Influence of the Initial Length of the Cu Bars on the Structure and Micro-Hardness of Friction-Welded and Open-Die Forged Al/Cu Bimetallic Joints

Veljko MILAŠINOVIĆ1,2*, Sergii VOINAROVYCH3, Karlo RAJČ4, Krzysztof KRASNOWSKI5, Ana ALIL6, Nenad RADOVIĆ4, Bojan GLIGORIJEVIĆ6
1 VTM Solutions doo., Jagodina, Serbia; 2 VEMID doo., Jagodina, Serbia; 3 E. O. Paton Electric Welding Institute, Kyiv, Ukraine; 4 University of Belgrade, Faculty of Technology and metallurgy, Department of metallurgical engineering, Belgrade, Serbia; 5 Instytut Spawalnictwa, Gliwice, Poland; 6 University of Belgrade. Innovation Center of Faculty of Technology and Metallurgy, Belgrade, Serbia

https://doi.org/10.240/ptk.018.30.1.187

In the present study, bimetallic joints of cylindrical aluminum (Al) and copper (Cu) bars were produced by using the same continuous drive friction welding (CDFW) processing parameters and different initial lengths of Cu bars. Subsequently, the obtained Al/Cu joints were open-die forged (cold pressed) under the same conditions. In order to evaluate the effects of different initial lengths of Cu bars and of the open-die forging process, micro-hardness and micro-structural analyses were performed. The cold pressing affected to a higher extent the properties of CDFW joints compared to the utilization of different initial lengths of Cu bars causing a general increase in micro-hardness in central regions adjacent to the Al/Cu interface as well as considerably different micro-structural properties. On the other hand, the different initial lengths of Cu bars caused subtle differences in the micro-hardness and micro-structural properties, which were more pronounced on the Cu side of the CDFW and pressed joints than those on the Al side. The observed differences in properties of CDFW joints derived as a result of the usage of different initial lengths of Cu bars joints were inherently transferred to the pressed joints after the utilization of open-die forging procedure.

Keywords: Friction welding; open-die forging; Al/Cu joint; structure; micro-hardness

Introduction

In general, continuous drive friction welding (CDFW) of two metals may produce three typical regions from a weld interface towards an unaffected base metal: (i) fully deformed or dynamically recrystallized (DRX) region, (ii) partially deformed region or thermo-mechanically affected zone (TM), and (iii) undeformed region or heat affected zone (HAZ) [1]. In previous studies, it has been shown that different CDFW parameters may differently affect the size and structural properties of these regions and consequently their mechanical properties [2,3]. However, in the available literature, there is neither study that has dealt

* Corresponding author: v.milasinovic@gmail.com
with the possibilities to reduce the consumption of Cu as a raw material for the production of CDFW Al/Cu joints nor a study that has reported the effects of cold pressing of these joints.

When the testing of large quantities of Al/Cu bimetallic joints is considered, consumption of Cu, as a raw material, is of significant importance. For tensile testing of Al/Cu joints, it is recommended to produce joints by using a longer initial length of Cu bars, whereas for the examination of micro-structure or other properties of these joints, Cu bars of shorter lengths can be used. In order to introduce the lower consumption of Cu for the testing of larger quantities of Al/Cu joints, it is necessary to determine whether the usage of different initial lengths of Cu bars produces the same micro-structural effects in joints obtained by using the same processing parameters or not. In the present study, we have analyzed the micro-structural properties and micro-hardness profiles of Al/Cu bimetallic joints produced by using the similar CDFW processing parameters and different initial length of Cu bars. Also, we have evaluated the mentioned properties of these joints in the open-die forged (cold pressed) condition.

1 Experimental

1.1 Materials and processing

Cylindrical bars made of Al (99.5 % purity, Ø 16 mm) and Cu (99.95% purity, Ø 12 mm) were joined by using the CDFW process (Figure 1a). In first CDFW experiment, Al/Cu joints were produced with Cu bars of 30 mm in length (Figure 1b), whereas in second CDFW experiment the length of Cu bars was 100 mm (Figure 1c). In both cases, the welding parameters were similar and the initial length of Al bars was 110 mm. Subsequently, the as-welded cylindrical CDFW Al/Cu joints (hereinafter: CDFW joints) were subjected to cold pressing (open-die forging) in their radial direction by using the hydraulic press (Figure 1d) (hereinafter: pressed joints). Cold pressing was performed in a single stage to the final thickness of 6.0±0.3 mm. Similarly to CDFW experiments, pressed joints were obtained in two experiments with shorter (3 cm) (Figure 1e) and longer (10 cm) (Figure 1f) initial lengths of Cu bars by using the similar pressing parameters.

Figure 1. (a) CDFW process; (b) CDFW joint with initially shorter Cu bar; (c) CDFW joint with initially longer Cu bar; (d) hydraulic press; (e) pressed joint with initially shorter Cu bar; (f) pressed joint with initially longer Cu bar

1.2 Sample preparation and characterization

Prior to examination, the CDFW and pressed joints were cut parallel to and at 10 to 12 mm from the Al/Cu interface (see cutting planes 1 and 2 in Figures 1b, 1c, 1e, and 1f) and then were cut along the central axial axis (see cutting planes 3 in Figures 1b, 1c, 1e, and 1f). After cutting, the samples were cold mounted in epoxy resin in silicone rubber mould with planes 3 facing the bottom of the mould. Subsequently, the planes 3 for analysis were ground with SiC water-proof papers (P-500, P-1000, P-1500, P-2000, and P-3000) and then polished with diamond pastes with mean particle sizes of 6, 3, and 1 µm. The final polishing of the planes 3 was performed with non-crystallizing colloidal silica with mean particles size of 0.05 µm.
The micro-structural properties of the as-welded Al/Cu joints were examined by the light optical microscopy (Reichert Jung MEF3). The presence of Al₅Cu₅ intermetallic interlayer at the Al/Cu interface was observed on the polished surface of Al/Cu joints by using the bright-field light and magnification of ×1000. In order to observe the structural properties of the Cu side of the joints, the polished joints were chemically etched in the fresh solution containing ~2.3 ml of H₂O₂, ~25 ml of NH₄OH, and ~25 ml of distilled H₂O for 40-60 s at room temperature. After chemical etching, the Cu sides were examined by using the bright-field light under magnification of ×100. In order to observe the structural properties of the Al side of the joints, the polished joints were electrochemically etched in Barker’s reagent (120 s, 20 V) and then were analyzed by using the polarized light microscopy under magnification of ×50. The typical appearance of samples for micro-structural analysis after etching is shown in Figure 2.

![Figure 2. The cold mounted samples in epoxy resin with electrochemically etched surface in Barker’s reagent.](image)

Micro-hardness (HV0.01) measurements were performed at University of Belgrade in Tribology laboratory of Faculty of Mechanical Engineering by using the micro-Vickers hardness tester TH710 (Beijing TIME High Technology Ltd). In the case of each sample, the micro-hardness profile was taken along the central region of the polished surface in the direction perpendicular to the Al/Cu interface (Figure 2). The measurements usually started at 250 µm distance from the Al/Cu interface on the Al side of the joints and ended at 200 µm distance from the Al/Cu interface on the Cu side of the joints. Each measurement was performed by using the dwelling time of 15 s at room temperature in ambient air.

## Results

### 2.1 Micro-hardness measurements

The micro-hardness profiles taken from the Al/Cu joints in the present study are shown in Figure 3. The results of these measurements showed that the effects of the initial length of Cu bars were present but significantly less pronounced than the effects of the open-die forging (cold pressing) process.

In the case of CDFW joints, on the Al side, in the area adjacent to the Al/Cu interface, the micro-hardness was 3 to 5 HV0.01 units higher in joints produced with the longer Cu bars than in the joints produced with the shorter Cu bars. However, on the Cu side, the micro-hardness was 3 to 10 HV0.01 units higher in the joints produced with the longer Cu bars and these values extended over the larger distance from the Al/Cu interface compared to the Al side. The areas where these differences were observed are depicted with the exclamation marks in Figure 3.

In the case of pressed joints, not only that the micro-hardness values were generally higher compared to the values detected in the CDFW joints but also the effects related to the utilization of different initial lengths of Cu bars were inherited.

In the case of Al/Cu interface, the micro-hardness did not show values higher than those observed on the Cu side of the joints, which would be the typical result when the presence of Al₅Cu₅ intermetallic interlayer of significant thicknesses is considered.
2.2 Micro-structural properties

2.2.1 Al side

On the Al side of the CDFW (Figures 4a and 4b) and pressed (Figures 4c and 4d) joints, the DRX zones of similar sizes were observed. In CDFW joints, these zones usually contain small equiaxed DRX grains [2,3] and expand from the interface, which is on the far right side in the Figure 3, to the first appearance of deformed structure (behind the green vertical lines), which is the beginning of the thermo-mechanically affected zone (TMAZ). The width of DRX zones was between 0.8 (Figure 4a) and 1.0 (Figure 4d) mm.

Based on the small differences in the width of DRX zones, it can be generally assumed that the utilization of the different initial length of the Cu bars had an insignificant effect on the micro-structural properties of Al side of the CDFW and pressed joints. However, considering that the electrochemical etching in Barker’s reagent produced indistinguishable grain boundaries in the DRX zones, especially in the region adjacent to the Al/Cu interface, the cause of slightly increased values in micro-hardness (see exclamation marks in Figure 3) remains to be further investigated.

By comparing the micro-structures of CDFW and pressed joints, the open-die forging (cold pressing) process had a significant effect on the micro-structural properties of CDFW joints. The micro-structure outside of the DRX zones appeared to be finer in the pressed joints than in CDFW joints, i.e. the deformed grains appeared to be thinner. Although the micro-structure could not be analyzed properly, it is reasonable to assume that the cold pressing caused further grain refinement in the DRX zones.

Figure 4. Micro-structure of Al side of the CDFW joints produced with (a) shorter and (b) longer Cu bar and micro-structure of Al side of the pressed joints produced with (c) shorter and (d) longer Cu bar. The length of the green scale bars in the upper left corners is 300 µm.
2.2.2 Al/Cu interface

In contrast to the microhardness measurements performed on the Al/Cu interface (Figure 3), the bright-field light microscopy of polished joints did confirm the presence of Al$_x$Cu$_y$ intermetallic interlayer (Figure 5). In all cases, the thickness of this interlayer extending along the Al/Cu interface on the Al side of the joints was lower than 0.2 µm. This result is in good agreement with our previously published article [3]. It is noteworthy of mentioning that the interlayer appeared discontinuously along the Al/Cu interface.

![Figure 5. Micro-structure of Al/Cu interface region of the CDFW joints produced with (a) shorter and (b) longer Cu bar and micro-structure of Al/Cu interface region of the pressed joints produced with (c) shorter and (d) longer Cu bar. The length of the green scale bars in the lower right corners is 5 µm.](image)

Based on the results, it is evident that the open-die forging (cold pressing) process did not promote further growth of the Al$_x$Cu$_y$ intermetallic interlayer. However, this process affected the morphological appearance of the Al/Cu interface, which became serrated (Figures 5c and 5d). Such appearance is the result of Cu penetration inside the Al on a micro-scale due to the presence of large stresses introduced with the cold pressing.

2.2.3 Cu side

In contrast to Al side (Figure 4), the micro-structure on the Cu side (Figure 6) could be easily revealed by using the mentioned chemical etching solution (section 2.2). The micro-structure of CDFW joints produced with the different initial lengths revealed noticeable differences. The width of the DRX zone in CDFW joints produced with the shorter Cu bars (Figure 6a) was generally larger compared to the CDFW joints produced with the shorter Cu bars. In pressed joints, the analogous effect was observed (Figures 6c i 6d).

In pressed joints, there was a clear difference in micro-structural properties located in the region further from the DRX zones. Namely, in the case of joints produced with the longer Cu bar (Figure 6d), there was an inhomogeneous appearance of small DRX grains along the grain boundaries in the form of necklace. The presence of these grains was significantly higher than in the joints produced with shorter Cu bars (Figure 6c). Also, notice that the largest Cu grains that were present in the joints produced with the longer Cu bars (Figure 6c) were smaller in size than the largest Cu grains that were present in the joints produced with the shorter Cu bars (Figure 6c). These differences might be related to the discontinuous dynamic recrystallization (dDRX) and meta-dynamic recrystallization (mDRX) phenomenon in Cu [4,5] (section 4).
Figure 6. Micro-structure of Cu side of the CDFW joints produced with (a) shorter and (b) longer Cu bar and micro-structure of Cu side of the pressed joints produced with (c) shorter and (d) longer Cu bar. The length of the green scale bars in the lower right corners is 50 µm.

3 Discussion

It is well known that the heat generated on the Al/Cu interface during the CDFW process generally transfers by thermal conduction in radial and axial direction of the cylindrical bars and then further transfers by natural convection in the surrounding atmosphere [6]. In the present study, it can be assumed that the heat transfer in the radial direction by thermal conduction was approximately the same because the same initial diameters of Al and Cu bars were utilized in the experiments. Therefore, for this moment, only the differences in heat transfer in the axial direction of Al and Cu bars will be taken into account during the further discussion.

Considering the simplest form of heat transfer equation for thermal conduction \( Q/\Delta t = -k \times A \times \Delta T/\Delta x \), where \( Q/\Delta t \) is the generated heat transfer rate, \( k \) is the thermal conductivity of Al or Cu, \( A \) is cross-sectional area of Al or Cu bar, \( \Delta T \) is the temperature difference between Al/Cu interface, where heat is generated, and opposite end of the Al or Cu bar, and \( \Delta x \) is the length of Al or Cu bar [7], the experiments were designed to observe solely the effects of the initial length of Cu bar. Due to the utilization of the same CDFW parameters, it was assumed that the initial temperature difference between the Al/Cu interface and opposite end of the Cu bars (\( \Delta T \)) was approximately the same. By using the same initial diameters of Cu bars, cross-sectional area (\( A \)) was also approximately the same. Moreover, the thermal conductivity \( k \) was also constant. In this way, the heat transfer rate \( Q/\Delta t \) depended only on the initial length of Cu bars (\( \Delta x \)). In the case of joints produced with the shorter Cu bars (\( \Delta x=30 \text{ mm} \)), the heat transfer probably reached its equilibrium for the shorter time compared to the case of joints produced with the longer Cu bars (\( \Delta x=100 \text{ mm} \)) due to the presence of larger temperature gradient (\( \Delta T/\Delta x \)). In other words, the joints produced with the shorter Cu bars experienced higher temperatures sooner and for the longer period of time in contrast to the joints produced with the longer Cu bars, which might had experienced generally lower temperatures due to the smaller temperature gradient (\( \Delta T/\Delta x \)), which is reasonable assumption regarding the fact that both CDFW and open-die forging processes lasted up to several seconds.

The micro-structural properties and micro-hardness profiles on the Cu side generally confirmed the assumption made in the previous sentence. In general, regardless of the stacking fault energy (SFE), continuous dynamic recrystallization (cDRX) is observed in all metals during the cold/warm deformation at the temperatures lower than the half of their melting point [5]. However, in low SFE metals, such as Cu, at temperatures higher than half of their melting point, during the hot deformation, the discontinuous dynamic re-
crystallization (dDRX) is frequently observed [4, 5]. Such mechanism involves nucleation of new strain-free grains and their growth at the expense of regions with high dislocation density [4]. The nucleation of dDRX is usually initiated at the pre-existing grain boundaries where a heterogeneous necklace structure of equiaxed grains forms when there is a large difference between the initial grain size and the recrystallized grain size [4]. In the present study, such necklace structure formation was observed on the Cu side of the pressed joints (Figures 3c and 3d). Here, it will be emphasized again that the pressed joints produced with the shorter Cu bars probably experienced higher temperatures sooner and for the longer period of time because, when the straining was stopped after CDFW process, the temperature did not dropped immediately. For this reason, the pressed joints produced with the shorter Cu bars were probably subjected to prolonged annealing at higher temperatures and for a longer time interval than the pressed joints produced with the longer Cu bars. In such circumstances, the recrystallization nuclei produced in the material could grow with no incubation time into the matrix with higher stored energy [4]. This phenomenon is known as the meta-dynamic recrystallization (mDRX) or post-dynamic recrystallization (pDRX) and basically represents the continuous static recrystallization (cSRX) [4, 5]. As a result of dDRX and mDRX, which were, based on the previous discussion, more efficient in the pressed joints produced with the shorter Cu bars (Figure 3c), the mentioned necklace type of structure was more pronounced in the pressed joints produced with the longer Cu bars (Figure 3d). In other words, the lower annealing temperatures which were probably experienced in pressed joints produced with longer Cu bars could not efficiently recrystallize and grow dDRX grains during the dDRX and mDRX as in the case of pressed joints made with the shorter Cu bars. In addition, the larger micro-hardness values detected in CDFW and pressed joints produced with the longer Cu bars (Figure 3) indicated the larger presence of regions with higher stored energy in these joints compared to the joints produced with the shorter Cu bars, which is consistent with the described micro-structural observations.

In contrast to the Cu side, the microstructure of the Al side has suffered small changes in the narrow region adjacent to the Al/Cu interface. In the case of the CDFW and pressed joints produced with the shorter Cu bars, the micro-hardness values on the Al side were somewhat lower than in the joints produced with the longer Cu bars probably due to a more intensive thermal effect in the pressed joints produced with the shorter Cu bars during the dDRX and mDRX.

Although it might seem that the described differences are of no practical importance, the one should bear in mind that these joints in the form of Al/Cu bimetallic electrical connectors are subjected to the elevated temperatures (up to 250 °C) during their service life [3]. According to standards, when the thickness of AlxCy intermetallic layer at the Al/Cu interface reaches the thickness of only 2-3 µm, the mechanical properties of these joints drop to the point where their application is no longer acceptable. Therefore, although the small changes observed in the present study happened within the narrow region around the Al/Cu interface, they could be important when the critical thickness of Al,Cy intermetallic layer of only 2-3 µm is considered. For this reason, the future analyses will be focused on how these differences affect the kinetics of the Al,Cy intermetallic layer growth.

As already mentioned, the lower consumption of Cu as a raw material for testing of micro-structural, micro-and macro-hardness properties, electrical conductivity of Al/Cu joints etc., for which the samples of smaller sizes can be used, could be achieved by joining the Al bars with Cu bars of shorter initial lengths. Prior to the present study, it was hypothesized that the results of the mentioned analyses derived from the joints produced with shorter Cu bars could be compared to the results of tensile testing for which it is necessary to produce Al/Cu joints with the longer Cu bars. According to hypothesis, this comparison is valid if the micro-structural properties are similar for the cases of Al/Cu joints produced with different initial lengths of Cu bars and with the same processing parameters. However, by taking into account the obtained results, the micro-hardness measurements and micro-structural observations suggested the level of differences which cannot be ignored when the above mentioned standard recommendations regarding the critical thickness of Al,Cy intermetallic layer are considered.

4 Conclusions

Compared to the effect of different initial lengths of Cu bars, the open-die forging process generally introduced significantly higher micro-hardness and considerably different micro-structural properties in all investigated regions of the Al/Cu joints. On the Al side, the cold pressing promoted the formation of elongated grains in the axial direction in regions outside of the DRX zone. Inside of these zones, the changes introduced with the cold pressing process were imperceptible due to the poor effect of the electrochemical etching in the Barker’s reagent. At the Al/Cu interface, the cold pressing did not affect the thickness of the Al,Cu intermetallic interlayer, but it had affected the morphological appearance of the interface, which became
serrated. On the Cu side, the cold pressing introduced the necklace type of structure, which is typical for the dDRX process frequently observed in metals with low SFE.

Compared to the CDFW joints produced with the shorter Cu bars, the utilization of longer Cu bars produced somewhat larger micro-hardness values on the Al side of the CDFW joints in the region adjacent to the Al/Cu interface. This effect was more pronounced on the Cu side than on the Al side of the CDFW joints and was extending on the larger distances from the interface. The observed differences were inherently transferred to the pressed joints. On the Al side of all joints investigated, the DRX zones of the approximately same width were observed, whereas on the Cu side the width of the DRX zones was smaller in the case of both CDFW and pressed joints produced with longer Cu bars. Also, in the same samples on the Cu side, the necklace structure typical for the dDRX was more pronounced than in the samples produced with the shorter Cu bars. At the Al/Cu interface, the usage of different initial lengths of Cu bars had the insignificant effects.

5 Acknowledgements

We acknowledge the support for this study from the project funded by the Serbian Innovation fund (ID=920) won by the VEMID d.o.o. from Jagodina, Serbia as well as the support from the National project TR 34018 funded by the Ministry of education and technological development of Republic of Serbia. We also gratefully thank to Prof. Dr. Aleksandar Vencl from University of Belgrade, Faculty of mechanical engineering, (Belgrade, Serbia) for the assistance and advices provided during the micro-hardness measurements.

6 References


