Iranian Journal of Materials Forming 11 (1) (2024) 4-15

IJMF

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

Research Article

Effect of Tool Rotational and Welding Speed on the Mixed Mode Fracture Strength of Dissimilar Friction Stir Welded Aluminum Alloys

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ARTICLE INFO

Article history:

Received 19 March 2024
Reviewed 3 April 2024
Revised 21 April 2024
Accepted 22 April 2024

Keywords:

Friction stir welding
Aluminum 5052
Aluminum 5083
Mixed mode fracture
Tensile strength

Please cite this article as:

Rezghi Maleki, H., Abazadeh, B., Pashmforoush, F., & Ahmadzadeh, F. (2024). Effect of tool rotational and welding speed on the mixed mode fracture strength of dissimilar friction stir welded aluminum alloys. *Iranian Journal of Materials Forming*, *11*(1), 4-15. https://doi.org/10.22099/ijmf.2024.49770.1286

ABSTRACT

In the friction stir welding (FSW) process, a special rotating tool is used for welding different parts without utilizing any electrode as filler material. By rotating the cylindrical tool and sinking it into the line of connection between two parts, friction and disturbance are created, and at the same time, heat and pressure also rise to prepare the conditions for the welding. During the last two decades, a large number of research has been carried out to investigate the mechanical properties and microstructure of joints made from several similar and dissimilar alloys. Crack growth resistance of such joints under tensile, shear and mixed loading is an important design parameter to evaluate the lifetime of welded parts in friction stir welding, while there is limited research on combined mode I/II in FSW welding. To fill this research gap, in this research tensile and fracture strength in dissimilar FSW welding of AA5083/AA5052 aluminum alloys are investigated experimentally. For this purpose, two pin diameters, three pin rotation speeds and welding speeds have been selected as welding variable parameters. After carrying out the welding, the tensile and cracked mixed mode fracture tests were performed to determine the effect of considered parameters on the tensile and fracture strength of the joint. The results showed that the biggest tensile and fracture strength happens in different tool rotation and welding speeds for different loading angles (fracture modes).

1. Introduction

During the First and Second World Wars, welding advanced greatly. The needs of the military industry to create strong connections in the shortest possible time accelerated the development of this manufacturing method. In 1991, The Welding Institute (TWI) located in Cambridge, England, Introduced Friction Stir Welding (FSW) process. The main idea of friction welding is very simple. The two metals that are going to be welded, are placed tightly together, and a non-consumable special pin with teeth enters the connection line of these two metals and travels along the length of the connection line along with rotation. Pin performs two main functions:

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https://doi.org/10.22099/ijmf.2024.49770.1286

• Heating the part by friction
• Moving materials to connect

Heat is obtained with the help of friction between the pin and the workpiece and the plastic deformation of the workpiece. The concentrated heat softens the material around the pin and along with the rotating movement of the pin, it causes the material to move from the front of the pin to the back and as a result of this process, the connection occurs in a solid state due to the geometric structure of the pin. In FSW welding, the materials undergo a large deformation at high heat and the final structure has fine, coaxial crystal grains as well as favorable mechanical properties (see Fig. 1).

Esmaeili et al. [2] investigated the dissimilar friction stir welding of aluminum alloy 1050 to brass. The results showed that at low rotational speeds, the amounts of intermetallic compounds were very small, but using rotational speeds higher than 400 rpm caused the gradual production of pieces. intermetallic in the mixing and interface area, CuAl2 was the most obvious intermetallic compound in the composite structure of the mixing area, while CuAl2, Cu9Al4 and CuZn compounds were also detected. Increasing the rotational speed caused the intermetallic particles to thicken and expand. The optimal rotational speed of 450 rpm, an interface area with narrow interface components and a composite layer structure was created in the mixing area, which led to an increase in the tensile strength of the connection. Bizadi et al. [3] studied the connections of pure copper to 5083 aluminum alloy experimentally and investigated the effect of FSW parameters, rotation speed and welding speed on the microstructure and mechanical properties of the joint. Park and Kim [4] investigated the effect of tool rotation speed and tool reverse speed on friction performance during FSW tests on different alloys AA5052-O and AA6061-T6 and used a wide range of process parameters to determine the mechanical strength of welding dissimilar materials. The results showed that the optimum conditions are a travel speed of 61 mm/min and a rotation speed of 1600 rpm. Observations of the weld surface and plastic flow behavior showed that by reducing the compression speed, the welding effect at the welding site increased and the number of defects decreased.

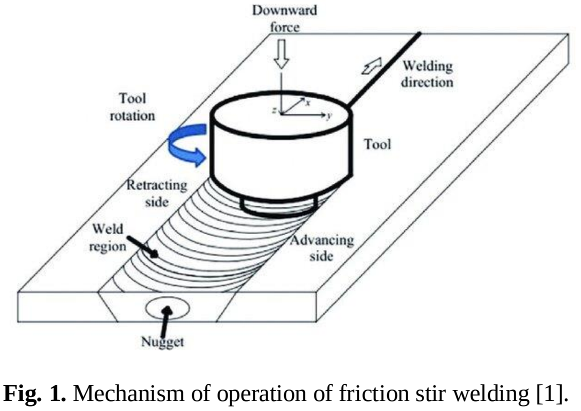

Fig. 1. Mechanism of operation of friction stir welding [1].

Park et al. [5] investigated the effect of material location on the properties of different FSW joints of AA5052-H32 and AA6061-T6 and showed that material mixing patterns in FSW joints differ depending on the position of the base material. For the given aluminum alloys, the materials are mixed properly when AA5052-H32 was on the advancing side and AA6061-T6 was on the retreating side than for the case of AA6061-T6 on the advancing side and AA5052-H32 aluminum alloy on the retreating side. It was found that for both material layout combinations, AA5052-H32 showed the lowest micro strength value in the heat affected zone (HAZ), which clearly explained the reasons for the fracture of the tensile test specimens on the 5052-H32 side. Abdullahzadeh et al. [6] noted that the high rotational speed of the tool and the speed of linear movement in the welding path cause friction and high heat in the welding place, and as a result, the possibility of creating a large number of brittle intermetallic compounds and hardness increases at the interface of Al-Cu welded area. Consequently, the possibility of small cracks in the welded interface increases. On the other hand, the low rotational speed of the work tool and the high linear speed reduce the heat input to the welding area and cause incomplete welding in the Al-Cu welded interface. This issue can increase the risk of failure due to crack growth in the interface when the connection is exposed to mechanical loads. Lee et al. [7] investigated the non-homogeneous joints of AA5052-H112 and

AA6061-T6 plates with thicknesses of 1 mm and 2 mm, respectively, with different tool rotation speeds and tool traverse speeds according to the fixed location of each material. It was found that the interface morphology is characterized by pulling and pulling up of the interface on the advancing and retreating side. The thickness of the AA5052 thin sheet reduces the vertical movement of the material. It was found that the amount of vertical movement increased and, as a result, the thickness of AA5052 decreased, when the preheating process is performed, either by increasing the tool rotation speed or by decreasing the tool passing speed, the common strengths mainly depend on the morphology and interface movement of the materials.

Rajkumar et al. [8] investigated the effect of pin geometry and welding linear speed in friction stir welding of aluminum alloys AA6061 and AA5052 at a rotation speed of 710 rpm, the results of their investigation showed that a hole was created at a linear speed of 28 mm/min. Ravikumar et al. [9] investigated the effect of welding parameters on the mechanical properties of dissimilar friction stir welds of AA6061-T651 and AA7075-T651 alloys with a thickness of 6 mm, and observed that the highest tensile strength (205.3 MPa) was obtained from the connection made with a screw square cone pin at a rotation speed of 900 rpm and a linear speed of 100 mm/min and the lowest tensile strength (178.01 MPa) show the connection made with a screw square cone pin at a rotation speed of 900 rpm and a linear speed of 90 mm/min. Al-Rubiai et al. [10] stated that the formation of intermetallic phases and low melting point, which can lead to crack propagation from the interface, is an important issue related to the dissimilar joining of Al-Cu metals even in cases when the FSW joining method uses the transmission electron microscope (TEM) method. Zhou et al. [11] showed that a thick intermetallic layer formed at the Al-Cu interface during the FSW process increases the brittleness. While the brittleness of the interface under mechanical loads leads to grain-type fracture, which often occurs at the interface between two metals.

Kavalier et al. [12] investigated the effect of welding parameters on the mechanical and microstructural properties of friction stir welding of AA6082-T6 and AA2024-T3 alloys with a thickness of 4 mm. In this research, the effect of the location of the base metal plates related to the tool has been investigated. The results showed that the best tensile and fatigue properties are obtained in the weld where the AA6082 alloy is on the progressive side. By changing the position of the plates, Firozdur and Ko [13] changed the copper and aluminum connections and improved its tensile strength, in addition to studying the microstructure and mechanical properties of the modified joints and comparing them with traditional joints. Mehta et al. [14] investigated the effect of dissimilar friction stir welding parameters of aluminum alloy 651T-6061AA to copper on the metallurgical and mechanical properties of the joint. The obtained results showed that the welding without defects was created by the cylindrical pin without thread, on the other hand, welding with the threaded pin caused various defects. The maximum tensile strength obtained was 131 MPa and the maximum hardness was 181 Vickers (in the mixing area), which is with the rotational speed 1500 rpm, advance speed of 40 mm/min, tool deviation angle of 2 degrees, pin offset of 2 mm and using cylindrical pin without thread was obtained. The axial force created was dependent on the tool shoulder diameter and its deviation angle. By keeping the axial force constant between 6 and 7 kilonewtons, a flawless connection can be obtained.

Torabi et al. [15] analyzed the fracture of dissimilar welded joints of Al 7075-T6 and Al 6061-T6 under both tensile and shear loading and compared the experimental results in order to provide the concept of equivalent material. In this research, the fracture strength as the investigation parameter was defined in terms of the maximum stress or load that a specimen can withstand before a fracture occurs. It is a critically important mechanical property, as it characterizes the material's resistance to failure under a range of applied forces and loading modes. Nishida et al. [16]

investigated mode I fracture toughness and crack growth behavior in dissimilar aluminum alloy plates (for example, AA3003/SUS304 aluminum alloy) welded by FSW method.

The literature review shows that most of the studies are carried out to investigate the effect of different parameters on the simple tensile strength or mode I tensile fracture strength and there is only limited research on the combined mode I/II (i.e. tensile-shear fracture strength) in FSW welding studies, while this loading condition happens in many industrial or structural circumferences. Therefore, to fill this research gap, in this paper, the brittle fracture resistance of dissimilar 5083 and 5052 aluminum alloys welded by FSW is investigated to find the effect of two impressive parameters i.e. tool rotation and welding speed on the mixed mode fracture strength.

2. Materials and Experimental Procedures

2.1. Aluminum sheets

The aluminum sheets used in this paper are 5xxx series aluminum of 5052 and 5083 aluminum alloy with the chemical composition and mechanical properties of Table 1 and Table 2 respectively, and the selected thickness of the plates is 3 mm for the test. In order to perform various tests and experiments, 18 specimens of each of the considered alloys were prepared with dimensions of 210 × 70 mm, and they were precisely cut with the surface of each sheet being polished. It was also necessary to smooth the cut edge of the aluminum, which is placed side by side in the friction welding of two aluminums, so that during the welding operation, there is no defect or gap in the direction of the movement of the pin. Finally, the surface of all the aluminum sheets were completely washed to remove any oil and fat for welding.

Table 1. Chemical compositions of 5052 and 5083 aluminum alloys (wt.%)

Aluminum alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn
5052	0.25	0.40	0.10	0.10	2.2-2.8	0.15-0.35	0.10
5083	0.4	0.4	0.15	0.4-1	4-4.9	0.05-0.25	0.25

Table 2. Mechanical properties of 5052 and 5083 aluminum alloys

Aluminum alloy	Density (kg/m^3)	Poisson's ratio	Young modulus (GPa)	Hardness (HB)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation at break
5052	2680	0.33	70.3	47	89.6	193	30%
5083	2660	0.33	71	77	145	290	25%

It is worth mentioning that 5052 aluminum alloy sheet is an easily weldable alloy and widely used in marine or corrosive environments due to its mechanical properties. Moreover, 5083 aluminum alloy has good corrosion resistance against sea water and chemical environments. The strength after welding of this sheet is very good. Similarly, this sheet has the highest strength among non-heat-treatable alloys.

2.2. FSW effective parameters

The effective parameters in the FSW welding process include the following:

1. Tool geometry
2. Pin rotation speed (w, rpm)
3. The speed that pin travels the connecting line, welding speed (v, mm/min)
4. Penetration depth of the pin inside the work piece
5. The angle between the pin and the workpiece

In this paper the pin rotation and welding speeds are investigated as the affecting parameter with the selected optimum tool geometry and angle from the initial tests.

Choosing the material of the tool is one of the very important design parameters. In this process, the tool must be wear-resistant, and, in addition, it must not lose its hardness due to the heat created in the process. Therefore, hot work steels can be a good suggestion for tool material.

To perform experimental tests, two H13 steel working tools were used. Hot work tool steel of standard 1.2344 (known as H13 hot work steel according to the British Standard), is a tool steel grade for heat work. The main feature of this grade is the alloy combination of chromium, vanadium and molybdenum elements, which increases the resistance of tool steel to shock and impact. Hot work tool steel H13 is highly regarded for its excellent heat resistance. The presence of high vanadium in this grade of tool steel can eliminate wear at both high and low temperatures. Vanadium always provides a high level and uniformity of machining. This steel tool is mostly used for casting aluminum, magnesium, etc. The presence of chromium makes it resistant to softening when used at high temperatures. H13 steel is resistant to premature cooling and premature checking of heat. Two working tools (pin) were made from a raw cylindrical piece with a diameter of 60 mm and a height of 100 mm that was machined to achieve the shoulder diameters of 15 mm and 18 mm with the height of 30 mm. They were cut and finally the pin part of the working tools was cut and shaped to a diameter of 5 mm and 6 mm respectively and a final height of 2.8 mm. Finally, a special glove was used to thread the pin (Fig. 2).

The initial tests of friction stir welding showed that the welded surface of 5 mm diameter pin was better than the other pin, thus the 5 mm pin was selected to prepare the main specimens (Fig. 3).

In addition to pin diameter, pin angle affected the welding quality as well. Therefore, welding was started with a zero-degree angle (that is the angle of the pin with the perpendicular line of welding direction), which caused the quality of welding to decrease and also created a gap under the tip of the pin, which caused a decrease in the strength of the weld and also affected the appearance of the weld (see Fig. 4(a)). By creating an angle of 1 degree in the end

Fig. 2. Final shape of pin.

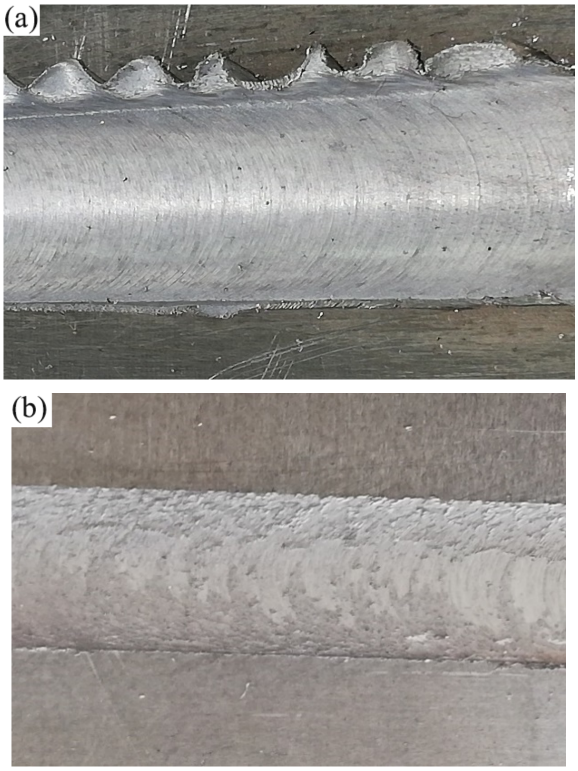

Fig. 3. Initial friction stir welded specimens using two different pins; (a) welding specimen using 5 mm diameter pin, and (b) welding specimen using 6 mm diameter pin.

of the milling machine (i.e., the angle between the vertical direction and the direction of the pin changed from 0 degree to 1 degree), the quality of the weld was improved and the strength of the weld in tensile tests effectively increased (Fig. 4(b)).

The rotation of the pin causes the material to move and mix around the pin, and this causes the material to move from the front of the pin to the back. A higher rotation speed of the pin produces a higher temperature because, it causes more frictional heat and more intense mixing and movement of materials. Therefore, with an increase in the pin rotation speed, it should not be expected that the produced heat will also increase uniformly, even though the friction coefficient on the surface changes with an increase in the pin rotation speed. Therefore, the weld created decreases in terms of strength properties. Thus, in this paper three rotation speeds of 800, 1000 and 1250 rpm were selected.

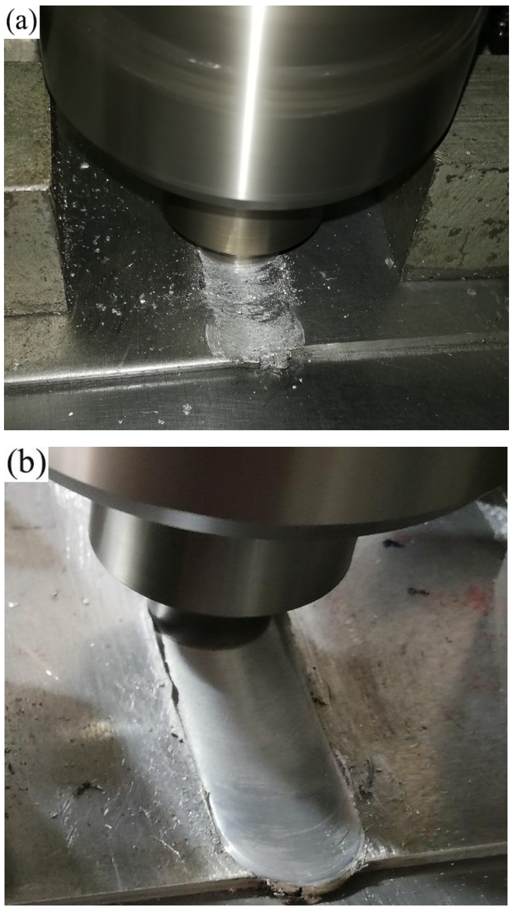

Fig. 4. The effect of pin angle on the welding quality; (a) pin angle of zero degree, and (b) pin angle of 1 degree.

Moreover, by increasing the welding speed, the amount of heat transfer from the welding area to the workpiece is reduced, so the effect of the welding process will be observed in a smaller area of the welding edges. On the other hand, the speed of the process will increase, and the created distortion will decrease. To study this parameter, the welding speeds of 25, 63 and 125 mm/min were selected in the experimental tests.

2.3. Tensile tests

ASTM E8 standard was used to make tensile test samples of FSW joints. The tensile test of dumbbell-shaped samples was performed by the SATNAM device, and the test was repeated 5 times for each sample type. Examples of tensile testing can be seen in Fig. 5.

2.4. Mixed mode fracture tests

The mixed mode fracture tests were performed using a modified Arcan fixture (Fig. 6). The modified Arcan fixture was produced with CM5 high resistance steel that had a thickness of 20 mm. A groove of 2.3 mm

Fig. 5. Prepared tensile test FSW specimen according to ASTM E8 to determine tensile strength.

thickness was also created in the center of its thickness in each half to fix the displacement of samples in the perpendicular direction of tensile loading. A number of holes on its outer edges was drilled to be used for 5 different loading directions and failure modes from pure mode I to loading condition of pure mode II. In this research, in order to make suitable test specimens to be used in the modified Arcan fixture, rectangular plates were cut from the welded samples of aluminum alloy 5083 and 5052 with a length of 140 mm and a width of 60 mm. To create cracks in the welded area, first a gap was created to make the stress concentration, and then the crack propagated from the end of this gap with the applied load. For this purpose, to create a crack with a final length of 30 mm, an edge gap with a thickness of 0.2 mm in the mid-line of the length of the sample, was created using a wire cutter. Therefore, the radius of the achieved crack tip is about 0.1 mm which was small enough to be considered as a sharp crack. Futhermore, in order to create a better stress concentration, a very thin groove was created at the end of the cracks employing a thin blade (Fig. 7).

To place the welded sheets inside the modified Arcan fixture, 4 holes with a diameter of 10 mm were made on the sheets, which are fixed by bolts and nuts on the Arcan fixture.

A static tensile test instrument with a maximum tensile capacity of 20 kN has been used for fracture tests. After assembling the samples in the modified Arcan fixture, a tensile force was applied at a constant speed of 5 mm/min and continued until the final fracture. To achieve the different fracture modes of pure I to pure II, the loading location was changed from hole number 1 to 5 on the fixture, and the values of the maximum applied load until the failure of the sample were recorded. A view of the test fixture under different loading conditions is shown in the Fig. 8.

3. Results and Discussion

In this section, the obtained results of experimental demonstrating the effect of tool rotation speed of friction welding on the tensile and fracture strength of friction stir welding are given.

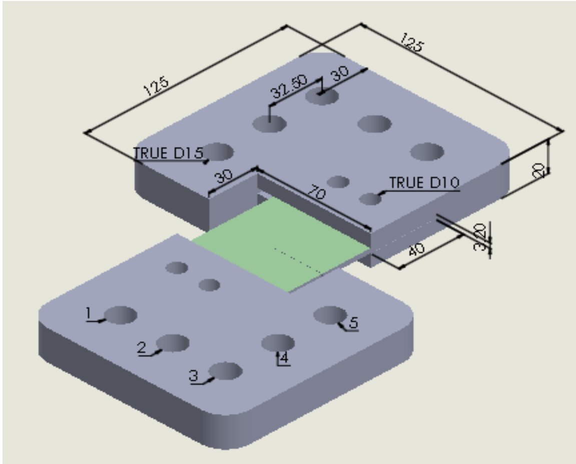

Fig. 6. Dimensions of the modified Arcan fixture (dimensions in millimeters).

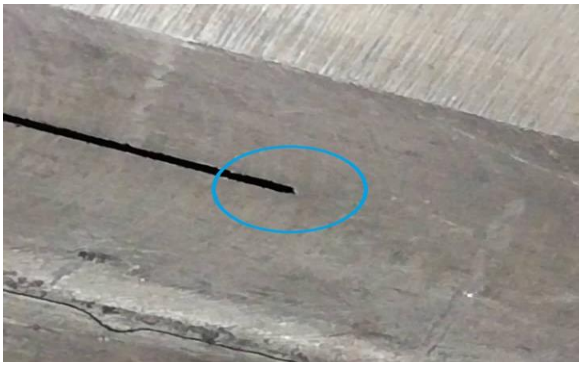

Fig. 7. The created notch using wire cut and a narrow cutter.

3.1. Tensile test of dumbbell-shaped samples

As mentioned in previous sections, dumbbell-shaped samples made under ASTM-E8 standards were cut from the part perpendicular to the weld and were welded at speeds of 800, 1000 and 1250 rpm (with three different welding speed of 25, 63 and 125 mm/min). In order to ensure the correctness of the tests and the accuracy of the obtained data, 5 samples were prepared for each test.

From the results of the tensile test of dumbbell-shaped samples, it can be seen that the rotational speed of the tool during friction stir welding is one of the most important and influential parameters in the mechanical properties of welding. In most of the cases, the necking and failure starts from the welding region which demonstrates the lower yield strength and final strength of the welded area compared to 5052 and 5083 aluminum alloys. Due to the lower

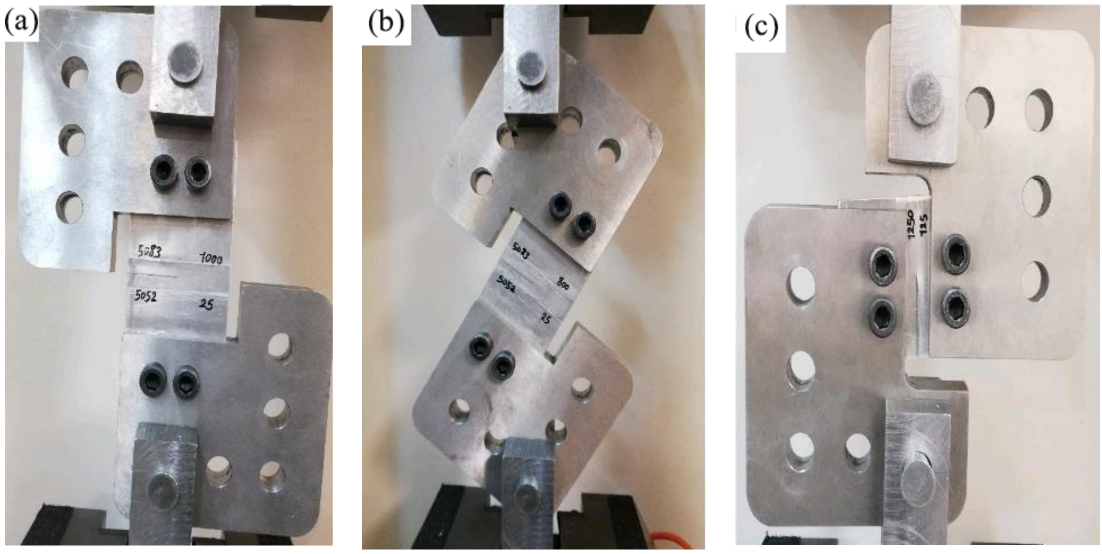

Fig. 8. Modified Arcan fixture and samples in different loading modes; (a) pure mode I (tension mode), (b) mixed mode I/II, and (c) pure mode II (shear mode).

strength of the 5052-aluminum workpiece than the 5083-aluminum workpiece, most of the parts break on the 5052-aluminum side. By performing the tensile test on all of the samples and placing them aside, as shown in the figure, due to the increase in rotational speed, we can see that the fracture point of the samples is closer to the middle of the welded area. Although the increase in rotational speed will increase the input heat, a large increase in temperature will also cause the two metals to become softer.

According to Fig. 9 obtained from tensile tests of FSW samples, it can be seen that, at the constant rotational speeds of 800 and 1000 rpm, the maximum tensile strength corresponds to a speed of 63 mm/min, while for rotational speed of 1250 rpm, the maximum tensile strength belongs to 125 mm/min specimens.

From the analysis and examination of the specimens with the linear speed of 25 mm/min it can be seen that due to the increase in the rotational speed, the trend of the graph has decreased. Therefore, at this linear speed, the highest tensile strength of the tested sample is at a rotational speed of 800 mm/min. The results of the linear speed of 63 mm/min show that, with the increase of the rotational speed, an increase in the welding resistance is observed at first and then changes to a reduction are observed. In this linear speed, the highest strength of the tested samples is at a rotational speed of 1000 mm/min. However, the growth trend is seen at the linear speed of 125 mm/min, unlike the speeds of 25 and 63, with the increase of the rotational speed. That is caused due to the rise in the input heat and the speed of the cutting tool increases the welding resistance.

3.2. Fracture strength at pure tensile mode I (0 degrees)

As it was mentioned, for the zero-degree fracture test of the samples, the pin corresponding to the jaws should be placed in holes number 1 of the Arcan fixture so that the samples are subjected to pure or normal tension. In other words, in pure tension, the direction of force is perpendicular to the welding direction and the gap created by the wire cut. At the beginning of the test, the backlash of the fixture and the patch were removed first, then with the increase of the tensile force, the gap started to open from the stress concentration area of the workpiece, and a crack started to form and grow from the stress concentration area and in the middle of the welding area.

From the analysis and examination of the data obtained from the Mode I fracture tests (see Fig. 10), it can be found that, at the rotational speed of 800 rpm, the maximum and minimum fracture strengths are related to the linear speeds of 25 mm/min and

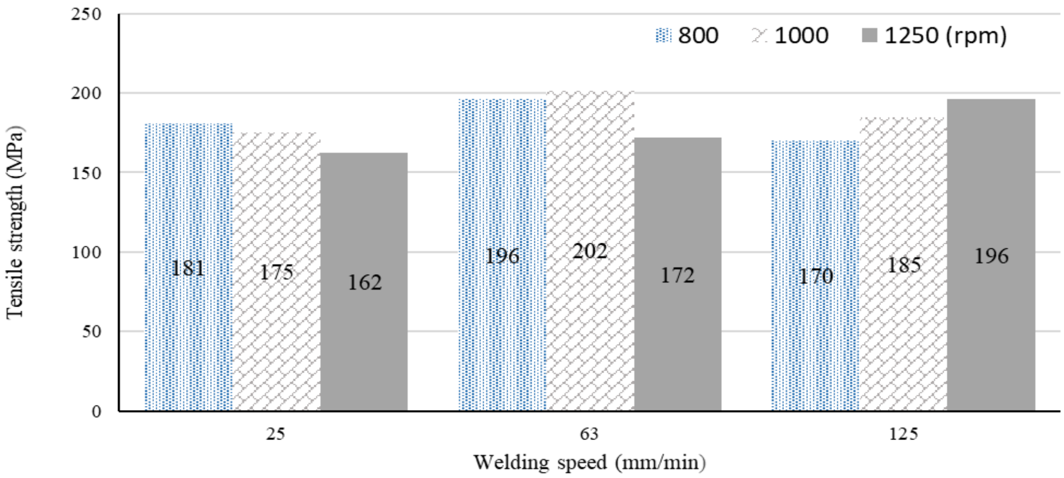

Fig. 9. Tensile strength of FSW samples.

63 mm/min, respectively. In addition, at a rotational speed of 1000 and 1250 rpm, the maximum and minimum strengths are related to linear speeds of 25 mm/min and 125 mm/min, respectively. Among all the samples, the maximum stress is related to the welded sample with a rotational speed of 800 rpm and welding speed of 25 mm/min, and the minimum stress is attributed to a rotational speed of 1250 rpm and a welding speed of 125 mm/min.

Furthermore, by increasing the rotational speed, a decrease in fracture strength happens. In other words, an increase in the rotational speed causes the resistance to the growth of the welded area to decrease and the hardness of the welded area moves toward ductile fracture.

3.3. Fracture strength at mixed mode I/II (45 degrees)

In the tests related to the mixed mode I/II of fracture, the loading angle of 45 degrees using hole number 3 of the modified Arcan fixture was used. In this type of test, by increasing the applied tensile force and approaching the yield point, the created cracks in the welded area were rarely opened, and after reaching the maximum force, the cracks started to suddenly grow to the final fracture. The data obtained from the fracture tests are depicted in Fig. 11. The analysis and examination of the data obtained from the fracture test of the mixed mode samples (45 degrees), shows that, at the rotational speeds of 800 and 1000 rpm, the maximum and minimum forces are corresponding to the linear speeds of 25 mm/min and 63 mm/min, respectively.

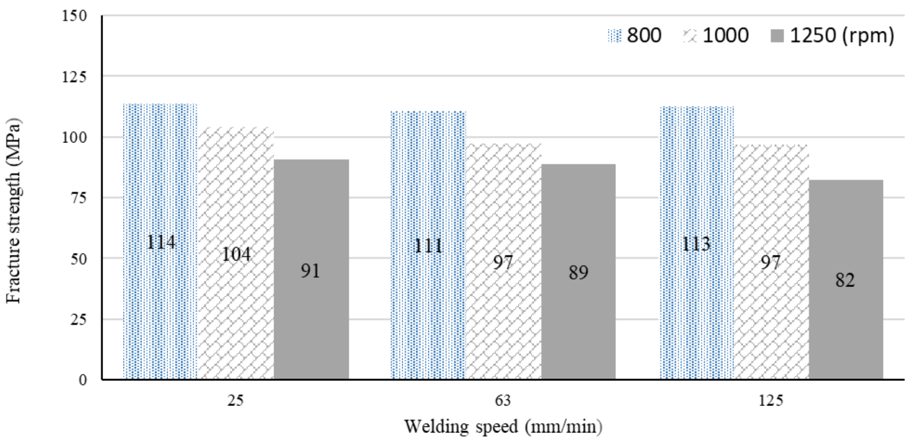

Fig. 10. Fracture strength at loading of 0 degrees (Mode I).

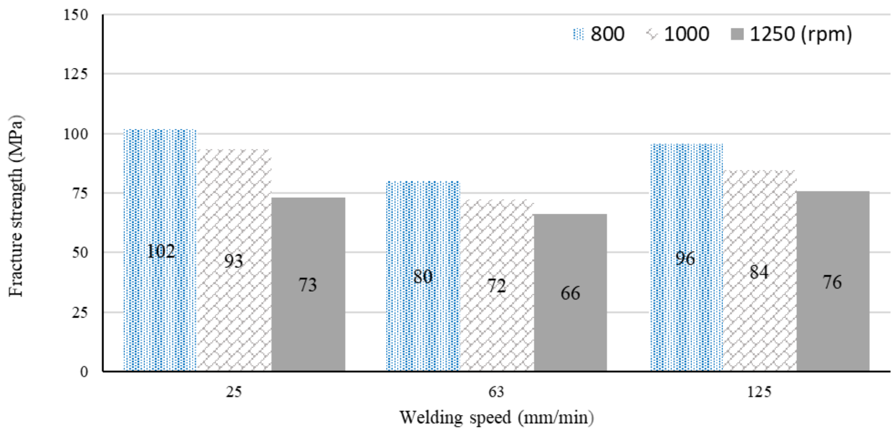

Fig. 11. Fracture strength at loading of 45 degrees (Mixed Mode I/II) using modified Arcan fixture.

However, at the rotational speed of 1250 rpm, the maximum and minimum force is corresponding to the linear speeds of 125 mm/min and 63 mm/min, respectively.

Finally, in this test, among all the samples, the maximum force is related to the welded sample with a rotation speed of 800 rpm and welding speed of 25 mm/min.

By comparing the data obtained from performing the normal tension and combined shear/tension tests, it is found that the fracture strengths of pure mode I are bigger compared to the fracture strength of samples under mixed mode loading.

3.4. Pure shear fracture test (pure mode II, 90 degrees)

In the fracture tests of pure shear mode, the welded samples were attached to the modified Arcan fixture, and the pin corresponding to the connection jaws was placed in hole number 5 of the fixture. In this test type, during the application and increase of the tensile force between the two welded workpieces, the crack cannot be opened due to the loading condition of pure shear mode, and it only tries to break the samples in their transverse direction. As shown in Fig. 8(c), with the increase of the tensile load, the right-side clamp which is attached to the upper jaw of the tension device, is pulled upwards and tries to separate the welded samples from the welding area. With the further increase of the tensile force and after it reaches the maximum shear strength, the smooth edge of the samples begin to protrude and the surface difference from the welded area eventually breaks.

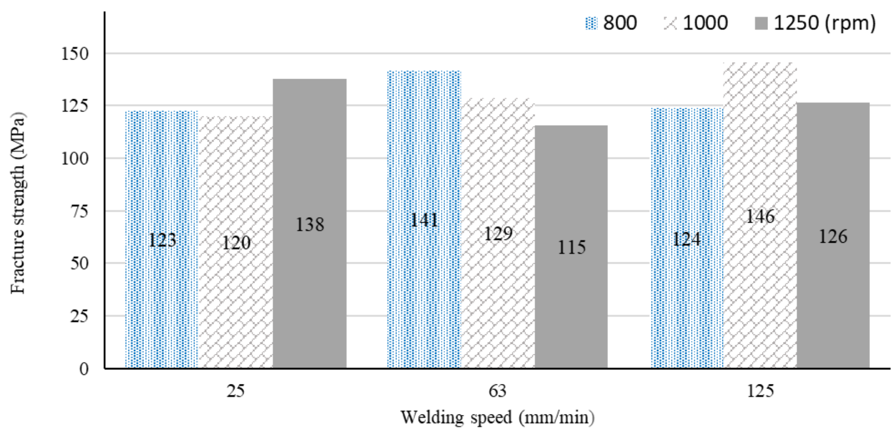

Fig. 12. Fracture strength at loading of 90 degrees (Mode II) using modified Arcan fixture.

The data obtained from the shear tensile test (90 degrees, see Fig. 12) show that, at the rotational speed of 800 rpm, the maximum and minimum force is related to the linear speeds of 63 mm/min and 25 mm/min, respectively, but at the rotational speed of 1000 rpm, the maximum and minimum force is corresponding to the linear speeds of 125 mm/min and 25 mm/min, respectively. Additionally, at the rotational speed of 1250 rpm, the maximum and minimum force corresponds to the linear speeds of 25 mm/min and 63 mm/min, respectively.

Finally, in this test, among all the samples, the maximum force is related to the welded sample with a rotation speed of 1000 rpm and an advance rate of 125 mm/min.

4. Conclusion

In this paper, the effect of different pin rotations and welding speeds on the tensile and mixed mode fracture strength of friction stir welding of dissimilar 5052 and 5083 aluminum alloy sheets were experimentally studied. The results are briefly as follows:

- The highest tensile strength corresponds to the welded samples with welding and rotational speeds of 63 mm/min and 1000 rpm, respectively.
- Increasing the rotational speed of the working tool improves the tensile strength of the FSW joint.
- The highest mode I fracture strength of the welded joints was obtained at a rotational speed of 800 rpm and a welding speed of 25 mm/min, and the trends show that the lower the welding speed and its rotational speed, the higher the mode I fracture strength of FSW joints.
- Increasing the rotational speed of the FSW pin in mode I fracture specimens, decreases the resistance to crack growth significantly. Additionally, increasing the welding speed insignificantly reduces the resistance to crack growth.
- At a rotational speed of 800 rpm and welding speed of 25 mm/min, the welded samples of mixed mode have the highest fracture strengths.
- Increasing the rotational speed of the FSW pin in mixed mode fracture specimens, causes a reduction in the fracture strength while increasing the welding speed decreases the fracture strength noticeably.
- In the mode II fracture specimens, the highest strength belongs to specimens with a rotational speed of 1000 rpm and a welding speed of 125 mm/min.
- Increasing the welding speed of mode II fracture specimens, enhances the fracture strength while as the rotational speed of the pin increases, the fracture strength decreases.

Conflict of Interests

The authors declare no conflict of interest in this research.

Funding

This research was funded by Shahid Chamran University.

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