Modeling the Texture Evolution of Cu/Nb Layered Composites During Rolling

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Metallic-based multi-layered nano-composites are recognized for their increased plastic flow strength, increased ductility, improved radiation damage resistance, improved electrical and magnetic properties, and enhanced fatigue-failure resistance compared to conventional metallic materials. One of the ways in which these classes of materials are manufactured is through accumulated roll bonding where the material is produced by several rolling and heat treatment steps during which the layer thickness is reduced through severe plastic deformation. In this article, a single rolling pass of the accumulated roll bonding process in which a Cu/Nb layered composite with an initial average layer thickness of 24 μm subjected to a 50% height reduction is examined. The initial state of the materials is characterized by electron backscatter defraction (EBSD) data. The initial data was used to create 40 numerical simulations that were combined to arrive at a statistically comparable data set. The results suggest very good agreement between the predicted and experimental textures for both the materials within the composite.

Metallic-based composite materials have long been recognized as a way to enhance the performance of metals and continue to receive attention as a way to design new materials for novel applications. This material design process has been facilitated by the recent rapid development of nanometer-scale mechanical probes, high-resolution imaging techniques, and advanced theory and computational tools. These metallic multilayer composites have typically been produced by physical vapor deposition techniques producing thin foils, or by traditional cold-worked rolling processes with intermediate annealing steps producing plates [1,2]. The latter of these processes is achieved through an accumulated series of rolling passes and is able to produce a practical amount of plate material and therefore has the better potential for commercial manufacture of bulk materials. It is this accumulated roll bonding (ARB) process that we wish to examine here–both the resulting material and its evolution of properties. In particular, this work presents efforts to represent the evolution of the structure of the individual layers and predict the evolution of crystallographic texture for a single rolling pass at a point in time late in the process but before the layer thickness is small enough to significantly alter the dislocation behavior within the layers.

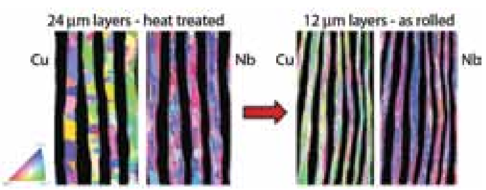

Fig. 1. EBSD data for sections of the heat-treated and rolled layered composite materials examined in this study. The rolling direction is vertical and the transverse direction is out of the page.

Over the past two or three decades crystal plasticity theory and simulation capabilities have developed into a commonly used and successful predictive tool for large plastic deformation of metallic materials [3]. Here we begin to apply crystal plasticity theory to the study of layered composite materials to examine the evolution of crystallographic texture well above the layer thickness where confined layer slip and interface dominance become important. This will demonstrate the applicability of existing theory to problems of this type and also provide insight into the kinematics and kinetics of composite deformation through the rolling process.

Many approaches have been implemented for generating synthetic or digital representations of polycrystalline microstructures. Here we follow on the work of Sintay [4,5] and extend it to include 3D layered materials as the foundation for the 2D simulations. Initial textures were assigned to the virtual grains using data from the five 200×200 μm EBSD scans (see Fig. 1) comprising a total area of 2×10^5 μm^2. A total area of 2×10^5 μm^2 is represented by the combined 40 simulations. The dislocation state of each layer (which cannot be assumed to be fully annealed) is represented through nano-hardness measurements.

A schematic representation of the isochoric boundary conditions used for the numerical simulations is given in Fig. 2. Each of the numerical models assumed an initial aspect ratio of 1:2. Plane strain was used as an approximation of the actual rolling process and therefore six-noded plane strain triangular hybrid elements were used within commercial finite element method software (ABAQUS) [6]. A constant displacement rate was imposed on the top surface to produce a 50% height reduction in 5 seconds. The simulations were performed isothermally at a temperature of 298 K.

Crystallographic orientation at each of the material points within the 40 models were combined to give the resulting pole figures in Fig. 3. In all, these results contain sampling of 420 Cu grains and 395 Nb grains for the combined numerical simulations. In general, the numerical technique developed for this layered composite system represents the

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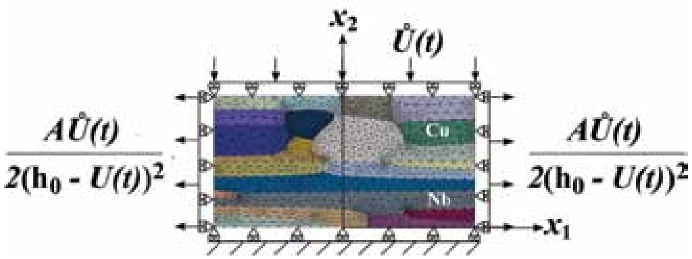

Fig. 2. Plane strain compression isochoric boundary conditions applied to a typical bilayer model with an initial 1:2 aspect ratio. The quantities A and h_0 are the surface area and initial height of the numerical model. X_1 corresponds to the rolling direction (RD), X_2 the normal direction (ND), and X_3 the transverse direction (TD).

experimental data well. In particular, the ability to represent the large transition in texture for the Cu but little for the Nb is noteworthy.

An example of the morphology and internal stress developed as a function of height reduction is given in Fig. 4 for one realization. It is interesting to note the discrepancy between the vonMises stress developed between the two layers. This suggests that the mechanical response of the composite introduces unique boundary conditions at the interface that allow for substantially different equivalent stress states in the two different materials. The simulation results also demonstrate the substantial evolution in interface shape, which qualitatively agrees with experimental observation.

A technique for representing the processing response of bi-metallic layered composite materials was presented here and successfully used to predict the single-pass rolling texture in each layer of the Cu/Nb system reduced from 24 to 12 µm average layer thickness. Each layer was represented by a statistically equivalent polycrystal morphology based upon EBSD data for each of the layered materials at the heat-treated 24-µm thickness condition. Nano-indentation experiments performed on the independent material layers for the heat-treated 24-µm condition were used to initialize the single crystal model for un-annealed conditions between rolling passes. Eight different morphological realizations and, within each of those, five different crystallographic realizations, resulted in a total of 40 numerical realizations used to compare to the experimental crystallographic texture data. This number proved to be adequate to provide the proper statistical diversity to allow for representation of the initial morphology and crystallographic texture for these layered composite systems.

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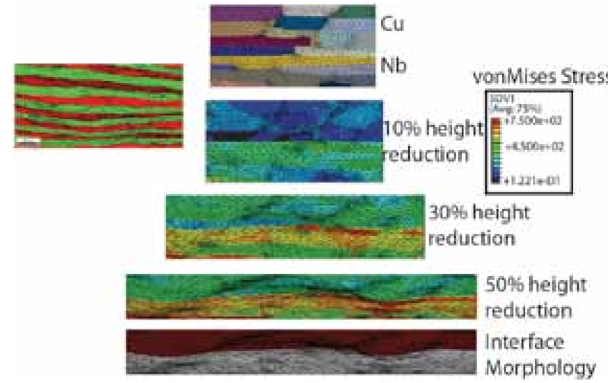

Fig. 4. Simulated deformation for one realization showing the evolution of vonMises stress with height reduction. Morphology of the experimental as-rolled 12-µm layer thickness microstructure is shown in the phase map to the left where green is Cu and red is Nb.

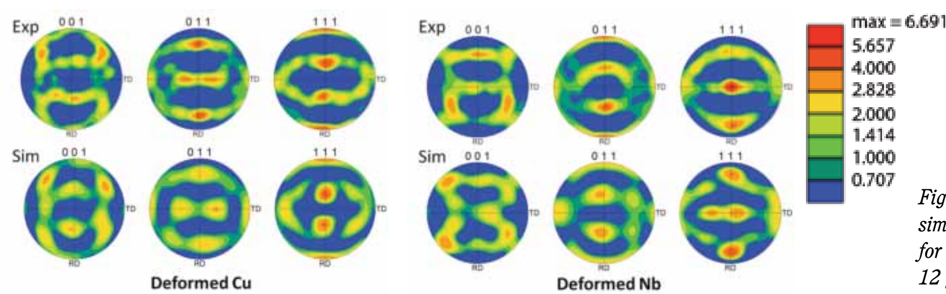

Fig. 3. Experimental and simulated equal area pole figures for the deformed Cu and Nb at 12 µm layer thickness.

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