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Microstructure, flow behavior, and bulk texture evolution of cold drawn copper–silver composites

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ABSTRACT

In the last 20 years, several groups used nanostructured composites to produce high strength conductor materials for magnetic applications. The mechanical strength of Cu–Ag composites is strongly influenced by metal forming operations. Within the scope of the paper, the microstructure, the mechanical behavior, and the texture evolution are investigated for two cold drawn Cu-63wt%Ag composite rods. The aim of these investigations is to understand the influence of the microstructure and texture evolution on the mechanical behavior. The investigation is carried out using optical microscopy, scanning electron microscopy (SEM) along with electron backscattered diffraction (EBSD), X-ray diffraction measurements (XRD), and compression testing. The microscopic images show that the drawn samples mainly have a lamellar structure of Cu and Ag phases. However, elliptical shaped regions of primarily solidified copper solid solution are also observed. With increase of plastic deformation, the average lamella thickness of both phases has been decreased. EBSD measurements show that abundant banded regions are observed in the Ag phase while very few banded regions are present in the Cu phase. The bulk XRD measurements reveal that both phases of the drawn samples initially have the same type of texture, and both phases develop the same brass-type [110]⟨112⟩ texture. The texture intensity increases for both phases as the drawing strain increases. Compression tests are performed at constant strain rate of $10^{-4}\ s^{-1}$ at room temperature. The stress–strain curves under compression are presented for two different drawn samples. The texture measurements after compression reveal that the texture becomes more pronounced.

1. Introduction

Copper based composites (Cu–Ag, Cu–Be, Cu–Nb, etc.) are used as high-strength conductors in pulse magnets, hybrid magnets, and resistive (bitter) magnets because of their unique combination of high mechanical strength and high electrical conductivity [1–4]. In general, two-phase Cu–Ag composites containing 6–72 wt% Ag are used as conductor materials for the application in magnets produced by cold drawing along with intermediate heat treatments [5–9]. The microstructure will strongly influence the mechanical properties of Cu–Ag composites [10]. By changing the concentration of Ag in Cu-based composites and also different processing methods, the morphology and texture result in anisotropy of the mechanical properties. Therefore, various new and improved Cu–Ag composites have been used in the field of magnetic applications. However, some questions have to be answered, such as: (1) what is the appropriate Cu–Ag composition, and (2) what processing technique develops the required mechanical properties. For example, with increase in the concentration of Ag, i.e., 7 wt%, 24 wt %, 72 wt%, the ultimate tensile strength increases with increase in the drawing strain [11]. Furthermore, the strength level can be increased by an appropriate heat treatment [11,12]. In the study by Heringhaus [13], compression and tensile tests have been conducted for Cu-72 wt% Ag eutectic composites, in which the mechanical properties are presented as a function of the wire deformation. Following cold-drawing to high strains, the eutectic Cu–Ag composites develop an ultimate tensile strength as high as 1.15 GPa [13]. During the metal forming operation by cold working, the lamellar nature of these two phases, one a Cu-rich, and the other an Ag-rich solid solution, have been compressed and

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elongated resulting in a fine and dense structure. The phase boundaries and grain boundaries of these two phases block the dislocation movement through the alloy, causing an increase in strength of the material. Therefore, such work-hardened composites containing a fine layer structure, show higher strength than that expected from a simple rule of mixture [5,14,15]. Following cold drawing operations, the Cu–Ag composite experiences microstructural changes. Therefore, the rods produced by drawing exhibit anisotropic properties. An important example of an anisotropy is the crystallographic texture.

Many studies of the texture evolution during large plastic deformations have been concentrated on single phase metals. For example, the texture evolution of silver has been examined during equal channel angular extrusion (ECAE) [16,17]. In the case of two phase Cu-based composites, the presence of the second phase will affect the texture evolution. In the recent work, these effects have been studied for Cu–Nb composites under plastic deformation by accumulative roll bonding [18,19]. Recently, the local and global texture analysis of CuAl alloys have been examined by wire drawing, where microstructure change has been investigated by varying the stacking fault energy [20]. The texture evolution of an eutectic Cu–Ag composite for different rolling reductions has been described by Ref. [21]. As they report, the alloy-type rolling texture is found for both Cu and Ag phases. An unusual texture in the Cu phase of the Cu–Ag eutectic composite has been observed, and explained in terms of twinning mechanism, i.e., Ag contributes propagation of twins into Cu. Of these different methods, the most common and simple method for strengthening composites includes cold drawing (strain hardening) [22]. It is clear that the texture of different drawing reductions also influences the mechanical properties. Besides, the effect of texture in the near-eutectic cold drawn Cu-63 wt% Ag composite due to plastic deformation on the mechanical properties has not yet been reported. With increase in the cold drawing operation, the mechanical strength is increased, and the texture increases significantly. We performed the experimental investigations on two differently cold drawn Cu–Ag rods to estimate the texture evolution and also to study the influence of the mechanical behavior. These rods (diameters d_1, d_2) with drawing reductions $\eta_1 = 0.9$ and $\eta_2 = 2.1$ ($\eta = ln(A_0/A)$), respectively, are chosen to determine the benefits and limitations in producing high strength conductor materials, where A_0 and A are the initial and the current cross section of the specimen, respectively.

In the present work, near-eutectic (Cu-63wt%Ag) cold drawn samples of diameter 12.42 mm and 6.73 mm are examined to determine the influences that changes in the microstructure and texture, have on the mechanical behavior. The microstructural refinement and the anisotropy are accompanied by the evolution of texture. This understanding of the development of texture in the rods will provide a basis for the development of new conductor materials with optimum microstructure. Besides the detailed microstructural investigation of the cold-drawn Cu–Ag rods, this work also reports the significance of the anisotropy of two different rods to the development of the conductor materials. The investigation has been carried out using optical and scanning electron microscopy, electron backscattered diffraction (EBSD), X-ray diffraction (XRD), and compression testing. Macro-texture XRD measurements show that both Ag and Cu phases develop a brass-type texture, which is also present after compression tests with different intensities. The EBSD measurements reveal that the Ag phase consists of shear bands or twinned regions, while in the Cu-phase very few shear bands or twinned regions are observed. The brass-type {110}⟨112⟩ texture expected for the Ag-phase and not for the Cu-phase, has been discussed previously [21]. The metal or copper-type {112}⟨111⟩ texture is expected for rolled pure copper and its alloys [23,24]. Possible reasons for this brass-type texture for the copper phase are presented in the section Results and discussion.

2. Experimental procedure

The Cu–Ag rods are supplied by the 'Allgemeine Gold-und Silberscheideanstalt' in Pforzheim, Germany. The material with initial diameter of 20 mm was processed by continuous casting. After casting, the rods are swaged to 20% reduction, and then cold drawn to reduction in diameter of 12.4 mm and 6.7 mm from a starting diameter at room temperature. Two different textured Cu–Ag rods (d_1, d_2) are examined to describe the microstructure development and the evolution of crystallographic texture. The samples are cut in both longitudinal and transverse directions for microstructural observations. The sample direction and the cutting plane are shown in Fig. 1a. Fig. 1b displays the cylindrical rods. In order to study the effect of the microstructure on the mechanical behavior, the samples are manufactured from the drawn rods in two different directions (longitudinal and transversal) by using an electric discharge machining (EDM) process. The samples are denoted by a symbol T in the transverse direction and L in the longitudinal direction.

The samples are cold mounted in an epoxy resin, grinded using silica carbide (SiC) paper (180-2400 grit), machine polished with 3-μm diamond particles and a fine polish with 1-μm diamond particles using a water based lubricating solution. The specimens are chemically etched for 45 s in Nital solution (30% nitric acid in 70% ethanol) for imaging. After that a final OPS polishing step and an ion polishing with 3 kV Ar ions for 1 h (GATAN PECS) was applied to obtain a smooth clean surface suitable for EBSD measurements. The samples are examined in a scanning electron microscope (FEI ESEM XL30 FEG equipped with EDX and EBSD) and in a reflected light microscope (Inverted light microscope ZEISS Axiovert 200 M equipped with Film and AxioCam MRc 5).

The uniaxial compression test is a simple test for the study of the flow behavior and also for the determination of the mechanical properties. In this type of test, the specimen shape allows more surface for texture measurements. The samples are tested in compression along longitudinal L and transversal T directions to gain a better understanding of the influence of different microstructure on the yield strength of the material. Besides the compression tests also shows the anisotropic nature of samples since the rods are cold drawn. The tests have been performed for both cylindrical samples in the two directions (longitudinal and transversal) on a universal testing machine (Zwick/Roell Z100). The tests are performed at a constant strain rate of $10^{-4}\ s^{-1}$ at room temperature. The initial dimensions of the specimen are 1.7 mm in diameter and 2.5 mm in height. To minimize the friction between the surface of the samples and the supporting holders, a Boron Nitride (BN) lubricant spray is used.

For the macro-texture using X-ray diffraction measurements (XRD), the samples (uncompressed, compressed) are mounted in a cold setting epoxy resin, are grinded using SiC sheets with grade numbers (P300, P480, P800, P1200, P2400, P4000) and machine polished with 3 μm diamond particles and finished using 1 μm. Finally, the samples are placed in the vibrating polishing machine for 20 h using MasterMet 2 suspension. These samples are cleaned in ultrasonic cleaner for 10 min using isopropanol alcohol solution. For XRD measurements we used the X-ray diffractometer XRD3000PTS built by Rich. Seifert & Co. GmbH & Co. KG, Ahrensburg, Germany. The XRD3000PTS is a 4-axis diffractometer to analyze the phases and texture. We operated the measurements by using an X-ray tube with chromium anode in point focus mode and 1D-detector with secondary K_β filtering. Raw texture data is