Deformation behaviour of Cu-Al clad composites produced by rotary swaging

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Abstract. Al/Cu composites are an advantageous perspective material applicable in various industrial branches, from electrotechnics to transportation industry. This study focused on the investigation of Al/Cu clad composites produced by rotary swaging at two different temperatures, 20°C and 250°C. The composites were swaged from the original 30 mm down to 5 mm with the total swaging degree of 3.58, however, samples were acquired after multiple steps. The influences of the processing conditions on the structure were studied via scanning electron microscopy; the analyses mainly focused on the deformation behaviour of the component metals and the possible development of intermetallic phases on their interfaces, as well as on the grains orientation. During processing, the radial swaging forces were recorded with our own developed KOMAFU S600 system for dynamic detection of swaging forces. According to the results of the analyses, the swaging temperature influenced significantly the behaviour of the composites, as did also the total imposed strain. The composite swaged at 250°C was affected more notably, the cross-sections of the Al wires in the composite were deformed due to the influence of the radial swaging dies movement more significantly than in the composite swaged at 20°C. This effect was evident for all the investigated swaging steps and increased with increasing total imposed strain. The higher swaging temperature also decreased the plastic flow of the material; the deformation work was 730.3 kJ for 250°C composite and 650.7 kJ for the 20°C one. Tensile testing revealed similar effect; while the UTS for both the composites was slightly higher than 280 MPa, the plasticity of 250°C composite was evidently higher.

1. Introduction
Advances in production and manufacturing technologies introduce increasing demands on the innovative materials, one of which are composite materials advantageously providing the ability to create various combinations of mechanical, as well as physical properties. This makes them suitable for various applications e.g. in electrotechnics, aerospace and marine industry, as well as in biomedicine [1–3]. Among the favourable forms of composites are clad composites, sometimes denoted as hybrid materials. Various clad composite systems, such as Ti-TiBw [4], Ti/Cu [5], Ni/WC [6], Al/Cu/steel [7] and Mg/Al/steel [8], have already been studied. Nevertheless, the majority of the studies deal with the Al/Cu system [9–12]. This combination of materials is favourable for its beneficial thermal and electrical conductivity and low density, as well as the advantageous weight and cost when compared to Cu. Cu/Al clad composites can for example be applied for air-cooling fans, and armoured cables [13], and as alternatives to copper in aerospace and automotive industry and electrotechnics.
Among the conventionally applied processes for composites manufacturing are various types of welding [14–16]. However, they feature the disadvantage of high processing temperatures introducing local structure modifications, which can result in the development of internal stresses or formation of intermetallic compounds at the interfaces (although these can also be introduced by a heat treatment) [17]. Nevertheless, composites can also successfully be manufactured at ambient temperatures (under cold conditions) by application of large plastic (shear) strains via conventional methods (rolling [8], extrusion [18] etc.), as well as non-conventional ones (severe plastic deformation – SPD – processes [18–21]).

One of the most favourable methods to manufacture long composite work-pieces is rotary swaging (RS), which can advantageously be used to manufacture copper-based-clad-composite wires to be used as conductors in the automotive. RS also ensures dimensional accuracy and high quality surface and therefore eliminates subsequent machining. As recently reported by Kocich et al, RS is suitable for fabrication of clad composites in forms of wires, tubes and long rods [17]. Zhang et al [22] used RS for production of bimetallic tubes.

The aim of this study was to investigate the influence of the swaging technology, which was performed at two different temperatures, on the structural development of the processed Al/Cu clad composites. Among the aims was to observe the influence of the selected processing temperature on the structure development and possible occurrence of intermetallic compounds at the Al-Cu interfaces. The radial swaging forces, affecting primarily the radial flow of the processed material, were recorded during swaging and the properties of the swaged pieces were assessed via tensile testing. Scanning electron microscopy was further used for supplemental analyses of texture development.

2. Experimental methods
The Cu/Al clad composites were produced using the rotary swaging (RS) technology. The original materials were electro-conductive commercial purity (CP) Cu (0.002% O, 0.015% P, 0.002% Zn, bal. Cu) and electro-conductive CP Al (0.20% Si, 0.25% Fe, 0.05% Cu, balance Al). To observe the influence of the preparation conditions, RS was performed at two different temperatures (room temperature for composite A and the temperature of 250°C for composite B), the selection of which ensued from our previous research [13,17].

For both the samples, the original outer diameter of the Cu shell was 30 mm and the diameters of the 19 Al wires were 3 mm (figure 1). Both the composites were processed to 5 mm and, during swaging, 10 mm, 6 mm and 5 mm samples were acquired. The individual reduction ratios summarized in table 1 were computed using the \( \varphi = \ln \left( \frac{S_0}{S_n} \right) \) relation, where \( S_0 \), \( S_n \) were the entering and final cross-sectional areas, respectively. Our own KOMAFU S600 system for dynamic detection of swaging forces was used to record the radial swaging forces during processing [23].

The investigations of the swaged composites mechanical properties were performed via tensile testing. The parameters for the tensile tests were the following: specimens with length of 150 mm; strain rate of \( 1.47 \times 10^{-3} \) s\(^{-1}\). Detailed analyses of the structures of the swaged composites and the interfaces between the individual components were performed via scanning electron microscopy (SEM) and using the energy dispersive spectroscopy (EDX) and electron backscatter diffraction (EBSD) analyses. The samples were ground on SiC papers and electrolytically polished. EBSD analyses were processed on transversal cuts using a JEOL FESEM 7000F device with an EDAX DigiView High Resolution Camera.
| RS pass number | total deformation degree φ (°) |
|---------------|-------------------------------|
| 1             | 0.36                          |
| 2             | 0.81                          |
| 3             | 1.08                          |
| 4             | 1.39                          |
| 5             | 1.75                          |
| 6             | 2.20                          |
| 7             | 2.77                          |
| 8             | 3.22                          |
| 9             | 3.58                          |

3. Results and discussion

3.1. Deformation behaviour

The wires within the composites were categorized as the axial wire, the inter-layer wires and the outer-layer wires. Wires shape changes after swaging were obvious, however, the plastic flow was different for composites A and B.

For all the A and B composites, the shape of the axial wire cross-section changed the least; its diameter was comparable for both the 10 mm samples (the diameters of circumscribed circles were 943 µm for composite A and 935 µm for composite B). However, the axial wire diameters were larger for composite A than for composite B with continuing swaging.

The shape changes of the inter-layer wires were more notable. Their original shapes were preserved the most in 10 mm composite A, however, 10 mm composite B already exhibited evident changes. To evaluate the deformation of the wires cross-sections, the ratios of two perpendicular dimensions were calculated (the largest dimension related to the largest perpendicular dimension expressed in percent) and summarized in table 2. For composite A, the ratio of the two dimensions was approximately 40% for the 6 mm and 5 mm samples, while for composite B it was approximately 30%. The reduction steps thus had comparably homogenous effects on the composites, which behaved more or less as single-component materials. However, the radial flow was more intense for composite B, the wires cross-sections of which got flatter and more elongated, due to the elevated swaging temperature, which decreased the composite flow stress, supported the development of restoration processes, and thus facilitated the plastic flow of both the composite components [17].

The mentioned phenomena affected the most the behaviour of the outer-layer wires. Whereas the cross-sections of the outer-layer wires in 10 mm composite A changed comparably to the inter-layer ones, the 10 mm composite B (figure 2(a)) outer-layer wires cross-sections exhibited significant deformation – their elongation was more evident than for the inter-layer wires. The most notable cross-section deformation exhibited the wires in 5 mm composite B (figure 2(b)).

Table 2. Differences in two largest perpendicular wires dimensions.

| Diameter (mm) | 10  | 6  | 5  |
|---------------|-----|----|----|
| Inter-layer wires |     |    |    |
| Composite A   | 98% | 40%| 43%|
| Composite B   | 95% | 33%| 29%|
| Outer-layer wires |      |    |    |
| Composite A   | 94% | 24%| 34%|
| Composite B   | 73% | 17%| 10%|
The specific shapes of the Al wires in the swaged composites were caused primarily by the radial shear component of the imposed strain introduced by the simultaneous effect of rotation and centripetal movement of the hammering dies [23]. The swaging force vector consists of the normal and radial components, the normal component of which influences the axial plastic flow, while the radial component influences the radial plastic flow of the swaged material.

3.2. Swaging parameters

The swaging force developments in time for the 10 mm samples are shown in figures 3(a) and 3(b). The figures clearly show that lower forces were recorded for composite B, which corresponds to its lower flow stress introduced by the elevated swaging temperature, as written above. The average swaging force was 80 kN for this composite, while for composite A it was almost 90 kN. The occurring restoration processes influencing the flow stress and facilitating the plastic flow thus affected also the swaging forces and the deformation work, which was 750.3 kJ for composite A and 717.7 kJ for composite B.

The development of the swaging force during the single pass was also different for both the composites. For composite A, the force increased steeply in the moment when the swaged material got to the reduction zone of the dies and further increased slightly with continuing swaging. This phenomenon was related to the effect of the free end [17]. At the beginning of swaging, the material is not constrained in the axial direction and its flow is easier than in the subsequent swaging stages, in which the radial movement of the material is constrained by the dies and the axial movement by the swaged end. The load to the machine then increases with progressing swaging pass [1]. On the other hand, the force for composite B exhibited more or less steady development during the whole pass, which can be attributed to the elevated swaging temperature and decreased flow stress.

Figure 2. SEM image of: cross section of 10 mm composite B (a); cross section of 5 mm composite B (b).

Figure 3. Development of swaging forces: 10 mm composite A, (a); 10 mm composite B (b).
A more detailed study of the relation of structure phenomena and the swaging forces development for multiple steps is being prepared for a subsequent publication.

3.3. Microstructure development

The evolution of (sub)structure and possible development of intermetallic phases were investigated via scanning electron microscopy (SEM). The presence of intermetalllics was observed via SEM-EDX analyses. For the 10 mm samples, the development of the intermetallic phases on the interfaces of both the composites A and B was neglectable. However, the intermetalllics started to be notable especially for composite B with continuing swaging. The presence of mixed phases was observed for all the 6 mm and 5 mm samples, but the extent and form of their development was different.

As can be seen in figure 4(a), 6 mm composite A exhibited localized thin bands of intermetalllics on the very interfaces of the two metals; the detected phases were Al\textsubscript{2}Cu\textsubscript{3} and Al\textsubscript{4}Cu\textsubscript{9}. The intermetalllics were cracked in some locations, but mostly adjoined the wires and did not crumble away. On the other hand, the intermetalllics within composite B occurred in a greater extent (figure 4(b)); the detected phases were AlCu\textsubscript{2}, Al\textsubscript{2}Cu\textsubscript{3} and Al\textsubscript{4}Cu\textsubscript{9}. The fact that recent studies have shown even the temperature of 300° C to be safe from the viewpoint of intermetalllics development [13,17] points to the fact that the original swaging temperature of 250° C increased notably during swaging due to the development of deformation heat [24]. Similarly to the behaviour of the Al wires, the behaviour of intermetallics was also affected by the radial movement of the dies causing local accumulation of intermetallics in preferential locations. Although intermetallic phases are known to be brittle [2], the elevated temperature and high imposed strain imparted them higher plasticity and, although mostly crashed, they surrendered to the behaviour of the surrounding material and exhibited the tendency for radial plastic flow, as observed also for the Al wires (documented in Section 3.1).

![Image](a)

![Image](b)

**Figure 4.** Development of intermetallic phases for 6 mm composite A (a); 6 mm composite B (b).

3.4. Texture

Due to the limited length of this contribution, only a short insight into the texture development via pole figures (PFs) acquired perpendicular to the swaging axis is presented herein, while a deeper study is being prepared for a subsequent publication.

Figures 5(a) and 5(b) depict the texture of the central Al wire of composite A after swaging to 10 mm and 5 mm, respectively, whereas figures 5(c) and 5(d) show the texture of the Cu sheet of composite A (middle diameter) after swaging to 10 mm and 5 mm, respectively. The grains within the Al wires and also the Cu sheet exhibited a strong tendency to form the \langle111\rangle fibre (Copper texture) [25], however, especially the Cu sheet featured the presence of the \langle001\rangle fibre (Goss texture), too. Similar texture development was observed in FCC metals after imposing shear strain (deformation via severe plastic deformation processes) [26]. The 10 mm sample featured larger deviations from the ideal texture orientations, the intensities of which increased with continuing swaging. The texture intensities were higher for the 5 mm sample due to the high imposed shear strain, although restoration processes can be expected to have occurred during swaging from 10 mm to 5 mm. Nevertheless, these
would most probably primarily influence the grain size, which will more in detail be analysed in a subsequent publication. These findings document the influence of the radial (shear) component of the swaging force.

![Textures in composite A](image)

**Figure 5.** Textures in composite A: central Al wire in 10 mm sample (a); central Al wire in 5 mm sample (b); Cu sheet (middle diameter) in 10 mm sample (c); Cu sheet (middle diameter) in 5 mm sample (d).

### 3.5. Tensile tests

In order to correspond with the measurements of the swaging parameters, the herein presented tensile tests results were acquired for the 10 mm samples. The final stress-strain curves are depicted in figure 6. The Figure shows that the ultimate tensile strength (UTS) was comparable for both the composites (UTS of 285 MPa and 282 MPa for composites A and B, respectively). However, their plasticity and deformation behaviour, indicated by the curve slope, were quite different.

![Stress-strain curves](image)

**Figure 6.** Stress-strain curves for 10 mm composites A and B.
The curve for composite $A$ exhibited steeper initial increase, which points to higher deformation strengthening. The elongation before reaching the yield strength and the elongation to failure were also lower for composite $A$ than for composite $B$. This proves the structure of composite $A$ to have a higher accumulation of defects (precipitates) and dislocations than the structure of composite $B$ [27]. These findings correspond to the above drawn partial conclusions; the elevated swaging temperature provided composite $B$ with better plasticity, and facilitated the plastic flow when compared to composite $A$ featuring more obstacles for dislocations movement.

4. Conclusions
This study was focused on the deformation behaviour of Al/Cu clad composites produced using rotary swaging at two different swaging temperatures (25°C and 250°C). The temperature of 250°C advantageously decreased the flow stress of the composite, which resulted in decreased swaging forces and deformation work (lower load on the machine), as well as increased plasticity, while the 20°C one exhibited significant work hardening. However, for 6 mm and 5 mm samples, 250°C together with the high imposed (shear) strain induced local development of intermetallic phases on the interfaces of the two metals, which exhibited tendencies to crack. The texture analyses revealed a strong formation of $<111>$ fibre in both the components. A deeper study of mechanical, as well as electrical properties is being prepared for a subsequent publication. According to the results, the rotary swaging technology was successfully proven as practically applicable for fabrication of Al/Cu clad composites in the industrial scale.

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