

## Microstructure and Mechanical Properties of Friction Crush Welded Joints of Oxygen-Free Copper (C1020) Sheets

Abduljabbar S. Joma<sup>1,\*</sup>, Akeel D. Subhi<sup>1</sup>, Fadhil A. Hashim<sup>2</sup>

<sup>1</sup>Department of production Engineering and Metallurgy, University of Technology, Baghdad-Iraq

<sup>2</sup>Department of Materials Engineering, University of Technology, Baghdad-Iraq

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### ABSTRACT

Friction crush welding application (FCW) provides versatile applications in sheet metals welding. In this work, different tool rotational speeds (220, 410, 920, 1500 rpm) and feed rates (20, 43, 80, 150 mm/min) were used to weld oxygen-free copper sheets with flanged edges. Evaluation of Cu-Cu joints was performed successfully using optical microscope, vickers hardness and tensile test. The results showed that the microstructure was significantly influenced by welding parameters used. Different defects were recognized in the welding zone. The highest hardness of 63 HV and tensile strength of 105 MPa were obtained at tool rotational speed of 1500 rpm and feed rate of 115 mm/min.

## 1. Introduction

Friction welding is used for joining metals and alloys in a solid state where the resulting heat is responsible for welding due to a relative movement between two components under pressure. Conventional friction welding processes such as rotary, linear, and orbital friction welding are categorized according to the nature of the movement relative to their interfaces. Friction stir and crush welding processes are other group of friction welding categorized according to the relative motion between a non-consumable tool and the workpiece, Ranjan S. et al., 2007[1], Sandeep K. et al., 2012[2], Huda M. et al., 2013[3], Pulak M. Pandey, 2016[4]. In friction crush welding (FCW), the coalescence among metals or alloys is achieved mainly through two processes represented by friction-based heating, and crushing mechanism where the feed rate and

tool rotational speed play an important role in distributing the pressure in the contact zone, Schindele P., 2012 [5]. Florian A. Besler et al., 2016 [6], conducted friction crush welding using tool rotational speed of 18000 rpm and feed rate of 250-7000 mm/min on three materials namely copper DHP, aluminum AW5754 and steel DC01. They found that the yield strength percentages of welded similar materials were 95%, 90 % and 62% of parent metals of (DC01), (AW 5754 H22) and (Cu-DHP), respectively. They also found that the welding region was characterized by fine grain structure. Florian A. Besler et al., 2017 [7], also showed that the additional wire used to join aluminum alloy (EN AW-5754), steel (DC01), and copper (Cu-DHP) using tool rotational speed of 18000 rpm and feed rate of 2000-10000 mm/min was enhanced the bond strength of welded joints. Moreover, they found that the

\* Corresponding author.

E-mail address: [abdaljabbar\\_saad@yahoo.com](mailto:abdaljabbar_saad@yahoo.com)

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highest bond strength percentages obtained were 77, 69 and 98 of the parent materials of aluminum alloy (EN AW-5754), copper (Cu-DHP) and steel (DC01), respectively. G.S. Brar et al., 2017 [8], studied the effect of friction crush welding parameters like tool profile, tool rotational speeds (220-740 rpm) and feed rates (15-45 mm/min) on the bond strength of welded joint using Taguchi method. They showed that tool profile is the major factor affecting the bond strength. G.S. Brar et al., 2017 [9], also demonstrated that friction crush welding of 2 mm thick 6061T-6 Al alloy using tool rotational speeds of 220- 740 rpm and feed rates of 15-45 mm/min was achieved by a specific tool profile design. They also concluded that the maximum bond strength was obtained with increasing tool rotational speed and the feed rate.

The impetus for this work is to study the possibility of achieving friction crush welding of flange edged copper sheets using tool rotational speeds of (220 - 1500 rpm) and feed

rates of (20 - 150 mm/min). The microstructure and mechanical properties of the friction crush welded Cu-Cu joint are studied in this work. The characterization of the defects formed in the weld joints during welding is also achieved.

## 2. Experimental work

Horizontal milling machine was used to conduct friction crush welding experiments in this work. The rotating tool was mounted over the arbour of machine as shown in Figure1. The arbour was connected to the electric motor; hence different rotation speeds of tool could be obtained. The tool in the form of disc was manufactured from high-strength low alloy steel (A514 R) with chemical composition illustrated in table 1. The copper sheets were properly clamped by suitable fixtures; thus, the gap could be maintained between copper sheets. The chemical composition of oxygen-free copper (C1020) sheet was illustrated in Table 2.



Fig. 1. Horizontal milling machine used

**Table 1** Chemical composition of friction crush welding tool (A514 R)

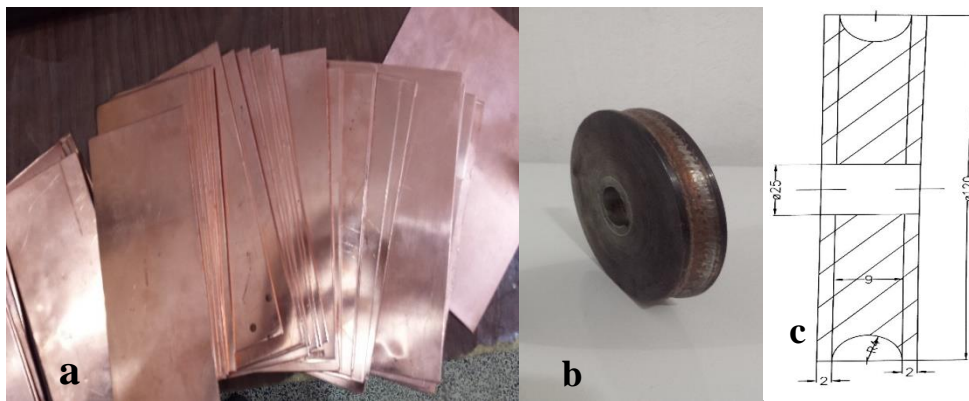
Fe %	Mn %	Mg %	Zn %	Cu %	Ni %	Al%	C%	Cr%	Si %	Mo%	Co%	Ti%	V%	W%
97.3	0.894	0.009	0.003	0.111	0.39	0.028	0.246	0.567	0.254	0.167	0.018	0.005	0.007	0.025

**Table 2** Chemical composition of oxygen-free copper (C1020) sheet.

Cu %	Mn %	Mg %	Zn %	Fe%	Ni %	Al%	Be%	Cr%	Si %	Ag%	Co%	Sn%	Pb %
99.95	0.003	0.001	0.02	0.003	0.007	0.001	0.001	0.001	0.004	0.002	0.002	0.002	0.01

The friction crush welding tool was rotated at different speeds. These rotational speeds were 220, 410, 920 and 1500 rpm. In other side, the different feed rates used in the experiments were

20, 43, 80 and 150 mm/min. The copper sheets and friction crush welding tool with its dimensions were illustrated in Figure 2.



**Fig. 2.** Photograph of (a) copper sheets, (b) FCW tool and (c) dimensions of FCW tool in mm

The dimensions of copper sheets of 150x75x2 mm with 4.72 mm flange height and 1mm gap were used. The gap among the two copper sheets that filled by the additional material of flanged edges during welding was determined accurately through several experiments achieved. The height of flanged edge was calculated by equating the volume of material required to form the weld to the volume of material of flanged edges of two copper sheets as shown in Figure 3. The formula used for calculation of flanged edge height (A) can be expressed as in equation (1) [8].

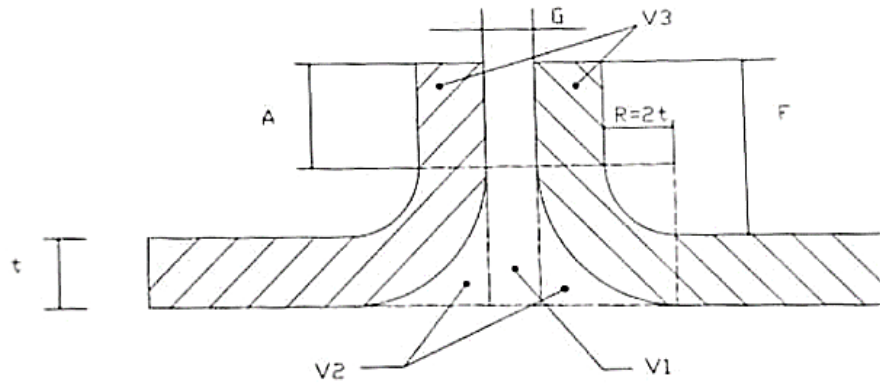
$$A = G + (4t - (\pi R^2 h / 4t)) \tag{1}$$

where, (G) is the gap among copper sheets, and (h) describes the height used in calculation of additional material volume.

The total height of flange (F) is given by the equation 2 [8].

$$F = A + t \tag{2}$$

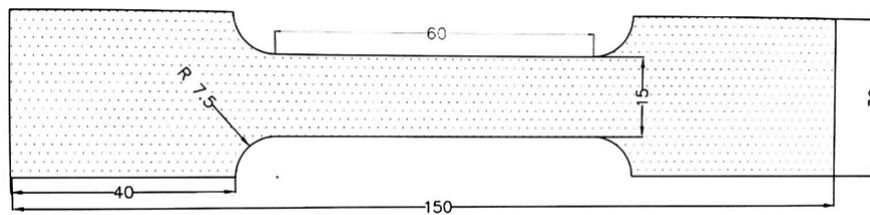
where, (t) is the thickness of copper sheet.



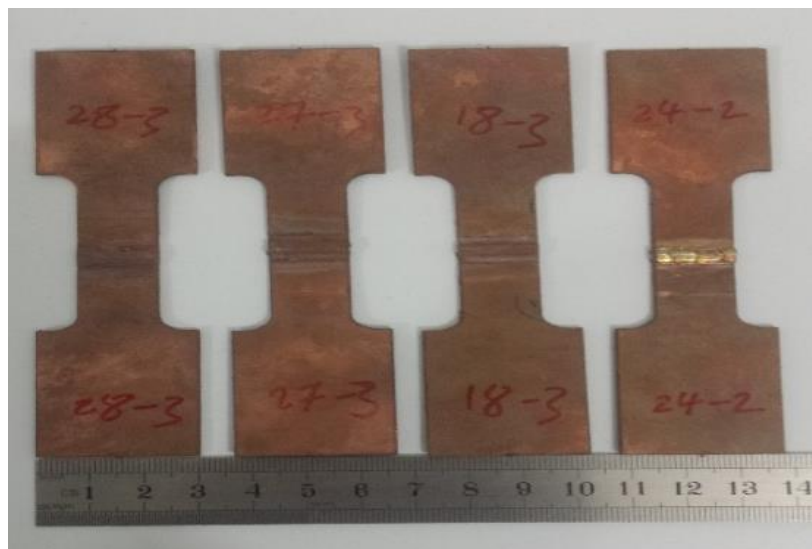
**Fig. 3.** Sketch of joint design of friction crush welding

Tensile test specimens were manufactured by using CNC water jet machine. Tensile test of each FCWed joint was performed at room temperature using universal testing machine of WDW-200E model. The tensile test specimens were performed

according to the specification of DIN EN ISO 4136 [10]. The dimensions of tensile test specimen with some of prepared tensile test samples are shown in Figure 4.



(a)



(b)

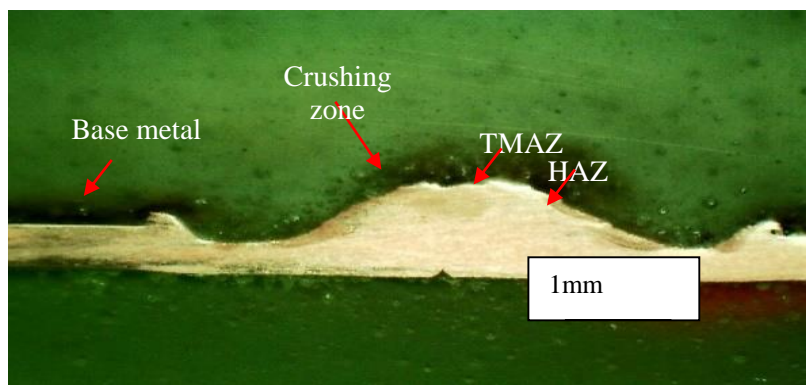
**Fig. 4.** (a) Tensile test specimen dimensions, (b) A set of tensile test Specimens.

Hardness test was carried out by using vickers hardness model HVS-1000. A 500g load was applied with holding time of 15 second during the test. The readings were taken across the welded joint with interval of 1 mm distance. Microstructural investigation of the weld zone was conducted by preparing the surface using grinding and polishing processes. Grinding process was performed by employing different emery papers. Polishing process was achieved using alumina slurry followed by the use of diamond paste. The etching was achieved using (5 g FeCl<sub>3</sub>, 50 ml HCl, 100 ml distilled water) etching solution. The microstructure was observed using optical microscope model Optika-Italy.

### 3. Results and discussion

The macrostructure of cross-section of FCWed copper sheets (Figure 5) illustrates that

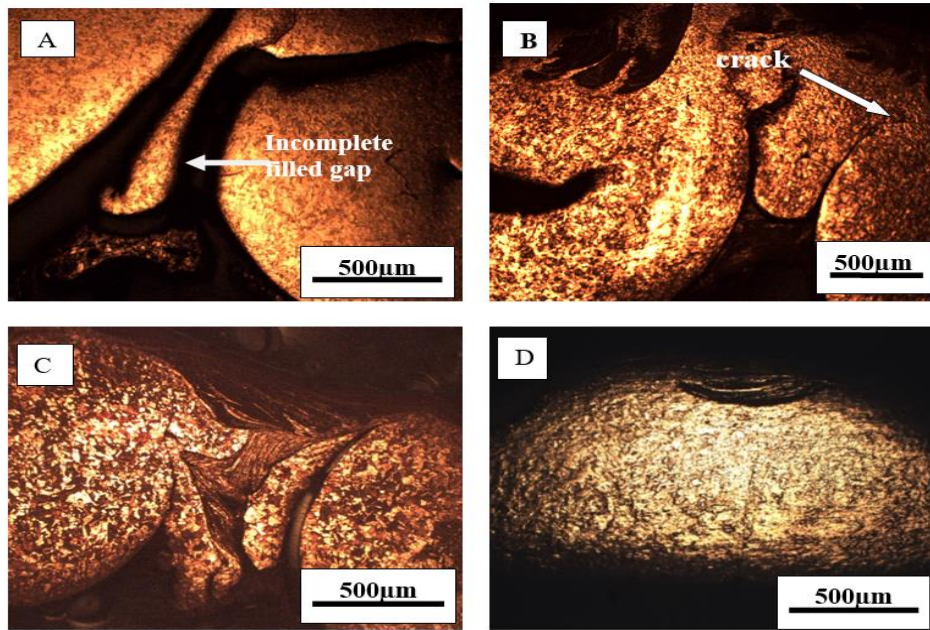
three zones can be recognized. The first is the crushing zone distinguished in the middle of the weld joint. This zone, represents the gap between the sheet metal parts, must be filled with additional materials during the crushing process. Due to the intensive material deformation and high temperature generation, this area is mainly affected by oxidation inclusions. The second is the thermodynamically-affected zone (TMAZ) recognized beside the crushing zone. TMAZ was characterized by thermo-mechanical deformation which results in a recrystallized fine - grained microstructure. The third is the heat-affected zone (HAZ) which lies between the (TMAZ) and the parent metal. This zone was exposed to thermal treatment, but did not show any plastic deformation, resulting in different microstructural properties in comparison with the parent metal.



**Fig. 5.** Macrostructure of FCWed copper joint at 1500 rpm tool rotational speed and 115 mm/min feed rate

The effect of tool rotational speed and feed rate on the microstructure of cross-section of FCWed copper is shown in figure 6. It is clear that the formed crushing zone has several defects like cracks and an incomplete filled gap between the two copper sheets. These defects can reduce the strength of FCWed copper joint. Figure 6 also shows welding defects according to the FCW parameters used. At low feed rate (Figure 6-A),

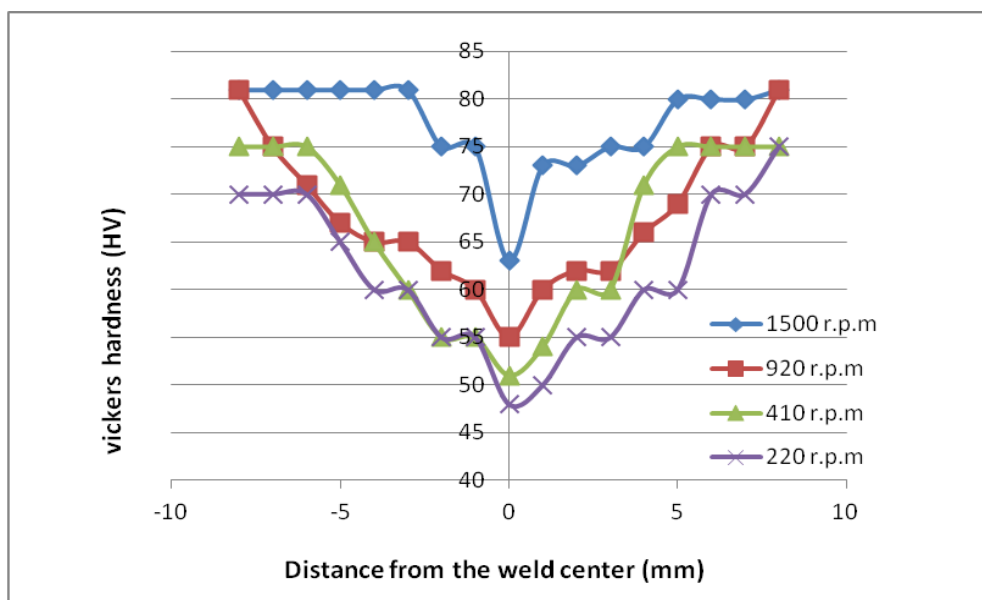
incomplete filled gap and bad joining were recognized. Increasing the feed rate causes a decrease in the size of cracks. It was observed that the joint gap was completely closed at a feed rate of 115 mm/min (Figure 6-d). Therefore, tensile strength can be enhanced by increasing tool rotational speed and feed rate.



**Fig. 6.** Microstructure of FCWeld Cu-Cu joints at different tool rotational speeds and feed rates (A) 220 rpm tool rotational speed and 20 mm/min feed rate, (B) 410 rpm tool rotational speed and 43 mm/min feed rate, (C) 920 rpm tool rotational speed and 80 mm/min feed rate, (D) 1500 rpm tool rotational speed and 115 mm/min feed rate

The relationship between hardness and distance along cross sectional area of FCWeld copper joint is illustrated in Figure 7. It was noticed that the hardness decreased in crushing zone (CZ) compared with that of the thermo-

mechanical affected zone (TMAZ) and heat affected zone (HAZ). This is due to frictional heat and plastic flow generated during friction crush welding.



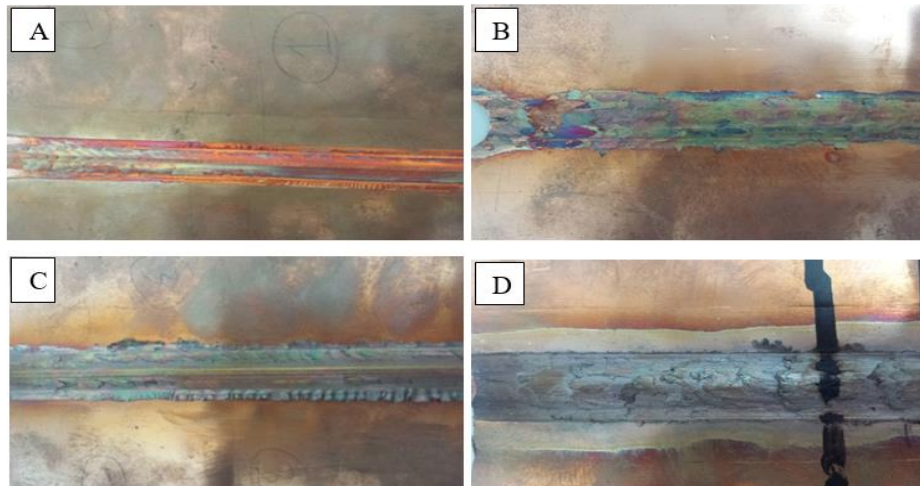
**Fig. 7.** The hardness distribution along a cross section of FCWeld copper joint at various tool rotational speeds

The welding lines of FCWeld copper joints at different tool rotational speeds and feed rates are shown in figure 8. The welding line means nothing

without knowing the microstructure and resulting defects in the FCWeld joint. The smooth welding line (Figure 8-A) indicated that the welding joint

was good but when compared with the microstructure as in figure 6-A, there was no doubt to reject this welding joint. Contraversially, figure 8-D indicated that several layers of cracks formed on the welding line. The microstructure of this

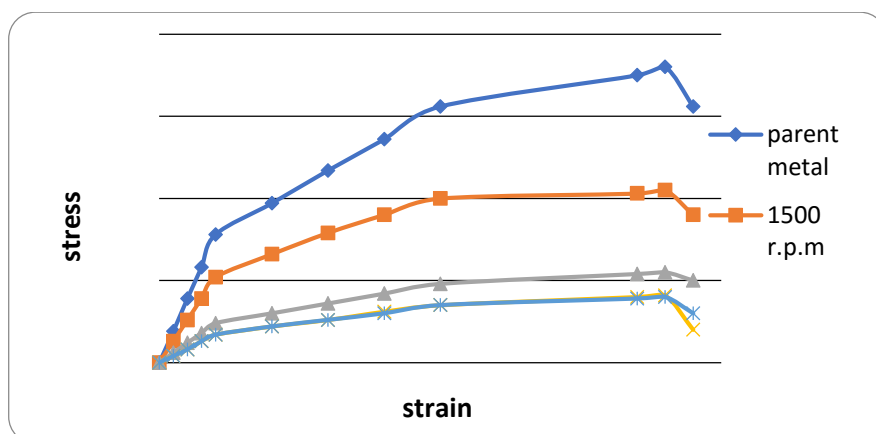
welding joint (Figure 6-D) showed that it was entirely solid. Therefore, this means that it is important to significantly control welding parameters to reduce or prevent the formation of surface crack.



**Fig. 8.** Welding lines at different tool rotational speeds and feed rates (A) 220 rpm tool rotational speed and 20 mm/min feed rate, (B) 410 rpm tool rotational speed and 43 mm/min feed rate, (C) 920 rpm tool rotational speed and 80 mm/min feed rate, (D) 1500 rpm tool rotational speed and 115 mm/min feed rate

Figure 9 shows the stress-strain curves of parent copper and FCWed copper joints. It is obvious that the tensile strength increased with increasing tool rotational speed and feed rate. This is attributed to the level of thermal heat input associated with a given feed rate. The highest strength of 105 MPa was recognized at a feed rate

of 115 mm/min and tool rotational speed of 1500 rpm. This value corresponds to 62% of the parent metal strength. The increased bond strength of FCWed copper joint may be related also to the fracture of oxide layers presented at the interface between the two copper sheets due to deformation in the crushing zone generated by FCW.



**Fig. 9.** Stress-strain curves of parent metal and FCWed Cu-Cu joints

#### 4. Conclusions

The most important points related to the assessment of copper joints manufactured by friction crush welding can be summarized below:

- 1- The recognized cracks and an incomplete filled gap in the weld joint were responsible for reducing the joint strength.
- 2- Reduced hardness in crushing zone compared with other zones was related to frictional heat and plastic flow.
- 3- Control of welding parameters is extremely important to reduce or prevent the formation of surface cracking.
- 4- The highest hardness and maximum tensile strength of FCWed Cu sheets were 63 HV and 105 MPa, respectively, obtained at a tool rotational speed of 1500 rpm and a feed rate of 115 mm/min.

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