Effect of friction crush welding parameters on the properties of welded joints of C1020 copper sheet

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Abstract. Challenges in joining sheet metals can be encountered using traditional friction welding and the solution is achieved by friction crush welding. In this work, the influence of flanged edge heights (2, 2.5 and 3 mm) and gaps (0.5 and 1 mm) between Cu sheets of Cu-Cu joints on the microstructure and mechanical properties were investigated. The welding experiments were performed using tool rotational speed of 1500 rpm and feed rate of 150 mm/min. Optical microscope, SEM, hardness and tensile tests were used to evaluate Cu-Cu joints successfully. The results indicated that the significant characteristics of Cu-Cu joints were obtained using 2.5 mm flanged edge height and 0.5 mm gap between Cu sheets. These characteristics were 66 HV hardness and 118 MPa tensile strength. Fracture surface analysis of FCWed joints indicated the brittle-ductile mixed fracture mechanism.

1. Introduction
Friction welding is a solid-state joining process that produces coalescence of materials under compressive force contact of workpieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces. There is no melting under normal conditions for faying surfaces during welding. Filler metal, flux and shielding gas are not required in this process [1]. Friction crush welding (FCW) is a new technique used for welding of thin sheets in a solid state. In FCW, a tool having a specific profile rotates around the horizontal axis and the workpieces with flanged edges, sometimes an additional wire may be used, are placed against each other with specific gap and a frictional
contact is made between tool and workpieces during welding [2]. FCW is achieved mainly by two processes. These processes are friction-based heating and crushing mechanism of material. The feed rate and the tool rotational speed are expected to change in resistance during the process resulting in pressure distribution in the contact area [3]. The other parameters affecting FCW are tool geometry and joint design. FCW clearly offers a high-speed process that requires simple edge preparation and can be applied to off-plane geometries. The FCW principle is illustrated in figure 1 [4].

Figure 1. Principle of FCW [4]

Copper can be used for a wide range of applications from sheets of various thicknesses to manufacturing complex structures. Examples of possible applications include magnetic resonators, heat exchangers, air conditioners, coolers for metallurgical ovens, bus bars, and superconductors [5]. Welding of copper is usually difficult by conventional fusion welding processes due to high thermal diffusivity which is about 10 to 100 times higher than of many steels and nickel alloys with a wide heat-affected zone (HAZ) and a significant distortion with high residual stresses. In addition, the heat input is much higher than almost any other material, and weld speeds are quiet low [6,7]. Oxygen free copper (C1020) is a group of high purity wrought copper with oxygen level close to 0.001% or less. It has very high electrical and thermal conductivity, excellent hot and cold forming properties and a good corrosion resistance, especially in an industrial atmosphere, water vapor, non-oxidizing acids and neutral saline solutions due to a good adherence of the oxide layer [8].

G.S. Brar et al., 2017 [9] found that tool profile, tool rotational speed and feed rate had a major influence on the bond strength of the welded joint using Taguchi method as the tool profile had the largest role in influencing the bond strength. G.S. Brar et al., 2017 [10] also demonstrated that the bond strength of friction crush welded 2 mm thick 6061T-6 Al alloy using tool rotational speeds of 220-740 rpm and feed rates of 15-45 mm/min was increased with an increase in the tool rotational speed and feed rate. M.E. Abdullah, et al. (2020) [11] investigated the effect of orbital friction crush welding parameters on the weld strength of commercial aluminum. They concluded that the maximum tensile strength reached
26.5 MPa at a tool rotation speed of 1000 rpm, where the tensile strength decreased with a decrease in the tool rotational speed. In addition, the maximum temperature reached 274 °C using 1000 rpm tool rotational speed and 1.35 flange ratio. H.T. Elmetwally et al. (2020) [12] found that increasing the rotational speed of FCW tool raises the weld temperature and improves the strength of welded joints. They also found that the trapezoidal profile gave the highest strength value when compared to other profiles.

This study is designed to investigate the properties of Cu-Cu joints performed by FCW without the use of additional wire. In this work, the microstructure characterization, defect analysis, and determination of mechanical properties were carried out. Characterization of fracture surface for the specimens tested in a tensile test was also performed.

2. Experimental work

Since there are no specialized friction crush welding machines, a milling machine type IWASHITA, Japan with different rotational and linear speeds has been used to weld oxygen-free copper (C1020) sheets with dimensions of 150 mm x 75 mm x 1mm. The milling machine is set up to fit the job. The machine is equipped with welding tool, backing plate and fittings to be suitable for FCW (figure 2). The tool in the form of disk was manufactured from high-strength low alloy steel (A514 R) with chemical composition illustrated in Table. 1. The chemical composition of oxygen-free copper (C1020) sheet was illustrated in Table. 2.

![Figure 2. Milling machine used in welding process](image)

| Table 1. Chemical composition of friction crush welding tool (A514 R) |
|-------------------|---|---|---|---|---|---|---|---|---|---|
| Element wt.%     | C  | Si | Mn | Ni | W  | Co | Cr | Al | Mo | V  | Cu | Fe |
| Measured         | 0.234 | 0.253 | 0.894 | 0.390 | 0.025 | 0.018 | 0.567 | 0.028 | 0.167 | 0.007 | 0.114 | Rem. |
Table 2. Chemical composition of oxygen-free copper (C1020) sheet

| Element | wt.% | Si   | Fe   | Sn   | Mn   | Mg   | Cr   | Ni   | Zn   | Ag   | Pb   | Bi   | Cu     |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|--------|
| Measured|      | 0.004| 0.003| 0.002| 0.003| 0.001| 0.005| 0.02 | 0.002| 0.010| 0.005| Rem  |        |

The friction crush welding tool was rotated at speed of 1500 rpm. In other side, the feed rate used in the experiments was 150 mm/min. The copper sheets and friction crush welding tool with their dimensions were illustrated in figure 3.

Figure 3. (a) Cu sheets prepared for welding (b) FCW tool and (c) dimensions of FCW tool in mm

Different flanged edge heights (2, 2.5 and 3 mm) and gaps (0.5 and 1 mm) between Cu sheets along the welding line were used in all FCW experiments as illustrated in Table. 3.

Table 3. Flanged edge heights and gaps between Cu sheets used in FCW experiments

| Specimen Symbol | Gap between Cu sheets (G), mm | Flanged edge height (A), mm |
|-----------------|-------------------------------|----------------------------|
| A               | 0.5                           | 2.5                        |
| B               | 0.5                           | 2                           |
| C               | 0.5                           | 3                           |


The gap between the two copper sheets that filled by the 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 volume of material of flanged edges of two copper sheets as shown in figure 4. The formula used for determination of flanged edge height (A) can be expressed as in equation 1 [9].

\[ A = G + (4t - (\pi R^2 h/4t)) \]  

(1)

Where (G) is the gap between Cu sheets, (h) is the height of cylinder used in calculation of material volume that fill the gap between Cu sheets.

The total height of flanged edge (F) is calculated by the equation 2 [9].

\[ F = A + t \]  

(2)

Where (t) is the thickness of Cu sheet.

Figure 4. Schematic diagram of Cu-Cu joint design

Several tensile test specimens have been prepared according to DIN EN ISO 4136 standard. Tensile test was performed using universal testing machine model WDW-200E. A set of prepared tensile test specimens is illustrated in figure 5.
The hardness test was performed with the Vickers Hardness Tester (HVS-1000). Measurements of the hardness values were made at several points located on either side of the welding line across the welded joint. A 500 g load was applied during hardness test on the cross section of the welded joint for 15 s.

Microstructural investigation of the weld zone was conducted by preparing the cross section of welded joint surface using grinding and polishing, respectively. Grinding was performed by employing different emery papers, and then it follows the use of alumina slurry for polishing. The etching was achieved using (5 g FeCl3, 50 ml HCl, 100 ml distilled water) etching solution. Optical microscope type Optika-Italy and scanning electron microscopy (SEM) type (FEI 9922650) with high-resolution were used to characterize the microstructure.

3. Results and discussion
The macrostructure of FCW ed joints through the cross-section for a group of similar Cu-Cu joints is presented in figure 6. It is clear that distinct regions such as the crush zone (CZ), the thermomechanical affected zone (TMAZ) and the heat affected zone (HAZ) can be recognized. FCW ed joints show material flow along welded Cu-Cu sheet joints. The welding areas of some welded joints also have various defects that affect the strength of the weld. The material flow and weld defects were clearly dependent on the FCW parameters used as flanged edge height and the gap between the Cu sheets. Figure 6 (A) shows good weld quality and good material flow between the Cu sheets in the weld zone, as well as that the weld area was not defective. Good material flow between copper sheets within the weld zone can also be observed in figure 6 (B-D). It is clear that filling the gap between the Cu sheets has an important role in the complete welding of the joint. Moreover, the large gap between Cu sheets and insufficient metal led to defects. Figure 6 (E) shows small welding line thickness, and the cause may be excessive gap between Cu sheets and insufficient flanged edge metal. Figure 6 (F) shows poor characteristics due to excessive height.
of flanged edge and inconvenient gap between Cu sheets resulting in defects and inappropriate welding of the joint.

Figure 6. Macrostructure of FCWed joints cross section of similar Cu-Cu joints at different flanged edge heights and gaps between Cu sheets (A) 2.5 mm and 0.5 mm, (B) 2 mm and 0.5 mm, (C) 3 mm and 0.5 mm, (D) 2.5 mm and 1 mm, (E) 2 mm and 1 mm and (F) 3 mm and 1 mm
Figure 7 represents the microstructure of FCWed Cu-Cu joints at different flanged edge heights and gaps between Cu sheets. It is clear that fine and equiaxed recrystallized grains without weld defects and with complete gap filling between Cu sheets can be recognized indicating that they possess high tensile strength (figure 7A). The fine dynamic recrystallization grains are observed due to the high heat generation and plastic deformation. The crack is clearly recognizable and the reason for its formation may be an incomplete filled gap between the Cu sheets (figure 7B). Cracks are observed in figure 7(C) and may be caused by an excessive metal gap between the Cu sheets. The large gap between Cu sheets and insufficient flanged edge metal led to defects as in figure 7(D,E). Also, several cracks and incomplete weld zone can be clearly distinguished. Excessive height of the flanged edge and the gap between the Cu sheets results in poor weldability to the joints and poor properties (figure 7F).

![Figure 7](image_url)

**Figure 7.** Microstructure of FCWed Cu-Cu joints at different flanged edge heights and gaps between Cu sheets (A) 2.5 mm and 0.5 mm, (B) 2 mm and 0.5 mm, (C) 3 mm and 0.5 mm, (D) 2.5 mm and 1 mm, (E) 2 mm and 1 mm gap and (F) 3 mm and 1 mm
The relationship between hardness and distance along the cross-sectional area of the FCWed joint at different flanged edge heights and gaps between the Cu sheets is illustrated in figure 8 of the six welds examined systematically. It is obvious that hardness is closely related to both sides of welded Cu-Cu joints. For the six welds, from the crush zones, the weld A had the highest hardness of 66 HV, and the hardness values of weld B to F were ~ 64 HV, ~ 62 HV, ~ 60 HV, ~ 58 HV and ~ 55 HV, respectively. For each weld, the total hardness gradually decreases from base metal to a certain value in crush zone. Generally, base metal has the highest overall hardness of approximately 80 HV while the lowest value (55 HV) is found in crush zone (weld F), indicating that the hardness distribution along the direction of the curves correlated with the depth that was affected by the weld defects. The main defects of the weld were cracks, the cause of their formation may be related to an incomplete filled gap between the Cu sheets as explained before. While both sides of the weld line have almost the same exact hardness difference. F.A. Besler et al. [2] found that the FCWed copper reveal increased grain size in the heat affected zone and in the crush zone relative to the material unaffected by heat and this coarse grain effect may also be responsible for the reduction in hardness and bond strength. It is obvious that the high conductivity of copper causes the release and dissipate of the heat generated due to the high friction between the FCW disk and the Cu sheet during welding. This means that copper causes a greater thermal effect to the material. From this, the retention period of heat in the crush zone is very low and certainly not sufficient to completely recrystallize the deformed grains which reflect the drop in the hardness value in the crush zone for all FCWed joints.

Figure 8. The hardness distribution along cross-sectional area of FCWed joints at various flanged edge heights and gaps between Cu sheets. (A) 2.5 mm and 0.5 mm, (B) 2 mm and 0.5 mm, (C) 3 mm and 0.5 mm, (D) 2.5 mm and 1 mm, (E) 2 mm and 1 mm gap and (F) 3 mm and 1 mm
Figure 9 shows the stress-strain curves of the oxygen free copper sheet and FCWed Cu-Cu joints. Oxygen-free copper has the highest tensile strength of 180 MPa and elongation of 15% compared with Cu-Cu joints. For FCWed joints, the tensile strength and elongation of specimen F to specimen A were increased. The tensile strength of specimen A was about 118 MPa, and this value corresponds to 65% of the strength of oxygen-free copper and the elongation was 13%, as the crush zone possesses fine, equiaxed recrystallized grains without welding defects and with filling of the gap between the Cu sheets. The tensile strength of sample B was about 81 MPa and the elongation was 12%. This decrease in tensile strength and elongation is due to the crush area possessing fine recrystallized grains with some weld defects and an incomplete filled gap between the Cu sheets. The tensile strength of sample C was about 75 MPa and elongation was 11%, which due to the crush area has cracks and may be caused by an excessive metal gap between the Cu sheets. Whereas 71 MPa and 70 MPa of tensile strengths with 9% and 8% of elongation were obtained in sample D and E, respectively. This decrease in tensile strength and elongation is due to the fact that the crush zone possesses many cracks and incomplete weld area. Finally, for specimen F, the tensile strength was about 68 MPa and the elongation was 5%, where the excessive height of the flanged edge and the gap between the Cu sheets resulted in defects and incomplete welding of the joint resulting in a weak tensile strength.

![Stress-strain curves](image)

**Figure 9.** Stress-strain curves of the oxygen free copper sheet and FCWed Cu-Cu joints at various flanged edge heights and gaps between Cu sheets. (A) 2.5 mm and 0.5 mm, (B) 2 mm and 0.5 mm, (C) 3 mm and 0.5 mm, (D) 2.5 mm and 1 mm, (E) 2 mm and 1 mm gap and (F) 3 mm and 1 mm.

Figure 10 (A-C) shows the SEM micrographs of different locations in the crush zone of Cu-Cu joints. The good quality of weld joints and good material flow between Cu sheets are seen in figure 10 (A), and
this is due to the complete weldability of the Cu sheets along the welding line in the solid state. Some microcrack and small void were observed due to increased heat input. Figure 10 (B) shows the welded joint with good flow of material between the Cu sheets with some defects such as cracks, voids and excessive crush due to the greater input of heat and plastic deformation. In figure 10 (C), the quality of the welded joint gradually decreases due to an increase in the weld defects and the material flow between the Cu sheets decreases due to an excessive height of flanged edge.

**Figure 10.** Scanning electron microscope images at different locations in the crush zone of Cu-Cu joints using different flanged edge heights and gaps between Cu sheets. (A) 2.5 mm and 0.5 mm, (B) 2 mm and 0.5 mm, (C) 3 mm and 0.5 mm.
Figure 11 shows SEM micrographs of the fracture surface of FCWed Cu-Cu joint using 2.5 mm flanged edge height and 0.5 mm gap between Cu sheets. The tensile fracture of the joint exhibits some cleavage-type fracture which represents lower ductility to the joint. Also, it is evident that the brittle fracture occurs in the border region of the crush zone. The crush zone is the weakest region of the FCW joint due to concomitant lowest hardness, and thus the fracture occurs in this region. The overall morphology of the fracture surface indicated brittle-ductile mixed fracture mechanisms. Observations of high magnification of the tensile fracture surface revealed an overall transgranular failure. Moreover, incomplete coalescence and shallow dimples covering some of the failure areas were also observed.

![Figure 11. SEM images of fracture surface of tensile tested Cu-Cu joint using 2.5 mm flanged edge height and 0.5 mm gap between Cu sheets.](image-url)
4. Conclusion

The overall investigation of FCWed joints characteristics clearly indicated that they were dependent on FCW parameters. The incomplete filled gap between the Cu sheets and cracks in the crush zone were the main defects that were identified. The hardness of FCWed joints decreases as the height of the flanged edge and the gap between the Cu sheets increases. The tensile strength decreases with the change of the flanged edge height and the gap between the Cu sheets, and is affected by the weld area. The highest hardness and maximum tensile strength of FCWed joints were 66 HV and 118 MPa, respectively, obtained using a flanged edge height of 2.5 mm and a 0.5 mm gap between the Cu sheets. Observation of SEM images of the FCWed joint fracture surface revealed two types of fracture; ductile and brittle.

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