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Optimization of Electro-Mechanical Properties in Cu-ETP Conductors: Impact of Severe Cold Drawing Ratios for Power Grid Applications

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ABSTRACT

High-purity electrolytic copper (ASTM C11000 grade, 99.9% Cu) is a cornerstone material for global electrical power transmission and industrial energy distribution systems. This study investigates the impact of multi-pass cold wire drawing on the coupled mechanical and electrical performance of these wires, focusing on heavy-duty industrial cabling requirements. A broad range of reduction rates, from 0% to 89.45%, is systematically explored to simulate industrial manufacturing conditions. Results indicate that increasing the reduction rate significantly strengthens the material, with ultimate tensile strength rising from 237.32 to 433.13 MPa. This reinforcement, essential for mechanical cable reliability, occurs with only a marginal 4.1% decline in electrical conductivity. These findings demonstrate that the microstructural evolution during severe drawing maintains an efficient electron mean free path, ensuring minimal energy loss during power transport. This work provides critical data for optimizing the balance between structural integrity and electrical efficiency in high-performance power transmission networks.

If your paper have nomenclature write it in table like below:

NOMENCLATURE			
Cu-ETP	Electrolytic Tough Pitch Copper	*HV*	Vickers Microhardness (MPa)
d	Wire diameter (mm)	*EB*	Elongation at Break (%)
A	Section area (mm^2)	ρ	Electrical Resistivity (Ω•mm^2/m)
R	Reduction Rate (%)	σ	Electrical Conductivity (m/Ωmm2)
YS	Yield Strength (MPa)		
UTS	Ultimate Tensile Strength (MPa)		

1. INTRODUCTION

Copper (Cu) remains a foundational material in modern engineering, maintaining a hegemonic position across electronics, power transmission, and high-technology equipment sectors [1]. Characterized by exceptional electrical and thermal conductivity, surpassed only by silver, copper has become the global benchmark for the fabrication of conductors, transformers, and critical infrastructure essential for the global green energy transition [2, 3]. In high-performance fields such as aerospace, the reliability of copper is paramount; for instance, approximately 95% of the conductive wiring in a modern commercial aircraft is copper-based, highlighting its indispensable role within complex onboard electrical systems [4, 5]. The final performance of copper conductors is inextricably linked to their thermomechanical processing history and the evolution of their crystalline structure [6].

In Algeria, the cable industry has emerged as a strategic pillar of industrial development, where the production of high-quality wires depends on the mastery of sophisticated metallurgical processes and the optimization of deformation parameters [7, 8]. Cold wire drawing is the primary manufacturing method used to achieve specific geometric dimensions and mechanical requirements through severe plastic deformation (SPD). This process induces a profound restructuring of the metal's matrix, leading to significant grain refinement and a high density of lattice imperfections [9, 10, 11]. While cold drawing enhances the yield strength and hardness of copper through work hardening, it simultaneously impacts the mobility of charge carriers, creating a complex trade-off between strength and conductivity [12, 13]. The physical mechanism underlying this evolution is based on the interaction between lattice defects and conduction electrons [14]. As the reduction rate increases, the proliferation of dislocations, the formation of sub-grain boundaries, and the emergence of point defects act as scattering centers, reducing the electron mean free path and consequently increasing electrical resistivity [15, 16]. This phenomenon is fundamentally described by Matthiessen's rule, which states that total resistivity is the sum of thermal vibrations and residual resistivity arising from structural defects [17, 18]. Although scientific literature is rich in studies regarding copper alloys, research that simultaneously quantifies the precise correlation between mechanical strengthening and electrical degradation over an extensive deformation spectrum reaching extreme reduction rates near 90% remains relatively scarce [19, 20].

The objective of the present study is to bridge this gap by evaluating the interdependent electromechanical behavior of high-purity copper wires (99.9% Cu). We investigate a wide range of reduction rates: 0%, 10.53%, 49.17%, 62.72%, 72.34%, 79.60%, 84.93%, 89.07%, and 89.45%. By employing a combination of uniaxial tensile testing, Vickers microhardness measurements, and high-precision resistivity analysis, this work aims to establish a predictive relationship between the degree of cold work and material performance [21, 22]. The findings are intended to optimize industrial wire drawing parameters, ensuring the production of high-performance conductors that balance mechanical rigidity with optimal electrical efficiency for modern energy networks [23, 24].

2. MATERIALS METHOD

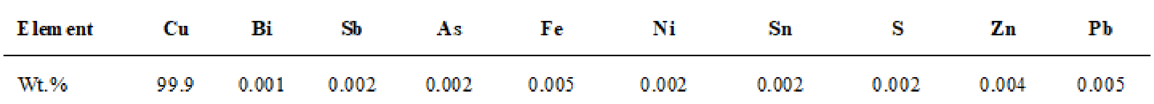
2. 1. Material Characterization

The raw material used in this study is high-purity electrolytic copper, grade ASTM C11000 (ETP). The specimens were provided by the Cable Industry Company (ENICAB, Biskra, Algeria) in the form of continuous cylindrical wire rods with an initial diameter of 8.5 mm (Figure 1).

Figure 1. Initial Cu-ETP wire rod with a diameter of 8.5 mm provided by ENICAB

The detailed chemical composition of the studied copper is summarized in TABLE 1.

TABLE 1. Elemental composition of the investigated ETP copper (wt. %).



Element	Cu	Bi	Sb	As	Fe	Ni	Sn	S	Zn	Pb
Wt.%	99.9	0.001	0.002	0.002	0.005	0.002	0.002	0.002	0.004	0.005

With a copper content of 99.90% (Table 1), this metal strictly adheres to the International Annealed Copper Standard (IACS) requirements for electrical-grade conductors. The specific chemical composition is a critical determinant of the electro-mechanical synergy during severe plastic deformation. While the matrix is near-intrinsic, trace elements such as Iron (Fe), Nickel (Ni), and Zinc (Zn) are maintained at very low concentrations (0.002–0.005%) to minimize electron scattering centers within the lattice, thereby preserving high conductivity. Concurrently, the controlled presence of Arsenic (As) and Antimony (Sb) plays a strategic metallurgical role by increasing the recrystallization temperature, which ensures the stability of the work-hardened state against adiabatic heating during high-speed industrial drawing.Furthermore, the limited concentrations of Bismuth (Bi) and Lead (Pb), which exhibit low solid solubility and tend to segregate at grain boundaries, are strictly monitored to prevent embrittlement, allowing the material to reach extreme reduction rates of up to 89.45% while maintaining sufficient residual ductility. This precise chemical balance ensures that the copper rods possess the necessary metallurgical integrity for multi-pass cold drawing without premature fracture or significant degradation of transport properties.

2. 2. Industrial Wire Drawing Procedure

The cold wire drawing process was executed using electrolytic copper (Cu-ETP) wire rods with an initial diameter of d= 8.5 mm from the ENICAB facility. Specimens were extracted at various stages along the multi-pass drawing line. Prior to the operation, the rods underwent a cleaning and degreasing protocol. During the sequence, the wire was lubricated with synthetic oil to counteract frictional forces and adiabatic heating, preventing thermal softening or localized dynamic recovery of the copper matrix.

The intensity of the cold-working is expressed by the reduction of area *(A%).* According to the principles of plastic deformation (8), the deformation rate was calculated as shown in Equation (1):

$$A\% = \frac{S_0 - S_f}{S_0} 100 \qquad (1)$$

This approach allowed for the characterization of nine distinct reduction levels: 0%, 10.53%, 49.17%, 62.72%, 72.34%, 79.60%, 84.93%, 89.07%, and 89.45% (Figure 2).

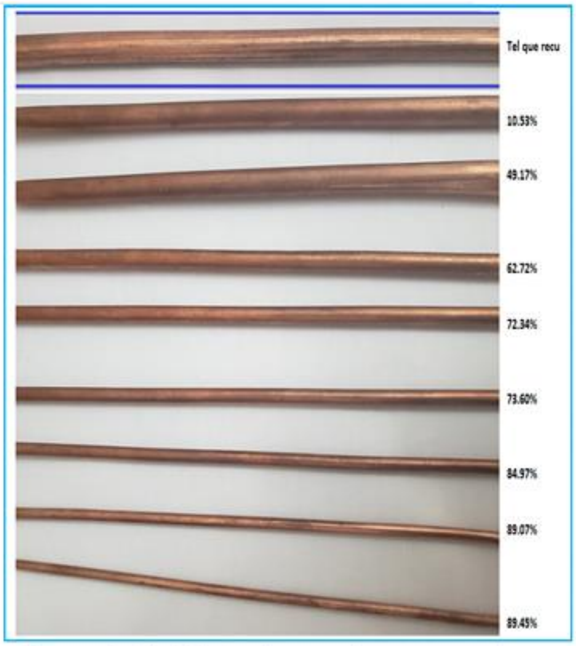


Figure 2. Cu-ETP wire specimens at various reduction stages (0% to 89.45%)

Wires were sectioned using a precision hacksaw at low speed under water coolant to prevent unintentional annealing. Tensile specimens were prepared with a gauge length of L = 30 cm, adhering to international protocols for electrical conductor testing.

2. 3. Surface Preparation

To maintain the integrity of the experimental results, a specialized surface treatment was conducted within the Metallurgy Laboratory of ENICAB (Biskra, Algeria). The protocol aimed to eliminate all industrial residues and surface defects at a stable ambient temperature (25 ± 2 °C). Initially, the copper wires were immersed in an ultrasonic **acetone** bath for 15 minutes to dissolve organic films and lubricants. After being rinsed with distilled water, the samples were dried using a forced hot-air flow to prevent the initiation of surface oxidation. For microhardness investigations, the wire cross-sections were carefully polished using a series of abrasive SiC papers (600 to 2500 mesh) and finished with a 1 µm diamond paste to obtain a high-quality surface. This rigorous preparation, carried out under industrial laboratory standards, ensured that contact resistance and surface roughness did not interfere with the subsequent electrical and mechanical measurements.

2. 4. Vickers Microhardness Testing

To quantify the mechanical reinforcement and strain-hardening distribution, microhardness measurements are conducted at ambient temperature using a digital HVS-1000Z microhardness tester equipped with a diamond pyramidal indenter. A constant load of 0.2 kgf is applied for a dwell time of 15 seconds to ensure stable indentation profiles. Characterization is performed on longitudinal sections prepared to a mirror finish (0.5 µm). For each reduction rate, five independent indentations are recorded at regular intervals to ensure statistical reliability and assess homogeneity. Average values and standard deviations are calculated to represent the hardness evolution as a function of cumulative drawing strain, reflecting the dislocation density within the Cu-ETP lattice.

2. 5. Mechanical Characterization and Tensile Testing

Uniaxial tensile tests are performed at controlled ambient temperature to analyze the macroscopic mechanical response of the Cu-ETP wires. The experimental campaign is conducted at the ENICAB laboratory using a high-precision Zwick/Roell universal testing machine in accordance with ISO 6892-1 standards. Specimens covering the full deformation spectrum (0% to 89.45% reduction) are tested at a constant crosshead speed of 5 mm/min until failure. This controlled strain rate ensures quasi-static loading conditions for the acquisition of high-resolution stress-strain curves. To eliminate surface artifacts and premature stress concentrators, all specimens are polished to a 1200-grit finish prior to testing. This characterization allows for the precise determination of yield strength (YS), ultimate tensile strength (UTS), and elongation at break (A%), providing essential data for evaluating the structural integrity of conductors used in power transmission infrastructure.

2. 6. Electrical Performance and Resistivity Measurement

The electrical transport properties are evaluated at the ENICAB laboratory using a high-precision RESISTOMAT (Type 2303) digital micro-ohmmeter, specifically designed for low-resistance industrial conductors. This characterization is essential to verify if the cold-drawn wires maintain their performance according to the International Annealed Copper Standard (IACS). To achieve maximum metrological precision, the system utilizes the four-point Kelvin sensing method, which effectively isolates the test specimen's resistance from the parasitic contact resistance of the leads and terminals. Each wire sample is prepared with a total length exceeding the bridge distance to provide a strictly calibrated measurement zone of 1000 mm. To counteract the high temperature-sensitivity of copper, all tests are conducted at a stabilized ambient temperature of 20 ± 0.5 °C. By injecting a stabilized DC current through the one-meter wire section, the potential drop is recorded to calculate the electrical resistivity. This rigorous approach allows for a precise quantification of the scattering mechanisms, where the increased density of crystalline defects, primarily dislocations and sub-grain boundaries induced by the 89.45% reduction, acts as scattering centers that reduce the electron mean free path within the Cu-ETP matrix.

3. RESULTS

3. 1. Mechanical Properties

3. 1. 1. Evolution of Vickers Microhardness

The experimental results, illustrated in **Figure 3**, demonstrate a progressive and substantial enhancement of the mechanical resistance as the deformation increases, reaching its peak at the maximum reduction of 89.45%. This hardening behavior is a classic manifestation of **strain-induced reinforcement** in high-purity electrolytic copper.

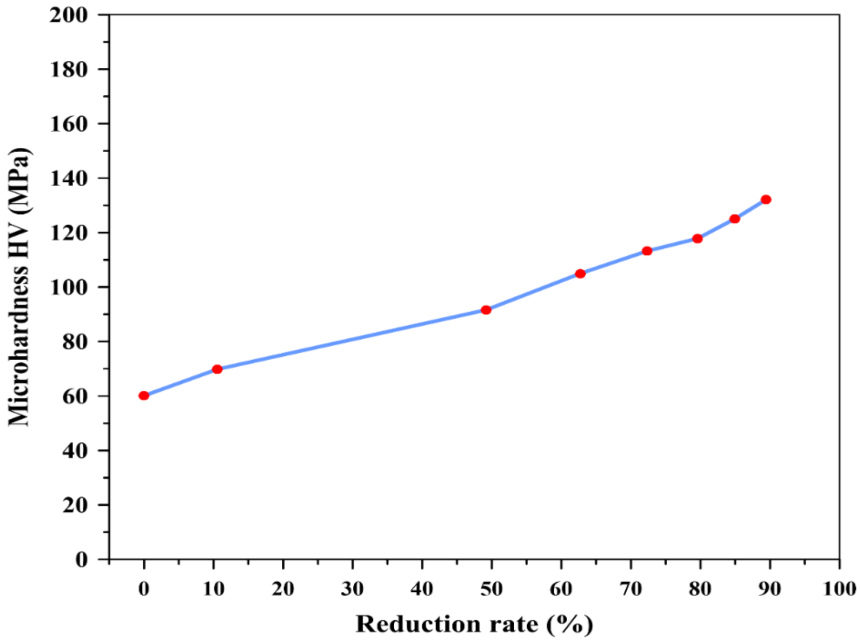


Figure 3- Effect of wire drawing on the microhardness of Cu-ETP copper wires

At the initial stages of drawing (up to 49.17%), the microhardness rises sharply. This trend is physically governed by the **Taylor hardening law**, which states that the material's flow stress is proportional to the square root of the dislocation density. As the wire passes through successive dies, the cumulative plastic strain triggers a massive proliferation of lattice defects. These dislocations form complex entanglements and cellular sub-structures that act as potent barriers to further slip, significantly increasing the energy required for dislocation motion [25]

As the deformation reaches extreme levels, especially near the final 89.45% threshold, the rate of hardening begins to show a slight saturation. This phenomenon reflects a dynamic competition between **dislocation multiplication** and **localized recovery processes**. Despite the near-intrinsic purity of the C11000 grade, the severe plastic deformation (SPD) induces a profound structural refinement, where original grains are subdivided into elongated sub-grains. This evolution ensures the superior mechanical rigidity necessary for high-tension industrial energy distribution networks [11, 12, 18]

3. 1. 2. Tensile Properties and Deformation Behavior

The mechanical response of the Cu-ETP wires under uniaxial tension is summarized in **Table 2. Summary of Mechanical Properties for Cold-Drawn Copper Wires**. The data demonstrates a clear and progressive strengthening effect as a function of the reduction rate.

3. 1. 2. 1. Overall Stress-Strain Response

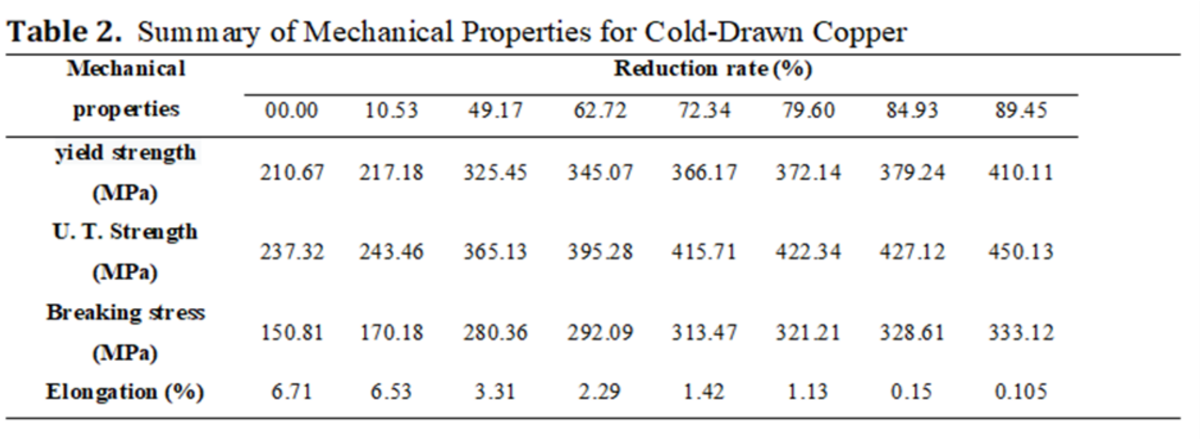


Table 2. Summary of Mechanical Properties for Cold-Drawn Copper

Mechanical properties	Reduction rate (%)							
	00.00	10.53	49.17	62.72	72.34	79.60	84.93	89.45
yield strength (MPa)	210.67	217.18	325.45	345.07	366.17	372.14	379.24	410.11
U. T. Strength (MPa)	237.32	243.46	365.13	395.28	415.71	422.34	427.12	450.13
Breaking stress (MPa)	150.81	170.18	280.36	292.09	313.47	321.21	328.61	333.12
Elongation (%)	6.71	6.53	3.31	2.29	1.42	1.13	0.15	0.105

The complete deformation history is captured by the tensile curves, which show the transition from a ductile annealed state to a high-strength work-hardened state. This evolution is critical for assessing the material's energy absorption capacity during industrial processing.

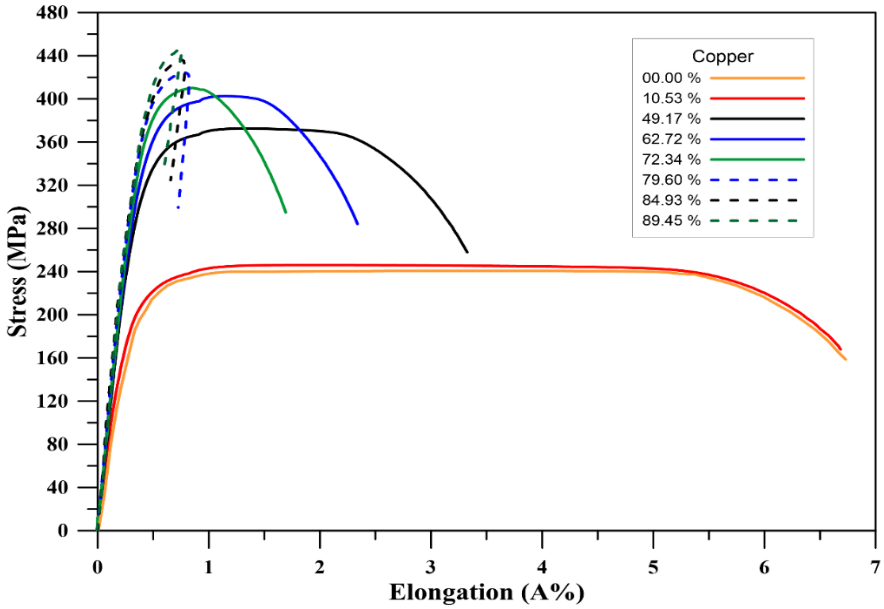


Figure 4- Tensile curves obtained for the copper wires (after wire drawing) with a strain rate of 5 mm.min-1

3. 1. 2. 2. Effect on Yield Strength (YS)

The yield strength rises from 210.67 MPa to 385.11 MPa. This evolution reflects the transition from elastic to plastic behavior, which becomes increasingly difficult as the drawing passes multiply. The proliferation of "forest dislocations" during severe plastic deformation (SPD) creates a dense network of obstacles, requiring higher initial stress to trigger the movement of mobile dislocations [16, 25].

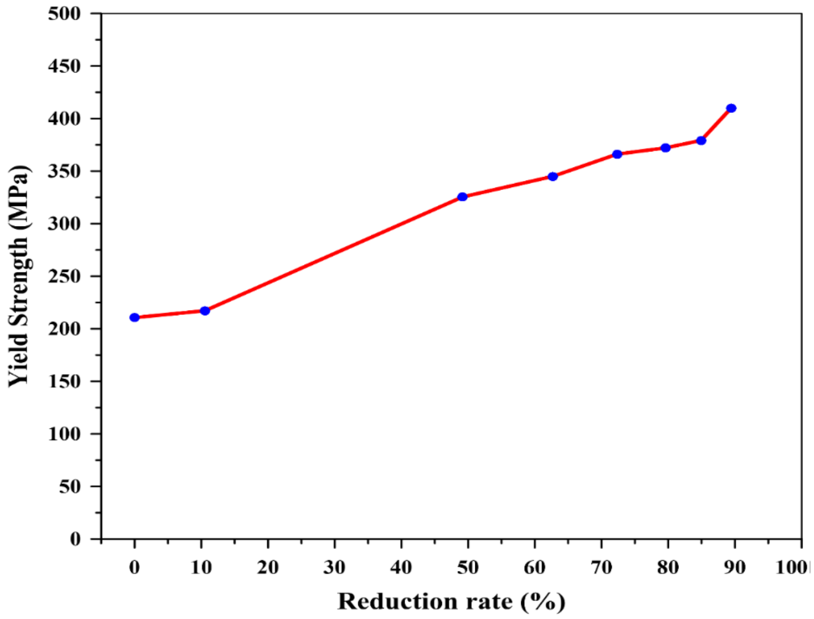


Figure 5- Variation of the copper yield strength (YS) as a function of the cold drawing reduction rate

3. 1. 2. 3. Evolution of Ultimate Tensile Strength (UTS)

The ultimate tensile strength (UTS) follows a similar upward trajectory, reaching a peak of 433.13 MPa at 89.45% reduction. According to the **Taylor hardening law**, this rise is a direct consequence of the increased dislocation density. The reduction of the sub-grain size effectively limits the mean free path of dislocations, leading to a near-saturation of the material's strengthening capacity [11, 22].

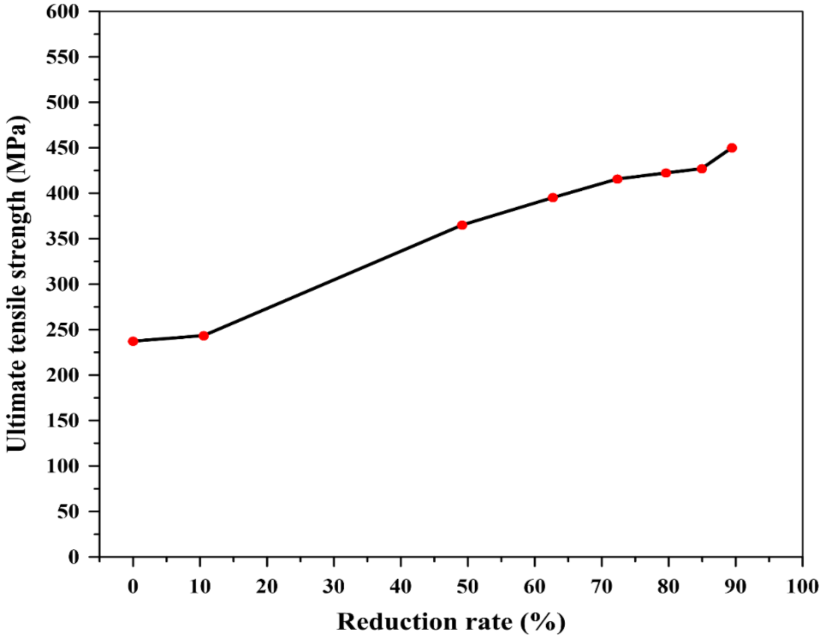


Figure 6- Variation of the copper ultimate tensile strength (UTS) as a function of the cold drawing reduction rate

3. 1. 2. 4. Ductility and Elongation at Break (E%)

In stark contrast, the elongation at break exhibits a drastic downward trend, dropping from 6.71% to a critical threshold of 0.105%. This depletion of ductility is a hallmark of extreme cold work, where the accumulation of internal micro-strains restricts further plastic rotation of the grains. The material reaches a quasi-brittle state where the capacity for uniform elongation is almost entirely consumed [3,4].

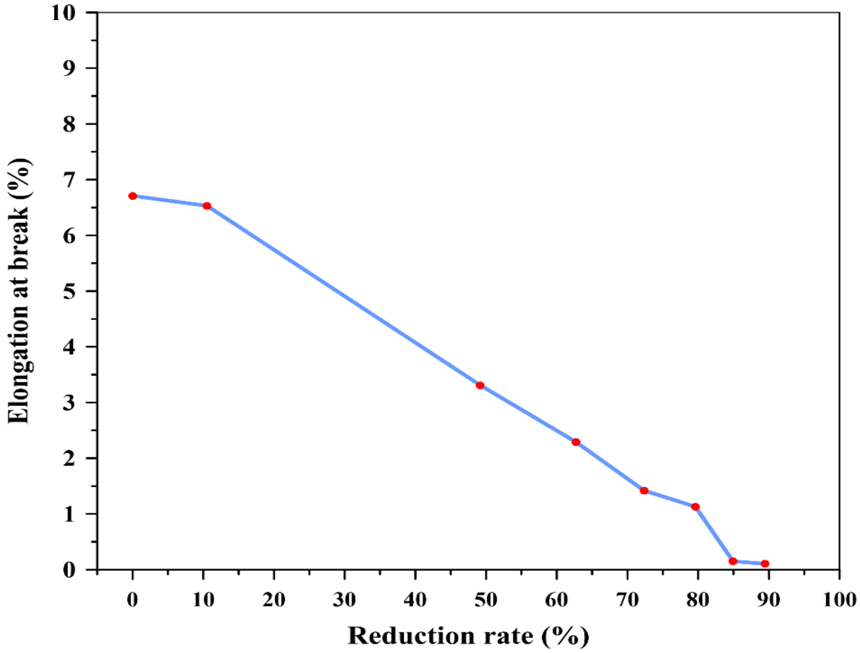


Figure 7- Variation of the copper elongation (E%) as a function of the cold drawing reduction rate

3. 1. 2. 5. Analysis of Fracture Stress and Material Integrity

The evolution of the fracture stress as a function of the reduction rate provides critical insight into the terminal load-bearing capacity of the Cu-ETP wires. As detailed in **Table 2**, the fracture stress increases from **150.81 MPa** to **333.12 MPa** at the maximum deformation of 89.45%.

This upward trend is consistent with the global strengthening of the copper matrix. However, from a metallurgical perspective, the narrowing gap between the ultimate tensile strength (UTS) and the fracture stress at extreme reduction rates is significant. This convergence indicates that the material's plastic reservoir is nearly exhausted. At 89.45% reduction, the wire reaches a state where the onset of necking is almost immediately followed by catastrophic failure, a typical behavior of quasi-brittle materials induced by severe plastic deformation (SPD) and dislocation saturation [25].

Despite this, the consistent rise in fracture stress confirms that the multi-pass drawing process at ENICAB effectively increases the overall mechanical reliability of the conductors, ensuring they can sustain high operational tensions without premature breakage.

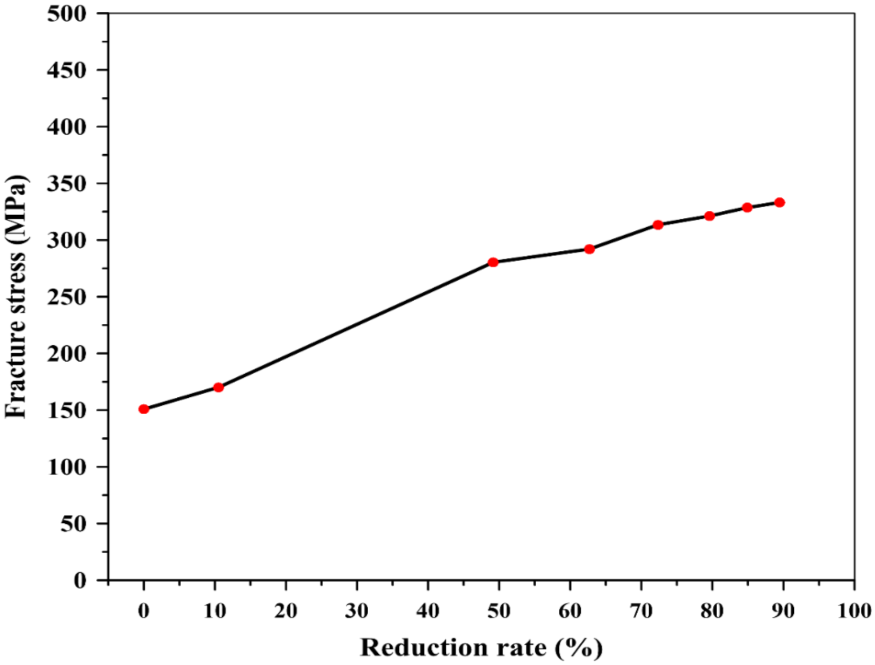


Figure 8- Variation of the copper fracture stress as a function of the cold drawing reduction rate

3.2. Electrical Properties

3. 2. 1. Analysis of Electrical Resistivity and Scattering Mechanisms

The evolution of electrical transport properties for high-purity copper (Cu-ETP) as a function of the reduction rate is summarized in **Table 3** and illustrated in **Figure 9**.

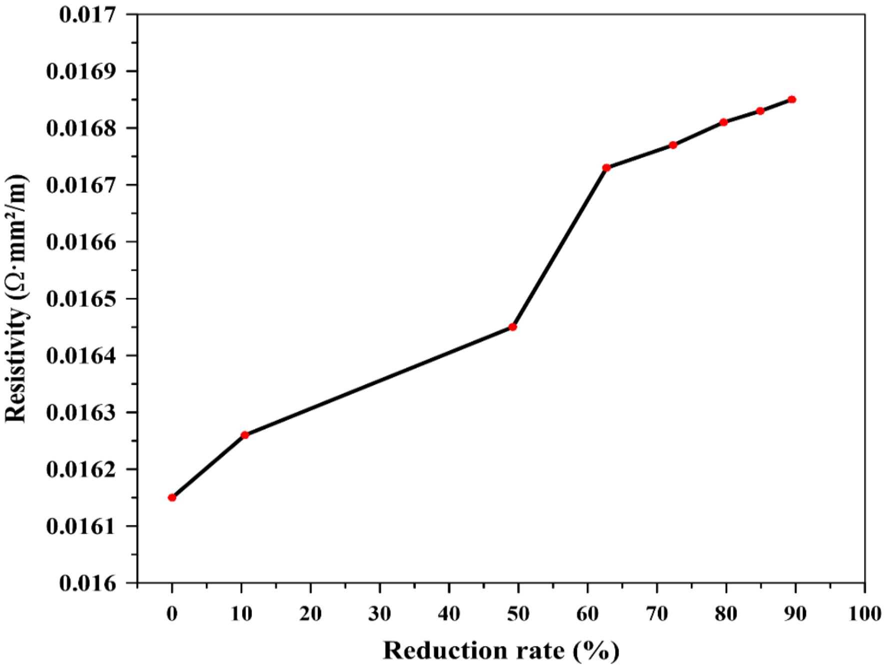


Figure 9- Variation of the electrical resistivity of copper wires as a function of the reduction rate

The experimental data reveals a progressive increase in electrical resistivity, rising from **0.01615 (**Ω·mm²/m) in the annealed state to **0.01685 (**Ω·mm²/m) at the maximum deformation of 89.45%.

Quantitatively, this represents a total resistivity increase of 4.33%, which evolves in a quasi-proportional manner with the cumulative reduction rate. This degradation is fundamentally rooted in the scattering mechanisms induced by severe plastic deformation. According to the semi-classical **Drude model**, the resistivity is inversely proportional to the relaxation time (τ) between two successive collisions of a conduction electron. In a perfect crystalline lattice at 0 K, electrons would flow without resistance. However, the multi-pass drawing process introduces a massive density of lattice imperfections that act as physical obstacles.

According to **Matthiessen's rule**, the total resistivity (ρ_{total}) is the sum of various contributing factors:

$$\rho_{total} = \rho_{thermal} + \rho_{dislocations} + \rho_{boundaries} + \rho_{impurities} \qquad (2)$$

As the reduction rate reaches 89.45%, the **scattering cross-section** increases significantly. The primary obstacles are:

Dislocation Forests: The high density of dislocations creates localized strain fields that disrupt the periodic potential of the lattice, forcing electrons to deviate from their ballistic path.

Sub-grain Boundaries: The structural refinement into ultra-fine cells creates a high density of interfaces. These boundaries act as semi-permeable barriers, increasing the probability of electron reflection and back-scattering [13, 16].

Point Defects: The intense friction generates vacancies and interstitial atoms which serve as short-range scattering centers, further reducing the **electron mean free path** (λ).

3. 2. 2. Evolution of Electrical Conductivity and Industrial Efficiency

The measurements of electrical conductivity, illustrated in **Figure 10**, show a decline from **61.9159** to **59.3471** (m/Ωmm^2).

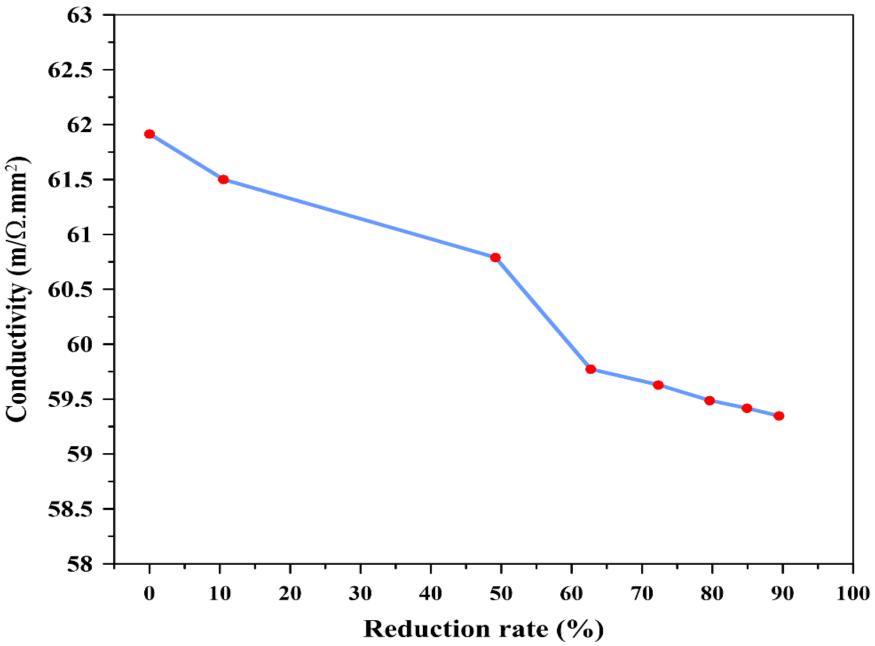


Figure 10- Evolution of Electrical Conductivity and Industrial Efficiency

This **4.15% decrease in conductivity** is inversely proportional to the increasing reduction rate, reflecting the growing impedance of the copper matrix.

From a fundamental perspective, the conductivity (σ) is defined by the relation:

$$\sigma = ne^2\tau \tag{3}$$

While the density of charge carriers (n) remains constant for Cu-ETP, the **mean time between collisions** (τ) is drastically reduced by the "disorder" introduced during the 89.45% reduction. Each pass through the drawing die forces the grains to elongate and the dislocation tangles to tighten, effectively creating a "stochastic maze" for the conduction electrons.

However, the remarkable result is that even after this intense deformation, the **conductivity remains at 95.85% of its initial value**. This suggests that even under extreme work-hardening, the core of the copper grains remains sufficiently "clean" to allow efficient transport. The electrons manage to navigate through the dislocation cells, confirming that high-purity Cu-ETP is an ideal candidate for industrial applications requiring both high mechanical tensile strength and low energy dissipation [19, 22].

4. CONCLUSION

The present research conducted a systematic and high-precision investigation into the interdependent electromechanical properties of high-purity electrolytic copper wires (99.9% Cu) subjected to severe industrial cold drawing. By exploring an extensive deformation spectrum reaching a critical reduction rate of 89.45%, this study establishes a comprehensive performance map for Cu-ETP conductors. The experimental findings lead to the following fundamental conclusions:

Regarding the mechanical evolution, the multi-pass drawing process induces a massive structural reinforcement, where the ultimate tensile strength (UTS) and yield strength (YS) were enhanced by 82.5% and 82.8%, respectively. This strengthening, peaking at 433.13 MPa, is physically rooted in the Taylor hardening mechanism and the intense proliferation of dislocation forests within the copper matrix. However, this mechanical gain is coupled with a 98.4% collapse in ductility, which identifies the 89.45% reduction threshold as the practical metallurgical limit to avoid catastrophic fracture during industrial cabling and installation.

From an electrical transport perspective, the material demonstrates exceptional stability despite the massive structural disorder. The resistivity increased by only 4.33%, ensuring that the wires maintain 95.85% of their initial conductivity according to the IACS standard. This confirms that the scattering mechanisms induced by dislocations and sub-grain boundaries remain secondary to the high intrinsic purity of the matrix, which preserves an efficient electron mean free path.

The industrial significance of this work is paramount. By quantifying the precise correlation between mechanical hardening and electrical degradation, this study provides a robust predictive framework for the cable industry (ENICAB). It demonstrates that high-performance conductors can be manufactured to withstand extreme mechanical tensions in modern power grids without significantly compromising energy efficiency. These results are essential for the design of next-generation energy transmission networks, where balancing structural integrity with minimal Joule effect losses is a strategic priority for global energy distribution and the transition to green infrastructure.

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