Effect Of Orbital Friction Crush Welding Parameters On Aluminum Tubes

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Abstract: Orbital friction crush welding (OFCW) is a new solid-state welding technology addressed to join thin metal tubes without melting of the base metal. In this study, the base metal of the joints was commercial aluminum from the same grade which defined by the outside diameter 60 mm and tube thickness of 3 mm. The tube edges are prepared to flange by a simple spinning tool on the welding side. Three OFCW tools are used to investigate the effect of tool profile on the heat generation and mechanical properties of welded joints. The experimental works array was designed using Taguchi method. The results of several working conditions are discussed and presented.

Keyword: Solid-state welding, friction crush welding, orbital friction crush welding, welding strength, Aluminum tubes, relative motion of the tool, Taguchi method

1 INTRODUCTION

Friction welding process one of common solid-state welding processes used to join applications of metals such as solid bars, plates, sheets, and tubes. The theory of friction welding is based on the conversion of mechanical energy, whether rotational or linear to heat energy [1]. In friction welding, the relative motion of the tool usually used for joining thin thicknesses which difficult to weld it by other friction welding techniques [2]. The relative motion of the tool contains two main welding techniques; friction stir welding (FSW) and friction crush welding (FCW) [3]. FSW has been used since 1991 as a patent in the welding institute (TWI) for joining aluminum and its alloys [4]. The concept of FSW is a non-consumable cylindrical tool includes two basic parts shoulder and probe. FSW able to weld thin similar and dissimilar metals in addition; welding different thicknesses [4], [5]. The second category of relative motion of the tool is FCW. The concept of FCW process is simple, where a non-consumable rotating tool have a disk geometry with a specific groove used to crush a certain volume of base metal [3], [6]. The first implementation of FCW in 2016 for joining similar common sheet metals of aluminum, copper, and steel. The edges of the workpieces prepared usually to flange by any simple forming process. The previous investigations indicated similar thin metals able to join by FCW technique. Welding parameters of the relative motion of the tool have clear effect on the welding quality. Several works were discussed and presented the influence of FSW parameters on the microstructure and mechanical properties of different welded joints [4], [7]–[10]. Since the process of FCW is modern (i.e. does not exceed a few years), the previous works discussed the concept and accept of FCW technique for joining similar metals but it have limitation for discussed the effect of the welding tool geometry on the heat generation or on the mechanical properties of the welded joints.

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Welding of pipes and tubes is one of the most important issue which widely used for structural purposes and transport liquids or gases. A lot of investigations applied conventional friction welding for joining tube with tube, tube with solid bar, and tube with sheet or plate [11]–[13]. Although many previous studies have discussed conventional friction welding for joining pipes, it limited to produce complete product because machining operations are needed to remove internal and external flash defect. In addition to the above; conventional friction welding incompatible with thin wall thicknesses of tubes or pipes. In relative motion of the tool; FSW used to joining thin tubes or pipes to avoid conventional method defect, but it need filler metal in the keyhole after the friction stir tool eject. In this paper, a new attempt to produce welded joints by a new welding technique called orbital friction crush welding (OFCW) on one step without internal flash. Many experimental works (a large array) used to investigate the effect of the friction crush welding parameters on the welding strength. Three welding parameters are considered namely the tool profile, the rotation speed, and the flange ratio. Temperature are measured during the welding process by digital thermocouple type (K). The relation between welding parameters are discussed and presented.

2 EXPERIMENTAL WORK

2.1 Tool profile

The friction welding tool is the only source of the heat generation in the relative motion of the tool, therefore the OFCW tool designed with a large contact surface with the workpieces. Three tool profiles are designed for crushing and heating the base metal flanges namely, V-profile (A), Isosceles trapezoid profile (B), and Concave profile (C) as illustrated in figure (1). The tools made from rolled steel which is one of the common materials used in friction welding tools due to high material strength and low material wear.

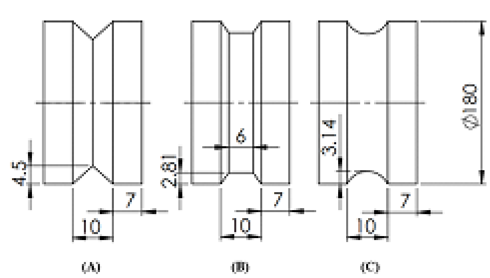


***Fig.** (1) Different shapes in the tool profile design; (A) V-profile, (B) Isosceles trapezoid profile, and (C) Concave profile*

2.2 Crushing material
The joints prepared and formed to flanges by a simple spinning tool. The height of flanges (i.e. add crushing material) depending on the total sum of gap volume and profile volume as shown in figure (2).

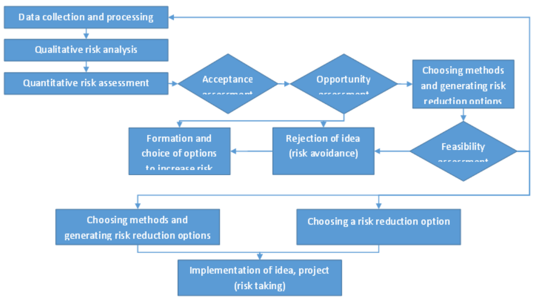


***Fig. (2)** Joint design in orbital friction crush welding with V-profile*

The general law of volume provides on the total volume before deformation equal the total volume after deformation. The theory of add flanges height to crush it by using handling calculation as follow;

$$V_{profile} + V_{Gap} = 2 * V_{Flange} \quad (1)$$

Both profile volume and gap volume easy to calculate actual values by any engineering drawing software such as SolidWorks, Autodesk Inventor, etc.

$$V_{Flanges} = 2 * Area * thickness \quad (2)$$

$$V_{Flanges} = 2 * \left[\frac{\pi\, D_{Flange}^2}{4} - \frac{\pi D_{out}^2}{4}\right] * t$$
$$V_{Flanges} = \frac{2\pi t}{4}\left[D_{Flange}^2 - D_{out}^2\right] \quad (3)$$

$$D_{Flange} = \sqrt{\frac{4 * V_{Flanges}}{2\pi t} + D_{out}^2} \quad (4)$$

2.3 Material Properties and welding conditions
The base metal used in this investigation was commercial aluminum tube. The tubes have 3 mm wall thick and 60 mm outer diameter. The chemical compositions and mechanical properties of this material are reported in table (1) and table (2) respectively.

***Table (1)** Chemical composition (wt %) of commercial aluminum alloys*

Fe	Si	Mg	Cr	Zn	Ti	Ni	Cu	Mn	Sn	Pb	V	Co	Al
1.32	0.475	0.433	0.147	0.115	0.101	0.077	0.067	0.058	0.029	0.024	0.012	0.01	Balance

***Table (2)** Mechanical properties of aluminum alloy*

Aluminum	0.2% Yield stress (MPa)	True UTS (MPa)	Elong. %	n	K (MPa)	HV
Before annealing	224	245	11.7	0.12	334	78
After annealing	81	118	31.1	0.17	150	41

Aluminum tubes were machined to 150 mm in length and the end of one side formed to flange by simple spinning forming tool at room temperature (cold working) or slightly above. The ratio between flange diameter and outside diameter of the tube called the flange ratio. The flanges are formed in different diagonal proportions 1.25, 1.35, and 1.45. The specimens placed against each other with constant gap then fixed on a cylindrical mandrel by bolts as shown in figure (3). A continues drive machine (lathe machine) have a motor power 13KW used to rotate the mandrel by 630, 800, and 1000 rpm. External motor 3KW was used to rotate the welding tool against the direction of the mandrel. Three tool profiles (A), (B), and (C) were used to Manufacture the weldments. Experiments are designed by Taguchi array L27 (33) as shown in table (3). The temperature was measured during the welding process using thermocouple type (K). Digital multimeter connected to the thermocouple wire parties to get the values of the temperature directly. The thermocouple was calibrated in boiled oil to eliminate the measuring error.

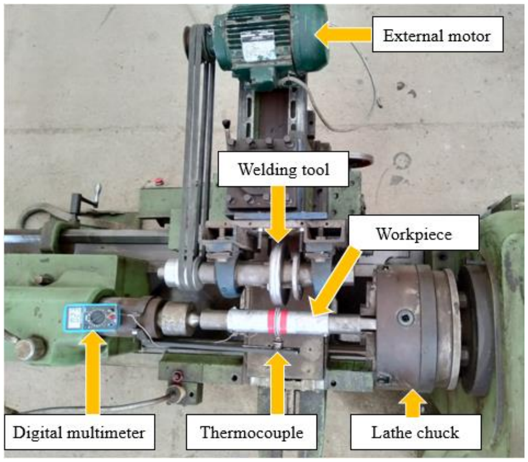


***Fig. (3)** Orbital friction crush welding setup*

***Table (3)** Control factors and different levels*

Factor	Control factor	Level 1	Level 2	Level 3
I	Rotation speed (rpm)	630	800	1000
II	Flange ratio	1.25	1.35	1.45
III	Tool profile	A	B	C

3 RESULTS AND DISCUSSION

3.1 Characteristics of base metal
Considering table (2), that shows the results of average both of tensile tests and Vickers microhardness tests before and after annealing. The characteristics of base metal after annealing process become more suited for formability for instance; the proof stress, the ultimate tensile strength (UTS), the strength coefficient (K), and Vickers hardness number (HV) are decreased. In contrast, the Elongation and the strain-hardening exponent (n) are increased.

3.2 Temperature observation during the welding process
Temperatures of welded specimens were measured at different combination parameters (rotational speeds, flange ratios, and welding tool profiles) refers to Taguchi array L27 (33). The peak temperatures measured during the welding process are recorded then classified according to the welding

tool profile. Figure (4) depicts the change in the measured temperatures using the tool profile (A), where the temperature was recorded from 178℃ to 248℃. At rotation speed 630 rpm, the temperature indicated that the flange ratio is an important parameter which increase the welding temperature approximately 45℃ from flange ratio 1.25 to 1.45. the difference in temperature reduced markedly with increasing the rotation speed. The highest value of the welding temperature recorded using profile (A) it does not exceed 37.6% from the melting temperature of aluminum 660℃. Figure (5) is shown the temperatures measured using the profile (B). The welding temperature started from 157℃ to 249℃. The peak temperature in this case up to 37.7% from the melting point. Although there is a difference in the tool design between the profile (A) and the profile (B) with the surface of the workpiece, the maximum temperature does not exceed 38% in each of them. The last group of temperature measurements using the profile (C) as shown in the figure (6). The minimum temperature recorded 161℃ at 630 rpm then reached to 274℃ at 1000 rpm. The peak temperature value up to 41.5% compared to the melting temperature of base metal.

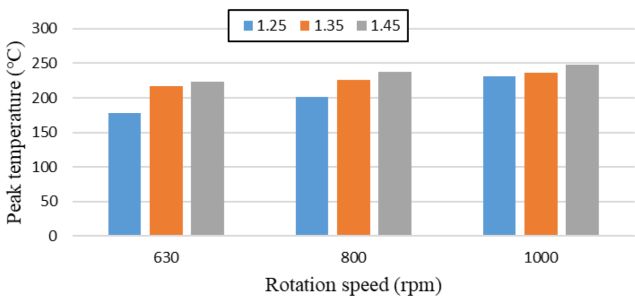


Fig. (4) *Effect of welding parameters on the temperature generated by using profile (A)*

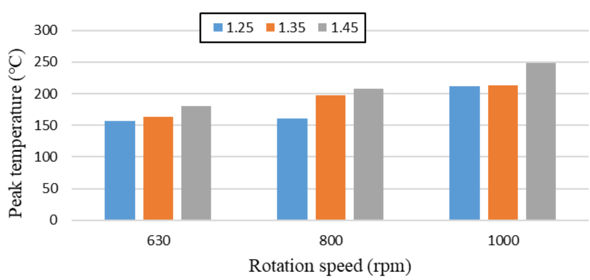


Fig. (5) *Effect of welding parameters on the temperature generated by using profile (B)*

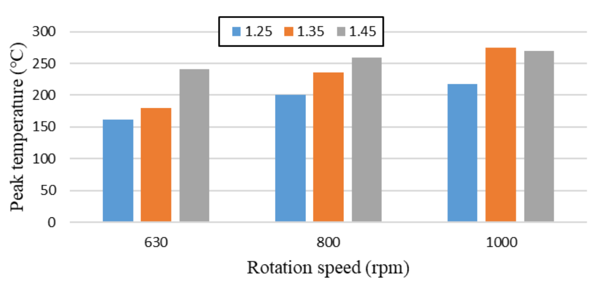


Fig. (6) *Effect of welding parameters on the temperature generated by using profile (C)*

3.3 Effect of welding parameters on the welding strength

Tensile test was performed on the welded joints at different welding parameters, which showed the maximum tensile strength of the welded joints. The maximum tensile strength reached to 26.5 MPa at the rotational speed 1000 rpm. We also noticed that the tensile strength decreases with a decrease in rotational speed, where 17.7 MPa was recorded at the rotational speed 800 rpm. These above values are relatively small compared to the tensile strength of the original metal because the rotation speed of the lathe machine was limited. Figure (7) is shown the shape of the welded samples before and after the tensile test. The fracture location of the specimens indicated that there are some layers of the base metal bonded together during friction crush welding.

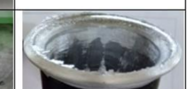
Welding conditions		Before tensile test	After tensile test
rpm	Flange ratio		
1000	1.25		
800	1.25		
630	1.25		

Fig. (7) *Effect of welding parameters on the fracture shape*

3.4 Validation

Analysis of data was conducted using Taguchi experimental design to study and develop the outcome of control parameters. The Taguchi method for three factors with three levels was used to design the orthogonal array. The experiments Analysis were made based on L27 (33) using MINITAB software version 18. Figure (8) presents the influence of the welding parameters on the peak temperature measured during the welding process. The main effect parameters respectively are the flange ratio, the rotation speed, finally the tool profile.

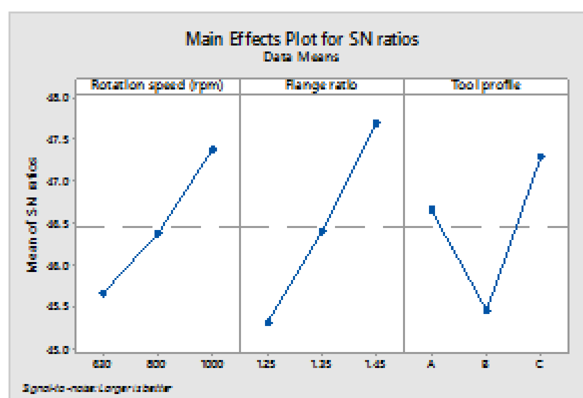


Fig. (8) *Main effects plot for the working condition on the welding temperature*

4. CONCLUSIONS

In this work, aluminum tubes are welded by new welding technique called orbital friction crush welding (OFCW) as a development of friction crush welding addressed to join thin metal tubes. Temperature, welding strength, and microhardness are measured to evaluate the welding strength. Several important conclusions in this study are emerged:

- The welding temperature is an important response to evaluate the welding penetration comparison with the melting temperature of the base metal.
- Welding strength increase with increasing the rotational speed, which was limited, this led to a decrease in the efficiency of welded joints.
- Signal to noise ratio (S/N) used to show the influence of welding parameters on the welding temperature to classified and identify the main welding parameters effects on the welding strength.

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