Residual Strains and Fatigue Performance in High-Strength Cu/25%Ag Metal Matrix Composites

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Introduction

The highest non-destructive magnetic fields are achieved by the pulsed-field technique, where the use of compact magnet coils ensures a large filling ratio. However, the generation of very strong pulsed magnetic fields is ultimately limited by mechanical failure of the coils due to the Lorentz force exerted on the current-carrying wires. In a compact coil, the layers of conducting wire are in contact and radial stress can be transmitted and this causes internal strain. Non-destructive magnets of pure copper are strength-limited to ~40 T. For higher field, some reinforcement is needed. Most straightforward is the use a stronger wire with sufficient conductivity (to suppress the Joule heating) and mechanical strength (to resist the stress generated by the Lorentz force). This can be achieved in copper-matrix composites where reinforcement is achieved by implanting or drawing particles, whiskers or filaments into a copper matrix. Development of new high-strength and durable coil materials presumes an understanding of the co-deformation behavior and residual strain evolution since these parameters affect the short- and long-term fatigue performance.

The most promising wire materials for high-performance pulsed magnets are cold-drawn copper-matrix composites with silver as a reinforcement material [1]. Here, we present the results of finite-element modeling and neutron-diffraction studies of cold-drawn Cu/25%Ag composite materials under load.

Finite Element Modeling

The main goal was to develop a finite element model (FEM) of a silver fiber embedded in a copper matrix to get some insight into the development of the residual stresses of Cu/25%Ag composite wire after the application of a load. For the FEM, we assumed cylindrical and continuous silver fibers in a copper matrix. The finite element model consisted of 1,950 fifteen-node wedge elements and 13,650 twenty-node brick elements. For the boundary conditions, the nodes along the center of the cross section were allowed to displace along the direction of the load and fixed in all other degrees-of-freedom. The node located at the center of the beam was fixed in all degrees-of-freedom.

Different FEM models were investigated. One consisted of isotropic mechanical properties for copper and silver (model 1), another model assumed isotropic properties for copper and orthotropic ones for silver (model 2), and a third model assumed orthotropic properties for both (model 2). The mechanical properties used in the analysis are listed in Table 1.

Table 1 Mechanical Properties used in the FEM Analysis

Isotropic Properties				Orthotropic Properties			
	Ag	Cu				Ag	Cu
E (GPa)	72	117		C_{11} (GPa)		124	168.4
				C_{12} (GPa)		93.4	121.4
				C_{44} (GPa)		46.1	75.4
Strain Hardening For Ag							
Strain	0.000	0.005	0.010	0.020	0.030	0.040	0.050
Stress (MPa)	115	122	128	138	145	154	157
Strain Hardening For Cu							
Strain	0.000	0.005	0.010	0.020	0.030	0.040	0.050
Stress (MPa)	350	535	707	1061	1410	1737	2066

In Figure 1, some exemplary residual stresses after loading is shown. We find that isotropic mechanical properties for copper and orthotropic properties for the silver (model 2) yield the smallest residual strains. Moreover, it should be noted that the silver fiber is in compression with respect to the 11 and 22 directions for this model, while it is in tension for models 1 and 3. However, experimental data are required to determine which of the models is most accurate.

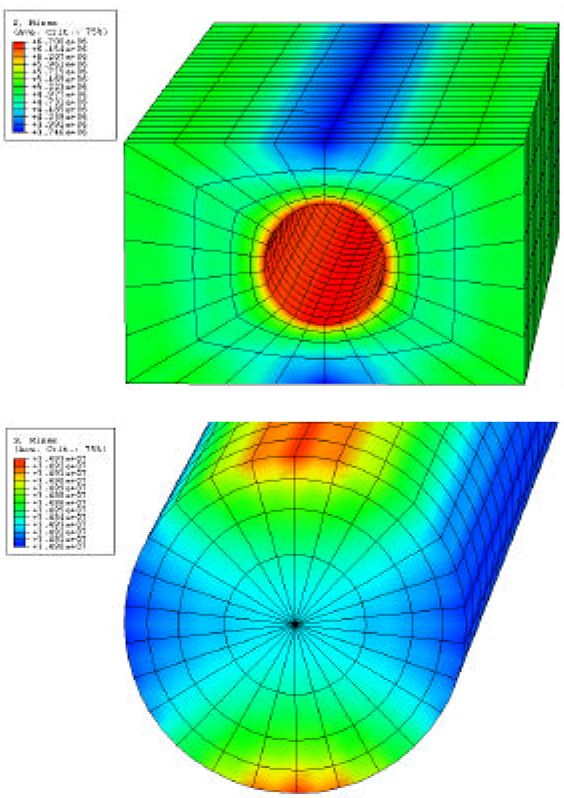

Figure 1 Residual stresses of the Cu matrix and the Ag fibers and the Cu matrix after application of a load

Assuming no strain hardening, our model 2 was found to closely match the measured stress-strain curve up to about 300 MPa, beyond which copper yields.

Neutron-diffraction studies

Neutron-diffraction experiments were performed to gain more insight into the development of the residual strains and the fatigue performance of cold-drawn Cu/25%Ag composites. The specimens were exposed to cyclic mechanical loading at 20% or 40% of the elastic limit, and they were found to develop cracks after about 10^6 or 10^5 cycles, respectively. Using the General Purpose Powder Diffractometer (GPPD) at the Intense Pulse Neutron Source (Argonne National Laboratory) and the Neutron Powder Diffractometer (NPD) at the Manuel Lujan jr. Neutron Scattering Center (Los Alamos National Laboratory), we studied the development of texture and residual strains after cyclic loading.

Before a load was applied, we found that the Ag are strongly aligned along the drawing direction, while far less texture was found in the case of the Cu matrix (though it was not fully isotropic either). This finding is consistent with the findings from FEM. The texture of the specimens was found to be unaffected by the cyclic loading. Similarly, within error bars, the lattice parameters of Cu and Ag did not change as a function of mechanical cycling. However, the evolution of residual strains as a function of cyclic loading is reflected in the changes of the line widths of nuclear Bragg reflections. We observe substantial broadening of the peaks of both, Cu and Ag, with increasing number of cycles. The profile coefficients can be taken as a measure of strain broadening; and we find that longitudinal strains in both Cu and Ag increase with the number of cycles (see Figure 2), while there is no similar increase of transversal strains.

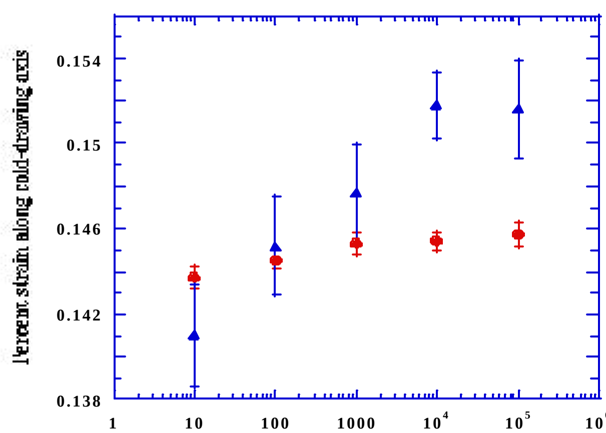

Figure 2 Development of the longitudinal percent strain of Cu (circles) and Ag (triangles) in Cu/25%Ag composites as a function of cyclic loading to 20% of the elastic limit.

References

1. Han, K. *et al.* The fabrication, properties and microstructure of Cu-Ag and Cu-Nb composite conductors. *Materials Science and Engineering* A000 (1999) 1-16.