Ultra-fine grained (UFG) Cu has a potential to be used as a conductor for next generation magnets because of its high strength. However, UFG Cu suffers from embrittlement. The low ductility of UFG materials has invariably limited their application for making high field magnets. This report describes a process in which high ductility is achieved in UFG Cu without sacrificing strength by plastically deforming UFG Cu in liquid nitrogen.

A high-purity (99.99%) Cu bar with a diameter of 20 mm was processed at room temperature by equal-channel angular extrusion (ECAE). The ECAE-processed Cu bar was cryogenically drawn at 77 K to form a UFG Cu wire with a diameter of 4.5 mm. Both the wire and dies were immersed in liquid nitrogen to ensure that cryogenic drawing was performed at 77 K. The UFG wire was then cryogenically rolled to a thickness of 0.2 mm. This was indicated by ECAE+D+R. For tensile testing, the samples were cut into dog-bone-shaped specimens with a gauge length of 10 mm and a width of 2 mm, and polished to a thickness of 0.1 mm.

Figure 1a shows that the UFG ECAE+D+R sample has superior mechanical properties compared to the UFG ECAE sample. The UFG ECAE Cu sample has a 0.2% yield strength of 410 MPa (Ω). Necking occurs rapidly after the stress reaches a maximum value, yielding a uniform elongation of only 1.3% and an elongation to failure of only 5.9% in the UFG ECAE sample. By contrast, the yield strength is increased to 500 MPa in the UFG ECAE+D+R sample. This strength is equivalent to the strength obtained from cryogenic deformation from coarse-grained samples [2]. The UFG ECAE+D+R sample undergoes strain hardening, giving a uniform elongation of 3.5% and a subsequent elongation to failure of 11.8% [3]. The limit of uniform elongation is marked (Π) on every curve. Quantitative electron backscatter diffraction (EBSD) analysis was used to obtain information on the distributions of the GB misorientations (Fig. 2). It is assumed that the peak occurring near 60° for UFG ECAE+D+R Cu is probably formed during the cryogenic deformation. This confirms previous observations that cryogenic processing introduces a large number of twin boundaries with misorientation angles of 60° [4]. Such structure was found to have no significant impact on conductivity of pure Cu. The UFG ECAE+D+R sample has a high fraction (58%) of HAGBs with misorientations > 15°, whereas in the UFG ECAP sample the fraction of HAGBs is only ca. 32 %. Therefore, the enhanced ductility is attributed primarily to the presence of a high density of preexisting deformation twins and also possibly to a large fraction of high-angle grain boundaries formed during cryogenic processing.

![Fig.1 Stress strain curves of UFG Cu tensile engineering and true stress–strain curves of the UFG ECAE-D+R, UFG ECAP, and coarse-grained (CG) Cu samples [1].](image1)

![Fig. 2. Distribution of grain boundary misorientation angles for the UFG ECAE-D+R and UFG ECAP samples measured by EBSD. The data indicates that more twins are in UFG ECAE-D+R than in UFG ECAP samples [1].](image2)

**References**


This work was supported by the National High Magnetic Field Laboratory under NSF DMR-0084173. We thank Y Zhao, J F. Bingert, Y T. Zhu, in Los Alamos National Laboratory, X Liao from The University of Sydney in Australia, A V. Sergueeva and A K. Mukherjee from University of California, R. Z. Valiev,Ufa State Aviation Technical University, Russia, T. G. Langdon, University of Southern California. for collaborations.