ISSN 2616-5767 Vol.8, Issue 5: 59-63, DOI: 10.25236/AJETS.2025.080508

Effects of Rolling Processes and Aging Treatment on the Properties and Microstructure of Cu-Cr-Zr Alloys

Rongfeng Yu[1,2], Lingling Li[2,*], Desheng Li[3]

[1]Inner Mongolia New Envision Group Co., Ltd., Hohhot, Inner Mongolia, China
[2]College of Intelligent Manufacturing, Putian University, Putian, Fujian, China
[3]Tongfang Electronic Technology Co., Ltd., Jiujiang, Jiangxi, China
**Corresponding author*

Abstract: *This study systematically investigates the effects of cold-rolling deformation (30%, 60%, 90%) and aging treatment (450 °C/1 h) on the microstructural evolution and strength–conductivity performance of a Cu-1.0Cr-0.1Zr alloy. The results show that 90% cold deformation combined with aging treatment yields the best comprehensive properties, with a tensile strength of 411.7 MPa and an electrical conductivity of 63.7% IACS. Microstructural analysis reveals that nanoscale Cr/Zr-enriched phases precipitate dispersively during aging, significantly strengthening the matrix; meanwhile, solute atoms are desoluted from the Cu matrix, greatly reducing electron scattering and effectively improving conductivity. This strengthening mechanism fully demonstrates the synergistic effects of precipitation strengthening and solid-solution purification, providing theoretical support for the design of high-strength and high-conductivity copper alloys.*

Keywords: *Cu-Cr-Zr alloy; rolling; aging; microstructure; mechanical properties*

1. Introduction

As a representative of high-strength and high-conductivity copper-based materials, Cu-Cr-Zr alloys significantly enhance mechanical properties through precipitation strengthening while maintaining excellent electrical conductivity. They are widely used in railway contact wires, integrated circuit lead frames, high-power heat dissipation devices, and other fields. Existing studies indicate that cold plastic deformation and aging heat treatment profoundly influence the strength–conductivity matching characteristics of the alloys by regulating dislocation density, grain orientation, and second-phase precipitation behavior. However, current preparation processes rely heavily on vacuum smelting, which entails high costs, limited billet size, and insufficient microstructural uniformity, severely restricting large-scale engineering applications. In this context, this study prepares large-size Cu-1.0Cr-0.1Zr ingots using the aluminothermic reduction method and systematically investigates the effects of 30%–90% cold-rolling deformation combined with aging treatment at 450 °C/1 h on the microstructure, mechanical properties, and electrical conductivity of the alloy. The synergistic mechanisms of dislocation strengthening, grain-refinement strengthening, and nanoscale precipitate strengthening are thoroughly analyzed to establish a mapping relationship among processing, microstructure, and properties, providing a technical pathway for the low-cost and efficient industrial preparation of high-performance Cu-Cr-Zr alloys.

2. Experimental Design

In this study, cast Cu-1.0Cr-0.1Zr alloy ingots were successfully prepared using the aluminothermic reaction method under a protective atmosphere of 5 MPa argon, effectively limiting oxidation and significantly improving compositional uniformity. Subsequently, metallographic specimens and rolling billets were obtained by electrical discharge wire cutting. Multistep cold rolling was carried out on a two-high rolling mill at room temperature, with a reduction of 0.02 mm per pass and total deformation levels set at 30%, 60%, and 90%, thereby constructing processing-state microstructures with different dislocation densities and grain orientation distributions. After rolling, the specimens were immediately subjected to aging treatment at 450 °C/1 h in a box-type resistance furnace to dynamically regulate the nucleation and growth behavior of Cr/Zr precipitated phases. Specimen preparation strictly followed metallographic analysis procedures: after sequential grinding with water abrasive papers and mechanical

ISSN 2616-5767 Vol.8, Issue 5: 59-63, DOI: 10.25236/AJETS.2025.080508

polishing, a mixed etchant of $FeCl_3$–HCl–H_2O (5g + 50mL + 100mL) was used to reveal microstructural morphology, which was observed using a MeF3 optical microscope to support subsequent analysis of microstructural evolution mechanisms.

Mechanical and physical property tests were conducted in accordance with standardized procedures. Tensile specimens were machined into rectangular cross-sections with a gauge length of 20 mm based on GB/T 6397—1986, and tests were performed on a WDW−100D electronic universal testing machine under a constant loading rate of 0.2 mm/min. Three parallel samples were tested for each condition to improve data reliability, and fracture morphology was analyzed via SEM to identify the fracture mode. Microhardness measurements were conducted using an HBRVU−187.5 hardness tester with a load of 1 N and a holding time of 10 s, with five measurements taken per sample. Electrical conductivity was measured using a Sigma2008B/C eddy-current conductivity meter, with five measurements taken away from edge regions, and the results expressed in %IACS. This multi-parameter testing system comprehensively covers key indicators such as strength, ductility, hardness, and electrical conductivity, providing a solid data foundation for analyzing the synergistic strengthening mechanisms of cold deformation and aging.

3. Experimental Results and Analysis

3.1 Microstructural Analysis

Optical microstructural observations show that the as-cast Cu-1.0Cr-0.1Zr alloy consists of an α-Cu matrix and dispersed black Cr-rich second-phase particles. These particles are uniformly distributed but relatively coarse, reflecting the primary precipitation characteristics caused by Cr segregation during solidification. After aging treatment at 450 °C/1 h, the number of precipitates increases and their size becomes coarser, indicating that thermal activation promotes Cr atom diffusion, leading to the aggregation and growth of certain metastable phases, although the overall distribution remains relatively uniform. Notably, cold-rolling deformation exerts a strong regulatory effect on precipitation behavior: at 30% deformation, the dislocation density remains relatively low, and the morphology of the precipitates is similar to that of the as-cast state, with no significant refinement observed; however, when the deformation increases to 60% and 90%, the high-density dislocation network and deformation bands provide abundant heterogeneous nucleation sites for precipitates, promoting further refinement of the second phase. The precipitates become highly dispersed with an effectively increased volume fraction, demonstrating the strengthening effect of cold deformation–induced precipitation (Figure 1).

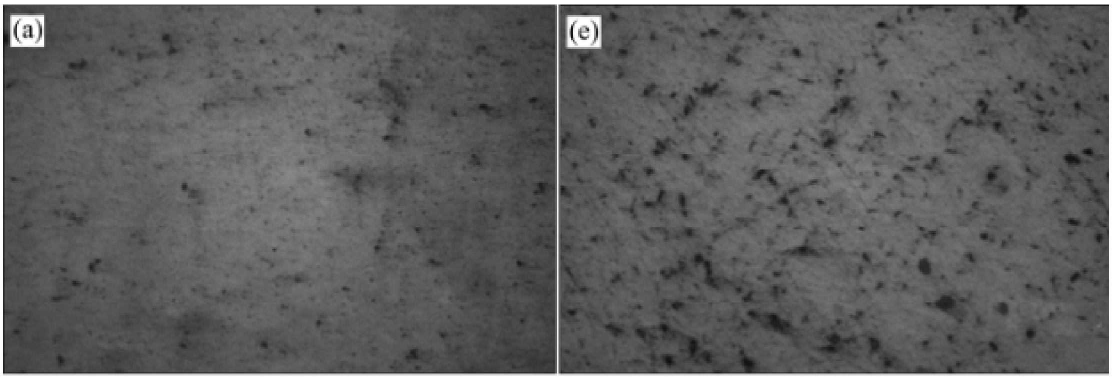

Figure 1. Optical micrographs of Cu-1.0Cr-0.1Zr alloy under different processing conditions

After further aging treatment, the precipitates in the low-deformation samples (30%, 60%) exhibit pronounced coarsening, consistent with the Ostwald ripening mechanism. However, in the 90% high-deformation sample subjected to the same aging conditions, the precipitates remain fine and uniformly distributed, indicating that the high-density dislocations and subgrain boundaries exert a strong pinning effect on precipitate migration, effectively suppressing their growth kinetics. This phenomenon reveals the intrinsic mechanism of the synergistic regulation of precipitation microstructures by large plastic deformation and aging. The crystal defects introduced by high strain not only promote the dispersed nucleation of precipitates but also construct a thermally stable barrier during subsequent heat treatment. While maintaining high strength, this microstructural configuration also creates favorable conditions for optimizing electrical conductivity[1].

3.2 Analysis of Material Properties

To systematically investigate the mechanisms by which rolling deformation and aging treatment influence the strength–ductility and electrical conductivity of the Cu-1.0Cr-0.1Zr alloy, this study integrates mechanical properties, electrical conductivity, and fracture morphology data to construct the following comprehensive performance comparison (Table 1).

Table 1. Comparison of Comprehensive Properties of Cu-1.0Cr-0.1Zr Alloy under Different Processing Conditions

Processing Condition	Tensile Strength **σ_b/MPa**	Yield Strength **$\sigma_{0.2}$/MPa**	Elongation **δ/%**	Hardness/ **HV**	Conductivity/ **%IACS**	Fracture Characteristics
30% Rolling	260.8	220.5	9.43	~112	~52.1	Shallow dimples, good ductility
60% Rolling	324.3	292.1	7.54	~118	~48.5	Mixed ductile–brittle fracture with evident tear ridges
90% Rolling	397.5	361.5	8.52	124.3	40.8	Cleavage-dominated, typical brittle fracture
30% Rolling + Aging	272.9	222.6	7.55	~114	~58.2	Increased dimples, slightly reduced ductility
60% Rolling + Aging	381.6	303.1	13.09	~138	~60.4	Refined dimples, significantly improved toughness
90% Rolling + Aging	411.7	364.7	25.72	127.6	63.7	Numerous uniform dimples, fully ductile fracture

Data analysis shows that although 90% cold rolling reduces the electrical conductivity to 40.8% IACS and induces brittle fracture, subsequent aging treatment—through precipitate desolution and dislocation rearrangement—not only increases the conductivity to 63.7% IACS but also enhances the elongation by 199.4%, simultaneously improving material strength and ductility. This result demonstrates that high-density dislocations act as heterogeneous nucleation sites for precipitates during aging to strengthen the matrix, while recovery and recrystallization effectively improve deformation compatibility[2]. In comparison, the strength increment after aging is the greatest at 60% deformation (+78.5 MPa), yet its overall performance remains inferior to that of the 90% deformation + aging condition. These findings indicate that large plastic deformation combined with precise aging treatment can effectively decouple the strength–conductivity trade-off in copper alloys, offering a new pathway for designing high-strength and high-conductivity materials[3].

4. Discussion and Analysis

4.1 Mechanism of the Effects of Rolling on the Electrical and Mechanical Properties of Cu-Cr-Zr Alloys

During cold rolling, high-density crystal defects are introduced, dynamically regulating the mechanical properties of the Cu-1.0Cr-0.1Zr alloy. As the deformation increases from 30% to 90%, dislocations continuously multiply and accumulate at grain boundaries and subgrain boundaries, forming dislocation entanglements that severely hinder dislocation slip, thereby causing the material strength to continuously increase[4]. Meanwhile, large strain induces grain refinement and forms a high-density dislocation network, providing abundant heterogeneous nucleation sites for Cr/Zr precipitates, promoting their dispersed and refined distribution, and further strengthening the matrix.However, defects such as dislocations and vacancies introduce lattice distortion, enhancing the scattering effect on conduction electrons. As a result, electrical conductivity decreases progressively with increasing deformation, dropping to 40.8% IACS in the 90% cold-rolled state. It is noteworthy that these defects also accelerate solute atom diffusion, promoting efficient precipitate desolution during subsequent aging and creating favorable conditions for conductivity recovery[5].

The above strengthening behavior can be quantitatively described by dislocation strengthening theory, where the strength increment follows the relation:

$$\Delta\sigma = \mathrm{Gb}\rho^{\frac{1}{2}} \tag{1}$$

In the equation, Δσ represents the yield strength increment caused by dislocation strengthening (unit: MPa); G is the shear modulus of the copper matrix (approximately 48 GPa); b is the magnitude of the Burgers vector (for FCC copper, b ≈ 0.256 nm); and ρ is the dislocation density (unit: m^{-2}). This equation indicates that the strength enhancement is proportional to the square root of the dislocation density. In

ISSN 2616-5767 Vol.8, Issue 5: 59-63, DOI: 10.25236/AJETS.2025.080508

the experiment, the significant increase in ρ under 90% deformation effectively increases Δσ, which is highly consistent with the measured tensile strength of 397.5 MPa. This mechanism illustrates how cold rolling, through the regulation of microstructural defects, contributes to enhancing material strength and provides a theoretical basis for understanding defect evolution and performance optimization during subsequent aging[6].

4.2 Mechanism of the Effects of Aging on the Electrical and Mechanical Properties of Cu-Cr-Zr Alloys

To systematically investigate the regulatory mechanism of aging treatment on the strength–conductivity synergy of the Cu-1.0Cr-0.1Zr alloy, this study, based on experimental data and theoretical analysis, constructs the following table correlating aging-induced strengthening with electrical conductivity, systematically examining the intrinsic relationship between microstructural evolution and macroscopic property response (Table 2).

Table 2. Comparison of the Effects of Aging Treatment on Precipitation Characteristics and Properties of Cu-1.0Cr-0.1Zr Alloy

Processing Condition	Average Precipitate Radius/**μm**	Precipitate Volume Fraction	Dominant Strengthening Mechanism	Yield Strength Contribution of Second Phase**$\Delta\sigma_p$/MPa**	Elongation Trend	Conductivity/ **%IACS**	Evolution of Fracture Characteristics
30% Rolling	3.17	0.0499	Weak dislocation strengthening	3.6	Good ductility	~52.1	Mainly ductile dimples
90% Rolling + Aging	0.201	0.119	Orowan bypass dominant	77.8	Significant increase (+199%)	63.7	Brittle → high-density uniform dimples

Analysis indicates that 90% large deformation introduces high-density dislocations and lattice defects, providing abundant nucleation sites for Cr atom clusters during aging, which greatly increases the number of precipitates and further refines their size[7]. The extremely fine and high-density second-phase particles have very small interparticle spacing, making it difficult for dislocations to cut through; instead, the Orowan bypass mechanism dominates the strengthening process, resulting in a $\Delta\sigma_p$ of 77.8 MPa, accounting for more than 51.5% of the total yield strength increment and serving as the main contributor to strength enhancement[8]. Simultaneously, a large number of solute atoms desolve from the Cu matrix, effectively reducing solid-solution electron scattering; combined with partial dislocation recovery and reduced vacancy concentration during aging, lattice distortion hindrance to electron migration is minimized, and electrical conductivity increases to 63.7% IACS[9].Crucially, the dispersed precipitates not only impede dislocation motion but are uniformly distributed in the matrix, suppressing local shear concentration. Together with the reduced defect density, this transforms the fracture mode from cleavage brittle fracture to fully ductile fracture, significantly increasing elongation[10]. These results confirm that large-strain cold rolling combined with precise aging can, through the mechanism of "precipitation strengthening + solid-solution purification + microstructural recovery," effectively overcome the strength–conductivity trade-off in copper alloys, achieving simultaneous optimization of high strength, high ductility, and high electrical conductivity[11].

5. Conclusions

This study systematically analyzed the synergistic regulation of microstructure and properties of Cu-1.0Cr-0.1Zr alloy by rolling deformation and aging treatment. With increasing cold-rolling deformation, the rapid rise in dislocation density leads to significant increases in strength and hardness, while enhanced lattice distortion causes a decrease in electrical conductivity. After aging treatment at 450°C for 1h, the 90% deformed sample achieved the best comprehensive performance, with a tensile strength of 411.7 MPa, elongation increased to 25.72%, and electrical conductivity restored to 63.7% IACS. The strengthening mechanism originates from the high-density, finely dispersed nanoscale Cr precipitates, which effectively hinder dislocation motion via the Orowan bypass mechanism, while solute desolution significantly reduces solid-solution scattering in the Cu matrix, achieving simultaneous optimization of strength and conductivity. These findings provide a critical processing pathway for the industrial preparation of high-strength and high-conductivity copper alloys.

ISSN 2616-5767 Vol.8, Issue 5: 59-63, DOI: 10.25236/AJETS.2025.080508

Acknowledgments

This paper was supported by the following fund project: Putian University Scientific Research Start-up Fund (No. 2024066).

References

[1] Liu Jinsong, Tang Xujing, Wang Songwei, et al. Effect of La microalloying and warm-rolling on the microstructure and properties of Cu-Cr-Zr alloys [J]. Rare Metal Materials and Engineering, 2025, 54(8): 2125–2135.

[2] Hua Siming. Effect of solution temperature on the microstructure and properties of Cu-Cr-Zr alloys [J]. Metal Heat Treatment, 2025, 50(6): 139–144.

[3] Xiang Chaojian, Lou Huafen, Zhang Xi, et al. Microstructure and properties of continuously cast–extruded Cu-Cr-Zr alloys [J]. The Chinese Journal of Nonferrous Metals, 2023, 33(6): 1821–1830.

[4] Liu Dezhi, Liu Jingang, Zhao Xingchuan, et al. Effect of directional solidification rate on the microstructure and mechanical properties of Cu-Cr-Zr alloys [J]. Special Casting and Nonferrous Alloys, 2023, 43(1): 62–67.

[5] Zhang Chenggong, Qiao Zhenxing, Shi Zhiming, et al. Effect of Yttrium on the microstructure and properties of high-strength, high-conductivity Cu-Cr-Zr alloys [J]. Journal of Chinese Rare Earths, 2024, 42(2): 294–303.

[6] Kurita Hiroki, Diguet Gildas, Froemel Joerg, Narita Fumio.Stress sensor performance of sputtered Fe-Si-B alloy thin coating under tensile and bending loads[J].Sensors and Actuators: A. Physical,2022,343-335.

[7] Song Wei, Wang Hai, Li Yi, Zhang Shuyuan, Ren Ling, Yang Ke. Ultrafine grained metastable Ti6Al4V5Cu alloy with high strength and excellent low-cycle fatigue property[J]. Journal of Materials Science and Technology,2022,240-250.

[8] Trejgis K., Ledwa K., Bednarkiewicz A., Marciniak L. Corrigendum to "Impact of host composition and dopant ion concentration on the thermometric properties of a Eu3+ activated fluoride-based single-band ratiometric luminescent thermometer"[J].Journal of Alloys and Compounds,2022,914-917.

[9] Daramola Ayobami, Fraczkiewicz Anna, Bonny Giovanni, Nomoto Akiyoshi, Adjanor Gilles, Domain Christophe, Monnet Ghiath. Atomistic investigation of elementary dislocation properties influencing mechanical behaviour of Cr15Fe46Mn17Ni22 alloy and Cr20Fe70Ni10 alloy[J].Computational Materials Science,2022,211-213.

[10] Kashkarov E.B., Sidelev D.V., Pushilina N.S., Yang J.,Tang C., Steinbrueck M. Influence of coating parameters on oxidation behavior of Cr-coated zirconium alloy for accident tolerant fuel claddings[J]. Corrosion Science,2022,20-24.

[11] A. A. Malikov, A. V. Sidorkin, V. D. Artamonov, Yu. V. Kovalev. Modeling the Efficiency of Precision Control and the Dimensional Tool Wear Index in the Shaving-Rolling Process[J].Russian Engineering Research, 2025,45(8):1139-1145.