Int J Adv Manuf Technol (2016) 84:1889–1896
DOI 10.1007/s00170-015-7834-3

ORIGINAL ARTICLE

Bending vibrational tool for friction stir welding process

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Received: 7 June 2015 / Accepted: 10 September 2015 / Published online: 22 September 2015

Abstract Beside beneficial aspects of friction stir welding such as solid-state joining process, no melting, no recasting, etc., there are some disadvantages like considerable axial forging force especially for high-strength materials. Researchers have developed several innovative ideas to diminish the process problems. In the present study, to investigate the effect of bending vibrations, an ultrasonic vibratory tool of friction stir welding, in bending mode, has been designed and manufactured. Firstly, the vibratory tool was designed for the operating resonance frequency of 20 KHz in ABAQUS software. This tool consists of transducer, horn, and welding tool. Using the optimal dimensions achieved from the modal analysis, the FSW tool has been manufactured. Then, experimental investigations verify the validity of the tool design process, such as clamping flange position, resonance frequency, and so on. The friction stir welding of aluminum Al6061 and Teflon plates has been done with lathe machine. FSW-assisted ultrasonic vibrations in bending mode show some advantages in comparing with linear mode, such as decreased tool length and increased efficiency of vibrational energy transferring to the tool tip. Finally, with respect to the indicated improvements, reduction and rise of welding forces and temperature have been observed, respectively.

Keywords Vibrations · Ultrasonic · Transducer · Welding · Friction · Bending

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Abbreviations

μ_s	Friction coefficient
F_N	Tool axial force
ξ	Amplitude
f_w	Frequency
A_{FR}	Fictional area between tool and work piece
q_{FR}	Thermal flux

1 Introduction

In 1991, friction stir welding process was invented by The Welding Institute (TWI) and introduced as a method of solid-state bounding of low melting point materials. At first, the FSW process was applied to weld aluminum plates [1, 2]. The most prominent shortage of FSW application is for heavy-duty and high-strength material such as titanium and steel alloys. The FWS process of high-strength materials in comparison with weaker materials needs more powerful and strong welding machines. Besides, reduction of tool life and consequently changing of FSW tools repeatedly raises the expenses. Dominating these problems, researchers have developed new methods to assist welding of hard materials. Using induction generated by coil in front of rotary FSW tool, to soften material, is one of them [3]. But heat concentration produced by coil in an especial area is impossible since coil heated all the nearby instruments especially the FSW tool. In other cases, fusion welding methods like LASER or PLASMA were added to help the FSW process [4, 5]. The last mentioned methods are under investigations regarding the fact that their consumptions are high and unreasonable. According to Fig. 1, an inconsumable rotary tool along with a central pin plunges into the bounding line of two sheets which is tightened by simple fixture to a backing plate. After the plunge step, the tool moves horizontally on the weld line.

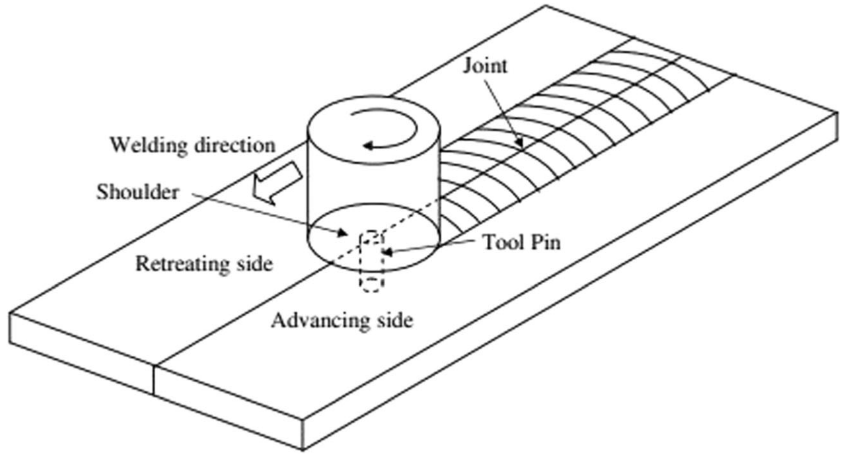

Fig. 1 Schematic of friction stir welding process

In this process, the tool shoulder acts as a thermal source, while the pin stirs the material under the tool which is softened by concentrated heat. Heat is generated by frictional work and severe plastic deformation of work piece. Combination of rotational and linear motion along the seam weld of the FSW tool causes material movement from the front to the back of the tool pin. On the other side, tool shoulder applies axial forging pressure leading to suitable weld properties.

Y. H. Zhao et.al [6] investigated the effect of pin geometry on mechanical properties and weld quality of aluminum alloys FSW. They found that pin geometry has remarkable effects on the plastic flow of materials.

Analysis of temperature distribution in FSW process is important since temperature distribution helps to understand microstructural characteristics such as grain size, grain boundary, and mechanical properties of the weld [7]. Mahoney et al. measured temperature distribution near the weld zone and showed that maximum temperature occurred near the nugget zone [8].

In addition, after the 1950s, applications of ultrasonic energy in plastic deformation of metals and alloys have been investigated comprehensively. Beneficial effects of ultrasonic vibrations especially in regard to reduction of forming force have been confirmed by several researchers. The usage of ultrasonic vibrations along with tension test of a material reduces the yield stress of that material. Also, investigations revealed that application of ultrasonic energy during the forming process reduces forming forces while it accelerates forming process and improves product quality [9]. The advantages of these effects have been confirmed in different production processes such as machining, welding, drilling, and so on [10, 11]. For example, superimposing the ultrasonic vibration-assisted machining and drilling of hard alloys, like titanium, has had desirable results [12, 13].

S. Amini et al. during their comprehensive study about ultrasonic applications such as turning, forming, and welding, they have performed the following investigations: Different pin shapes along with non-concentric pin in FSW process have been designed [14]. In this research, the axial force, temperature variations, and mechanical properties of FSW weld were studied. The results represented that the more powerful tool applied to stir material from the front to the back of the tool, the more weld strength in uniaxial tension test it had. Also in this article, results showed that FSW with tool with non-concentric pin in feed 100 mm/min and rotational speed of 1120 rpm had the best tensile strength. Besides, reduction of axial force was the other outcome of the use of tool with non-concentric pin in comparison with one that had coaxial pin and shoulder of tool. Also, the author studied the effects of the application of ultrasonic vibration in bending mode-

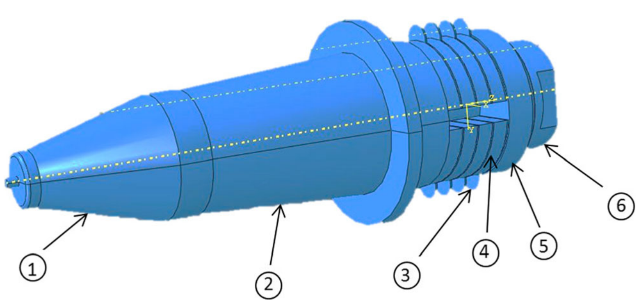

Fig. 2 The assembled model of vibrational FSW tool: *1* tool and concentrator, *2* matching, *3* cupper sheet, *4* piezoelectric pieces, *5* backing, *6* fasteners

Table 1 Material properties of different parts of FSW vibrational tool

Young's modulus (Pa)	Poisson ratio	Density (kg/m^3)	Material	Part name
207e9	0.292	7868	CK45	Fasteners (screw and nut)
207e9	0.292	7868	CK45	Backing
207e9	0.292	7868	CK45	Matching
67.4e9	0.3	7517	PZT4	Piezoelectric
120e9	0.3	8910	Cu	Cupper sheets
207e9	0.292	7868	CK45	Tool

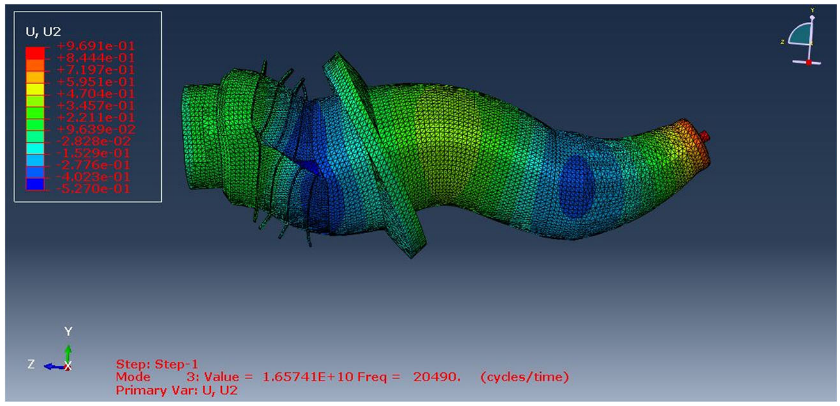

Fig. 3 Deformed model of FSW vibrating tool in bending mode

assisted turning process on surface quality, cutting force, and tool erosion [15]. The results indicated that applying ultrasonic vibration in bending mode improved surface quality and decreased cutting force and tool erosion. The other investigations about ultrasonic vibration in turning process, finite element model of turning enhanced ultrasonic vibration, and vibrational drilling could be found in references 16–18, 19, 20, and 21, 22, respectively.

Previous and last studies of S. Amini and his coworkers [23] in regard to FSW-assisted ultrasonic vibration imply the application of vibrational FSW tool in linear resonance mode. In this article, FSW process of aluminum 6061-T6 plates has been performed by turning machine and transducer was designed for working linear frequency of 20,347 Hz. Results revealed that ultrasonic vibration-assisted FSW increased temperature of weld zone and welding axial force decreased 25 %. Furthermore, in uniaxial tension tests for samples which were welded by UaFSW, 10 % increase in strength and elongation was observed. The other consequence of this research was 10 % rise in hardness of advancing weld side, while vibration had no effect on retreating side.

Vahdati et.al [24] for the first time implemented the ultrasonic vibration in incremental forming process. They designed and manufactured a vibrational forming tool. Results denoted that superimposing of linear vibration parallel to the tool axis reduced normal forming force to 23.5 and 26.3 % along the vertical and horizontal tool movement, respectively. In addition, comparing spring back coefficients in vibrational forming with forming without vibration showed that ultrasonic vibrations decreased the amount of spring back.

Park et al. studied FSW-assisted ultrasonic vibrations [25–27]. Vibrations applied to the tool along feed direction caused facile tool plunge and movement along weld line. Addition of ultrasonic vibration energy to frictional work in FSW process includes some advantages like improvement of weld quality, reduction in welding forces, and increase in tool life. In this study, horn natural frequency was chosen as the nearest amount to the working frequency of generator.

Shi et al. added ultrasonic vibrations with separate inclined ultrasonic horn (angle of 40° between the horn axis and weld line) to the aluminum plates in FSW process [28]. The horn was placed 20 mm away from the weld line, and it was designed for natural working frequency of 20 KHz with amplitude of 40 μm. Results showed that vibration has developed material plastic flow near the tool pin. Reduction of axial FSW force and improvement of weld mechanical properties are other consequences which were derived from this study.

In this research, bending vibrational FSW tool has been designed and manufactured. According to previous studies [23, 26], investigations about superimposing of linear vibrations in two directions of feed and tool axis have been studied. It seems that the use of vibrational FSW tool in bending mode helps the process via more suitable material stirring. Finally, by using equipment setup, the researches performed some of their experiments and measured temperature and welding forces.

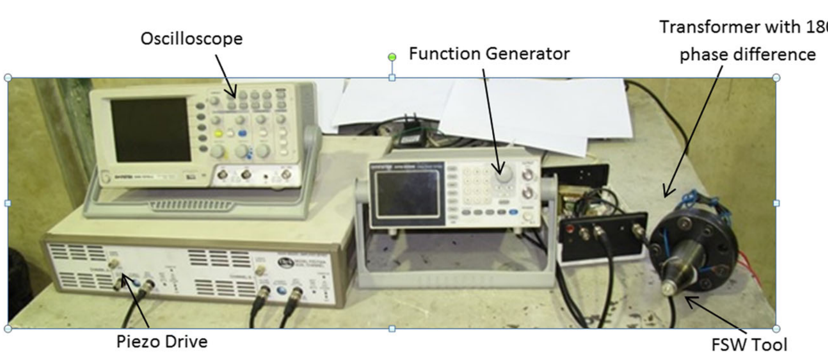

Fig. 4 Vibrational FSW tool in bending mode, attached to the piezo drive and function generator

Fig. 5 Assembled FSW vibrational tool and its flange

2 Materials and methods

In this study, ultrasonic vibrations were superimposed to the FSW tool in bending mode. It means that the tool rotates and vibrates simultaneously.

Vibrational FSW tool consists of three main parts: transducer, concentrator (horn or transmitter), and FSW tool. In order to shorten the length of the transducer, it was merged to a concentrator. At first, to obtain the exact transducer dimensions capable of working in 20 KHz (=working generator frequency), it was simulated in finite element modal analysis through ABAQUS software. The mentioned transducer consisted of steel backing, nut (which was a part of backing), eight pieces of piezoelectric in the shape of half ring, cupper sheets, and a stud bolt. Then, to achieve the best FSW tool dimensions, the whole main three parts of the vibrational tool were analyzed numerically all together.

In this process, conical geometry has been adopted for the FSW tool pin. Larger diameter, conic apex angle of tool pin, and diameter of tool shoulder were selected 3.5 mm, 12°, and 16 mm, respectively. According to Fig. 2, the total length of assembled vibrational FSW tool is 177.8 mm, and also, distance between the tool flange (=position of vibrational wave node) and the tool tip is 112.3 mm.

Fig. 6 Tool flange fixture

Fig. 7 The way of transferring electricity from the generator to the transducer

After creation of each part in part design environment of ABAQUS software, according to Table 1, material properties were allocated to each one. Tool material should be chosen sufficiently durable, hard, and erosive resistant which it could be suitable for aluminum alloys welding. Therefore, heat-treated CK45 has been selected as FSW tool material.

In assembly, environment parts were imported independently and assembled with suitable constrains. For modal analysis, in step environment, frequency analysis was adopted in the range of 18 to 24 KHz for preliminary tool model, since the best working frequency of the generator is 20 KHz. Then, in order to achieve the frequency of about 20 KHz for the whole tool model, dimensions of transducer and tool were changed. After each dimensional change, the model was submitted for numerical solution. In interaction environment, the whole attached surfaces were tied together from the end to the tip of the assembled FSW tool. Also, any model was meshed with standard-3D stress, tetra elements.

According to geometrical and mechanical specifications of FSW vibrational tool, after hundreds of iterations for model solutions, the best model with bending vibrational mode was obtained. The node (with zero amplitude) is suitable to be placed as tool fixing point (tool flange) by chuck of turning machine. On the other hand, in this model, the difference between resonance modes of frequency is large enough, in which there is no natural frequency mode except bending

Fig. 8 The vibrational FSW setup on a turning machine

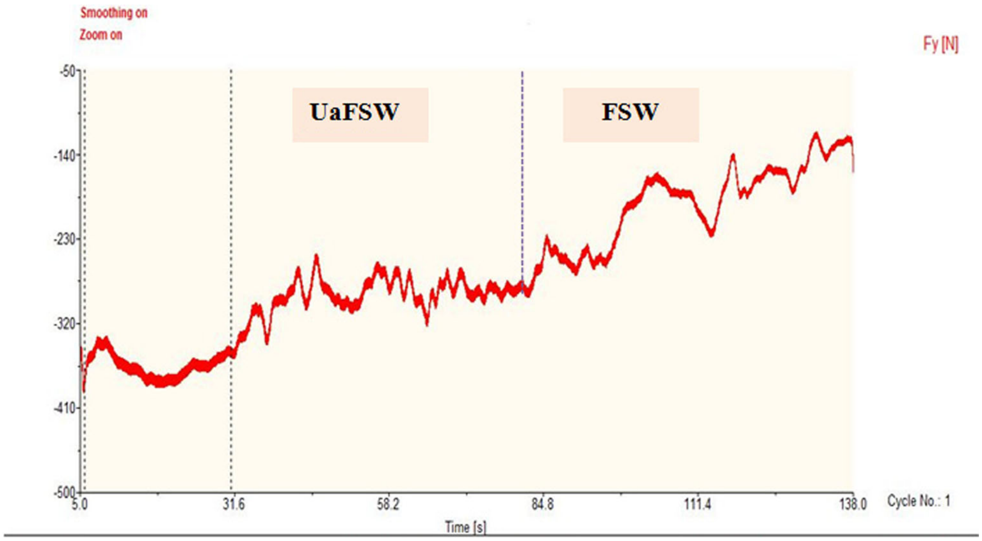

Fig. 9 Welding force on Teflon plates along feed direction with and without vibrations

mode in limit of 19 to 21 KHz. Figure 3 depicts simulated final model of FSW vibrating tool in bending mode.

As shown in Fig. 3, the natural frequency of bending mode is 20,490 Hz. The tool tip is in maximum amplitude (=antinode) and tool flange is placed in minimum amplitude (=node). Beside tool vibration, the flange of the tool is used to be fixed by chuck for rotation.

According to final numerical model dimensions, parts were manufactured and assembled. In order to obtain the real resonance frequency of tool set, piezo drive, manufactured by Treck Company, which is equipped with two output frequency channels, was used. As shown in Fig. 4, the mentioned device is capable of producing any phase difference between two outputs. To achieve bending wave source, piezoelectric pieces should be stimulated in 180° phase difference for each channel. In order for the output sinusoidal electric wave, which has been set by function generator, to be amplified and divided into two electric waves with 180° phase difference, it was entered to piezo drive. Finally with vibrational tool scan by piezo drive, the frequency of resonance in bending mode was achieved 20,100 Hz, which almost was in accordance with modal analysis in ABAQUS software.

According to Fig. 4, the bending resonance frequency could be recognized through the shape of vibrational waves by oscilloscope or function generator. The mentioned piezo drive is not capable enough to provide powerful vibrations suited for FSW application. Hence, an MPI generator with 2000-W power was replaced. The MPI generator has just one output. Therefore, to obtain two electrical waves with 180° phase difference, an especial transformer was designed and applied.

All eight piezoelectric pieces, polarized along *Z* direction, were selected, and electrical field applied to half ring piezoelectric pieces on each side had 180° phase difference. In this condition, whenever one half piezoelectric was expanded, the other half was contracted and vice versa. Frequency of these expansions and contractions was equal to the natural

Fig. 10 Welding force on aluminum 6061-T6 plates along feed direction with and without vibrations

frequency of FSW tool in bending mode. Therefore piezoelectric pieces actuated the tool in bending mode of resonance frequency. It should be mentioned that the amplitude of vibrations was set to 40 μm.

In order to rotate the whole vibrational tool, it should be fixed in chuck of turning machine just from nodes (points with almost zero amplitude). Accordingly, in tool modal analyses, flange was placed at wave node (as seen in Fig. 5).

As it was mentioned earlier, tool flange was designed so that the whole tool can be fixed in chuck at flange position. Figure 6 shows designed tool fixture, by which tool flange is held. The position of the node is just a point, regarding the fact that the tool flange has the thickness of 4.5 mm. While half of the flange thickness is in positive vibration, the other half is in negative vibration, simultaneously and vice versa. The flange must be thick enough to withstand welding forces and to be able to transfer rotational movement. Anyway, according to what is mentioned earlier, the tool flange has somewhat vibrations. These residual vibrations were damped through the use of Teflon washers at the contact faces of flange and fixture.

In order to transfer electric current from the generator to the rotating transducer, rotary connectors had been used. While one side of the connector remains stationary, the other side rotates with the tool and transfers electric current to the piezoelectric pieces. As Fig. 7 shows, the connector was placed at the end hole of turning spindle.

As the rotary connector has two outputs and the transducer needs two positive electric current with 180° phase difference, so both of the connector outputs had been connected to the positive pole. Then, the negative pole of two piezoelectric sets, which have the same phase, attached to the body of the turning machine.

3 Results and discussion

According to Fig. 8, in order to evaluate the correct performance of the FSW vibrational tool in bending mode, the tool and aluminum or Teflon samples along with dynamometer were assembled on turning machine with the model of T50 manufactured by MACHINE SAZI TABRIZ Company. The chuck rotates the FSW tool and transverse support feeds aluminum or Teflon plates by its linear movement.

As Fig. 8 shows, aluminum plates, as welding samples, were fixed in a fixture, which was assembled to the axis of turning spindle perpendicularly. Backing plate of the fixture was tightened on the dynamometer surface. The dynamometer was used to measure welding forces. Whereas longitudinal support provides tool plunging into and retracting from the work pieces at the beginning and the end of FSW process, respectively, the transverse support provides linear movement along the weld seam.

Table 2 Comparison of welding force of aluminum plates with and without vibrations

Mean weld force (N)	Welding condition
364.1	Without vibrations
289.9	With vibrations

3.1 Comparison of FSW forces with and without vibrations in bending mode on Teflon

In this experiment, force of FSW on Teflon plates was measured in feed direction. Welding parameters were selected as follow:

- Teflon plate dimensions, 120 mm × 60 mm × 8 mm
- Rotational speed, 710 rpm
- Feed rate, 142 mm/min
- Working frequency of ultrasonic wave generator, 20,100 Hz

At the beginning of this experiment, the FSW process was performed with tool vibrations in bending mode, and in the middle to the end, there was no vibration on Teflon plates. Figure 9 shows welding force of Teflon plates along feed direction throughout the experiment. As Figure 9 represents, welding force with vibrations is reduced 53.2 % in comparison with welding force without vibrations.

3.2 Comparison of FSW forces without and with vibrations in bending mode on aluminum 6061-T6

Similar to previous section, in this experiment, force of FSW on aluminum 6061-T6 plates was measured in feed direction. Welding parameters were selected as follow:

- Aluminum plate dimensions, 120 mm × 60 mm × 3.5 mm
- Rotational speed, 710 rpm

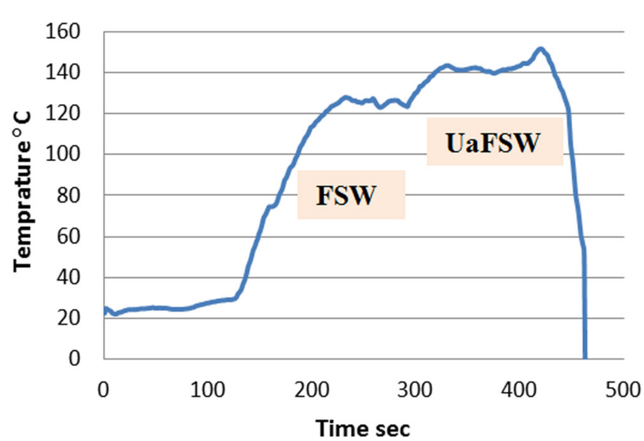

Fig. 11 Temperature variations of tool shoulder with and without bending vibrations

- Feed rate, 78.1 mm/min
- Working frequency of ultrasonic wave generator, 20, 100 Hz

Like the previous experiment, the test was begun with vibrations and finished without vibrations. Figure 10 depicts welding force of aluminum plates along feed direction throughout the experiment.

According to Fig. 10, vibrations have reduced welding force of aluminum plates likewise Teflon which was observed in the previous section.

The ultrasonic energy was added in order to have a better material stirring, also, and reduction of material strength due to vibrational forming. These are the main reasons of easier material flow from ahead to the back of the tool, and consequently as Table 2 illustrates, reduction of welding force was decreased 20.4 %.

3.3 Welding temperature with and without vibrations

During the FSW process of aluminum sheets, temperature of tool shoulder was measured. Although temperature of weld zone is higher than tool shoulder, temperature variations in tool shoulder have direct relation with temperature weld zone. Equation 1 shows that there is a direct relation between the amplitude of vibrations and FSW heat generation [29].

$$\dot{q}_{\mathrm{FR}} = \frac{\mu_{\mathrm{S}} \times F_{\mathrm{N}} \times 4 \times \xi \times f_{\mathrm{w}}}{A_{\mathrm{FR}}} \qquad (1)$$

Diagram of Fig. 11 depicts the measured temperature in an experiment with the following conditions:

- Aluminum plate dimensions, 120 mm×60 mm×3.5 mm
- Rotational speed, 710 rpm
- Feed rate, 99.4 mm/min
- Working frequency of ultrasonic wave generator, 20, 100 Hz

As Fig. 11 illustrates, superimposing of ultrasonic vibrations in FSW process causes temperature growth. Furthermore, in comparison with other hybrid processes like preheating FSW process with electrical coils which softens material [3], the application of ultrasonic energy not only reduces forging force (because it softens the material by increasing its viscoelastic properties), but also vibration increases frictional work and as a consequence enhances tool heat input toward weld area.

4 Conclusions

In this study, a novel vibrational FSW tool with bending mode was designed and manufactured. In order to produce bending wave in FSW tool body, two sets of piezoelectric pieces were used and induced with 180° phase difference. In order to validate tool performance, some experiments have been conducted. Results revealed that the use of ultrasonic vibrations in bending mode, comparing with a simple FSW tool, could improve FSW process by reducing welding forces and increasing welding temperature. Furthermore, a shorter vibrational tool length, in comparison with previous studies, brought the following benefits: (1) easier setup on turning machine, (2) lesser ultrasonic energy dissipation, and (3) transfer of ultrasonic waves to the tool tip with a higher efficiency.

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