Correlation of Texture and Residual Stress in Twist Channel Angular Pressed Laminated Al/Cu Composites

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Abstract. Composites are generally materials consisting of a minimum of two phases or components, which are selected for their advantageous properties the combination of which provides the final composite material with better specific properties than those of (the original) single-phase materials and alloys. One of the composite types is clad composites, or laminated composites, consisting of layers of individual (metallic) materials. The presented study deals with laminated Al/Cu composite billets, which were processed via the severe plastic deformation (SPD) method of twist channel angular pressing (TCAP). The primary advantage of the SPD methods in general is their ability to introduce significant shear strain, resulting in substantial refinement of the grains of the processed materials, which consequently enhances their properties. The study is specifically focused on assessing the effects of single and double TCAP pass on the specific lattice rotations induced via the severe shear strain within the reinforcing Cu wires, which typically manifest in the changes in residual stress distribution and modifications in texture. The results revealed that after the first TCAP pass, the imposed strain was not homogeneous across the cross-section of the TCAP-ed composite sample as the individual Cu wires featured differences in the distribution of residual stress, as well as in the observed ideal texture orientations. Nevertheless, the second TCAP pass introduced substantial homogenization of the imposed shear strain, which manifested in a more homogeneous distribution of residual stress across the individual wires compared to the first pass. Also, the distribution of ideal texture orientations was more homogenized after the second pass, as all the Cu fibres exhibited the dominance of ideal shear A fibre texture.

1. Introduction

Composite materials typically consist of more than two different components separated by discrete interfaces [1,2]. The combination of metals featuring different advantageous properties brings about the possibility to create innovative materials with enhanced properties. Composites usually consist of a matrix and other reinforcing phases, and are typically characterized according to the reinforcing phase (e.g. discontinuous composites with reinforcing particles or short fibres) [3]. However, regardless the type of the reinforcing element, the grain size of the matrix, and size and distribution of the reinforcing elements are the primary factors influencing the final mechanical and utility properties of the composite [3]. By this reason, application of specific processing methods, such as the techniques of severe plastic deformation (SPD), for example equal channel angular pressing [4,5], twist channel (multi) angular pressing [6–8], twist extrusion [9], high pressure torsion [10], high pressure sliding
[11], accumulative roll bonding [12], etc., can be advantageous, among for conventional alloys, also for composite materials, from the viewpoint of mutually achieving high quality of bonding, and ultra-fine-grained (UFG) structure.

Clad composites, also denoted as layered materials or hybrid materials, are a specific type of composite materials consisting of (the minimum of) two layers of different metals bond at discrete interfaces [13]. The preparation methods of various types of these materials (e.g. Ti/Cu [14], Al/Mg [15], Al/steel [16], Mg/steel [17], etc.) have been studied by researchers worldwide. They typically combine rolling and other technologies, such as explosive bonding [18], or apply modifications of the rolling technology, such as asymmetrical rolling [19], which was applied to fabricate Al/Cu clad composites [20].

Composites combining both the Al and Cu are specific, since both the component metals exhibit superior electric conductivity. Optimized processing providing composites combining both the Al and Cu results in the production of materials with relatively light weight, and lower price compared to copper. Al/Cu clad composites have prospective application e.g. in the automotive, aerospace, and electrotechnics [21,22]. Due to the light weight and advantageous mechanical properties, they are expected to replace steel in specific applications in aircrafts and vehicles in the near future; researchers have documented satisfactory durability of the composites during dynamic loading at strain rates up to 100 s⁻¹ [23]. Such high shear strain rates support refinement of grains, and impart friction at the interfaces due to differences in the plastic flows of the metals, which eventually supports bonding of the cladded metals via atomic diffusion. However, the internal heat generated by the mentioned structural phenomena increases the actual processing temperature, which can impart formation of intermetallic phases at the interfaces.

Since the conventional forming methods, such as rolling, forging, extrusion, etc., have limitations, unconventional forming methods, such as the mentioned SPD methods, has become popular also to manufacture clad composites. They are beneficial primarily since they can impart (significant) grain refinement, introduce uniform distribution of secondary (precipitated) particles, and homogenize the structures. Moreover, the applied severe shear strain supports breakage of possibly present oxide layers at the interfaces of the component metals, and diffusion via generating lattice defects [24]. Several works documented significant enhancement of the mechanical and utility properties of clad composites prepared via SPD methods. The methods with probably the highest potential is high pressure torsion (HPT) [25]. By applying very high pressure, HPT enables to impose substantially high strains without introducing defects to the processed samples. Moreover, the high shear strain supports redistribution of precipitated (secondary) particles. As regards the mostly applied and researched equal channel angular pressing (ECAP) method, the shear strain imposed into the composite during a single pass ECAP is not as high as e.g. during HPT [26]. Nevertheless, the amount of the imposed strain can be increased by implementing modifications of the process, e.g. by modifying the dies, or by implementing (partial) back pressure [27].

The twist channel angular pressing (TCAP) method is based on the ECAP method, however, it combines a bend deformation zone with a twist deformation zone (i.e. main deformation zone, MDZ, and twist deformation zone, TDZ) in a single channel. This particular die design enables to introduce severe shear strain into the processed (composite) specimen during a single pass [28]. The method has been successfully applied before to provoke the formation of uniform UFG structures within single-phase materials. The efficiency of a single pass TCAP was reported to be higher than the efficiency of double pass ECAP, as regards the structure refinement and its homogenization [29].

The herein presented study is primarily focused on investigating the effects of single and double pass TCAP on the orientations of grains within the reinforcing Cu wires inserted in the Al matrix of
the newly designed Al/Cu clad composite. The texture analyses are supported with the distribution of residual stress depicted via internal grains misorientations, the combination of which provides a complex view on the deformation behaviour of the composite components during TCAP.

2. Materials and Methods

The primary aim of the work was to evaluate the character of grains within the reinforcing Cu wires of a self-designed Al/Cu clad composite after TCAP processing. The particular focus was on performing the correlation between the observed grains orientations and the presence of internal grains misorientations, i.e. residual stress, within the structures. The original component metals were commercially pure (CP) Cu of 99.97% purity (composition (in wt. %): Cu plus 0.0073 Ni, 0.0060 Sn, 0.0030 Zn, 0.0030 Fe, 0.0023 Si), and CP Al of 99.97% purity (composition of (in wt. %): Al plus 0.125Fe, 0.023Cu, 0.021Zn, 0.016Mn, 0.016Mg, 0.015Ti, 0.10Si). The designed clad composite was composed of an Al sheath and five inserted Cu wires, see Figure 1a for schematic depiction of the cross-section of the designed composite.

The study deals with single and double pass TCAP. Schematic depiction of the TCAP die can be found elsewhere (e.g. [30]). The billets were at first processed via a single pass, and subsequently subjected to a double pass TCAP via the deformation route C (the billet was inserted to the second pass rotated by 180° - see ref. [31] for the details of the individual TCAP deformation routes and strain paths). Figure 1b shows the composite billets processed via single and double TCAP passes. Before assembling the billets, the component metals were heat treated for 30 min at 500 °C in an electric furnace to relax possible residual stress originating from previous processing, and homogenize the structures. The original billets were designed with square cross-sections and their dimensions were 12 mm × 12 mm × 130 mm (length). Room-temperature TCAP processing was performed using a hydraulic press with the extrusion rate of 5 mm s⁻¹, MoS₂ was used as lubricant.

Figure 1: Schematic depiction of designed composite billet (a); experimentally processed composite billets (b).

The analyses of texture and grains misorientations within the clad composite billets processed via TCAP were performed using scanning electron microscopy (SEM), by the electron backscatter diffraction (EBSD) method in particular. The used microscope was Tescan Lyra 3 XMU FEG/SEMxFIB system equipped with Symmetry EBSD detector. The composite samples were prepared by manual grinding and subsequently polished via a combination of manual and electrolytic polishing. Scanning by EBSD was performed with the accelerating voltage of 20 kV, and steps of scanning of 50 nm. The subsequent evaluation of the scanned data was performed using AZtecCrystal 1.1 software by Oxford Instruments, and ATEX software [32].

3. Results and discussions

3.1. Texture characteristics

The effects of both the twist and main deformation zones on the developments of textures, i.e. grains orientations, within the reinforcing Cu wires of the extruded Al/Cu cladded billets were evaluated via stereographic projection, i.e. pole figures (PFs). The original Cu wires subjected to the initial heat treatment featured more or less random grains orientations with the tendency to form recrystallization
mentioned phenomena are also non-negligibly related to the development of residual stress.
Figure 2: Pole figures for individual Cu wires within composite billet extruded via single pass TCAP: upper left (a); upper right (b); axial (c); bottom left (d); bottom right (e).
Figure 3: Pole figures for individual Cu wires within composite billet extruded via double pass TCAP: upper left (a); upper right (b); axial (c); bottom left (d); bottom right (e).
3.2. Residual stress
Figures 4a and 4b document the internal grains misorientations (depicted in rainbow colour scheme from 0° to 15°) pointing to the presence of residual stress in the reinforcing Cu wires within the composite billets processed via the single and double TCAP pass, respectively. The figures show that the presence and distribution of the residual stress within the axial Cu wire was comparable after the first and second TCAP pass. On the other hand, for the peripheral Cu wires, the presence of residual stress was more significant after the second pass, as the scans for the wires of this composite billet featured greater densities of the areas exhibiting higher internal grains misorientations. However, the high misorientations, i.e. residual stress, were more or less homogeneously distributed throughout the structures, which points to the lack of significant stress peaks within the Cu wires’ structures (especially for the bottom couple of the Cu wires, which corresponds to the lower maximum texture intensities observed for these wires). Mutual comparison of the presence and distribution of the residual stress within the structures of the peripheral Cu wires and the axial Cu wire shows that the presence of residual stress was more pronounced in the peripheral Cu wires after both the single and double TCAP passes. The results of residual stress analyses are in accordance with the analyses of texture – as mentioned, less significant presence of the residual stress corresponded to the relatively lower intensities of ideal shear texture orientations for the bottom couple of the Cu wires after the second TCAP pass. This was true also for the upper couple of the Cu wires after the first TCAP pass.

Figure 4: Residual stress depicted via grains misorientations for individual wires within composite billets processed via: single pass TCAP (a); double pass TCAP (b).

4. Conclusions
The aim of this study was to perform experimental investigations of self-designed laminated Al/Cu composites processed via the twist channel angular pressing (TCAP) method. In particular, the study focused on evaluating the effects of single and double TCAP pass on modifications in texture and residual stress within the reinforcing Cu wires. The results showed that the first TCAP pass introduced satisfactory imposed strain to impart formation of ideal shear texture fibre orientations, however, the strain was not homogeneous across the cross-section of the processed composite as the individual Cu wires featured differences in their ideal orientations. Nevertheless, processing via double TCAP pass (deformation route C) imparted substantial homogenization of the imposed shear strain, as all of the reinforcing Cu fibres exhibited the dominant presence of ideal A fibre shear texture. The results of the analyses of residual stress corresponded to the results of texture analyses; the Cu fibres exhibiting higher texture intensities also exhibited greater presence of internal grains misorientations pointing to the presence of residual stress.
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