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Effect of welding conditions on mechanical and microstructure properties of friction stir welded aluminum alloy 2024-T4

M. M. Ghanem[1], A. A. Abdel-Hakeem[2] N. A. Abdel-Raheem[3] and M. R. El-Kousy[3]

[1]Central Metallurgical Research and Development Institute (CMRDI), Egypt
[2]Aircraft Factory, AOI, Egypt
[3] Department of Metallurgical Engineering, Cairo University, Egypt
*corresponding author: ghanem105@yahoo.com

Abstract: The heat-treatable high strength AA2024 aluminum alloy is widely used in airplane fuselage structure due to its high strength-to-density ratio. Currently, riveting is the main joining process used in manufacturing airplane fuselage. The AA2024-T4 alloy has poor weldability by fusion welding because of its hot cracking susceptibility, porosity formation and degradation in mechanical properties Friction stir welding (FSW) is the promising process to weld this alloy. Therefore, the objective of this work is to study the effect of FSW welding parameters on microstructure evolution and mechanical properties of 2024-T4 welded joints at different rotational speed (450–1800rpm) and travel speed (11.2–45 mm/min) whereas, axial force and tool shape remain unchanged. Results clarified that mechanical properties and microstructure of joints are dependent on welding process parameters. Maximum ultimate strength of the joints is equivalent to 82% of the base material at appropriate rotation speed of 900 rpm and travel speed of 35.5mm/min.

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Keywords: Aluminum alloy AA2024 T4, friction stir welding (FSW), rotational speed, travel speed, mechanical properties, microstructure.

1. Introduction

Aluminum alloys are commonly used in several applications including aircrafts, automobile, tanks and ships, due to their outstanding characteristics such as high strength, corrosion resistance and good formability [1]. The high-strength heat-treatable Al-Cu alloys (2000 series) are widely used in manufacturing airplane components such as integral tank, skins, and fairings. The most common manufacturing methods used in joining these components' assembly are riveting and fastening. Using welding instead of riveting and fastening in these components would provide remarkable weight savings and reduction of manufacturing cost. However, the welding was rarely used in assembly of aircraft components due to poor weldability of airplane aluminum alloys (2000 and 7000 series) when using fusion welding [2].

Friction stir welding (FSW) is the newest promising solid-state welding process (Figure 1) developed by the Welding Institute (TWI) [3]. Friction stir welded joints basically composed of four distinct regions based on microstructure change with heat input. The formation of these regions depends on the material deformation under the effect of rotating FSW tool. The FSW pin tool geometry, dimensions and process parameters mainly affect the material deformation characteristics [4, 5].

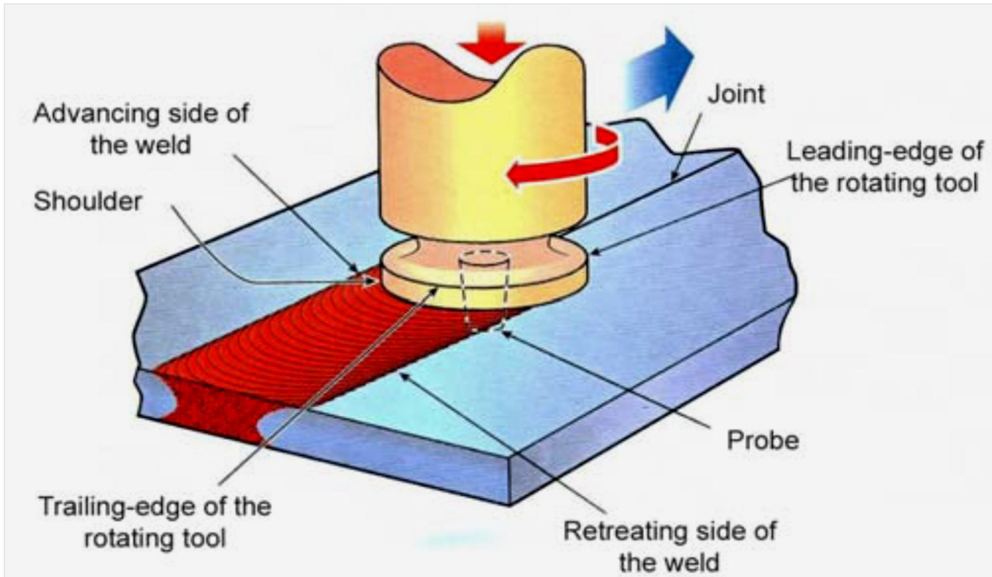
To understand effect of FSW welding conditions including welding speed and rotation speed on tensile strength; bendability and microstructure evolution of friction stir welded AA2024-T4 alloy joints, this study was initiated.

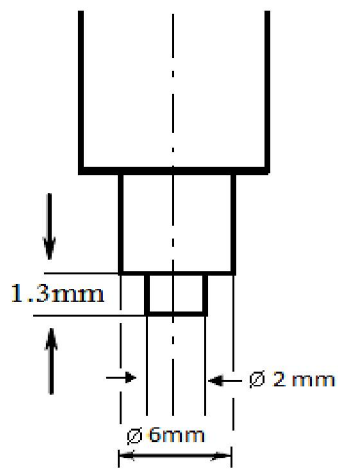
2. Experimental Work

The material used in welding experiments is 2024-T4 aluminum alloy provided by aircraft factory (AOI). The chemical composition and mechanical properties of Al 2024-T4 are given in Table 1. The dimensions of test pieces are 150×100×1.5 mm. prior to welding, the test specimens are first ground using stainless steel wire brush and sandpaper to remove the oxide film, and then cleaned with acetone.

To carry out FSW process, two aluminum plates were placed on a flat metal plate using special fixture (mechanical clamps) in milling machine. The direction of welding is perpendicular to the rolling direction. The welding parameters are given in Table 2 and the tool configuration is shown in figure 2. Pin tool angle of inclination to workpiece is fixed at 2°. For tensile and bend testing of welded joints, samples are machined according to (ASTM E8M-04) standard shown in figures 3 & 4, respectively.

Prior to microstructure examination; specimens were saw cut, polished using different emery papers and then etched using killer reagent. Chemical analysis of the base metal was examined using spectroscopic analysis.





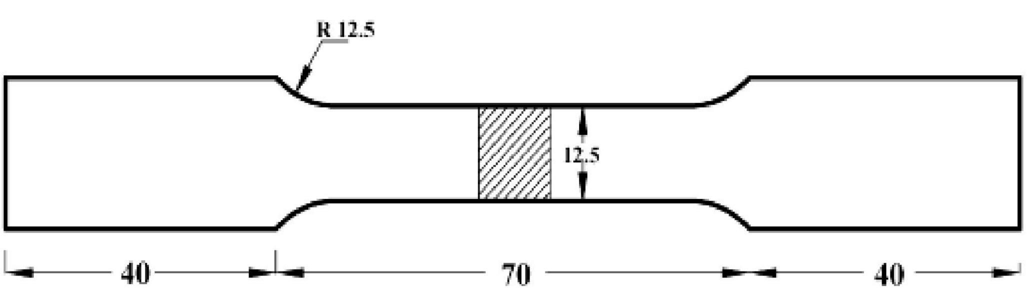
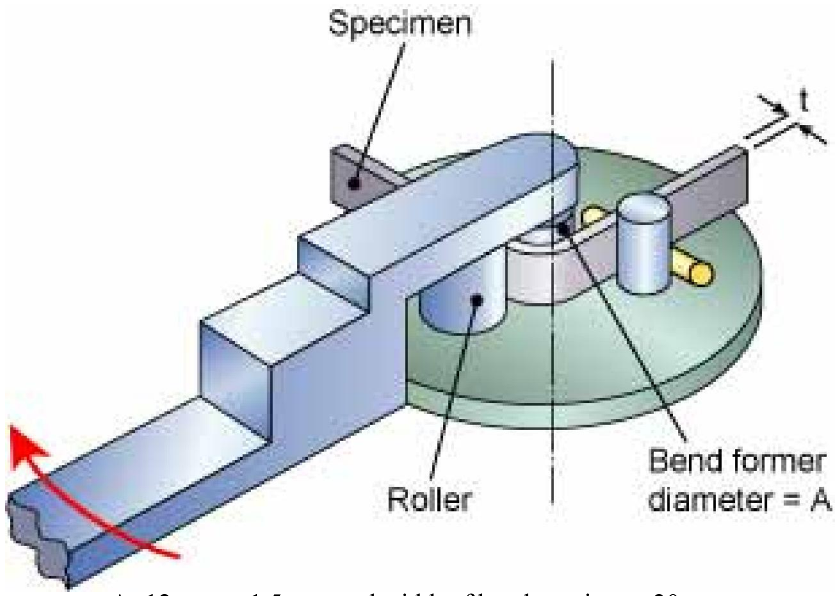


Figure 3. Flat tensile specimen dimensions, mm (ASTM E8-04).



A=12mm, t=1.5mm, and width of bend specimen=20mm
Figure 4. Bend Test Fixture.

Table 1. Chemical composition and mechanical properties of 2024-T4.

σ (MPa)	δ %	Cu	Fe	Mn	Si	Mg	Zn	Cr	Al
415	13	4.62	0.3	0.52	0.11	1.57	0.015	0.012	Balance

Table 2. Welding Parameters for FSW.

No.	Rotation speed (rpm)	Travel speed (mm/min)
1	1800	35.5
2	1400	
3	900	
4	710	
5	560	
6	450	
7	900	45
8		18
9		11.2
10	710	28
11		18
12		11.2

3. Results and Discussions

3.1 Macrostructure and microstructure

Optical micrographs of the weld joints are shown in figures 5, 6 & 9. Macrographs of the weld joints are shown in figures 7 & 8. The change in microstructure with welding conditions is shown in figure 5. Several reports have shown that, dynamic recrystallization during FSW leads to grain refinement, with grain sizes between 1.3 and 7 μm normally observed within the stirred zone/thermomechanical affected zone (SZ/TMAZ), depending on the welding conditions [5-8]. The equiaxed grain size in the SZ increased as function of heat input. The higher the heat input, the larger the grain size [4-6,13]. The shape of the weld zone is function of welding conditions, pin tool shape and thermal conductivity of the material [4, 11]. Optimizing welding conditions resulted in defect-free FSW joints as shown in figures 5 & 6**.** When welding conditions are not suitable, defects would appear in the welds as shown in figures 7-9. Voids formation occurred at high rotational speeds 1400 and 1800 rpm and travel speed of 35.5 mm/min as result of excess heat generation per unit length of the weld as shown in figures 7 & 8.

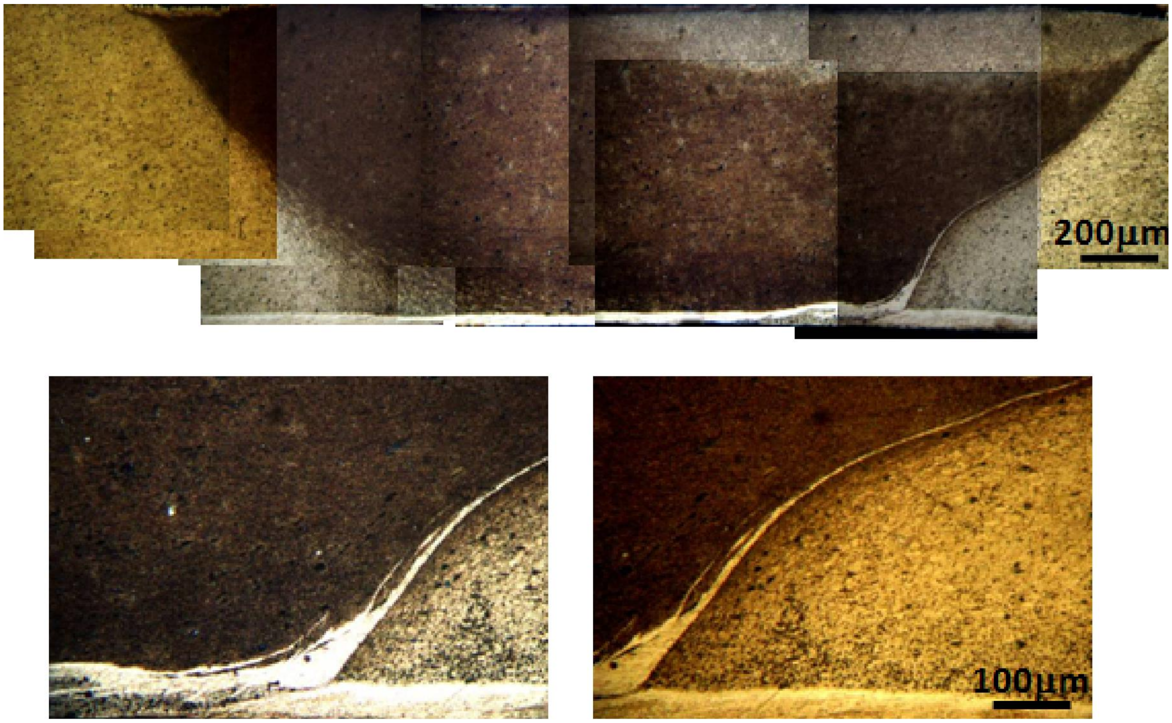


Figure 5. Optical micrographs at different magnifications welded at 710 rpm and 11.2 mm/min.

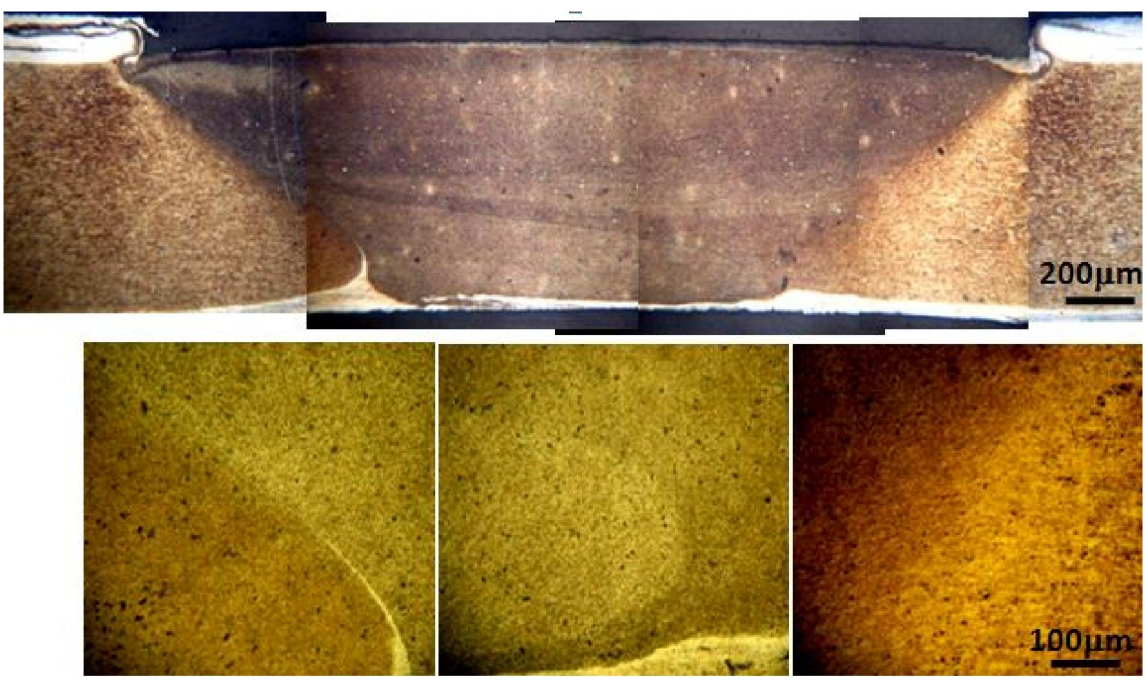


Figure 6. Optical micrographs of sample welded at 900 rpm and 11.2 mm/min

Figure 7. Macrograph of sample welded using 1800 rpm and 35.5mm/min

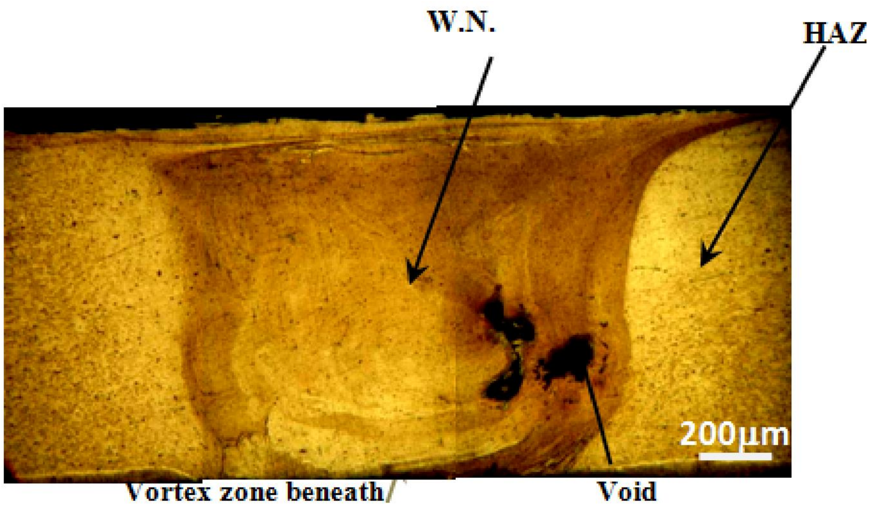


Figure 8. Macrograph of sample welded using 1400rpm and 35.5mm/min

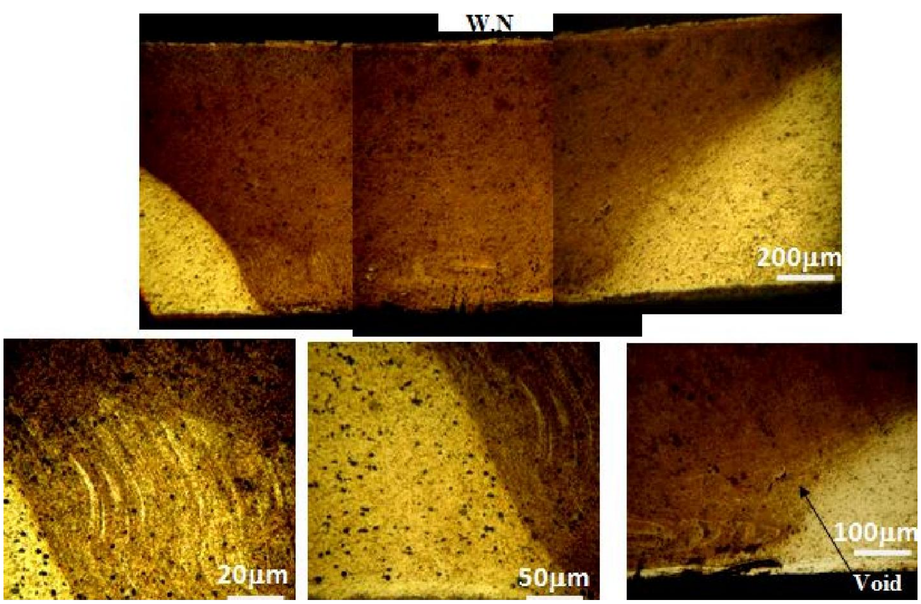


Figure 9. Optical micrographs of sample welded using 560rpm and 35.5mm/min

3.2 Tensile test

In order to evaluate the welded joints mechanical testing (tensile & bending) tests are carried out. Average of three tests at each condition was performed for tensile test as shown in figures 10 & 11. The graphs show the effect of friction stir welding parameters such as tool rotational speed and travel speed, on tensile strength and elongation of 2024-T4 welded joints.

3.3 Effect of rotational speed

Results of ultimate strength of the welded joints is lower than base material, whatever the rotational speeds used (i.e. 415MPa for base metal compared to less than 340MPa of welded joints). The highest ultimate strength (340MPa) was obtained at a rotation speed of 710 and 900 rpm as seen from figure 11. At lower rotation speed 560 rpm, ultimate strength of the FS welded joint was lower (204MPa) because low heat input generated at low rotation speed [14]. Microstructure examination explained the lowest ultimate strength at rotation speed 560rpm since low heat input produced voids in the stir zone. Increasing the rotation speed improved the tensile strength to certain rotation speed 900 rpm, beyond values, the ultimate strength decreased as shown in Figure 10. Increasing rotational speed beyond 900 rpm resulted in increasing the heat input per unit length of the joint. Heat Input (Energy / Length of Weld) = f_l (Power/Travel Rate); where f1 is the process efficiency and Power=torque * rotation speed), resulting in a decrease of tensile properties due to rise in temperature and softening.

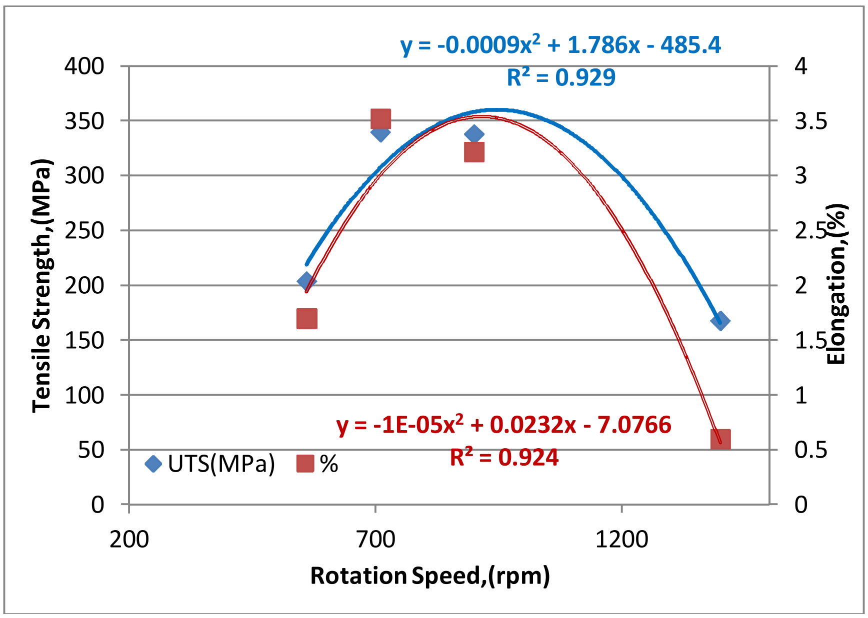


Figure 10: Effect of rotation speed on the ultimate strength and elongation at constant welding speed 35.5mm/min.

The elongation of samples welded at constant travel speed increases as the ultimate strength is increased figure 10. At rotation speed lower than 560 rpm, the welding joint lacks adhesion to the base metal because the generated heat was not sufficient to cause softening and material flow. Optimum tensile strength (340 MPa) was obtained at 900 rpm rotation speed which is equivalent to 82% of the base material. Increasing rotational speed beyond 900 rpm, all the mechanical properties, including ultimate strength and % elongation, drastically decreased to considerable low levels due to increasing heat input.

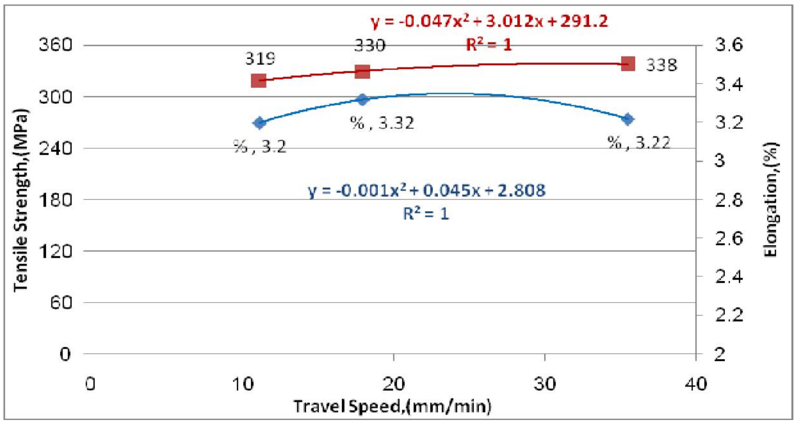
3.4 Effect of travel speed

Figure 11 shows the effect of travel speed on tensile strength and elongation of friction stir welded 2024-T4 alloy. At lower travel speed, (11.2 mm/min at constant rotation speed 900 rpm) tensile strength of the FS welded joint is lower (318 MPa). When the travel speed was increased, the ultimate strength increased. Lowering welding speed resulted in increasing heat input reducing cooling rate in the weld zone causing grain growth [11]. Increasing welding speed up to 18 mm/min, the ultimate strength of the welded joint reached maximum value of 330MPa. The same behavior of the ultimate strength was observed at constant rotation speed of 710 rpm, where tensile strength increased with increasing travel speed up to 35.5mm/min and then decreased with further increase in travel speed. This can be explained by the fact that the generated heat was not sufficient to get sound weld at travel speeds greater than 35.5mm/min.

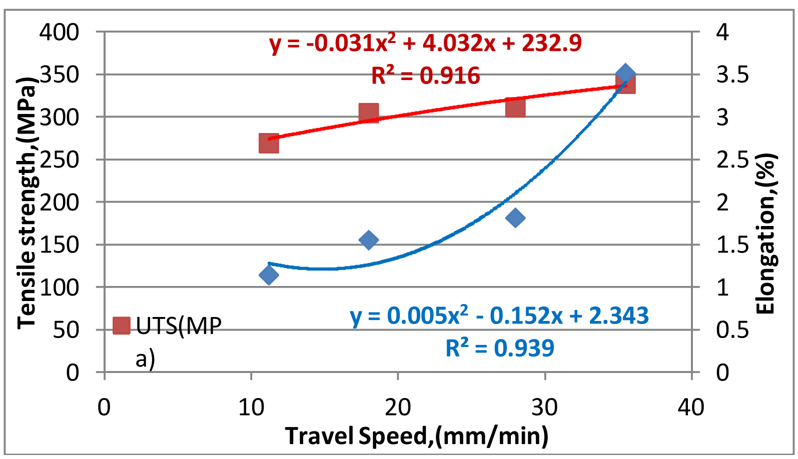
The tensile strength FSW aluminum alloy depends on travelling speed. As the travel speed increases resulted in heat input decreased, which in turn increase cooling rates of the joint [15-18].

At high travel speeds large size defects near surface was observed as shown in figures 7 & 8. Voids formed at high travelling speed are expected to be formed due to inappropriate heat input required to plastic deform the base alloy. The optimum welding parameters was obtained at 900rpm rotation speed and 35.5mm/min travel speed.

Concerning fracture site of weld joints, figures 12 and 13 are showing that all joints are broken mainly at weld zone (WZ) between the weld nugget (WN) and TMAZ. The weld nugget and TMAZ interface is weak zone. Therefore, joints are fractured at WN / TMAZ interface during the tensile testing except when the weld zone contains defects, figures 8 & 9.



(a)



(b)

Figure 11. Effect of welding speed on the tensile strength and elongation at different rotation speeds (a) 900 rpm, (b) 710 rpm.

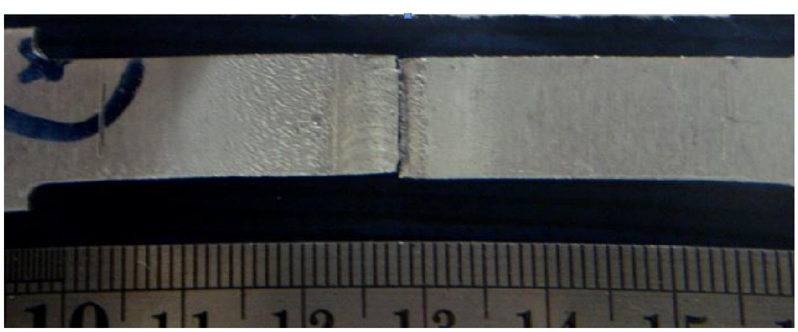


Figure 12. Tensile test fracture location for joint welded using 710 rpm-35.5mm/min.

3.5 Bending test

Close up views of the bend tested joints are shown in figure 13. Figure 13 shows the bend test results of welded alloy at different rotational speed and constant traverse speed (35.5mm/min). It is obvious that at higher rotational speed (1800 and 1400 rpm) the fracture was observed in the welded samples due to the present of voids.

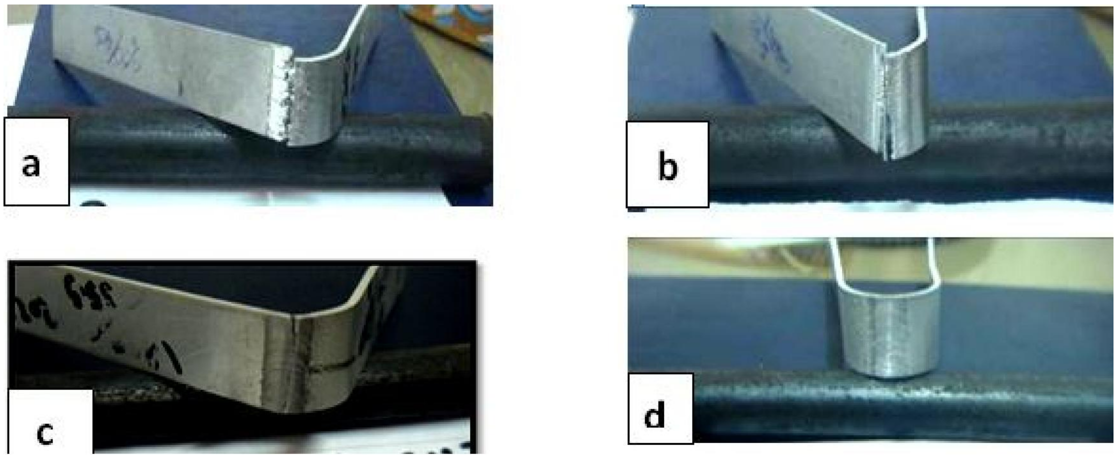


Figure 13. Close up views of the bend tested joints: (a) 900rpm-45mm/min, (b) 1400rpm 35.5mm/min, (c) 1800rpm-35.5mm/min, and (d) 710rpm-35.5mm/min.

Figure 13 shows the bending results of welded samples at different welding parameters. It is found that, the fracture was observed not only at the welding speed more than 35.5mm/min at constant rotation speed 900rpm but also at the rotation speed, more than 900rpm at constant travel speed 35.5mm/min.

At the travel, speed (45mm/min) the fracture was observed in the welded sample due to the lack of heat and plastic deformation this clear in Fig. 13. While at lower traverse speed, the welded samples were succeeded. At high rotation speed, more than 900rpm the joint produces void as shown in figures 7 & 8.

4. Conclusions

Based on results of this study the following conclusions could be addressed:

1. The highest values of ultimate strength and elongation of welded joints were obtained at rotational and travel speeds of 900rpm and 35.5mm/min, respectively.

2. Defect free joints were obtained at rotational speeds 710, 900 rpm and travel speeds 11.2, 35.5mm/min.

3. Optimum conditions having defect free and highest tensile properties for FWS welding of 2024-T4 alloy are 900rpm and 35.5mm/min.

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