Experimental Investigations of Microstructure of Al 1100 Alloys Welded by Friction Stir Welding Process

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Abstract: Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient and environment friendly. In this paper, hardness and tensile properties of welded zone of aluminum 1100 alloys by friction stir welding process was investigated and the effects of rotational and traverse speeds of tool on these parameters were studied. According to the results of this research, the hardness of weld material is higher than the base material and is increased by decreasing the rate of rotational speed to traverse speed. Also the yield strength of the weld material is 70% of the base material in best condition due to the weak thermo mechanically affected zone around weld nugget. Although in some samples the tensile strength of the weld material is equal to the base material.

Keywords: Aluminum 1100 Alloys, Friction Stir Welding, Hardness, Tensile Properties

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1 INTRODUCTION

The Al-1100 alloy, is the most commercially pure alloy among all of the aluminum grades. This alloy is available in the form of coil and sheet and has many applications in various industries due to its low cost, superior corrosion resistance and enough ductility. This alloy is particularly appropriate for applications where high corrosion resistance, formability and electrical conductivity are mandatory [1].

In friction welding, the materials are joined through plastic deformations of materials which are occurred due to the heat induced by friction. Some of the advantages of this approach are no needs to use a shielding gas, high welding speed and good mechanical properties. Friction stir welding (FSW) is a kind of friction welding process which was invented at The Welding Institute (TWI) of UK in 1991, firstly, to join the Al alloys and then was used widely due to the advantages of this welding method such as being energy efficient and environment friendly [2]. The FSW process is based on thermo-mechanical changes and the process temperature and its distribution have the main effects on obtained microstructure [3], [4].

Khodir and Shibayanagi [5], investigated the effects of welding speed and the position of sheets in retreating or advancing side on mechanical and micro-structural properties of weld material in welding of Al 7075 and 2024 alloys. Cavaliere and Cerri [6], studied the mechanical and micro structural properties of the welded joint of Al 7075 and 2024 alloys by FSW process. They found that the ultimate strength of welded joint of Al 7075 alloys and toughness and elongation of welded joint of Al 2024 alloys are very high. Zhang et al., [7], investigated the effects of traverse speed on created defects in friction stir welding of AZ31 Mg alloys. They resulted that, some holes are created in weld zone by increasing the traverse speed up to 200 mm/min. These holes are created in the center of weld zone in lower traverse speeds while they are transmitted to advancing side by increasing traverse speed.

Kostka et al., [8], welded Al 6064 alloys to AZ31 Mg alloys by FSW process and investigated the obtained joint with SEM and TEM. They resulted that in weld area, the fine grained Al12Mg17 phases and nano grained Al3Mg2 phases are obtained. Elangovan and Balasubramanian [9], [10], investigated different tool pin shapes in FSW process. They resulted that using square pin leads to a micro structure with no defects and better mechanical properties. Tang et al., [11], used some thermocouples to study the temperature distribution in the workpiece during FSW process. They also investigated the effects of tool rotational speed on temperature distribution. According to their results the peak temperature is mandatory by increasing tools rotational speed. Darras et al., [12], studied the effects of tools rotational speed and traverse speed on temperature distribution at weld nugget in FSW process of AZ31 Mg alloys. They resulted that increasing tools rotational speed and decreasing traverse speed leads to increasing workpiece peak temperature.

Li et al., [13] established a semi-coupled thermo-mechanical FEM model containing both thermal and mechanical loads to simulate the generation of welding stresses during FSW process. Their results showed that due to the effect of the tool force, the longitudinal residual tensile stresses became smaller and were asymmetrically distributed at different sides of the weld center; the peak of the tensile residual stresses at the retreating side was lower than that at the advancing side. Buffa et al., [14] and Asadi et al., [15] developed a 3-D Lagrangian incremental FEM simulation of FSW using DEFORM-3D. Their model correctly predicts the non-symmetric nature of FSW process, and the relationships between the tool forces and the variation in the process parameters.

Due to the lack of insight into the friction stir welding process of Al 1100 alloys, in this investigation the FSW process was used to weld the Al 1100 alloys. The hardness and tensile properties of welded samples were studied and the effects of tools rotational speed and traverse speed on hardness and tensile properties of the welded samples were investigated.

2 EXPERIMENTS

2.1. Experimental setup

In this investigation a vertical milling machine with a designed fixture on its table was used as a FSW machine. Fig. 1 shows the FSW machine with tool and workpiece on its table.

2.2. Experimental procedure

In this investigation the hardness and tensile properties of welded area by FSW process were studied and the effects of tools rotational speed and traverse speed on these parameters were investigated. The tools rotational and traverse speeds which were used in this study are summarized in table 1.

In order to investigate the hardness of the welded samples, a Vickers hardness testing machine was applied in 2 mm below the top surface of workpiece in the weld cross section. Tensile test samples were cut according to the ASTM-E8 standard perpendicular to the weld line and then prepared to perform the tensile test.

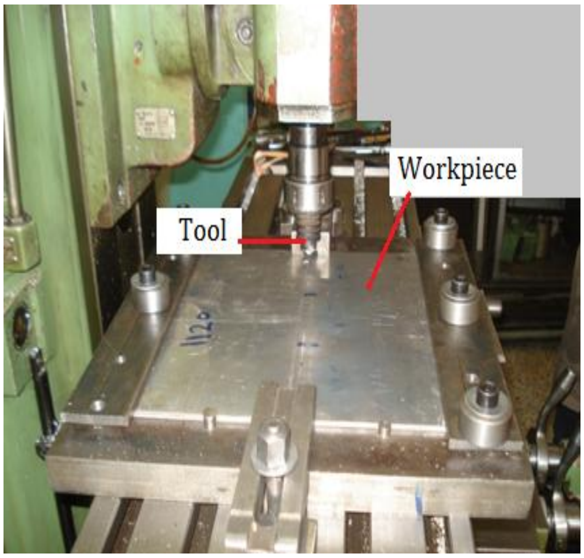

Fig. 1 FSW machine with tool and workpiece on its table

Table 1. The used tools rotational and traverse speeds in this investigation

#	Traverse speed (mm/min)	Tools rotational speed (rpm)
1	90	710
2	140	900
3	180	1120
4	280	1400

Table 2. Chemical composition of workpiece material (Al 1100 alloy)

element	Wt %
Al	99.3
Si	0.138
Fe	0.182
Mn	0.016
Cr	0.03

2.3. Experimental materials

2.3.1. Workpiece material

The workpiece materials which were welded in this study are Al 1100 alloys sheets with 500×75×5 mm dimensions. The chemical composition of the used workpiece in this study is summarized in table 2.

2.3.2. Welding tool

The tool which was used in this study has two parts and was created from pin and shoulder which were assembled together. The tools body and shoulder materials are 2344 hot work steel which has a central hole to locate a pin for positioning and also a screw for fixing. The pin is a 6×6 mm HSS bar which is located inside the tools body. Fig. 2a, shows the tool and Fig. 2b, shows the schematic design of the tool with its dimensions (mm). The created grooves on tools body were designed because of increasing heat transfer effects. Tools body hardness was about 52 Rockwell C while the tools deviation angle from vertical line was set around 3° according to the performed exploratory experiments.

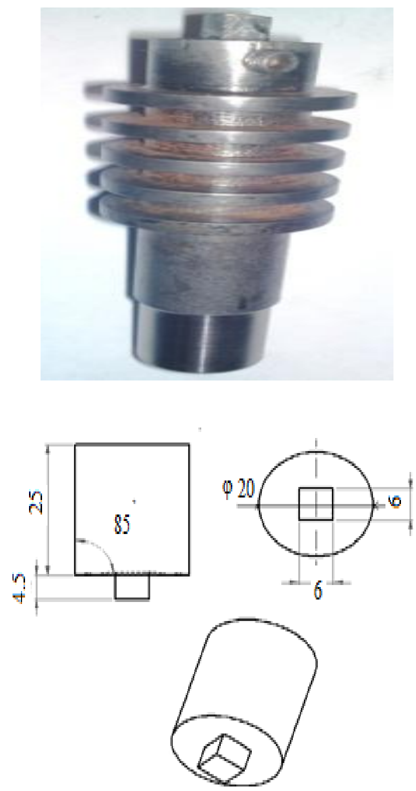

Fig. 2 (a) FSW tool used in this study, (b) schematic design of tool

3 RESULTS AND DISCUSSION

3.1. Hardness

The grains sizes and hard precipitates of secondary phases are the main parameters affecting the hardness of weld area in FSW process. The Al 1100 alloys are nearly pure and without any precipitates and secondary phases which can affect the hardness by dissolving in the base material, so the grains sizes is the only influencing factor on hardness in this case. Fig. 3 shows the variation of hardness in cross section of welded samples. According to the Fig. 3, the average hardness in weld zone is 91 Vickers and considering the hardness of base material which is 83 Vickers, a 9.6% increase in weld zone hardness can be seen in comparison with the base material hardness. It seems that the reason for this issue is related to performing a heat treatment in weld area due to increasing the temperature of weld area and then cooling in the ambient temperature.

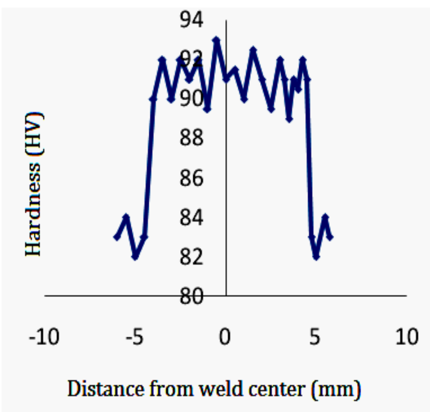

Fig. 3 Hardness curve of cross section of welded samples (tools rotational speed = 1120 rpm and traverse speed = 280 mm/min)

3.1.1. Effects of tools rotational speed and traverse speed on hardness

The Vickers hardness of weld area at different tools rotational and traverse speeds is shown in Fig. 4. According to the Fig. 4, the hardness is increased by increasing traverse speed and is decreased by increasing tools rotational speed. Increasing traverse speed leads to creation of finer grains while increasing tools rotational speed creates more heat due to more friction and plastic deformation which leads to more growth of grains. According to equation 1, which defines Hall-Petch effect [16], decreasing grains sizes, leads to higher hardness, so increasing traverse speed and decreasing tools rotational speed increases the hardness of the weld zone according to the Fig. 4.

$$H = H_0 + K_H d^{-1/2} \quad (1)$$

Where H is the hardness, H_0 is the equation constant, K_H is Hall-Petch constant and d is the average of grains sizes.

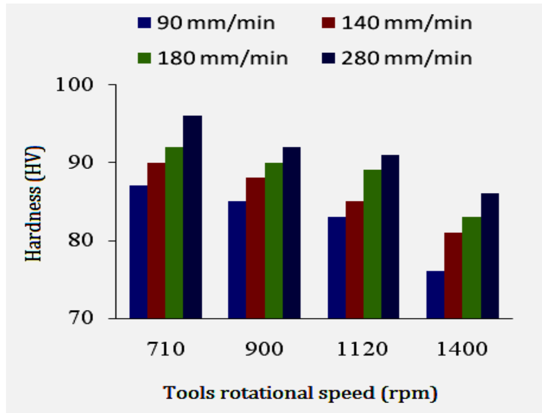

Fig. 4 Weld area Vickers hardness of samples at different tools rotational and traverse speeds

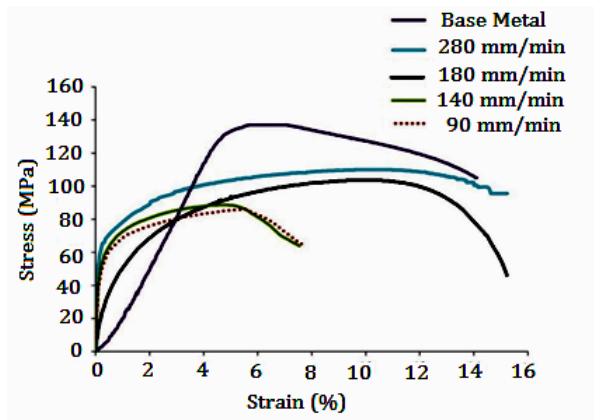

Fig. 5 Engineering stress-strain curves for base materials and welded samples in different traverse speeds (tools rotational speed = 900 rpm)

3.2. Tensile properties of welded samples

Figure 5, shows the engineering stress-strain curves for base materials and welded samples in different traverse speeds. According to the Fig. 5, the strength of welded samples is 70% of the base material in the best condition. Thermo-mechanically affected zone with stretched grains and heat affected zone with growth grains are two different areas around the weld zone. The strength of the heat affected zone which has lower dislocations density than the base material is lower than the base material because it has growth grains due to the heat induced by welding process and also due to a quasiannealing process which has occurred at heat affected zone. Thermo-mechanically affected zone which has more residual stress because of severe plastic deformation and non-occurrence of re-crystallization, has stretched grains and is talented to fracture during the tension test. Therefore the strength of welded samples is lower than the base materials.

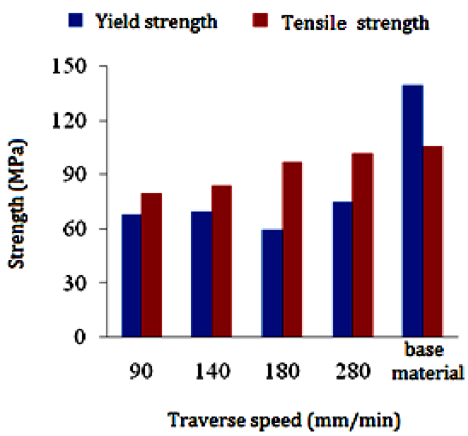

Fig. 6 Yield and tensile strength of welded samples in different traverse speeds (tools rotational speed = 1120 rpm)

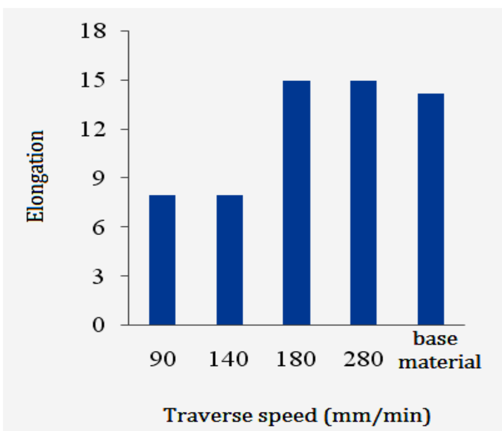

Fig. 7 Elongation of welded samples in different traverse speeds (tools rotational speed = 1120 rpm)

3.2.1. Effects of tools rotational speed and traverse speed on tensile properties

Figures 6 and 7 show the tensile properties of the base material and the welded samples at different traverse speeds. According to the Fig. 6, yield and tensile strengths of welded samples is increased by increasing the traverse speed and according to the Fig. 7, elongation is increased by increasing the traverse speed. In lower traverse speeds the created welds has lower strength and elongation due to the more generated heat which leads to growth of grains and softening the materials around the weld zone and creates some defects in the weld materials. Increasing traverse speed leads to improvement of strength and elongation.

Figures 8 and 9, show the yield and tensile strength and elongation of the weld material in different tools rotational speeds. According to the Figs. 8 and 9, the grains sizes are increased and coarser micro structure is obtained by increasing the tools rotational speed due to increasing heat generation in higher tools rotational speeds, so the yield and tensile strength and also elongation of weld material are decreased by increasing the tools rotational speed.

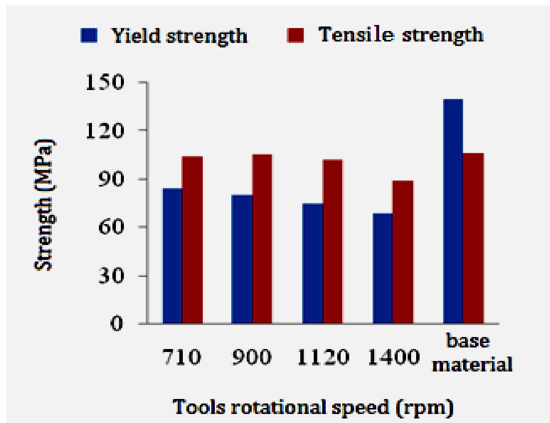

Fig. 8 Yield and tensile strength of welded samples in different tools rotational speeds (traverse speed = 180 mm/min).

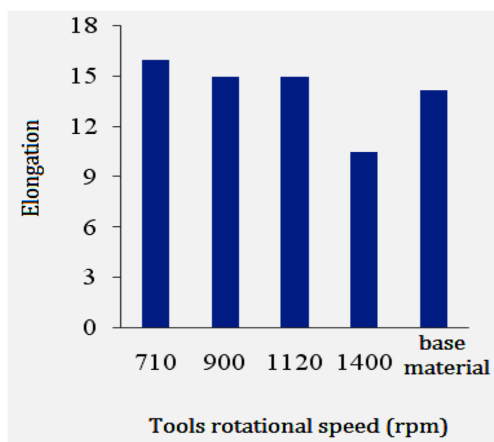

Fig. 9 Elongation of welded samples in different tools rotational speeds (traverse speed = 180 mm/min).

4 CONCLUSION

In this investigation, the hardness and tensile properties of Al 1100 alloys which were welded by FSW process were studied and also the effects of tools rotational and traverse speeds on these parameters were investigated. The main results of this investigation are summarized as follows:

(a) The hardness of the weld material is higher than the base material, and the hardness is increased by decreasing the ratio of tools rotational speed to traverse speed.

(b) The yield strength of the weld material is 70% of the base materials in the best condition, but tensile strength of some welded samples are as equal as the base materials. This is because of the weakness of thermos-mechanically affected zone around the weld nugget which is due to the growth and stretch of grains in this area because of the generated heat and applied strain on grains in this area.

(c) In lower traverse speeds and higher tools rotational speeds, the weld is weak and the yield and tensile strength of the weld material are low because of more generated heat, growth of grains, localized melting and creation of some defects in the weld materials in these conditions.

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