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Research article

Effect of friction stir welding parameters of aluminum alloy tubes on succeeding rotary draw bending

Alireza Soleymanipoor[a*], Hamid Montazerolghaem[a], Mohsen Loh-Mousavi[b]

[a] *Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran*
[b] *Department of Mechanical Engineering, Khomeinishahr branch, Islamic Azad University, Khomeinishahr, Iran*

*alirezasoleymanipoor@gmail.com

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Abstract
Thin-walled aluminum alloy tubes utilized for industrial applications like aviation and car manufacturing can be produced by various processes which are mainly divided into seamless and welded tubes. The utilization of welded tubes is desired to meet the increasing need for production efficiency and flexibility in design particularly when the shape cross section is asymmetrical. In this study, the possibility of attaining the defect-free and manufacturing of friction stir welded tube of AA 6061-T6 having a wall thickness of 2.5 mm was carried out and process parameters were optimized to get a visually defect-free welded tube. In the next step, the characterization of welded tubes using rotary draw bending of the welded tubes was done. With the increase in the welding speed, the average ovality in bent tubes was decreased and with the increase in the bending speed, the ovality was decreased in rotary draw bending of friction stir welded aluminum tubes.

Keywords: Friction stir welding, Rotary draw bending, Tube manufacturing methods.

1-Introduction

During the past decades, the use of lightweight tubular components of different aluminum alloys in automotive, marine, and energy due to economic and environmental regulations has been increasing. These tubular parts of aluminum alloys are widely utilized in many vehicles as structural members due to their low density, good energy absorption capability, and low cost [1,2]. Manufacturing of the Tubular components can be classified into seamless and welded tubes. Seamless tubes are mainly produced by extrusion, which is an expensive process and is limited to tubes with small diameters and uniform cross-sections. Hence, the utilization of welded tubes is desired to meet the increasing demand for production efficiency and flexibility in design when the shape cross section is asymmetrical, as shown in Fig. 1. [3]. The fusion welding of aluminum alloys is challenging due to oxidation, solidification, shrinkage, sensitivity to cracking, hydrogen solubility, and the resultant porosity problems. Friction stir welding as a solid-state joining process involves the joining of two metal pieces at the atomic level without melting aimed at joining materials that are so-called difficult to weld or even unwieldable such as 2xxx and 6xxx series of aluminum [4,5]. To ensure the quality of the friction stir welding joints, not only the use of a proper tool but also the optimization of the welding process parameters is required. The welding process parameters that control the weld properties and defects include the rotation speed of the tool, tool traverse speed or welding speed, tool tilt angle, tool plunge depth, and tool geometry that affect the microstructure and mechanical properties of the welded joints [6].

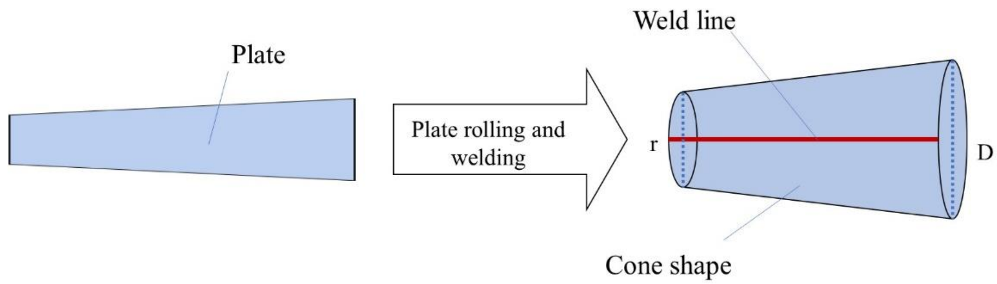

Fig. 1 Manufacturing of asymmetrical structures with rolling and welding from sheet.

Although various studies have been conducted on the friction stir welding of sheets or plates, little research has been done to perform welding on tubes or curvature. Friction stir welding of the tube is challenging due to its curved shape as well as proper clamping of curved edges of the pipe and controlling the applied forces from the rotational tool to the pipe [7]. The identification of welded tube properties is important for reliable and accurate assessment of subsequent forming processes such as tube hydroforming and rotary draw bending processes [8]. Although the tensile test is used to assess the formability and mechanical characteristics of welded tubes, its application is restricted when the joint path is not linear or when the welds are on curved surfaces.

D'Urso et al. (2013) performed friction stir welding on tubular specimens of AA6060-T6 alloy longitudinally and investigated the mechanical properties of friction stir welded tubes using tube bulge tests. The ratio between welding speed and rotational speed was the most significant parameter affecting the mechanical properties of the joints. The tube bulge test proved to be a valid method for the mechanical characterization of joints obtained by using friction stir welding techniques on non-flat parts [9]. Yuan et al. (2012) formed aluminum alloy tubes by friction stir welding and spinning. The results of bulge tests determined that as-spun tubes have higher strength and relatively low ductility among the tubes for work hardening and the residual stress compared with the uniaxial tensile properties and the weld nugget did not fail during the hydraulic bulge test [10]. Yuan et al. (2012) imposed Subsequent spinning combined with post-weld heat treatment to the friction stir welded tube and investigated the formability and microstructural stability of the friction stir welded tubes. The formability of tubes evaluated by the hydraulic bulge test improved after spinning and heat treatment [11]. Pang et al. (2014) produced a large diameter thin-walled aluminum alloy tube using a hybrid process, combining friction stir welding, spinning, and heat treatment. Rolled aluminum sheets were welded to form cylinders and subjected to spinning to get thin-walled tubes. The deformation of a friction stir welded tube during a hydraulic bulge test revealed that the tube's ductility increased with a nearly twofold greater bulge ratio than a spinning tube after annealing. But the annealed tube still showed a high nonuniform wall thickness distribution due to the inhomogeneous deformation characteristics [12]. Kim et al. (2016) stated the feasibility of curvature welding of AA 5083-O specimen. The characteristics of the friction stir welded joints were evaluated based on the deformation after the welding, tensile strength, and Vickers hardness of each test specimen. The welding results were visually satisfactory, and the joint strength was almost constant regardless of the welding speed. The joint efficiency was about 90% of that of the base material, while the elongation of the joints was about 50% of that of the base material [13]. Sen et al. (2022) attempted to weld the open cylindrical tube of AA 5083-O longitudinally by friction stir welding process. The parameter effects on the weld quality optimized to get a defect-free welded tube. X-ray, hardness, and uniaxial tensile tests of the weld zone were done to evaluate the weld quality. The joint efficiency was 87% and Failure of these samples took place in between the nugget zone and the thermo-mechanically affected zone [14].

Rotary draw bending is one of the most usual methods of tube bending that about 95% of the tube bending is done by this method [15]. Defects such as excessive wall thinning in the extrados or outside wall, wall thickening in the intrados or inner wall, cross-section ovality, and even wrinkles on intrados may arise as the result of process-induced stresses. During the bending process, wrinkling can be avoided, but cross-section ovality and wall thinning are inevitable [16]. Hassanpour et al. (2012) investigated the effect of anisotropy on tube wrinkling in rotary draw bending by simulation. By increasing normal and planar anisotropy (r0, r90), the amount of wrinkling decreased [17]. Ren et al. (2012) investigated the effect of welding line position on the outside or inside of the joint bending arc in tube bending by the finite element method. welding materials and heat-affected zone simulated and pointed out the effect of weld properties on the quality of bending, such as ovality due to differences in strain distribution are important [18]. Zhan et al. (2019) analyzed the spring back of welded tube considering the weld characteristics and variations of the weld material properties and the anisotropic parameter as well as the effect of the weld position in bending [19]. Liu et al. (2020) studied the effect of different constitutive relationships of QSTE700 rectangular welded tube on cross-sectional deformation in the rotary draw bending process and concluded that the wrinkling height of the inner flange and sidewall increases with the weld zone [20]. Cheng et al. (2022) investigated the plastic deformation behavior of welded tubes by the influence of weld line position and analyzed cross-sectional distortion and wall thickness distribution. The influence of welding line position on the shape of the bent tube was considered and the cross-sectional distortion of the welded tube was the smallest when the weld was arranged on the neutral axis of the bend. [21].

mechanical properties in the weld zone of welded tube vary from that in the parent zone and they affect the subsequent plastic forming process as well as rotary draw bending. In this study, rotary draw bending of friction stir welded tubes with the aim of characterization of friction stir welding parameters on bent tube qualities, particularly tube ovality, was experimentally studied. Firstly, the production of Friction Stir Welded tubes with visually defect-free appearance was attempted. In the next step, the characterization of welded tubes by using rotary draw bending of the welded tubes was done.

2- Tube manufacturing

2-1- Friction stir welding of tubes

The extruded and longitudinal cut tubes of aluminum alloy 6061-T6 were utilized for experiments. The chemical composition of the utilized aluminum alloy is shown in Table 1. The joint edge of the tubes was cleaned, placed in the designed fixture, and welded.

During friction stir welding operations, radial and axial forces were applied to the connecting parts which were necessary to design a high-rigidity fixture. It was also essential to have a filler mandrel inside the tube to prevent the penetration of the welding tool into the tube. In Fig. 2 the design and prepared set up to perform the welding on the milling machine table are shown. The fixture and mandrel were designed and produced according to the length, outside, and inside diameter (250 mm, 25mm, and 20mm respectively) of the tubes. The designed fixture consists of two symmetrical pieces that constrain the aluminum tube through clamp force (vice).

Table 1: Chemical composition of AA 6061.

Element	Si	Fe	Cu	Mn	Mg	Zn	Cr	Al
Weight %	0.66	0.70	0.26	0.12	0.82	0.11	0.19	Bal.

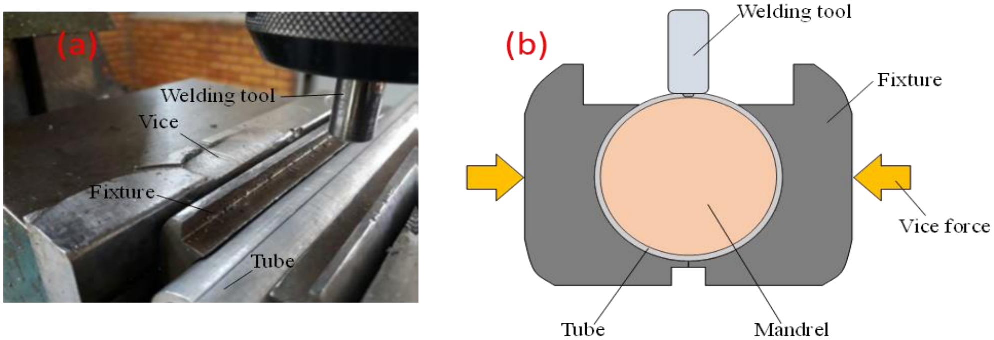

Fig. 2 (a) Friction stir welding set up, (b) schematic of welding set up.

To perform welding, a universal milling machine provides rotational speeds from 28 to 1300 rpm as well as travel speeds from 12 to 375 mm/min utilized. Rigid, high abrasion and heat resistance tungsten carbide with 82 HRC was used to produce the tool. The specification of the tool is given in Fig. 3. The tool was modified and optimized by experimental welding tests and the visually defect-free weld was gained by this tool. All welding was performed with different rotational speeds from 630 to 1050 rpm and welding speeds from 12 to 69 mm/min by applying 0° and 2° tilt angles to the tool. The welding parameters performed on the specimens are shown in table 2. The design of welding parameters was based on the as-welded visually defect-free welds such as no flash and no visual cavity or groove-like defects by experiments.

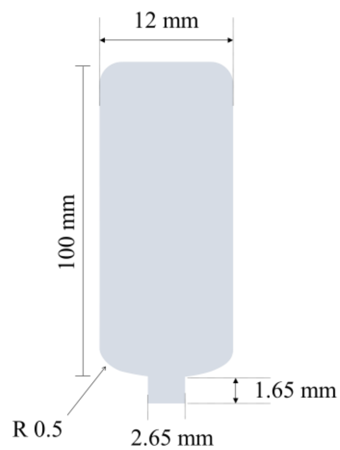

Fig. 3 Designed friction stir welding tool.

Table 2: Friction stir welding parameters.

Weld Experiment number	Tool rotational speed (rpm)	Welding Speed (mm/min)	Tilt angle (degree)
1	630	20	2
2	675	20	2
3	845	20	2
4	1050	20	2
5	1050	20	0
6	1050	12	2
7	1050	42	2
8	1050	69	2

2-2- Results of friction stir welding on tubes

2-2-1- Visual inspection of the welds

After performing the initial welding tests on the tubes, by considering the appearance of the welds, the welding tool was modified. By utilization of this tool and 0° tilt angle, the weld shape with discontinuity and visual cavities occurred. By application of a 2° tilt angle in the range of different rotational tool speeds from 675 to 1050 rpm and different welding speed ranges from 12 to 69 mm/min, continuous and defect-free welding shapes were generated. A 2° tilt angle was applied to the tool which led to soft and visually defect-free welds as well as applied more pressure from the tool to the workpiece and better transfer of materials from the front to the back of the tool. In welding with the rotational speed of 630 rpm, although the welding tool was optimized, weld cavity defect occurred due to low rotational speed as well as lack of sufficient heat generation in the weld line [22]. The results of different welding parameters are illustrated in Table. 3.

Table 3: The appearance of weld with different welding parameters.

Welding parameters	The appearance of the weld	Appearance quality
Rotational speed:1050 rpm, welding speed:12 mm/min, tilt angle:0°		Rejected, porosity on the surface
Rotational speed:1050 rpm, welding speed:20 mm/min (same 12, 42, and 69 mm/min), tilt angle:2°		Accepted, sound joint
Rotational speed: 845 rpm, welding speed:12 mm/min, tilt angle:2°		Accepted, sound joint
Rotational speed:675 rpm, welding speed:12 mm/min, tilt angle:2°		Accepted, sound joint
Rotational speed:630 rpm, welding speed:12 mm/min, tilt angle:2°		Rejected, lack of bonding

2-2-2- Weld cross-section microhardness test results

During friction stir welding, the material undergoes rough deformation at a relatively high temperature that causes changes in the welding regions. The hardness distribution across the middle surface cross-section of different welding zones with the rotational speed of 1050 rpm and welding speeds of 12 to 69 mm/min is shown in Fig. 4. The Vickers microhardness test with load of 98.07 Nm and dwell time of 15 seconds was conducted as per ASTM-E92-17. The hardness curves presented asymmetrical distribution concerning the weld centerline, on the other hand, the advanced side and retreating side showed different hardness distributions as well as different plastic flow [23]. The minimum hardness was obtained in the HAZ region, and the maximum value was presented in the BM. With the increase in the welding speed, the reduction rate in hardness of different regions of the weld decreased, on the other hand with the increase in welding speed, the heat generated during friction stir welding decreased and affected the hardness differently [24].

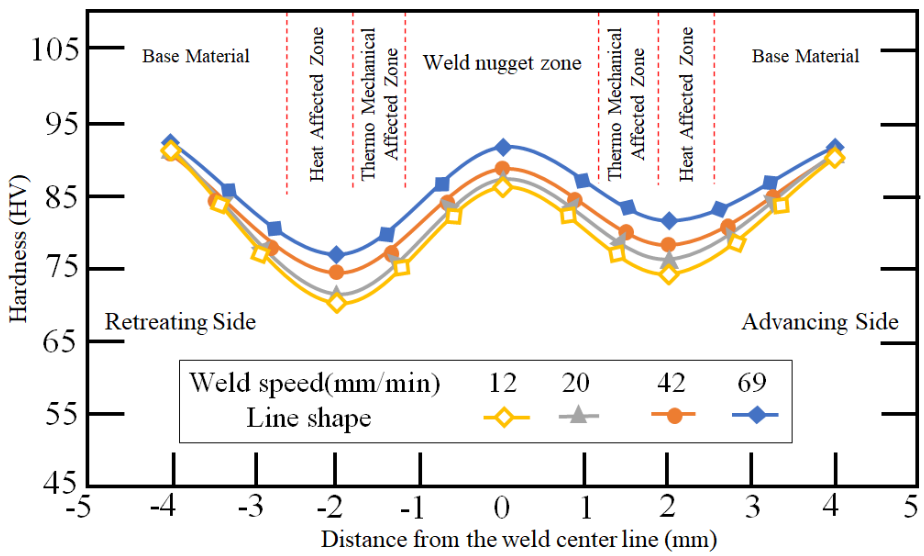

Fig. 4 Vickers hardness distribution of different traveling speeds at 1050 rpm.

3- Tube bending

3-1- Rotary draw bending of tubes

A rotary draw bending operation was performed on a subset of the friction stir welded tubes that were previously addressed (welded tubes with rotating speeds of 1050 rpm and welding speeds of 12, 20, 42, and 69 mm/min). The rotary draw bending machine made by ShuzTung company with the ability to adjust the feeding speed of the pressure die from 4 to 15 mm/s, the rotational speed of the bending die of 0.05 to 0.30 rad/sec was utilized. A simple plug hemispherical mandrel with dimensions of 100 mm in length and 19 mm in diameter was employed, along with a bending die radius of 35 mm. In tube bending, to evaluate the quality of welded tubes and characterization of the weld line position on subsequent bending quality, the weld line of the tubes was arranged on pressure, tension, and neutral bending axis, and finally the bending operation was performed. Bending experiments of welded tubes with different weld line positions are shown in Fig. 5. In the next step, the welded tubes with the same welding parameters were bent at different bending speeds. The performed bending parameters are shown in Table 4.

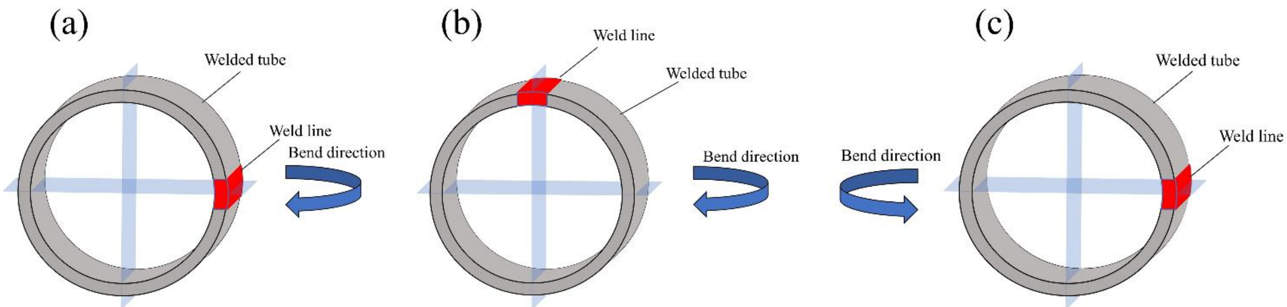

Fig. 5 Bending experiment of welded tubes with different weld line positions: (a) weld line in tension-(b) weld line in neutral axis- (c) weld line in compression.

Table 4: Performed bending parameters.

<table>
<tr><th colspan="2">Pipe Properties</th><th colspan="5">Bending Parameters</th></tr>
<tr><th>Weld Rotational Speed(rpm)</th><th>Traverse Speed (mm/sec)</th><th>Weld line position in bend</th><th>Pressure die speed (mm/sec)</th><th>Bending die rotational speed (rad/sec)</th><th>Bend angle (degree)</th><th>Bend radius (mm)</th></tr>
<tr><td rowspan="10">1050</td><td>12</td><td rowspan="4">Compression-tension- neutral bending axis</td><td rowspan="4">4.5</td><td rowspan="4">0.08</td><td>30</td><td rowspan="10">35</td></tr>
<tr><td>20</td><td>90</td></tr>
<tr><td>42</td><td>150</td></tr>
<tr><td>69</td><td>180</td></tr>
<tr><td rowspan="6">42</td><td rowspan="6">Compression</td><td rowspan="3">9.5</td><td rowspan="3">0.17</td><td>30</td></tr>
<tr><td>90</td></tr>
<tr><td>150</td></tr>
<tr><td rowspan="3">14.5</td><td rowspan="3">0.26</td><td>30</td></tr>
<tr><td>90</td></tr>
<tr><td>150</td></tr>
</table>

3-2- Results of rotary draw bending of tubes

After rotary draw bending of the tubes, neither rupture of the outer wall (extrados), nor wrinkle of the inner wall (intrados) occurred. The use of suitable mandrels and wiper dies played an essential role in the prevention of wrinkles in the inner wall. The bent tubes are shown in Fig. 6. To investigate the quality of the bent tubes, in addition to visual inspection, the parameter of ovality or non-circularity of the bent tubes was calculated. cross-section ovality $\boldsymbol{\psi}$ is defined using equation 1, where D_{max} is the maximum tube diameter after bending and D_{min} is the minimum tube diameter after bending.

$$\psi = \frac{D_{max} - D_{min}}{(D_{max} + D_{min})/2} \qquad (1)$$

The geometry of the bent tube before and after the bending process is shown in Fig.7.

Fig. 6 The bent tubes with different bending angles: (a) 30°- (b) 90°- (c) 150°- (d) 180°

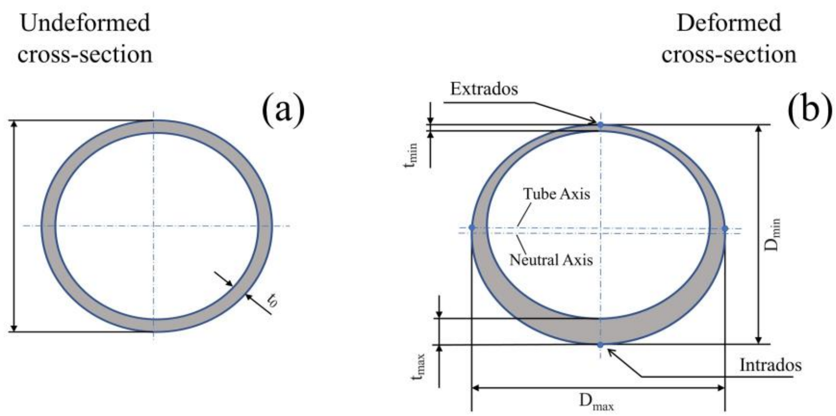

Fig. 7 Geometry of the tube: (a) before bending- (b) after bending

To interpret the results, they are plotted in Figs. 8 and 9. In Fig. 8 The relationship between welding speeds and cross-section ovality in different welding line positions is illustrated. With the increase in the welding speed, the average ovality in bent tubes decreased. On the other hand, as the structure of the weld was aligned with the base metal gradually (based on Fig. 4), effect of weld line position i.e., being in tension, compression, or neutral axis, did not have a noticeable effect on the cross-section ovality. In the same welding speed, the most significant difference in the cross-section ovality was 1.44% in the welding speed of 12 mm/min and in the welding speed of 20, 42, and 69 mm/min was 0.65%, 0.42%, and 0.29% respectively. The relationship between bending angle and cross-section ovality at different bending speeds is illustrated in Fig. 9. As the bending speed increased, the ovality of bent tubes decreased. The strength of the tube increased with an increase in bending speed due to the sensitivity of plastic deformation to strain rate, which has a direct effect on ovality in the result. Moreover, the usefulness of a proper mandrel, such as a hemispherical mandrel in rotary draw bending, in eliminating and controlling cross-section ovality has been proven in the references. Bending without a mandrel can cause the cross-section to collapse because the tube lacks support. As a result, the degree of cross-section ovality is the highest. On the other hand, bending with a mandrel results in relatively small degrees of cross-section ovality due to the support provided. The degree of cross-section ovality is relative to the support area of the mandrel, with larger contact areas resulting in smaller degrees of ovality. The contact area between the mandrel and the tube, from largest to smallest, are the hemispherical mandrel, ball-and-socket mandrel, and cylindrical mandrel. The larger the contact area, the larger the friction force that reduces the slide of the inner wall of the tube on the mandrel, thus reducing the ovality of the tubes[25,26].

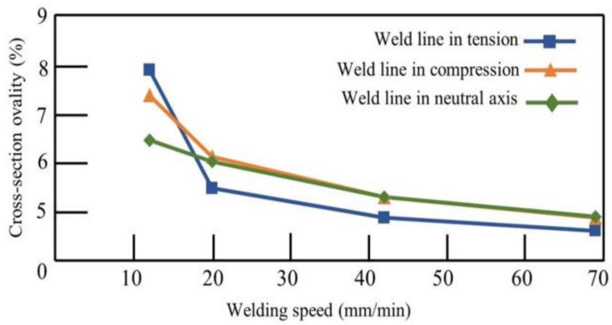

Fig. 8 Relation between welding speed and cross-section ovality in different welding line positions.

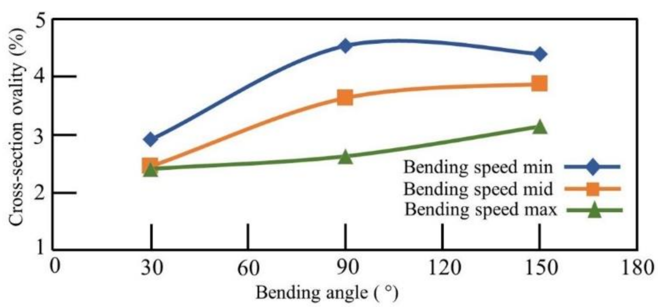

Fig. 9 Relation between bending angle and cross-section ovality in different bending speeds.

4- Conclusion

In this research, rotary draw bending operations on friction stir welded tubes of AA 6061 with 2.5 mm in wall thickness and 25 mm in diameter were performed. To investigate the effect of welding and bending parameters on the final quality of the formed tubes, different experiments were performed. The following results were obtained:

1- Friction stir welding with the tool in shoulder diameter of 12 mm, pin height of 1.65 mm with rotational speeds of 1050 rpm, and welding speeds from 12 to 69 mm/min with the 2-degree tilt angle of the tool produced visually defect-free weld.

2- The results of the weld cross-section microhardness test showed that the welded tubes had different hardness profiles, which varied with different rotational speeds. Moreover, an increase in welding speed reduced the heat generated during friction stir welding, leading to different effects on the hardness. Specifically, less heat generated during welding resulted in fewer changes in the microstructures of the weld line, resulting in a more uniform and homogeneous structure that closely resembled the base material.

3- After the bending operation, the ovality of the bent tubes decreased as the welding speed increased. Regardless of whether the weld line position was in the tension, compression, or neutral axis, the difference in the cross-section ovality of the tubes reduced as the structure of the weld gradually aligned with the base metal. The average tube ovality was measured to be 7.43%, 5.89%, 5.17%, and 4.80% at welding speeds of 12, 20, 49, and 69 mm/min, respectively.

4- After the bending operation, the ovality of the bent tubes increased with an increase in bending angle and decreased with an increase in bending speed. On the other hand, a greater bending angle put more strain on the tubes, which enhanced ovality.

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