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Fabrication and characterization of cold-swaged multilayered Al–Cu clad composites

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ABSTRACT

This study was focused on microstructure development and mechanical properties of three-layered Al–Cu clad composites with different stacking sequences. The composites were fabricated using cold rotary swaging (RS). To evaluate strain distribution of the individual clad composites, two variants with the overall true strain 2.2 and 2.7 were fabricated. Subsequently, heat treatments were applied to examine structure changes and a possible development of intermetallic layers.

The Cu/Al/Cu composites featured 20% higher tensile strength and microhardness after RS when compared to the Al/Cu/Al. The bending strengths were similar. Decrease of microhardness toward the swaged rods axes confirmed decrease of strain intensity. The grain size in the composites after RS was significantly refined. The structures featured bimodal grain size with a majority of grains smaller than 5 μm. A higher annealing temperature introduced higher softening. Both the heat treatment modes caused development of intermetallic layers, although their occurrence was localized for the Al/Cu/Al composite. The higher temperature resulted in an increase of intermetallic layers, but their thickness was under 2 μm. Metastable Al_2Cu_3 phase occurred at the lower temperature. This phase was not detected after annealing at the higher temperature. The interfacial layers consisted of $AlCu_3$, Al_2Cu and AlCu intermetallic compounds.

1. Introduction

Advance in technology goes hand in hand with increasing demand for materials with enhanced properties. One of the possibilities satisfying this demand in various industrial branches is production of clad composite materials, in which materials with different properties are connected together. These materials are likely to be labeled as hybrid materials [1]. Fabrication of composite materials is one of the main focuses of up-to-date research. Design and development of clad composite materials with optimized combination of properties includes selection of the individual component materials and their sequences. It is necessary to take into account not only the properties of the individual materials, but also their possible interactions.

Various composite systems, such as steel/Al [2], steel/Al/Cu [3], Mg/Al/steel [4], and Ti–TiBw/Ti [5], have already been experimentally manufactured. However, the majority of works has been focused on the Al/Cu clad composite system due to its high thermal and electrical conductivity and low density, as well as the advantage of competitive price in comparison with single Cu materials [1,6–11]. These properties are among the reasons for applicability of these composites in air-cooling fans, armored cables or bus-bar conductor joints [9]. Cu/Al composites seem to possibly substitute pure copper in automotive and aerospace industry and electrotechnics. As study [10] highlights, the weight of the two-layered clad composites can be reduced by 40% when compared to Cu alloys with equivalent properties, which can result in almost 50% cost savings. Contradictory demands on properties of one single material are also the reason for the increasing interest in hybrid metal materials [11].

Among the already known processes of composite materials fabrication are solid state welding [12], explosive welding [13–15] and friction welding [16]. The main disadvantages of the conventional welding methods are high operating temperatures and their unsuitability for production of long products. Due to this, hybrid materials with limited shapes can only be produced using these processes. Nevertheless, composites can also be

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manufactured under lower temperatures or under cold conditions with application of plastic deformation. Using these technologies, excellent bonding of similar and dissimilar materials can be achieved. At present, conventional (extrusion [17–19] and rolling [7,10]), as well as non-conventional, methods for production of composite materials are investigated. The most commonly used non-conventional ones are the severe plastic deformation (SPD) processes, such as accumulative roll bonding (ARB) [20–25] and equal channel angular extrusion (ECAE) [26].

The disadvantage of some methods is the existence of residual stresses in the material after processing. Usually, the stress is located at the areas of bond interfaces and their vicinities [27,28]. To relax the stress, heat treatment is a commonly applied solution. The heat treatment is often performed also to achieve increased formability, which is needed for secondary processing, such as cold rolling or deep drawing. On the other hand, as a result of such a treatment a danger of formation of a brittle Cu_xAl_y intermetallic phases occur in the areas of bonding of the individual layers. Possible increase in thickness of the intermetallic layer can have a deteriorating effect on strength of the bond, as well as on the mechanical and electrical properties of the bonded layers [29–31]. It is thus necessary to optimize the temperature and time of heat treatment with regard to the properties of the processed composite.

As was already mentioned, only some of the technologies can be applied to produce long axi-symmetric composite work pieces. The commonly known and used manufacturing process is rolling. One of the most suitable methods for production of long clad composites is also rotary swaging (RS). Among the main advantages of swaging process is a high quality surface and dimensional accuracy of the swaged pieces, which eliminate the necessity of subsequent machining. In this sense, this technology can be used e.g. to fabricate copper clad-composite wires used as conductors in the automotive industry. Although rotary swaging is known for quite a long time, little attention has been paid to clad composites manufacturing by this technology.

The aim of this study was to provide detailed information about the influence of RS technology on the final microstructures and properties of the processed composites. For our experiment, we selected two different materials (Al, Cu) with the purpose of fabrication of two different three-layered clad composites. We researched the differences between the individual stacking sequences, as well as the strain distribution from the outer radius to the central axis of the individual clad composites. Tensile and bending properties were investigated via mechanical testing with integrated recording of acoustic emission. Microhardness and microstructure characteristics were investigated as well. Other objectives of this research were to investigate the influence of various subsequent heat treatments and to detect a possible occurrence of intermetallic phases.

2. Experimental methods

The Cu/Al/Cu and Al/Cu/Al clad-composites were fabricated using cold rotary swaging (RS) process. Materials used in this study were copper (99.97% purity, 0.002% O, 0.015% P, 0.002% Zn) and aluminum of the commercial purity (0.20% Si, 0.25% Fe, 0.05% Cu, balance Al). In order to define the influence of stacking sequences on the final properties, two variants were experimentally investigated. The first variant was swaged with the Al/Cu/Al stacking sequence (composite A), the second one had Cu/Al/Cu stacking sequence (composite B) (Fig. 1). The fabrication technology of the individual composites of circular cross-sections is schematically depicted in Fig. 1. The overall initial outer diameter of both the composites was 30 mm. The outer diameter of the inserted tube was 20 mm and the central rod had the diameter of 10 mm (Fig. 1).

During swaging, various deformation reductions were applied. The individual imposed true strains computed using the Eq. (1), where S_0, S_n are the initial and final cross-sections, respectively, are summarized in Table 1.

$$\varphi = \ln(S_0/S_n) \tag{1}$$

Both the composites were rotary swaged under cold conditions within six passes to the diameter of 10 mm (reduction ratio 88% i.e. $\varphi = 2.20$). A part from both the swaged rods was cut and subsequently swaged down to the diameter of 7.5 mm in one pass (reduction ratio 94% i.e. $\varphi = 2.77$). During the swaging process, the actual temperatures of the clad composites were measured using a thermocouple. The individual values are depicted in Table 1.

To determine the influence of a heat treatment on the mechanical properties of the individual layers, the swaged clad composites were subjected to two different heat treatment modes (i.e. 300 °C/30 min and 350 °C/30 min).

The mechanical properties of the swaged composites were examined using tensile and bending tests. All the tests were performed on a Testometric M500-50CT device at room temperature. Each of the samples for tensile tests had a circular cross section with 7.5 mm in diameter and 120 mm in length. During tensile tests, the strain rate was $1.3 \times 10^{-3}\ s^{-1}$. The samples for bending

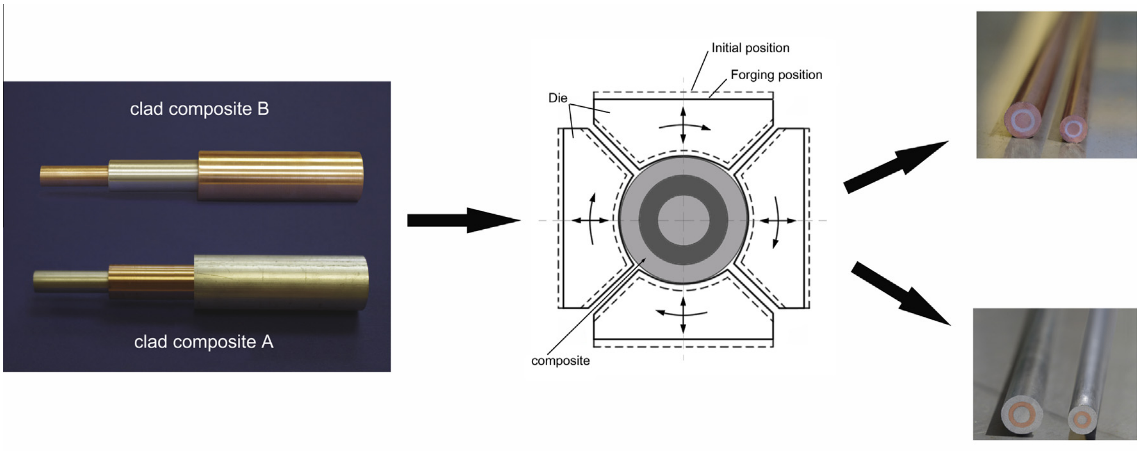

Fig. 1. Schematic depiction of the fabrication technology of the composites.