



**MT 26**  
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on Magnet Technology  
Vancouver, Canada | 2019

**23/09/2019**

# High strength - high conductivity silver nanowire-copper composite wires by spark plasma sintering and wire-drawing for non-destructive pulsed fields

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**LNCMI and CIRIMAT, Toulouse, France**



**LNCMI**  
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N. Ferreira

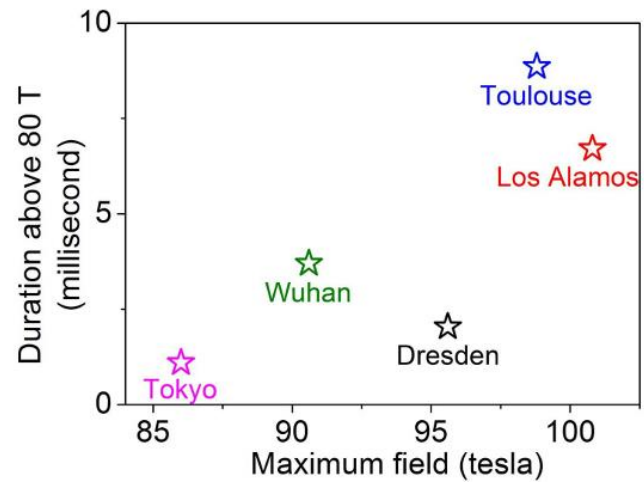


Ch. Laurent  
D. Mesguich  
A. Lonjon  
G. Chevallier  
C. Estournès



Centre de microcaractérisation  
Raimond  
**CASTAING**  
A. Proietti

# Non-destructive pulsed high magnetic fields of long duration

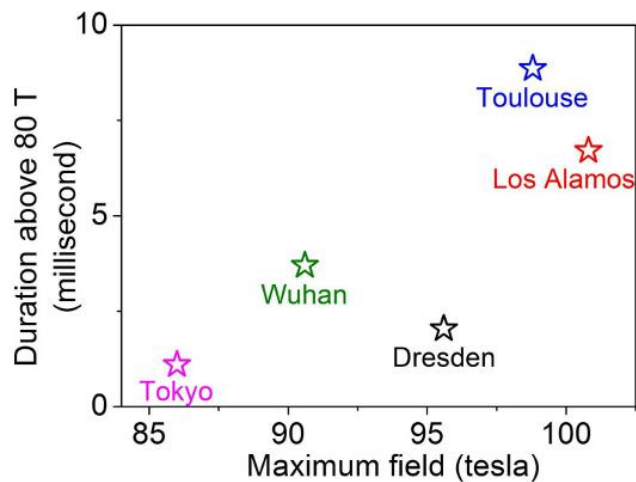


Long pulse duration

$$\Delta t \propto \frac{1}{\rho}$$

**Copper wires**

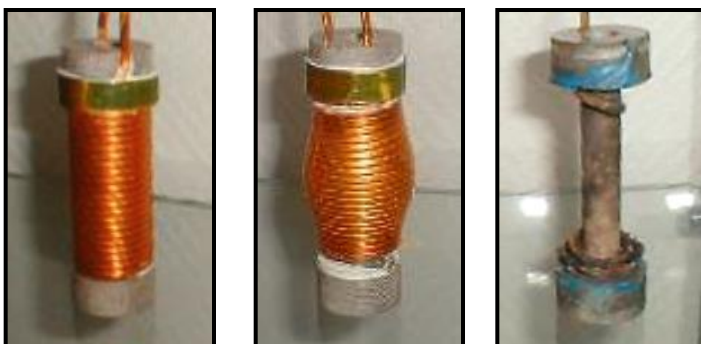
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**Copper wires**

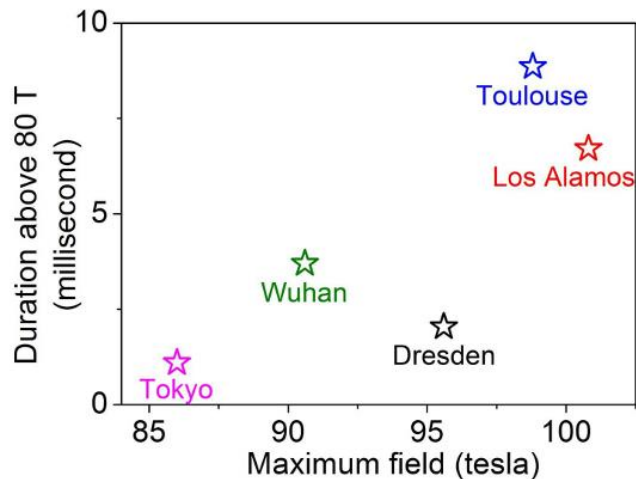


Non-destructive pulsed magnetic fields

Wires that can resist to Lorentz force

Pure Cu not strong enough

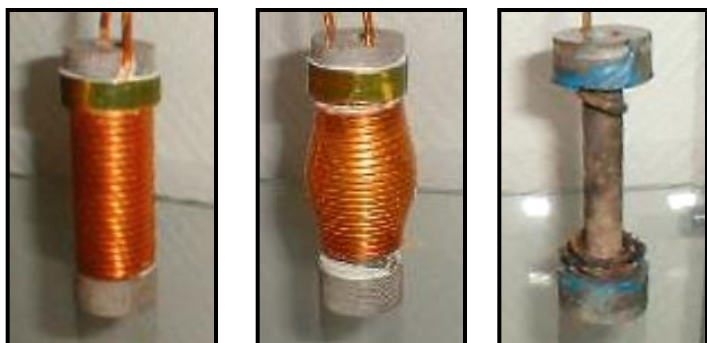
# Non-destructive pulsed high magnetic fields of long duration



Long pulse duration

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**Copper wires**



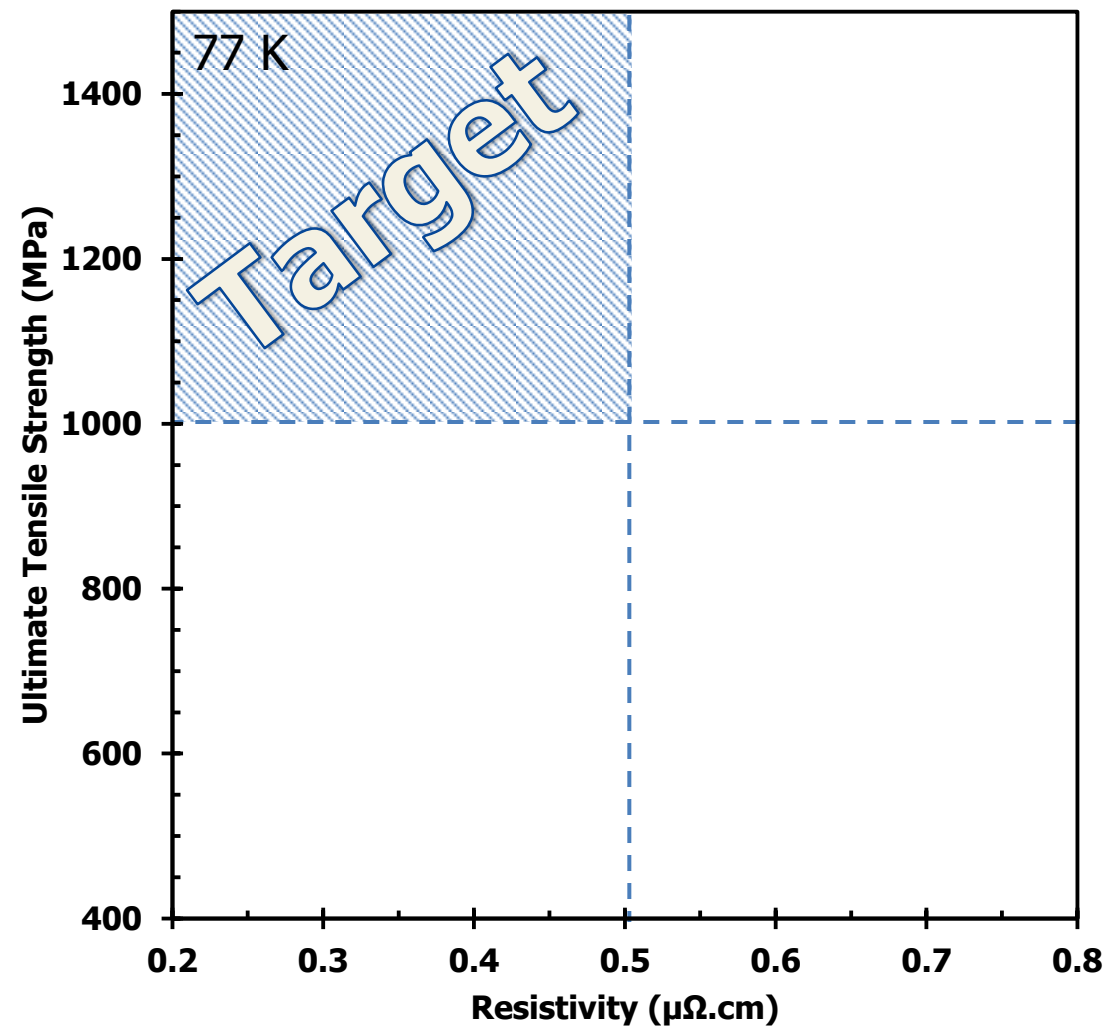
Non-destructive pulsed magnetic fields

Wires that can resist to Lorentz force

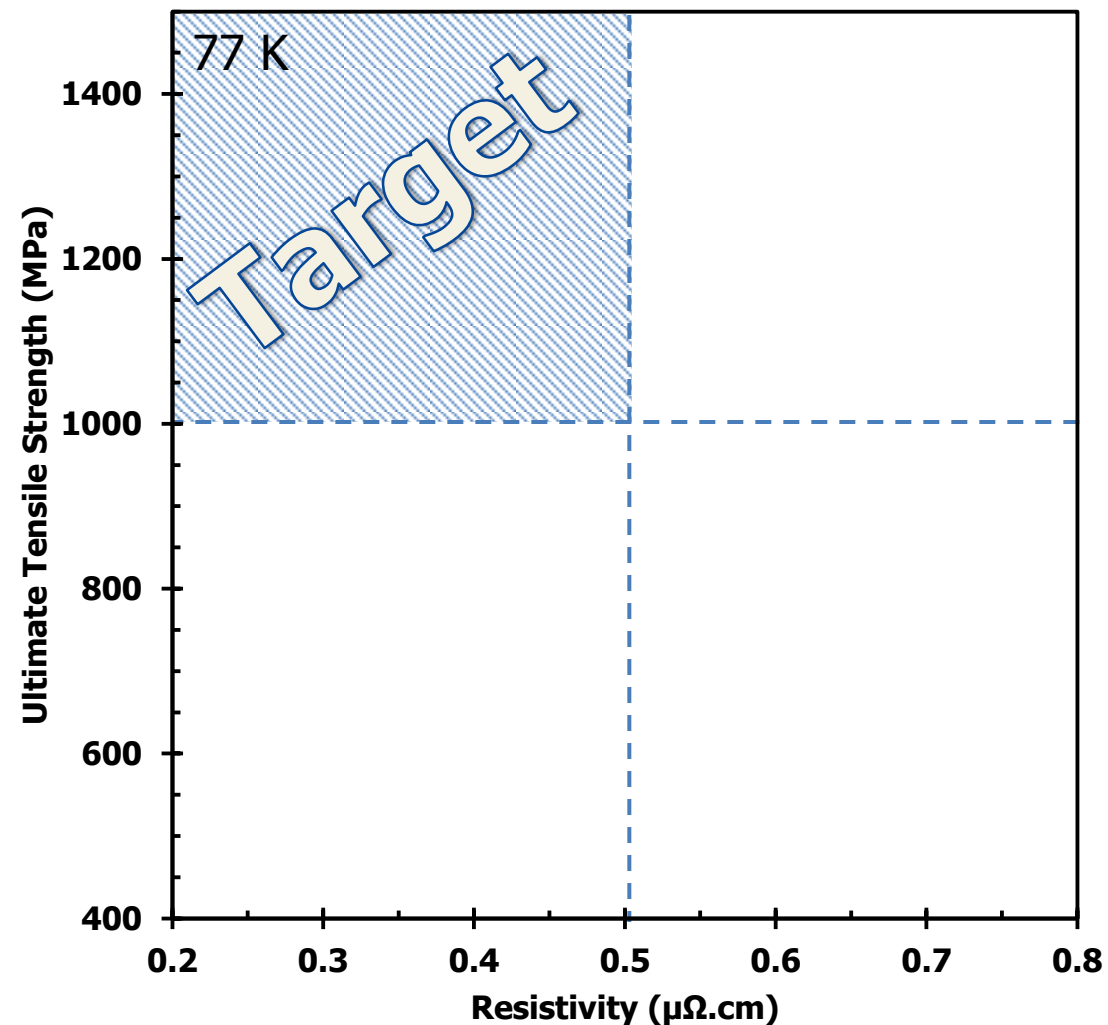
Pure Cu not strong enough

**Copper-based wires**  
+ **mechanical reinforcement**

# High strength - high conductivity wires



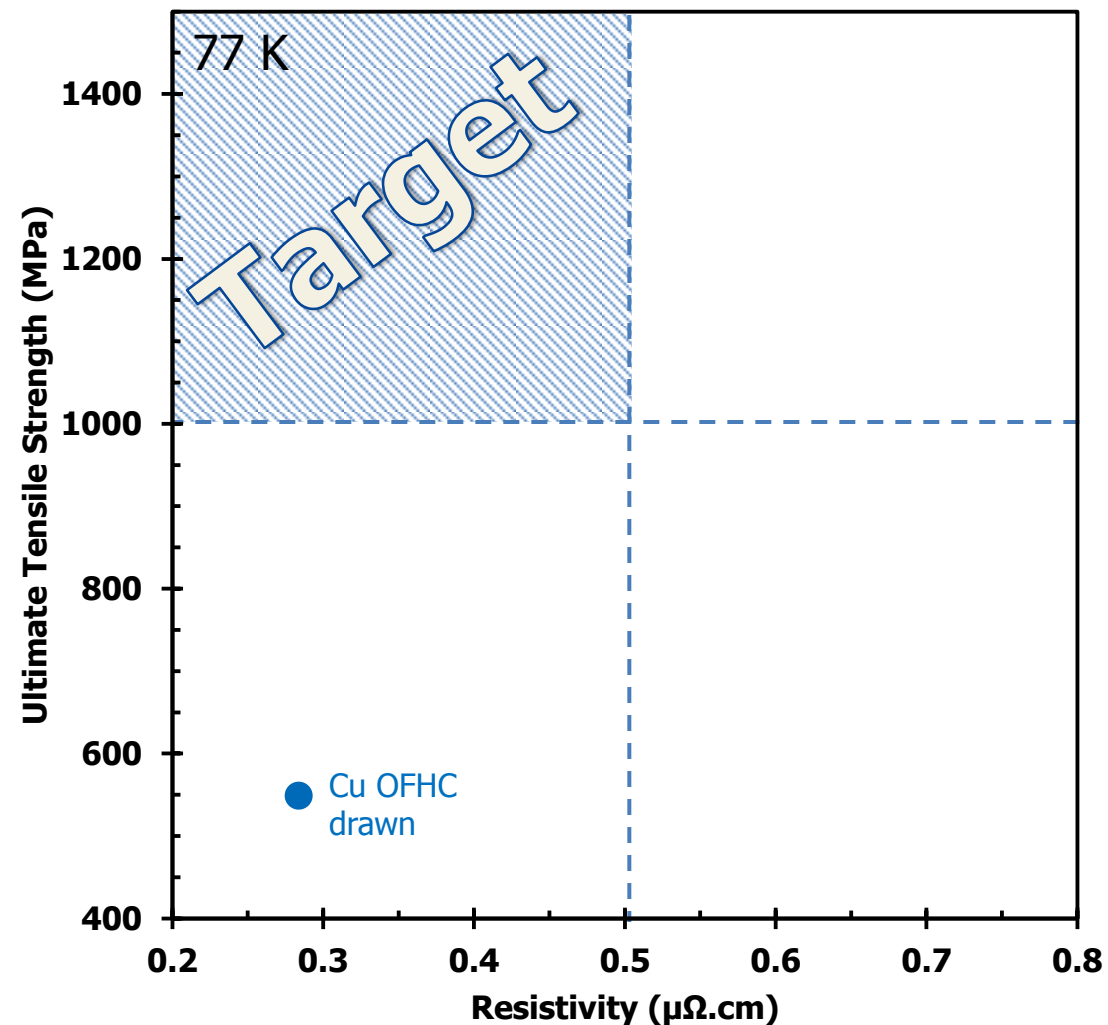
# High strength - high conductivity wires



## Strengthening

Grain refinement (Wire-drawing)

# High strength - high conductivity wires

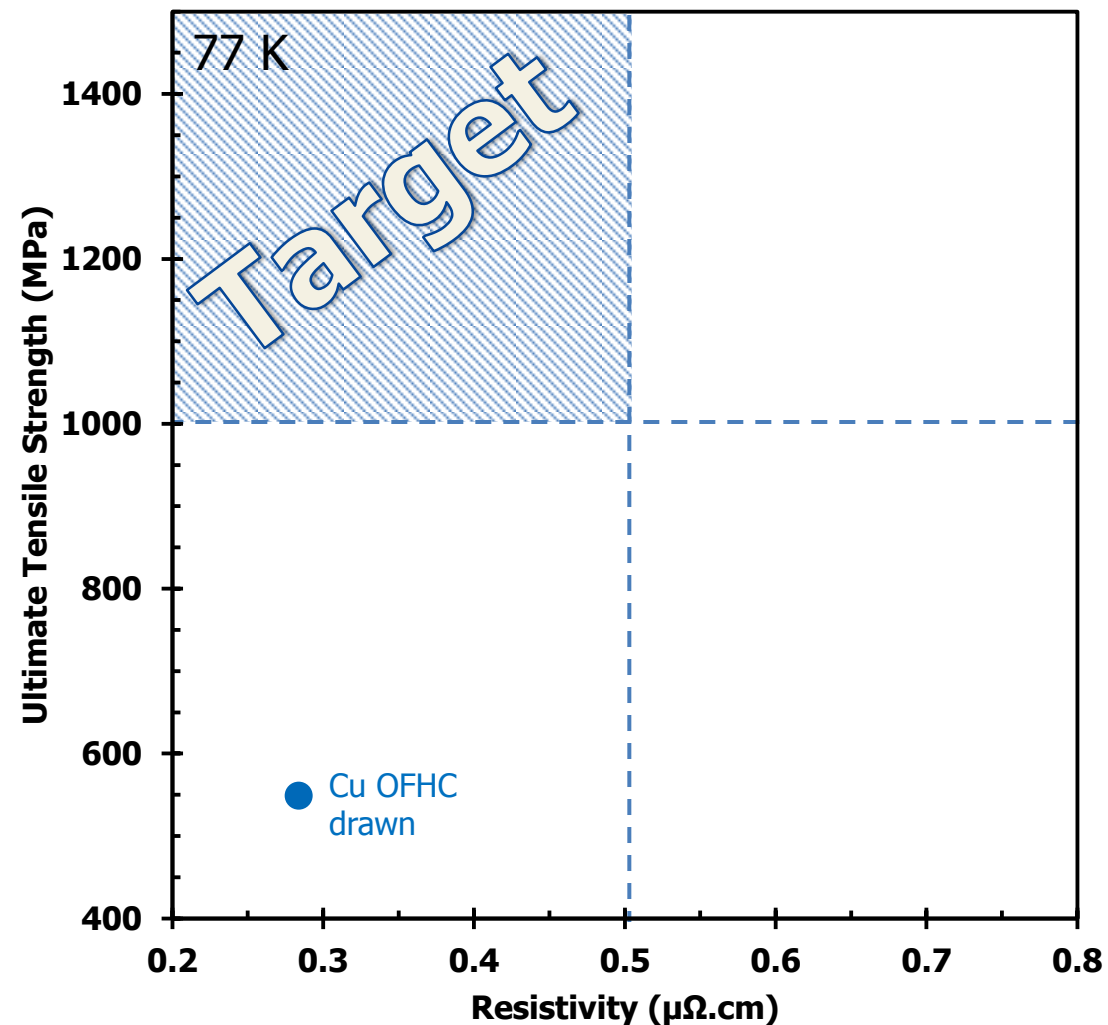


## Strengthening

Grain refinement (Wire-drawing)



# High strength - high conductivity wires



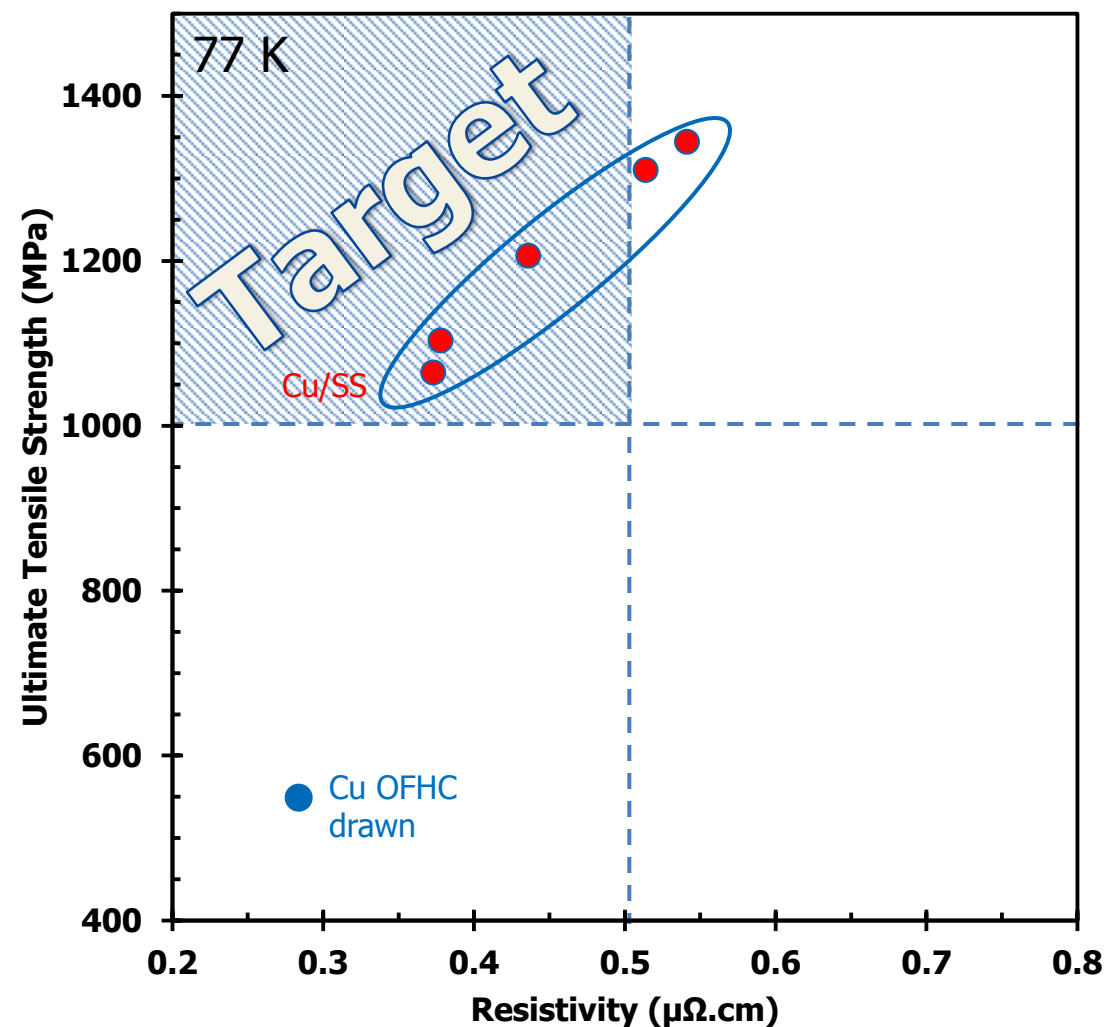
## Strengthening

Grain refinement (Wire-drawing)

Introducing another phase (composite)



# High strength - high conductivity wires

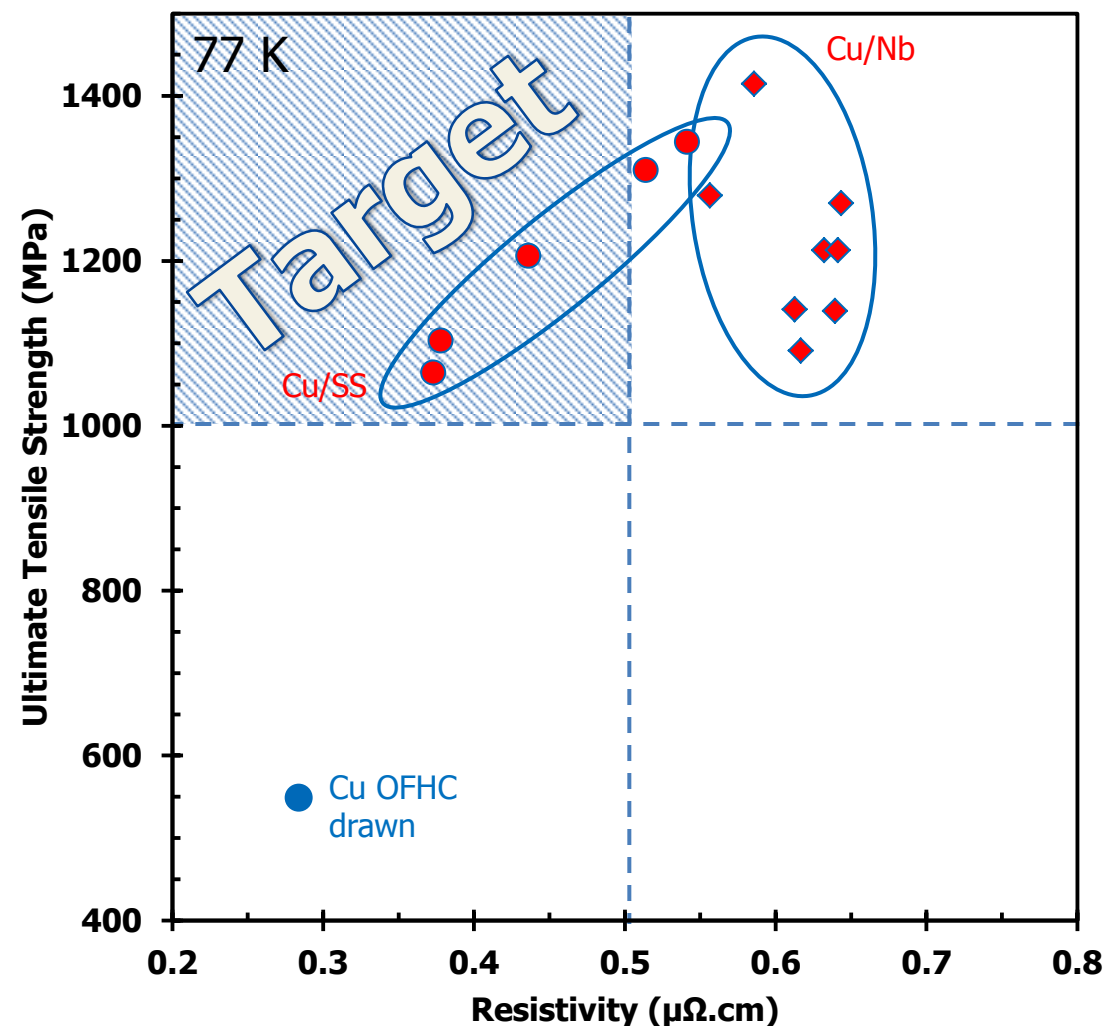


## Strengthening

Grain refinement (Wire-drawing)

Introducing another phase (composite Cu/SS)

# High strength - high conductivity wires

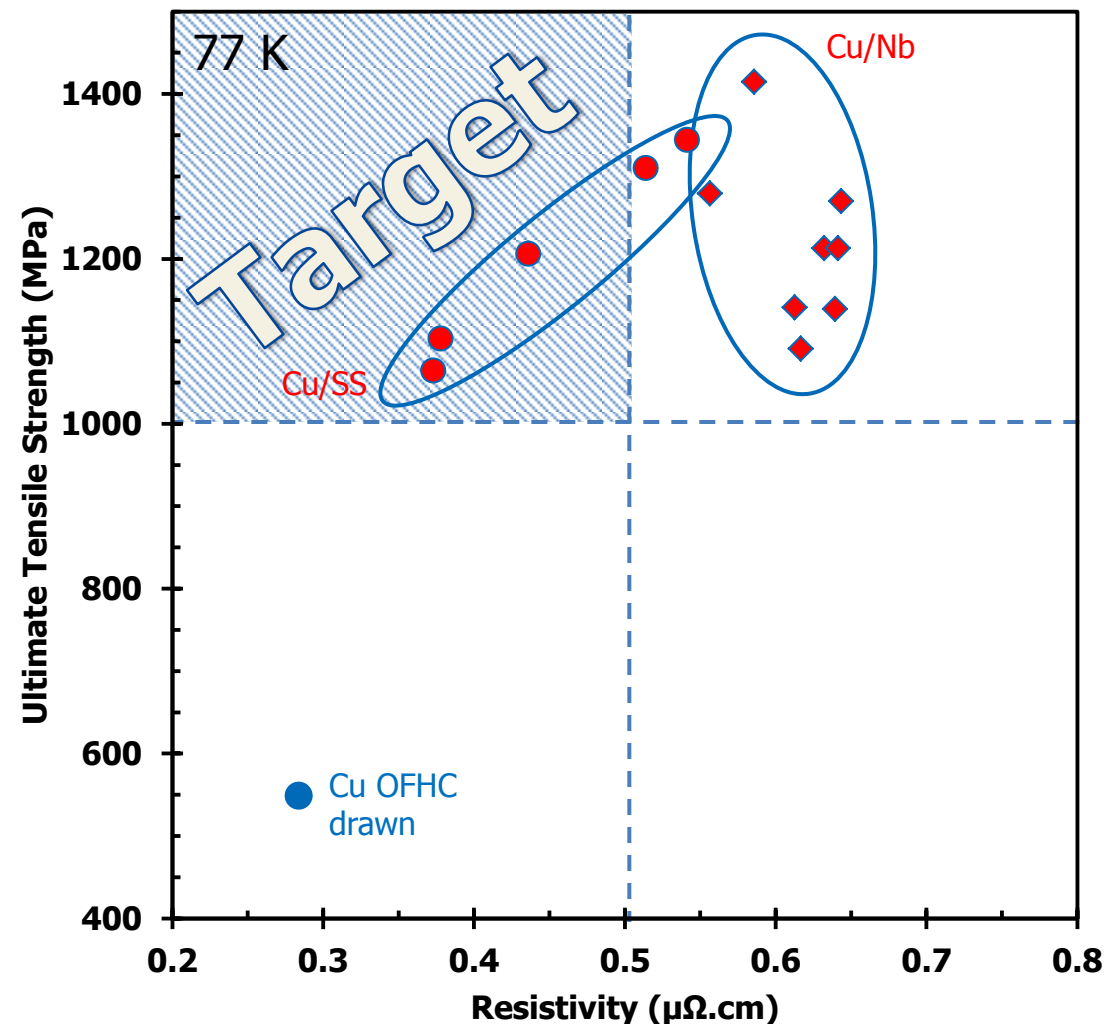


## Strengthening

Grain refinement (Wire-drawing)

Introducing another phase  
(composite Cu/SS Cu/Nb)

# High strength - high conductivity wires



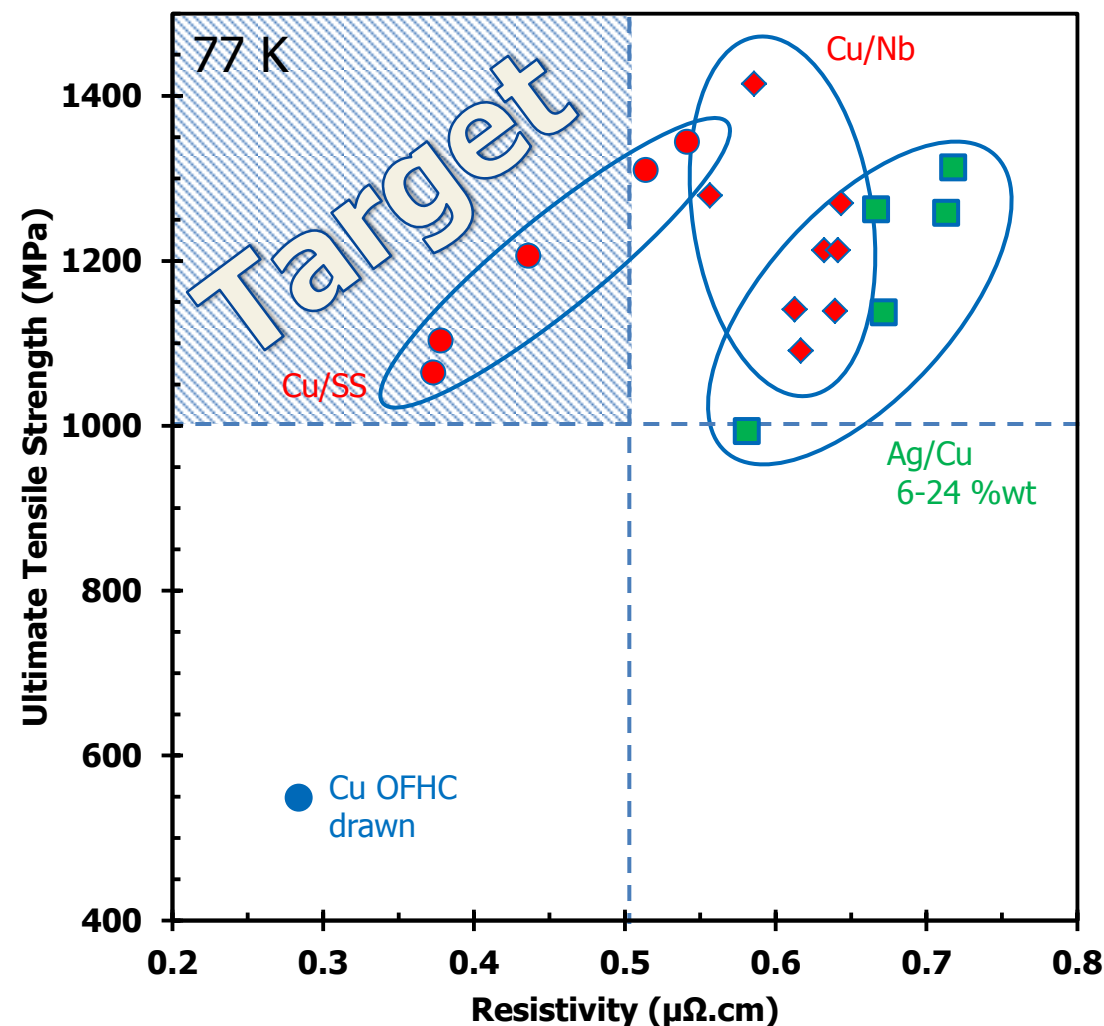
## Strengthening

Grain refinement (Wire-drawing)

Introducing another phase  
(composite Cu/SS Cu/Nb)

Alloying

# High strength - high conductivity wires



## Strengthening

Grain refinement (Wire-drawing)

Introducing another phase  
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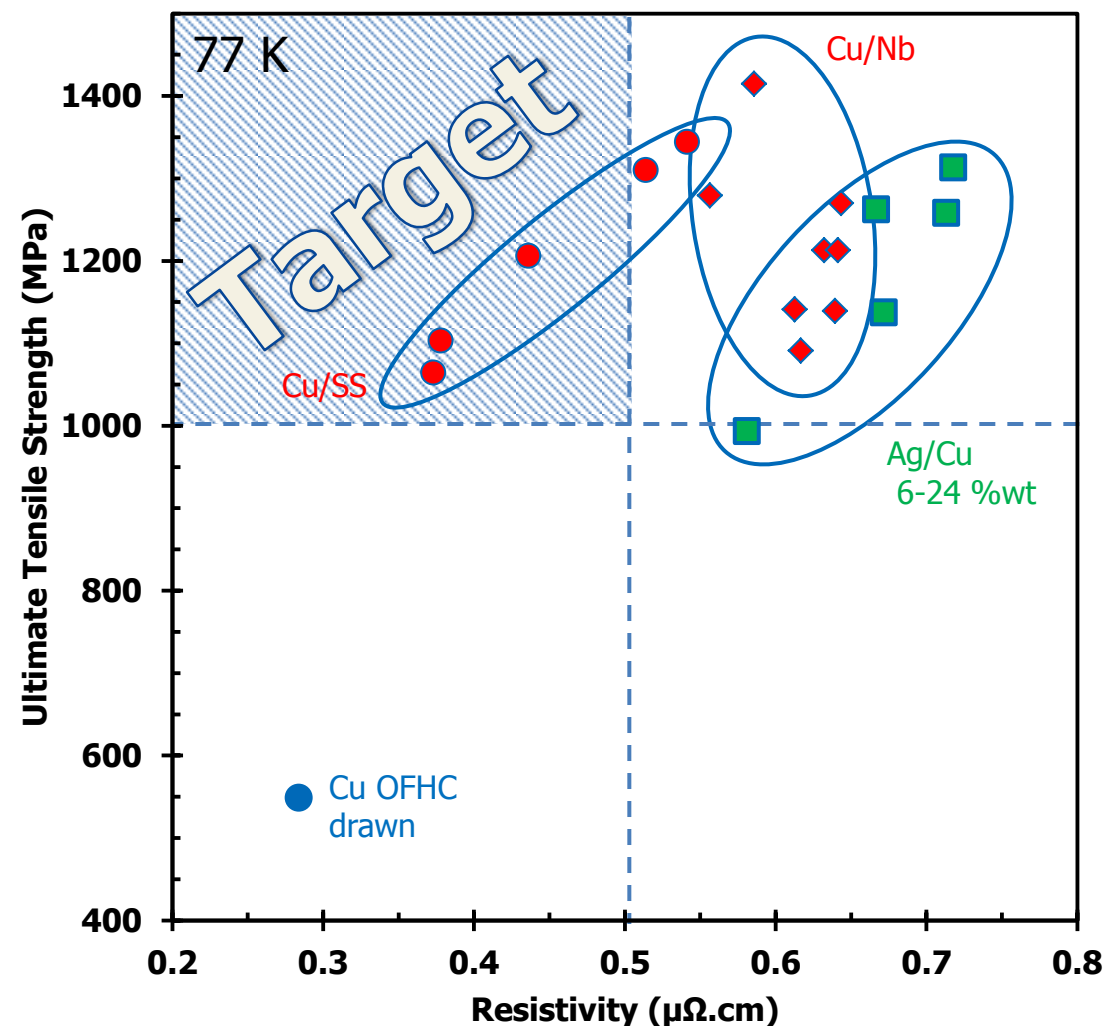
Alloying (Ag/Cu)

Cu/SS : Lecouturier, *Phys. B Condensed Matter*, 2004

Cu/Nb : Vidal, *Scripta Mater.*, 2007.  
Dubois, *Adv. Eng. Mater.*, 2012.

Ag/Cu : Sakai, *Appl. Phys. Lett.*, 1991.  
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# High strength - high conductivity wires



## Strengthening

Grain refinement (Wire-drawing)

Introducing another phase  
(composite Cu/SS Cu/Nb)

Alloying (Ag/Cu)

but

scattering of conducting electrons ↗  
electrical resistivity ↗

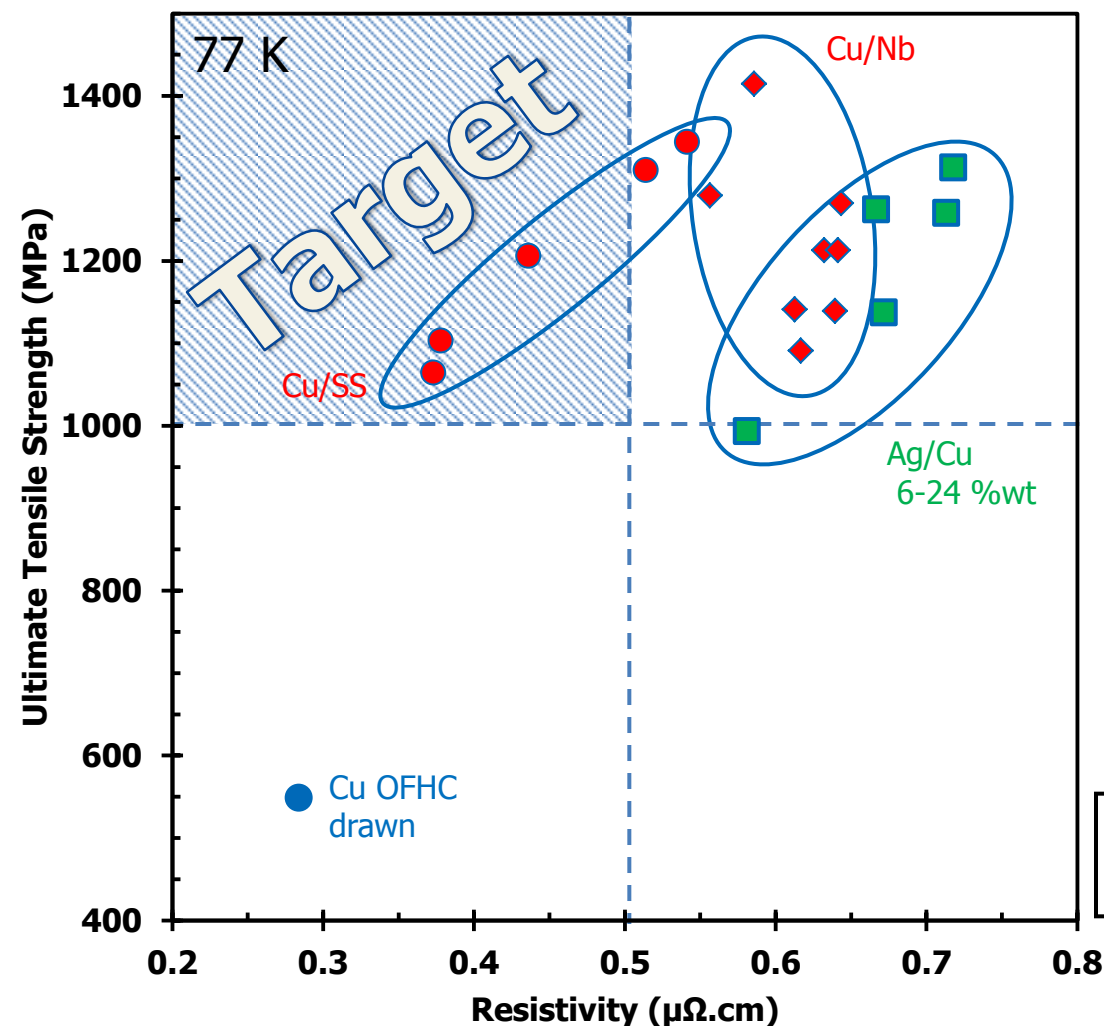
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# High strength - high conductivity wires



## Strengthening

Grain refinement (Wire-drawing)

Introducing another phase  
(composite Cu/SS Cu/Nb)

Alloying (Ag/Cu)

but

scattering of conducting electrons ↗  
electrical resistivity ↗

Best compromise with **composite effect** and **grain refinement**

Cu/SS : Lecouturier, *Phys. B Condensed Matter*, 2004

Cu/Nb : Vidal, *Scripta Mater.*, 2007.  
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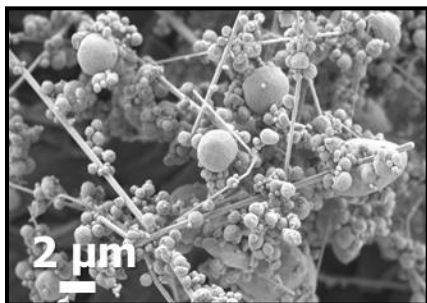
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Zuo, *Mater. Sci. Eng. A*, 2014.



# High strength - high conductivity Ag-Cu composite wires



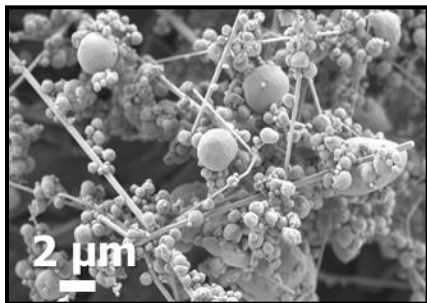
# High strength - high conductivity Ag-Cu composite wires



**14 g**

**Ag-Cu composite powder**  
CIRIMAT

# High strength - high conductivity Ag-Cu composite wires



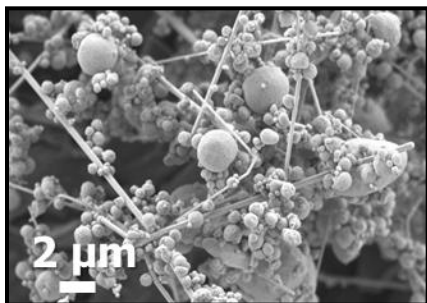
14 g

Ag-Cu composite powder  
CIRIMAT

Spark plasma  
sintering



# High strength - high conductivity Ag-Cu composite wires



14 g

**Ag-Cu composite powder**  
CIRIMAT

**Spark plasma sintering**

**Cylinder**  
CIRIMAT and PNF<sup>2</sup>

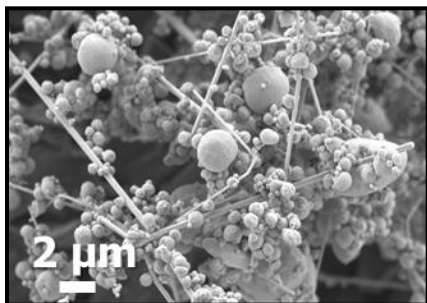


Ø 8 mm L 30 mm





# High strength - high conductivity Ag-Cu composite wires



14 g

**Ag-Cu composite powder**  
CIRIMAT

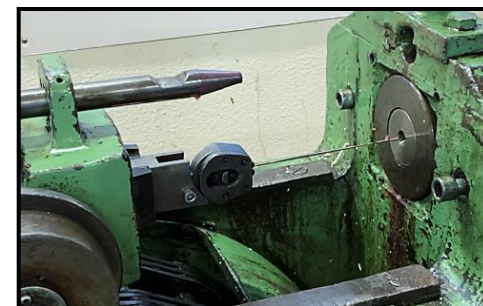
**Spark plasma sintering**

**Cylinder**  
CIRIMAT and PNF<sup>2</sup>

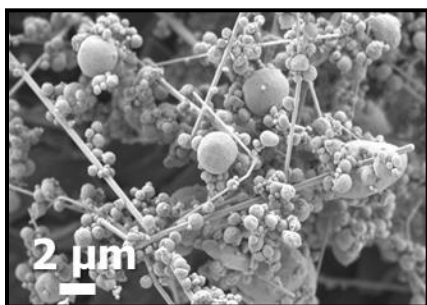
**Wire drawing**



Ø 8 mm L 30 mm



# High strength - high conductivity Ag-Cu composite wires



14 g

**Ag-Cu composite powder**  
CIRIMAT

**Spark plasma sintering**



Ø 8 mm L 30 mm

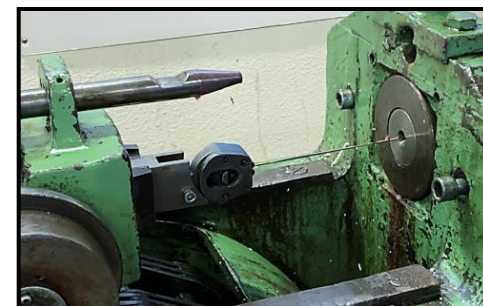
**Cylinder**  
CIRIMAT and PNF<sup>2</sup>

**Wire drawing**



Ø 1.023 – 0.198 mm

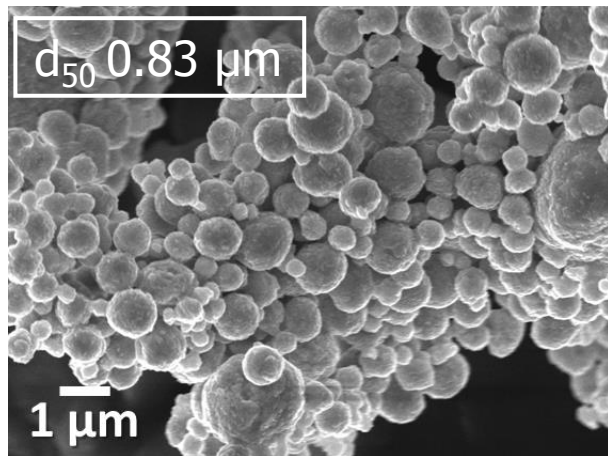
**Wire**  
LNCMI



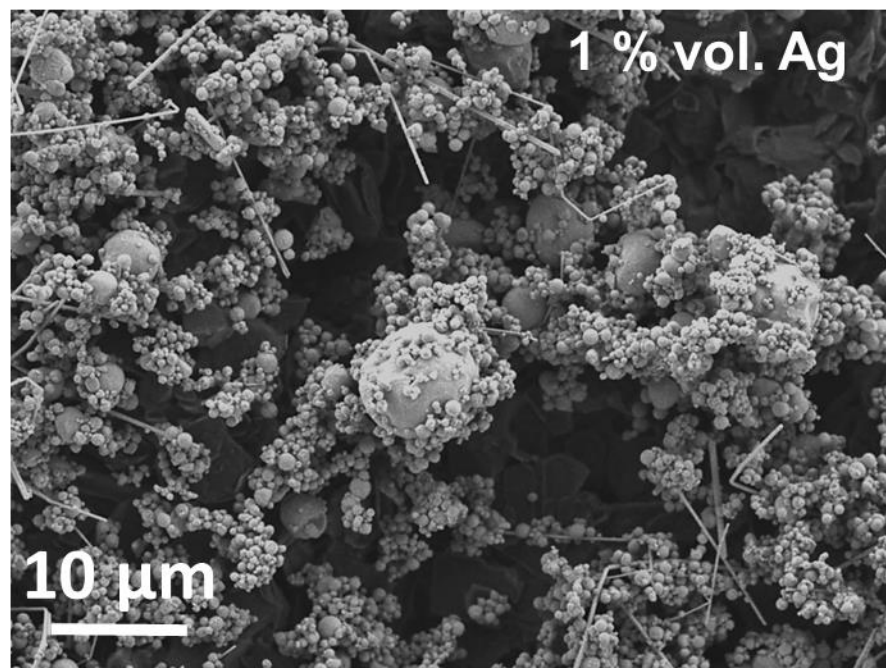


# Composite powder preparation

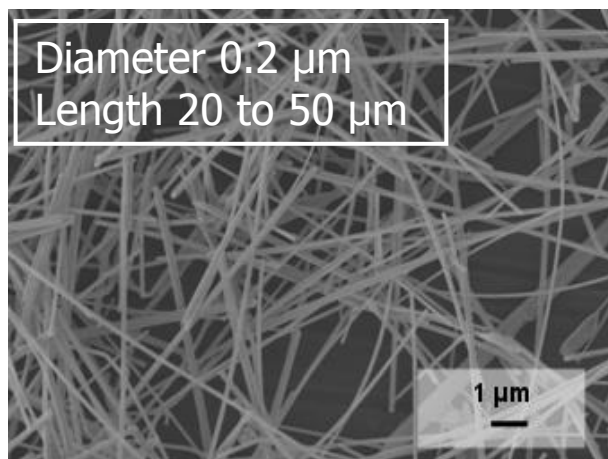
## Spherical commercial Cu powder



**Low Ag content to limit the increase of resistivity**



## Lab. made Ag microwires

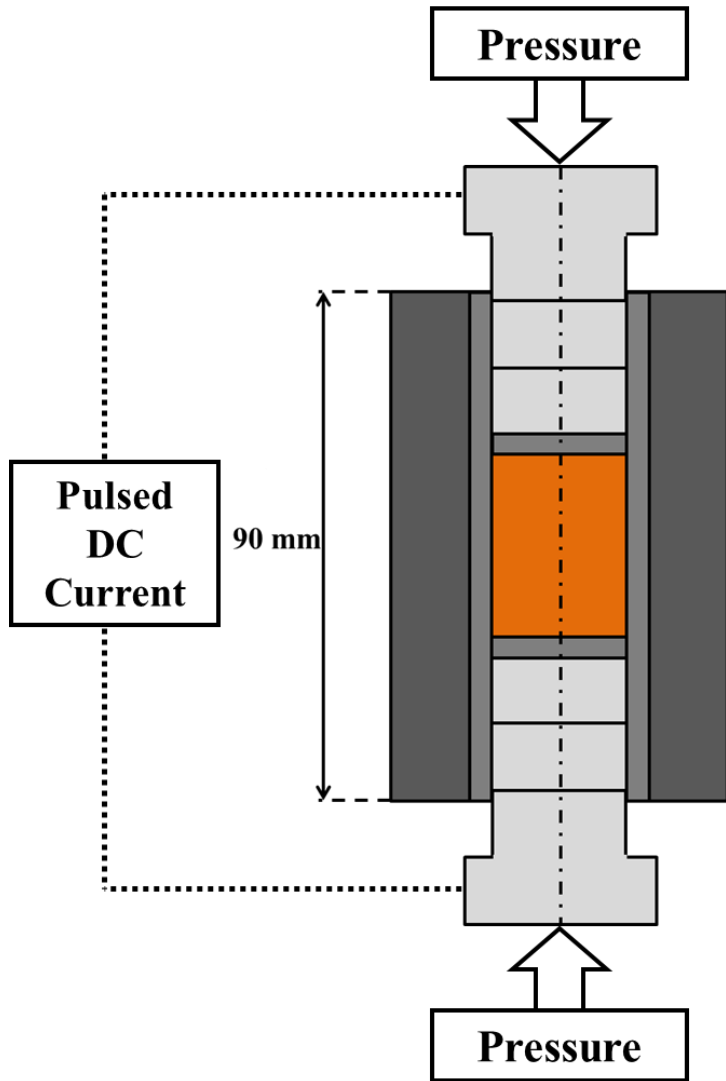


**Ag-Cu composite powder**  
**1, 5 or 10 % vol. Ag**

Tardieu, Mater. Sci. Eng. A, 2019.

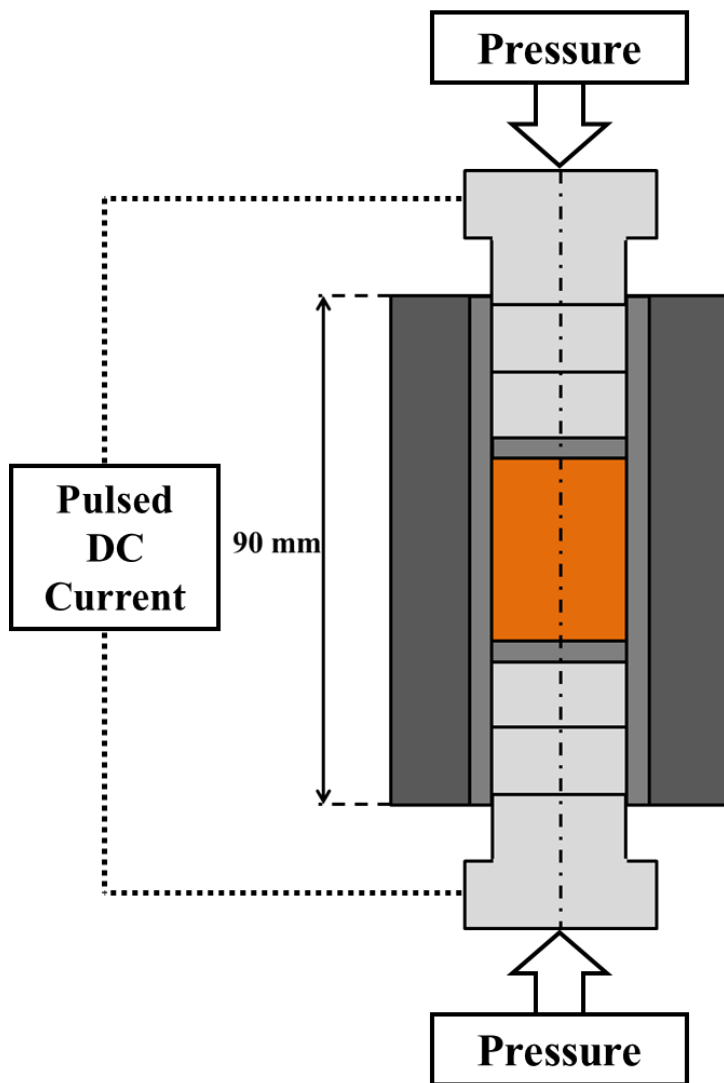
Patent PCT/EP2019/069990 2019

# Sintering by Spark Plasma Sintering



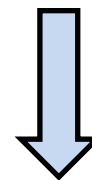


## Sintering by Spark Plasma Sintering



Low sintering temperature

Low duration

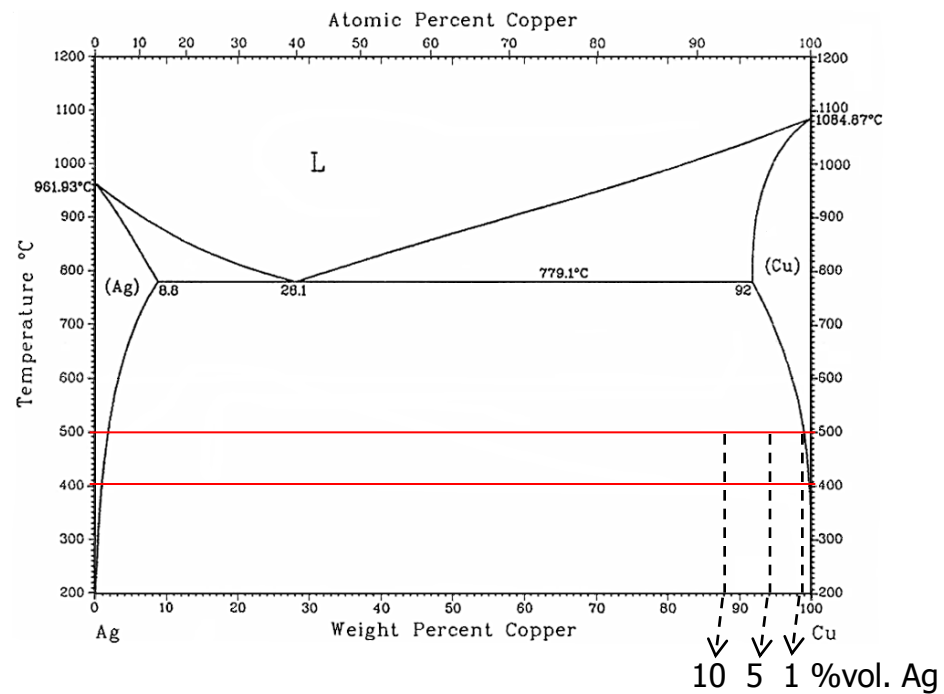
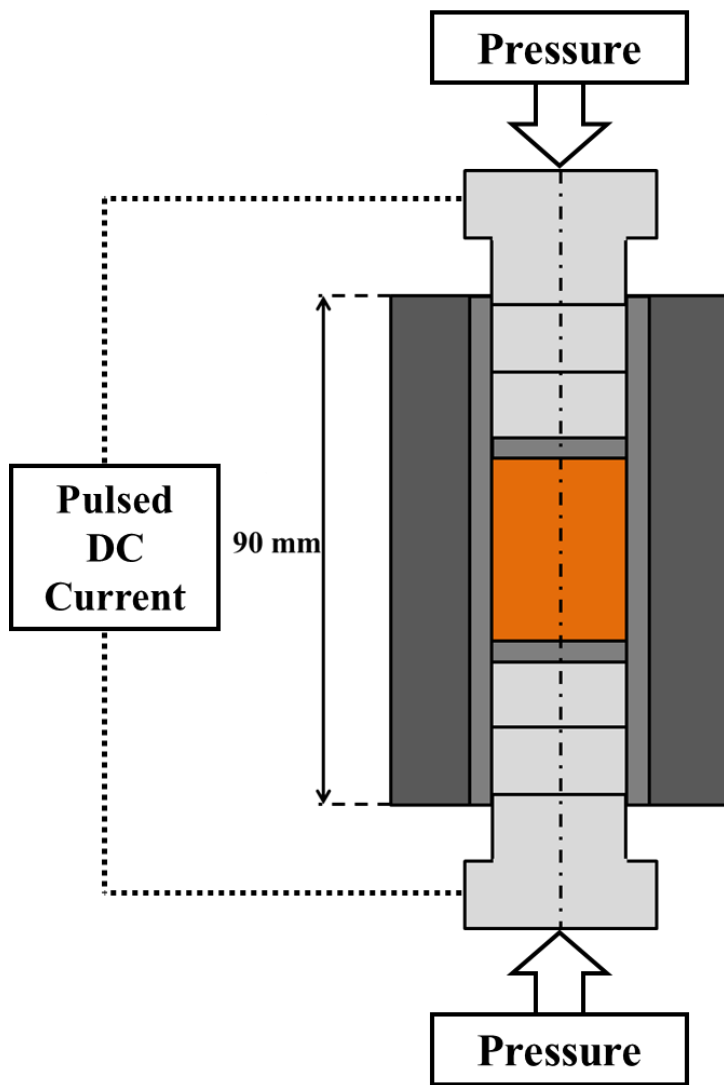


**Low grain growth**

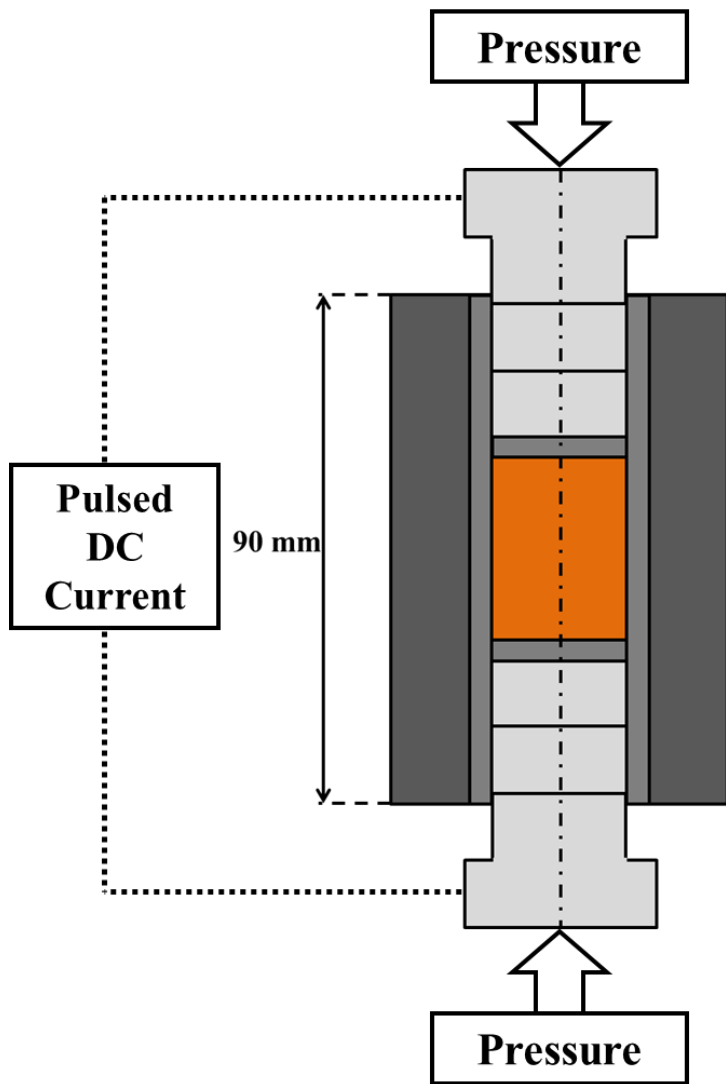
**No melting**



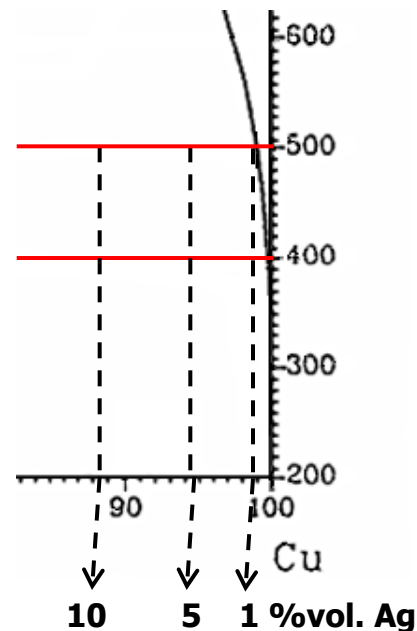
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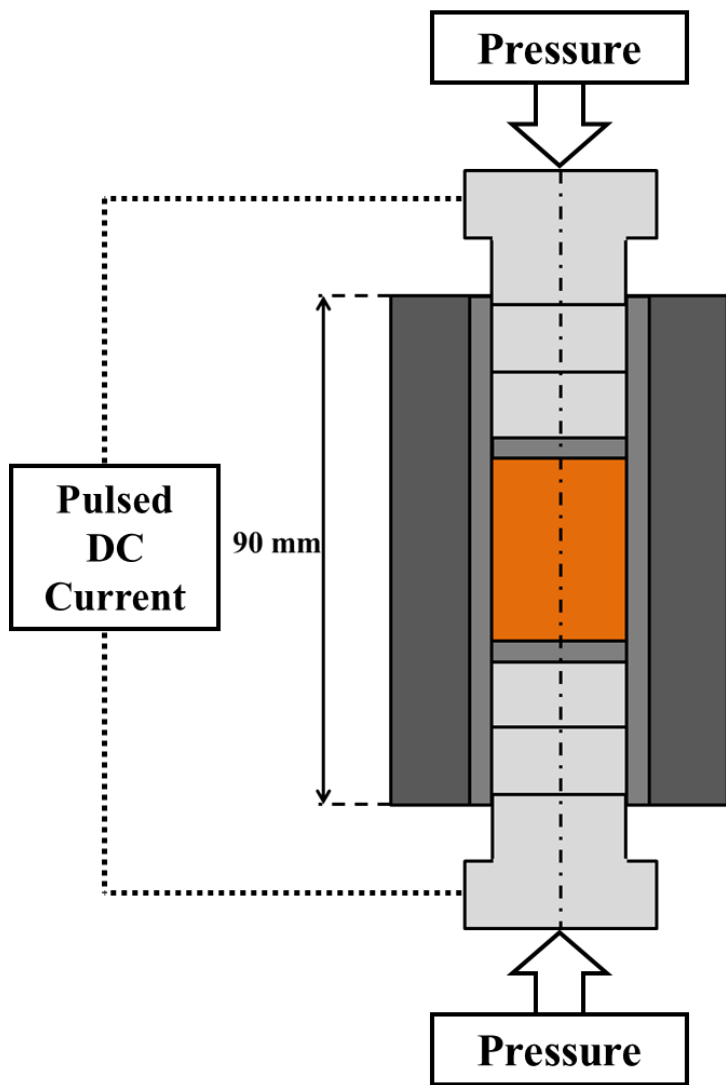
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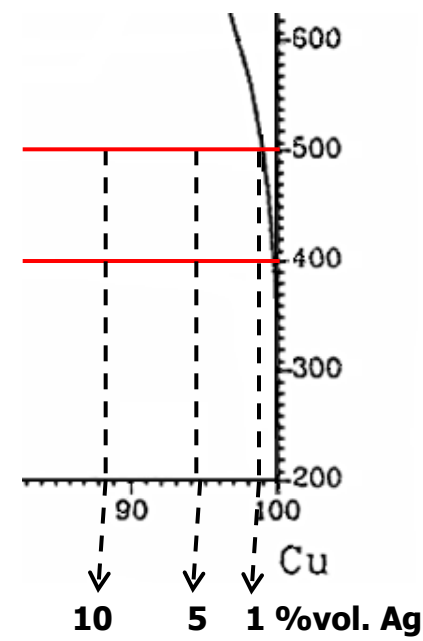
**400 °C**  
**Ag solubility in Cu**  
**< 0.1 % vol.**



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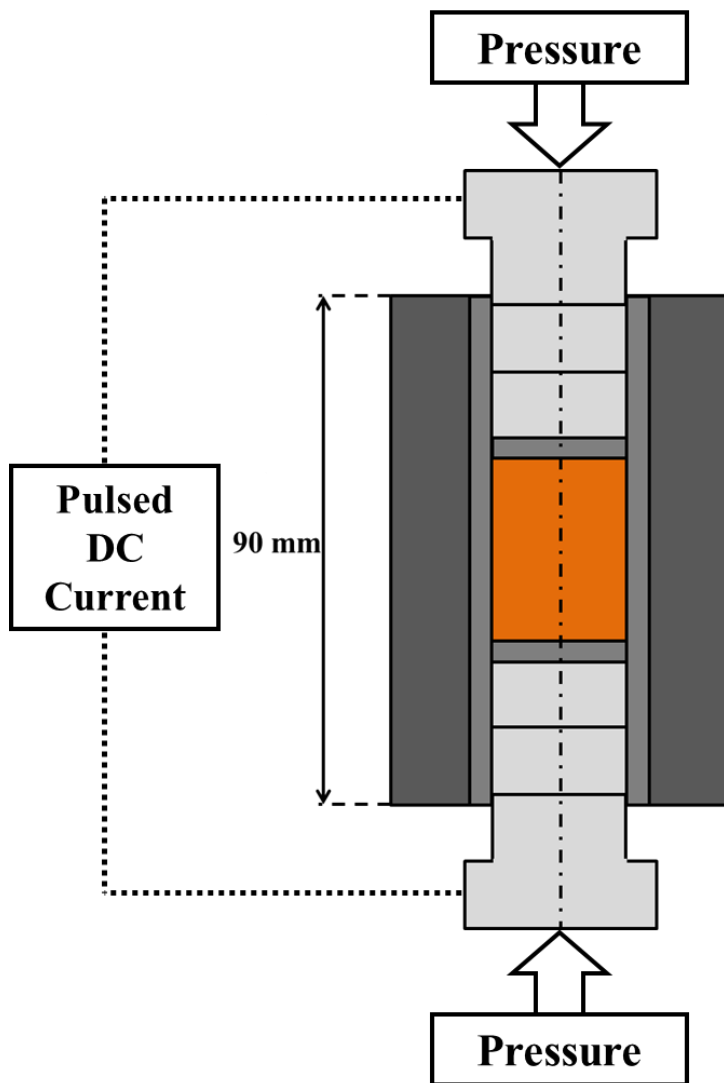


**400 °C**  
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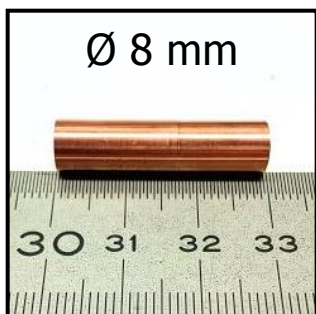
**400 or 500 °C, 25 MPa, 5 min**

# Sintering by Spark Plasma Sintering

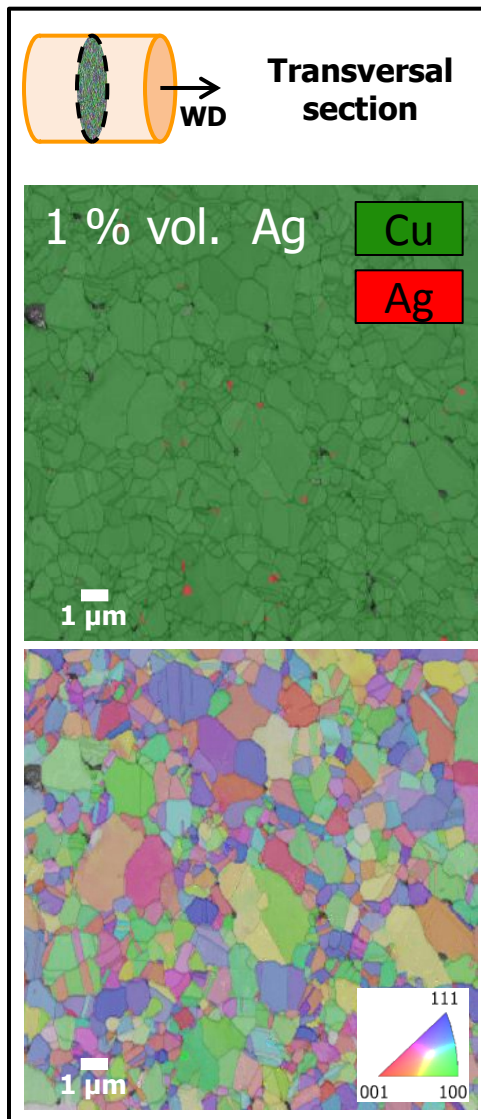


**Cylinder**  
**Ø 8 mm**  
**L 30 mm**

# Cylinder microstructure



Densification  $94 \pm 2\%$



**2 phases (composite)**

**Low grain growth**

**Cu  $d_{50} = 0.91 \mu\text{m}$**

**Ag  $d_{50} = 0.27 \mu\text{m}$**

**Isotropic grains**

**No particular texture**

## Room temperature wire-drawing

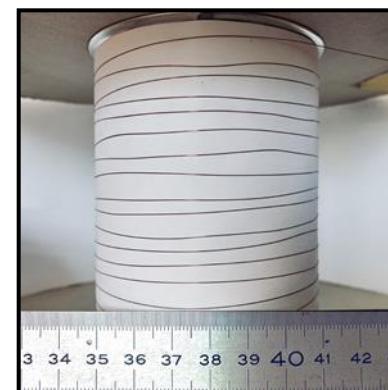


**Cylinder  $\varnothing$  8 mm**

**L 30 mm**



**49 passes**

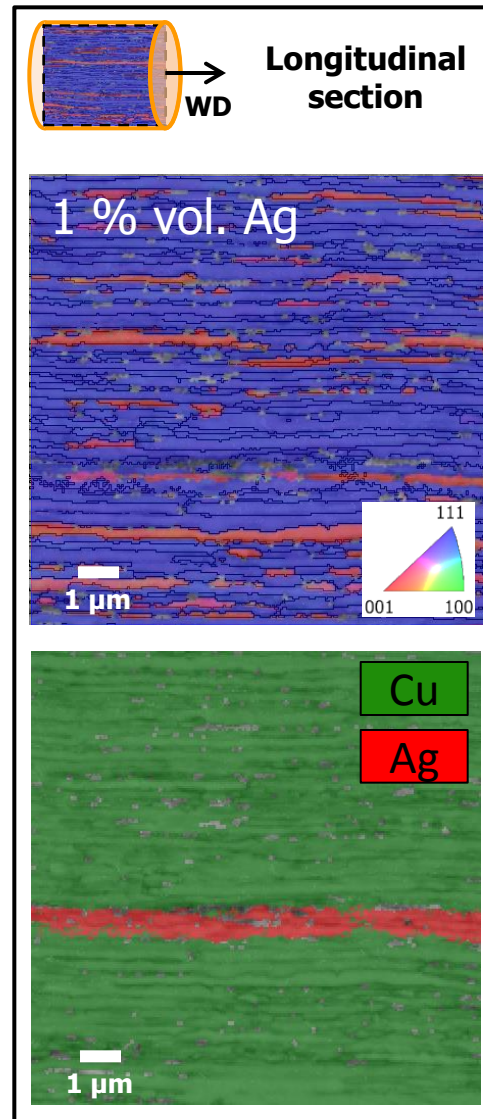
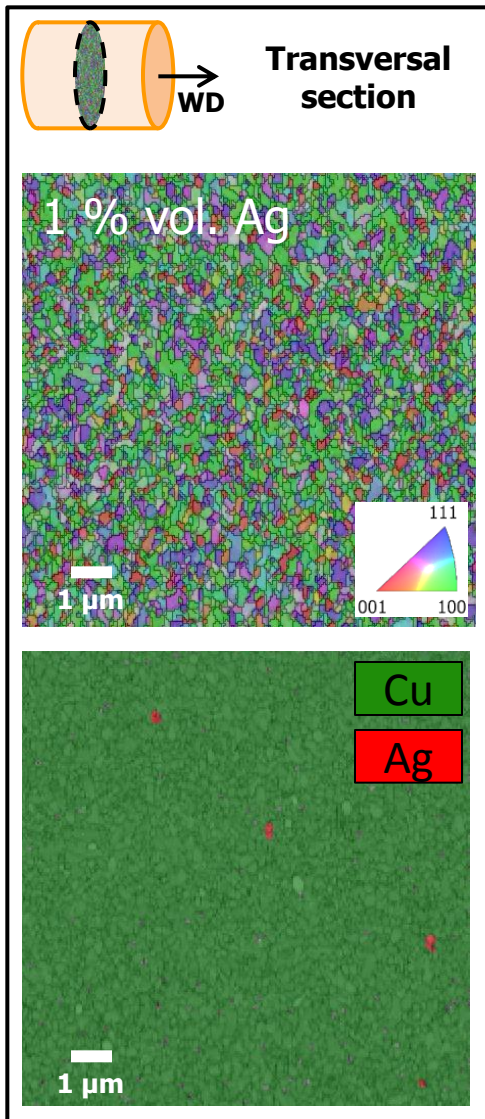


**Wire  $\varnothing$  0.2 mm**

**L 48 m**



# Wire microstructure



**Ultrafine grains**  
 Cu  $d_{50} = 0.20 \mu\text{m}$   
 Ag  $d_{50} = 0.17 \mu\text{m}$

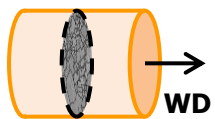
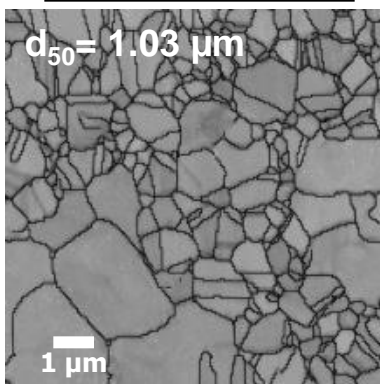
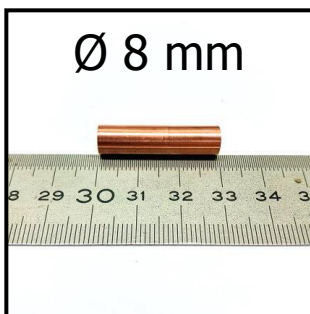
**Long grains**  
 $L > 5 \mu\text{m}$

**Cu and Ag texture**  
 $\langle 111 \rangle, \langle 100 \rangle$



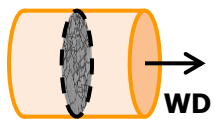
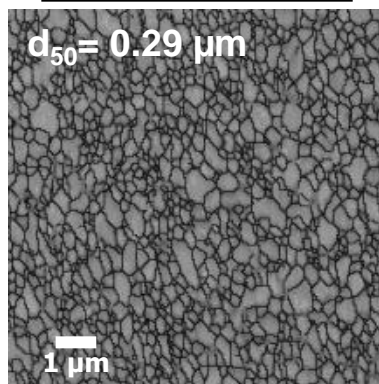
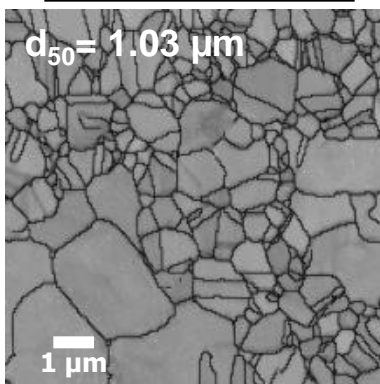
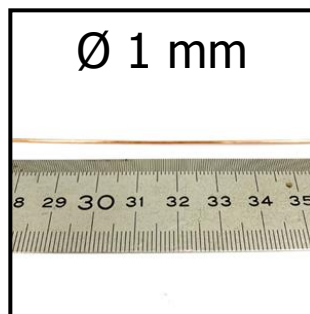
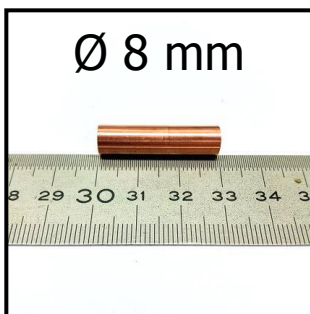
# Grain refinement (nanostructuring)

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Transversal section

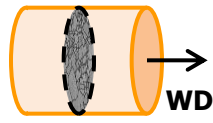
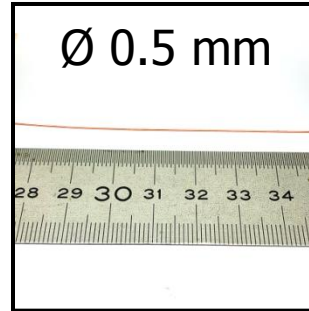
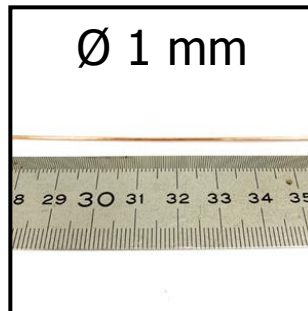
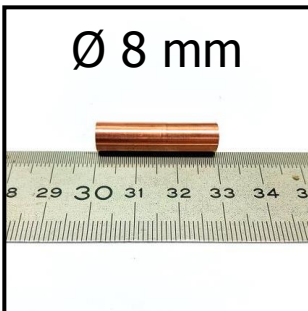
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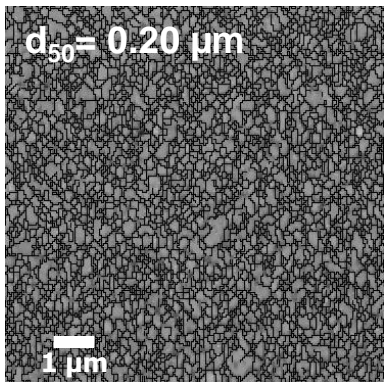
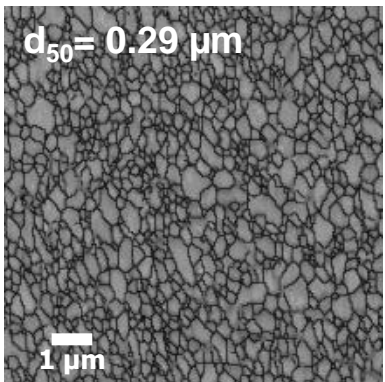
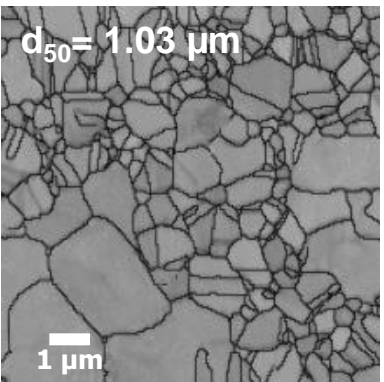
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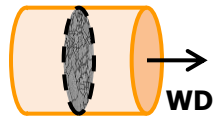
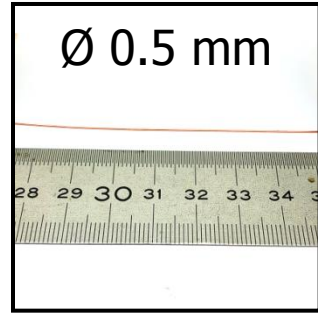
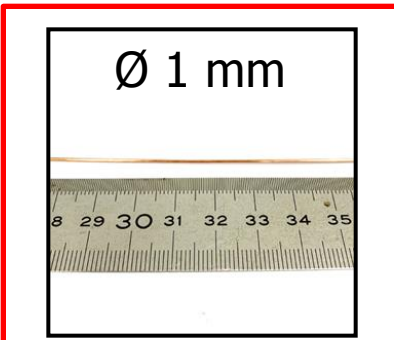
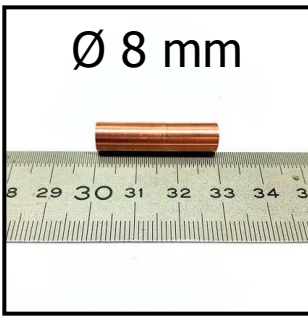
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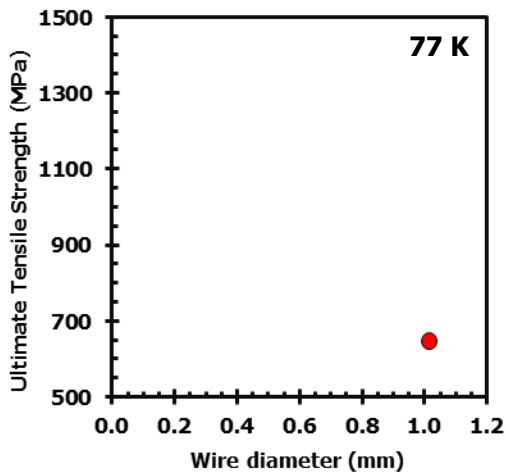
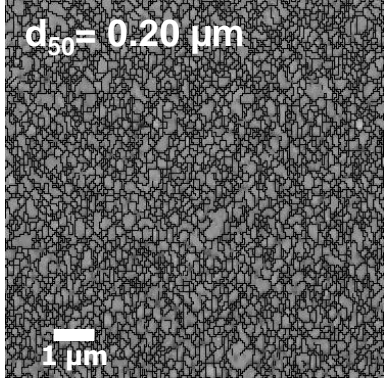
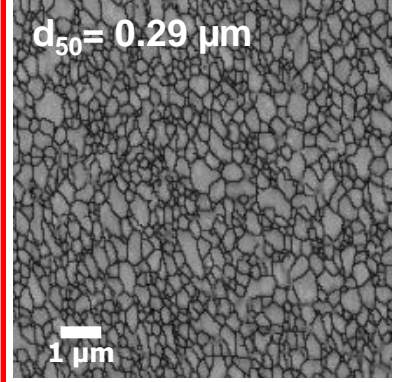
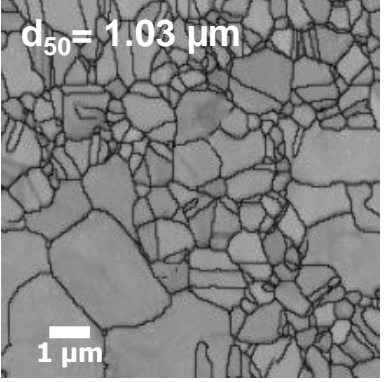
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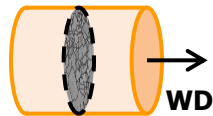
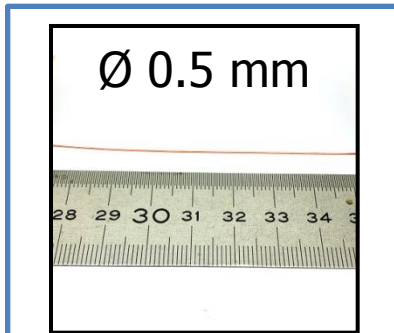
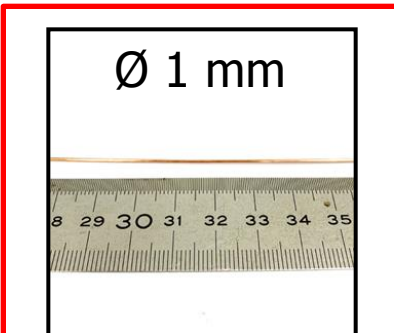
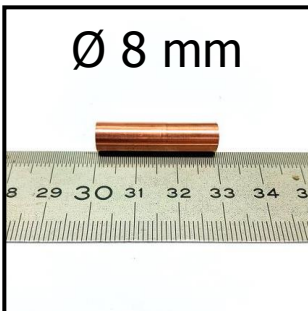
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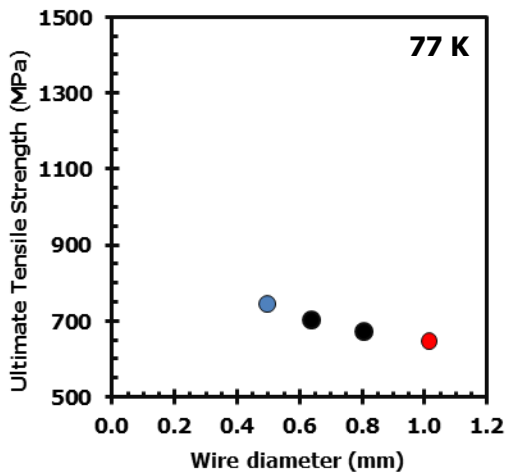
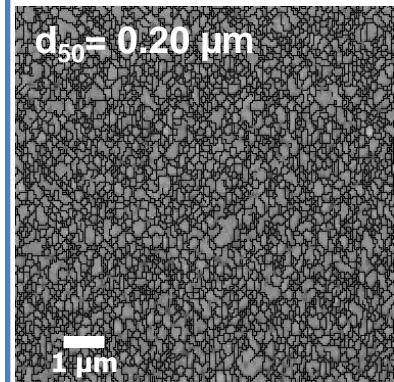
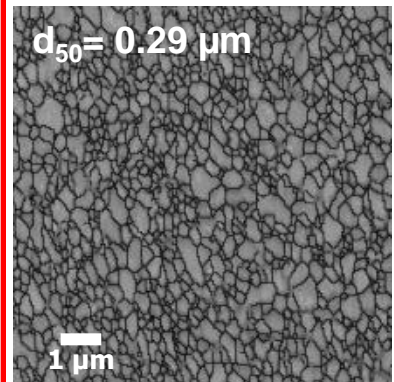
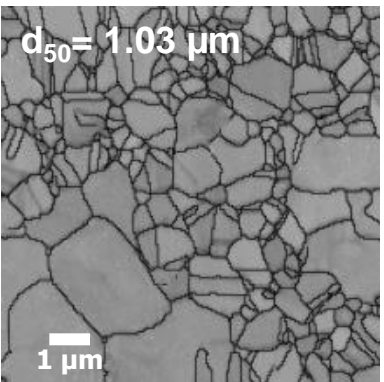
Transversal section



# Grain refinement (nanostructuring)



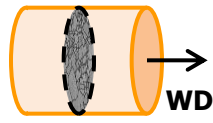
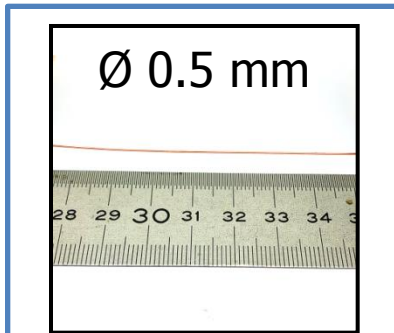
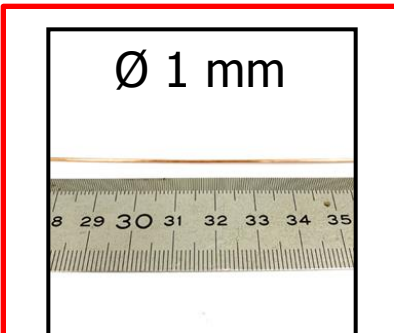
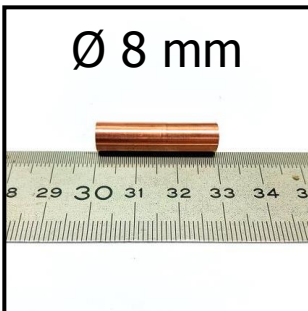
Transversal section



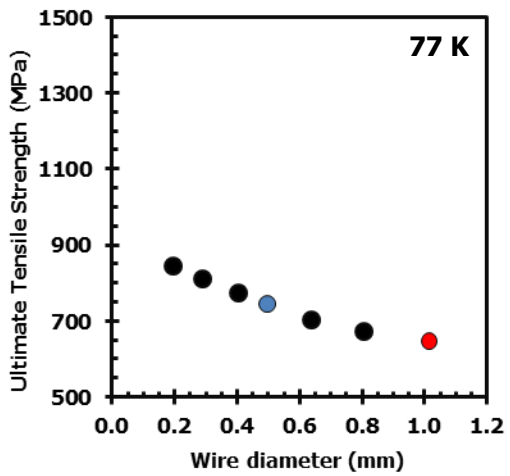
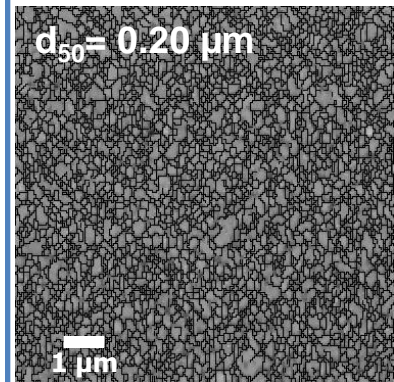
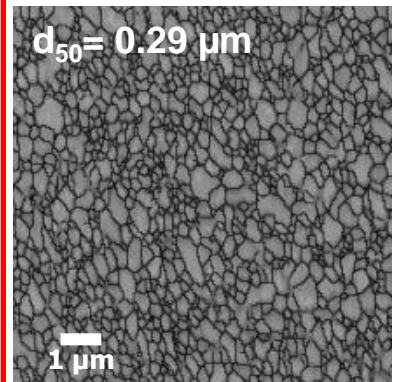
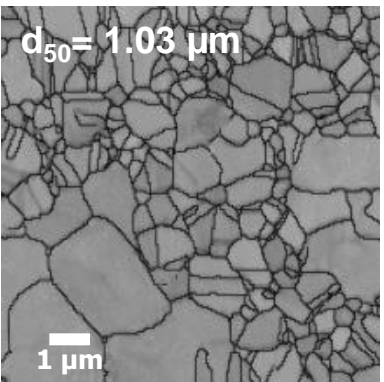
● Cu/400



# Grain refinement (nanostructuring)



Transversal section

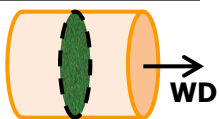
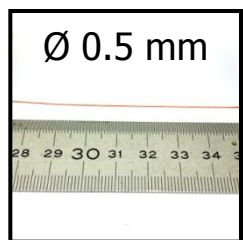


● Cu/400

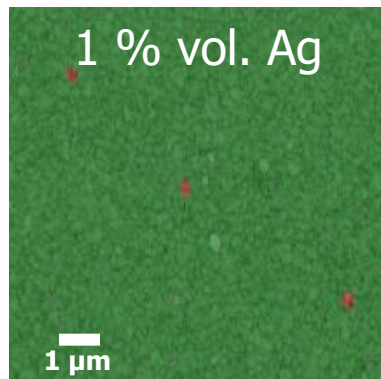


## Introducing another phase

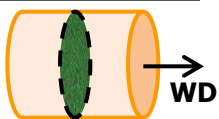
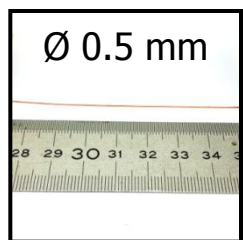
## Introducing another phase



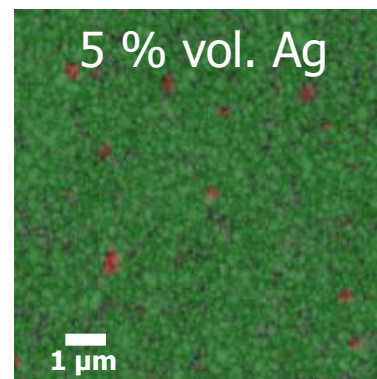
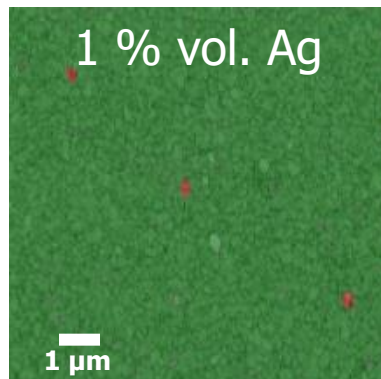
Transversal  
section



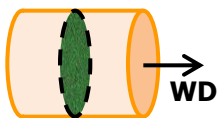
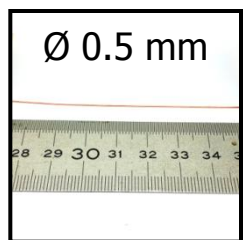
## Introducing another phase



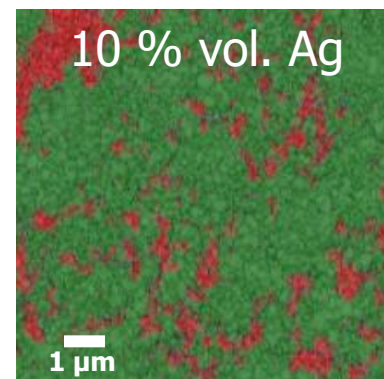
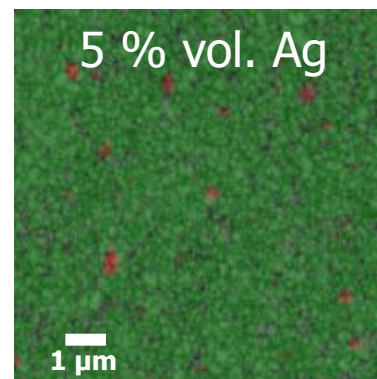
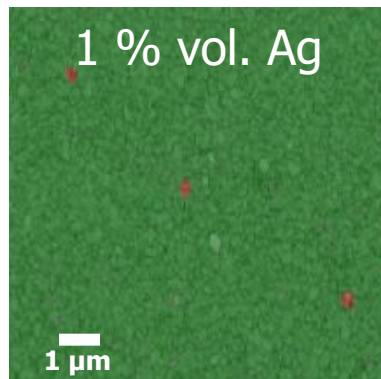
Transversal  
section



## Introducing another phase



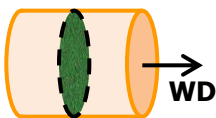
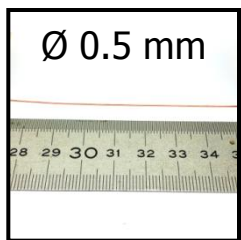
Transversal  
section



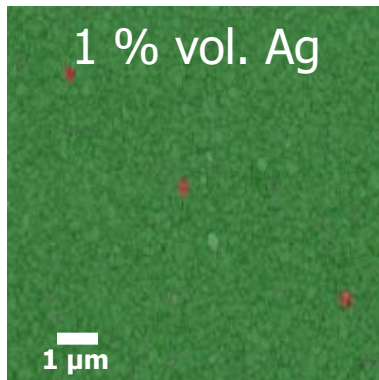




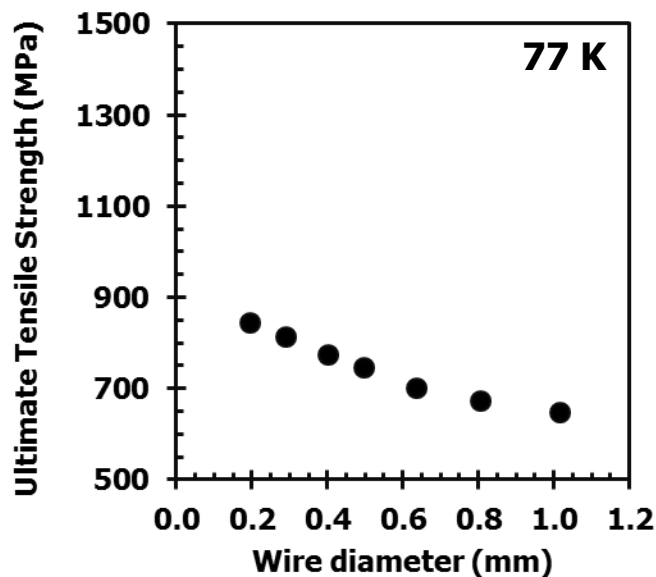
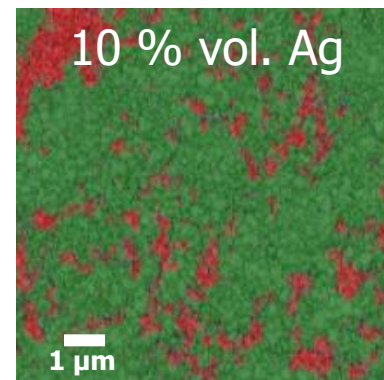
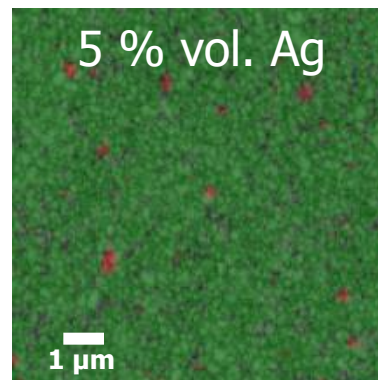
# Introducing another phase



Transversal section



Cu Ag

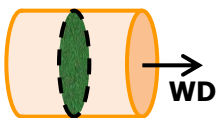
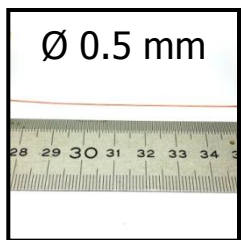


● Cu/400

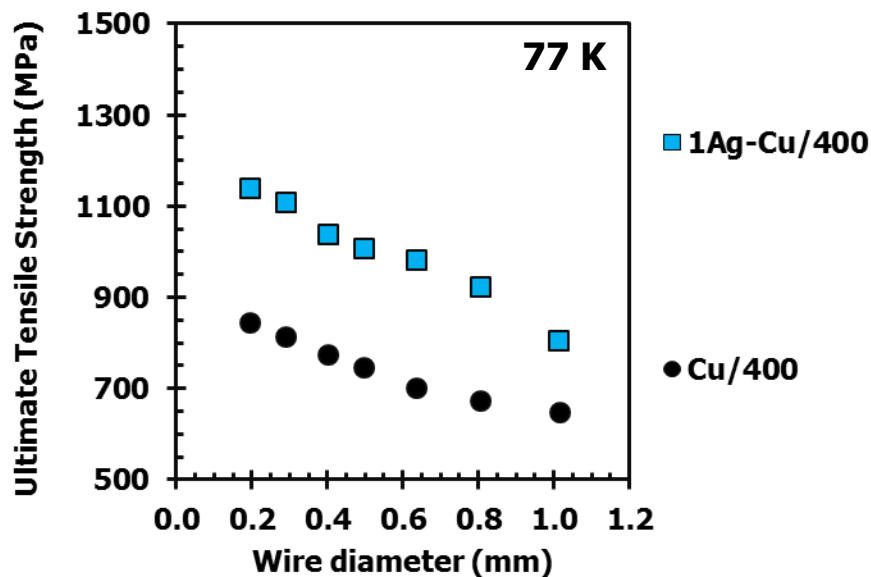
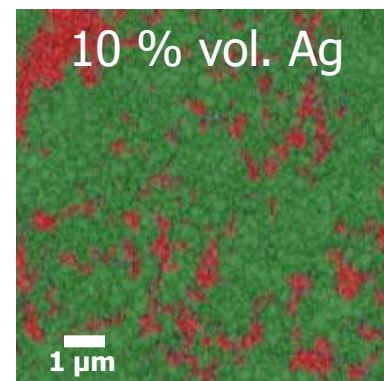
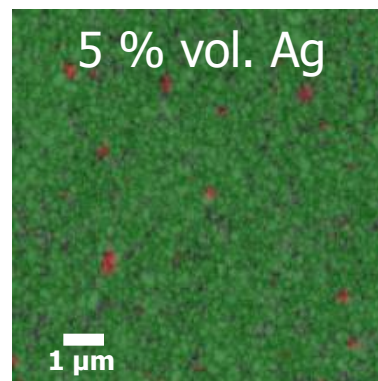
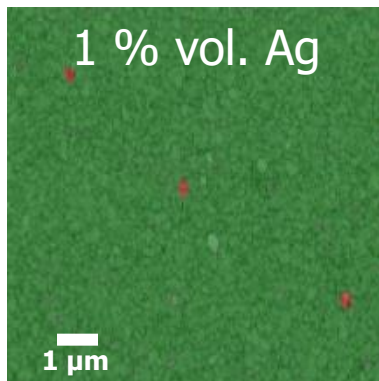




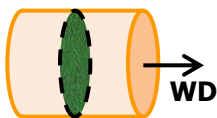
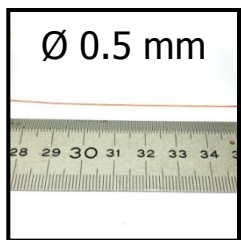
# Introducing another phase



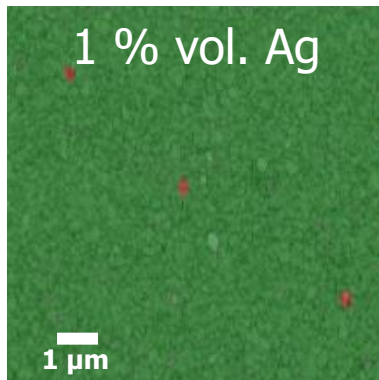
Transversal section



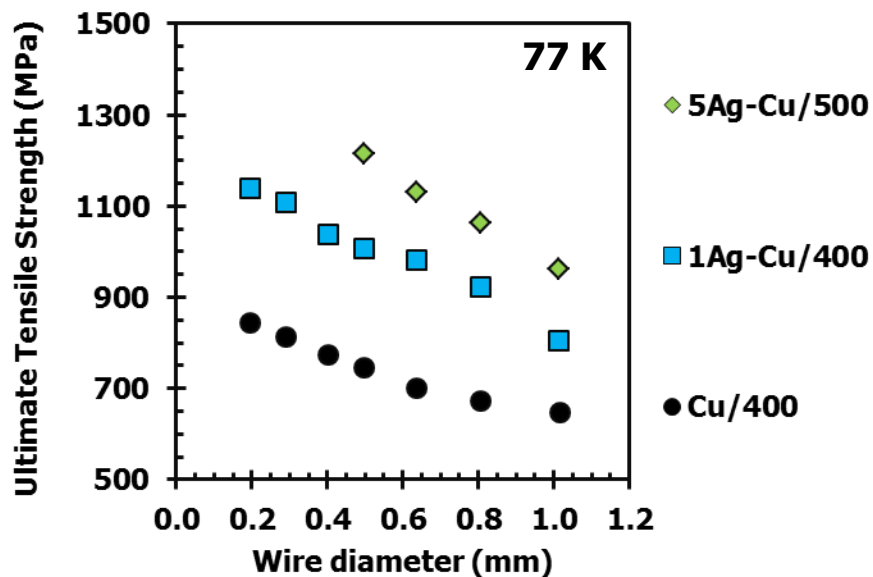
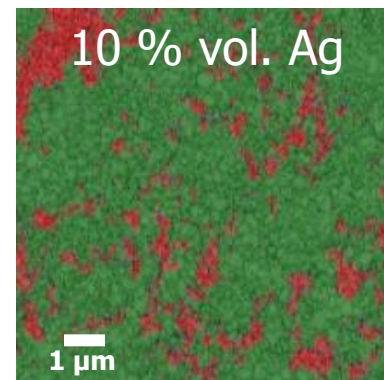
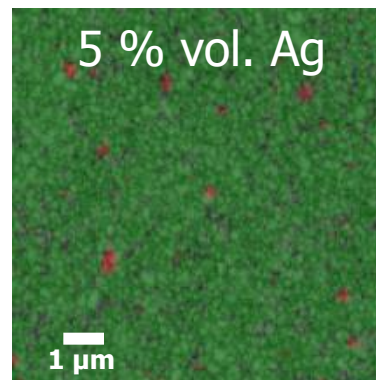
# Introducing another phase



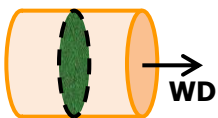
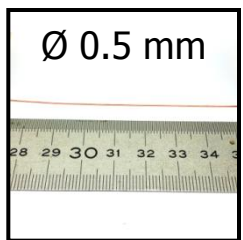
Transversal section



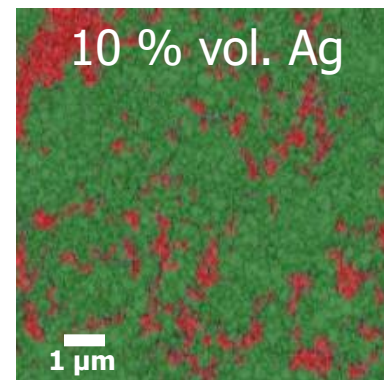
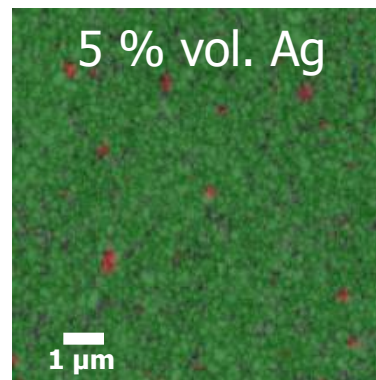
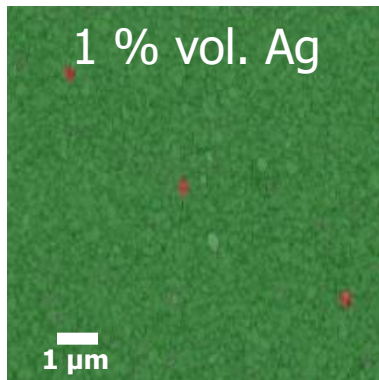
Cu Ag



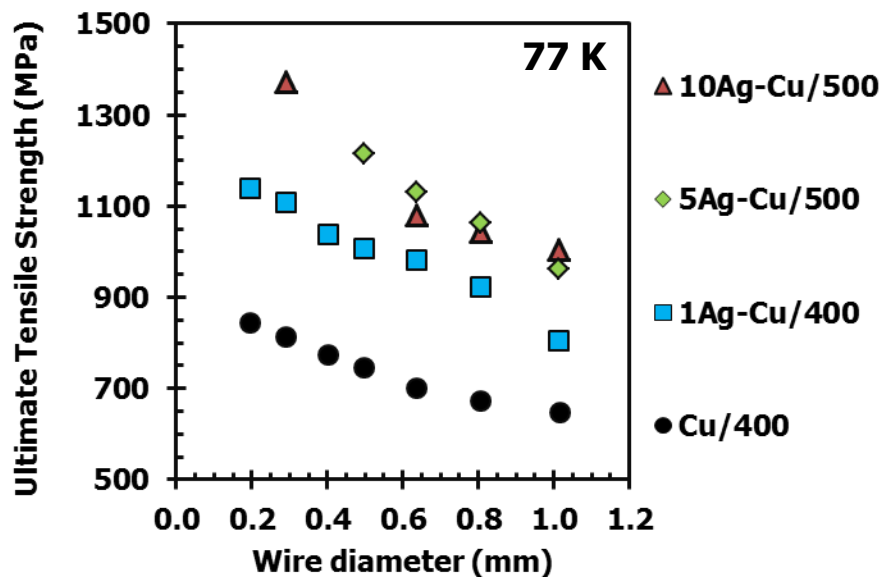
# Introducing another phase



Transversal section



Saturation

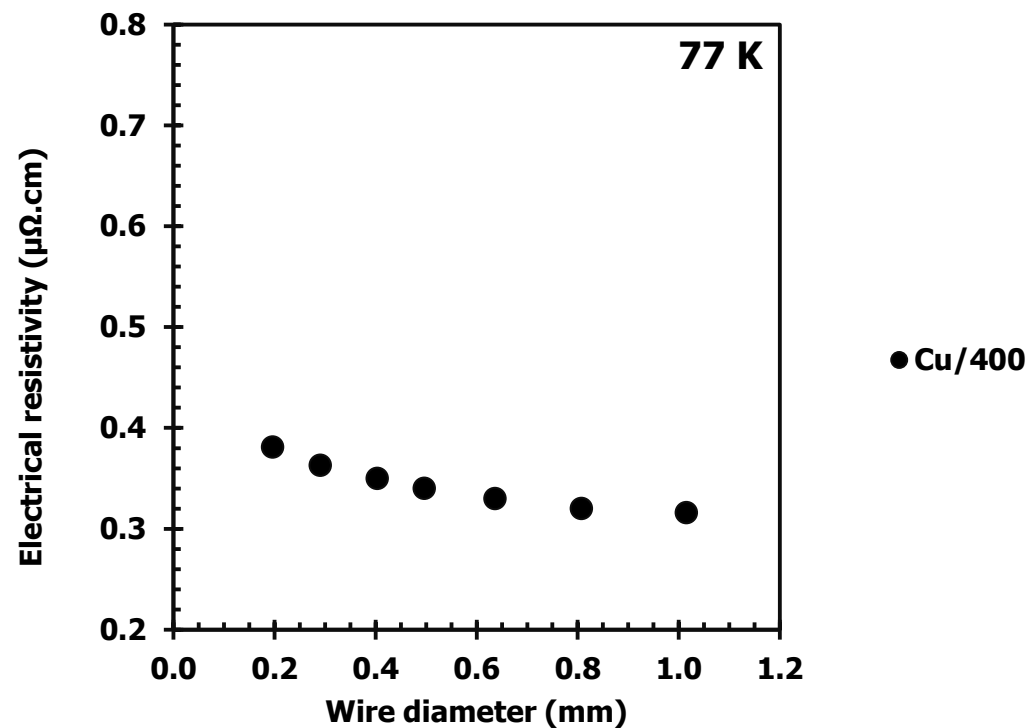


## Electrical characterization

**Grain refinement (nanostructuring)**

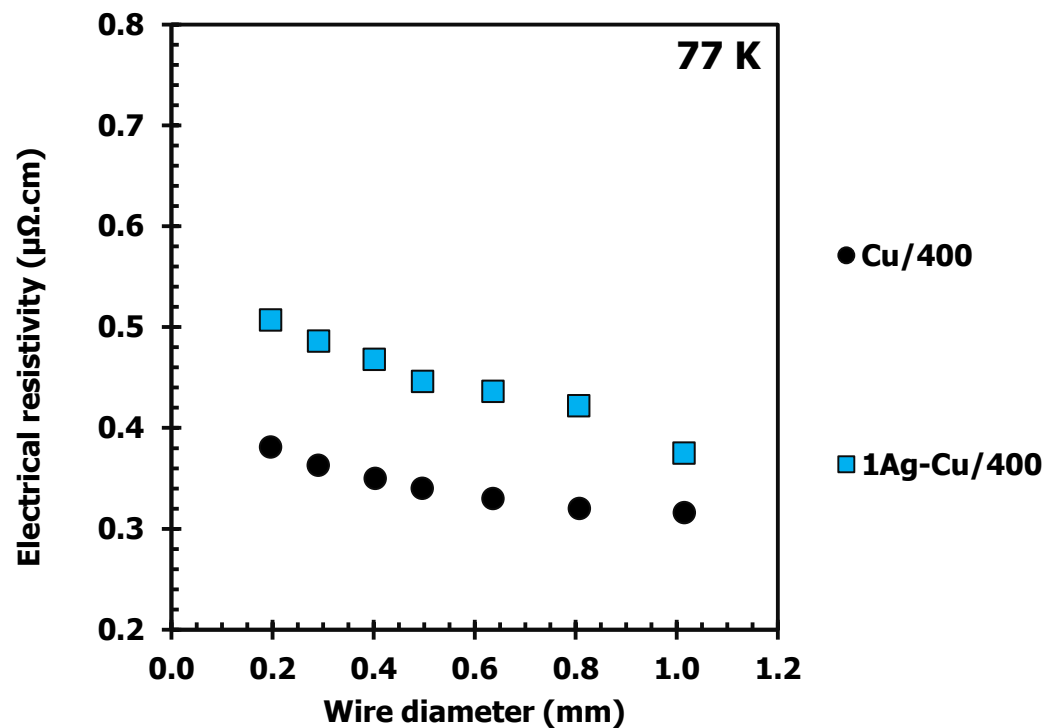
**scattering of conducting electrons ↗**

**electrical resistivity ↗**



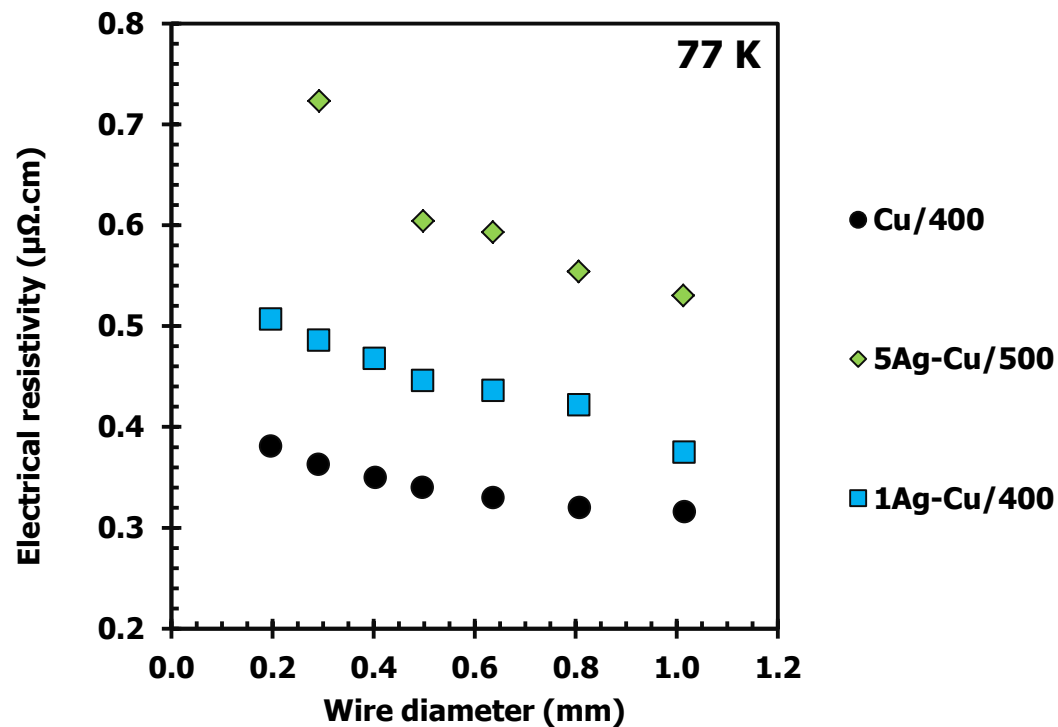
# Electrical characterization

Introducing another phase  
scattering of conducting electrons ↗  
electrical resistivity ↗



# Electrical characterization

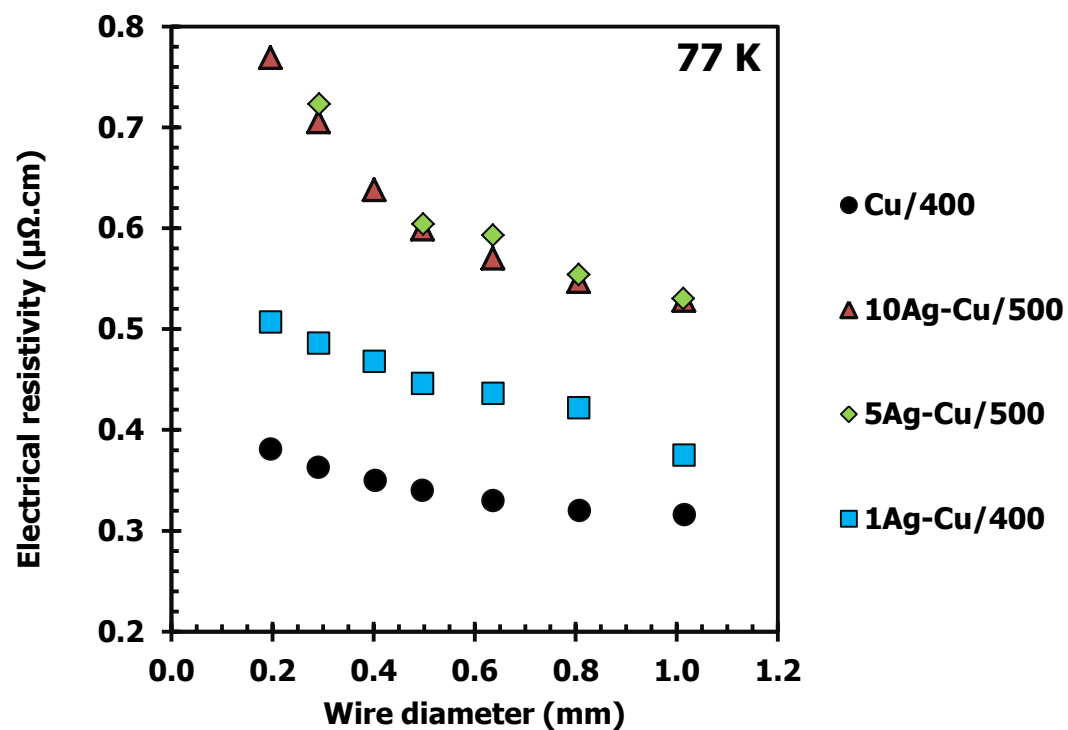
Introducing another phase  
scattering of conducting electrons ↗  
electrical resistivity ↗

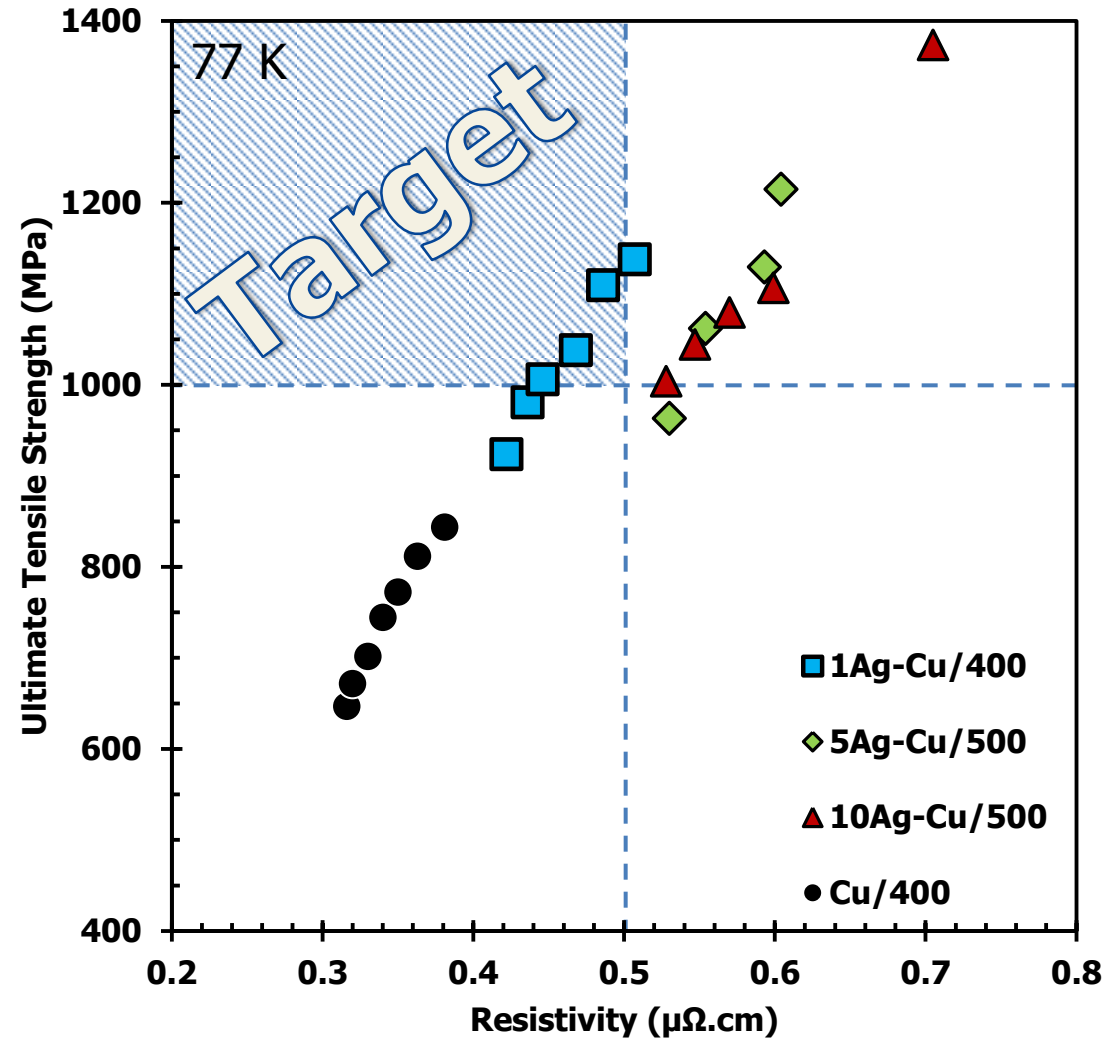




# Electrical characterization

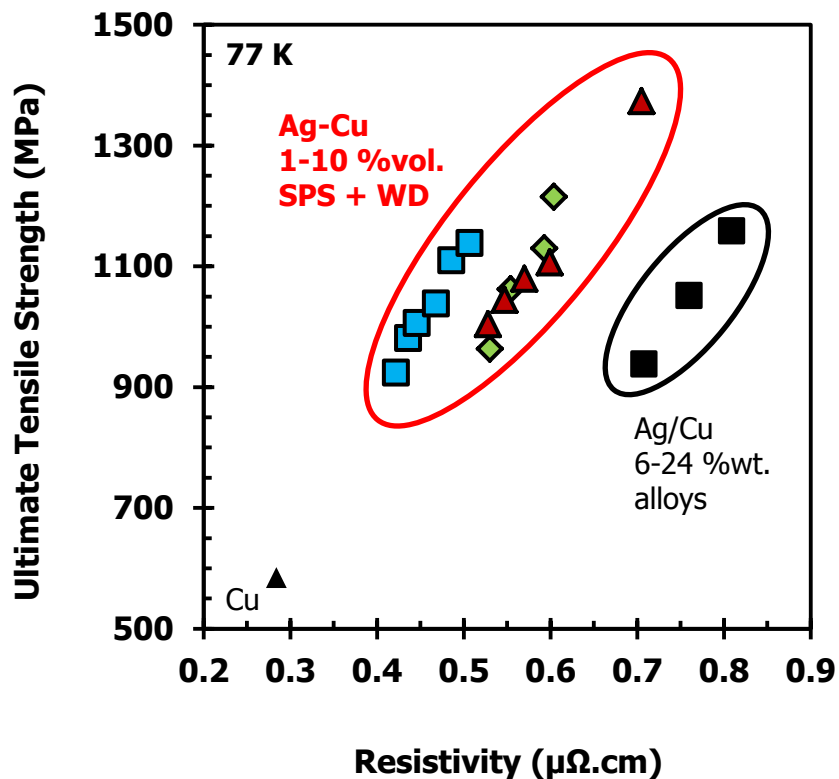
Introducing another phase  
scattering of conducting electrons ↗  
electrical resistivity ↗



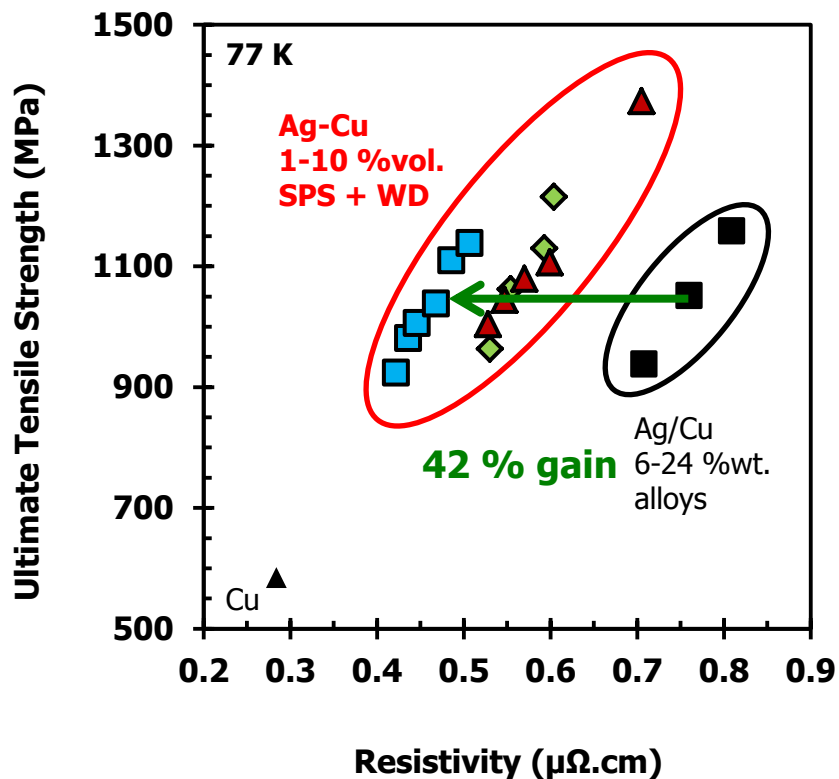


**1Ag-Cu/400** best compromise high strength / low resistivity

## Pulsed fields

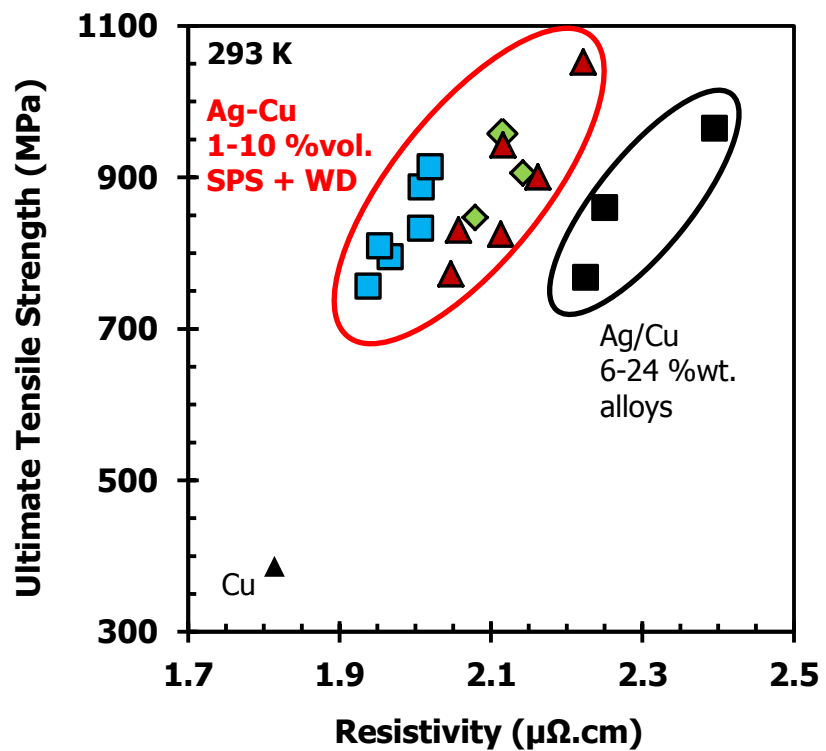


## Pulsed fields

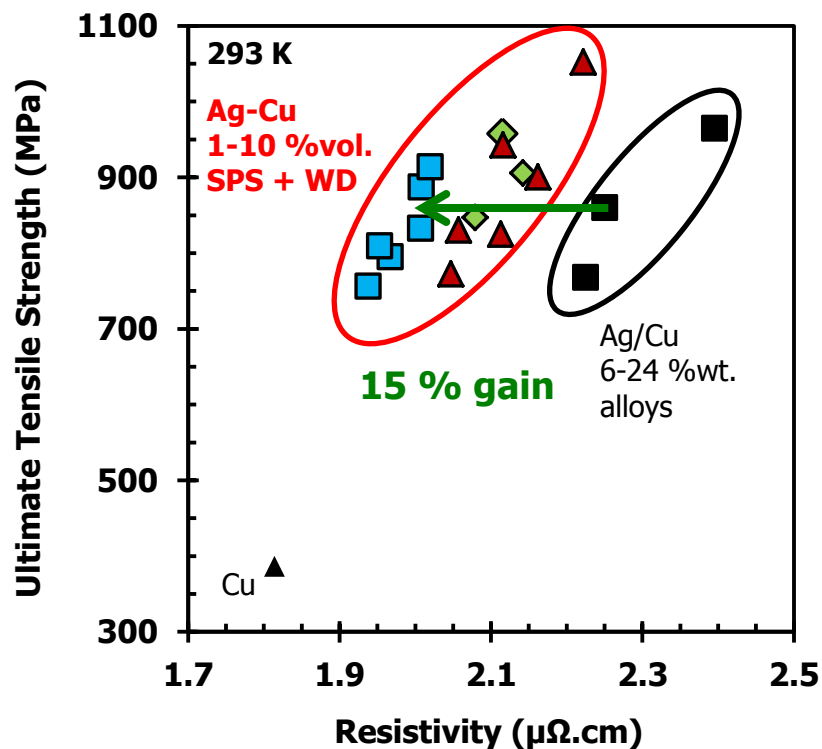


Longer pulse duration

## Steady fields



## Steady fields

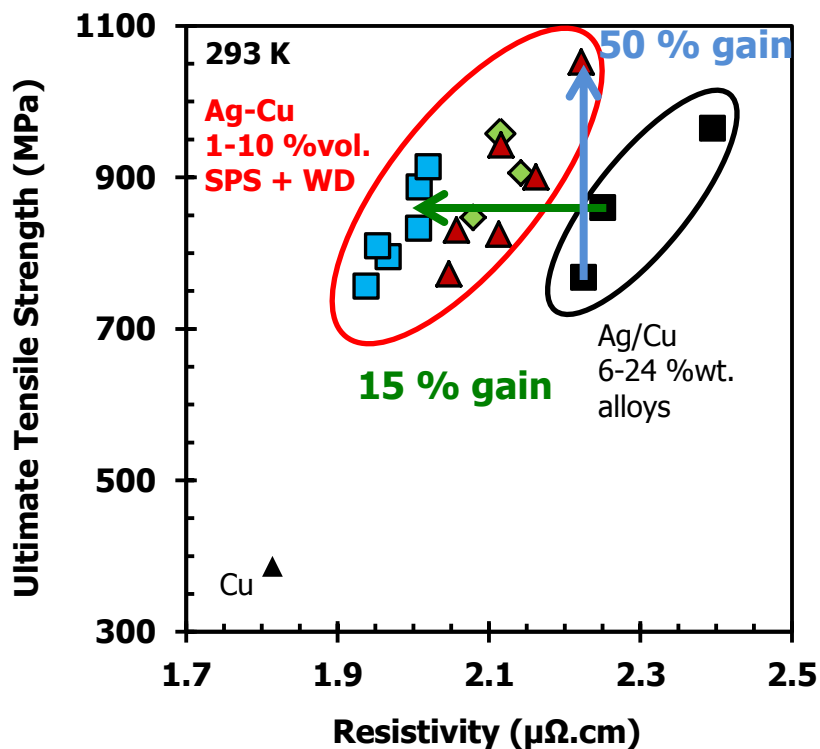


Decrease  
electrical consumption





# Steady fields



Decrease  
electrical consumption

Higher magnetic fields

# Conclusion

## Cu-Ag **composite** wires

Prepared by combination of **Spark Plasma Sintering** and **Room-temperature drawing**

The **composite** wires containing only **1 vol. % Ag** offer the best combination of high strength (**1100 MPa** at 77 K) and low electrical resistivity (**0.50  $\mu\Omega$ .cm** at 77 K)

And

Compare favorably with Ag/Cu **alloy** wires containing about 20 times more silver.

## Acknowledgments



**LNCMI**

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