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An investigation on micro-hardness, micro-structure and ductility of clad layer in copper clad aluminum wire under multi stage–NCWD

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The copper clad aluminum (CCA) wire was fabricated by roll forming of copper foil around the aluminum wire rode. Non-continuous wire drawing (NCWD) was employed to study the effect of wire drawing parameters on ductility, micro-hardness and microstructure of the copper clad layer. The NCWD process continued without intermediate annealing until cracks were observed on the copper clad layer. The cracks appeared after a 78% reduction in the cross-section. The micro-tensile test was performed on specimens with transverse curvature to determine elongation. A modified correction factor was introduced to correct the effect of curvature size on elongation. The introduced correction factor proportional to the sample characteristics was between 0.7 and 1.4. Moreover, variations in the hardness and microstructure of the copper clad layer were investigated in the base metal and at the welding zone. Before beginning the wire drawing process for the annealed CCA wire with a diameter of 10.1mm and a Cu clad thickness of 0.48mm, the hardness, ductility, UTS and grain size of the clad layer were 87HV, 43%, 103MPa and 80μm, respectively. At the end of NCWD for 10° and the 20% reduction ratio of the die, the diameter of CCA wire reached 4.7mm with a 0.22mm thickness of Cu clad. The hardness, ductility, UTS and grain size of the clad layer were 157HV, 2.9%, 325MPa and 8μm, respectively.

1. Introduction

Metallic multilayer materials, also called multilayer composites [1, 2], cladding materials [3], clad composites [4, 5], clad plates [6, 7], bimetal composites [8, 9], composite rods [10, 11] and clad wires [12], have been widely used in many industrial fields such as kitchen utensils [6, 13–15], automobile industry [9, 14, 16, 17], aerospace [6, 18], shipbuilding [6], biomedical devices [19] and heat exchangers [9, 14, 16, 17]. Various combinations of materials like Al/St [6, 9, 20], Al/Ti [7, 18, 21, 22], Al/Mg [11], Al/Ag [23], Al/Cu/Al [4, 5], Cu/Zn/Al [1], STS/Al/Cu [13], Cu/Ti [8], Ti/Cu/Ti [24], Ni/Cu [16] and Cu/St [12, 25] have been employed to exploit excellent mechanical, physical, and chemical properties of each material in a new unit material. Copper clad aluminum (CCA) wire is one of the most practical metallic multilayer materials for electrical applications, which provides several advantages, including higher electrical conductivity, higher mechanical strength and better solder ability in comparison with Al, as well as lower density and cost in comparison with Cu [4, 5, 25].

CCA wire is a suitable alternative for copper wires in the automobile industry, because it can provide at least a fifty percent weight reduction with the same order of electrical conductivity in comparison with copper wires [26]. On the other hand, as it is well known, when the electrical current frequency increases, the electric current flows mainly near the outer surface of wire (skin effect) [5, 27]. For these reasons, CCA wire has been widely used as a conductor material for signal transportation, telecommunications [28] and armored cables [29].

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several processes such as extrusion [29, 30], spiral extrusion [31, 32], caliber rolling [33, 34], rotary swage [4, 35, 36] and cold wire drawing [37, 38]. Meanwhile, during wire coiling, bending and stretching occur in the wire. On the other hand, with increasing the plastic strain during cross-section reduction (such as wire drawing on CCA wire), the ductility of the copper clad layer decreases and some defects including cracks appear at the surface. Therefore, to improve the wire ductility, an annealing process is performed. However, the annealing process produces an intermetallic layer between the copper clad and the aluminum core. This decreases electrical conductivity, especially on the contact point between two tips of wires or between wire tip and other equipment. The most common process of reducing the cross-section of CCA wire is cold wire drawing, which is performed in several steps. Therefore, the effect of wire drawing parameters is highly important on the clad layer ductility. Knowing the effect of wire drawing parameters on the ductility of the copper clad layer helps to select a suitable time of annealing, which can prevent to produce defects. The micro-hardness test can be used as an indicator to investigate the effect of forming process parameters on the clad layer ductility [39, 40]. The effect of some forming process parameters has been investigated on the hardness variations of the CCA cross-section in several literatures. However, the effect of the wire drawing process has not been so far reported on the ductility and micro-hardness of the copper clad layer in CCA wire.

Rhee et al investigated the effects of the die angle and the extrusion ratio on micro-hardness variations of the copper clad aluminum rod cross-section [29]. They reported that hardness increased with an increasing extrusion ratio and that hardness distribution became more uniform when the extrusion ratio and the die angle increased. Kim et al studied the effect of caliber rolling pass numbers on the hardness of the copper clad aluminum rod cross-section [34]. They used experimental and numerical studies for their research works. They showed that the copper clad hardness increased with an increase in the number of rolling passes. Sapanathan et al investigated the effect of axi-symmetric forward spiral extrusion (AFSE) process parameters on micro-hardness variations of the copper clad aluminum cross-section [41]. They revealed that hardness was higher near the interface (the intermetallic layer) and outer periphery regions of the copper clad layer than in the middle region of the material. Sasaki et al, Gueydan et al and Hug et al investigated the effect of drawing temperature and heat-treating on the intermetallic layer thickness and the copper clad aluminum cross-section micro-hardness [42, 43]. Their results showed that both the interface hardness and the intermetallic layer thickness increased by annealing.

Although, the effect of some parameters has been investigated on hardness variations of the CCA cross-section in some literatures, there is no report about the effect of the wire drawing process on the ductility and micro-hardness of the copper clad layer in CCA wire. This work focused on studying the effect of the die angle, the cross-section reduction rate of the die and the total cross-section reduction rate of wire drawing on the ductility, microstructure and micro-hardness of the copper clad layer in CCA wire. As a novel method, the micro-tensile test was used to determine the ductility of a thin clad layer that micro-tensile specimens have transverse curvature. A modified correction factor for elongation was introduced to correct the size and curvature effect.

2. Experimental procedure

2.1. Synthesis

A CCA wire rod was made using a commercially pure copper foil and an electro-conductive aluminum wire rod. The diameter of the aluminum wire rod was 9.5 mm and the thickness of the copper foil was 0.45 mm. Before making the CCA wire rod, the copper foil was cleaned from oxidation and oil. As shown in figure 1, the production process of CCA wire was carried out in three steps [44]. Some sub steps of the first step are shown in figures 1(a)–(d). First, the caliber roll forming of the copper foil was performed around the aluminum wire. Then, welding the seam of the copper clad layer was carried out using TIG welding in the longitudinal direction (figure 1(e)). Finally, the blank space between the copper clad and the aluminum core wire, as well as the knob of welding (figure 1(f)) was eliminated (figure 1(g)) by warm wire drawing at 90 °C–150 °C. The diameter of the CCA wire rod was 10.1 mm, while the volume ratio of Al to Cu was 85:15. To obtain a good deformation in order to reduce the CCA cross-section and eliminate the effects of seam welding and caliber roll forming, at first, the CCA wire rod was annealed at 350 °C for 4 h under the vacuum condition. Then, it was cooled to room temperature at the oven atmosphere [37, 45, 46]. For the initial bond between the two layers as well as the complete removal of the probable gap between them, the wire diameter was dropped from 10.1 to 9.2 mm by drawing (one-step drawing).

2.2. Sample preparation

The non-continuous wire drawing (NCWD) process was carried out at room temperature without annealing treatment between the drawing steps. The process was performed using vegetable oil as a lubricant. The volume
ratio of 85:15 (as ASTM: B566) remained constant between the aluminum core and the copper clad during the NCWD steps using successive dies [32]. The NCWD process continued until the total cross-section reduction rate $R_{ct} = \frac{A_i - A_f}{A_i}$, where $A_i$ and $A_f$ stand for the initial and final area sections, respectively, reaching about 78%. The NCWD process was carried out with a rate of 70 cm/min. Specimens were carried out with a conical die with three angles ($\alpha$) of 10°, 20° and 30° and the three cross-section reduction rates $R_a = \frac{D_i^2 - D_o^2}{D_o^2}$, where $D_i$ and $D_o$ respectively stand for the inlet and outlet wire diameters of 10%, 15% and 20%. Parameters of the prepared samples are shown in table 1, where 79 specimens were prepared.

2.3. Microstructures

To prepare the specimens for microstructure and micro-hardness testing, one centimeter from each wire was separated and mounted using Levocit powder and fluid. The mounted specimens were grinded using a Struers apparatus with 180 and 320 mm sandpapers with the vertical force of 5NT for each specimen, 150-rpm counter-clockwise speed for sandpapers, and 150-rpm counter-clockwise speed for holder specimens. For polishing, the vertical force of 10 N and other previous parameters, along with papers with 9, 3 and 1 $\mu$m grades, were used. After that, all the samples were polished with Ops of 0.5 micrometer. Finally, after preparation of the samples as mirror-like surfaces with regular manner, they were chemically etched at room temperature with a mixture of 60 ml of distilled water and 40 ml of nitric acid. The Axio-Imager optical microscope was used for OM examinations.

2.4. Micro-hardness

The micro-hardness of Vickers was measured according to the ASTM: E384-17 standard. The indentations were carried out using a load of 10 gr and dwell time of 15 s by a Buehler Micromet micro-hardness tester. The measurements were performed on the copper clad layer, as shown schematically in figure 2(a). The micro-hardness test was performed according to figure 2(a) and repeated five times for the base metal as well as for the weld zone in each sample. The applied microscope used to test micro-hardness has distance meter and by using this equipment, 10 experiments were performed on each specimen according to figure 2(a).

The samples were divided into two groups to distinguish the weld zone from the base material: A: samples with up to 50% reduced cross-section and B: samples with more than 50% reduced cross-section. The weld zone in the copper clad layer for the samples up to 50% reduced cross-section was detected by observing the interlayer...
| Step | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|------|---|---|---|---|---|---|---|---|---|----|----|----|----|
|      | $R_a$% | $R_{a1}$% | $R_{a2}$% | $R_{a3}$% | $R_{a4}$% | $R_{a5}$% | $R_{a6}$% | $R_{a7}$% | $R_{a8}$% | $R_{a9}$% | $R_{a10}$% | $R_{a11}$% | $R_{a12}$% | $R_{a13}$% |
| 20   | 17.02 | 34.4 | 46.6 | 57.56 | 66.1 | 72.36 | 78.3 | —  | —  | —  | —  | —  | —  | —  |
| 10   | 17.02 | 29.5 | 40.05 | 49.04 | 56.78 | 63.28 | 68.82 | 74.3 | —  | —  | —  | —  | —  | —  |
| 15   | 17.02 | 26.48 | 34.41 | 40.2 | 46.32 | 50.16 | 55.2 | 61.09 | 64.71 | 68.04 | 71.31 | 74.1 | 76.46 |
| 20   | 17.02 | 33.92 | 46.9 | 57.43 | 65.88 | 72.88 | 77.41 | —  | —  | —  | —  | —  | —  | —  |
| 20   | 17.02 | 30.34 | 40.66 | 49.66 | 57.04 | 63.28 | 69.37 | 74.98 | —  | —  | —  | —  | —  | —  |
| 10   | 17.02 | 27.33 | 34.57 | 40.46 | 46.32 | 51.28 | 55.86 | 60.97 | 64.7 | 68.93 | 72.05 | 74.06 | 77.23 |
| 15   | 17.02 | 33.92 | 47.04 | 56.65 | 67.14 | 74.2 | 77.89 | —  | —  | —  | —  | —  | —  | —  |
| 20   | 17.02 | 33.92 | 47.04 | 56.65 | 67.14 | 74.2 | 77.89 | —  | —  | —  | —  | —  | —  | —  |
| 30   | 17.02 | 32.14 | 42.18 | 50.72 | 59.78 | 64.24 | 69.80 | 74.60 | 77.41 | —  | —  | —  | —  |
| 15   | 17.02 | 25.29 | 32.79 | 39.44 | 45.59 | 50.58 | 55.99 | 60.35 | 64.24 | 67.81 | 71.1 | 74.  | 76.56 |
| 10   | 17.02 | 25.29 | 32.79 | 39.44 | 45.59 | 50.58 | 55.99 | 60.35 | 64.24 | 67.81 | 71.1 | 74.  | 76.56 |
| 15   | 17.02 | 25.29 | 32.79 | 39.44 | 45.59 | 50.58 | 55.99 | 60.35 | 64.24 | 67.81 | 71.1 | 74.  | 76.56 |
| 30   | 17.02 | 25.29 | 32.79 | 39.44 | 45.59 | 50.58 | 55.99 | 60.35 | 64.24 | 67.81 | 71.1 | 74.  | 76.56 |
at the cross-section area of them, as shown in figure 2(b). An optical microscope was used to diagnose the welding zone from the base metal via observation of the interface line between the copper clad and the aluminum core in cross-section. The weld zone in the copper clad layer was not detected by observing the boundary between the samples with more than 50% reduced cross-section. In these samples, identification of the weld zone from the base metal was carried out using metallography with the observed structural difference between the weld zone and the base metal.

2.5. Ductility
The diameter of the CCA wire specimens was between 4–10 mm. To prepare the tensile test specimen from the copper clad layer, the wire cut EDM method was employed as the most appropriate method. In this method, due to continuous cooling, temperature change was minimal due to heat distribution in the sample. Tensile specimens, as shown in figure 3, were machined according to ASTM E8-04 and the diameter of the CCA wire specimens [39, 47]. The aluminum wire was not cleaned from the oxide before cladding to prevent interlayer bonding. In addition, the annealing operation was not performed during the NCWD process. Thus, there was an extremely weak interface bonding between copper and aluminum in all the samples. As a result, after the wire cut EDM, micro-tensile samples were easily peeled from aluminum without any force. That is, no metallurgical bonding was established between the copper coating layers and the aluminum core. As shown in figure 3, the prepared sample had a curvature equal to the corresponding wire radius.

Figure 2. (a) The schematic illustration of micro-hardness measurement positions in two regions in the cross-section of the copper clad layer; (b) Diagnosis of the welding zone position using an optical microscope.

Figure 3. Tensile sample preparation: (a) tensile specimen dimensions and (b) wire cut EDM from the specimen with a 8.18 mm diameter.
During bulk deformation, ductility of a material is determined by simple uniaxial tensile testing, which is known as the engineering strain at fracture. In other words, ductility is the percentage of the elongation or reduction ratio of the cross-sectional area of the material to the final strain, which is determined using equation (1) for the striped specimens [48].

\[ \epsilon_{f0} = \frac{L_f - L_0}{L_0} \times 100 \]  

(1)

The sample gauge length \( L_0 \), width \( w \), and thickness \( t \), according to figure 4, as well as the test speed and the alignment of the two sides of the sample during the test affect the test result. The Bertella-Oliver equation (equation (2)) was proposed to correct elongation with different cross-section areas and gauge lengths. In this equation, the slimness ratio \( K \) is determined using equation (3) \( (A_0 = tw) \), while the constant of the material \( a \) is determined using equation (4), by performing two tensile tests of the same material with different dimensions [48].

\[ \epsilon_f = \epsilon_{f0}(K)^{-a} \]  

(2)

\[ K = \frac{L_0}{\sqrt{A_0}} \]  

(3)

\[ -a = \frac{\ln \epsilon_{f2} - \ln \epsilon_{f1}}{\ln K_2 - \ln K_1} \]  

(4)

For comparability of elongation (ductility) values of specimens with different geometries, the use of the Bertella-Oliver correction factor is recommended. However, if a tensile test specimen is separated from the wall of a thin tube along the length, the (A-A) cross-section of the specimen shown in figure 4 at the gauge length will have curvature, as shown in figure 5. If the radius of curvature varies for different specimens, a different correction factor from the Bertella-Oliver equation is required. An appropriate correction factor for this case was not provided in previous references. Therefore, for samples with cross-section similar to that in figure 5, the modified slimness ratio \( K_c \) was proposed according to equation (5). Here, the cross-sectional area was obtained through equation (6). Moreover, similar to the Bertella-Oliver equation, the constant of the material \( a \) was calculated from equation (7). By using the modified slimness coefficient and equation (2), elongation and resulting ductility were obtained.

\[ K_C = \frac{L_0}{\sqrt{A_{CO}}} \]  

(5)

\[ A_{CO} = 2tr_{D} \sin^{-1} \left( \frac{w_D}{2r_D} \right) \]  

(6)
In equation (6), the relationship between the CCA wire diameter and the curvature radius of the test specimen was \( \rho_{2} = \frac{D_{2}}{2} \). In experiments performed on the specimens listed in table 1, sample length changes were recorded during the tensile test using a digital microscope, as shown in figure 6, and the initial and final lengths of the fracture moment were specified by measuring two pixels marked on the specimen.

\[ -a = \frac{\ln e_{f2} - \ln e_{f1}}{\ln K_{C2} - \ln K_{C1}} \] (7)

3. Results and discussion

3.1. Microstructure

The effect of the total cross-section reduction rate on the geometric patterns of the interface at the weld zone is shown in figure 7. Moreover, the cross-section image of the sample with a diameter of 9.20 mm is shown in figure 7(a). It has a total area reduction of 17.02% and the knob was clearly observed at the weld zone. The thickness of the copper clad layer in the maximum level was 0.599 mm; however, the thickness of the other regions of the base metal belonging to the copper clad layer was equal to 0.441 mm. As demonstrated in figure 7(b), with the section’s diameter of 7.05 mm and \( R_{at} = 51.28\% \), the knob of the weld zone was not detectable and the entire area of the copper clad had the approximate thickness of 0.309 mm. According to the observations, after reducing the cross-section up to 51.28%, the copper clad was uniform throughout the region [12, 49, 50]. In figure 7(b), the dark part in the interface was aluminum oxide and some intermetallic materials, as indicated in figure 7(c). Moreover, figure 7(d) shows the EDAX test position. According to EDAX shown in figure 7(e) and some references, the mentioned intermetallic compounds included \( \text{Al}_{4}\text{Cu}_{9}, \text{Al}_{2}\text{Cu}, \text{and AlCu} \) [26, 28, 42, 46].

As can be observed in figures 8 and 9, the weld zone was easily detectable by the microstructure. Indeed, the weld microstructure (figure 8(a)) consisted of a coarse and elongated grains growing in the opposite direction of heat transfer (i.e., casting microstructure); while, an equiaxed microstructure (figure 8(b)) was formed within the copper clad base metal (i.e., wrought microstructure).

The effect of the total reduction ratio to the microstructure, grain size and micro-hardness of the base metal of the copper clad layer is illustrated in figure 10. It is obvious that the grain size of the copper clad decreased by decreasing the total reduction ratio (or reducing the wire diameter), which, in turn, increased the micro-hardness. This can be attributed to the enhancement of dislocation density and the formation of sub grains [51]. It should be noted that by increasing the reduction ratio to above 35%, the increase in micro-hardness was slower due to microstructure saturation caused by dislocations [34, 52, 53].

According to figure 11, casting microstructure at the weld zone was effectively refined by increasing the total reduction ratio. As can be observed, the coarse and elongated grains were replaced with an equiaxed fine grain through the occurrence of strain hardening, which, in turn, increased the micro-hardness of the weld zone significantly.

The important point to consider is the lower hardness of the weld zone in comparison to the base metal in the initial passes (figures 10(d) and 11(d)). However, by decreasing the wire diameter, the difference in hardness decreased and a relatively uniform hardness was achieved along the copper clad.
3.2. Micro-hardness

Variations of micro-hardness with regard to decreasing the cross-sectional area ($R_{at}$) of the copper clad on the base metal for drawing with a die of 10° and $R_a = 20\%$ are demonstrated in figure 12(a). As the diagram shows, with increasing $R_{at}$, micro-hardness was enhanced with a steady gradient and it increased from the initial value of 92HV to about 130HV at $R_{at} = 50\%$. After that, in $R_{at} = 72\%$, the hardness value increased to 140HV. The variation of micro-hardness with regard to decreasing $R_{at}$ on the weld zone of the copper clad for the die angle of 10° with $R_a = 20\%$ is shown in figure 12(c). As presented in the figure, initial hardness was 79.4HV and with decreasing cross-section up to 50%, the hardening trend increased linearly to about 133HV; then, hardness remained almost constant. By comparing figures 12(b) and (d), hardness at the weld zone was significantly the same as that in the base metal in all diameters.

Figure 7. Geometric patterns of the interface at the weld zone with the total reduction ratios of (a) 17.02% and (b) 51.28%, (c) the dark part in the interface (d) the EDAX test position, (e) the EDAX of the Al and Cu interface.

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In the experiment of the effect of the total cross-section reduction rate ($R_{at}$) during the drawing process with the die angle of $10^\circ$ and $R_a = 10\%$, it was observed that with increasing $R_{at}$, micro-hardness increased in the base metal of the copper clad and at the weld seam zones.

As shown in figure 13, the average hardness before reducing cross-section in the copper clad base metal was 92 HV. However, after reducing cross-section up to 76%, it was reduced to 140 HV. Hardness decreased with an almost constant rate up to about 50% reduction in cross-sectional area and then variation of hardness became almost constant with decreasing the cross-sectional area. In figure 13, the maximum difference between the maximum and minimum hardness for a specimen was about 16 HV. As shown in figure 14, changes of micro-hardness during the drawing process were observed using dies with an angle of $10^\circ$ and a $R_a = 10\%$ cross-sectional reduction related to the copper clad seam weld zone. Before surface reduction in the copper clad seam weld zone, the average hardness increased to about 146 HV. Hardness increased with an almost constant rate up to about 56% decrease in cross-section and then variation of hardness became almost constant or decreased with decreasing the cross-sectional area. In figure 14, the maximum difference between the maximum and minimum hardness for a specimen was about 30 HV. According to figures 13 and 14, there was a significant difference in terms of the average hardness between the weld zone and the base material.

The die angle is an important parameter in the NCWD process so that with increasing the die angle, the drawing force increases [54]. Increasing the drawing force is not desired because it ultimately causes the wire to rupture during the wire drawing process [54, 55]. Particularly in the CCA wire, increasing the tensile strength to a critical level will initially cause a peripheral rupture of the copper clad [31]. However, in the NCWD process,
with reducing the ductility of the copper clad after each step of drawing, the probability of the rupture of the copper clad increases \[5, 12, 56\]. Knowing the effect of the die angle on the hardness of the copper clad layer in multi-stage wire drawing helps to make a decision in designing the process of production in the CCA wire drawing process \[54, 57\]. The die angle, which produces the minimum increase in hardness and thus results in the lowest ductility in the copper clad, is the most favorable angle \[54, 57\]. The effect of the die angle with \(R_a = 20\%\) from \(R_{at} = 34\%\) to 78\% is shown in figure 13. Each point on the curve is the average of five repetitions of the micro-hardness test according to figure 2. As can be observed, samples drawn at a die angle of 30° at all drawing steps showed a greater micro-hardness than a die with a 10° and 20° angle. However, with increasing \(R_{at}\), the micro-hardness difference decreased at various angles. The effect of the die angle with \(R_a = 15\%\) from \(R_{at} = 32\%\) to 78\% is demonstrated in figure 14. Accordingly, the 10° die angle increased hardness less than the 20° and 30° angles. However, with increasing \(R_{at}\) (final drawing stages), the difference in hardness decreased at different angles \[58\]. As shown in figure 15, the die angle with \(R_a = 10\%\) had no significant effect on hardness variations of the copper clad in the NCWD process. By increasing the total cross-section reduction percentage, the wire diameter and thickness of the copper clad decreased. The effects of contact stresses between the die and the wire surface in the plastic region and the resulting unevenness of the plastic strains increased with the die angle \[2, 59, 60\]. As the copper clad became thinner, unevenness in the plastic strains in the central region of the copper clad thickness became more similar to that in the near-surface area \[50, 55, 61\]. This can be due to the more similarity of the hardness values, resulting in the ductility of the copper clad in the total cross-section reduction ratio to be greater than 70\%.

Decreasing \(R_a\) by increasing the number of wire drawing stages would increase production costs and reduce the drawing force in multi-stage wire drawing \[54\]. However, choosing a proper \(R_a\) for drawing CCA wire depends on the effect of this parameter on ductility variation of the copper clad layer during wire drawing stages \[54\]. The effect of decreasing \(R_a\) on changes of hardness variations of the copper clad during drawing stages with

Figure 9. The EDAX map for distinguishing black particles: (a) the SEM observation of particles, (b) the percentage of O, C and Cu, C) oxygen patterns and (d) copper patterns.
a die angle of 10 degrees is shown in figure 16. With increasing Ra from 10% to 15%, micro-hardness decreased at Ra greater than 50%. As observed in figure 17, the micro-hardness of the copper clad weld zone was less at Ra = 15% than at Ra = 10%. The effect of Ra with the die angle of 20° on micro-hardness change at the weld zone is shown in figure 18. Although the values were not significantly different, it is clear that the average amount of micro-hardness decreased with increasing Ra, and this trend was in good agreement with increasing Ra.

3.3. Correction factor
According to equation (1) to equation (7), the applied elongation correction factor depends on the factor (a) and the slimness ratio. As indicated in figures 19(a) and (b), the slimness ratio depends on the CCA wire diameter, width, thickness and length of the micro tensile sample gauge zone. As the wire diameter decreases, the slimness ratio increases. In this study, 18.1% of the CCA wire cross-section was copper. Therefore, in all diameters, \( t = 0.457 \text{ Dmm} \). Moreover, with increasing the length of the gauge zone, the slimness ratio increases and it decreases with increasing the width of the gauge zone. According to equation (1), the correction factor was reduced by increasing the slimness ratio. According to equation (7), factor (a) was obtained by two tensile tests and the elongation of two samples, which had with different dimensions but the same ductility. Therefore, the factor a depends on the ductility and slimness ratio of the two samples. As the copper clad ductility was reduced by decreasing the diameter of CCA wire during the NCWD process, the amount of the factor (a) varied for different samples. According to figures 19(c) and (d), as the factor (a) decreases, the amount of correction factor increases.

3.4. Ductility
Heat treatments performed on CCA wire increased the ductility of the layers, but also created brittle intermetallic compounds between copper and aluminum. The thickness growth of the intermetallic compound depends on heat treatments of time and temperature [38, 42, 46]. However, growth of intermetallic compound thicknesses do not depend on wire dimensions, indicating no marked influence of plastic deformation [5, 38]. Intermetallic compounds increase the electrical resistance of CCA wires [38]. Therefore, the heat treatment decreases the electrical conductivity of CCA wires. In this work, the cold NCWD was performed without any intermediate annealing treatment. This part elaborated on the ductility and ultimate tensile straight (UTS)
measurements of the copper clad layer of CCA wire in order to highlight the impact of the Rat presence. The values of ductility and UTS as a function of Rat for the copper clad layer is shown in figure 20. In this case, parameters of dies are $R_a = 20\%$ and $\alpha = 10^\circ$. Generally, ductility decreases and the ultimate tensile stress increases gradually with increasing $R_a$.

The copper clad of the specimen with the diameter of 10.1mm for $R_a = 0\%$ had ductility of 43% and UTS of 103MPa. According to figure 10 for this sample, the average grain size was $80 \mu m$ and the average hardness was 92 HV. Sasaki et al investigated the effect of wire drawing of copper clad steel (CCS) wire on mechanical properties of the copper clad and the steel core [25]. The hardness of the copper clad was dependent on the hardness of the steel as well as on the $R_a$ value. Thus, the hardness of the copper clad was 60HV ($HV = -9.577d + 157.2$, $d$: CCA diameter) for CCS wire with a diameter of 10.1mm and a low-carbon steel core and 70.5HV ($HV = -8.76d + 159$) for high-carbon steel core [25]. As shown in table 1, in the first step, the wire diameter decreased to 9.2mm after drawing $R_a = 17.44\%$ and, as shown in figure 20, the amount of ductility decreased by 17% and UTS increased to 283MPa. According to figure 10, the average grain size decreased to $34 \mu m$ whereas hardness increased to 111HV. In the work of Sasaki et al, the hardness of the copper clad of CCS wire with the same diameter as that of this sample with high-carbon steel core was 78.2HV [25]. In the second step, after drawing $R_a = 34.4\%$, the wire diameter decreased to 8.18 mm. As shown in figure 20, the amount of ductility decreased by 4.5%, while UTS increased to 299MPa. According to figure 10, for this drawing step, the average size decreased to $23 \mu m$ and hardness increased to 124HV. In the work of Sasaki et al, the hardness of the copper clad of CCS wire with the same diameter as that of the second sample with high-carbon steel core was 87HV [25]. Variations in ductility and UTS as a cubic function of $R_a$ with standard deviations of 0.998 and 0.985, respectively, are shown in figure 20. Moreover, figure 20, figures 21 and 22 show the effect of changing $R_a$ on the ductility and UTS trends.

Considering the cubic functions at $R_a = 50\%$, ductility at $R_a = 20\%$, 15% and 10% was 6.4%, 3.5% and 5%, respectively. Thus, ductility was greater at $R_a = 20\%$. Moreover, UTS at $R_a = 20\%$, 15% and 10% was 310 MPa, 322 MPa and 327MPa, respectively. Therefore, UTS was minimum at $R_a = 20\%$. The effect of changing $\alpha$ on the ductility and UTS trends is shown in figure 20, figures 23 and 24. Considering cubic functions at $R_a = 50\%$, ductility at $\alpha = 10^\circ$, 20° and 30° was 6.4%, 5.6% and 3.62%, respectively. Thus, ductility was
higher at $\alpha = 10^\circ$. Further, UTS at $\alpha = 10\%$, 20\% and 30\% was 310 MPa, 324 MPa and 319 MPa, respectively. Therefore UTS was the lowest at $\alpha = 10\%$.

4. Conclusions

In this study, fabrication of copper clad aluminum wire was carried out by caliber roll forming of a copper foil around the aluminum wire and welding the seam. Then, with the NCWD process without any intermediate annealing, the wire diameter decreased. The effect of die angle, die reduction ratio and total wire reduction ratio
was investigated on the ductility, microhardness and microstructure of the copper clad layer. The following conclusions were obtained:

1. During the NCWD process without using the annealing treatment between the steps, the average hardness and UTS of the copper clad increased and the average grain size and ductility decreased with decreasing the diameter of CCA wire. The amount of increased hardness was more significant between R at: 1%–50% than
Figure 17. Effect of the total cross-section reduction rate of $\alpha = 10^\circ$ at the weld zone with die reduction ratios of 10% and 15%.

Figure 18. Effect of the total cross-section reduction rate of $\alpha = 20^\circ$ at the weld zone with die reduction ratios of 10%, 15% and 20%.

Figure 19. Effect of wire diameter at the slimness ratio with (a) $W = 2$ mm and (b) $L_0 = 10$ mm and effect of the factor (a) at the correction factor with (c) $L_0 = 10$ mm, $W = 2$ mm, (d) $D = 4$ mm and $W = 2$ mm.
between R_{60}: 50\%-78\%. In addition, during this process, the hardness of the weld zone was less than that of the base metal in the copper clad, almost for all of the diameters.

2. The micro-hardness and UTS of the copper clad layer in the samples using the die with the angle of 10 degrees was less than that of the other used die angles (20 and 30 degree). In addition, the clad layer ductility during the NCWD stages for the die angle of 10 degrees was better related to larger angles.

3. By increasing the R_{60} of the die from 10\% to 15\%, the rate of increase in the micro-hardness of the copper clad layer decreased during NCWD.

4. The maximum ductility and minimum UTS in the clad layer were observed in the die with R_{60} = 20\%. 

Figure 20. The effect of the total reduction ratio on ductility and UTS with R_{60} = 20\% and \alpha = 10^\circ.

Figure 21. The effect of the total reduction ratio on ductility and UTS with R_{60} = 15\% and \alpha = 10^\circ.

Figure 22. The effect of the total reduction ratio on ductility and UTS with R_{60} = 10\% and \alpha = 10^\circ.
5. The decrease in ductility and the increase in UTS against the total reduction of cross-section from $R_{at} = 0\%$ to $R_{at} = 35\%$ was severe. This trend changed for the greater $R_{at}$ and the slope of changes decreased sharply. Thus, ductility at $R_{at} = 35\%$ was around 7%.

6. The defined correction factor was dependent on the dimensions and ductility of the micro tensile samples and the diameter of CCA wire. This factor ranged from 0.7 to 1.44 for the samples.

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