

# Innovative rotary swaged Al/Cu laminated wire conductors: characterisation of structure and residual stress

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**Abstract.** This study presents innovative, uniquely sequenced Al/Cu laminated composite wires having perspective usage for various applications, from transportation to electrotechnics. The composites were processed via the industrially applicable technology of rotary swaging, which was performed at 20 °C and 250 °C to provide the possibility to compare the effects of different swaging conditions on structure characteristics of the wires. The work-pieces were gradually swaged down to the final wire diameters of 5 mm, the total swaging degree for each swaged-piece was 3.6. After swaging, both the aluminium components of the swaged wires exhibited recrystallized ultra-fine-grained (UFG) structures with minor presence of residual stress, certain presence of stress was observed within the refined Cu structures. Microhardness measurements revealed occurring work hardening, especially for the 20 °C swaged composite.

## 1. Introduction

Research and development throughout virtually all the industrial fields has led to the emergence of various modern equipment, as well as to the introduction of a wide range of innovative materials. Heterogeneous laminates, gradient structures, and laminated and clad composites are modern materials consisting of two or more components bond at adjoining interfaces [1-4]. They are gaining increasing interest throughout various industrial and commercial branches provided by their ability to achieve enhanced properties when compared to the individual components (e.g. increased strength, better thermal and electric conductivity, enhanced corrosion resistance, decreased density, etc.). Among the most popular composite systems consisting of metallic components is the Al/Cu one [5]. Copper is used for its excellent heat and electric conductivity, while aluminium is favoured for its low density, while having reasonable strength and conductivity properties [6]. Beside other advantages, both the metals have a wide applicability, especially in the automotive and as electric conductors.

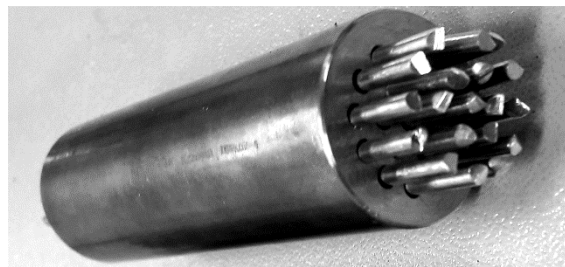
Clad composites are typically produced by welding, however, welding technologies are performed at high processing temperatures and can introduce local structure modifications and result in the formation of intermetallic phases at mutual interfaces [2, 7]. By this reason, plastic deformation methods, and especially the methods of severe plastic deformation (SPD), are advantageous for production of clad composites since they can be performed at lower temperatures and usually also at room temperature. Among the widely used and/or researched SPD methods are for example equal channel angular pressing (ECAP) [8, 9] and its modifications (TCAP [10], TCMAP [11], etc.), high pressure torsion (HPT) [12, 13], accumulative roll bonding (ARB) [14], and rotary swaging (RS) [15-17], which was used to manufacture the herein studied composites. RS is a versatile technology



enabling to manufacture various axially symmetrical products via a repeated action of a set of rotating dies. The dies affect the work-piece surface with compressive radial forces by which they incrementally impose the combination of shear and compressive strains into the work-piece. The nature of the process enables to avoid large stress gradients and supports progressive grain refinement and improvement of mechanical and utility properties. The study focuses on preparation of 5 mm clad composite wires at two different swaging temperatures. The aim is to provide detailed description of the influence of RS on the development of structure and residual stress.

## 2. Experimental methods

The original materials the swaged composites from which were fabricated were electro-conductive CP Cu (0.015 % P, 0.002 % O, 0.002 % Zn, balance Cu) and electro-conductive CP Al (0.25 % Fe, 0.20 % Si, 0.05 % Cu, balance Al). The Al shell had the original diameter of 30 mm, while the Cu wires diameters were 3 mm each (figure 1). The composite was processed via rotary swaging (RS) at 20 °C – room temperature – and at 250 °C; the temperatures were selected based on our previous research described e.g. in studies [5, 18-20].



**Figure 1.** Material before swaging.

Both the composites were gradually swaged down from the original 30 mm to the final 5 mm. The total reduction ratio was calculated using equation (1), where  $S_0$  and  $S_n$  are the cross-section areas at the input and output of the swaging dies, respectively. The reduction ratio for the 5 mm wires was 3.6.

$$\varphi = \ln \left( \frac{S_0}{S_n} \right) \quad (1)$$

The subsequent analyses focused on the influence of processing temperature on the development of substructure and residual stress. Thorough investigations of structures of the swaged composites were carried out via scanning electron microscopy (SEM). The performed examinations were done via electron backscattered diffraction (EBSD) analyses. The samples were ground on SiC papers to 2000 grit and subsequently polished electrolytically. EBSD analyses were performed on transversal sections using a JEOL FESEM 7000F equipment with an EDAX DigiView High Resolution Camera. SEM-EBSD scans were also used to provide an insight into the residual stress development. The scans were evaluated via the OXFORD Instruments [21] and ATEX [22] software. The grain size parameter was assessed as the average area of the individual grains (in  $\mu\text{m}^2$ ). Residual stress was evaluated via analyses of internal misorientations in the scale from 0° (blue colour) to 15° (red colour).

## 3. Results and discussion

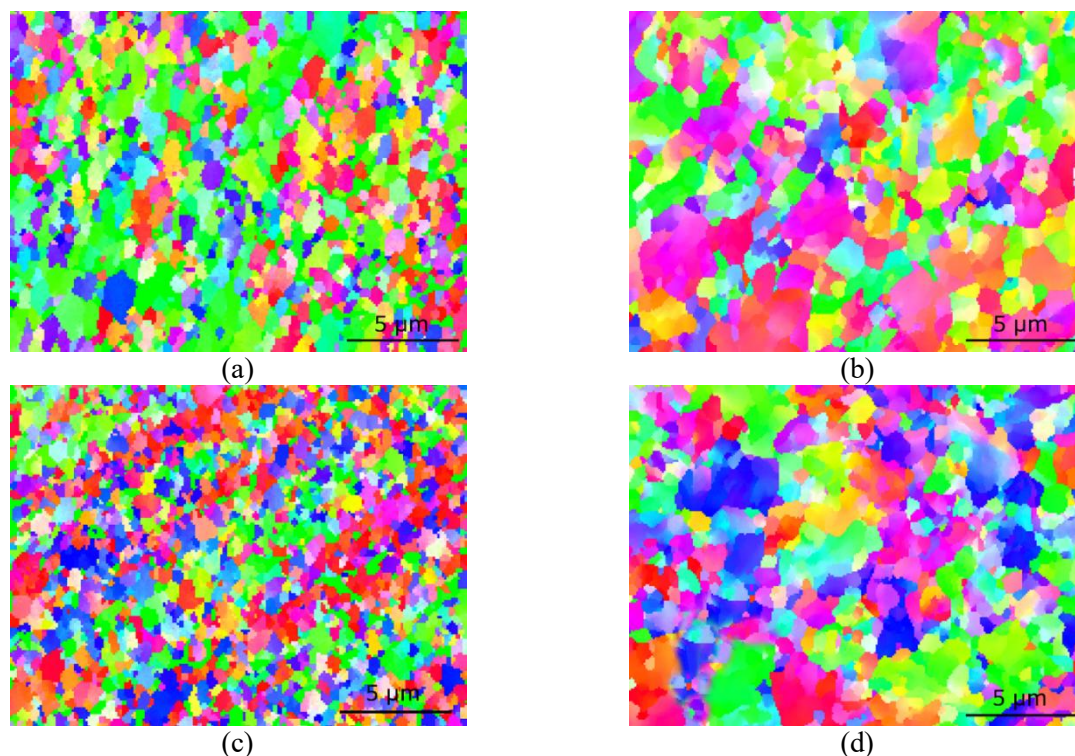
### 3.1. Structure characterization

Figures 2a to 2d depict the results of EBSD analyses of 5 mm composites after the final swaging pass to 5 mm via orientation image maps (OIM) taken to the direction of the swaging axis. The structures of both the Al and Cu components of both the swaged composites evidently exhibited restoration and significant grain refinement. However, the grains within the Cu component were larger than within the Al. This can be attributed to the intrinsic properties of Al (activation energy and stacking fault energy) [23]. Despite the fact that the imposed energy introduced recrystallization within both the Cu and Al

components, the flow stress and high stacking fault energy of Al facilitate boundary migration and substructure development, which supported restoration and recrystallization within Al even during room temperature processing [24]. Also, the lower flow stress causes the Al to consume the imposed strain more easily than the Cu.

The analyses of average grain areas show that the grains within the Cu component were smaller for the 20C composite than for the 250C one ( $2.1$  and  $2.9 \mu\text{m}^2$ , respectively). Nevertheless, various shades of the colours depicting the ideal orientations within the individual grains point to substantial substructure development and formation of ultra-fine subgrains. This supposition was confirmed by the relatively high fractions of low angle grain boundaries (LAGBs) with misorientations lower than  $15^\circ$  pointing to the presence of subgrains [25] (46 % and 49 % for the 20C and 250C composites, respectively). The average grain areas for the Al component were  $0.62$  and  $0.39 \mu\text{m}^2$  for the 20C and 250C composites, respectively. As can be seen, the higher swaging temperature influenced positively the grain refinement within the Al component, but both the composites featured ultra-fine grained (UFG) Al structure. Also, due to the fact that the Al tended to be influenced by the imposed strain more intensively than Cu, recrystallization was more intense for this component and the level of substructure development, evaluated via the presence of subgrains characterized with LAGBs the volume fraction of which was 31 % and 27 % for the 20C and 250C composites, resp., was lower.

Similar conclusions were drawn in our previous study examining clad composites with the stacking sequence consisting of Cu sheath with Al wires [5, 7, 18]; the studied composites also exhibited substantial grain refinement during the last swaging pass and featured the formation of UFG structure. The Cu sheath exhibited substructure development with subgrains with the diameters of around  $0.1 \mu\text{m}$  and more than 50 % of the individual grains within the 250C composite Al component had the diameters of about  $0.5 \mu\text{m}$ . These findings prove that the technology of rotary swaging is suitable for production of Cu/Al clad composite wires from the viewpoint of their microstructure.

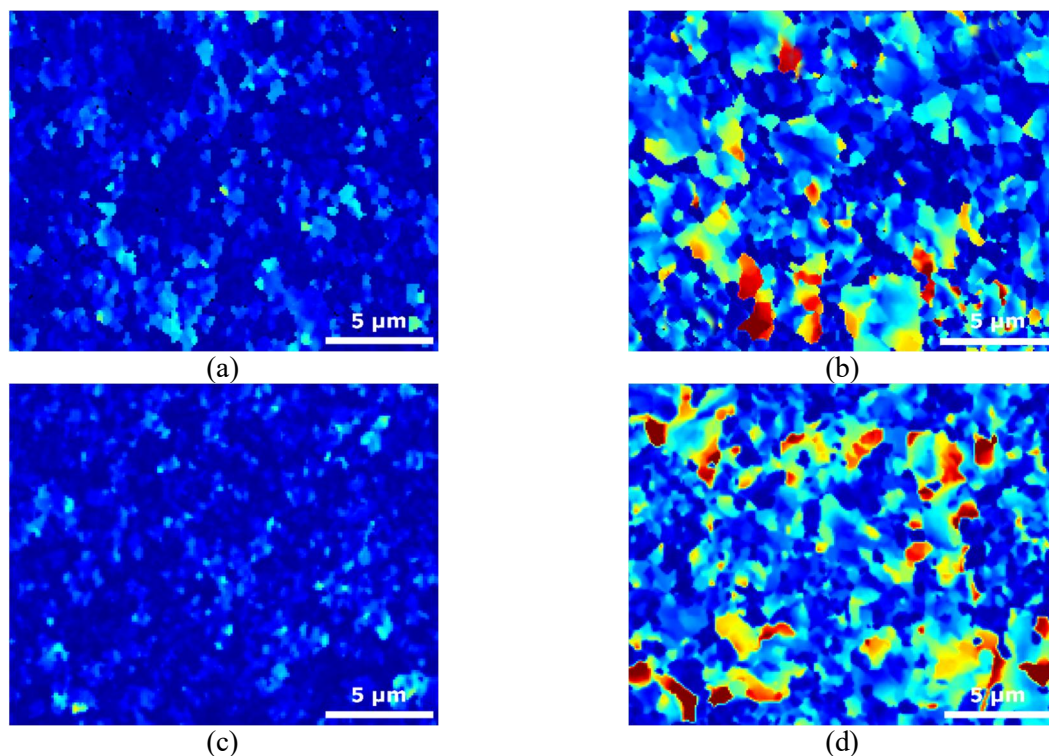


**Figure 2.** Orientation image maps for composites swaged at  $20^\circ\text{C}$  – Al component (a), Cu component (b); swaged at  $250^\circ\text{C}$  – Al component (c), Cu component (d).

### 3.2. Residual stress

Residual stress within a processed material can occur as a result of various causes, such as local heating during processing or inhomogeneous quenching, as well as due to non-uniform distribution of the imposed strain usually occurring when deformed under cold conditions [26]. For composites and multi-phase materials, residual stress usually develops as a result of the different properties of the individual component materials.

The analyses of residual stress were performed via evaluations of internal grains misorientations in the range from  $0^\circ$  to  $15^\circ$  (the rainbow scale from blue to red). Figures 3a to 3d show misorientations for the Al and Cu components of 20C and 250C composites, respectively. As can be seen, the fine grains within both the Al components featured only a minor presence of low misorientations, which corresponds to the above drawn conclusions about development of new stress-free grains. On the other hand, certain occurrence of internal misorientations pointing to the presence of residual stress was observed within both the Cu components; yellow and red regions within the grains point to the development of substructure and presence of low angle grain boundaries (LAGBs), the volume fractions of which were relatively high for both (Section 3.1). The findings thus correspond to the above drawn conclusion of substructure development within Cu for both the composites.



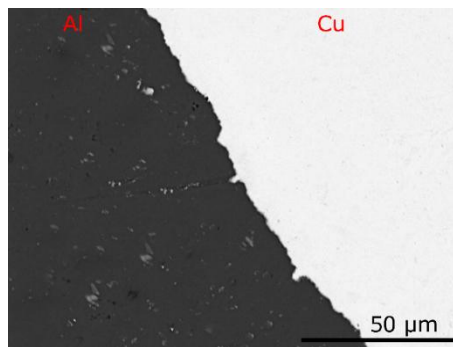
**Figure 3.** Maps of internal grains misorientations for composites swaged at 20 °C – Al component (a), Cu component (b); swaged at 250 °C – Al component (c), Cu component (d).

The differences in the occurrence of misorientations for the Al and Cu components can be attributed to the following factors. The above discussed intrinsic properties of Al provided this component with the ability to consume the imposed strain more readily, which resulted in a more intense recrystallization, lower grain size, and minor occurrence of residual stress when compared to Cu. Also, the lower stacking fault energy aggravated the conditions for recovery of Cu, which resulted in larger grain size and more substantial substructure development, i.e. the presence of internal grains misorientations. Mutual comparison of misorientations within the 20C and 250C composites did not reveal substantial effect of the swaging temperature on the occurrence of residual stress most probably due to the fact that the Al component exhibited recovery/recrystallization already during room temperature swaging and increase in the processing temperature only resulted in further grain

refinement. For the Cu component, the temperature of 250 °C was most probably not sufficient to significantly influence the restoration processes within this component and only resulted in a slight grain growth (i.e. secondary recrystallization the necessary energy for which is significantly lower than the energy necessary for primary recrystallization ensuring grain refinement [23]).

### 3.3. Microhardness

The HV values for the Cu and Al original materials were 84.7 and 25.6, respectively. The results of microhardness measurements for the composites showed that the average microhardness value for the 20C composite Al component was 54.9 HV, while for the Cu component it was 107.4 HV. The values for the 250C composite components were 46.2 HV for Al and 103.8 HV for Cu. Whereas the Cu component HV values were comparable for both the composites, the Al component exhibited more substantial hardening within the 20C composite. This can be attributed to the deformation induced precipitation observed within the Al matrix of this composite; the Fe-rich precipitates within the matrix are depicted in the SEM-BSE scan in figure 4 (the figure also shows perfect bonding of both the components). The deformation induced precipitation was observed especially in the region of Al matrix adjacent to the periphery of the swaged composite due to the direct effect of the swaging dies.



**Figure 4.** 20C composite Al-Cu interface 20 with evident precipitates in Al.

The comparison of the swaging temperatures shows that the higher temperature imparted lower HV values for both the components. This finding is in accordance with the results of measurements of deformation forces presented in our previous study [19]; the lower swaging temperature increased the flow stress and aggravated the plastic flow, which consequently imparted work hardening and resulted in higher HV values within both the components. The results of the herein presented HV measurements also correspond to the results of previously performed tensile and bending tests [19].

### 4. Conclusions

This study was focused on the deformation behaviour of Al/Cu clad composites produced using rotary swaging at two different swaging temperatures (20 °C and 250 °C). Structure analyses revealed that both the swaging temperatures resulted in the formation of UFG structures within the Al component and significant grain refinement within the Cu one. The processing temperature did not exhibit to have any substantial effect on the presence of residual stress, the occurrence of which was observed within the Cu component of both the composites. Room temperature processing resulted in higher work hardening of the Al primarily due to the deformation induced precipitation of Fe-rich particles. Suffice to say, the rotary swaging technology was successfully proven as practically applicable for fabrication of Al/Cu clad composites in the industrial scale from the viewpoint of microstructure and mechanical properties. Due to the prospective use of these composites as electro-conductive materials in the automotive, a study of electrical properties is being prepared for a subsequent publication.

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