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ORIGINAL ARTICLE

Study of ultrasonic vibrations' effect on friction stir welding

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Abstract In this paper, effect of ultrasonic vibrations on friction stir welding (FSW) is studied. Ultrasonic vibrations were employed on the tool in pin direction (perpendicular to the welding direction). To do this study, a vibration tool was designed by Abaqus software in a way to have a longitudinal frequency about 20 kHz and was then manufactured and assembled with an ultrasonic transducer and was controlled using an ultrasonic generator to oscillate ultrasonically with a peak-to-peak amplitude of 10 μm. After preparation of experimental setup, some experiments were performed on AA6061-T6 as a work material, and the effect of ultrasonic vibrations on force, temperature, tensile strength, and hardness was investigated in FSW. Based on the achieved results, ultrasonic vibrations can decrease force and increase temperature in FSW.

Keywords Friction stir welding (FSW) · AA6061 alloy · Ultrasonic · Force · Welding temperature · Hardness

1 Introduction

Weld is a permanent connection which can be performed in melted or solid state, with or without filler material and with or without pressure. One of the welding methods is friction stir welding (FSW) in which a rotary tool for producing frictional heat and plastic deformation during welding process is used [1]. Figure 1 shows a schematic picture of FSW.

In FSW, tool includes pin and shoulder that the ratio of their dimensions is very important in enhancing heat production to the maximum by which material flows and force decreases [2]. Zhao et al. [3] studied the effect of pin geometry on joint and its mechanical properties in FSW of aluminum alloys. They claimed that pin design affects material flow, drastically.

Temperature is the most important factor in every welding process. Mahoney et al. [4] measured temperature distribution in proximity of stir zone and found that maximum temperature is in the end of stir zone. In FSW, there are some parameters that highly affect material movement and temperature distribution and influence microstructure. One of the parameters is rotational speed of the tool which causes heat production in the middle of stir zone. Therefore, if this parameter increases, temperature increases too. By increasing rotational speed, mixing process of plastic material in the stir zone may improve which is a positive achievement. On the other hand, by increase of the rotational speed of the tool, the rotational speed of the shoulder increases and produces more heat energy on welding surface. It should be noted that shoulder plays a really important role in production of heat (about 95 % of the whole produced heat). Of course, in joints with different materials, increase of temperature of weld surface may enhance the production of fragile intermetallic structures in the weld surface and results in increase of fragility of weld surface and possibility of weld fracture [5, 6]. Another parameter is feed speed. By increasing feed speed, heat movement from weld zone to the workpiece decreases; therefore, effect of welding can be seen smaller in the weld zone sides. On the other hand, welding speed increases too. Pin offset is another parameter that is important, especially for welding of metals with different properties. Pin penetrates into the softer metal and, by adjustment of offset, penetrates into the harder metal with higher melting temperature [5]. For welding two different metals, rotation direction is another effective parameter [5]. Angle of tool can also affect welding process. Tool angle can be changed from 0° to 4° for different materials, but for most materials, the best range is 2.5° to 3.5°. The effect of this angle is increase of strength and production of equal microstructure

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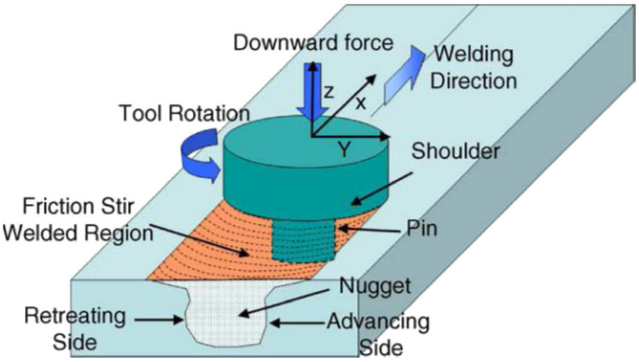


Fig. 1 Friction stir welding process [1]

[7, 8]. Another parameter is the force used to push tool into the material that is entitled "downward force." Generally, there is an optimum value for downward force. If this force becomes less than this optimum value, vertical material flow is not good, and some tracks will be produced in the weld. If this force increases more than its optimum, it causes the reduction of weld section and spraying material around the weld zone [6]. Another parameter is force of workpiece clamp that can affect the quality of the joint by influencing the stress distribution and the amount of residual stresses [6]. Shoulder diameter is also an important parameter. In the most cases, shoulder diameter is determined by trial and error [9]. Material softening and flow are affected highly by shoulder diameter which shows the importance of this parameter [10]. Pin diameter is also significant. The best pin diameter value is about sheet thickness [1]. Another parameter is tool geometry which plays a very important role in material flow and can control the movement speed of FSW [1].

One of the research topics in FSW is a combination of this process with ultrasonic vibrations. In a study that Park et al. [11, 12] performed, ultrasonic assisted FSW (UAFSW) was investigated by exerting ultrasonic vibrations in feed direction of the tool. Adding ultrasonic vibrations to FSW offers some advantages such as better weld quality, less welding forces, and increase of tool life [13]. In UAFSW, ultrasonic vibrations are added to the welding (feed) direction which can improve tool penetration and its movement in the welding direction [11].

In this paper, some experiments were performed by the prepared setup to find the effect of ultrasonic vibrations assistance on welding force, tool temperature, tensile strength, and workpiece hardness. By changing feed speed and rotational speed, the effects of these parameters on welded parts produced by FSW and UAFSW were investigated.

2 Setup preparation and experiments

In this study, ultrasonic vibrations were exerted to the rotary tool in pin direction. A lathe machine was used to rotate tool by its jaw chuck and to move workpiece linearly by its support.

Horn is a part through which ultrasonic vibrations concentrate. This part is used as an interface between ultrasonic transducer and tool. Actually, the reduction of its diameter from the section by which it connects with ultrasonic transducer toward the section by which it connects with tool causes ultrasonic waves concentrate. This is so useful to increase ultrasonic energy efficiency. For designing a horn, longitudinal resonance frequency of horn should be near the longitudinal resonance frequency of transducer. A conical design was chosen for horn because of its high efficiency and easy-to-manufacture characteristic. Since there are high forces on the tool in FSW and rotary movement can only be applied to the horn and tool from node points (there are some node and anti-node points on a wave, and the anti-node points are used for clamping a horn), horn material should have enough strength. On the other hand, ultrasonic transducer is sensitive, and its temperature should not become higher than a determined limit; so, horn material should not have high thermal conductivity. In this work, stainless steel (AISI 304) was chosen as a horn material because of its appropriate strength and low thermal conductivity relative to other materials such as aluminum. Stainless steel also has low damping in transferring ultrasonic vibrations.

Tool material should have high strength, good hardness, and low thermal conductivity in order to prevent other equipment from damage. AISI H13 was selected as a tool material in this study. This steel is appropriate for welding of aluminum sheets with thickness of 0.5–50 mm. After manufacturing of the tool, heat treatment was performed on it.

The small diameter of horn (the section by which horn connects with tool) should not be bigger than the tool diameter because of energy efficiency. The small diameter of the tool was 15 mm; therefore, 16 mm was chosen as the small diameter of horn. Since resonance frequency of ultrasonic generator and transducer was 20 kHz, horn and tool length was changed to reach a resonance frequency near 20 kHz for both of them (the set of horn and tool). To design horn and tool, modal analysis was performed with C3D4 mesh type in Abaqus software. Mechanical properties used for designing horn and tool are shown in Table 1.

After performing modal analysis, the appropriate length of horn and tool could be achieved as 125 and 4 mm long, respectively. In fact, by modal analysis, it is possible to find

Table 1 Mechanical properties of horn and tool material

	AISI 304	AISI H13
Density (×1,000 kg/m^3)	8	7.76
Poisson's coefficient	0.29	0.29
Yang's modulus (GPa)	193	200

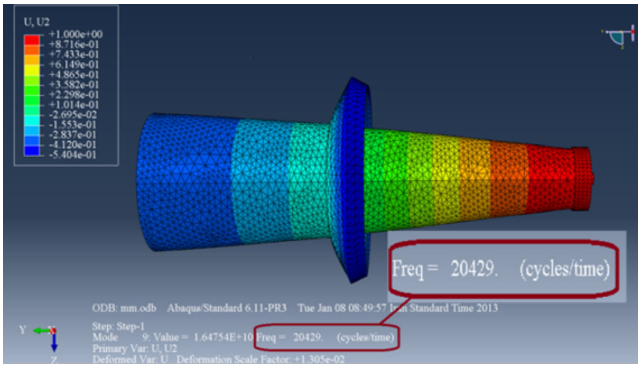


Fig. 2 Longitudinal mode shape of horn and tool in a frequency of 20,429 Hz

Table 2 UAFSW parameters

Rotary speed (rpm)	Feed speed (mm/min)			Deviation angle (°)
500	64	100	142	0
710	64	100	142	0
1,000	64	100	142	0

natural frequency of a workpiece. If FEM software is used to do this analysis, it is also possible to see the mode shape of oscillations at any natural frequency. Since, in this study, designing the horn to have appropriate natural longitudinal frequency near 20 kHz was required, this analysis was performed on horns with different dimensions to find the best design. The designed set (horn plus tool) had a longitudinal resonance frequency of 20,429 Hz. Figure 2 shows a longitudinal mode shape of horn and tool in a resonance frequency of 20,429 Hz.

After manufacturing of horn and tool with the achieved dimensions, both of them assembled with an ultrasonic transducer and connected to the ultrasonic generator for scanning its resonance frequencies (the ultrasonic generator used for experiments had the ability to scan and find natural frequencies). To find natural resonance frequency of manufactured set (horn + tool), frequency range of generator was chosen as 20–21 kHz. As shown in Fig. 3, the natural resonance frequency of the set was 20,347 Hz in reality which is near the frequency achieved by modal analysis. This negligible error (between modal analysis and practice) is because of some errors between theory and reality such as some simplifications used in modal analysis. In this study, 5 μm was selected as vibration amplitude in the UAFSW experiments.

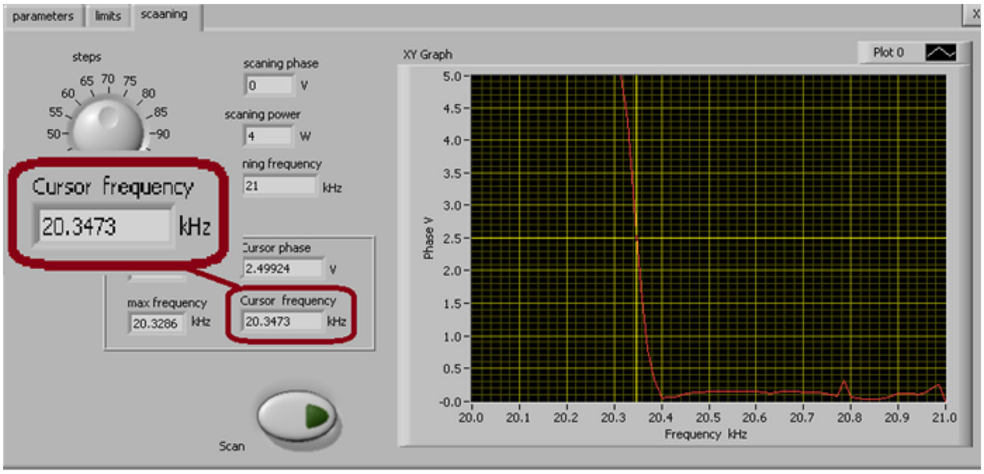
Dynamometer and workpiece fixture were clamped on the cross slide of lathe machine. By moving in longitudinal feed direction of machine, tool penetrates into work material, and then, by cross feed motion, tool moves through welding direction. Since dynamometer was sensitive to the high temperatures, fixture was manufactured with characteristic to prevent any heat transfer.

Workpieces were Al6061-T6 with dimensions of 120 mm × 60 mm × 3.5 mm. Ultimate tensile strength of workpiece is 309 MPa and microhardness is 82 HV (0.2). Half of the workpiece was welded by UAFSW, and another half was welded by FSW. Tool geometry was a conical pin with a bigger diameter of 3.5 mm, conical angle of 12°, and 3.3 mm high. Tool material was AISI H13 which was hardened as much as 52Rc. Table 2 shows experimental parameters.

Experimental equipment used for this study was the following:

- Lathe machine (TN 50A)
- Ultrasonic generator (MPI)
- Rotary connector
- Kistler dynamometer (9257B)
- Dual IR video laser thermometer (Extech VIR50)
- Material testing machine (Galdabini 25 kN)
- Microhardness tester (H1000B)

Fig. 3 Natural frequency of fabricated horn and tool in a frequency of 20,347 Hz



Cursor frequency 20.3473 kHz
scaning phase 0 V
scaning power 4 W
ning frequency 21 kHz
Cursor phase 2.49924 V
max frequency 20.3286 kHz
Cursor frequency 20.3473 kHz

Fig. 4 Specimen for tensile test

For measuring tool temperature, focal points of two laser radiances were focused on a point on tool which was located in a distance of 2 mm upper than workpiece surface. By using a thermometer, it was possible to measure temperature in a range of 50–2,200 °C with accuracy of 2.2 °C. For calibrating the system, there were some coefficients related to different materials in which aluminum coefficient was chosen.

To measure tensile strength of workpiece material and weld, specimens were cut using a wire cut machine according to ASTM E8/E8M (Fig. 4), and then, they were tested using the material testing machine with a speed of 5 mm/min. The used microhardness tester (H1000B) had an ability to measure microhardness in a scale of Vickers by applying 10–1,000 g of load with magnification of×400. For measuring microhardness, tester was placed on a section which was 1.5 mm far from the weld surface. The 200-g load was applied on the surface for 10 s. Hardness from weld surface was measured in points with a distance of 1 mm far from each other in both forward and backward directions. Figure 5 shows UAFSW setup and workpieces.

After preparation of experimental setup, some experiments with three rotary speeds and three feed speeds were performed on workpieces welded by both FSW and UAFSW. In experiments, welding forces and temperatures were measured. Figure 6 shows workpieces that were welded by FSW and UAFSW.

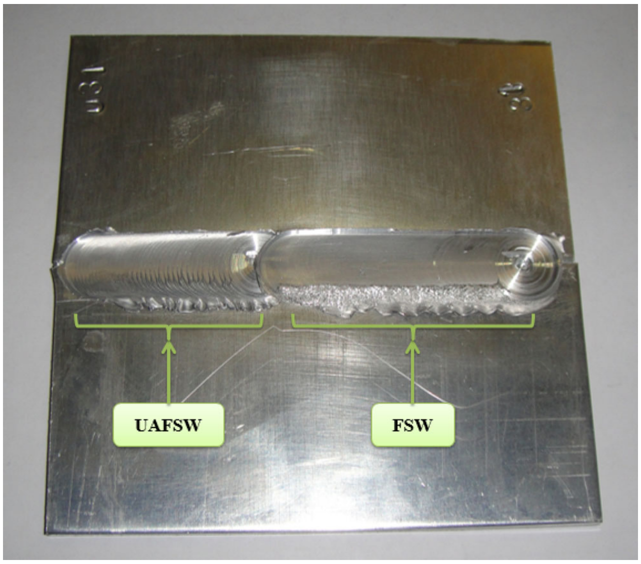


Fig. 6 Welded workpiece by FSW and UAFSW with a rotary speed of 1,000 rpm and a feed speed of 64 mm/min

3 Results and discussion

3.1 Results of force tests

Measured forces in these experiments are downward force and welding force (in feed direction). For observing the effect of ultrasonic vibrations on floating stage of the tool, data acquisition of dynamometer was adjusted on 10,000 Hz. As shown in Fig. 7, tool was put into the workpiece in floating stage, and after 15 s, ultrasonic vibrations were applied on the tool for 35 s for making sure that ultrasonic equipment works well, and vibrations will not be damped by force. When magnifying (about 0.002 s) a part of the chart where ultrasonic vibrations were applied, it can be seen that in floating stage, the tool vibrates very good.

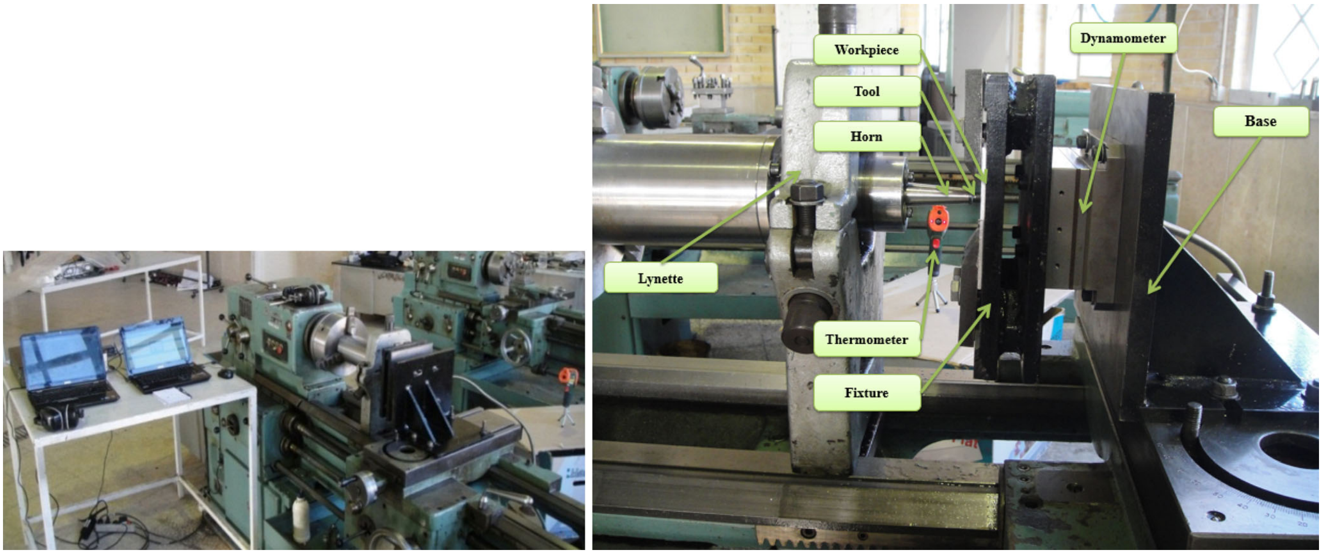


Fig. 5 Preparation of UAFSW

Fig. 7 Effect of vibrations in floating stage in UAFSW

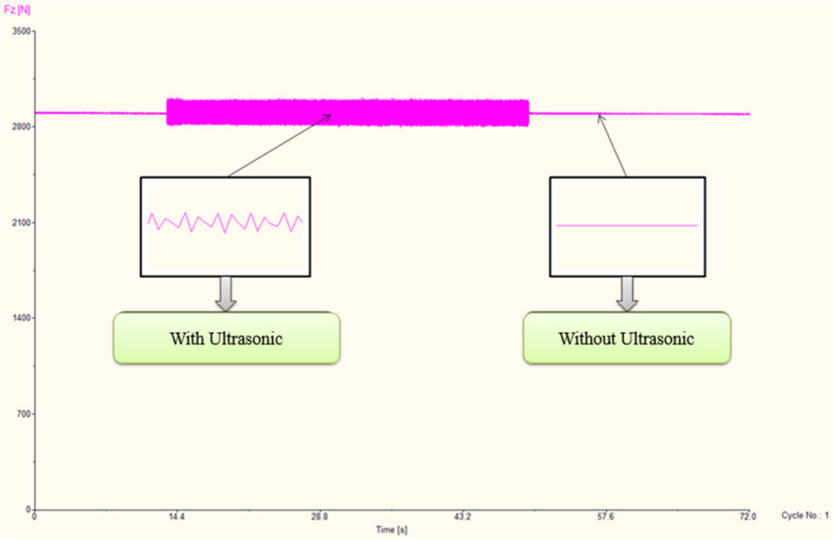


Fig. 8 Downward force in FSW and UAFSW with a rotary speed of 710 rpm and a feed speed of 142 mm/min

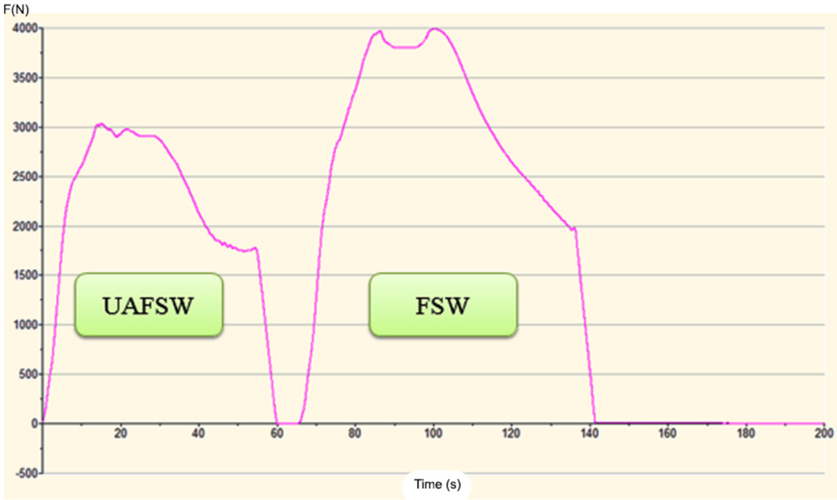


Figure 8 shows downward forces in FSW and UAFSW with a rotary speed of 710 rpm and a feed speed of 142 mm/min. It can be seen that ultrasonic vibrations can reduce downward force and improve tool penetration in floating stage in which the most force is needed in FSW.

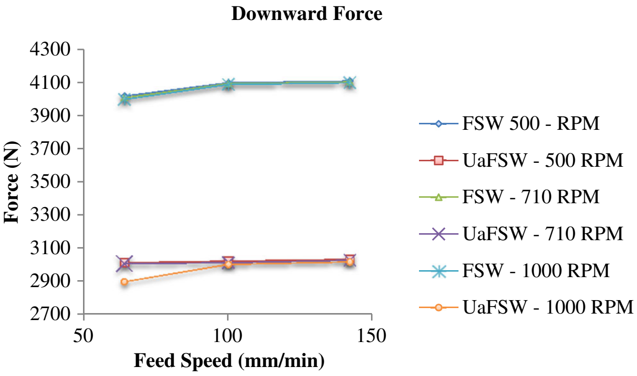


Fig. 9 Maximum downward force versus feed speed in rotary speeds for FSW and UAFSW

As shown in Fig. 8, downward force increases from penetration till shoulder reaches to the workpiece surface where first peak produced in the chart. By starting the feed motion, the second peak will be produced in the maximum value, and then, by increase of the temperature as a result of friction between rotary shoulder and workpiece surface, forces start to decrease. By adding ultrasonic vibrations to the tool in pin direction, maximum of downward force can be reduced about 25 % in FSW.

Figure 9 shows charts of the maximum downward forces versus feed speeds for three rotary speeds (500, 710, and 1,000 rpm) in FSW and UAFSW.

As shown in Fig. 9, increase of feed speed increases forces, slightly. Slope of the force increase in UAFSW is less than that in FSW. In UAFSW, longitudinal vibrations are in pin

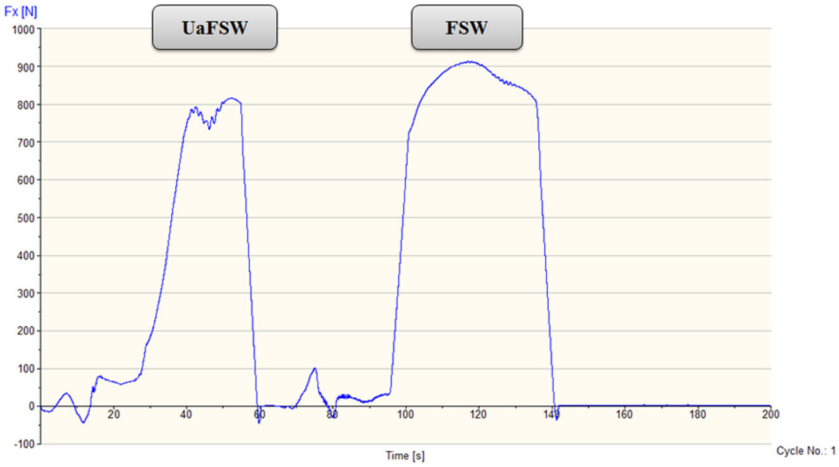


Fig. 10 welding force in FSW and UAFSW

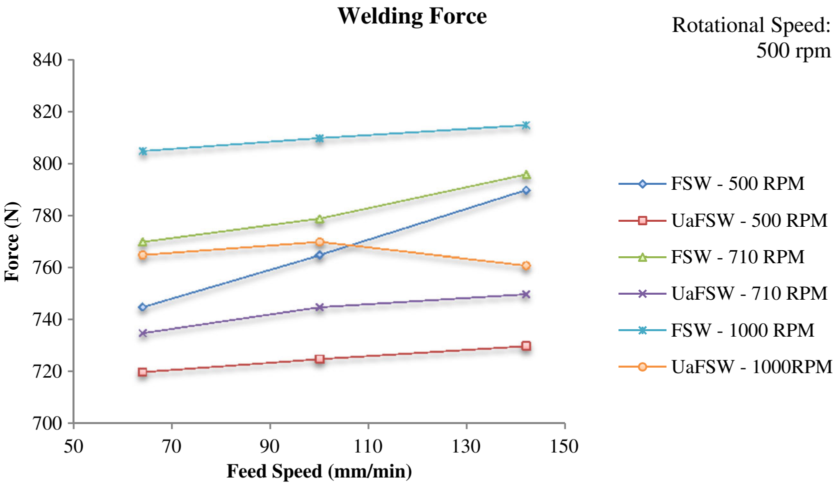


Fig. 11 Maximum welding force versus feed speed in rotary speeds of 500, 710, and 1,000 rpm

direction which can affect material movement from the front of pin toward its back and improve material movement. Another observation is that by increasing a rotary speed, downward force decreases, because by increasing a rotary speed, stirring of the material increases which raises temperature. In UAFSW, ultrasonic vibrations can increase stirring of the material more and then decreases downward force more than those in FSW.

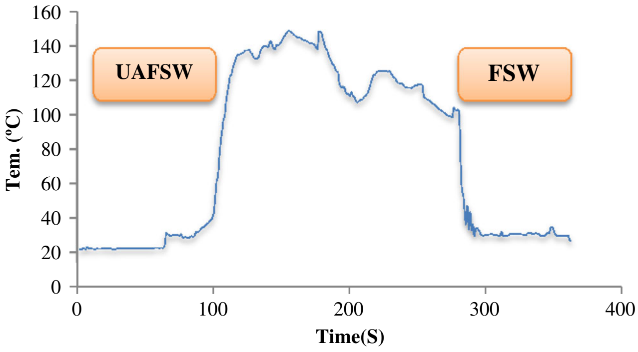


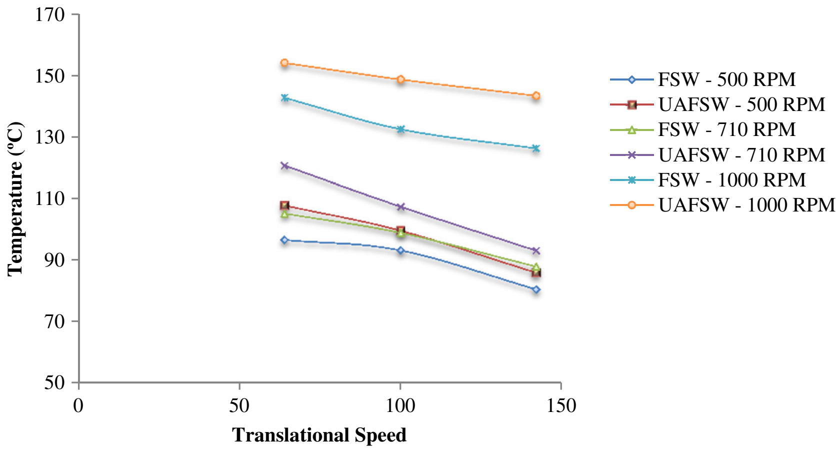
Fig. 12 Tool temperature in FSW and UAFSW in a rotary speed of 1,000 rpm and a feed speed of 100 mm/min

Figure 10 shows forces in welding direction of FSW and UAFSW for a rotary speed of 710 rpm and a feed speed of 142 mm/min. Penetration step of tool into the workpiece will not produce any force in welding direction, and the first peak is in the time of pin penetration, and force decrease happens after the first peak where shoulder connects with workpiece surface. The second peak is because of tool stop before feeding step, and then, by the start of feed motion, forces increase.

Figure 11 shows charts of maximum welding forces versus feed speed for three rotary speeds (500, 710, and 1,000 rpm) in FSW and UAFSW. During experiments, ultrasonic vibration was switched off, and process changed from FSW to UAFSW.

With an increase of rotary speed, increased slope of forces decreases with an increase of feed speed; this is because of stirring enhancement around the pin that reduces material movement from the front of pin toward its back, resulting in raising forces slightly in welding direction.

Fig. 13 Effect of feed speed on tool temperature



As shown in Fig. 11, increase of feed speed can increase welding forces for both FSW and UAFSW. It is because by increasing the feed speed, the material should move from the front of the pin toward its back faster that can cause an increase of forces. By increasing rotary speed, the slope of forces' increase with feed speed will decrease.

3.2 Results of temperature tests

In this study, the temperature of top surface of the shoulder during welding was measured. Figure 12 shows the measured temperature in FSW and UAFSW for one welding pass. In this figure, procedure of temperature increase in the ratio of the time is shown for a rotary speed of 1,000 rpm and a feed speed of 100 mm/min for both FSW and UAFSW.

As shown in Fig. 12, ultrasonic vibrations increase the temperature because they increase stirring in UAFSW more. Tool temperature was also measured in FSW and UAFSW, and maximum temperature change versus feed speed is shown in Fig. 13.

As shown in Fig. 13, by enhancing feed speed, tool temperature decreases because tool rotates less in a similar path in comparison with when feed speed is more and tool can go through the path much faster that temperature will not change drastically. By increasing rotary speed, tool temperature will increase because of friction and stirring increase.

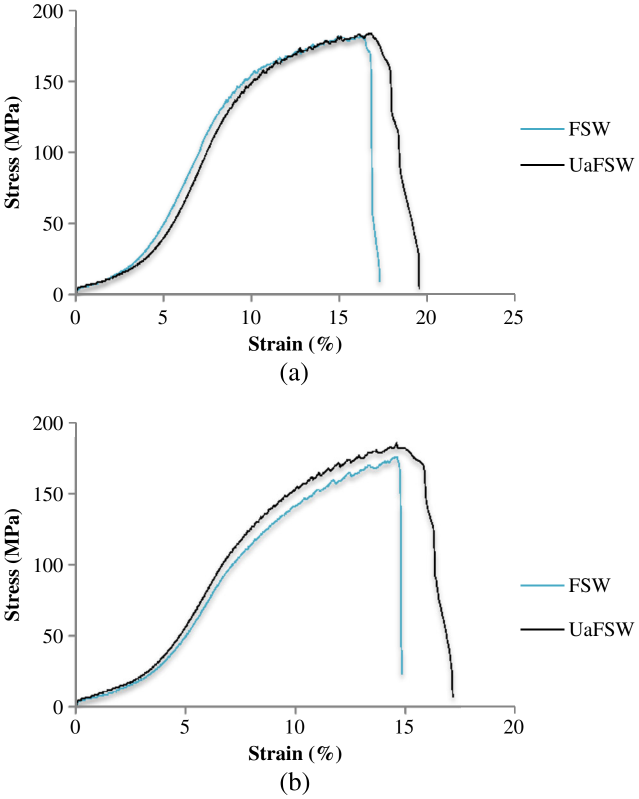
3.3 Results of strength tests

After performing experiments, the specimens were prepared according to ASTM E8/E8M (Fig. 14). Then, tests were performed using the Galdabini machine with a speed of 5 mm/min in room temperature for base material and all of welds.

Fig. 14 A sample specimen prepared for tensile test

Tensile tests were performed for welded parts produced by FSW and UAFSW with a rotary speed of 1,000 rpm and feed speeds of 64 and 100 mm/min. Figure 15 shows the charts achieved by tensile tests.

As shown in Fig. 15a, in a feed speed of 64 mm/min, ultrasonic vibrations did not have any drastic effect on strength, and they could only increase the elongation for about 10 %. However, for a feed speed of 100 mm/min (Fig. 15b),



(a)

(b)

Fig. 15 Tensile test chart in a rotary speed of 1,000 rpm at **a** 64 mm/min and **b** 100 mm/min

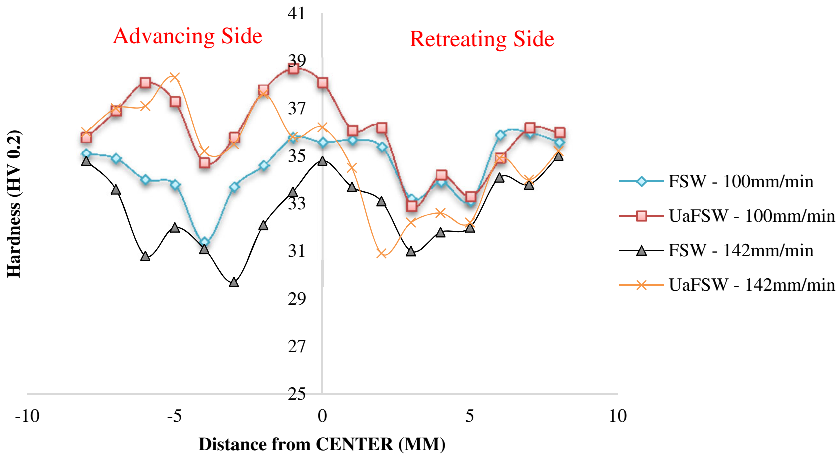


Fig. 16 Hardness distribution on cross section in a rotary speed of 1,000 rpm at 100 and 142 mm/min

ultrasonic vibrations could increase the strength and enlargement for about 10 %.

3.4 Results of microhardness tests

Microhardness tests were performed on parts welded by FSW and UAFSW with a rotary speed of 1,000 rpm and feed speeds of 100 and 142 mm/min. Figure 16 shows the profile of hardness distribution on a cross section of welded workpieces.

As shown in Fig. 16, by approaching to the weld center from both sides of welding zone, hardness decreases which is located in thermo-mechanical region, but by approaching to the stir center, hardness increases. The effect of ultrasonic vibrations on hardness is only increase of hardness in advancing path less than 10 %, and they do not have any drastic effect on retreating path.

4 Conclusion

In this study, the effect of ultrasonic vibrations (applied to pin direction) on FSW of AA6061-T6 workpieces was investigated. Studied parameters included downward force, welding force (in welding direction), temperature, strength, and microhardness, and their changes by rotary and feed speeds for both FSW and UAFSW were studied. The achieved results can be summarized as follows:

– Ultrasonic vibrations can reduce downward force about 25 % because they can improve penetration. Enhancement of feed speed increases downward force slightly, and reduction of rotary speed decreases this force.
– Ultrasonic vibrations do not have any drastic effect on welding force in feed direction, and they can reduce this force less than 10 %. Increase of feed speed increases welding force since material should move from the front of the tool toward its back, faster. By enhancing rotary speed, the slope of the force increase with feed speed increase diminishes and causes a small enlargement in welding force.
– Adding ultrasonic vibrations to FSW increases temperature because they enhance stirring. Enhancing of feed speed reduces tool temperature because tool can pass through welding path faster, but increase of rotary speed increases tool temperature since it enhances friction (between shoulder and tool) and stirring.
– Ultrasonic vibrations enhance strength and also elongation less than 10 %. Using UAFSW does not have any drastic effect on the hardness of welded parts in retreating path compared to FSW, but hardness increases about 15 % in advancing path.

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