The microstructure and low-temperature mechanical properties of ultrafine-grained copper: effect of deformation and annealing

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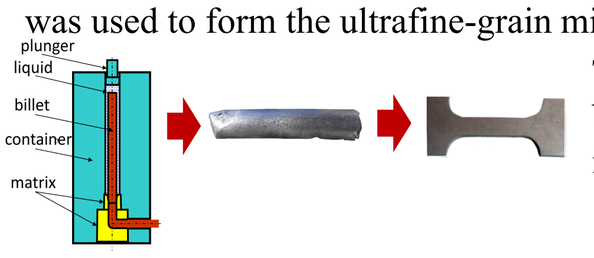
A comparative analysis of the mechanical properties and microstructure of oxygen-free copper in the ultrafine-grained (UFG) and coarse-grained (CG) states is carried out.

Methods

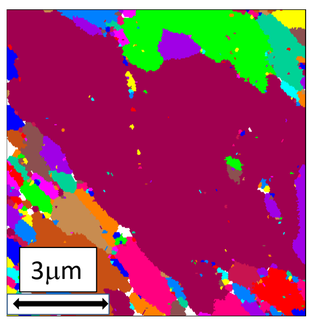
The SPD method by Angular Hydroextrusion (AHE, 5passes, B_c route) method was used to form the ultrafine-grain microstructure of the Cu.



The flat dog-bone samples have been machined by electrical spark erosion and stamping from the ingots.

The microstructure of the samples in the initial state and after deformation at various temperatures has been studied using a scanning electron microscope (FEI Zeiss Auriga Compact) equipped with the electron backscatter diffraction (EBSD) camera.

Ultrafine-grained (UFG) copper



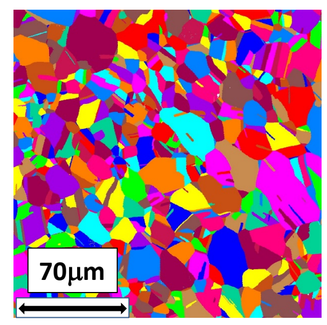
Grain size~ 500 nm
Dislocation density ~ 10^{15} m^{-2}

annealing 600 ^{0}C

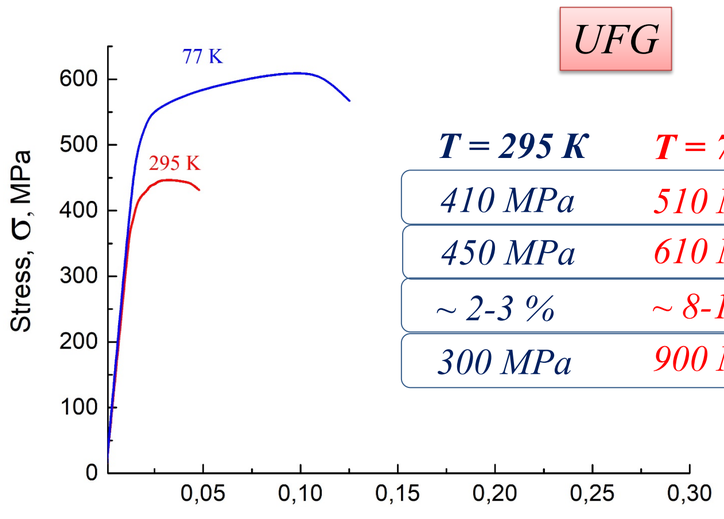
Coarse-grained (CG) copper

The coarse-grained state was achieved by high-temperature annealing of UFG samples at a temperature of 600 ^{0}C for 1 hour in a vacuum.

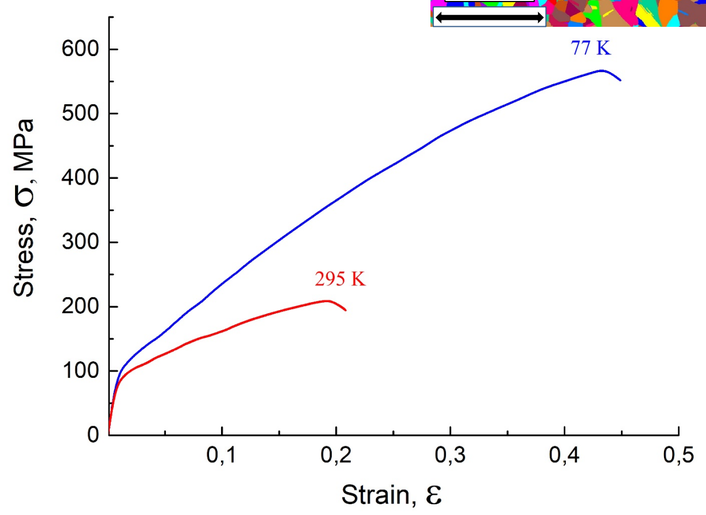
Grain size~ 20 μm
Dislocation density ~ 10^{13} m^{-2}



Plastic deformation was carried out by tension at a constant strain rate $\dot{\varepsilon}$~10^{-4} s^{-1} at the temperatures of 77 K and 295 K.

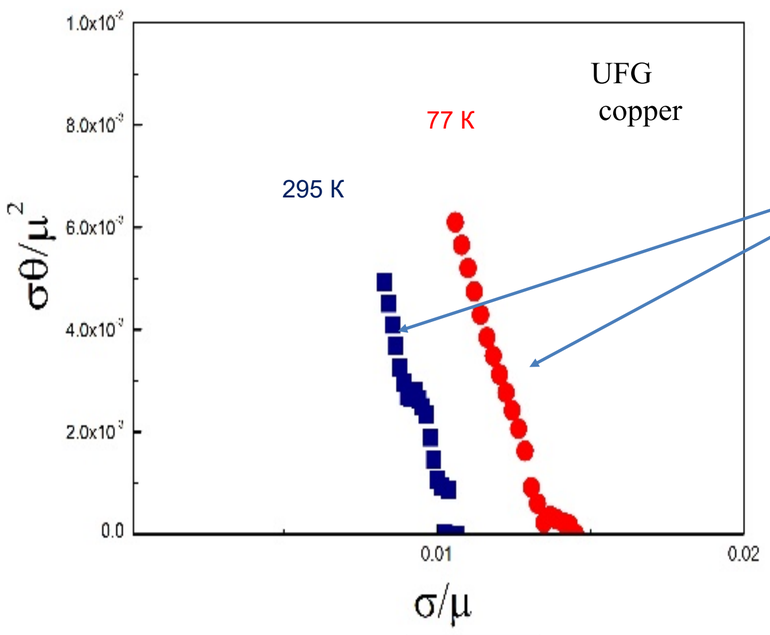


UFG			*CG*	
T = 295 K	***T = 77 K***		***T = 295 K***	***T = 77 K***
410 MPa	*510 MPa*	*Yield strength*	*80 MPa*	*100 MPa*
450 MPa	*610 MPa*	*Tensile strength*	*210 MPa*	*570 MPa*
~ 2-3 %	*~ 8-10 %*	*Uniform deformation*	*~ 20 %*	*~ 40-45 %*
300 MPa	*900 MPa*	*Strain hardening coefficient*	*750 MPa*	*1500 MPa*



Strain hardening in Kocks-Mecking coordinates

σ– stress,
θ– strain hardening coefficient,
μ– shear modulus



Annihilation of dislocations

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Dynamic recovery

Accumulation of dislocations

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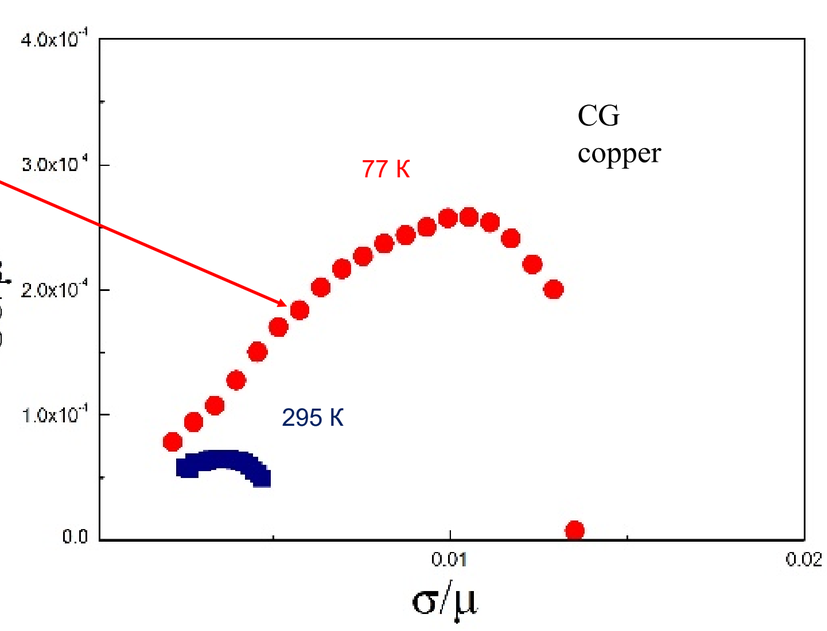
Strain Hardening



The increase of dislocation density, which occurs due to grain fragmentation during the formation of an ultra-fine-grained structure in copper, leads to the activation of the dynamic recovery mechanism (partial softening)

Smaller grain size (UFG)
+
higher dislocation density

Shorter distance between dislocations, their sources and sinks

Higher speed of dynamic recovery

This significantly affects the strengthening and stress relaxation already at cryogenic temperatures of 77 K, which is significantly different from the behavior of coarse-grained copper, where this effect becomes noticeable only at temperatures above room temperature.