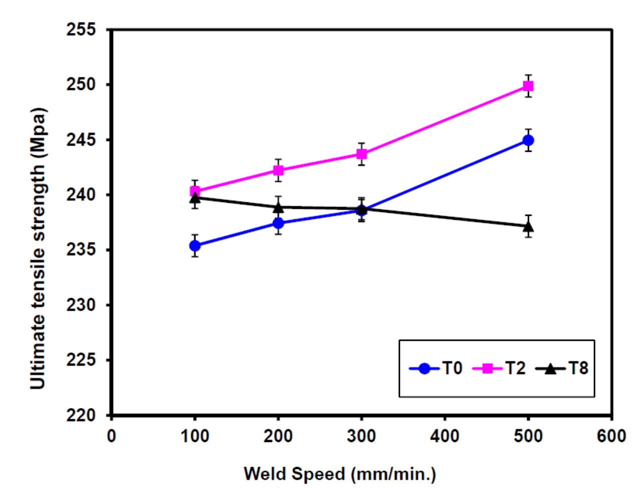

Fig. 10. Tensile strength of 5754-H24 FSW joints.

4. CONCLUSIONS

The effect of tool pin eccentricity on the mechanical properties and microstructure of 5754-H12 FSW aluminium alloy is investigated. Based on present results, we concluded that:

1. The nugget zone area of 5754-H24 FSW aluminium alloy is larger when a tool pin with 0.2 mm eccentricity is applied, than when a tool pin eccentricity of 0.8 mm or a tool pin without eccentricity. Using T2 FSW tool at 600 rpm rotation speed and 500 mm/min welding speed, the area A_{NZ} is 39.45 mm^2, while using T0 and T8 it is 37.17, and 35.34 mm^2, respectively.
2. Using a tool pin with 0.2 mm eccentricity at 600 rpm rotation speed produces a friction stir weld joint with higher mechanical properties, and finer microstructure at 500 mm/min welding speed.
3. It could be stated that smooth tool pin eccentricity is becoming one of the main technical parameters of friction stir welding. Present results show that a tool pin eccentricity of 0.2 mm results in acceptable improvement in mechanical properties and microstructure.

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