J Fail. Anal. and Preven. (2018) 18:1625–1630
https://doi.org/10.1007/s11668-018-0562-x

TECHNICAL ARTICLE—PEER-REVIEWED

Experimental Investigation on the Effect of Tool Rotational Speed on Mechanical Properties of AA6082-T6 Friction Stir-Welded Butt Joints

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Submitted: 22 May 2018 / in revised form: 18 October 2018 / Published online: 9 November 2018

Abstract In this study, the effect of tool rotational speed on mechanical properties of AA 6082-T6 aluminum alloy was investigated. Different welded joints were produced by using four rotational speed (500, 710, 1000 and 1400 rpm) and constant welding speed at 80 mm/min. Mechanical properties of the welded joints were evaluated by hardness measurement on the transverse section and tensile testing. The experimental results show that the tool rotational speed has a significant effect on weld mechanical properties of joints.

Keywords AA 6082-T6 · Friction stir welding · Butt joints · Mechanical properties · Rotational speed

Introduction

Friction stir welding (FSW) was developed in 1991 and has rapidly become an important process for joining aluminum alloys as a solid-state welding process that offers an attractive alternative to fusion welding [1, 2]. This welding method is very attractive for the joining of aluminum and many other relatively light metallic alloys and as a result has many applications in the marine, shipbuilding and automotive industries. In these industries, friction stir welding gives a variety of solutions because it can weld among others many dissimilar aluminum alloys, whose joining is very difficult using other welding processes [3]. The process is especially well suited to butt and lap joints in aluminum since aluminum is difficult to weld by arc welding.

During FSW, a rotating tool equipped with a specially designed pin and shoulder is plunged between edges of elements to be joined and moved along the welding line. The friction between the tool and joined materials generates heat necessary to plasticize the material. The heat obtained in this way plasticizes the material around the probe, and its rotation and movement along weld line cause the mixing of joined materials. During the FSW process, the material is subjected to significant plastic deformations at elevated temperature (lower than the melting point of the material to be joined) which, consequently, leads to the refinement of grains, which is advantageous from joint strength point of view [4].

For FSW, both tool rotation rate (*N*) and traverse speed (*V*) exert a significant effect on the thermal input and mechanical properties. However, when both rotational speed and welding speed change, it is hard to evaluate quantitatively the parameter dependence of the thermal input and mechanical properties.

Due to the combined effect of tooling, FSW produces five different microstructure zones, the nugget in the center of the weld where the pin has passed, a shoulder contact zone on the top surface, thermo-mechanically affected zones (TMAZ) on each side of the nugget, a heat affected zones (HAZ) adjacent to the TMAZ that experiences a thermal cycle but not a mechanical shearing and the unaffected parent material [5–7].

Aluminum–magnesium–silicon (Al–Mg–Si) heat treatable wrought alloys, although of only medium strength, appear to have a weldability advantage over high-strength

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aluminum alloys. For this reason, Al–Mg–Si alloys are widely used for structural components in welded assemblies. However, Al–Mg–Si alloys (6000 series) are crack sensitive when they are fusion welded without filler metal [8]. Recently, AA6082 aluminum sheets are gaining popularity in automotive body structure applications.

This paper presents the results of an experimental setup in which the aluminum alloy AA6082-T6 was FS welded, using various tool rotational speeds. Mechanical properties of the test welds were assessed by means of static tensile test and Vickers microhardness measurement.

Experimental Procedure

The material under investigation was a 6082-T6 aluminum alloy under the form of rolled plates of 2 mm thickness. Plates were welded perpendicularly to the rolling direction. The chemical composition and the mechanical properties are shown in (Tables 1 and 2), respectively. The employed tool rotating speeds were 500, 710, 1000 and 1400 rpm with constant welding speed of 80 mm/min.

For friction stir welding process, cut edges are finished with milling operation so that interfaces can be properly matched. The machine used for the production of the joints was a vertical milling machine. The fixture was first fixed on the machine bed with help of clamps Fig. 1a. The plates were held in the fixture properly for friction stir welding as shown in Fig. 1b. A 12 mm tool shoulder diameter with tronconical pin diameter of 4 and 1.86 mm long was used. Tool profile used in this study is shown in Fig. 1c. A high-alloy, high-chromium steel tool with exceptional high temperature, high tenacity and high wear resistance was used for this work. This selection of material was also motivated by cost and availability.

Two aluminum plates of size 200 mm × 70 mm were prepared to obtain four friction stir-welded joints at selected tool rotational speeds. Specimens for the tensile strength analysis and microhardness test were cut perpendicular to the weld line, as shown in Fig. 2. Tensile test specimens were prepared from each weld in accordance with ASTM, EM-08, having dimension of 50 mm gauge length and 12.5 mm width. The tensile test was carried out using an INSTRON universal machine, Fig. 3.

Results and Discussion

Visual Inspection of Joints

The first observation of the welded joints showed an excess of lateral flash in the retreating side (RS). This defect results from a slight penetration of the shoulder which gives the possibility of the material to flow outwardly. On the bottom of the joint, there is a good junction between the two plates. Figure 4 shows the top and bottom of the welded joint.

Figure 5 gives an observation on the profile of the joint. We see that there is no defect, cracking or internal defects (tunnel effects), and so we can say that we have a good weld joint and a good junction in visual quality.

Microhardness Tests

The hardness profiles are extremely useful, as they can assist in the interpretation of the weld microstructure and mechanical properties. Vickers hardness tests were conducted using a Shimadzu HMV-2000 with 600 g and 0.5 mm distance between successive indentations.

The evolution of the hardness in the welded joint is related to the microstructural changes generated by the welding. Thus, for structurally hardened alloys, the dissolution or growth of the hardening precipitates leads to a decrease in hardness in the HAZ and TMAZ relative to the base metal. Figure 6 shows the evolution of the HV hardness of the welded joints for different speeds of rotation and a fixed welding speed 80 mm/min. The mean value of the hardness in the weld zone ZS is lower than that of the base metal for all samples.

It is noted that the hardness of the base material has been affected by the welding. For the rotational speeds of 500, 710 and 1000 rpm, the hardness values remain almost stable in the welded zone. At each increase in the rotational speed, the hardness increases. This is due to the increase in

Table 2 Mechanical properties of the base metal AA6082-T6

Re (MPa)	Rm (MPa)	*A*%	*E* (GPa)	HV	$T_{melting}$ (°C)
249	310	11	67	107	650

Table 1 Chemical compositions in % of 6082 aluminum alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.7–1.3	Max 0.5	0.1	0.4–1.0	0.6–1.2	Max 0.25	Max 0.2	Max 0.1	Rest

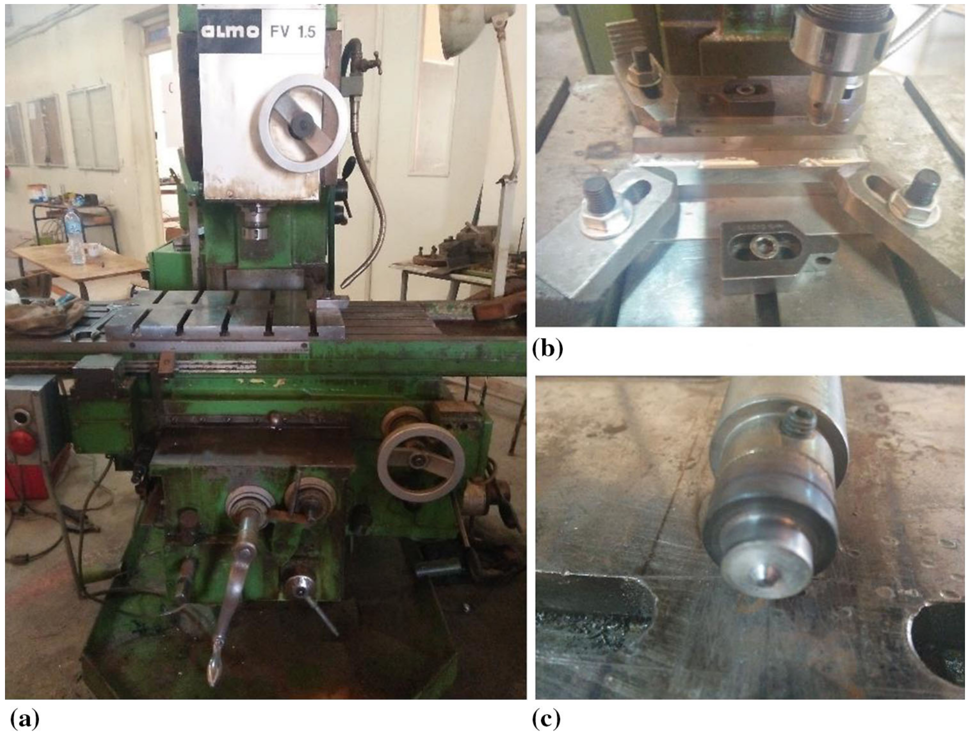


Fig. 1 (**a**) Vertical milling machine used for friction stir welding. (**b**) Clamping of plates. (**c**) FSW tool

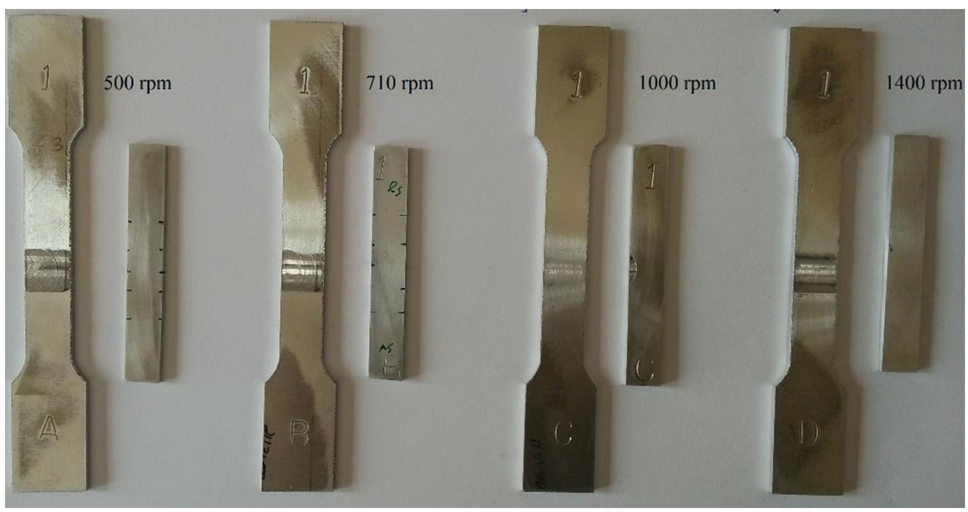


Fig. 2 Tensile and microhardness specimens, for each joint FS welded with different rotational speed at constant welding speed 80 mm/min

frictional heat between the shoulder and the surface of the specimens, and the stirring rate. While for a rotational speed of 1400 rpm, there is a large difference in hardness compared to others and a dissymmetry between the advanced side and the retreating side. This is due to a large amount of heat absorbed. Arbegast and Hartley [9] have suggested a pseudo-heat index (N^2/V) to describe the dependence of welding parameters on the generated heat. It has been shown that for many aluminum alloys, a general relationship between the maximum temperature and the FSW parameters can be expressed by Eq 1.

$$\frac{T}{T_m} = K\left(\frac{N^2}{vx10^4}\right)^{\alpha} \qquad \text{(Eq 1)}$$

where the exponent α varies between 0.04 and 0.06, and the constant K between 0.65 and 0.75.

T_m, in °C, is the melting point of the alloy.

N is the rotational speed, and V is the welding speed.

The maximum temperature reached is 441.27 °C, when welding with the parameters 1400 rpm-80 mm/min. This temperature simulates the temperature of the heat treatment of this alloy, resulting in an increase in hardness.

Fig. 3 Universal machine used for tensile tests

Tensile Tests

The tensile tests were conducted at room temperature and performed in order to determine the FSW process parameters that ensue obtaining the highest tensile strength. One specimen was taken for each weld joint.

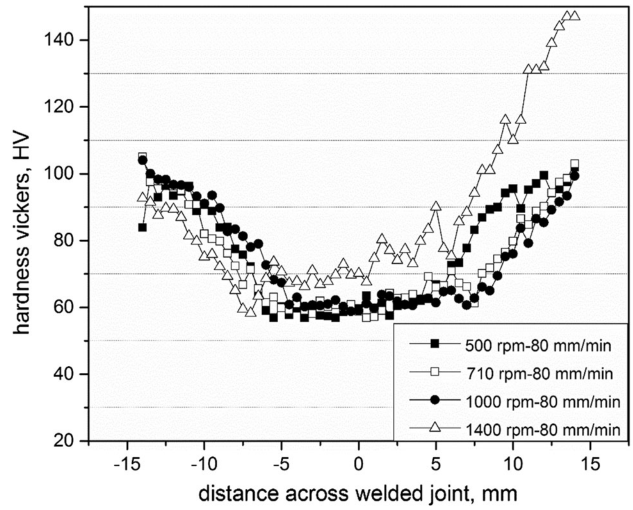
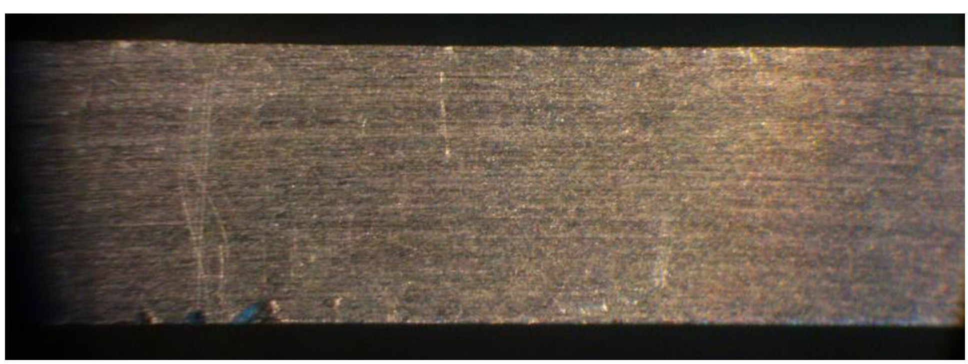


Fig. 6 Microhardness profile on the transverse section showing the effect of the tool rotational speed at constant welding speed of 80 mm/min

(a) **(b)**

Fig. 4 (**a**) On top and (**b**) bottom of weld joint

Fig. 5 Microscopic observation of a cross section FSW joint (X40)



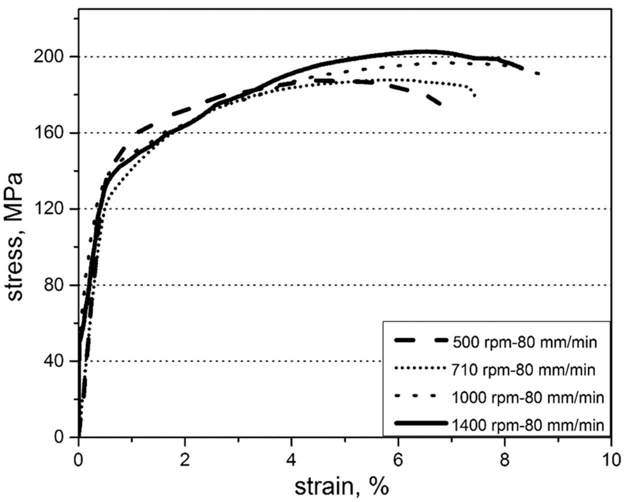


Fig. 7 Engineering stress–strain response for the as welded samples showing the effect of the rotational speed

Table 3 Tensile test results for effect of rotational speed at constant welding speed 80 mm/min

Rotational speed (rpm)	UTs (MPa)	Efficiency (%)
500	187.49	60.48
710	187.88	60.60
1000	196.86	63.50
1400	202.67	65.37

The results of the tensile tests for different rotational speeds are given in Fig. 7. The mechanical properties of the base metal have been disturbed by welding. For rotational speeds of 500, 710 and 1000 rpm, we notice that with increasing rotation speed, the ultimate tensile strength and elongation increase. At 1400 rpm, there is a decrease in elongation, but the tensile strength remains higher than the others. Also, at a higher rotational speed, the heat generated by friction is higher. This heat gives rise to more intense agitation and mixing, which gives a stronger welded joint.

The test results for butt joints are presented in Table 3, where the joint efficiency is presented as a ratio of joint tensile strength to base material tensile strength in percentage. The tensile test specimens ruptured in the HAZ. The tensile test specimens after tensile testing are shown in Fig. 8.

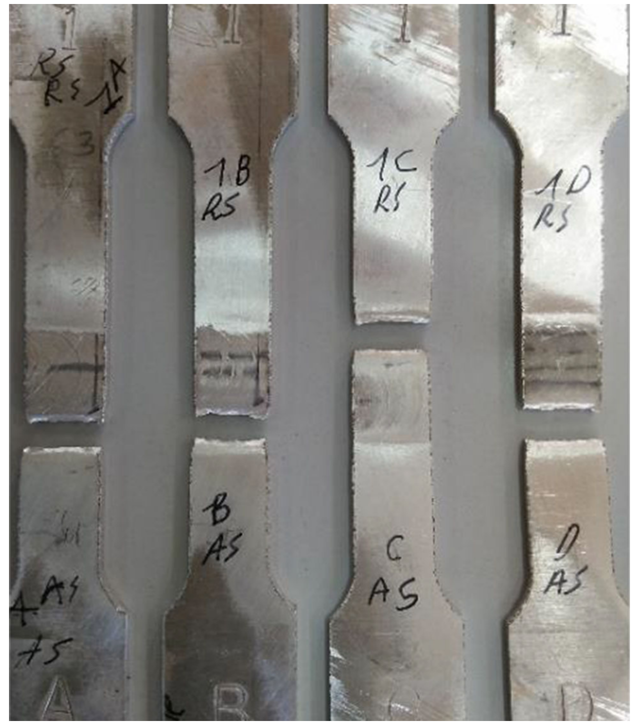


Fig. 8 Tensile specimen after test

Conclusion

Friction stir welding of 6082-T6 using four different tool rotational speed has been conducted. Based on the tests and the analysis of results, the following conclusion can be extracted:

1. Friction stir welding of alloy AA 6082-T6 resulted in a dynamically recrystallized zone, TMAZ and HAZ. A softened region has clearly occurred in the friction stir-welded joints of 6082-T6 alloy.
2. Mechanical properties of FS welds aluminum alloy 6082-T6 are influenced by process parameters. The tensile strength of FS welds is directly proportional to the rotational speed, and it is lower than that of the parent metal.
3. The drop of microhardness was observed in the heat affected zone. This zone corresponds to the failure location in tensile tests.
4. The maximum tensile strength achieved in the FSW joint is 65.37% of the parent metal tensile strength using 1400 rpm for rotational speed and welding speed of 80 mm/min.

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